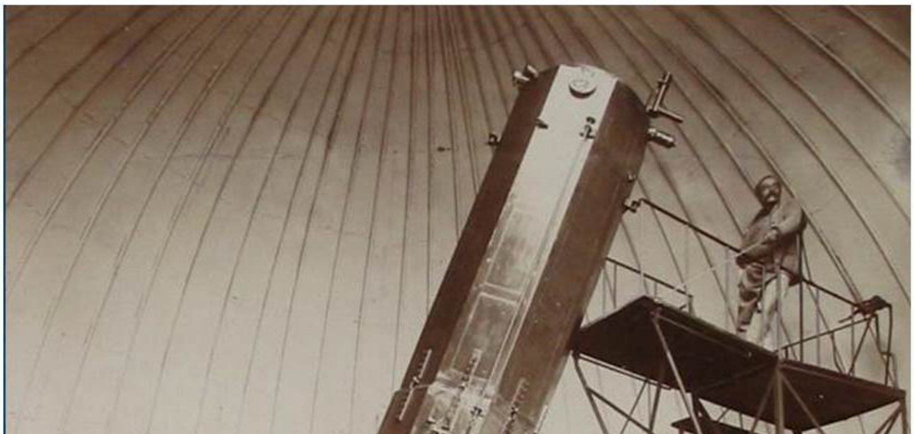
JOURNAL OF ASTRONOMICAL HISTORY AND HERITAGE



Vol. 19 No. 2 July/August 2016

JOURNAL OF ASTRONOMICAL HISTORY AND HERITAGE
ISSN 1440-2807

The *Journal of Astronomical History and Heritage* (*JAHH*) was founded in 1998, and since 2007 has been produced three times yearly, now in March/April, July/August and November/December. It features review papers, research papers, short communications, correspondence, IAU reports and book reviews.

Papers on all aspects of astronomical history are considered, including studies that place the evolution of astronomy in political, economic and cultural contexts. Papers on astronomical heritage may deal with historic telescopes and observatories, conservation projects (including the conversion of historic observatories into museums of astronomy), and historical or industrial archaeological investigations of astronomical sites and buildings. All papers are refereed prior to publication. There are no page charges, and *in lieu* of reprints authors are sent a pdf or Word camera-ready version of their paper so that they can generate their own reprints on demand.

Prospective contributors may download the 'Guide for Authors' directly from the internet by accessing http://www.narit.or.th/en/files/GuideforAuthors.pdf or request it from Professor Wayne Orchiston (wayne.orchiston@narit.or.th). Intending contributors should carefully follow these guidelines when preparing manuscripts. Papers should be emailed to Professor Orchiston, or posted to him at:

National Astronomical Research Institute of Thailand
191 Huay Kaew Road
Suthep District
Muang
Chiang Mai 50200
Thailand

Book reviews should be emailed to Dr Clifford Cunningham (asteroid4276@comcast.net).

The *JAHH* is now an electronic journal. All content back to Vol. 1 (1998) may be downloaded free of charge from either the Journal's web site at http://www.narit.or.th/en/index.php/jahh or the SAO/NASA Astrophysics Data System site (http://bit.ly/1bMwxBr) and its 11 mirror sites around the world. The electronic version of the journal will continue to be produced three times a year (nominally in April, August and December) and posted on both sites. Those who want a hard copy may print one out or have it done by their local printers. For this reason a single pdf of each entire issue (including the cover) is available on the site at NARIT.

COVER IMAGE

The 80-cm telescope delivered to Toulouse Observatory in 1875. Although construction began under Léon Foucault and Marc Secretan, neither lived to see the result. From about 1855, the pair had begun to devise and perfect silvered-glass mirrors for telescopes. This freed astronomy of an archaic speculum technology and paved the way for reflecting telescopes of 5-m and more in diameter. Read William Tobin's fascinating paper, beginning on page 106.

JOURNAL OF ASTRONOMICAL HISTORY AND HERITAGE
ISSN 1440-2807

VOLUME 19 NUMBER 2 JULY/AUGUST 2016

CONTENTS

Page

Papers

Book Reviews

Published by the National Astronomical Research Institute of Thailand, 191 Huay Kaew Road,
Suthep DistrIct, Muang, Chiang Mai 50200, Thailand.

Journal of Astronomical History and Heritage, 19(2), 106–184 (2016).

EVOLUTION OF THE FOUCAULT-SECRETAN REFLECTING TELESCOPE

William Tobin
6 rue Saint Louis, 56000 Vannes, France.
E-mail: william@tobin.fr
orcid.org/0000-0002-0533-411X

Abstract: Léon Foucault developed the silvered-glass reflecting telescope in collaboration with the instrument maker Marc Secretan. Almost immediately, they began selling 4- and 8-(French)-inch Newtonian telescopes in wooden tubes to amateurs. Several 4-inch examples have survived. As Foucault attempted to make larger diameters he moved from spherical to paraboloidal mirrors and developed tests to determine the errors of the surfaces he was polishing, of which the knife-edge test is the most informative and sensitive. The errors were then corrected with *retouches locales*, i.e. local repolishing. He also introduced the concept of *pouvoir optique*, or optical power, to characterize the performance of his mirrors. He made several professional reflecting telescopes, culminating in the 80-cm instrument now at the Marseilles Observatory. A number of his instruments are illustrated in physics textbooks of the time. Foucault predominantly adopted an *f*/6 focal ratio with a prism secondary close to the prime focus and a microscope-like eyepiece assembly to bring the image to the observer. In 1865, with Marc's son Auguste, Foucault announced a metal-mounted 10-cm alt-az amateur instrument, which soon became available in larger sizes and with equatorial mounts. Several examples survive. In 1866 the head of the Secretan workshop, Wilhelm Eichens, split from the firm. Marc died in 1867, followed by Foucault in 1868. Foucault's pupil Adolphe Martin published some of Foucault's mirror- and lens-making secrets. Martin worked with both Eichens and, episodically, the Secretan firm; but though able to figure small mirrors he proved incapable of finishing 80- and 120-cm ones begun under Foucault destined for the Toulouse and Paris Observatories. Auguste Secretan associated with Paul and Prosper Henry for mirror figuring. The Secretan offering of silvered-glass telescopes reached its apogee in 1874 with advertised diameters from 10 to 80 cm. Auguste died that year and the firm was taken over by his cousin Georges Secretan. Production of silvered-glass reflectors and other scientific instruments languished, and focal ratios slowed. Production appears to have revived after R. Mailhat became Director of the company's workshops and then founded his own firm. In 1903 the Secretan Company offered a simplified 125-mm reflector designed specially for members of the Société Astronomique de France, perhaps promoted by Georges' son Paul. Foucault-style reflecting telescopes were offered by other makers too, including Jules Duboscq, Édouard Lutz and Albert Bardou. Following Georges' death in 1906 the Company was operated by Paul before being sold to Charles Épry in 1906 who associated with Gustave Jacquelin in 1913. Only 125- to 200-mm amateur reflectors were offered in their 1924 and 1942 catalogues. Non-specific advertisements for reflectors continued beyond amalgamation with the Morin Company in 1963, but disappeared after a subsequent merger with the Société de Recherches et de Perfectionnements Industriels c.1967.

Keywords: Reflecting telescope, silvered glass, Léon Foucault, Secretan firm, Wilhelm Eichens, Adolph Martin, Henry brothers.

1 INTRODUCTION

A key step in the development of the modern telescope was the invention in 1856–1859 of the silvered-glass reflector by Léon Foucault (1819–1868; Figure 1). Reflective elements are of course exempt from chromatic aberration, and compared to speculum metal, glass permitted cheaper, lighter, stiffer and less-brittle mirrors with a smaller coefficient of thermal expansion. When darkened by sulphide, the silver surface could be renewed without the refiguring required by tarnished metal mirrors. Crucially, Foucault's method of *retouches locales,* or *local corrections* (whereby errors of form were discerned by optical testing and then corrected with local repolishing) opened the way to large apertures with fast focal ratios. (Here, and throughout this paper, all translations from the French are mine unless stated otherwise.) The superior reflectivity of silvered glass promoted the subsequent development of Cassegrain and other systems with two reflections. It is no wonder that Foucault's invention has been described by Ray Wilson, the renowned optical designer, as "... *one of the most important advances in the history of the reflecting telescope.*" (Wilson, 1996: 414; his italics).

I have outlined Foucault's development of the silvered-glass reflector elsewhere (Tobin, 1987 and especially 2003). Here I establish the advances and their chronology in greater detail, taking account of newly-discovered manuscript and printed material (e.g. Foucault, 1852–1865; 1857a; 1863; Sebert, 1867–1868).

Foucault's telescope experiments were conducted in association with the Swiss-born mathematician Marc Secretan (1804–1867; Figure 1), who was the owner of a large firm making precision instruments as well as being the Paris Observatory's official optician. Secretan was from Lausanne. He had trained as an advocate, but had taught mathematics at the Collège (now Université) de Lausanne before moving to Paris where he had partnered with the optician N.M.P. Lerebours (1807–1873). When the partnership

Figure 1: (left) Léon Foucault (1819–1868), photographed by the Paris-based Robert J. Bingham, no doubt in the 1860s (courtesy: www.thenewstribe.com); (right) Marc Secretan (1804–1867) (after: de Gramont and Peigné, 1902; courtesy: Bibliothèque Nationale de France).

expired in December 1854 he had become sole owner of the firm (Thiac, 1858), which for many years continued to invoke the name of Lerebours & Secretan in its advertising (e.g. Table 1; Brenni, 1994). At some point, Foucault entered into an exclusive contract with Secretan for the commercialization of his reflecting telescope (Rayet, 1868: 232). In this paper, I attempt to outline how the design of Foucault-Secretan reflecting telescopes evolved over time. This is interesting for at least three reasons:

(1) We can see how the design and underlying science developed.
(2) We can track how scientific and commercial constraints affected these changes and gain insights into the scientific instrument-making trade.
(3) The chronology will be useful to curators and others attempting to date and understand specific Foucault-Secretan reflectors.

We can divide such heritage instruments into three classes:

(i) There are the unique instruments that were produced by Foucault as he developed his telescope-making ideas.
(ii) There are the generally-larger telescopes produced for professional astronomers. These two categories sometimes overlap, as with Foucault's biggest and best-known telescope, the 80-cm reflector now at the Marseilles Observatory.
(iii) There are the mostly-smaller instruments sold to amateur astronomers or educational institutions.

Secretan died in June 1867, though as we shall see, he had already relinquished command of the firm to his son Auguste François (1833–1874). Foucault died the following February. This paper primarily concerns instruments developed by Foucault with Marc and Auguste Secretan. However the Secretan firm continued to trade in one form or another, advertising reflecting telescopes until the 1960s. I outline what little I have been able to discover concerning these subsequent developments, providing, I hope, a skeleton which others may be able to flesh out.

There were six principal sources of information available for putting together this narrative:

(1) Foucault's own publications and the very few of his private papers that have survived. In this context, the scientific papers inventoried after his death (Tobin, 2003: xii) include a tantalizing "List of mirrors made by Foucault" which unfortunately has not survived (Inventaire des Divers Cotes, n.d.: Cote 11ème, pièces 25 à 26).

Table 1: Catalogues by the Secretan firm and direct successors (Épry, Jacquelin) that mention silvered-glass reflecting telescopes. Several are absent from the *Handlist of Scientific Instrument-Makers' Trade Catalogues* (Anderson et al., 1990). See Notes 1–3 for how I dated undated ones. Since the 1924 and 1942 catalogues occasionally appear on sales sites such as eBay, often with wildly inaccurate date attributions, Figure 2 reproduces their covers and title pages. Trading and workshop addresses are cited because these may help in dating individual instruments accompanied by trade cards or similar documentation. The catalogue previous to the 1858 'Addition' was Lerebours and Secretan (1853), then trading from 13 Place du Pont-Neuf with workshops at 23 Rue de l'Est.

Date	Full title *Sales address* Workshop address (if given) *Location of copies*
1858	Maison Lerebours & Secretan. Secretan, Successeur. Addition relative aux nouveaux instruments d'acoustique. Janvier 1858. Addition relative aux nouveaux instruments d'optique. Errata au Catalogue de 1853. *13, place du Pont-Neuf, à Paris.* *Princeton University Library, bound with Kœnig (1873) and other ephemera (call no. ReCAP 8209.532). Available via books.google.com or www.hathitrust.org (incomplete scans).*
1868	Extrait du Catalogue de SECRETAN successeur de Lerebours & Secretan. Opticien de Sa Majesté l'Empereur, de l'Observatoire et de la Marine. Optique. – Électricité. – Calorique. – Pneumatique. – Météorologie. – Balances. – Mathématiques. – Nivellement. – Arpentage & Géodésie. – Astronomie. *Place du Pont Neuf, 13.* Rue Méchain, 9. *Bibliothèque National de France (call no. 8° WZ 3942).*
1874	Catalogue et Prix des Instruments d'optique, de physique, de chimie, de mathématiques, d'astronomie, et de marine Qui s'éxécute ou se trouvent dans les Magasins et Ateliers de SECRETAN, Successeur de Lerebours et Secretan, Constructeur d'instruments de précision à l'usage des sciences. Deuxième partie. Géodésie, Astronomie, Météorologie, Marine (appareils divers). *13, Place du Pont-Neuf.* 9, rue Méchain *Bibliothèque Nationale de France (call nos. V-52642, M-8901).*
1878a	Catalogue SECRETAN. Instruments usuels par G. Secretan, Membre de la Société de Géographie. Première partie. Optique. *13, Place du Pont-Neuf.* 28, Place Dauphine et 24, Boulevard d'Enfer. *Bibliothèque Nationale de France (call nos. 4° V 626, M-8889).*
1878b	Exposition universelle de 1878. Exposition SECRETAN. Classe 15. Par G. Secretan, Membre de la Société de Géographie. *13, Place du Pont-Neuf.* 28, Place Dauphine et 24, Boulevard d'Enfer. *Cornell University (call no QC373.06 S44). Available via www.hathitrust.org for US users only.*
1885	Maison LEREBOURS et SECRETAN. Secretan, Successeur. Catalogue illustré, orné de 569 figures. Troisième partie. Instruments de précision, comprenant: Physique générale, Chaleur, Lumière, Acoustique, Magnétisme, Électricité statique, Électricité dynamique, Mécanique, Marine, Météorologie et Instruments divers. *13, Place du Pont-Neuf.* *NOAA Central Library, Silver Spring (item No. 12307 m/0215 L 615).*
c.1898	Maison Lerebours & Secretan. G. SECRETAN S^{seur}, Opticien-Constructeur. (No further title. Cover shows a woodcut of a meridian circle and the contents relate to terrestrial and astronomical refracting telescopes, reflecting telescopes, meridian circles, accessories and sextants.) *13, place du Pont-Neuf* *Smithsonian Institution, on-line at www.sil.si.edu/DigitalCollections/Trade-Literature/Scientific-instruments . Extracts given when a copy was sold on eBay in 2008 indicate the Smithsonian copy lacks a final dozen or so pages of illustrations.*
c.1898	Maison Lerebours & Secretan. G. SECRETAN S^{seur}, Opticien-Constructeur. (No further title. Cover shows a woodcut of a meridian circle and the contents relate to terrestrial and astronomical refracting telescopes, reflecting telescopes, meridian circles, accessories and sextants.) *13, place du Pont-Neuf* *Smithsonian Institution, on-line at www.sil.si.edu/DigitalCollections/Trade-Literature/Scientific-instruments . Extracts given when a copy was sold on eBay in 2008 indicate the Smithsonian copy lacks a final dozen or so pages of illustrations.*
1901–1902	G. SECRETAN, Successeur de Lerebours & Secretan. Extraits du Catalogue de la Maison Secretan. *13, Place du Pont-Neuf* *In L'Industrie Française des Instruments de Précision (1901–1902), pp. 247–252. On-line at Digital Mechanism and Gear Library, www.dmg-lib.org and Smithsonian Institution www.sil.si.edu/DigitalCollections/Trade-Literature/Scientific-instruments .*
1906a	M^{son} Lerebours & Secretan. G. SECRETAN, Ingénieur-Opticien, S^{uccr}. Catalogue d'Astronomie & d'Optique faisant suite à celui de Géodésie. Ch. V, Astronomie; Ch. VI, Météorologie; Ch. VII, Baromètres; Ch. VIII, Jumelles & longues-vues; Ch. IX, Microscopes; Ch. X, Instruments pour explorateurs. *13, Place du Pont-Neuf.* 28, Place Dauphine et Quai de l'Horloge, 41. *Musée des Arts et Métiers, on-line at cnum.cnam.fr .*
1911a[1]	Ancienne Maison LEREBOURS et SECRETAN. G. SECRETAN. Catalogue et Prix. Ch. EPRY, Constructeur, Successeur. Geodésie, Topographie, Nivellement, Astronomie, Sciences. *Anciennement Place du Pont-Neuf 13, et Chaussée d'Antin, 11* *Actuellement Tous nos services 40, rue Hallé (XIV^{e})*

	Musée des Arts et Métiers, on-line at cnum.cnam.fr .
1915	Lerebours et Secretan. Maison fondée en 1789. SECRÉTAN. Ch. Épry & Jacquelin, Succ^{rs}. Instruments d'Astronomie. Optique Scientifique. *20, Boulevard Saint-Jacques.* *Musée des Arts et Métiers, on-line at cnum.cnam.fr .*
1924[2]	Lunettes Astronomiques. Ancienne Maison Lerebours & Secretan, Fondée en 1789. SECRETAN. Ch. Épry & Jacquelin, Succ^{rs}. *151, Boulevard Auguste-Blanqui, Paris (XIII^{E}).* 12–20, Boulevard St-Jacques. *Trilingual catalogue (French, English, Spanish), private collection of Guy Barbel.*
1942[3]	Instruments Astronomiques. Anciennes Maisons: Lerebours & Secretan fondée en 1789; Georges Prin, Successeur de W. Eichens & P. Gautier. SECRETAN, Ch. Épry & Jacquelin, Successeurs. Société à Responsabilité limitée. Capital 650 000 francs. *151, Boulevard Auguste Blanqui, Paris (XIII^{E}).* Ateliers à Cachan (Seine), 55, Rue Etienne-Dolet. *Bibliothèque Nationale de France (call no. 8° WZ 3942) and author's collection, on-line at archive.org .*

2) Advertisements and catalogues produced by the Secretan firm and others (Tables 1–4). Some of the latter have become available on-line in recent years, but the resource is limited because few relevant catalogues were produced during the years when Foucault was developing the silvered-glass telescope. And unfortunately advertisements printed on the covers of magazines have often been discarded when libraries bound individual issues into volumes, or have been bound out of order, though usefully a number of examples have been reprinted by Andrews (1994; 1996) and Thiot (1995), and some survive in the digitizations of Google Books and NASA's Astrophysics Data System.

(3) Evidence from surviving telescopes, of which I have been keeping a tally for more than two decades.

(4) Comments in the popular and specialised press, particularly by the Abbé François Moigno (1804–1884) in the weekly science reviews *Cosmos* and *Les Mondes,* which he edited and largely wrote, and by the physicist and astronomer Jacques Babinet (1794–1872) in the *Jour-*

LUNETTES ASTRONOMIQUES

Ancienne Maison
LEREBOURS & SECRÉTAN
Fondée en 1789

SECRETAN

CH. ÉPRY & JACQUELIN, SUCC^{rs}

151, Boulevard Auguste-Blanqui, 151
PARIS (XIII^{e})

Téléphone :
GOBELINS 34-87

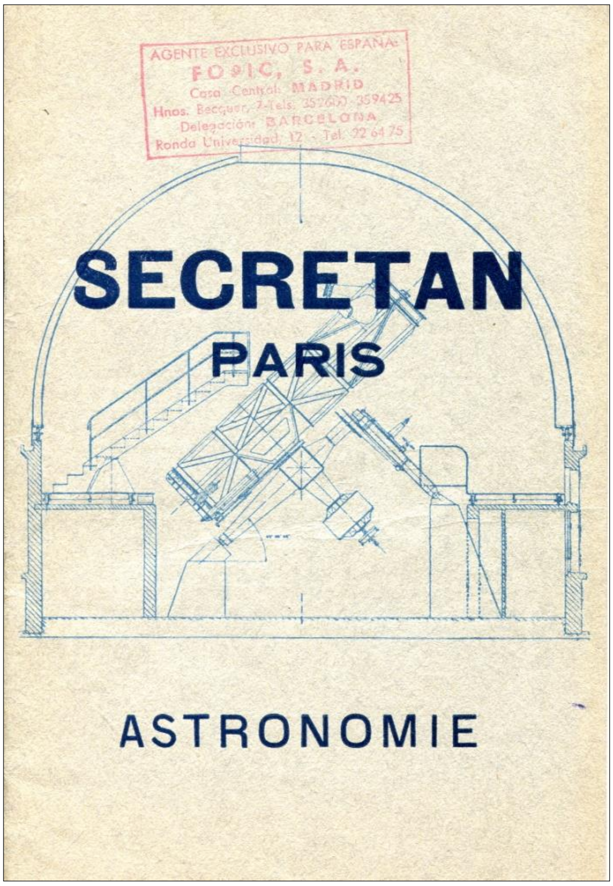
Télégrammes :
SECRÉTANUM-PARIS

ATELIERS :
12-20, Boulevard St-Jacques

Compte Postal :
PARIS 7.726

Registre du Commerce :
SEINE 15.445

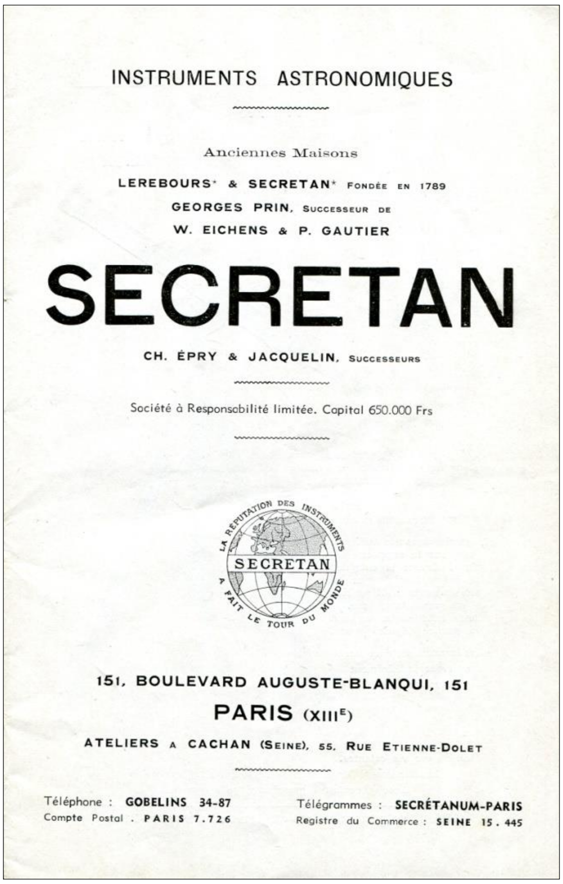
Figure 2: Covers and title pages for the Secretan catalogues first published in 1924 (this page) and 1942 (on page 110). The former were later distributed with overstamped dates of 1926 (buff wrappers) and 1929 (blue wrappers); a similar fate probably befell the latter catalogue too (after: eBay advertisements and author's collection).



AGENTE EXCLUSIVO PARA ESPAÑA:
FOSIC, S. A.
Casa Central: MADRID
Hnos. Becquer, 7 - Tels. 352600 - 359425
Delegación: BARCELONA
Ronda Universidad, 12 - Tel. 22 64 75

SECRETAN
PARIS

ASTRONOMIE



INSTRUMENTS ASTRONOMIQUES

Anciennes Maisons
LEREBOURS* & SECRETAN* FONDÉE EN 1789
GEORGES PRIN, SUCCESSEUR DE
W. EICHENS & P. GAUTIER

SECRETAN

CH. ÉPRY & JACQUELIN, SUCCESSEURS

Société à Responsabilité limitée. Capital 650.000 Frs

LA RÉPUTATION DES INSTRUMENTS SECRETAN A FAIT LE TOUR DU MONDE

151, BOULEVARD AUGUSTE-BLANQUI, 151
PARIS (XIII^{E})
ATELIERS A CACHAN (SEINE), 55, RUE ETIENNE-DOLET

Téléphone : GOBELINS 34-87
Compte Postal . PARIS 7.726
Télégrammes : SECRÉTANUM-PARIS
Registre du Commerce : SEINE 15 . 445

nal des Débats, a daily Parisian newspaper for which Foucault also wrote until 1862.

(5) The accounts and administrative correspondence of the Paris Observatory, which have recently become available to researchers.

(6) Perhaps unexpectedly, there are illustrations and descriptions in contemporary physics textbooks. Indeed, it was once I had understood that some of these descriptions related to unique instruments, rather than to commercial models (cf. Section 6 below), that the available information fell into a reasonably coherent pattern and I was prompted to write this paper.

Nevertheless, the evidence is often fragmentary, so the reader must keep in mind that as additional details become available, some of what follows may need revision.

To keep the main text short and readable, I relegate many of the details to Notes. Numerous illustrations are provided to help curators and others evaluate any newly-discovered Foucault-Secretan telescope. It should be noted that in French the word 'télescope' has become specific to a reflecting telescope and will be used in this sense here. A refractor is a 'lunette'.

Table 2: Dimensions (as given), prices and other details for silvered-glass telescopes and unmounted mirrors advertised in Secretan and successors' catalogues, as cited in Table 1. All are mounted in metal unless preceded by 'W' indicating a wooden mount. Figure numbers refer to this paper and indicate woodcuts that illustrated the catalogues.

Catalogue	Alt-azimuth mounting	Equatorial mounting
1858 *See also Figure 5*	W, 108 mm, 250 fr, Figure 5 W, 216 mm, 1,600 fr	
1868	10 cm, 550 fr, Figure 51	16 cm, 1,800 fr W, 16–80 cm, 1,600–25,000 fr, Figures 50 and 34
	Silvered, parabolized mirrors: "...200 fr per square of 10 centimetres..."	
1874 *See also Appendix 2*	10 cm, 500 fr, Figure 51 160 mm, 1,200 fr 200 mm, 2,000 fr	6 cm, 1,800 fr 16 cm, motorized, 2,500 fr 20 cm, motorized, 4,500 fr 30 cm, motorized, 9,000 fr 40 cm, motorized, 18,000 fr

		50 cm, motorized, 35,000 fr W, 16 cm, 1,650 fr, Figure 50 W, 16 cm, motorized, 2,350 fr W, 20 cm, motorized, 4,000 fr W, 30 cm, motorized, 6,000 fr W, 40 cm, motorized, 9,000 fr W, 50 cm, motorized, 13,000 fr W, 80 cm, motorized, 29,000 fr, Figure 34
	Silvered, parabolized mirrors: 150 fr per 10-cm x10-cm square circumscribing the mirror	
1878a *Instruments usuels*	10 cm, 500 fr, Figure 51 160 mm, 1,200 fr 200 mm, 2,000 fr	“See our astronomy catalogue (1874) for all instruments of position”
	Silvered, parabolized mirrors: diameter 10 cm, 150 fr; 16 cm, 385 fr; 20 cm, 600 fr; 30 cm, 935 fr; 40 cm 2,400 fr; 50 cm, 3,750 fr; 60 cm, 5,400 fr; 80 cm, 12,000 fr	
1878b *Exposition universelle*	Figure 51 “In my 1878 catalogue will be found all the instruments for elementary astronomy, and in my 1874 catalogue all those, so-called ‘of position,’ for the use of observatories ...”	
1885	10 cm, 500 fr 160 mm, 1,200 fr 200 mm, 2,000 fr “For more details, see our 1878 catalogue...”	
c.1898	100 mm, 450 fr, Figure 51 135 mm, 750 fr 160 mm, 1,000 fr 200 mm, 1,750 fr “The focal lengths initially adopted have been increased to improve the image and permit celestial photography.”	
	Telescope mirrors: diameter 100 mm, 80 fr; 135 mm, 150 fr; 160 mm, 200 fr; 180 mm, 260 fr; 200 mm, 320 fr; 225 mm, 500 fr; 250 mm, 675 fr; 300 mm, 800 fr; 400 mm, 1,300 fr.	
1901–1902	“Foucault telescopes with silvered-glass mirrors”	
1906a	100 mm, 450 fr, Figure 51, plus two others with full tripod and table mount 125 mm, 750 fr 160 mm, 1,000 fr 200 mm, 1,750 fr 125 mm “specially destined for members of the Société Astronomique de France”, 300 fr, Figure 84.	100 mm, 1,000 fr 125 mm, 1,300 fr 160 mm, 1,800 fr 200 mm, 3,800 fr
	Telescope mirrors: diameter 100 mm, 80 fr; 125 mm, 150 fr; 150 mm, 200 fr; 200 mm, 320 fr; 225 mm, 550 fr; 250 mm, 550 fr; 300 mm, 750 fr; 400 mm, 1,300 fr	
1911a	160 mm, f/6, 1,000 fr 200 mm, f/6, 1,750 fr 250 mm, f/6, 2,600 fr 125 mm, f/8, Société Astronomique de France, 450 fr	
1915	Figure 86 (left, centre) 100 mm, 425 fr; fine adjustments, 605 fr 125 mm, 520 fr; fine adjustments, 700 fr 140 mm, 690 fr; fine adjustments, 870 fr 160 mm, 1,000 fr; fine adjustments, 1,200 fr 180 mm, 1,360 fr; fine adjustments, 1,560 fr 200 mm, 1,830 fr; fine adjustments, 2,500 ft Eyepieces sold separately, 15 fr each.	Figure 86 (right)
	Parabolic mirrors: diameter 70 mm, 75 fr; 80 mm, 100 fr; 110 mm, 150 fr; 125 mm, 200 fr; 130 mm, 225 fr; 140 mm, 275 fr; 160 mm, 375 fr; 200 mm, 600 fr; 250 mm, 900 fr; 300 mm, 1,400 fr; 350 mm, 2,000 fr; 400 mm, 2,600 fr	
1924	Figure 86 (left, centre) 125 mm, 2,000 fr; fine adjustments, 2,500 fr 140 mm, 2,750 fr; fine adjustments, 3,250 fr 160 mm, 4,000 fr; fine adjustments, 4,750 fr 200 mm, 7,000 fr; fine adjustments, 8,000 fr	Figure 86 (right)
1942	Figure 86 (centre) 125 mm, fine adjustments 160 mm, fine adjustments 200 mm, fine adjustments The 160-and200-mm instruments have plane-mirror secondaries rather than a prism.	

Table 3: Catalogues by other Parisian instrument makers that include silvered-glass telescopes, up until the early 20th century.

Date	Full title *Sales address* Workshop address (if given) *Location of copies*
1860 Chevalier	Catalogue explicatif et illustré des instruments d'optique et de météorologie usuelles de la Maison Charles-Chevalier, ingénieur. *158, Palais Royal* 1bis, Cour des Fontaines, près le Palais-Royal (Ci-devant quai de l'Horloge) *Bibliothèque Nationale de France (call no. 8° W 6070) and on-line at Smithsonian Institution, www.sil.si.edu/DigitalCollections/Trade-Literature/Scientific-instruments .*
1864 Duboscq	Catalogue systématique des Appareils d'Optique construits dans les ateliers de J. Duboscq, élève et successeur de M. Soleil. *21, Rue de l'Odéon* *Bibliothèque Nationale de France (call no. 8° V 4382) and on-line at Musée des Arts et Métiers, cnum.cnam.fr .*
1867 Duboscq	Catalogue systématique des Appareils d'Optique construits dans les ateliers de J. Duboscq, élève et successeur de M. Soleil. *21, Rue de l'Odéon* *Bibliothèque Nationale de France (call no. 8° V 4382) and on-line at Musée des Arts et Métiers, cnum.cnam.fr .*
1870 Duboscq	Catalogue systématique des Appareils d'Optique construits dans les ateliers de J. Duboscq, élève et successeur de M. Soleil. *21, rue de l'Odéon* *Bibliothèque Nationale de France (call no. 8° V 4382) and on-line at Smithsonian Institution, www.sil.si.edu/DigitalCollections/Trade-Literature/Scientific-instruments .*
1872 Lutz	Catalogue des instruments d'optique construits par Édouard Lutz, opticien fabricant. *49, Boulevard Saint-Germain (49, Rue des Noyers)* *Bibliothèque Nationale de France (call no. 8° V 4382) and on-line at Smithsonian Institution, www.sil.si.edu/DigitalCollections/Trade-Literature/Scientific-instruments .*
1874 Picart	Catalogue alphabétique des appareils d'optique, polarisation, projections, lumière, microscopes construits par A. Picart *20, Rue Mayet, Faubourg Saint-Germain, ci-devant, Boulevard de Montparnasse, 38* *Bibliothèque Nationale de France (call no. 8° V 4382).*
1876 Duboscq	Catalogue systématique des Appareils d'Optique construits dans les ateliers de J. Duboscq, élève et successeur de M. Soleil, père. *21, Rue de l'Odéon* 30, Rue Monsieur-le-Prince *Bibliothèque Nationale de France (call no. 8° V 4382) and on-line at Musée des Arts et Métiers, cnum.cnam.fr .*
1882 Lutz	Catalogue des instruments d'optique construits par Édouard Lutz, opticien fabricant. *82, Boulevard Saint-Germain* *Bibliothèque Nationale de France (call no. 8° V 4382) and Musée National de l'Éducation, Rouen (call no. 2006.06403).*
1885 Duboscq	Maison Jules DUBOSCQ fondée, en 1819, par SOLEIL père. Historique & Catalogue de tous les instruments d'optique supérieure appliqués aux science et à l'industrie. *21, Rue de l'Odéon* *Bibliothèque Nationale de France (call no. 8° V 4382) and on-line at Smithsonian Institution, www.sil.si.edu/DigitalCollections/Trade-Literature/Scientific-instruments .*
1889 Pellin	Maison Jules DUBOSCQ Fondée, en 1819, par SOLEIL Père. Ph. PELLIN, Ingénieure civil, Successeur. Historique & Catalogue de tous les Instruments d'Optique supérieure appliqués aux science & à l'industrie. *21, Rue de l'Odéon* *Musée des Arts et Métiers, on-line at cnum.cnam.fr .*
c.1890 Lutz	Extrait du Catalogue générale des instruments d'optique construits par Édouard Lutz, Opticien, Officier de l'instruction publique. *65, Boulevard Saint-Germain* 65, Boulevard Saint-Germain *Author's collection, on-line at archive.org .*
1892 Bardou	Instruments d'Optique. A. Bardou. Prix Courant. *55, Rue de Chabrol* *Collection of P. Brenni.*
1893 Ducretet & Lejeune	Catalogue des Instruments de Précision de E. Ducretet & L. Lejeune. Première et deuxième partie. Physique Générale. *75, Rue Claude Bernard, Paris* *University of Michigan, on-line at archive.org .*
1899 Bardou	Instruments d'optique. Maison Bardou Fondée en 1819. J. Vial, Ing^{r} E.C.P. Successeur. Fourunisseur du Ministère de la Guerre, du Ministère de la Marine et des Gouvernements étrangers. *59, rue Caulaincourt (Ci-devant 55, rue de Chabrel), Paris.* *Sold on eBay in 2016. Seller's extracts on-line at archive.org .*

1900 Pellin	Instruments d'Optique Et de Précison. Ph. Pellin, Ingénieur des Arts et Manufactures. Successeur de Jules Duboscq. V^{e} Fascicule. Réflexion – Réfraction – Vision. *21, rue de l'Odéon* 30, rue Monsieur-le-Prince *Smithsonian Institution, on-line at www.sil.si.edu/DigitalCollections/Trade-Literature/Scientific-instruments . Lacks covers.*
1905 Ducretet	Catalogue raisonné des Instruments de Précision de E. Ducretet. Première et Deuxième parties. Physique Générale. 5ème édition. *75, Rue Claude Bernard, Paris* *Musée des Arts et Métiers, on-line at cnum.cnam.fr .*
c.1908 Mailhat	Ateliers de Mécanique et Optique pour les Sciences et l'Industrie. R. Mailhat, Constructeur. *41, Boulevard Saint-Jacques, Paris (14^{e})* *Erfgoedbibliotheek Hendrik Conscience, Anvers (Antwerp). This copy is overstamped "ACTUELLEMENT 10, Rue Emile-Dubois & 25, Rue de la-Tombe-Issoire PARIS (14^{e})", the addresses given by Mailhat (1909).*
c.1913 Mouronval	Mécanique & Optique pour les Sciences et l'Industrie. Ateliers R. MAILHAT, Ex-Directeur et aquéreur des Anciens Ateliers Secrétan. MOURONVAL Successeur, Ancien élève de l'École polytechnique. Catalogue d'Astronomie A2. *Formerly: 30, Rue du Faub^{g} St-Jacques & 41, Boul^{d} St-Jacques.* *Currently: 10, Rue Émile-Dubois, Paris (XIV^{e}).* *Musée des Arts et Métiers, on-line at cnum.cnam.fr .*

Table 4: Dimensions (as given), prices and selected other details for silvered-glass telescopes advertised in the catalogues listed above in Table 3. Figure numbers refer to this paper and indicate woodcuts or photographs that illustrate the catalogues.

Catalogue	
1860 Chevalier	"NEW TELESCOPE WITH MIRRORS, In silvered glass, M. Léon Foucault's system. This system promises great services in astronomy, because one can now make big telescopes much more easily than with completely dioptric designs. 200. M. Léon Foucault's Télescope, of 108 mm aperture, 52 cm focal length, with stand. 250 fr"
1864 Duboscq	"282. Silvered-glass mirrors with correctly spherical, elliptical or parabolic surfaces. (M.L. Foucault's local-correction method.) 81 mm diameter 625 [mm] focal length 200 fr 108 mm " " " 250 " 135 mm " 810 " 350 " 160 mm " 920 " 500 " 283. Telescopes of L. Foucault's system having the diameters and focal lengths indicated above."
1867 Duboscq	"283. Telescopes of L. Foucault's system having various diameters and focal lengths."
1870 Duboscq	"266. Telescopes of L. Foucault's system, having various diameters and focal lengths." (A handwritten annotation indicates prices from 500 to 3,000 fr.)
1872 Lutz	166. Foucault system telescopes with the same diameters, focal lengths and prices as given for mirrors alone in Duboscq's 1864 catalogue. "167. Foucault telescope. – M. Bourbouze's arrangement. The mirror can be replaced by an achromatic objective. – One can screw on a straight-through eyepiece so as to transform the *télescope* into a field or astronomical *lunette*. The same eyepiece can serve as a microscope. The objective can be mounted on a separate stand for projection experiments. It can also be used for photography 600 fr."
1874 Picart	"Telescope, M. Foucault's, 0^{m} 10 diameter 550 fr idem idem 0^{m} 16 diameter 1,200 fr idem idem 0^{m} 20 diameter 2,000 fr"
1876 Duboscq	"231*bis.* Foucault system telescopes, according to diameter and focal length of the mirrors. From 500 to 4,000 fr."
1882 Lutz	"240. Foucault telescope – Figure 90 (top) – The instrument's body is in brass, polished and varnished, or varnished matt black. It is suspended by two steel trunnions which engage in two pierced cast-iron risers, between which the body of the instrument passes freely. These two risers are attached to a moving circular base set on a cast-iron triangular foot, with three levelling screws, which can be placed on a table such that the horizon or the zenith can be scrutinized in every direction by seated or standing observer. The finder placed looks as good in a drawing room as in a physics laboratory, can replace a telescope that is seven near the mirror is easy to use for astronomical pointing. This instrument, easily portable, which or eight times more voluminous, costing three times as much. 241. Foucault telescope. – New very portable model, with finder, 80-mm diameter mirror, 1 terrestrial and 2 astronomical eyepieces magnifying from 80 to 200 times, mounted on a pillar and cabriole legs in brass, carrying box. 350 fr. 242. Foucault telescope, with finder, 105-mm (4-*pouce*) mirror, 1 terrestrial and 3 astronomical eyepieces magnifying from 80 to 300 times, divided altitude circle, mobile base on triangular cast-iron foot with 3 levelling screws. Figure 90 (top). 700 fr."

	243. As 242, except 135-mm (5-*pouce*) mirror, 4 astronomical eyepieces, magnifications 100–450. Divided azimuth scale and stop button. Figure 90 (top). 900 fr. 244. As 243, except 140-mm (5½-*pouce*) mirror, magnifications 150–550. 1,000 to 1,500 fr. 245. As 167 in 1872 catalogue, but without mention of Bourbouze. 700 to 800 fr.	
1885 Duboscq	"368. Telescopes of L. Foucault's system, according to diameter and focal length of the mirrors, from 500 to 4,000 fr."	
1889 Pellin	"574. Telescope with Foucault mirror of 0^m.10 opening, two eyepieces (model in wood 300 fr 575. Telescope with Foucault mirror of 0^m.10, model in brass, with finder, Figure 51 500 fr 576. Telescope with 0^m.16 mirror 1,100 fr 577. Telescope with 0^m.20 mirror 2,000 fr All the instruments in the present Catalogue are made in our Workshops. The instruments are marked M^{on} Jules Duboscq Ph. Pellin"	
c.1890 Lutz	149. As No. 241 in 1882 catalogue. 350 fr. 150. As No. 242 in 1882 catalogue. Figure 90 (top). 700 fr. "151. Bigger telescopes, according to the diameter 900 to 1,500 fr."	
1892 Bardou	"AZIMUTHAL TELESCOPES with silvered glass mirror 45. Telescope with finder; glass mirror of 10-cm diameter, parabolized and silvered; mounted in cast iron, six-branched stand for observing standing up; three eyepieces magnifying from 50 to 200 times. Figure 51. 450 fr." 46. As No. 45, except 16-cm mirror, 60–300 magnifications 1,050 fr. 47. As No. 45, except 20-cm mirror, 65–400 magnifications 1,800 fr. "EQUATORIAL TELESCOPES Mounting in metal 48. Telescope with finder with prism; glass mirror of 16-cm diameter, parabolized and silvered; equatorial mounting; 20-cm declination circle; hour-angle circle 37-cm in diameter; 4 eyepieces magnflying from 60 to 300 times; Figure 92"	
1893 Ducretet & Lejeune (Froment successor)	"Foucault telescope with 10-cm diameter mirror, silvered by Foucault's process. Mounted in cast iron. Supplementary foot. Four eyepieces. Finder. Dark glass for the Sun. 600 fr." Motorized equatorial mount and direct vision spectroscope available separately.	
1900 Pellin (Duboscq successor)	"206. Telescope with Foucault mirror, mounted azimuthally, with finder, 100-mm diameter mirror, 3 eyepieces magnifying from 50 to 200 times. 490 fr. Figure 51. 207. Telescope ditto, 160-mm diameter mirror, 3 eyepieces magnifying from 60 to 300 times. 1,200 fr. 208. Telescope ditto, 200-mm mirror, 3 eyepieces magnifying from 65 to 400 times. 2,000 fr."	
1905 Ducretet	As in 1893 catalogue	
	Alt-azimuth mounting	Equatorial mounting
c.1908 Mailhat	Figure 51 100 mm, 475 fr 135 mm, 825 fr 160 mm, 1,100 fr 180 mm, 1,450 fr 200 mm, 1,850 fr 225 mm, 2,350 fr 250 mm, 2,850 fr All come with a squat, 3-legged foot; the two smallest sizes have an interchangeable tripod	Figure 83 100 mm, 1,700 fr 135 mm, 2,000 fr 160 mm, 2,500 fr 180 mm, 3,500 fr 200 mm, 4,440 fr 225 mm, 5,500 fr 250 mm, 7,000 fr
	"The focal length is about 7 times the diameter of the mirror"	
c.1913 Mouronval	Figure 51 100 mm, 375 fr without foot, 475 fr with 135 mm, 680 fr without foot, 825 fr with 160 mm, 940 fr without foot, 1,100 fr with 180 mm, 1,260 fr without foot, 1,460 fr with 200 mm, 1,630 fr without foot, 1,850 fr with 225 mm, 2,090 fr without foot, 2,350 fr with 250 mm, 2,530 fr without foot, 2,850 fr with 275 mm, 3,110 fr without foot, 3,500 fr with 300 mm, 3,900 fr without foot, 4,350 fr with "We also make Cassegrain types... We also make these telescopes with a simplified mount, a wooden mount, etc."	Engraving of Figure 83 Available for fixed or variable latitude, and optionally with slow motions in hour angle only, with slow motions and divided circles on both axes, and with a clockwork motor. Sample prices: 100-mm mirror, fixed latitude, no options 800 fr, full options 1,650 fr; corresponding variable-latitude prices 900 and 1,780 fr. For a 200-mm mirror respective prices are 2,500, 3,950, 2,775 and 4,285 fr. For a 300-mm mirror, 5,700, 8,200, 6,200 and 8,840 fr.

2. SPHERICAL MIRRORS

2.1 The First Reflector

Foucault was appointed as Paris Observatory's physicist in 1855 as part of the reorganisation concomitant with the appointment of a new Director, Urbain Le Verrier (1811–1877), of Neptune-discovery fame (e.g. Lequeux, 2009a; Tobin, 2003). An immediate task, which Foucault never completed, was to figure a pair of 29-inch (74- or 75-cm) diameter crown and flint glass discs into a telescope objective. For lens testing Foucault knew he would need a collimator, but this led to a vicious circle, since a collimator lens could not be tested without another collimator. However a mirror can be self-tested by placing a pinprick light source close to its centre of curvature and using a microscope to examine the tightness and symmetry of the resulting neighbouring image. Foucault tried to make a metal collimator mirror, but quickly switched to glass as a substrate, which he knew could be made reflective via the chemical deposition of silver from unheated silver nitrate solution using a process discovered in the 1830s by the German chemist Justus von Liebig (1803–1873). Foucault had written about the procedure in 1845 (Foucault, 1845) and five years later had employed silvered glass for his fingernail-sized spinning mirror used to compare the speeds of light in air and water (Tobin, 1993). Getting a good silver layer on a bigger surface was more difficult, however, and it took six months to master the process (Foucault, 1857a), which he improved in coordination with a Mr Robert and a Mr James Power, the licensees in Paris of patented improvements to a procedure devised by a certain Thomas Drayton of Brighton in England.[4] When the Scottish physicist Sir David Brewster (1781–1868) visited Foucault in June 1857, he was shown the entire process. “After deposition the silver surface is slightly rough,” he noted, “or rather not well polished, but it is polished to perfection by a little cotton and a small quantity of rouge.” (Gordon, 1869: 282). A few months later Foucault visited Sir John Herschel (1792–1871) in England and gave him a small mirror (Figure 3) and a piece of platinized glass which appear to reflect his investigations into ways to make glass reflective (Thoday, n.d.).

Of course a collimator mirror can equally act as a telescope mirror. As Foucault wrote (1857b: 339) “... the collimator in turn became a new telescope.”

Figure 3: Tarnished silvered mirror roughly 100 mm in diameter given to Sir John Herschel when Foucault visited him at Collingwood on 11 September 1857. The mirror is much faster than those made by Foucault for astronomical use, who also gave Herschel a sector of platinized glass. The interest appears to have been methods for making glass reflective. The two items are now in the Science Museum, London, inventory 1943-55 (author’s photograph).

Foucault presented his first, small telescope at the end of January 1857 to a Saturday-night meeting of the Société Philomathique (Foucault, 1857c; 1857d) and a fortnight later in a written note sent to the more-austere Académie des sciences (Foucault, 1857b; 1857e). Reporting on the meeting, Babinet wrote “Amongst astronomical news, I see nothing more important than the new type of reflecting telescope devised by M. [Monsieur] Foucault ...” (Babinet, 1857a). Foucault told the Academy that his telescope had a “... 10-cm diameter ...” and a 50-cm focal length (Foucault, 1857b: 340), values repeated later (Foucault, 1859a). But elsewhere (correcting an obvious misprint) he wrote that the instrument had a “... useful ...” (Foucault, 1857a) or “... real ...” (Foucault, 1858a: 47; or 1858b) diameter of 9 cm, and when what was presumably the same instrument was taken to observe the total solar eclipse in Spain in 1860, it was inventoried as of 11-cm size (Enumération des objets, 1860). In his *Mémoire* on telescope making published in early 1860, Foucault added that mounted as a Newtonian, the mirror he had shown at the Académie “... gave good images and permitted magnifications of 150–200 times … It has been preserved as the first example that was presented to a learned society.”[5] (Foucault, 1859a: 198).

Figure 4 shows a small Newtonian telescope conserved at the Paris Observatory. The associated transport box has “L. Foucault” written on it in his handwriting. Besides being fitted-out to accept the telescope, the box has space for three

Figure 4: Probably Foucault’s first telescope from January 1857 (Paris Observatory inv. 251). The aperture stop that slots at the front of the mirror cell has been raised to be more evident. Its diameter is 3¼ French inches (*pouces)* or 88 mm. The focal length of the mirror is 530 mm, corresponding to an *f*/6.0 focal ratio (courtesy: Observatoire de Paris/F. Auffret).

Table 5: Sizes of astronomical objective lenses offered by Secretan in 1868.

Diameter specified In catalogue	0m11	0m135	0m16	0m19	0m217	0m244	0m27	0m30	0m325	0m35	0m38
Supposed (pouces)	4	5	6	7	8	9	10	11	12	13	14
actual diameter (mm)	108.3	136.3	162.4	189.5	216.6	243.6	270.7	297.8	324.8	351.9	379.0

eyepieces. The woodwork of the telescope tube is simple, and there is no stand, indicative of a prototype. I think it probable that this is Foucault's first telescope, at least as far as the mounting is concerned, but that the mirror could be one of at least two produced at about the same time, as I explain in a footnote.[6] Inside the tube, a metal arm survives which once held a reflective prism to turn the light through 90° towards the eyepiece assembly, which, like the prism, has been lost. The idea of using a prism dates back to Newton in 1672 (e.g. Cohen, 1993) and optical layouts using prisms were published in his *Opticks* in 1704 and later in Diderot and D'Alembert's *Encyclopédie* (1767). I will discuss Foucault's prism and eyepiece choices further in Sections 2.3.1 and 2.3.2.

Why is there a multiplicity of quoted sizes—9, 10 and 11 cm—and how might they square with the internal diameter of the mirror cell and full diameter of the mirror shown in Figure 4, which are 121.5 mm?

A first point to consider is that Foucault would almost certainly have used a glass blank from Secretan's optical shop. Table 5 lists Secretan's lens sizes from the very-detailed catalogue "Extract ..." published in 1868 (see Table 1). The stated metric dimensions seem strange until it is realized that they actually correspond to integral numbers of French inches (≡ 27.069 mm), which to avoid confusion with Imperial units, I will henceforth refer to as *pouces.* (The glassmaker Georges Bontemps (1799–1883) confirms that "... opticians have generally kept the use of *pouces* for objective diameters." (Bontemps, 1868: 690).) The *pouce* was divided into 12 *lignes,* so we can expect to find halves, thirds, quarters and sixths as common divisions. Foucault's 121.5-mm glass blank is not a dimension appearing in Table 5, but does correspond closely to 4 *pouces* 6 *lignes*, or 4½ *pouces*.

For any reflecting telescope, there is an inevitable ambiguity concerning the term 'diameter'. Does a numerical value refer to the full dimension of the mirror, to the diameter to which it is stopped down in its mount, to the entrance aperture if not defined by the mirror stop, or even to the inner or outer diameters of the tube, which are easy to measure and may plausibly be given in descriptions published in auction-house or similar catalogues? For Foucault's 11 and 9 cm, the answer would seem to be that the lip against which the mirror would have rested has an inner diameter of 112 mm, while the inner diameter of the sliding stop is 88 mm (my measurements), the aperture at which Foucault ultimately used his telescope. Further, 112 and 88 mm correspond closely to 4¹/₆ and 3¼ *pouces.* This use of pre-revolutionary units was not limited to optics. Tobin et al. (2007) have shown that this was also the case for the pendulum bobs engineered by Gustave Froment (1815–1865) with which Foucault made his famous public demonstrations of the Earth's rotation in 1851 and 1855. It is also apparent that Foucault liked round, even numbers, preferring to state the 6⅓ *pouces* (172 mm) of his Panthéon bob as 18 rather than 17 cm. Characterising his first telescope as '10-cm' falls into this tradition, and we shall see or suspect similar fuzziness in the characterisation of other telescopes. Already the stated 50-cm focal length gives a second example. Barrose (pers. comm., 2002) has tested the mirror shown in Figure 4. Its focal length is actually 530 ± 0.5 mm. The edges are turned down over at least 1 cm, consistent with ultimately stopping it down to less than 10 cm for good performance. With an 88-mm stop, the mirror was used at *f*/6.0.

2.2 Larger Apertures

Foucault had shaped his 10-cm mirror using the standard optical-fabrication procedure of the time. A copper 'ball' and 'basin' were turned to approximately the desired mirror curvature on a lathe. They were then worked against each other using progressively finer emery until they slid over each other with equal ease in all directions, indicating matched spherical surfaces. Next the mirror blank was ground against the ball until it too matched. The ball was then covered with paper which acted as a matrix to hold the finer, softer rouge used to polish the mirror surface (Foucault, 1859a). Three months after presenting his first telescope, Foucault (1857a) reported using the same procedures to complete a 16-cm mirror with a 1.50-metre focal length (~f/9). (Later he claimed "... a real aperture of $0^{m}.18$ ..." (Foucault 1858a: 47; or 1858b), and even later stated that he had made a 22-cm mirror with 1.5-m focal length (Foucault, 1859a: 198). Was he misquoting from memory, or were there several mirrors?) At the same time, he was busy working on a mercury switch for spark coils and an improved Nicol-type polarizing prism, followed by an overseas trip to show off his telescope and prism at the Dublin meeting of the British Association for the Advancement of Science.[7] Perhaps this was why the first test on the sky of what populariser Moigno described as a mirror of "... seven *pouces*, approximately eighteen centimetres ..." was not until 24 September 1857, ten days after Foucault's return to Paris (Moigno, 1857a):

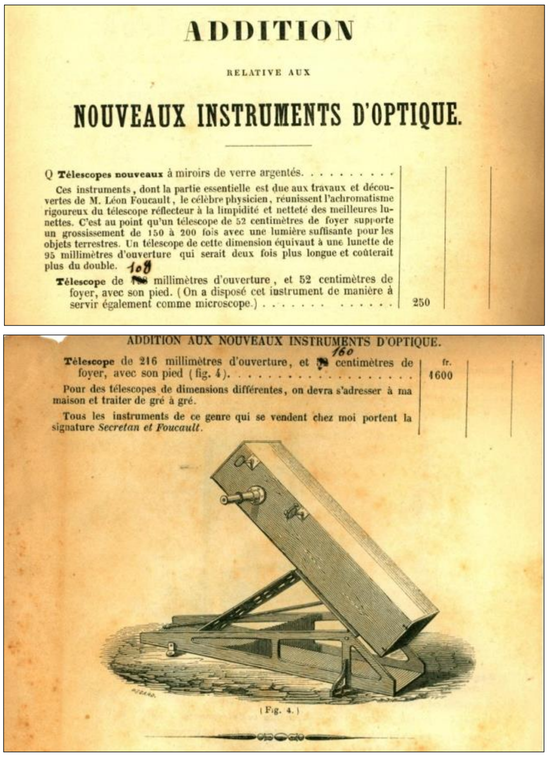
> … Seen in this second mirror, Jupiter was a magnificent sight; we saw distinctly five distinct equatorial belts with different widths and perfectly outlined … the instrument easily provided real magnifications of 2 to 300 times; stars appeared very round and perfectly defined in the eyepiece; the amount of light was considerably more than with the previous mirror type [metal].

Seven *pouces* is actually 189.5 mm. Perhaps initially only the interior 6 *pouces* (16 cm) were well formed.

2.3 Small Telescopes for Sale

Foucault and Secretan now had a product to sell. Babinet continued to mention Foucault's telescope in his newspaper column: in November 1857 he praised its performance on land and sky, for perceiving ships at night, and even for scrutinizing insects "... at a small distance ..." (Babinet, 1857b). Two months later Secretan published a 4-page addition to his catalogue in which Foucault telescopes were advertised, including a woodcut (Table 1; Figure 5).

Produced perhaps in haste, the 'Addition' contains a number of errors. The advertisement, minus the engraving, was repeated on a flyleaf of a brochure published in August 1858, which confirms the penned-in corrections seen in Figure 5 (Lissajous, 1858: 13).[8] The advertised *ouvertures* (apertures) of 108 and 216 mm are indubitably 4 and 8 *pouces,* with focal lengths corresponding to 19 (or perhaps 19½) and 60 *pouces*, respectively. Foucault himself was more circumspect concerning the apertures: in May (1858a: 47; or 1858b) he announced "... real apertures ..." of 9 and 18 cm, and (no doubt rounded) focal lengths of 0.50 and 1.50 m, respectively.



ADDITION

RELATIVE AUX

NOUVEAUX INSTRUMENTS D'OPTIQUE.

Q **Télescopes nouveaux** à miroirs de verre argentés. . . . .

Ces instruments, dont la partie essentielle est due aux travaux et découvertes de M. Léon Foucault, le célèbre physicien, réunissent l'achromatisme rigoureux du télescope réflecteur à la limpidité et netteté des meilleures lunettes. C'est au point qu'un télescope de 52 centimètres de foyer supporte un grossissement de 150 à 200 fois avec une lumière suffisante pour les objets terrestres. Un télescope de cette dimension équivaut à une lunette de 95 millimètres d'ouverture qui serait deux fois plus longue et coûterait plus du double.

Télescope de 108 millimètres d'ouverture, et 52 centimètres de foyer, avec son pied. (On a disposé cet instrument de manière à servir également comme microscope.) 250

ADDITION AUX NOUVEAUX INSTRUMENTS D'OPTIQUE.

Télescope de 216 millimètres d'ouverture, et 160 centimètres de foyer, avec son pied (fig. 4). . . . . fr. 1600

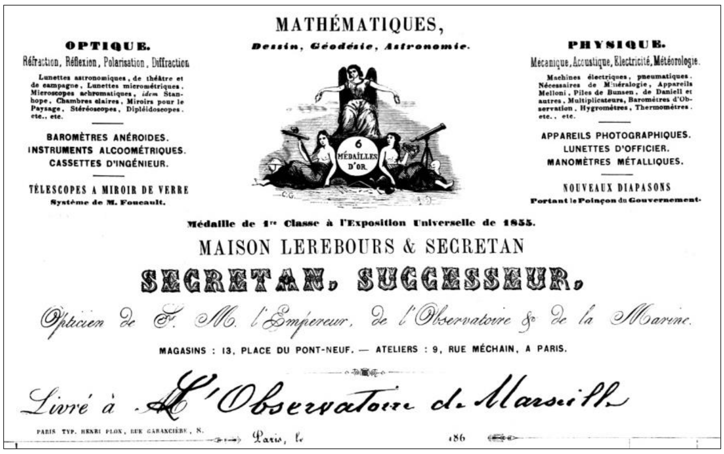
Pour des télescopes de dimensions différentes, on devra s'adresser à ma maison et traiter de gré à gré.

Tous les instruments de ce genre qui se vendent chez moi portent la signature *Secretan et Foucault*.

(Fig. 4.)

Figure 5. Four- and 8-*pouce* Foucault telescopes advertised in January 1858 in a 4-page "addition" to Secretan's catalogue (Table 1). Two typographical errors have been corrected in ink. It is announced that the instruments are signed, and that larger sizes are available by negotiation (courtesy: R. Smeltzer).

The advertised prices are 250 fr (francs) for the smaller telescope and 1,600 fr for the larger one.[9] To put these sums in context, Foucault's annual salary as Observatory Physicist was 5,000 fr. The 250-fr price for the 4-*pouce* is to be compared with the 600 fr charged for an astronomical-quality 95-mm refractor with finder and pillar-and-claw table stand, but no slow motions (Lerebours and Secretan, 1853: 19). As Babinet (1857a) had noted earlier, "The price is … much less than everything that has gone before." By early 1859 Secretan's billhead was heralding Foucault-system *télescopes* (Figure 6).[10]



MATHÉMATIQUES,

Dessin, Géodésie, Astronomie.

OPTIQUE.

Réfraction, Réflexion, Polarisation, Diffraction

Lunettes astronomiques, de théâtre et de campagne, Lunettes micrométriques, Microscopes achromatiques, *idem* Stanhope, Chambres claires, Miroirs pour le Paysage, Stéréoscopes, Dipléidoscopes, etc., etc.

BAROMÈTRES ANÉROIDES.
INSTRUMENTS ALCOOMÉTRIQUES.
CASSETTES D'INGÉNIEUR.

TÉLESCOPES A MIROIR DE VERRE
Système de M. Foucault.

PHYSIQUE.

Mécanique, Acoustique, Electricité, Météorologie.

Machines électriques, pneumatiques, Nécessaires de Minéralogie, Appareils Melloni, Piles de Bunsen, de Daniell et autres, Multiplicateurs, Baromètres d'Observation, Hygromètres, Thermomètres, etc., etc.

APPAREILS PHOTOGRAPHIQUES.
LUNETTES D'OFFICIER.
MANOMÈTRES MÉTALLIQUES.

NOUVEAUX DIAPASONS
Portant le Poinçon du Gouvernement.

Médaille de 1re Classe à l'Exposition Universelle de 1855.

MAISON LEREBOURS & SECRETAN

SECRETAN, SUCCESSEUR,

Opticien de S. M. l'Empereur, de l'Observatoire & de la Marine.

MAGASINS : 13, PLACE DU PONT-NEUF. — ATELIERS : 9, RUE MÉCHAIN, A PARIS.

Livré à M. l'Observatoire de Marseille

PARIS TYP. HENRI PLON, RUE GARANCIÈRE, 8. Paris, le 186

Figure 6: Billhead from the early 1860s trumpeting the wide variety of Secretan products, including Foucault-system telescopes (after: Secretan, 1864; courtesy: www.e-corpus.org).

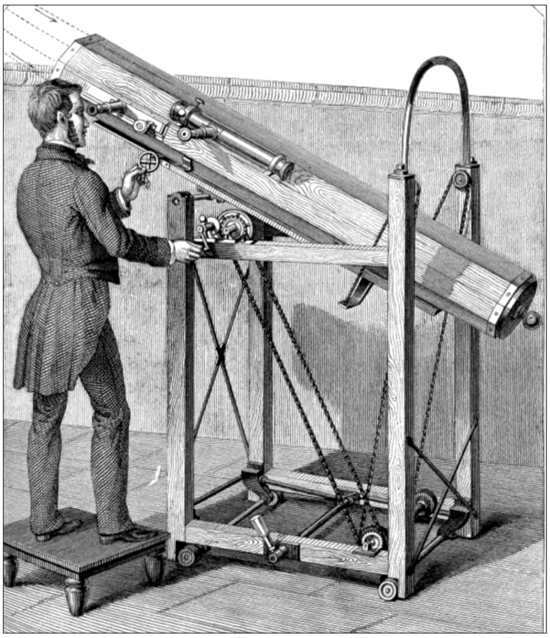


Figure 7: Foucault telescope built c.1858 by Froment for the École Polytechnique, taken from Ganot's *Cours de Physique* (1859a) (courtesy: F. Gires/ASEISTE).

2.3.1 8-*pouce* Telescopes and a Telescope for the École Polytechnique

I am unaware of any extant 216-mm Foucault-Secretan telescope. The "Fig. 4" woodcut of the catalogue 'Addition' claims to represent one (Figure 5), but given its conformity with the 4-*pouce* instruments discussed in the next section, this must be another error. However, an illustration of a Foucault reflector published in a physics text in 1858 may indicate what the 8-*pouce* telescopes were like.

Adolphe Ganot (1804–1887) was a private physics tutor to science and medical students. He was also the prolific author of two physics textbooks (Khantine-Langlois, 2006; Simon, 2009; 2011). Taking advantage of advances in the printing industry, both were highly illustrated with woodcuts ('xylographs'), and both were frequently revised to take account of new developments. Ganot's *Traité Élémentaire de Physique*, first published in 1851, was the more technical, and was praised by Foucault (1853) as a "... charming work, simply written ..." The *Cours de Physique* was simpler, aimed at "... society people ... and persons foreign to the notions of mathematics ..." (Ganot, 1859a: title page). Its illustrations of apparatus often included human users rather than the disembodied hands or eyes characteristic of the more-formal *Traité*. By the time Ganot relinquished authorship in 1880 or 1881, the *Traité* and *Cours* print runs had totalled 204,000 and 51,500 copies respectively (Ganot, 1880).

The first edition of the *Cours* and the eighth edition of the *Traité* are nominally dated 1859, but in fact were published in September and October 1858 (Journal Général de l'Imprimerie, 1858b; 1858c; 1858d; 1858e). Figure 7, from the *Cours*, shows a Newtonian telescope "... brought back into fashion by the recent improvements which M. Foucault has just brought to the construction of the concave mirror ..." (Ganot, 1859a: 372).[11] The octagonal wooden tube is mounted on an alt-azimuth stand reminiscent (i) of William Herschel's 10-foot telescopes because of its rectangular wooden cage structure, and (ii) of Cauchoix's mount because of its adjustment chains. In Figure 7 the observer's right hand adjusts these chains to alter the telescope's altitude, while his left hand turns a worm gear to track the target in azimuth.

Adopting the man's height to be that of Foucault to set the scale (1.65m, Tobin, 2003: 18—people were smaller in the nineteenth century), we can gauge from Figure 7 that the mirror had a 20–25 cm diameter and a focal length of about 160 cm, concordant with Secretan's advertisement and a mirror that is spherical if the effective focal ratio is 162 cm/18 cm ≈ *f*/9. However, Ganot clearly states that this telescope was made by Froment, not Secretan (Ganot, 1859a: 372). In any case, the octagonal wooden tube and a substantial stand seem inevitable features for a reflector of this size, consistent with a much higher price compared to the more-simply mounted 4-*pouce* instruments discussed in the next section.

Figure 8 shows the optical layout, which unlike Figure 7 was printed in both the *Cours* and

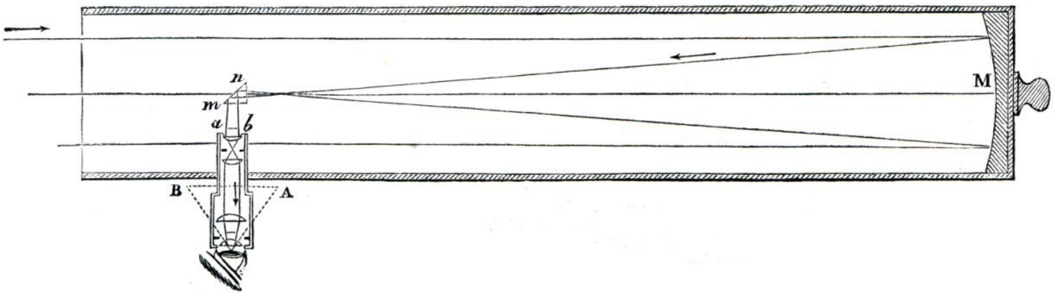


Figure 8: The optical layout of Froment's Foucault reflector. This diagram was published in both Ganot's *Cours* and *Traité* (1859a; 1859b) (courtesy: F. Gires/ASEISTE).

the *Traité*. The proportions in Figure 8 have obviously been distorted for clarity, but the knob behind the mirror in both Figures 7 and 8 makes it clear that both relate to the same instrument, which the *Cours* states was made for France's prestigious École Polytechnique. The ray diagram in Figure 8 does not conform with the accompanying descriptions since if paraxial rays cross before the prism they cannot also form an extended image at *ab*. (This error was corrected in the 10th edition of the *Traité* (Ganot, 1862), where to simplify the pedagogy the four-part eyepiece assembly was reduced to only a single lens which is shown convex, though this is a simplification because the complex eyepiece and relay lenses adopted by Foucault give upright images.) As with the instrument shown in Figure 4, Figure 8 indicates that a small prism bends the optical path through 90º. A pair of relay lenses re-images the prime focus to outside the tube where different eyepieces can be interchanged to obtain different magnifications. The relay lenses permit the use of a small prism and have the added advantage of furnishing an upright image, which is desirable commercially for terrestrial use. Echoing Foucault (1858d: 165), Ganot (1859b: 442) characterised this lens arrangement as "... a veritable microscope ...", and indeed the resolvable detail in the intermediate image would have been at the micrometre scale. Available magnifications of 50× to 800× were stated, with 10× for the magnification of the finder. For focusing, the eyepiece assembly and prism were mounted on a slider which could be moved *parallel* to the length of the tube via a rack and pinion. In Figure 7 the focus knob attached to this pinion is visible directly above the azimuth wheel.

This telescope has not survived in the collections of the École Polytechnique (Thooris, pers. comm., 2014).

2.3.2 4-*pouce* Telescopes

The woodcut in the Secretan catalogue 'Addition' of January 1858 (Figure 5) undoubtedly represents a 4-*pouce télescope*. The following September, a weekly illustrated paper, the *Magasin Pittoresque,* published its own engravings complete with observer (Figure 9). Four months later, another weekly, the *Musée des Sciences,* reprinted the 'Addition' woodcut (Lecouturier, 1859).

At least seven of these small Foucault-Secretan telescopes have survived, listed in Table 6. Figure 10 shows general views of one telescope. The optics are laid out as for the École Polytechnique device (Figure 8), except that the prism is fixed and focussing involves moving the eyepiece and relay lenses with a rack-and-pinion in a direction *perpendicular* to the tube. The instrument is mounted as an alt-azimuth in a square, wooden tube catalogued as walnut (S. Turner, pers. comm., 1998; Wolf, 2014). The altitude is set by a pair of hinged boards, one of which engages with notched racks, akin to a reading stand. Each notch changes the elevation by 2 degrees (Wolf, 2014). In the other board, a knurled knob and screw (missing in Figure 10) presses against a brass cup and provides fine altitude adjustment. For alignment in azimuth the whole telescope must be moved.

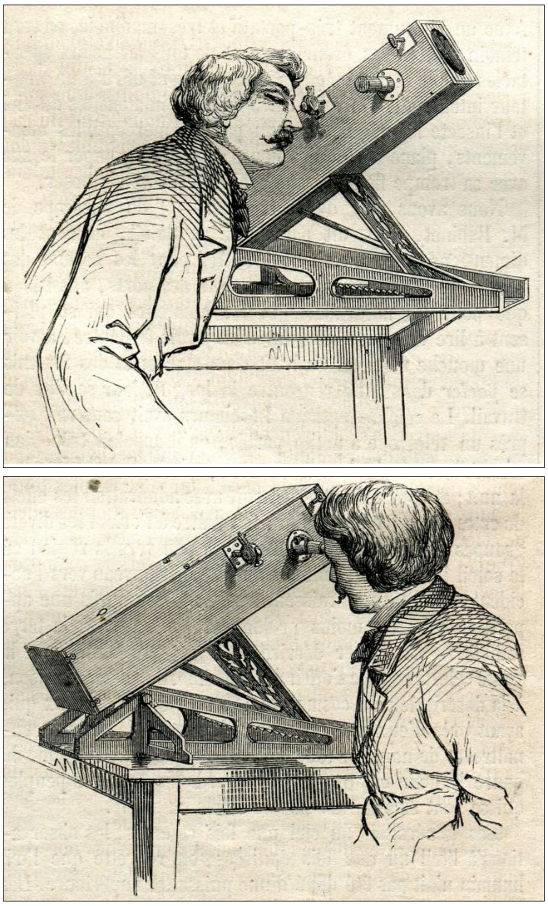


Figure 9: Foucault-Secretan 9-cm wooden-tubed reflector. (Upper) Using the finder sights. (Lower) Using the telescope. The engravings were printed again in another science weekly in mid-1862 (Zurcher, 1862) (after: De l'astronomie observatrice, 1858: 312; author's collection).

Duplicate pairs of hinge knuckles and a removable keeper rod permit the tube to be attached with the eyepiece on either right or left.

Lithographed operating instructions have survived with the Smithsonian Institution instrument (Figure 11). I have endeavoured to render their extraordinary mixture of officialese and colloquialisms in the translation given in Appendix 1.

On one side of the tube is a circular label signed by Foucault to guarantee authenticity (Figure 12). For most, the woodwork is stamped

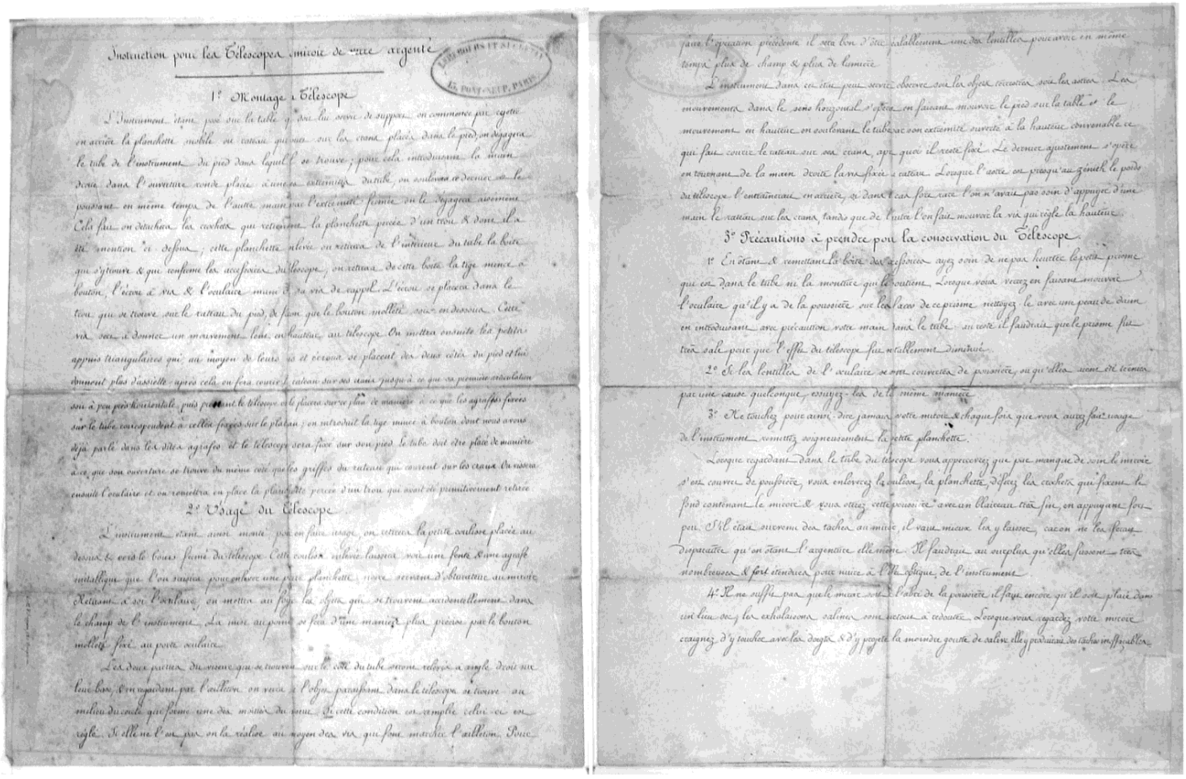
Table 6: Known surviving 4-*pouce* Foucault-Secretan telescopes mounted in square wooden tubes. I have only personally examined the Science Museum one. Information about the rest has been provided by others or garnered from photographs.

Collection/inventory number	Secretan serial number	Comments	Additional description and/or images
Prytanée National Militaire, La Flèche	2	Finder with objective lens and eyepiece.	
	3	Geometric finder.	Chanteloup (2004: 194) www.aseiste.org
Private collection of Prof. Edward D. Wolf, Trumansburg, NY / TRE16	4	Has been renovated by Wolf. Geometric finder.	Wolf (2014)
Deutsches Museum, Munich / 9051	?	An altitude meter has been added.	Auflage (1983: 90)[12]
Smithsonian Institution, Washington / 1979.0889 and NMHT 330623	none surviving	Finder sights have been displaced. Has been remounted equatorially.	Tobin (2003: 290, 291)
Science Museum, London / 1971-479	26	Mirror-cell wooden body and retaining brass sleeve have been reversed; mirror is held by four wooden fingers. Woodwork has been strengthened with brass straps. Finder with objective lens and eyepiece.	collectionsonline.nmsi.ac.uk
Private collection of Patrick Fuentes, France	42	Serial number on body and mirror, which has a 90-mm diameter. Geometric finder. Probably original dust cover.	www.astrosurf.com/rtaa/ rtaa2011_expo.html

Figure 10: The Wolf wooden-tubed No. 4 reflector before restoration (courtesy: Auction Team Breker).

with a serial number (Figure 13).

Figure 14 shows a mirror cell. The mirror is mounted against a brass sleeve. A folded copper sheet acts to cover the mirror when not in use. A small sliding hatch (Figure 15, also visible closed in Figure 10) gives access to this cover. I have measured the overall diameter of the Science Museum mirror as well as the effective aperture defined by the retaining sleeve. These and other measures are reported in Table 7. The concordance of the optical properties (effective diameter, focal length) strengthens the case that the Paris Observatory instrument is a prototype for the commercialized versions. We can further conclude (i) that a smaller, 4-*pouce* mirror blank was adopted for initial production, later reduced and metricated to 90 mm, (ii) that the 4-*pouce* dimension probably referred to the *outer* diameter of the tool used to cut the blank which in consequence is slightly smaller, (iii) that the Secretan advertisements (Figure 5; Lissajous, 1858) were puff concerning the *ouverture* of the telescope, whereas (iv) Foucault was accurate in stating a 9-cm real aperture, but rounded when quoting a ‘0^{m}.50’ focal length. This leads to tentative predictions concerning the 8-*pouce* size of telescope, should an example emerge. The mirror blank will be a millimetre or two less than 8 *pouces* in diameter with effective aperture of 6½ *pouces*, and the focal length will be closer to 60 *pouces* than the 1.50 m quoted by Foucault. In all cases where I have information, the mirror glass has no colour cast or tint, suggesting that optical glass was used, though not necessarily of the best quality, since internal bubbles and striations are of no importance for a mirror.



Instruction pour les Télescopes à miroir de verre argenté

1° Montage du Télescope

2° Usage du Télescope

3° Précautions à prendre pour la conservation du Télescope

Figure 11: Lithographed instructions accompanying the Smithsonian Institution telescope (courtesy: Steven Turner).

Les Télescopes
a miroir de verre qui se
vendent dans la maison
SECRETAN portent tous
la signature ci-dessous

L Foucault

Figure 12: Foucault's signature guaranteeing authenticity of the Science Museum telescope (author's photograph).

Figure 13: Serial numbers stamped into the wood of the Wolf 9-cm telescope No. 4. (From left) (a) Under the triangular stabilising feet. (b) At the mirror-cell end of the square tube. (c) In a flange of the mirror cell. (d) Under the altitude adjustment hinge (courtesy: Ed Wolf).

Figure 14: Mirror cell of the Wolf telescope No.4 before renovation. The copper dust slide is disengaged. The silvering is absent in places and heavily tarnished elsewhere (courtesy: Ed Wolf).

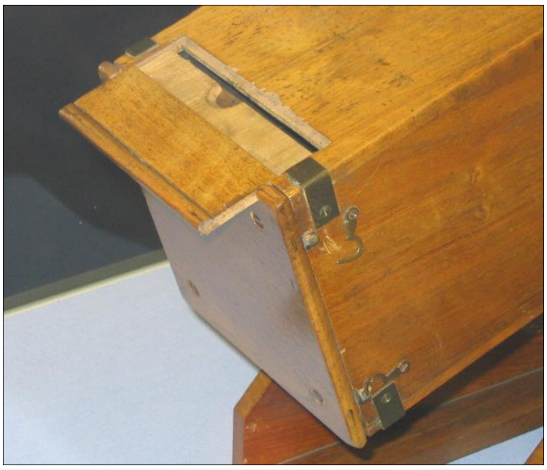


Figure 15: Access hatch to the mirror dust slide of the Science Museum telescope No. 26 (author's photograph).

Table 7: Properties of some early Foucault-Secretan telescopes in square wooden tubes.

Telescope	Full mirror diameter	Effective aperture	Focal length
Obs. Paris, Inv. 251	121.5 mm	88 mm	530±0.5 mm
Secretan 'Addition' 1858 and Lissajous, 1858: 13	*"108 millimètres d'ouverture"*		*"52 centimètres de foyer"*
Wolf, No. 4, TRE16	106.36 mm	87.25 mm	533 mm
Science Museum, No. 26, 1971-479	106.6±0.5 mm	87.5±0.5 mm	
Fuentes, No. 42	90 mm		540 mm
Conversions	*4" ≡ 108.28 mm* *4½" ≡ 121.81 mm*	*3¼" ≡ 87.97 mm*	*19" ≡ 514.31 mm* *19½" ≡ 527.85 mm*

Figure 16: No. 42 9-cm telescope, with eyepiece assembly held by friction, geometric finder and what appears, from the match of the wood, to be an original square dust shutter. The serial number is marked on the body of the instrument and is also engraved on the glass in writing that resembles Foucault's writing (Fuentes, pers. comm., 2015) (after: www.astrosurf.com/rtaa/rtaa2011_expo.html).

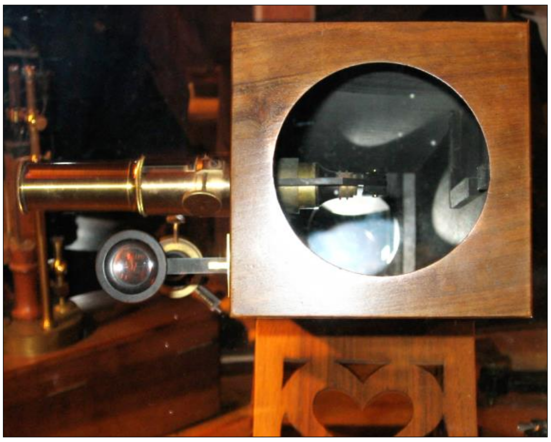


Figure 17: Prism and eyepiece assembly of the Prytanée No. 2 telescope (courtesy: D. Bernard).

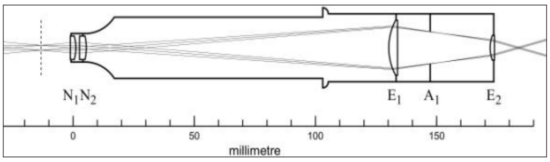


Figure 18. Optical layout and ray trace for the eyepiece assembly of the Wolf 4-pouce telescope No. 4. The ray trace corresponds to the maximum field of view and a relaxed eye (see text); the dashed line indicates the corresponding entrance focal plane For component parameters, consult Table 8. Friction alone retains this assembly within a close-fitting, movable outer sleeve displaced by a rack and pinion.

Some of the telescopes have clearly been modified. The Science Museum mirror cell has been reversed and its woodwork has been strengthened with brass brackets. The Smithsonian tube has been remounted as an equatorial and the finder rings displaced (Tobin, 2003: 290). Shims have been added behind the Wolf telescope mirror.[13] The instructions of Appendix 1 reveal telescopes delivered without any cover to block the entrance aperture, so a cork and wood bung at the Science Museum and a metal stopper at the Deutsches Museum must be later additions. However, the design seems to have evolved to include a cover, because the Fuentes *télescope* No. 42 (Figure 16) has a covering plate which looks original because of the closely matching timber (and hooks, cf. Figure 21).

Other differences also seem original. The eyepiece assemblies of the Deutsches Museum and Fuentes telescopes appear to be held and focused by friction alone (e.g. Figure 16), and this is concordant with the woodcuts of Figures 5 and 9. Yet the lithographed instructions refer to an "... eyepiece furnished with its adjusting screw ...", and indeed the other five telescopes have a rack-and-pinion focusing device and their eyepiece assemblies have a different appearance.

Figure 17 shows how the first optical surface of the relay lenses can lie close to the reflecting prism. Figure 18 sketches the eyepiece assembly for the Wolf telescope. There are obvious similarities with the simplified achromatic microscopes sold by Secretan, from which the design was evidently derived (Figure 19; see also Table 11). The nose-piece is composed of two, presumably achromatic elements, N_1, N_2, and there is a Huygens-like eyepiece, E_1, E_2. The ray bundles shown correspond to the fully-illuminated mirror and an eye focussed on infinity. Dotted lines indicate the corresponding focal plane of the assembly, which when the telescope is adjusted of course coincides with the prime focus of the mirror. The field-of-view is limited by the stop A_1 and corresponds to 1.9 mm diameter at this prime focus or 0.2° on the sky. Although A_1 is slightly mis-sized and misplaced, this is not a significant issue because of the narrowness of the ray bundles. There is good eye relief, but the exit pupil is only a millimetre or so in diameter, with the result that floaters in the eye will have been very evident (confirmed by Wolf, pers. comm., 2014). The magnification is 145×. The diameter of the circular aperture at the front of the Science Museum telescope tube is 95.0mm (3½ *pouces*) sufficient for a 0.8° unvignetted field-of-view, confirming that the field is limited by the stop A_1.

From the eyepiece boxes and contents shown in Figure 20 it can be seen that at least sometimes the eyepiece assembly was delivered with a third nose-piece lens to provide additional magnification options, as for the simplified achromatic microscope. A second 'veritable microscope' could also be supplied, with a blunter nosepiece, perhaps indicative of a larger field of view (cf. Section 8.1 below). For storage and transport the eyepiece box could be slipped into the telescope tube: retaining rails are visible to the right in Figure 17.

Table 8: Lens and aperture specifications for the Wolf TRE16 eyepiece assembly (Wolf, pers. comm. 2014). Measurement uncertainties ~0.5 mm for diameters and ~1 mm for positions and focal lengths. The equivalent focal length is –7.2 mm. For an eye focused at infinity, the entrance focal plane position is –13.2 mm. See also Figure 18.

Component	Position (mm)	Clear diameter (mm)	Focal length (mm)
N_1	0.0	9.0	21
N_2	4.1	9.0	32
E_1	132.1	21.0	41
A_1	147.4	12.5	
E_2	173.0	9.4	21

The finder too appears to have been available in two forms. Figure 21 compares the finders of the Prytanée instruments Nos. 2 and 3. The former has a tubeless telescope as finder whereas the latter only has sight holes. Optical finders are also found on the Science Museum and Smithsonian Institution instruments, but all others have geometrical ones. Nevertheless, it is finder lenses that are mentioned in the lithographed instructions (Appendix 1). The eye-end alignment screws are also mentioned in the instructions and are apparent on the engravings and on all of the seven surviving telescopes (e.g. Figures 10, 16, 17 and 21). The whole instrument could be packed away in a transport box (illustrated in Wolf, 2014). For this, the finder rings fold flat.

For the smaller telescope Secretan' s cata-

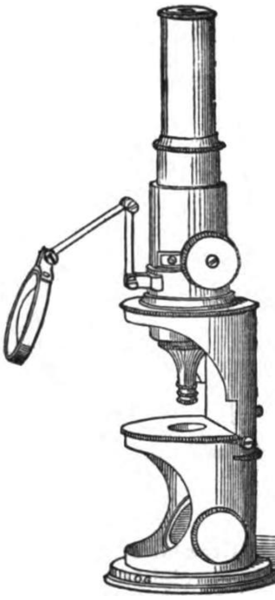


Figure 19: Lerebours' simplified achromatic microscope sold with three stackable nosepiece lenses, rack-and-pinion focusing and even a right-angle prism option (not illustrated) for horizontal use. The similarity with certain of the Foucault-Secretan telescopes is evident (after: Lerebours and Secretan, 1853: 7; courtesy: Universiteitsbibliotheek Gent via Google Books).

Figure 20: (Upper) Eyepiece box of the Prytanée No. 2 telescope, with the 'blunt' style of eyepiece assembly (courtesy: L. Chanteloup/PNM). (Lower) Eyepiece box of the Science Museum No. 26 telescope with an eyepiece assembly like the 'simplified achromatic microscope' seen in Figure 19. *Three* nosepiece lenses have been unscrewed from the associated tube. An indentation for the blunt assembly is seen; the blunt assembly itself is pictured at collectionsonline.nmsi.ac.uk (author's photograph). A note attached to the No. 2 box indicates that the cone-like indentation was provided for a dust brush. Another indentation present in both boxes must be for the eyepiece of the finder that equips each instrument (see text).

Figure 21: Comparison of the finder provisions on the two Prytanée *télescopes*. No. 2 (upper) is provided with an eyepiece and objective lens (see also Figure 17). Thumbscrews and a sprung-loaded pin permit optical alignment with the main telescope. For No. 3 (lower) the arrangement is purely geometric. A peep-hole defines a viewpoint for a sighting ring. Cross hairs have subsequently been soldered across this ring, but are unlikely to have been effective owing to the eye's inability to focus simultaneously on a nearby object and the sky (courtesy: L. Chanteloup/PNM).

logue 'Addition' adds the intriguing claim "(This instrument has been arranged so that it can also serve as a microscope.)" (Figure 5). It is unclear what is meant, and this possibility is not addressed in the lithographed instructions. The 1853 Lerebours & Secretan Catalogue offered a "Microtélescope ..." (1853: 40), a metal-mirrored reflecting telescope invented by Noël Lerebours (Lerebours père) in 1818 (Le Rebours, 1915). This microtélescope could serve both as a telescope and as a "... microscope enabling the examination of an insect placed at distance ..." (Lerebours and Secretan, 1853: 40). Of course if the telescope can be focused on sufficiently nearby objects, the magnification will act like a microscope, and we have seen that Babinet reported examining insects this way. This seems the likely interpretation of the advertisement, and Figure 22 shows a wasp's wing imaged thus by the Wolf telescope despite the tarnished and fragmentary state of its mirror silvering (cf. Figure 14). But as an alternative, the 'veritable microscope' of the eyepiece assembly can be unscrewed and in the absence of any stand used as a hand-held microscope, as I have verified with the No. 13 and 20-cm telescopes discussed below in Sections 6.2 and 8.1. Whatever was meant, this cannot have proved to be an important sales feature, and the claim was not repeated in later catalogues and advertisements.

Figure 22: The Wolf 4-*pouce* telescope used to image a wasp's wing. A ~2-cm aperture was used to select the best part of the surviving mirror silvering. It was possible to focus on the specimen placed about 4 m in front of the mirror with the eyepiece assembly still just held by the rack-and-pinion mounting sleeve. Field diameter ~8.4 mm (courtesy: Ed Wolf).

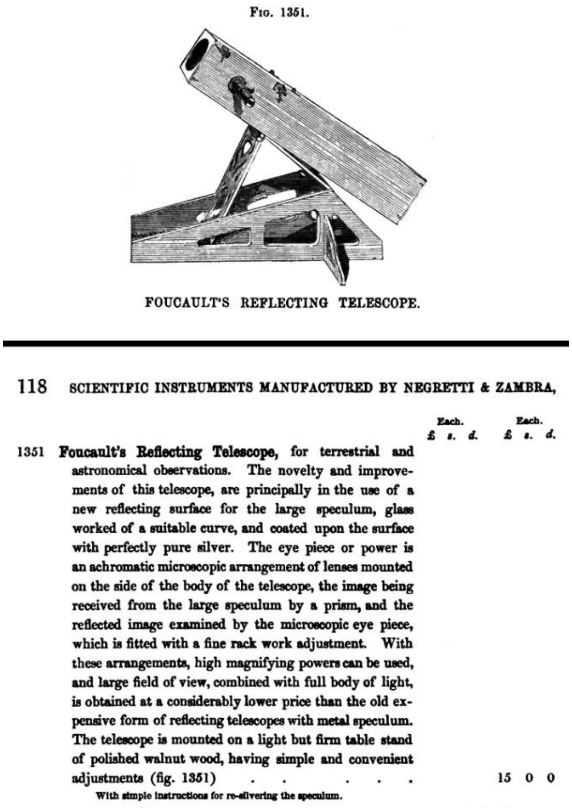


FIG. 1351.

FOUCAULT'S REFLECTING TELESCOPE.

118 SCIENTIFIC INSTRUMENTS MANUFACTURED BY NEGRETTI & ZAMBRA,

	Each. £ s. d.	Each. £ s. d.
1351 **Foucault's Reflecting Telescope,** for terrestrial and astronomical observations. The novelty and improvements of this telescope, are principally in the use of a new reflecting surface for the large speculum, glass worked of a suitable curve, and coated upon the surface with perfectly pure silver. The eye piece or power is an achromatic microscopic arrangement of lenses mounted on the side of the body of the telescope, the image being received from the large speculum by a prism, and the reflected image examined by the microscopic eye piece, which is fitted with a fine rack work adjustment. With these arrangements, high magnifying powers can be used, and large field of view, combined with full body of light, is obtained at a considerably lower price than the old expensive form of reflecting telescopes with metal speculum. The telescope is mounted on a light but firm table stand of polished walnut wood, having simple and convenient adjustments (fig. 1351)		15 0 0

With simple instructions for re-silvering the speculum.

Figure 23: Foucault's telescope advertised in Negretti & Zambra's catalogue for 1859 (courtesy: Google Books and Internet Archive).

Foucault's 4-*pouce* telescope was imported into England by Negretti & Zambra in London. Figure 23 shows the corresponding entry from their 1859 catalogue. The price, £15, was a 50% mark-up on the £10-equivalent of the French price. This does not seem unreasonable, but some years later an anonymous critic complained that for such a telescope, this was "... a price considerably beyond its merits ..." (Silvered mirror telescopes, 1867: 176). The telescope was still in Negretti & Zambra's catalogue as late as 1887, "Supplied to order ...", now for £20 (Negretti & Zambra, 1887: 255). This is enigmatic, because this form of telescope was rapidly superseded in Paris (see Section 8.1).[14]

The serial numbers (Table 6) suggest that forty or more of these 4-*pouce* telescopes were made (see also Section 11).

3 EVALUATING PERFORMANCE

Returning to mid-1857, Foucault then suffered a setback. A "... 40-cm ..."[15] glass disc had been poured, but two months' work showed it would not keep its form (Foucault, 1857a). Foucault attributed this to over-rapid cooling. Presumably grinding and polishing released stresses, changing the shape. He vowed to pay attention to this factor in the future. Foucault did not specify the source of his glass, but the following year he was working with Saint Gobain glass.

Foucault experienced another difficulty at this time: Le Verrier tried to sack him. Details are outlined elsewhere (Tobin, 2003), but he resisted.

Progress was rapid in 1858 and is fairly fully documented. In early March Foucault reported a 32-cm diameter mirror to the Société Philomathique, which he reckoned could separate ⅔ of an arc second, revised a week later to half an arc second, though he did not specify how he determined these values (Foucault, 1858e; 1858f). In May he reported that he had also completed a 36-cm mirror.[16] Both, he said, "... give very good images at the prime focus of $3^{m}.50$." (Foucault, 1858a: 47; or 1858b). This corresponds to *f*/11 and *f*/10 respectively. "But to escape from vague estimates which might give rise to delusions," he added, "I wanted to express numerically the optical quality of these two mirrors considered as telescope objectives." To do this he used a target ruled with equal black and white lines which he removed to the point at which he could no longer resolve the lines with the mirror. With this new procedure he found that his 32-cm mirror

> ... shows distinctly the two-thirds of an [arc] second, or in other terms that it renders separately visible two points separated by the three-hundred thousandth part of their distance from the mirror. (Foucault, 1858a: 48; or 1858b).

He continued:

> The sharpness so defined makes it possible to compare instruments without having to try them side by side; thus it will be possible to eliminate the equivocal, and evaluate meaningfully the progress possible with this new design of telescope.

4 PARABOLIZATION AND POUVOIR OPTIQUE

Thus far Foucault's telescopes were sufficiently slow or small that spherical aberration was minor and good images could be achieved with spherical mirrors, though by modern criteria they were slightly outside what would be acceptable for visual use. (Scaling computations presented in Figure 5.4 of Rutten and van Venrooij (2002), a 9-cm mirror needs parabolizing if faster than ~*f*/8, an 18-cm if faster than ~*f*/11, and a 36-cm if faster than ~*f*/14.) Foucault's next advance was to produce an ellipsoidal mirror, presented at the Société Philomathique on 15 May 1858. This mirror had an announced 24-cm diameter with foci at 1.10 and 9 m. "Without wanting to go into practical details ...", Foucault (1858g: 49; or 1858h) stated that this had been done "... by hand repolishing of the surface and attentively following the successive changes in the optical effects." In other words, he had begun to use at least some of the three optical tests which he would ultimately use to guide the final corrective repolishing of his mirrors—tests which, as Sir John Herschel put it, made the errors of form "... glaringly conspicuous" (Herschel, 1860: 142). On 3 July Foucault reported having parabolized a second mirror of the same size,[17] with a focal length of 1 m (i.e. ~*f*/4.2) capable of resolving two points separated by 1/250,000th of their distance from the mirror (Foucault, 1858i; 1858j). This was only eight years after his spinning mirror experiment had shown that light travels slower in water than in air, so driving the final nail into the coffin of the particle theory of light, which predicted the opposite. For images that are affected by aberrations, stopping down the objective usually *improves* image quality. Foucault was palpably pleased to find that his image quality was *poorer* if he reduced the illuminated area of the mirror with a movable diaphragm, a result which:

> … agrees fully with theoretical predictions, because in the wave theory the convergence of a conical beam is all the more exact if the extreme rays cross over at a wider angle (Foucault, 1858i: 52; or 1858j).

I note that this first parabolic mirror cannot be the one used in the École Polytechnique telescope on account of the significantly different focal ratio (see also Section 6.2 below).

At the beginning of August Foucault outlined his progress in a *Mémoire* sent to the Académie des Sciences, where it was presented by the physicist J.-B. Biot (1774–1863) (Foucault, 1858k). "... a deep silence reigned in the chamber ..." reported Moigno (1858b), indicative of the academicians' interest in this work. Foucault had parabolized a 33-cm mirror (focal length

Figure 24: Wooden models used by Foucault when explaining his knife-edge test (Paris Observatory, inv. 244). The test reveals errors of form in exaggerated relief. At left, there has been too much polishing in a ring midway between centre and edge. At right, the center is overpolished and the edge is turned down (courtesy: Observatoire de Paris/F. Auffret).

2.25m, *f*/7) which in calm air on the morning of 22 July 1858 had split the close double star γ^2 Andromedae, which at the time had a separation of about 0.5″ (Woolley and Symms, 1937). In a fuller text in *Cosmos*, Foucault (1858d) noted that it took less than 6 hours to turn the initial mirror surface into a paraboloid. He also introduced the *pouvoir optique*, or optical power, defining it as the cotangent of the angular spacing of his test grid when just resolved. The test grid was now ruled on a plate of silvered glass by Froment. Froment probably also built the telescope tube and mount.[18] Foucault measured 400,000 for the optical power of his 33-cm mirror.[19]

Almost immediately the 33-cm reflector was used from Foucault's house on the rue d'Assas by his friends and neighbours to observe Donati's Comet (C/1858 L1; e.g. see Faye, 1858a; Moigno, 1858c; 1858d; 1858e). Hervé Faye (1814–1902), one of Foucault's colleagues at the Observatory, opined that "... for optical power, for perfection of the images, M. Foucault's telescope left me wanting for nothing more." (Faye, 1858b: 775). Drawings were made by a certain Charles Bulard (1825–1905), one of the numerous individuals whom Le Verrier had fired from the Observatory. A further invention was also announced (Moigno, 1858f). Foucault mounted the mirror on an inflatable rubber cushion, and via a nozzle at the eyepiece adjusted the pressure in order to counteract gravitational flexure of the glass and so obtain optimum image quality. In the opinion of England's Astronomer Royal, Sir George Airy (1801–1892) "The success of this contrivance is complete." (Report of the Council, 1860: 147). It should be noted that Foucault will almost certainly already have used rubber bladders, which were commonly used for storing gases, when employing limelight earlier in his career (e.g. Fizeau and Foucault, 1844).

Figure 25: The only remaining vestige of Foucault's first 33-cm telescope may be this chipped 33-cm mirror preserved in Algiers at the Centre de Recherche en Astronomie, Astrophysique et Géophysique (formerly the Observatoire d'Alger) (courtesy: Françoise Le Guet Tully and Marc Heller).

At the end of 1858 Foucault sent details of his optical tests to the Académie, where they were presented by the crystallographer Henri de Senarmont (1808–1862) (Foucault, 1858l; Moigno, 1858g). To outline them briefly: the first involved examining the tightness of the image of a point source with an eyepiece. The second involved examining the image of a rectangular grid of wires. The third, the knife-edge test, involved looking at the mirror from downstream of the image of a point source. How the light dimmed when the image was cut through by a sharp edge revealed shape errors in exaggerated relief, indicating where *retouches locales* were needed (Figure 24). Foucault also published his tests in greater detail in Moigno's *Cosmos* (Foucault, 1858m). They soon became availabe in English (Foucault, 1859c; Herschel, 1860). For a modern overview of the three tests, see e.g. Tobin (2003).

5 LARGE APERTURES FOR PROFESSIONAL ASTRONOMY

While all this was happening, Le Verrier had returned to the fray against Foucault. In mid-1858 he cut off Foucault's salary and forbade him entry to the Observatory (Favé, 1858). This is no doubt why, in his paper published in August's *Cosmos*, Foucault had concluded (1858d, 168):

> These results … are also of some interest because of the modest expenditure that has sufficed to obtain them. Thanks to the selflessness of the honourable and learned maker M. Secretan, who for two years has not ceased to put the resources of [his] great enterprise at my disposal, these costs have remained within such bounds that a single individual has been able to bear them.

The final comment is slightly disingenuous, as I will discuss in Section 7. Nevertheless, although the resources within his control would have permitted Foucault to acquire and polish larger mirrors at Secretan's works, to mount them as telescopes he needed institutional support.

Exactly what happened next is not completely clear. In December 1858, Moigno (1858h) reported that Bulard would become observer at a refounded Algiers Observatory, taking with him a 50-cm Foucault telescope. Two weeks later Moigno added that Foucault was "... at this moment putting the final touches to a 50-cm telescope." (1859a: 33). This is partially confirmed a fortnight later by Le Verrier, who was doubly indignant because the reorganisation of the Algiers Observatory wrenched control from the Ministry of Education and the Paris Observatory, *and* because Foucault was supporting this new enterprise with a telescope. He complained that "... a big mirror … is finished, that it is very good … but that it is destined for the Algiers Observatory!" (Le Verrier, 1859; his underlining). Yet when Bulard went off to Algeria in September 1859, it was not a 50-cm instrument but Foucault's 33-cm telescope, the one used to observe Donati's Comet, that he took with him, probably with two mirrors,[20] at least one of which appears to have survived (Figure 25). Algiers Observatory inventories show that the telescope was not equatorially mounted (e.g. Trépied, 1884).

Foucault filled some time by incorporating an aberration-correcting silvered-glass mirror within a catadioptric microscope, which Bulard used to make some hasty sketches of human blood corpuscles (Foucault, 1878). Happily, a truce with Le Verrier was called early in 1859 thanks to the intervention of the Emperor's aide-de-camp (Tobin, 2003).

Reading between the lines is now necessary. Foucault returned to the production of a ~40-cm mirror. In his telescope-making *Mémoire* written a little later, he stated that "... attacking a diameter of 42 cm, the workman assigned to shape the mirror failed on five separate attempts." (Foucault 1859a: 198). This is more-or-less confirmed by a bill issued by Secretan on 22 June 1859 for the supply of a "... $0^{m}41$ ..." disc and corresponding telescope tube, eyepieces and accessories. Included in the invoice was redoing the surface four times, and a fifth change involving a change of curvature (Secretan, 1859b). It was at this point, Foucault continued, that he felt "... the imperious necessity of studying the form of the surfaces ..." and developed his three test procedures. But they had been devised many months earlier with smaller mirrors! Foucault appears to have been simplifying, and also in his claim that it was only then that he had the idea of applying a local correction. His next comment is bitter but illuminating. "This idea, decried by the artisans, nevertheless succeeded perfectly ..." (Foucault 1859a: 199). The *retouches locales* on smaller surfaces had been done at Foucault's home on the rue d'Assas, and my reading is that he encountered opposition introducing them in Secretan's workshop. Be that as it may, in July Le Verrier was telling the Académie that Foucault had completed a 2.50-m focal-length *télescope* for the Observatory, whose mirror diameter is variously described as 40 cm, 15 *pouces*, or 42 cm (Foucault, 1859a; 1859d; Moigno, 1859b). It would seem at this point that the mirror was mounted in a temporary tube placed on an old "... chain mount ..." (Secretan, 1859b). Early in the new year, Secretan (1860a) billed for a full equatorial mount and 42-cm mirror cell, which would seem to be the full mirror diameter.[21] Figures 26–29 show the telescope.

Figure 26: The 40-cm telescope made by Foucault and Secretan for the Paris Observatory in 1859 (inv. 212). The original eyepiece assembly has been replaced. Coarse adjustment in declination in achieved via the support rod. Fine adjustment is provided by a screw engaging the underneath of the tube (cf. Figure 31) (courtesy: astro2009.futura-sciences.com and X. Plouchart).

The equatorial mount was the work of Wilhelm Eichens (1818–1884), the head of Secretan's workshop (Figure 30). For the mirror, ordinary commercial crown glass from the Saint Gobain glassworks was used, which has a green tint. The disc was ground to shape in the Paris factory

Figure 27: The 40-cm telescope is signed “Secretan à Paris” near the declination circle. The cursive font is also found in the firm’s signature on photographic lenses. There is no lock or fine adjustment (cf. Figure 41), these functions being provided by the rod and hinged plank seen in Figure 26 (author’s photograph).

Figure 28: To improve strength while minimizing weight, the mirror of the Paris Observatory 40-cm reflector has a curved back, which was polished for monitoring progress during silvering. The mirror is no longer held on an air bag. The green tint is characteristic of St Gobain crown glass (author’s photograph).

of Louis Sautter (1825–1912) who, like Secretan, was Swiss-born. Sautter’s trade included the manufacture of Fresnel lenses for light-houses, so he had the equipment to work large pieces of glass. In order to increase stiffness but reduce weight the mirror was given a convex rear, doubling in thickness from edge to centre. As to actual thicknesses, and without referring specifically to the 40-cm telescope, Foucault (1859a: 234) wrote of central thicknesses of “... at least a tenth of the diameter.” The mirror front was then worked spherical against a metal ball. The final polishing and *retouches locales* to paraboloidal shape were done at the Observatory. Despite the internal stresses of ordinary glass, the mirror held its optical form, although it was necessary to counteract gravitational sagging with an inflatable cushion. Ultimately, this contrivance cannot have been considered satisfactory, and was replaced in 1867 or 1868 by an adjustable metal spring (Figure 28).[22] The optical layout followed that adopted previously (Figure 8) except for an important innovation. The prism and relay-lens pair of the microscope introduced spherical aberration. These Foucault corrected with *retouches locales* to the primary mirror. “... contrary to normal usage,” he wrote (Foucault, 1859d: 86), this arrangement “… consists of correcting the eyepiece by the objective …” and many decades later was to lead to problems with at least two of his large professional telescopes when it had been forgotten that the mirror was not corrected on its own, but in combination with the prism and relay lenses.[23] Figure 29 shows the tube cap. Probably it is a replacement installed in 1867 (Eichens, 1867a), but its design is no doubt original because it is similar to that of the Paris Observatory 20-cm reflector discussed below (Section 6.2) and the telescope presented in Figure 100. “... chimney currents ...” were later noted as the “... plague of all reflectors ...” (Silvered mirror telescopes, 1867: 178). Aeration vents near the mirror were duly pierced.[24] The instrument could separate γ^2 Andromedae and had an optical power of 480,000, determined from a new design of resolution target composed of a leaf of ivory inscribed with

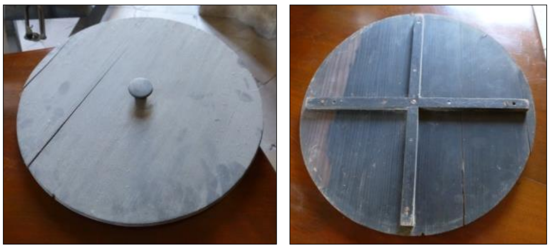


Figure 29: The dusty tube cap for the 40-cm reflector is made of thin wood strengthened with a wooden cross which also acts to hold the cap in position in the tube (author’s photographs).

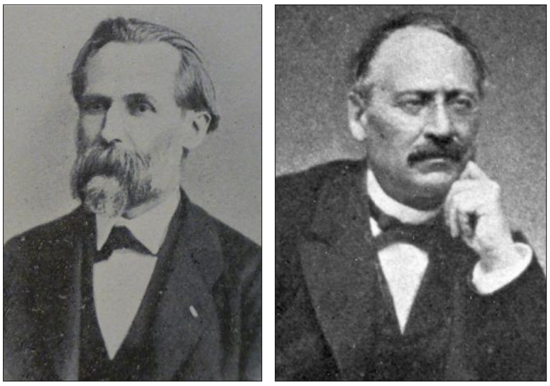


Figure 30: (Left) F. Wilhelm Eichens (1818–1884). (Right) Adolphe A. Martin (1824–1896). Details about both are scanty. Eichens was born in Berlin (Légion d’Honneur, 1862) and according to Caplan (2012) was declared legally insane towards the end of his life. Sebert (1896) gives a brief account of Martin, who died in Caen (Registre d’État Civil, 1896) (both after: de Gramont and Peigné, 1902; courtesy: Bibliothèque Nationale de France).

groups of black lines spaced by 1, ½, ⅓, ¼, … 1/10 mm and placed at 80 m.[25] Charles Wolf (1827–1918) and Georges Rayet (1839–1906) later used this telescope equipped with a dispersive, multiple prism to discover the hot, emission line stars which now bear their name (Wolf and Rayet, 1867).

The 40-cm telescope was considered portable. It was taken to observe the solar eclipse in Spain in 1860 (Chacornac, 1860a; 1860b). Le Verrier showed it off in Metz in April 1866 at a regional meeting of the Association Scientifique de France*,* of which he was the founder (Terquem, 1866: 227). It was also taken to observe solar eclipses in 1868 from the Malay peninsula in what is now Thailand (Orchiston and Soonthornthum 2017; Stephan, 1868) and in 1905 from Guelma in Algeria (Stephan, 1911). For this latter eclipse, the prism was replaced by a plane mirror to give a larger field and to bring the focus to the tube wall. Presumably this is the plane mirror now present in the telescope. Plate L2 of Stephan (1911) shows the telescope on an inclined ramp in order to adapt the polar axis to the North African latitude. The air vents are evident.

While he was completing the 40-cm telescope, Foucault wrote a comprehensive forty-page memoir detailing his procedures, which appeared in the 1859 volume of the Paris Observatory *Annales*, actually published in March 1860 (Foucault, 1859a; Journal Général de l'Imprimerie, 1860a). The dean of Britain's amateur astronomers commented on the "... praiseworthy liberality ..." of this (Webb, 1863: 130). Figure 31 from Foucault's memoir shows his adopted wooden mount with a rod to stabilise the tube in declination (cf. Figure 26). A handy knurled knob not far from the eyepiece allowed the observer to make fine adjustments in declination.

With his procedures published, printed evidence of Foucault's telescope-making now becomes sparser*.*

In early January 1860 Le Verrier petitioned the Education Minister for 45,000 fr to build and house what was to be Foucault's largest telescope (Le Verrier, 1860b).[26] But before this, Foucault had already ordered two large discs of glass, of 80- and 85-cm diameter.[27] One might expect that the 85-cm disc was conceived as a ball for working the smaller disc, but its specifications contradict this idea (Sautter, 1861).[28] In any event, it was the 80-cm disc that Foucault chose to shape, and he judged the size too great to work in the usual way against a similarly-sized ball. The initial spherical surface was engendered with a 50-cm glass tool and frequent checks with a spherometer. Polishing was performed by hand (Figure 32). The mirror was finished in early 1862 with a useful aperture of 78

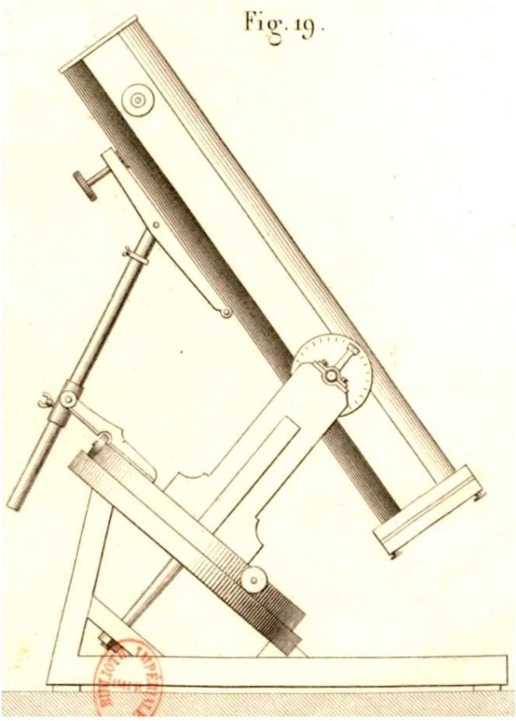


Figure 31: Eichens' mount, as illustrated in Foucault's memoir on telescope-making (after: Foucault, 1859a: Plate I; courtesy: gallica.bnf.fr).

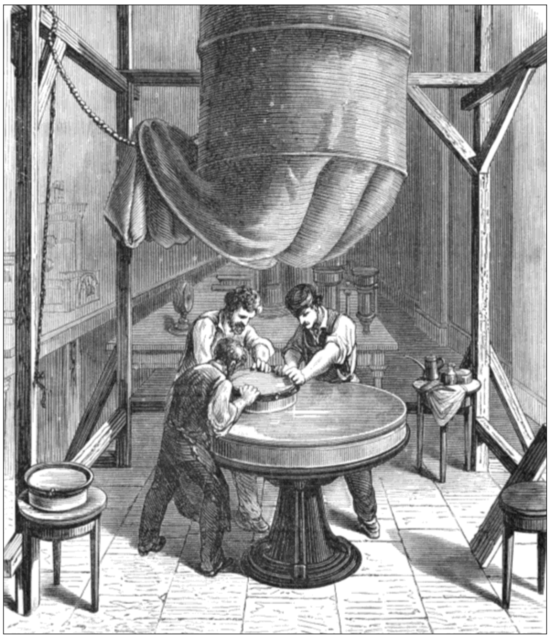


Figure 32: For diameters up to about 40 cm Foucault worked the mirror against a glass 'ball'. The increased forces needed to figure larger sizes were counteracted by employing several workmen or by suspending the upper piece from springs. Final polishing was accomplished with smaller tools, as illustrated here for the 120-cm mirror worked by Foucault's pupil Adolphe Martin in the 1870s. A decade earlier Foucault (1864a) had thought it "... extremely likely ..." that machine polishing would be needed for a mirror this big, and indeed the 120-cm mirror was not a success. The mirror is shown being worked in the Meridian Room of the Paris Observatory. The vertical cloth tube indicates that it was tested making use of the zenithal well that pierces the height of the Observatory (after: *L'Illustration*, No 1668, 117 (1875); author's collection).

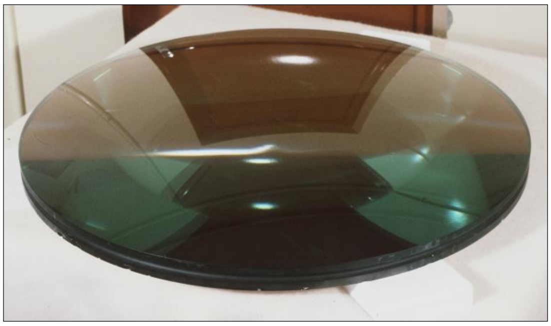


Figure 33: Foucault's largest telescope mirror, nominally of 80-cm diameter, completed in 1862. The groove in the edge is for attaching manipulating cords during polishing (author's photograph).

cm and a 4.5-m focal length (Foucault, 1862a; Figure 33).[29] It was temporarily mounted as an alt-azimuth instrument and used in Paris. It seems the mirror was mounted on an air bag, since a Secretan bill (1861b) includes 54 fr for a "Cushion in rubber", but the contrivance had disappeared by 1876 when the Scottish astronomer Charles Piazzi Smyth (1819–1900) visited Marseilles and noted "Mirror back all naked and exposed, very green glass and supported merely by a bar of wood across a central pad." (Brück, 2003: 44). In 1864 the telescope was remounted equatorially and installed under the clearer skies of Marseilles (Tobin, 1987). Figure 34 shows a flyer distributed by the Secretan firm illustrating the new mount. In his telescope-making memoir Foucault (1859a: 235) had written of Eichens' equatorial stand that "... nothing will prevent the addition of a clockwork motor as needed." Beginning in 1862 Foucault began to work on speed regulators, and the flyer shows and its text trumpets a regulated clockwork drive, which was powered by a 60-kg weight (Secretan, 1863). The complex history of such drives has already been broached by Caplan (2012), Darius and Thomas (1989), and myself (Tobin, 2003), and merits further study. The fixed eyepiece seen in Figure 34 proved impractical for a telescope of this size. In 1865–1866 the tube was cut down and the eye piece, prism and relay lenses set on a carriage that could revolve around the axis of the telescope tube to a more convenient angle (Foucault, 1865; Tobin, 1987: Figure 7).

Paris. Typ. H. Plon.

SECRETAN, Ingénieur-Opticien de S. M. l'Empereur et de l'Observatoire.

Magasins, place du Pont Neuf, 13; — Ateliers, rue Méchain, 9.

TÉLESCOPE A MIROIR DE VERRE ARGENTÉ

DE M. LÉON FOUCAULT

Construit pour le nouvel Observatoire de Marseille en 1864.

Cet instrument a 80 centimètres d'ouverture, 5 mètres de longueur focale et fonctionne à l'aide d'un mouvement d'horlogerie à régulateur isochrone.

Figure 34: Flyer from the Secretan firm c.1864 advertising the Marseille 80-cm reflector, now converted to an equatorial mount with a regulated clockwork drive. For photographs of the instrument, see Tobin (1987; 1998) and Tobin and Holberg (2008) (courtesy: Ville de Toulouse, Archives municipales, 5M40/1).

Figure 35: Toulouse Observatory's 33-cm Foucault telescope, much modified. Initially mounted as an alt-azimuth, an equatorial mount was under construction in 1863 (Petit, 1863). The base was strengthened in 1874 by Brunner. This photograph dates from after 1891, the year when a cast-iron mount by Eichens was installed, salvaged from another telescope (Lœwy, 1891), but before the tube was replaced with a metal one (Baillaud, 1899) (author's photograph from an original at the Paris Observatory).

Other professional telescopes were also made about this time. A 33-cm telescope was made for the Toulouse Observatory in about 1860 (Petit, 1863; Figure 35). The Musée des Arts et Métiers in Paris conserves a 33-cm Foucault mirror with almost the same declared focal length as Foucault's first 33-cm mirror (Figure 36).[30] Is this the Toulousian or even the original 33-cm one returned to Paris, or a remnant of yet another instrument? In September 1861 Bulard, now Director of the Algiers Observatory, returned to Paris to take delivery of a 50-cm telescope (Le Guet Tully et al., 2003). Was its mirror the one Moigno referred to in early 1859, or another one? The Algiers instrument was later remounted, but its mirror is now lost. As in Marseilles, a hump-backed observing 'bridge' was installed for eyepiece access (Le Guet Tully et al., 2003: 31, cf. Tobin, 1987: Figure 7). In 1863 Secretan quoted for an 80-cm telescope for Toulouse. Foucault began work on its mirror before his death, but the instrument was not delivered until 1875 (with a new mirror), and first put to use on 1 February 1876 (Bach et al., 2002; Lamy, 2008; Tisserand, 1876; Figure 37).[31] Also in 1863, Saint Gobain cast glass blanks for a 120-cm reflector for the Paris Observatory. Prompted no doubt by the success of the 80-cm telescope, this larger instrument had been suggested to the Education Minister as early as April 1862 (Le Verrier,

Figure 36: Front (left) and rear views of a 330-mm mirror attributed to Foucault conserved by the Musée des Arts et Métiers in Paris. The focal length claimed on a paper label is 2.29 m, close to the 2.25 m announced by Foucault. One might think that the octagonal wooden cell once formed part of a telescope. In this case, the black marks visible in the rear view would be paint to reduce reflections and the mirror would now be reversed for display purposes. But if this were the case, one would also expect the exposed circular cut of the wood around the mirror to be blackened too. The mirror is made of clear glass. The tarnished concave surface is protected behind an octagonal sheet of thin glass (author's photographs).

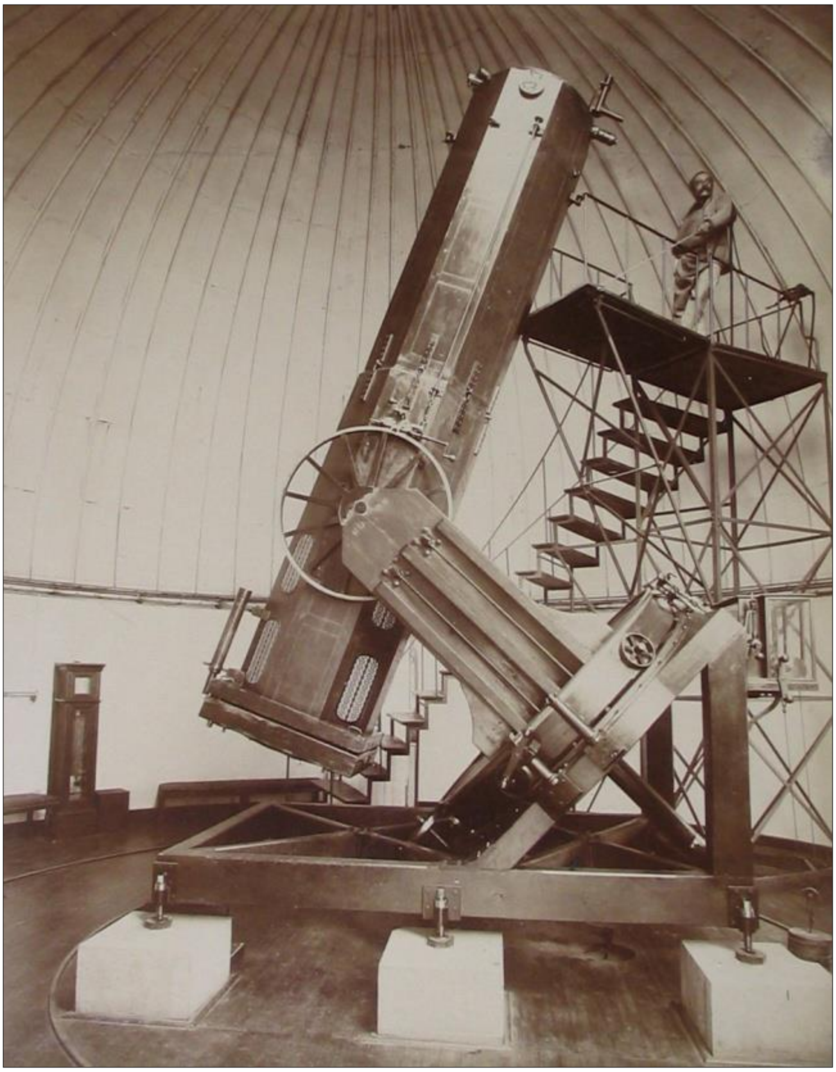


Figure 37: The Toulouse 80-cm telescope begun by Foucault. Following Foucault's death the mirror was worked unsatisfactorily by Adolphe Martin (see Section 7). The telescope was finally delivered with a new 84-cm mirror figured by the Henry brothers. Similarities with the Marseilles telescope are evident. The eyepiece appears to be moveable around the tube, as for the Marseilles 80-cm telescope after modification in 1865. In 1889 the wooden mount was replaced by a metal one built by Paul Gautier (e.g. Baillaud, 1899) (author's photograph from an original at the Paris Observatory).

Figure 38: Palais de la Découverte telescope, formerly the property of Félix Worms de Romilly. The sliding focusing plate and control knob are visible at the front of the tube (cf. Figures 7 and 40) but the eyepiece has been removed and its mounting hole covered with a circular brass plate (see text). The highly-polished octagonal tube is decorated with a slight step close to the position of the declination axis. The handle of one of two hand cranks for tracking in hour angle can be seen (author's photograph).

1862). A note from Foucault (1862b) estimated 30,000 fr for the cost of the optics. Again, there was a long delay before the telescope was finally delivered in 1876, but it proved unsatisfactory, as will be discussed further in Section 9.1.

In the 1860s the Bal Bullier, a dancing hall close to the Observatory, was decorated with some 240 'curiosities' for the amusement of clients, including a scale model of a Foucault silvered-glass telescope (Rouget, 1869). Did the model represent the Marseilles telescope, or perhaps the planned 120-cm one for Paris?

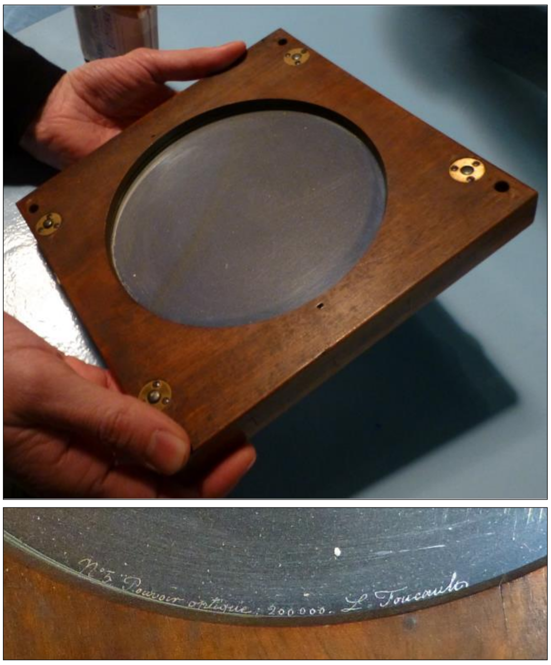


Figure 39: (Upper) Palais de la Découverte telescope mirror cell. (Lower) Foucault's inscription and signature at the edge of the mirror, which perhaps were made using a diamond because an inventory of Secretan's shop (Sebert, 1867–1868) mentions "3241° A [diamond] for writing" (author's photographs).

6 FOUR MORE TEXTBOOK ILLUSTRATIONS

Four textbook illustrations from the early 1860s reveal further details concerning the development of Foucault-Secretan telescopes at this time.

6.1 A Telescope Illustrated by Ganot (1860)

Figure 38 shows a telescope currently on display in the geometrical optics room of the Palais de la Découverte science centre in Paris. Some of the history of this device has recently been outlined by Trap and Tobin (2014). At the beginning of the twentieth century, the telescope was examined by the physicist Aimé Cotton (1869−1951; Cotton, 1905), who in 1937 removed the prism and eyepiece to convert it into a collimator for use in a speed-of-light demonstration in the newly-opened Palais de la Découverte (Kwal and Lesage, 1937: 232−234). We measured the mirror (Figure 39). Its full diameter is 153 ± 1 mm, close to 5⅔ *pouces* (Cotton (1905: 44*) quotes a "... useful diameter ..." of 15.2 cm), but the retaining brass collar reduces the effective aperture to 143 ± 1 mm, close to 5¼ *pouces*. The focal length is 680 ± 1 mm, corresponding to *f*-ratios of 4.4 and 4.8 depending on whether the full or effective mirror diameter is considered. Foucault engraved his signature into the metal plates of some of the daguerreotypes he snapped as a Sunday pass-time when a medical student in the early 1840s (Tobin, 2003: 36). Thus it is unsurprising that he inscribed this mirror with "Nº 5 Pouvoir optique: 200 000. L. Foucault." (Figure 39). This is the only one of his known mirrors that is signed, perhaps because it was made for a friend.

This telescope belonged to Félix Worms de Romilly (1824−1903), who if not an intimate, was certainly a very close acquaintance.[32] Worms de Romilly, or de Romilly as he later styled himself, was from a rich banking family and had studied law, but his passion was for physics. In 1888 he was President of the Société Française de Physique (French Physics Society) to which he bequeathed the telescope. In his will the telescope's fast focal ratio was explicitly stated to be unique (e.g. Société Française de Physique, 1903):

> The focus lies at a distance five times the diameter of the mirror: this is a difficulty which he [Foucault] only faced up to this one time.

This of course is not true. Foucault's first parabolic mirror was faster. But there can be no doubt that when Ganot (1860: 451) illustrated the 9th edition of his *Traité* with a Foucault reflector described as having "... a mirror of only 0$^{\mathrm{m}}$.16 diameter ..." and a horizontal extent "(l = 0$^{\mathrm{m}}$.70)" that the model for the accompanying woodcut (Figure 40) was de Romilly's telescope. The 9th edition was published on 18 June 1860 (Journal Général de l'Imprimerie, 1860b; 1860c), which provides an upper limit to the date of manufacture. The focus mechanism sliding *along* the length of the tube is clearly visible in the woodcut and Figure 38, and parallels the arrangement adopted for the École Polytechnique telescope (Figure 7). This arrangement must have proved unsatisfactory—probably the prism vibrated and perhaps there was a lateral image shift during focusing. In all other Foucault-Secretan instruments the prism is fixed and focus is achieved by moving only the eyepiece and relay lenses, and in a direction *perpendicular* to the length of the tube. Combined with the low serial number on the mirror (Nº 5), this suggests a date of early summer 1858 for this instrument, after Foucault's invention of the *pouvoir optique* and way to parabolize mirrors, which is nevertheless after the adoption of a fixed prism for the commercialized 4-*pouce* telescopes discussed in Section 2.3.2. We can imagine that Foucault gave this unique mirror to his friend Worms de Romilly who had Secretan install it in a luxurious polished-wood equatorial mounting with fine brass fittings. An Irish artisan visitor to an Exposition Universelle in Paris in a later decade commented on these two aspects of French work—sanding prior to varnishing using emery paper attached to a wooden pattern, which "... gives to the work a very square and uniform appearance ...", and "... the very fine quality of the brass used in their instruments, in regard to the closeness of the grain, and the absence of air bubbles ..." (Lambert, 1879: 476).[33] "... beautifully fitted up …" was the simpler comment provided by a former assistant at the Cambridge Observatory who had inspected several Foucault reflectors in Secretan's shop (Breen, 1863: 472).

The setting circles are divided to 1 minute in hour angle and 20 arcmin in what turns out to be north polar distance, further divided to 1 arcmin by a vernier (Figure 41). Use of the polar distance is not surprising, since it was still commonly used at the time, for example in the Paris Observatory *Annales* (e.g. Le Verrier, 1860c), the Cape Catalogue (e.g. Stone, 1873), or in the reports of new nebulae discovered with the Marseilles 80-cm *télescope* (e.g. Stephan, 1884). Figure 42 shows that the mirror does not appear to be made of tinted glass, though this is not definitive. Tints in photographs are not always reliable, and the illumination in the Palais de la Découverte geometrical optics room is low such that my eye might not have discerned a faint col-

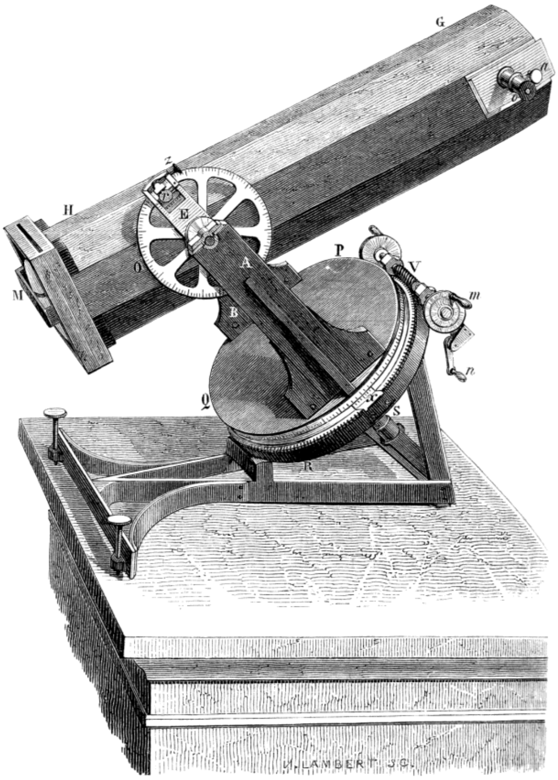


Figure 40: The Palais de la Découverte telescope represented in Ganot's *Traité Élémentaire de Physique* (1860) (courtesy: F. Gires/ASEISTE).

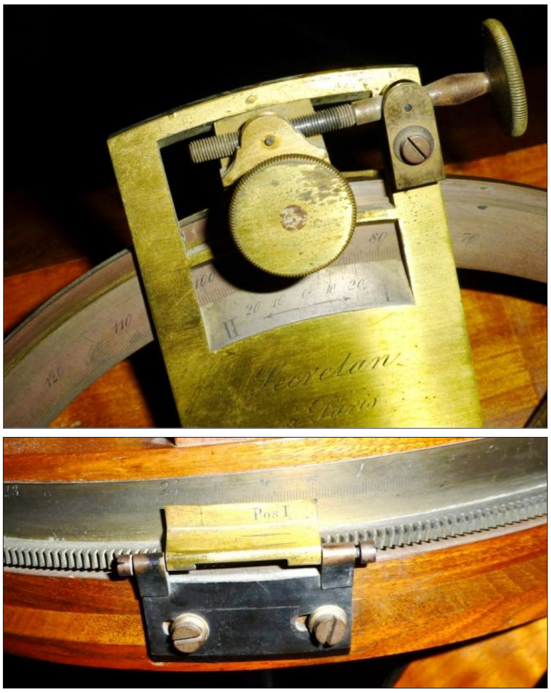


Figure 41: (Upper) Details of the declination setting circle, vernier and Secretan's name for the Palais de la Découverte telescope. The circle is calibrated in terms of north polar distance, 180°–0°–180°. The face-on knurled knob is the declination lock; the side-on screw is a fine adjustment. (Lower) Hour-angle circle, numbered 1–24 in hours increasing westwards, in accordance with the normal convention of a target's hour angle increasing with time (author's photographs).

Figure 42: The rear of the Palais de la Découverte mirror and mirror cell. The mirror rear was polished to permit monitoring of the silver deposition on the front (Foucault, 1859a). Heads are visible for four pairs of counteracting screws that provide for alignment of the optical axis of the mirror (author's photograph).

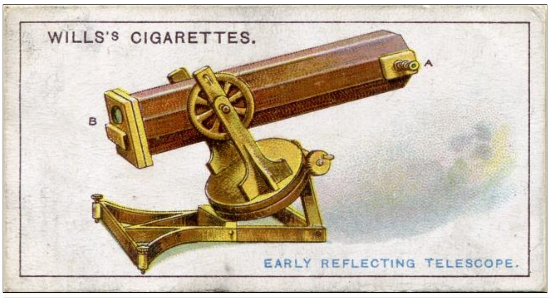


Figure 43: A Wills cigarette card inspired by the Worms de Romilly telescope. Dating from 1915, this was the 29th in a series of 50 on 'Famous Inventions'. The text on the reverse asserts that this is Newton's telescope! (Author's collection).

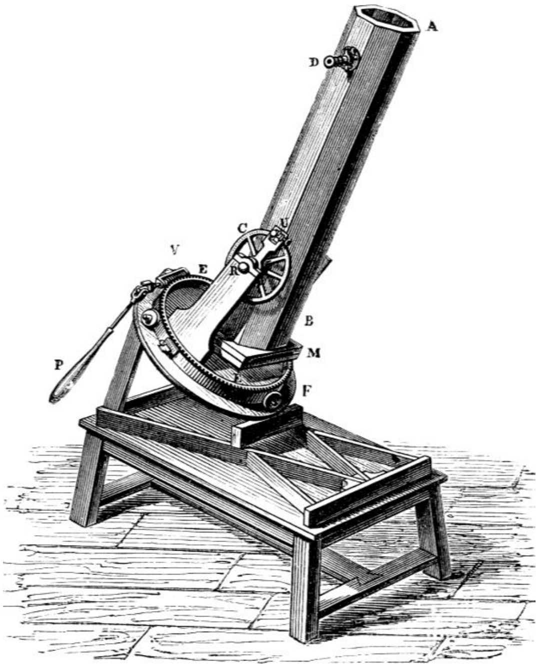


Figure 44: Foucault telescope illustrated in Drion and Fernet's *Traité de Physique Élémentaire* (1861). By means of the jointed rod thickening into a hand-hold the observer could track an object in hour angle while observing at the eyepiece (author's collection).

ouration. The mirror is held in place by a three-fingered spring and stout metal bar. The use of clear glass supports a date prior to early 1859, when Foucault states that he began using green-tinted St Gobain glass.

The woodcut shown in Figure 40 continued to appear in Ganot's *Traité* for over three decades, last appearing in the 21st edition in 1894 (Maneuvrier, 1894: 504). Ganot explicitly reserved the rights to his illustrations, but the engraving was reproduced by de Parville in his obituary of Foucault (1869: 168), and clearly inspired a modified version with background cityscape used by Clerc (c.1882: 478), and even a cigarette card (Figure 43)!

6.2 A Telescope Illustrated by Drion and Fernet (1861)

In the first edition of their *Traité de Physique Élémentaire,* published in 1861, Charles Drion (1827–1862) and Émile Fernet (1829–1905) published a woodcut of a Foucault *télescope* (Figure 44). It was stated that:

> This figure was made from a telescope of small dimensions which M. Foucault has had made, and which he has kindly made available to us: the construction details are the same as for those made, in bigger sizes, for the Paris Observatory. (Drion and Fernet, 1861: 814).

This strongly implies that the instrument was *not* made for the Paris Observatory. Using the engraving over a decade later in a new book, the *Cours de Physique*, Fernet (1875: 440) was even more explicit: "... a telescope that Foucault had had made for himself ..." And indeed, we have seen that Foucault explicitly stated that it was only when he wanted to attack larger apertures that he needed the Observatory's support.

It might therefore seem unlikely that the instrument illustrated by Drion and Fernet is the 20-cm reflector preserved at the Paris Observatory (Figure 45), but the resemblance is striking.[34] (An invoice shows that the major differences—the declination support rod, hinged plank and fine adjustment screw—were later additions: Eichens, 1868.) That it is the same telescope was made clear in 1876 when Albert Lévy (1844–1907), formerly of the Observatory, re-used the woodcut in a textbook he was revising (Delaunay, 1876).

The 20-cm reflector was taken to observe the aforementioned solar eclipse in Spain in 1860 (Enumération des objects, 1860), but in a planning document Le Verrier (1860a) noted that "It will be necessary to acquire this $0^{m}.20$ telescope ..." for the sum of 1,200 fr. Evidently Foucault *did* build this instrument for himself, but sold it on to the Observatory![35] Like the 40-cm telescope, the woodwork is rough, but the more-important metalwork is as carefully made as for the Worms de Romilly telescope. This is an instrument built for cost-conscious researchers, not for rich amateurs. The declination lock and fine control carry the signature and date "Secretan / Paris. / (1860)".

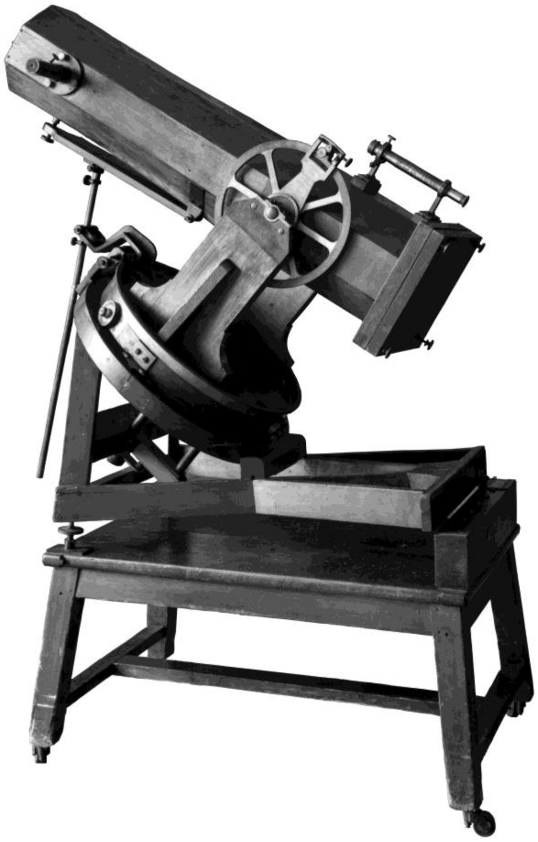


Figure 45: 20-cm reflector conserved at the Paris Observatory (inv. 174) photographed some years ago. The stabilising rod, hinged plank and adjustment screw for setting the declination are apparent. The mirror and its cell have been lost: the wooden plate closing the tube is a modern addition (cf. Figure 31). For a colour photograph, see Tobin (1998) (courtesy: Bibliothèque de l'Observatoire de Paris).

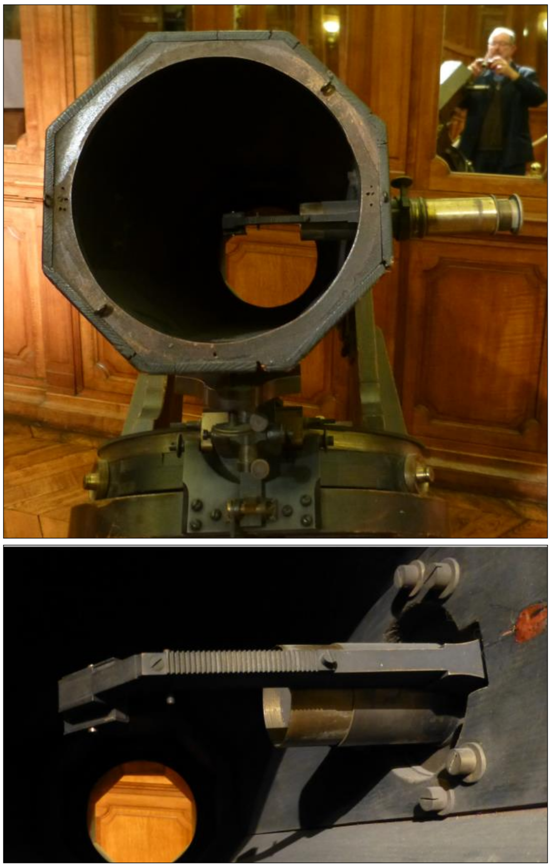


Figure 46: (Upper) The Paris Observatory 20-cm telescope is characterized by the 200-mm diameter aperture at the front of the tube. (Lower) A rack gear attached to the arm supporting the prism is no doubt part of the device used to support and adjust the photographic plate in Wolf and Rayet's lunar-eclipse photography in 1865. The opposite edge of the arm shows wear marks, as from a moveable carriage (author's photographs).

The mirror and its cell have been lost, but measurements I have made of the tube and eyepiece assembly show that its focal length must have been within a centimetre or so of 1.00 metre, a value confirmed by e.g. Wolf and Rayet (1865), and Danjon and Couder (1935: 690). The identity of focal lengths makes it seem very probable that the mirror was Foucault's first parabolic one, completed in July 1858 (see Section 4).[36] Perhaps this is why Le Verrier later described the telescope as "... (a masterwork from his hands!) ..." (Le Verrier, 1868a: 394), a sentiment echoed by Adolph Martin (see Section 7), who described the mirror as "... the most perfect ..." produced by Foucault (Wolf and Martin, 1874: 277). Even if its '24-cm' diameter was in reality 9 *pouces*, the cell could have been big enough. The '20-cm' characterisation of the telescope in fact corresponds to the inner diameter of the aperture at the front of the tube (Figure 46). With a larger mirror, this is the entrance aperture in an optical sense, and physically the most meaningful designation. The 20-cm telescope was taken to observe the 1860 solar eclipse (Enumeration des objets, 1860), but the claim that it was taken to observe the 1868 eclipse (Lequeux, 2009a: 159) is mistaken.[37]

The design of the eyepiece differs from the 4-*pouce* instruments. I was unequipped to measure individual lenses, but Figure 47 sketches the

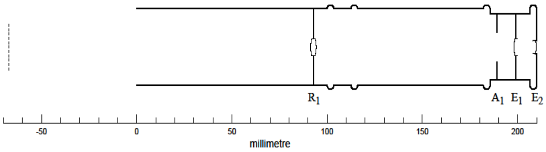


Figure 47: Layout of the eyepiece assembly of the Paris Observatory 20-cm telescope. The form of the inner surfaces of the eyepiece lenses could not be determined. The dashed line indicates the entrance focal plane. The eyepiece is not matched to the focal ratio of the primary mirror so must be a special one built for the Wolf-Rayet photography trials.

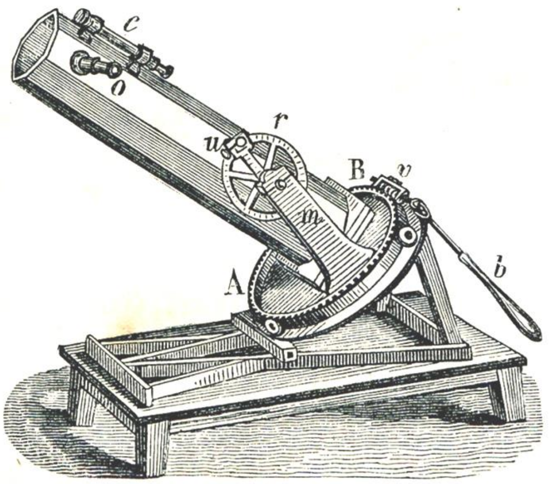


Figure 48: Woodcut presumably inspired by Figure 44 (after: Daguin, 1862; or 1863; courtesy: F. Gires/ASEISTE).

layout. The field of view is about 13 mm, or 0.75° on the sky, but the eyepiece is certainly not original because with the relay lens, R_1 some 150 mm distant from the focal plane, the eyepiece captures very little of the light of the telescope's ~f/5 beam. The large separation allows for the insertion of additional elements into the optical path, as indicated by a rack gear on the arm supporting the prism (Figure 46, lower). Presumably the eyepiece dates from the early lunar-eclipse photography by Wolf and Rayet (1865), where there will have been plenty of light.[38] They explain:

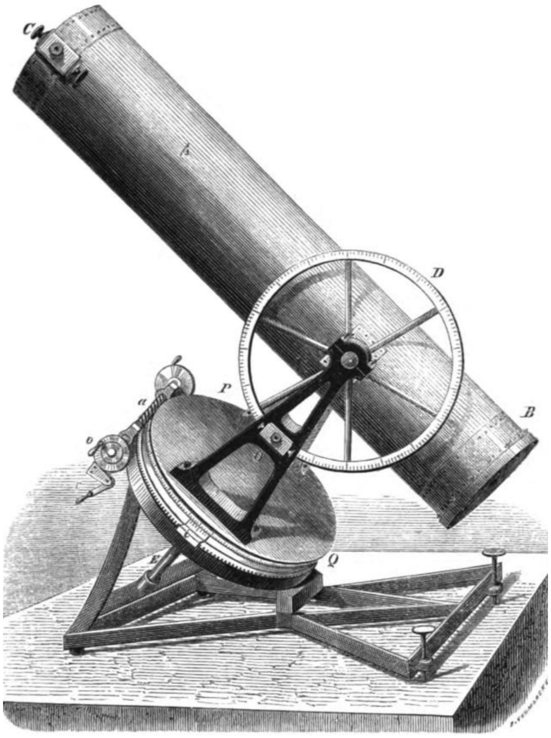


Figure 49: A Foucault telescope adapted for celestial photography in the early 1860s by Désiré van Monckhoven (see text). It is equipped with a filar micrometer at *C* (after: Monckhoven, 1863; courtesy: Google Books).

> The sensitized collodion surface is placed beyond the prism, in the focal plane of the mirror. Focusing is effected by moving the plate holder to the point where, through the eyepiece, one sees a net image of both the celestial object and the surface of the glass plate that is to be sensitized.

Since the specialized eyepiece is still in place, it would appear the telescope was not subsequently used for any major scientific purpose; and I have found no record of any later use. However a "... prismatic glass ..." was added to an eyepiece in 1867, suggestive of specroscopy trials (Eichens, 1867b). The "... Body ..." was repaired and the declination strut etc. were added in 1868 (Eichens, 1868). A Paris Observatory photograph shows the 20-cm among several Observatory telescopes ready to observe the 1907 transit of Mercury, but the sky was cloudy (Observation du passage de Mercure, 1907).

The Drion and Fernet woodcut would appear to be the inspiration behind an illustration later published by Pierre Adolphe Daguin (1814–1884), a Physics Professor at the University of Toulouse, who in 1866 became Director of the Toulouse Observatory. Figure 48 shows this woodcut, which first appeared in the second edition of his *Traité Élémentaire de Physique Théorique et Expérimentale* (1862) and later his *Cours de Physique Élémentaire* (1863).

6.3 A Telescope Illustrated by Monckhoven (1863)

Figure 49 is an illustration of a modified Foucault-Secretan telescope first published in 1863 in the 4th edition of the *Traité Général de Photographie* by the Belgian photographer Désiré van Monckhoven (1834–1882). He noted that Foucault's telescopes were "... the most apt for the reproduction of the heavens by photography ..." on account of their fast focal ratio (Monckhoven, 1863: 371). The foot was stated to be cast iron, but it would seem the rest of the telescope was originally in wood. Monckhoven implied he replaced the declination pillars by iron ones, and stated that he changed the octagonal wooden tube for a circular one in pine with metal reinforcements. The mirror was supported on a ring of straw! He acknowledged that the mount was stable, but added "It has a serious disadvantage, which is the difficulty of attaching a clockwork drive, because the friction in the system is large and irregular." (Monckhoven, 1863: 373). For photography the prism and eyepiece assembly were removed and a plate carrier with a thread for focusing was inserted at prime focus.

The interest of Figure 49 is the indication that by 1863 Secretan was providing base structures in cast iron for at least some of his small equatorial reflectors. Monckhoven's engraving was reused by Figuier (1869).

6.4 A Telescope Illustrated by Jamin (1866)

Figure 50 shows a wood-mounted telescope. The earliest appearance of this engraving that I have found is in the first edition of the *Cours de Physique de l'École Polytechnique* (1866), by Jules Jamin (1818–1886), Professor of Physics in that institution. Despite a certain resemblance to Ganot's xylograph (Figure 40), the focal ratio is clearly slower, and the eyepiece focus motion is perpendicular to the tube. The engraving is not due to Jamin, however, because it appears again in the catalogue "Extract ..." published by the Secretan firm two years later (Table 1; Section 9.1). Its appearance in 1866 shows that such telescopes were commercially available by this date, and we can suspect several years earlier. However the sole surviving telescope akin to that shown in Figure 50 that I am aware of is the 40-cm instrument made for the Reverend J.B.Z. Bolduc (1818–1889) in Quebec, and now in that city's Musée de la Civilisation. It was ordered in 1866 and completed in 1867 (Nadeau, 1943; 1944; also Lemay, 1979 for a more recent illustration).[39]

7 ARRANGEMENTS WITH SECRETAN—AND ADOLPH MARTIN

Marc Secretan's trade was diverse. Besides making and selling the wide variety of items that appeared in his catalogues, his enterprise built novel equipment to order, and was paid for this service. Foucault was punctilious about this distinction, as illustrated by an event in 1862 involving another instrument maker with whom he worked, Jules Duboscq (1817–1886): Foucault was annoyed that there had been a confusion between "... the achievements of the savant and those of the artisan …" (Moigno: 1862a: 447).[40] But when Foucault wrote about the costs that an individual client could bear (Section 5), he was being disingenuous. In February 1852, Louis-Napoléon Bonaparte, then still the Prince-President, had given him 10,000 fr to pay for the previous year's pendulum experiment in the Panthéon and to finance his future research. An additional 8,500 fr had followed by 1860 (Foucault, 1852–1865).[41] Between February 1858 and May 1859 Foucault paid Secretan *télescope* bills of almost 1,875 fr from these funds. Thereafter manufacture of professional telescopes and sales of amateur instruments must have begun to bring in money, because in January 1863 Foucault received an equalisation payment from Secretan of 114.30 fr, and when Secretan died four years later, Foucault was owed a further 6,264.60 fr, though over what period this had accumulated is unstated (Sebert, 1867–1968).

Also in 1863, the commercial arrangement between Foucault and Secretan plausibly evolved. Foucault was not one for "... patient and insipid drudgery …" (an expression he used in a newspaper article (Foucault, 1852)), and no doubt he found tedious the finishing of 40 or more 4-*pouce* mirrors, guaranteed by his signature. Indeed, as we will see in the next paragraph, in order to restrict demand Foucault kept his prices high. He decided to recruit an assistant. It is not known why he decided upon Adolphe Martin (1824–1896; Figure 30), a physics teacher at the Collège Sainte Barbe, Paris' oldest school, founded in the fifteenth century. Martin had devised what was subsequently called the tintype and other new positive photographic processes (Martin, 1852; 1853). Perhaps they met through the Société Française de Photographie, of which Foucault was a founding member and regular contributor, and where from 1861 Martin began presenting talks on photographic procedures (e.g. Foucault, 1861; Martin, 1861). It was later noted that Martin

> ... had generously put useful inventions into the public domain, which were profitably exploited [by others] … without trying to preserve the fruits of his efforts for himself and his family. (Sebert, 1896: 941).

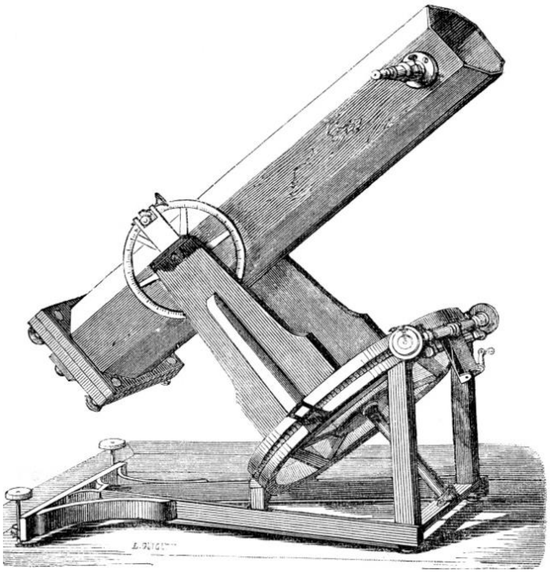


Figure 50: Engraving of a smaller, wood-mounted Foucault-Secretan telescope published in 1866 in a textbook, and probably previously in Secretan advertising matter (after: Jamin, 1866; courtesy: F. Gires/ASEISTE).

Although Foucault had published details of his procedures, it was another thing to put them into practice. A letter reveals that by the spring of 1863 Foucault had initiated Martin into the details of mirror testing and *retouches locales*. Reading between the letter's lines, it would seem that Martin was prepared to be as free with his new-gained optical knowledge as with his photographic inventions. This was not what Foucault wanted! He put his collaborator firmly in place:

> Having you yourself succeeded in applying the methods to two telescope mirrors, you ask me what I think would be the best course of action in the interest of science and art ...
>
> I think that after having received private instruction which led directly to rapid success, it would be correct and fair to keep the advanage you have acquired to yourself …

Recalling perhaps the artisans' scepticism concerning *retouches locales*, he continued:

> … the time has not yet come to spread these procedures to workshops where they cannot be properly applied … keep the knowledge ... to yourself until we agree by common accord that the time has come to make the methods known.
>
> In this way we shall be two, and only two. But if we want to remain masters of the situation, we have to agree how to satisfy the needs of clients without delay. So far, I have not shied away from asking a certain price which restricts demand and also maintains the dignity of the savant … You will soon realise that it is more advantageous and just as dignified to bring a surface to perfection as to give a lecture, or draft a questionable text.
>
> In summary, dear Sir, I find nothing better to say to you about this matter than to advise you to do just as I have done so far (Foucault, 1863).[42]

Martin acquiesced, but after Foucault's death in 1868 revealed some of the trade secrets: how Foucault had standardized on an *f*/6 focal ratio and adapted his parabolization procedure to fit within a shorter optical shop "... of which I was the sole other person who knew ..." (Martin, 1868a: 1058; also 1870a); how he made a 35-cm diameter optical flat so that lenses could be tested in autocollimation (Foucault, 1869; Martin, 1869; 1870b); and how he adapted his procedures to making lenses (Acloque, 1987; Saint-Claire Deville, 1868). A receipt dated just after Marc Secretan's death indicates the amounts that Martin, and presumably Foucault, charged for shaping mirrors: 120 fr for 10-cm, 384 fr for 16-cm, and 2,400 fr for 50-cm diameters (Martin, 1867).[43] Martin evidently subcontracted from Foucault, not Secretan, because at his death Foucault was owed 2,736.65 fr by the Secretan firm, of which 1,320 fr were paid on as owing to Martin (Crosse, 1868).

Still in 1863, in its spring, Martin devised a simpler and more-certain mirror-silvering procedure in which invert sugar replaced oil of cloves as the reducing agent. True to form, he announced his improved process, and subsequent refinements, widely and freely (Martin, 1863a; 1863b; 1863c; 1868b; 1868c; 1875). According to Foucault's friend Henri Saint-Claire Deville (1818–1881), this was the process thereafter used by Foucault (Saint-Claire Deville, 1868), although Foucault himself (1864b) wrote that Martin's solutions "... according to me, have the fault of working too fast." The procedure was later explicitly offered by at least one independent instrument maker (Laurent, 1878).

Arrangements were also changing on the Secretan side. Marc Secretan's first wife had died, and in 1859 he had remarried (Sebert, 1858). His new wife was French, but it seems that in due course the couple set up household in Lausanne, where his four daughters and mentally-handicapped son lived. This is because he signed powers of attorney in 1861 and 1864 allowing his other son, Auguste, who lived in Paris, to run the company for two and then six months during absences in Switzerland (Tandeau de Marsac, 1861; 1864). Auguste's role in running the company was clearly growing. In 1864, for example, Moigno (1864: 487) referred to "... the Misters Secretan, father and son." when writing about the company. A final power of attorney, signed in March 1865 in an increasingly spidery hand, gave Auguste control of the firm without time limit (Sebert, 1865). After Marc's death two years later it was stated that he had been "... back in Lausanne for more than a year ..." (Sebert, 1867–1868) and Gaudin (1867) confirmed that Auguste had been in charge of the firm for several years.

Foucault's 35-cm flat, probably completed in 1864, opened the way to testing by autocollimation and to optically-perfect lenses. Elsewhere I have outlined the subsequent story of Foucault's lens-making, his belief developed in 1860 that refractors were actually to be preferred to reflectors for low-contrast objects, and his conviction that the premier astronomical instrument would be a siderostat (Tobin, 2003). According to Le Verrier (1868b: 22), it was he who pushed Foucault and Secretan to create "... a beautiful optics institute ..." and enter into a more formal contract for the construction of professional objective lenses, signed on 22 March 1865.[44] Perhaps Auguste was also involved. Be that as it may, it would seem that Auguste was an impetus behind the next development in the commercialisation of Foucault's small telescopes: metal mountings.

8 METAL-TUBED TELESCOPES

8.1 A 10-cm Instrument

With their wooden stand lacking fine adjustment in azimuth, the 4-*pouce* telescopes can hardly have been very practical for tracking celestial objects. An improved product was clearly needed. Perhaps there was commercial pressure too. The catalogue produced in 1864 by Jules Duboscq advertised small silvered-glass mirrors and telescopes (Tables 3 and 4; see also Section 10). In any case, a letter from Auguste announced the Secretan company's new product in Moigno's *Les Mondes* in October 1865:

> I have just finished a new model of M. Léon Foucault's telescope with a parabolic, silvered-glass mirror, which has been built at the request of one of our physics teachers and for one of the great colleges of our city (Secretan, 1865b: 272).

Secretan went on to state a 10-cm mirror diameter with the expected *f*/6, 60-cm focal length, and a tube in "... bronzed copper ..." with fork in cast iron. A cast-iron foot was available for observing sitting down and a wooden tripod for observing standing up. The price was 550 fr, more than double the earlier wood-mounted instruments of the same size. Was this to 'restrict demand', at least in part? Magnifications from 60× to 220× were possible, a performance equalling that of a refractor costing 1,200 fr. The telescope gave an upright image and inverted sugar was used in the silvering. Secretan's letter was accompanied by an engraving (Figure 51). At the time, Moigno was delivering monthly public science lectures, and showed off the telescope at the next one (Moigno, 1865). The Paris Observatory immediately ordered two (Secretan, 1865c).

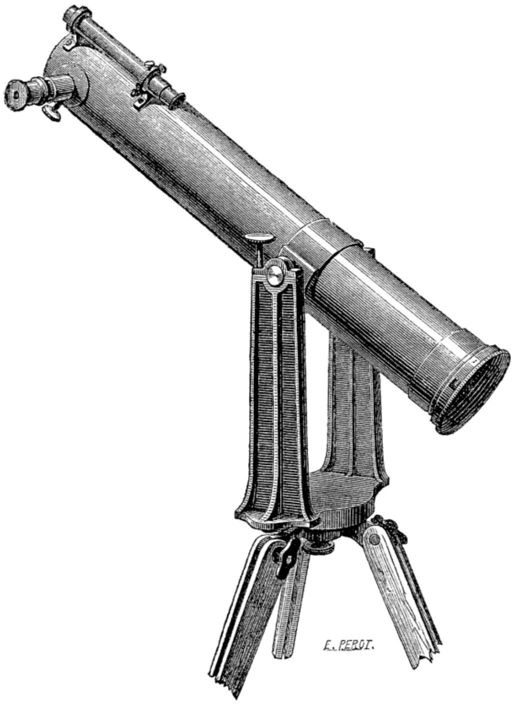


Figure 51: Woodcut of the 10-cm alt-azimuth telescope announced by Auguste Secretan in the autumn of 1865 (after: Secretan, 1865b).

Figure 52: 10-cm telescope at the Lycée Louis le Grand in Paris. There is no signature or serial number. Clockwise from left: (a) Overall view. Is the tripod original or a substitution? It is more stable than the one equipping Nos 13 or 236 (Figures 53 and 62), the legs of which easily splay open. (b) View of the front of telescope and dust cap, which screws on. (c) Mirror cell and spring. The mirror has been lost. (d) Bayonet attachment of the mirror cell to the telescope tube (author's photographs).

The Lycée Louis le Grand in Paris has a telescope of this general form in its museum (Figure 52). The tripod is different, but similar in its altitude joint to ones sold by Secretan (e.g. Lerebours and Secretan, 1853: Figure 59). It would appear to be original rather than a subsequent replacement because there are no trunnions or support band around the tube (cf. Figure 51). The rear of the mirror cell has slotted fixtures for retaining screws, whereas the—presumably later—telescopes shown in Figures 55

Figure 53: Secretan No. 13 metal-tubed 10-cm reflecting telescope, overall view (author's photograph).

Figure 54: Secretan No. 13 10-cm reflector, view of eyepiece, brass dust cap, finder and finder-alignment mechanism. The weighty dust cap with bayonet pins and crudely-cut slots to retain it (not visible) looks to be a replacement. Any lost cap must have been held on by friction, because there is no screw thread on the tube, unlike other 10-cm instruments (author's photograph).

and 61 simply have countersunk holes. The instrument looks very much like a prototype. Is the Lycée Impérial Louis le Grand (as it was then called) the 'great college' in question? Or could it have been the Lycée Saint Louis? Foucault's friend Jules Lissajous (1822–1880) was a physics teacher there, although not a very conscientious one (Brasseur, 2010). Another Saint-Louis suspect must be Émile Fernet, who had earlier published the engraving of Foucault's 20-cm telescope shown in Figure 44.

Figure 55: Secretan No. 13 reflector, mirror cell, maker's mark and serial number (author's photograph).

Figure 56: Secretan No. 13 reflector, mirror-cell back removed showing the clear glass and flat rear of the 100-mm mirror and the leaf spring that keeps it in position (author's photograph).

I know of very few examples of these 10-cm telescopes, listed in Table 9, though they were offered by Secretan and other makers until at least 1900 (see Sections 9 and 10).

Figures 53–57 show an instrument that I chanced across on the sidewalk outside an antiques dealer in Saint Ouen near Paris, with serial number 13. The mirror has a flat back and a metric diameter, 100.3 ± 0.2 mm, which the cell reduces to an optical diameter of 92.2 ± 0.2 mm. I obtained contradictory measurements concerning its focal length, which nevertheless must be no more than ~5mm different from the expected 600 mm.[46] The reflecting prism has approximately-square entrance and exit faces of 11–12 mm sides.

Figure 58 and Table 10 report the layout of its eyepiece assembly, which has been redesigned compared to the wooden-mounted 4-*pouce* instrument shown in Figure 18. It no longer looks to be a quick adaptation from a microscope design, and has more baffling, but if dated 1865, the design is prior to the rigorous sine condition soon to be introduced by Ernst Abbé. As with the Figure 18 instrument, only one eyepiece has survived. The equivalent focal length of the eyepiece proper is much the same as that of the 4-*pouce* instrument (30 vs. 41 mm) but the overall magnification is much less (65× vs. 165×). This is because the increased diameter and spacing of the relay lenses R_1, R_2 has increased the field of view to 0.62 ± 0.05°, as measured from the Moon and confirmed, near enough, from the ray trace (Figure 58). The ray trace shows that the field is defined by stop S_3 and vignetted by S_2. Since the eyepiece assembly performs acceptably as a microscope, the poor performance of No. 13

Figure 57: Secretan No. 13 10-cm reflector, prism assembly (upper) in position, and (lower) removed (author's photographs).

Table 9: Known surviving 10-, 16- and 20-cm Foucault-Secretan telescopes mounted in metal tubes.

Collection/inventory number	Marked serial no. and [date]	Supposed mirror diameter (cm)	Mount	Comments	Additional description and/or images
Lycée Louis le Grand, Paris	none	10	alt-az, fixed-leg tripod	Prototype?	www.aseiste.org
Tobin, Vannes	13	10	alt-az, tripod		tobin.fr
Offered on eBay.it June 2016	53	10	alt-az, tripod bracket, legs missing	Optics lost. Signed as for No. 13, brass parts as for No. 61, cap for eyepiece port as for No. 236	
Prytanée Nationale Militaire, La Flèche	61	10	alt-az, scroll legs		Chanteloup (2004: 193) www.aseiste.org
Van Spengen auction, Hilversum	?	10	alt-az, scroll legs		
Wolf, FRE1	236	10	alt-az, tripod		Wolf (2014)
Wolf, TRE17	18 [1866]	16	equatorial, table		Wolf (2014)
Musée Gassendi, Digne-les-Bains, 1967.2.61	59	16	equatorial		Turner (2006: 201–202) www.aseiste.org
Harvard University, Cambridge, 1997-1-0303	?	16	alt-az, scroll legs	*f*/7?	dssmhi1.fas.harvard.edu/emuseumdev
Observatoire Camille Flammarion, Juvisy	?	16	dual alt-az and equatorial mount[45]	*f*/6?	www.culture.gouv.fr/documentation/merimee/PDF/sri11/IM91001426.pdf (misidentified)
Observatoire de Rouen	?	16	alt-az	*f*/10? purchased 1884	
Observatoire de Dax	lost	16	equatorial	Mirror and cell lost	Flammarion (1890: 860)
Christie's auction South Kensington	lost	16	equatorial	motorized HA drive	Christie's (2008). Sale BKS-5429, lot 23
Museu da ciência, Coimbra. AST.I.098	67	20	equatorial	purchased 1874	www.astro.mat.uc.pt
Groupe d'Astronomie du Dauphiné	[1877]	20	equatorial		

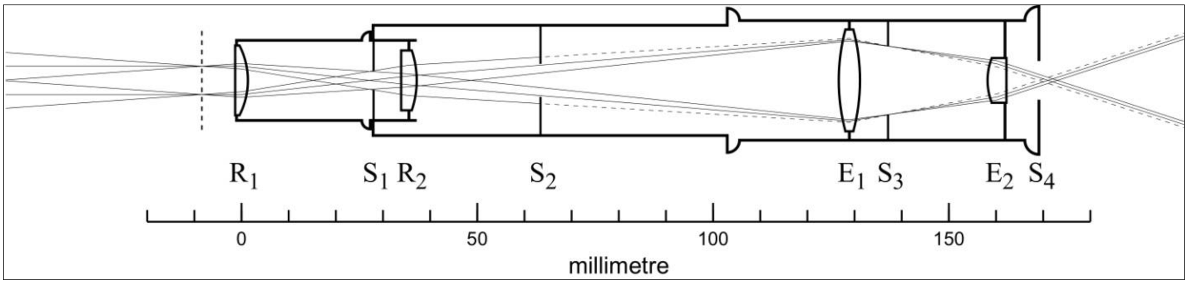


Figure 58: Optical layout and ray trace for the eyepiece assembly of the No. 13 telescope. The ray trace corresponds to a field of view of 0.57° and a relaxed eye. The dashed line indicates the corresponding entrance focal plane. For component parameters, consult Table 10.

as a telescope must be ascribed to problems with the mirror (see Note 45).

The externally-similar telescope in the collection of the Prytanée National Militaire in La Flèche carries serial number 61 (Figure 59). Photographs given by Chanteloup (2004: 193) show that it has survived with scroll legs and, like the Louis-le-Grand instrument, the dust cap is attached by a more-satisfactory screw thread. In addition, the optical arrangement is different. The mirror is considerably thinner than the 18.35-mm thickness of the No. 13 mirror, and is mounted in a threaded sub-cell. A cover is provided for the sub-cell, seen in Figure 60, which shows the contents of the accessories box. An associated handwritten label indicates that the

Table 10: Lens and aperture specifications for the Secretan Number 13 eyepiece assembly (my measurements). Measurement uncertainties are ~0.5 mm for positions and diameters and ~1.0 mm for focal lengths. The equivalent focal length is –9.3 mm. For an eye focused at infinity, the entrance focal plane position is –8.4 mm. See also Figure 58.

	Position (mm)	Clear diameter (mm)	Focal length (mm)
R_1	0.0	14.8	27.1
S_1	28.0	4.0	
R_2	35.5	12.7	32.9
S_2	63.4	7.0	
E_1	128.9	21.6	35.1
S_3	137.1	14.5	
E_2	160.2	9.5	21.8
S_4	169.1	8.2	

long tubes are terrestrial eyepieces, which must thus contain inverting lenses, while five small eyepieces are for celestial use.[47] The relay lenses have thus been eliminated, and it is true that increasing the focal length of the mirror by ~5 cm results in the standard Newtonian arrangement with only some off-axis vignetting by the prism, which is of similar size to the one in No. 13. The terrestrial and celestial eyepieces are presumably the same as those offered as standard with 108- to 190-mm *lunettes* (Secretan, 1874: 74).

Figure 59: Signature and serial number of the No. 61 10-cm telescope preserved at the Prytanée National Militaire (courtesy: L. Chanteloup/PNM).

Figure 60: Accessories box for the No. 61 telescope. At upper left is the covered mirror sub-cell. The long tubes are terrestrial eyepieces while the small eyepieces are for celestial use (courtesy: L. Chanteloup/MNP).

Figure 61 shows a 10-cm telescope sold in the Netherlands in 2010. Figure 62 shows an instrument in the aforementioned Wolf collection. The signature specifies serial number 236 and R. Mailhat as director of Secretan's workshops (Figure 63). The instrument can thus be dated to rather later, 1888–1894, the period when Mailhat (d. 1923) occupied this role (see Section 9.2). Figure 64 shows the eyepiece box (see also Figure 69). The optical arrangement has returned to the Foucault-Secretan standard, suggesting that the Prytanée National Militaire telescope may be a special case. The dust cap screws on, like No. 61. Troubetzkoy (1916) gives a photograph of another 10-cm instrument, which appears to have been modified by the addition of a counterweight.

Figure 61: Upside-down photograph of a metal-mounted 10-cm telescope sold on 22 October 2010 by the Van Spengen auction house in Hilversum. The scroll legs are apparent (courtesy: www.vanspengen.nl).

It is plausibly this form and 10-cm size of Foucault-Secretan alt-azimuth telescope that was described appreciatively as "... the good fortune of astronomy dabblers." (Cristal, 1875: 67). At about the same time, this telescope was immortalized in stone for a statue which graces the entrance gate to the Nice Observatory (Figure 65). The telescope was still advertised in the 1906 Secretan catalogue (Figure 66).

8.2 16-cm Apertures

The Secretan firm moved on to provide a larger aperture and an equatorial mounting. Figure 67 shows another telescope from the Wolf collection, which has the serial number 18 and date 1866 on the mirror cell (Figure 68). Its mirror diameter is 160 mm for a usable diameter in its cell of 149.5 mm. The mirror has a convex back and the glass has little or no green tint. The telescope is equatorially mounted. The eyepiece assembly has not been examined in detail but appears broadly similar to that of the metal-tubed 10-cm instruments, with the exception that the relay lenses are more separated, presumably to adapt to the greater focal length of the mirror (Figure 69). Figure 70 shows a similar instrument acquired by the Bishop of Digne, Julien Meirieu (1800–1884), which from its serial number must date between 1866 and 1874 (see Table 9). The bases of these two telescopes are made of cast iron, as with Monckhoven's telescope shown in Figure 49. Figure

Figure 62: General view of 10-cm telescope from the Wolf collection, Secretan serial No. 236, dated to 1888–1894. The tripod is similar to that equipping telescope No. 13, but the eyepiece barrel diameter is less (see Table 11) (courtesy: E. Wolf).

Figure 63: Signature of the No. 236 telescope (courtesy: E. Wolf).

Figure 64: The eyepiece box for telescope No. 236. When the eyepiece assembly is removed from the telescope tube, dust can be prevented from entering with the cap seen at upper left. The misprint "Maison Lerebourg & Secretan" on the business card surprises, but less-so when it is understood that in French "Lerebourg" and "Lerebours" are homophonous. The card gives 30, rue du Faubourg Saint-Jacques as the workshop address (cf. Table 1 and Section 9.2) (courtesy: E. Wolf).

Figure 65: Statue personifying astronomy holding a Secretan10-cm telescope at the gates of the Observatoire de Nice. Signed "G.J. THOMAS PARIS 1881", the sculptor is Gabriel-Jules Thomas (1824–1905). A first version in plaster dated 1877 is preserved at the Musée Camille Claudel in Nogent-sur-Seine (see www.culture.gouv.fr/documentation/joconde/fr/pres.htm)(courtesy:cadsol.ovh.org/Alpes-Maritimes and D. Collin).

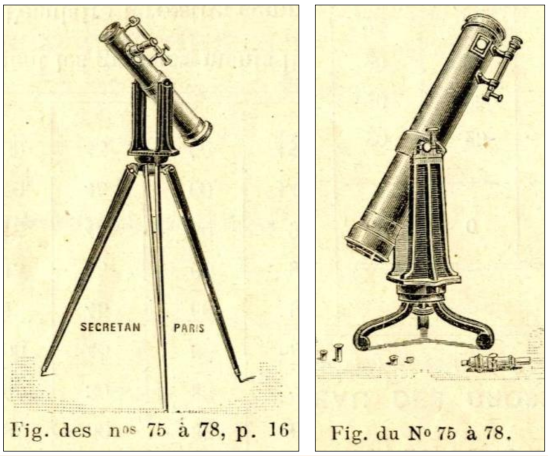


Figure 66: The 10-cm telescope still on sale in 1906, illustrated with tripod and scroll legs. The catalogue also printed the Figure 51 xylograph (after: Secretan, 1906a: 17; courtesy: I. Taillebourg, CNAM).

Figure 67: Metal-mounted 16-cm Foucault-Secretan telescope No. 18, dated 1866. In 1880 it was purchased by José Batlle y Ordonez (1856–1929), who was later President of Uruguay. The polar axis is set for a latitude of 35°, which is correct for Montevideo, but the hour-angle circle is labelled for the northern hemisphere (courtesy: E. Wolf).

Figure 68: Serial number and signature on telescope No. 18 (courtesy: E. Wolf).

71 shows a 16-cm instrument which belonged to the astronomy popularizer Camille Flammarion (1842–1925); it is explicitly stated that it was made by Foucault (L'Observatoire de Juvisy, 1887: 326–327).

9 SUBSEQUENT DEVELOPMENTS

9.1 1866 to 1874

We have already encountered Wilhem Eichens, who mounted Foucault's larger telescopes. When the case was being made for him to receive the Légion d'honneur in 1862, Foucault (1862e) noted his capacity to "... imagine the mechanical details needed to transform a theoretical idea into reality …" and summed up his crucial rôle in the company:

> Although the instruments in question have been made in the firm known by the Secretan name, in reality all these works of precision mechanics are the creations of M. Eichens, who for many years has been head of the workshops, and, one can say, of the company.

Figure 69: Eyepiece assembly comparison for the three Wolf collection telescopes with eyepiece and relays lenses detached. (Upper) 16-cm telescope, No. 18. (Middle) 10-cm telescope, No. 236. (Bottom) 4-*pouce* telescope, No. 4. In all cases, friction holds the 'microscope' barrel in the rack-and-pinion focus slider, which has a throw of about 2½ cm (courtesy: E. Wolf).

However, some discord arose.[48] A break-up threatened. In a letter which shows more understanding of human nature than usually attributed to him, Le Verrier wrote (1867) that he "... did everything to avoid this split ...", but as Eichens (1866) explained to him in August 1866:

> Yesterday I received a letter from M. Secretan son in which in elliptical but clear terms he told me that there could be no sort of arrangement with Monsieur his father and that in consequence our separation on October 1 was maintained.

Eichens went on to say that he was therefore setting up his own business, "... trusting to the protection of God and those people who have given me proof of their support ..."; and indeed, the Observatory subsequently contracted with him directly.

With its mechanical capacities amputated, the Secretan company's exhibit at the Paris Exposition Universelle of 1867 concentrated on optical productions, though a model was exhibited of the Paris Observatory equatorial refractor delivered in 1860. Sources differ as to exact items displayed: evidently they changed over time (e.g. Exposition Secretan, 1867; Lissajous, 1868; Moigno, 1867; Rayet, 1868). Lenses figured by Foucault's methods were shown, and at some point the new 10-cm alt-azimuth reflector may have been exhibited (Mesnard, 1868); but all agree on the presence of a 16-cm, *f*/6, silvered-glass telescope, equatorially-mounted in metal (except for Weld (1868a) who—presumably mistakenly—claimed a 9.4-inch (239-mm) mirror). "... this instrument," one commentator said, "was certainly the most interesting one exposed by M. Secretan." (Mesnard, 1868: 84). "... a most excellent instrument ..." said another, for whom "The chief interest consisted in the speculum, which was one of Foucault's." (Weld, 1868b: 427).[49] Camille Flammarion opined that Secretan's instruments, telescopes included, were "... built with a distinctive coquettishness and elegance." (Flammarion, 1867). The St Gobain company exhibited "... very fine discs designed for the mirrors of reflecting telescopes" (Barnard, 1869: 521).

At the end of June, half-way through the exhibition, Marc Secretan died while in Lausanne. Auguste took sole charge of the business. In the next year a catalogue "Extract ..." was published (Table 1), perhaps to capitalize on interest generated by the exhibition. It is a curious work in that its foreword, signed simply "SECRETAN", speaks of "The frequent contact that I had the good fortune to have with M.L. Foucault ..." Is this the father or the son writing?[50]

The 10-cm alt-azimuth and 16-cm equatorial instruments were the only metal-mounted telescopes offered; the latter cost 1,800 fr (Table 2). Both were advertised with a set of four eyepieces. All mirrors were stated to be *f*/6. Wood-mounted equatorials were also offered with apertures from 16 to 80 cm. The price for a mirror alone was "... 200 francs per square of 10 centimetres ...", for which the "... amplifying power is obtained by doubling its diameter in millimetres …" such that a 20-cm mirror, for example, cost 800 fr and permitted a maximum useful magnification of 400×. On a 10-cm mirror the mark-up would thus appear to be 80 fr over the 120 fr charged by Martin and Foucault for its polishing. The catalogue printed all three of the Secretan woodcuts already encountered (Figures 34, 50 and 51).

Figure 70: A similar 16-cm telescope to that shown in Figure 67, described by Bennett (2009: 566) as one of the "... highlights ..." of the Musée Gassendi in Digne. The eyepiece assembly is missing. The curved mirror rear rests against a matching curved metal cross, which arrangement probably facilitates collimation. The instrument was restored in 1991 (Turner, 2006). The arms of the original owner are engraved on the tube (courtesy: Collection Musée Gassendi, Digne-les-Bains).

To promote its business, no doubt, the Secretan firm made these three engravings available to others. They were reproduced by many authors, such as, for the 10-cm telescope: Exposition Secretan (1867), Guillemin (1874; 1882), Jamin (1866; 1870), and Marion (1867); for the smaller wooden telescope: Jamin (1866,

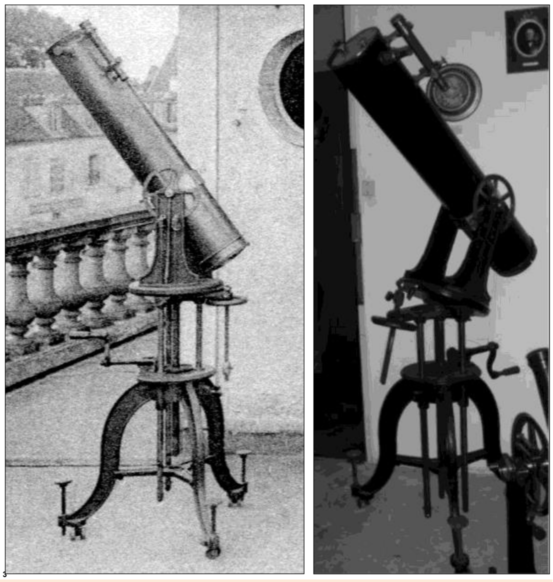


Figure 71: A 16-cm reflector from Flammarion's observatory at Juvisy, seen (left) on a postcard, and (right) in a modern photograph. The metal cambriole-leg stand can be adjusted to provide either an alt-azimuth or equatorial mount and is a modification (author's collection; and courtesy: G. Artzner).

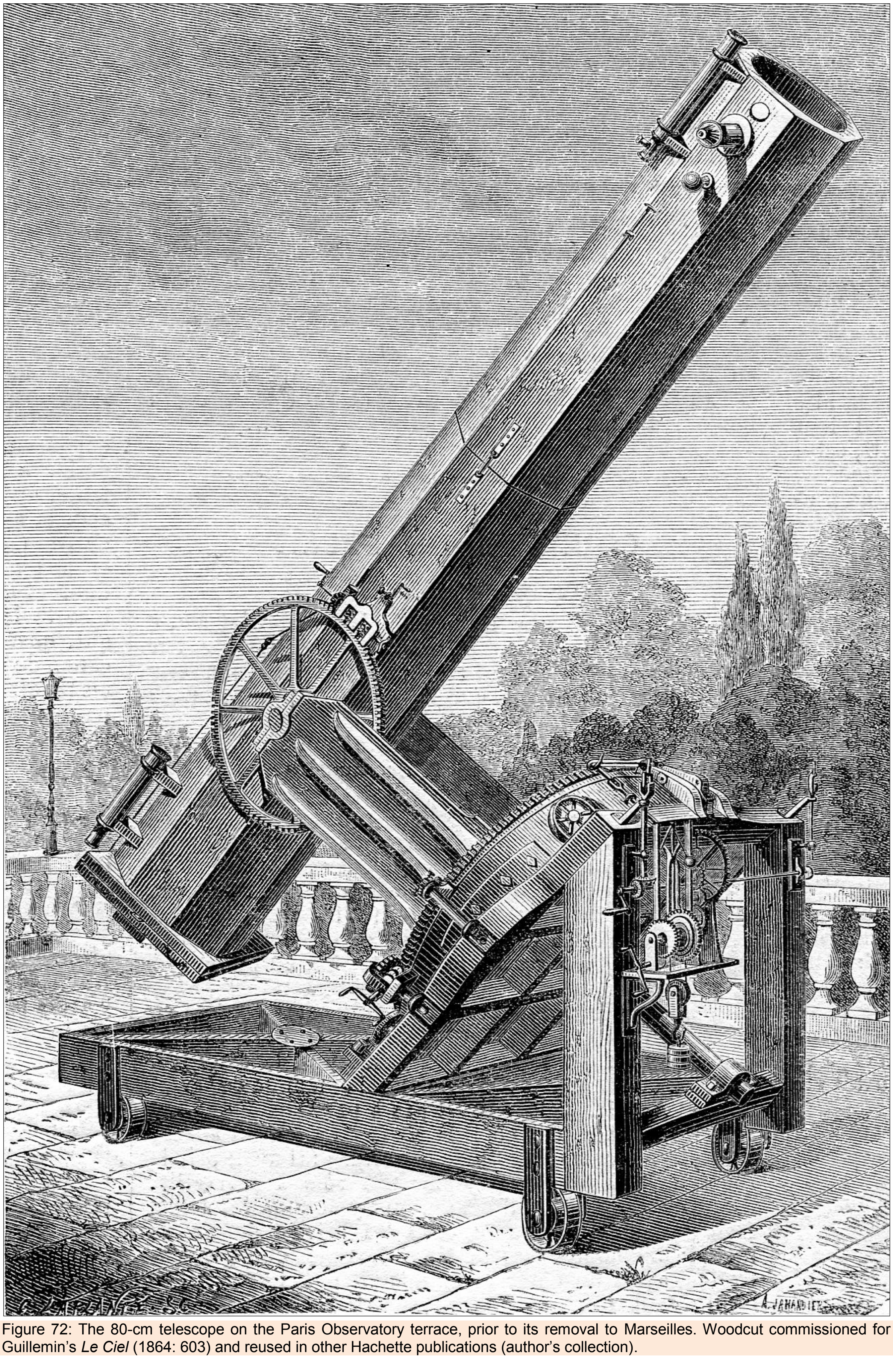


Figure 72: The 80-cm telescope on the Paris Observatory terrace, prior to its removal to Marseilles. Woodcut commissioned for Guillemin's *Le Ciel* (1864: 603) and reused in other Hachette publications (author's collection).

as already noted) and Rayet (1868); and for the Marseilles 80-cm telescope: André and Rayet (1874), Angot (1881), de Parville (1865, amputated of the two onlookers on the right), Figuier (1869), Jeunesse (1865, also amputated), Marion (1867), and Moigno (1864), who claims his to be the first publication of the xylograph. Publishing earlier, Boutan and d'Almeida (1861) had used the illustration from the Observatory's *Annales* (Figure 31), while the science writer Amédée Guillemin (1826–1893) went so far as to commission a private picture of the 80-cm telescope for his luxuriously-produced *Le Ciel* (Figure 72).

I am unaware of any other contemporary illustrations of Foucault-Secretan telescopes. As will be discussed in Section 10, the xylograph of the 10-cm metal telescope was later printed in several other instrument-makers' catalogues.

As a result of Marc's death, an inventory was made of the business (Sebert, 1867–1868). It comprises some 3,700 entries, most of which concern other subjects, but nevertheless it offers glimpses of how the firm built reflecting telescopes. It includes a series of glass discs for working mirrors, three devices for examining their surfaces, two associated stands, and two copper basins for silvering (entries 3361, 3492, 3494 and 3334), but otherwise there are no special tools.

There are raw materials such as slabs of Saint Gobain glass, "Metal for telescopes ...", and polishing necessities like paper and rouge (entries 3389, 3325, 3380 and 3370). There are some copper fittings and several eyepieces (entries 3067, and 2973, 2975 and 3061). There are also six copper boxes for puzzling 10-mm diameter telescope mirrors (entry 3335). Presumably 10-cm is meant. (Is the mirror-sub cell of the Prytanée National Militaire telescope (Figure 60) part of such a box?) Besides the 16-cm telescope on show at the Exposition Universelle, valued at 1,000 fr, there was a 40-cm instrument in the shop on the Place du Pont-Neuf, valued at 4,057 fr (entries 3550 and 3546). Presumably this is Bolduc's telescope awaiting despatch to Canada (Section 6.4). The quoted prices for such silvered-glass telescopes in 1874 were 1,800 and 9,000 fr, respectively (see Appendix 2): the differences suggest the commercial markup. In the workshops on the Rue Méchain there was a 16-cm mirror "… with striations …" which given its 5-fr value must have been unsatisfactory; two 10-cm *télescopes* "... in the hands of the workmen …", and also an uncompleted 80-cm one, which must be the instrument intended for Toulouse (entries 3428, 3009 and 3008). But there were no reflecting telescopes in stock, which contrasts with the many microscopes, spyglasses and other refracting telescopes available off the shelf. This suggests that silvered-glass telescopes were made to order, even for small sizes. This would seem to be true for many of the specialised instruments in the firm's catalogues, which were not in stock either.

The next misfortune to befall the firm was Foucault's death in February 1868, although he had fallen ill the previous summer. The firm was now deprived of both mechanical and optical expertise. Indicative of the company's difficulties is the fact that when Paris Observatory decided it needed a second 40-cm reflector, it did not order it from the Secretan company. The mirror was ordered from Martin, and the rest of the optics and the mounting from Eichens, whose mount (Figure 73) considerably resembles earlier instruments. About this time Eichens produced another design, seen in a 20-cm reflector built before 1874 for a certain Monsieur Séguin (Figure 74).


Figure 73: Not a Foucault-Secretan telescope! This 40-cm reflector for the Paris Observatory was completed in 1871. The mirror was figured by Martin for a cost of 2,400 fr (Martin, 1870c). The mechanical work, the 25-mm crown-glass prism and achromatic eyepiece were supplied by Eichens (6,500 fr: Eichens, 1871b). The tube is metallic. Although metal tubes reduce chimney currents, it was found necessary to insert four aeration vents near the mirror some months later (Eichens, 1872). The lower control rod locks the triangular structure in declination. The upper rod serves to move the tube against the structure, so providing fine control. The declination circle on the other side of the tube is very similar to the one on the Foucault-Secretan 40-cm telescope (Figure 27) (courtesy: astro2009.futura-sciences.com and X. Plouchart).

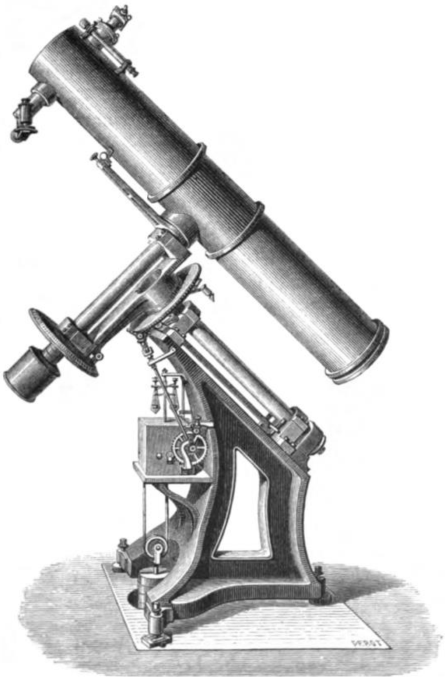


Figure 74: A 20-cm, f/7 silvered-glass reflector mounted by Eichens before 1874. A similar instrument dated to 1877 is conserved at the Université de Montpellier-2 (e.g. www.collections.univ-montp2.fr). I suspect the mirrors were made by Martin (after: André and Rayet, 1874: 121; courtesy: Google Books).

It would seem that Martin also continued to work for Secretan directly; but with little enthusiasm, perhaps because he was busy building mirrors for 1868 solar-eclipse and 1874 Transit-of-Venus expeditions.[51] In any case, Secretan reported in late 1873 that “M. Martin, either incapacitated, or through ill will ...” had not worked on the Toulouse 80-cm mirror (Lamy, 2008: 5, his translation). Paris Observatory also contracted with Eichens and Martin to finish building the 120-cm reflector which finally entered service in 1876 (Figure 75). Eichens’ work was exemplary, but it is notorious that Martin dishonestly hid his inability to produce a satisfactory mirror (e.g. Tobin, 1987).

The Second Empire fell at Sedan in September 1870. Paris was soon besieged for four months, followed by the bloody suppression of the Paris Commune in May 1871. During the siege a large Prussian shell fell on the Secretan workshop on the Rue Méchain. Auguste reported it destroying a “... fairly considerable ...” number of astronomical objectives and caused “... 18 to 20,000 francs …” of damage (Secretan, 1871). But neither an essential machine for dividing circles nor Foucault’s optical flat for testing objectives was damaged. “... relative to the risks run,” Auguste concluded, “I have again been very lucky.” His luck continued three years later when a fire broke out in the shop on the Place du Pont-Neuf and was mastered reasonably quickly (Faits divers, 1874; L’incendie de la nuit dernière, 1874).

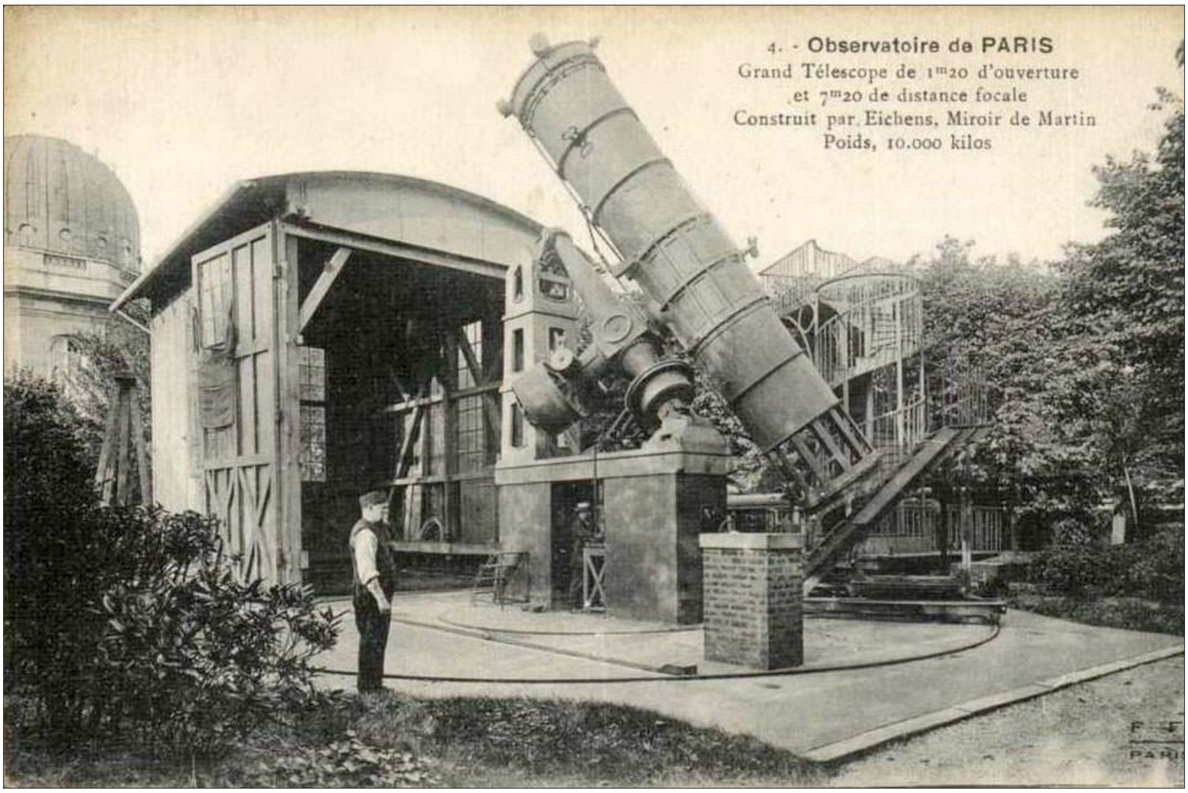


Figure 75: The 120-cm reflecting telescope, enclosure and helical observing platform. Proposed in 1862, the mirror blank was cast the following year, but the telescope was not completed until 1876. The optics never performed satisfactorily. Paris Observatory’s east wing and dome are visible in the background (courtesy: www.cparama.com).

According to Flammarion, salvation for Auguste's optical fabrication problems came in about 1873 when Flammarion (1874a) introduced him to the brothers Paul (1848–1905) and Prosper (1849–1903) Henry. The Henrys had been working at Paris Observatory since the mid-1860s, in the Meteorological Department. In about 1871 they had built a 30-cm silvered-glass reflector in their spare time, in consequence of which they were transferred to astronomical work and began to make mirrors and lenses, it would appear both for the Observatory and privately. In November 1873 Auguste was able to report that he had "... become independent for small-sized mirrors ..." as well as "... for those of large sizes." (Lamy, 2008: 5, his translations). During 1874 the Henrys shaped a new, 84-cm mirror for the Toulouse telescope (Figure 37). The mirror is signed "Secrétan Opt[icien]. Parabolisé par M.M. Henry fr[èr]es. Paris 1874" (Pérolle, n.d.). Another signed Henry mirror of slightly later date is the ~f/6 301.0 ± 0.5-mm diameter mirror from the "... 0^{m}.30 ..." telescope owned by M. Jules Thore of Dax (Flammarion, 1890: 860), and now at the Observatoire de Dax. Inscriptions read "Parabolisé par M.M. Henry frères Paris 1879 N^{o} 30" and "Pouvoir optique – 450 000" (Soulu and Dupouy, pers. comm., 2016). The octagonal tube of this instrument in unpolished wood has survived and is of characteristic Secretan conception.

In early 1874 Auguste Secretan finally produced the long-promised catalogue of astronomical and other instruments (Table 1).[52] It was the complement to a catalogue of chemical and other equipment published 12 years earlier (Secretan, 1862b). The 1874 catalogue represents the apogee of Auguste's work, and the silvered-glass telescope in particular, with the greatest offering and the most detail. "We congratulate him for his efforts and we applaud his successes." wrote a reviewer (Dufour, 1874). I have translated relevant parts of this key document in Appendix 2. The catalogue reprinted, slightly-edited, the descriptions of optical testing and optical power published by Foucault in the Observatory's *Annales*, vaunted in a company advertisement as "... all the more valuable because one looks for them in vain in most of the usual treatises." (Maison Secretan, 1876). Introducing this section, Auguste alluded to difficulties with optical fabrication, saying "We had the good fortune to meet Messieurs the Henry brothers, who were very willing to try to fill the gap left by Foucault." (Secretan, 1874: 110). The range of metal-mounted, alt-azimuth telescopes was extended to include 160- and 200-mm apertures. Figure 76 shows a 160-mm example. With equatorial mountings, available apertures were 16, 20, 30, 40 and 50 cm. Figure 77 presents a surviving 20-cm instrument.

Figure 76: Alt-azimuth 16-cm reflecting telescope conserved at Harvard University (see Table 9). Two locking screws are provided for the altitude axis (cf. Figure 53). The eyepiece assembly is not attached, but is similar to those of other metal-mounted instruments (courtesy: Collection of Historical Scientific Instruments, Harvard University).

Figure 77: Equatorially-mounted 20-cm reflector, serial number 67, acquired in 1874 by the University of Coimbra (see Table 9) (courtesy: Observatório Astronómico da Universidade de Coimbra).

Figure 78: 16-cm telescope with motor drive offered for sale by Christie's South Kensington in 2008 (see Table 9). The original mirror and cell are missing and have been replaced, so there is no signature or serial number. The eyepiece lenses are also lost. Like the Milan telescope (Figure 93), the tube has an additional external ring (courtesy: J. Duncan).

Wood-mounted telescopes were still available for "... institutions whose budgets are too limited ..." (Secretan, 1874: 96), with apertures of 16, 20, 30, 40, 50, 60 and 80 cm. The 16-cm instruments, both wood- and metal-mounted, were also advertised with a motor drive. Figure 78 shows such a telescope. The additional ring around the tube of the latter suggests that its tube can be split into two, perhaps to facilitate transport, unless it is just strengthening or permitted rotation of the prism and eyepiece to a convenient viewing position. Figures 77 and 78 reveal setting circles arranged essentially as for the Worms de Romilly *télescope* (Section 6.1).[53] For those who wanted to make their own tube and mount, the price of parabolized mirrors had fallen to 150 fr per 10-cm square.

Auguste had not long to live. Heart disease had become manifest during his service with the ambulances during the siege of Paris and had worsened in the spring of 1874. He was at work on 9 October when an aneurysm burst externally, killing him in a pool of blood. Summing Auguste up, Flammarion (1874a, his italics) wrote of a man "... so hard-working and so good. Secretan was not a *commercial trader*, but a true *artist*, at every instant sacrificing his own interests for the love of science."

Figure 79: (Left) Georges Secretan (or Secrétan) (1837–1906) (after: Obituary, 1906; courtesy: Bibliothèque Nationale de France). (Right) Gustave Jacquelin (1879–1939) (after: Flammarion, 1939; author's collection).

9.2 1874–1906

Auguste was unmarried. His cousin Georges Emmanuel Secretan (1837–1906), who had been a language teacher at the Collège de Lausanne, took over the business (Figure 79). It was under Georges that the firm sometimes began to use an 'é' in its publications – Secrétan.

For the first decade or so, Georges appears to have let innovation wither. According to a French commentator writing in 1889, "... from having been a very important manufacturing house thirty years ago ..." the firm had "... concentrated on supplying routine instruments since the death of M. Secrétan." (Teisserenc de Bort, 1891: 630). The catalogue published in 1878 (Tables 1 and 2) offers only 10- 16- and 20-cm silvered-glass telescopes (i.e. items 379–381 of the 1874 catalogue), though unmounted mirrors up to 80-cm are advertised. The only telescope illustrated is the 10-cm alt-azimuth one (Figure 51), and this is also the case in the brochure published for that year's Exposition Universelle in Paris (Tables 1 and 2). The 1885 catalogue offered only 10- 16- and 20-cm silvered-glass telescopes, with no illustrations. Telescope prices remained unchanged since 1874 (Appendix 2 and Table 2).

The reduced place allocated to silvered-glass telescopes in the Secretan catalogues no doubt mirrors the fact that the last quarter of the nineteenth century was a time when reflectors found little favour with astronomers, whether amateur or professional.

The slow uptake by professionals has been discussed by Lequeux (2009b). Part of the reason may have been the failure of the Edinburgh 24-inch and Paris 120-cm silvered-glass reflectors in the 1870s (Brück and Brück, 1988; Tobin, 1987) and the supposed failure of the (metal-mirrored) Great Melbourne Telescope. Gascoigne (1996) has claimed that the real problem with this telescope was that it was primarily conceived for making pencil-and-eye sketches of nebulae, which were no longer of any scientific interest. Despite this, Orchiston et al. (2017) have recently shown that the Melbourne telescope was nevertheless used very effectively for pioneering spectroscopic observations. In addition, silvered-glass reflectors were considered temperamental and difficult-to-use. Cornu (1876) admired the stability of focus of a photographic refractor compared to the "... constantly varying ..." focal position of a reflector when the ambient temperature changed. Even such advocates as the 'silvered-glass' astrophotographers Isaac Roberts (1829–1904) and A.A. Commons (1841–1903) came out in favour of refractors for the *Carte du Ciel* project in 1887. Roberts considered reflectors unsuitable for use by "... an ordinary assistant ..." (Congrès Astrophotographique International, 1887: 37), while Common reportedly compared them "... somewhat ungallantly, to the female sex" (Turner, 1912: 25).

The production of silvered-glass reflectors for amateurs also seems to have stalled in the last decades of the century. In an American report on the 1889 Exposition Universelle in Paris we read (Hastings, 1891: 226):

> It was somewhat surprising not to find reflecting telescopes, that is, the modern silver-on-glass type, better represented in the Exhibition, in view of the fact that it was invented in Paris, and that it is supposed to be peculiarly the amateur's construction … The suggestion that this type of telescope has become nearly as unattractive to the amateur as it has to the professional astronomer is obvious.

The report includes the interesting detail that the "... 9.9 inch ..." (250 mm) mirror exhibited by Secretan was figured by the Henry brothers, with the slow focal-ratio *f*/10. Figure 80 shows a 16-cm Secretan reflector acquired five years earlier, in 1884, by the Observatoire Populaire de Rouen (Libert, 1902). It, too, has a slow focal ratio, ~*f*/10. In 1885 a local Rouen observer, Ludovic Gully (b. 1841), reported that his 20-cm Secretan reflector was "... not very nett (it needs to be replaced by M. Secretan) ..." (Gully, 1885).[54] The implication might be that speed and economy of fabrication were forcing the Secretan firm to supply slower mirrors, because we have seen from the Dax instrument (Section 9.1) that the Henrys were quite capable of figuring *f*/6 ones. The company's c.1898 catalogue claims the change was "... to improve the image and permit celestial photography." (Table 2).

Camille Flammarion may partly have been responsible for amateur disenchantment with reflectors. As early as 1867 in a newspaper article he had written:

> … for amateur astronomers, we admit that, in our opinion, at equal power, a refractor is always preferable to a reflector. It is much easier to set a refractor on a star than to search for its reflection in a *télescope*, and much easier to apply it to various studies (Flammarion, 1867).

This text was reprinted as part of a compilation (Flammarion, 1870: 177), but his opinion probably had most effect on telescope buyers when propounded in a supplementary volume to his influential *Astronomie Populaire.* He had got used to pointing reflecting telescopes, admitting (Flammarion, 1882: 685) that the Foucault-Secretan 10-cm reflectors were "... simple and elegant, and very nice to use … [but] advises for preference refractors ..." because their objectives do not deteriorate, unlike reflectors whose

> … mirrors get spotted with the smallest drop of rain, and, especially in the air of big cities, tarnish, and require resilvering from time to time. This is a drawback and a source of worries and trouble.

Nevertheless, the 1870s did give rise to a new design of mount. Figure 81 shows a 200-mm example on which Secretan's name and the date 1877 are engraved. I have not found this form of equatorial mount in any Secretan catalogue, but Flammarion did include a woodcut of such a telescope in his *Les Étoiles* published in 1882 (Figure 82). The design appeared with an hour-angle drive in a photograph (Figure 83) in the c.1908 catalogue (Table 3) of R. Mailhat who bought part of the Secretan workshops in 1894 (see next paragraph). As with the 40-cm Eichens-Martin telescope (Figure 73), a triangular structure on the declination axis forms part of the coarse and fine controls in declination. The change of mount was perhaps definitive, because telescopes with the previous form of metal mount for which there is an established date all date from prior to 1877 (Figure 67 – 1866; Figure 77 – 1874 or before).

Figure 80: Secretan 16-cm alt-azimuth reflector at the Observatoire de Rouen dating from 1884 (see Table 9). The focal ratio is ~*f*/10 (courtesy: www.astrosurf.com/obsrouen).

Figure 81: An equatorial 200-mm Foucault-Secretan telescope dated 1877 belonging to the Groupe d'Astronomie du Dauphiné (GAD) (see Table 9). The GAD received it as a gift from the University of Grenoble and electrified the drive (Pouget, pers. comm., 2015). The finder telescope differs from those shown in Figures 82 and 83, suggesting it is a replacement (courtesy: G. Auzet).

Our French commentator from 1889 continued: "But recently Monsieur G. Secrétan has built up his workshops again ..." (Teisserenc de Bort, 1891: 630). This appears to have involved moving them to a new location, 30 rue du Faubourg Saint-Jacques, near the Observatory, and appointing Mailhat as their head from 1 January 1889 (Mailhat, 1909).[55] There was a link to Eichens and Secretan, because Mailhat had been trained by Paul Gautier (1842–1909), who in turn had worked for Secretan and later Eichens, taking over Eichens' business in 1880 (Brenni, 1996a). However the workshop build-up may have been modest. In 1894 it appears the premises were expropriated; and deciding to set up on his own, Mailhat bought their contents, which he says he "... immediately reorganised to return to the building of major astronomical instruments as well as the fashioning of objectives and mirrors, which had been abandoned." (Mailhat, c.1908: 3). From the Secretan viewpoint, old equipment was updated, and model optical and mechanical workshops were installed in new, larger premises, which judging from a letterhead were located at 41, quai de l'Horloge, not far from the retail shop on the Place du Pont-Neuf (Secretan, 1895; 1915).[56] It seems the company archives, which would be so informative had they survived, were split between the two firms. The Secretan direct successors claimed to be "... heirs to the [Lerebours & Secretan] archives ..." (Secretan, 1915:5), while Mailhat's successor stated that his company

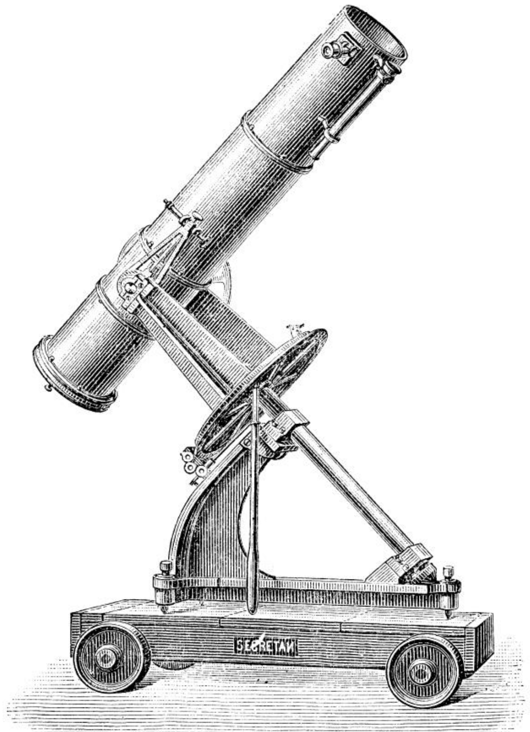


Figure 82: An engraving of a telescope similar to the one shown in Figure 81 was published by Flammarion (1882) and elsewhere. The reversed 'N' in Secretan is a common engraver's error (after: Desbeaux, 1891: 182; courtesy: F. Gires).

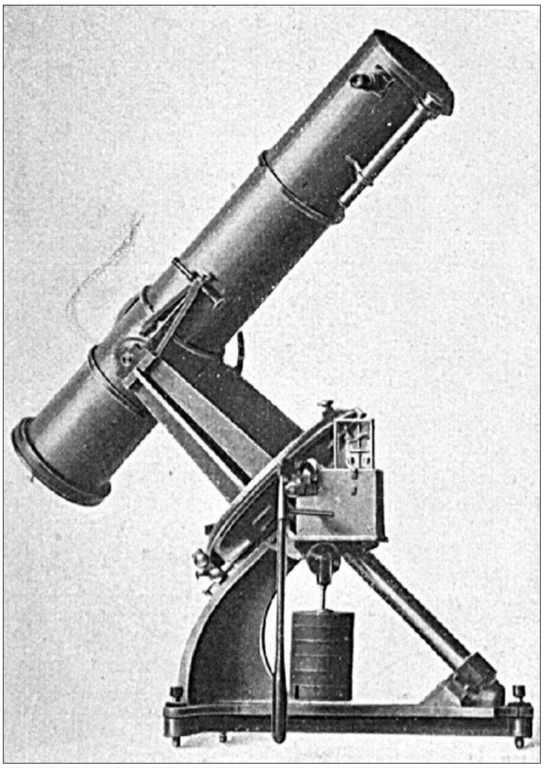


Figure 83: A telescope similar to the one in Figure 81, but incorporating an hour-angle drive. This photograph from Mailhat's catalogue c.1908 was the model for an engraving in the c.1913 catalogue of his successor Mouronval (Table 3). Another form of the photograph was printed by Troubetzkoy (1916) (courtesy: Erfgoedbibliotheek Hendrik Conscience, Antwerp).

> ... possesses, in its archives, documentary reminders of the great accomplishments in precision construction: The elaboration of Foucault's work on silvered-glass mirrors; Auguste Secrétan's optical work; The original Eichens-Secrétan drawings of the first large astronomical instruments, etc. (Mouronval, c.1913: 1).

As the century drew to a close, Georges' surviving son Paul Victor (b. 1879) became involved in the running of the business, as indicated by business letters signed by him (Secretan, 1895; 1896). His father had been a founding member of the Société Astronomique de France in 1887. In November 1902 Paul joined the Society (Présentation de nouveaux sociétaires, 1902), signifying an increasing interest in astronomy. Six months later a letter from "... M[onsieur] SECRETAN ..." (without specifying which one) announced that a 125-mm reflecting telescope had been developed "... for the use of amateurs …" and an example given to the Société Astronomique de France (Touchet, 1903: 312). Was Paul repeating Auguste's feat of developing a new model as his father aged? The focal ratio was *f*/8. Figure 84 shows an engraving of this instrument taken from the 1906 Secretan catalogue, attributed to Georges, where it was stated that the model was "... specially destined for members of the Société Astronomique de France ..." (Secretan, 1906a: 16; for a photograph, see Secretan, 1906b: 415). With three eyepieces giving magnifications of 80, 150 and 200 times, the price was 350 fr. Figure 85 shows an example.

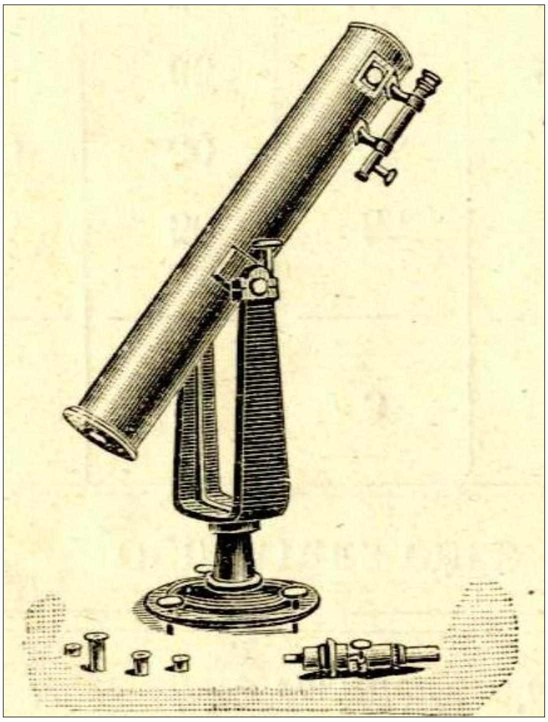


Figure 84: The new reflecting telescope "... of simple construction ..." devised by Secretan for amateurs in 1903 (after: Secretan, 1906a: 17; courtesy: I.Taillebourg, CNAM).

9.3 After 1906

Georges Secrétan died in October 1906 (Obituary, 1906). Paul and his sister Alice (b. 1878) inherited the business. Paul ran the firm for 5 years. He and Alice then sold it to Charles Épry (Ventes de fonds de commerce, 1911: 72). Épry produced a first catalogue in the autumn of 1911 which listed the new 125-mm reflector (with two eyepieces changed and an increased price) and old-style Foucault reflectors of 160- to 250-mm diameter (Table 1). In 1913 Épry associated with Gustave Jacquelin (1879–1939; Figure 79) (Flammarion, 1939). Despite being occupied with war supply, they published an extensive astronomy, science and optics catalogue in 1915 (Table 1). Amateurs were evidently an important market because the catalogue was illustrated with vignettes and biographies of scientists such as Tycho Brahé, Newton, Arago and Foucault, and provided a reading list of popular works by Flammarion, the Abbé Théophile Moreux (1867–1954), and others. Épry and Jacquelin clearly felt that Mailhat (and perhaps others) were abusing the Secretan name because they stated that they were the "Sole successors ..." of Lerebours & Secretan. "To shield our clients ... all our instruments carry our mark 'SECRETAN PARIS'..." (Secrétan, 1915: 5). They continued:

> ... and to strengthen the guarantee we have adopted new dimensions for the diameters of our optical elements, such that the small difference with the dimensions usually adopted suffices at a glance to distinguish our objectives amongst many others.

Figure 85: A surviving example of the simplified telescope. The cap is leather (courtesy: www.astrobin.com).

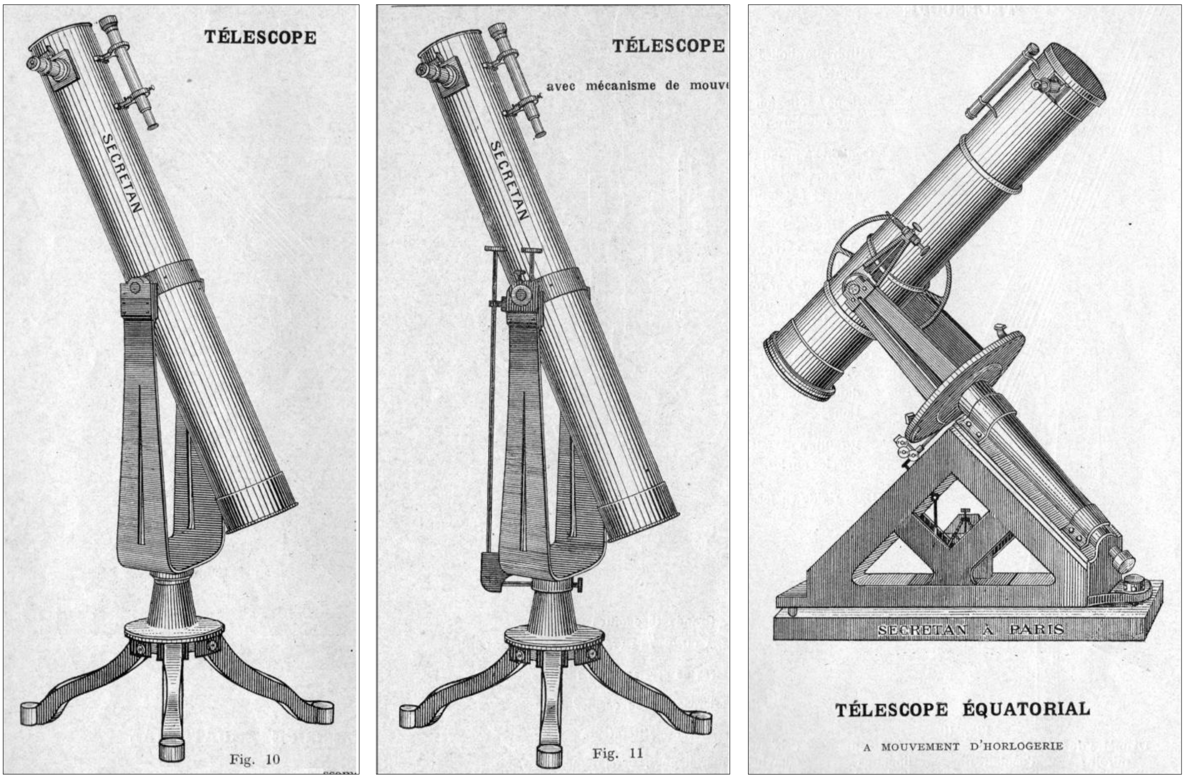


Figure 86: New forms of Foucault-Secretan telescope presented in Secretan's 1915 and 1924 catalogues. (Left) The 'amateur' form of Figure 84 modified by a cast-iron triple foot. (Centre) The same with fine adjustments in altitude and azimuth. (Right) An equatorial mount (after: the 1924 catalogue; courtesy: G. Barbel).

Although some new mirror diameters were offered in 1915 (140 and 180 mm, Table 2), this change applied primarily to refracting telescopes (cf. the 1911 catalogue, page 75).

The 1915 catalogue incorporated three new engravings of reflectors, shown in Figure 86. Small alt-azimuth instruments were offered with a surprisingly finely-divided range of sizes (Table 2). Focal ratios were not stated, but appear to be about *f*/8. The accompanying tables of magnification, if not misprinted, appear to take account of eyepiece aberrations and perhaps seeing. Optical test certificates and guarantees were supplied. The silvering was treated with a "... protective coating ..."[57] so "... maintaining its shine for many years." (Secrétan, 1915: 31, 29). I am unaware of any surviving telescope like those shown in Figure 86, which are probably too modern and considered of too little interest to have entered public collections.

The next Secretan catalogue was produced in 1924. The offering of small reflectors was reduced from six to a more-reasonable four sizes. Prices had more than tripled, reflecting the high inflation that had begun during the 1914–1918 war and was to continue until the depression of the early 1930s (Tableau de l'Inflation, 2015; see also Note 2 concerning overstamping of the 1924 catalogue).

The final Secretan catalogue that I have found is a slim one (28 pages) published in 1942. Georges Prin (1885–1959) was the successor to Paul Gautier (King, 1955). The Prin firm was incorporated into the Secretan company in 1934—a sort of homecoming! —and this was advertised on the catalogue's title page (Figure 2; Table 1) and, from the late 1940s, in advertisements in *L'Astronomie* and no doubt elsewhere.[58] Pride of place in the catalogue was given to the recently-completed 120-cm Newtonian reflector at the new French national observatory at Saint-Michel de Provence, which figured on the cover as an engineering drawing and inside as a photograph. This telescope reused the mirror from the ill-fated Martin-Eichens 120-cm Paris reflector (Section 9.1), reworked by the optician André Couder (1897–1979), and certain parts of Eichen's mounting (Prin, 1942). Soon afterwards a 4-cm chip flaked off the mirror edge during re-silvering, releasing stresses and destroying the image quality (Variétés, 1944; Figure 87).

The range of small reflectors was reduced yet further in the 1942 catalogue—only 125-, 160- and 200-mm diameters, with fine coordinate adjustments only; and for the larger sizes the reflecting prism was replaced by a plane mirror. The forks were stated to be in aluminium. The occupation years were again a time of double-digit inflation, which is no doubt why no prices were quoted.

In March 1963 the Secretan company amalgamated with the Henri Morin company, founded in the 1880s, and known particularly for surveying and drawing equipment (Legros and Boyelle-Morin, 1963). The new entity traded as Etablissements H. Morin-Secretan. The last advertisements that I have found for Morin-Secretan appear in *L'Astronomie* in the 1960s and include "Télescopes" (Figure 88). Around 1967 the firm merged with the Société de Recherches et de Perfectionnements Industriels (SRPI), a company that had been formed in 1918. This probably heralded the end of almost two centuries of telescope making by the firm, whether of reflectors or refractors, because I have found no Morin-Secretan-SRPI advertisements.[59] The joint company took out patents until at least 1981, and subsequently disappeared.

10 FOUCAULT-STYLE TELESCOPES BY OTHER MAKERS

The superiority of Foucault's reflectors was quickly apparent. In his 1860–1861 catalogue of available instruments, the optician Arthur Chevalier (1830–1872) noted that metal-mirrored reflectors were "... completely abandoned ..." and that with silvered glass, Foucault had "... recently developed practical means for producing reflecting telescopes ..." (Chevalier, 1860–1861: 67)

As we have seen, commercial restructuring meant that other companies also offered Foucault reflectors. Eichens left the Secretan firm in 1866 and produced the mechanical parts for many telescopes. Eichens' successor, Gautier, remounted the Toulouse 80-cm reflector in metal beginning in 1886 (for an engineering drawing and photograph, see Bach et al., 2002: 191–193). In the same year Gautier contracted to build a similar equatorial telescope for the newly-founded La Plata Observatory, with a mirror figured by the Henry brothers (Hussey, 1914). Gautier and the Henrys also built the 1-metre *grand télescope* for the Observatoire de Meudon, installed in 1891. Its revolutionary *f*/3 mirror was designed for photography and diffuse-object spectroscopy (Janssen, 1896). We have seen that Martin provided silvered-glass mirrors for eclipse and Transit of Venus expeditions. A 38-cm diameter mirror (focal length = 1.42 m, ~*f*/4) was polished by a Monsieur Cache, a worker in the Bardou company of optical fabricants, for observations of the 1871 solar eclipse (Flammarion, 1874b: 248; Janssen, 1873: 107).

The above were all professional instruments. But the Secretans rapidly lost the monopoly for the supply of amateur silvered-glass telescopes as well. I have found 'Télescopes de Foucault' offered in the catalogues of several other Parisian instrument makers (Tables 3 and 4). It must be noted that re-badging and on-selling was common in the Parisian scientific-instrument trade (Brenni, 1989; 2002), so it is very possible that some of the equipment sold by others may have still been made by Secretan or successors. Further, some components, such as iron castings, may well have been outsourced, and thus were perhaps available to several instrument makers. (There are no items obviously intended for casting in the 1867 inventory of Secretan's business (Sebert, 1867–1868).) The aforementioned Arthur Chevalier offered what is clearly the Foucault-Secretan 4-*pouce* télescope for on-sale in an 1860 catalogue (Tables 3 and 4), and we have seen that Duboscq offered small reflectors as early as 1864.

Figure 87: Martin's mirror from the Paris 120-cm telescope was refigured in the 1930s by the optician André Couder and installed in 1942 at the Observatoire de Haute-Provence. The mirror was chipped soon afterwards and is now on display at the Observatory. The damage has been hidden by the large bevel (courtesy: www.obs-hp.fr).

In his later catalogues Duboscq continued to offer "*Télescopes*, L. Foucault system", but with less details specified (Table 4). Foucault and Martin apparatus for the "... inspection and veri-

INSTRUMENTS D'ASTRONOMIE

SECRETAN

Lunettes Astronomiques — Télescopes

= CŒLOSTATS · CERCLES-MÉRIDIENS =

ÉQUATORIAUX · INSTRUMENTS DE PASSAGE

•

Ets H. MORIN-SECRETAN, 11 R. Dulong XVIIe CAR. 99-13

Figure 88: One of the last Morin-Secretan advertisements briefly mentioning reflecting telescopes ("Télescopes") (after: Etablissements H. Morin-Secretan, 1964; courtesy: Google Books

INSTRUMENTS D'OPTIQUE A L'USAGE DES SCIENCES

CINQ MÉDAILLES DE 1re CLASSE

GRANDE MÉDAILLE D'OR A L'EXPOSITION DE MOSCOU 1872

Ed LUTZ

FOURNISSEUR DES ÉCOLES FRANÇAISES ET ÉTRANGÈRES

Rue des Noyers, 49 (boulevard Saint-Germain).

SPECTROMÈTRES
DE
MM. BUNSEN et KIRCHHOFF

Spectroscopes de poche. 25 fr.

LUNETTES DE ROCHON
POUR MESURER LES DISTANCES

NOUVEAU MODÈLE DE
DIABÉTOMÈTRE DE ROBIQUET
ET DE
SACCHARIMÈTRE

PRISMES DE NICOL
DEPUIS 3 FRANCS LA PIÈCE

TÉLESCOPES DE FOUCAULT
Nouveau modèle.

MIROIR : DIAMÈTRE, 10 CENTIMÈTRES 1/2
CORPS : 85 CENTIMÈTRES
AVEC CHERCHEUR
1 OCULAIRE TERRESTRE
2 OCULAIRES ASTRONOMIQUES
ACCOMPAGNÉS D'UNE
BONNETTE EN VERRE NOIR.

LES OCULAIRES
PEUVENT SERVIR POUR MICROSCOPES

MONSIEUR,

J'ai l'honneur de vous présenter la photographie d'un nouveau modèle de télescope, à miroir parabolique, en verre argenté, de M. FOUCAULT, et de vous donner la description de cet appareil en quelques mots qui suffiront pour vous faire apprécier les avantages de cette nouvelle construction.

Le corps de l'instrument est en cuivre poli et verni ; il est supporté par deux tourillons en acier, montés sur deux montants en fonte de fer, entre lesquels le corps de l'instrument passe librement ; ces deux montants reposent sur un pied-de-biche en fonte de fer, qui peut se placer sur une table, en sorte que l'horizon et le zénith peuvent être interrogés dans tous les sens par l'observateur assis ou debout.

Le chercheur, placé près du miroir, est d'une manœuvre facile pour le pointage astronomique.

Le grossissement varie, suivant trois jeux d'oculaires, de 80 à 300 fois, ce qui permet d'observer Mercure, Vénus, Saturne, les étoiles doubles, les montagnes de la Lune, les taches du Soleil, les nébuleuses, etc.

Cet instrument, très-portatif, qui fait aussi bonne figure dans un salon que dans un cabinet de physique, peut remplacer un télescope sept à huit fois plus volumineux et coûtant trois fois plus.

Le prix de ce Télescope complet est de . . . . 500 francs.
Renfermé dans une boîte en noyer. . . . . 25 fr. en plus.

En espérant, que vous voudrez bien m'accorder votre confiance, que je m'efforcerai de justifier,
J'ai l'honneur de vous prier d'agréer, Monsieur,
l'assurance de ma parfaite considération.

ED. LUTZ.

PARIS. — IMPRIMERIE DE E. MARTINET, RUE MIGNON, 2

Figure 89: Printed letter sent to potential customers in the 1870s advertising Édouard Lutz's "New model" 10½-cm Foucault telescope (courtesy: R. Smeltzer).

fication ..." of plane and curved surfaces was offered in 1885 (Duboscq, 1885: 112). The following year the Duboscq firm was taken over by Philibert Pellin (1847–1923; Brenni, 1996b). The Pellin catalogue for 1900 reprinted the engraving shown in Figure 51 and offered 100-, 160- and 200-mm "Foucault mirror" telescopes for 490, 1,200 and 2,000 fr respectively (Tables 3 and 4).

The case of the manufacturing optician Édouard Lutz, born in Riga in 1832, is intriguing. On 8 November 1883 he wrote to Flammarion, reminiscing:

> … the first Foucault *télescopes* were built in my firm, in the time of my predecessor, Mon-

> sieur Berthaux, and under the orders of Monsieur Foucault himself, as well as with Monsieur Fizeau's help, and that since this time (1852–53) I have worked to improve and simplify the design … and facilitate portability … (Fuentes, pers. comm., 2015).

The dates 1852–1853 are clearly wrong, and Lutz's claim that the first Foucault telescopes were made by his predecessor is not substantiated by Foucault's writings. Nor is Lutz's spelling certain: at death, his predecessor was recorded as Antoine Sedelly Bertaud (1802–1862) (Registre d'État Civil, 1862). One of Bertaud's specialities was cutting crystals. He certainly cut glass and crystals for Fizeau (e.g. Fizeau, 1862: 440). Perhaps he also cut the Iceland spar for Foucault's polarising prism in 1857, i.e. the time when Foucault was beginning his telescope work, and this is the origin of Lutz's confusion. Other —much later—authors claim rather that Bertaud was already using a system of local corrections in his work, and this was the inspiration for Foucault's *retouches locales* (d'Ocagne, 1904: 398; Laussedat, 1875: 1287; 1901: 125). Whatever the truth, the company was well-prepared to take up Foucault's ideas.

It is unclear when Lutz took over the Bertaud firm,[60] but he did produce a catalogue in his own name in 1872, in which he offered Foucault photometers and polarising prisms as well as "Foucault system" reflectors with exactly the same diameters, focal lengths and prices as offered by Duboscq in 1864 (Table 4). Was Lutz on-selling Duboscq wares? Several facts suggest it may have been the inverse. Lutz's catalogue included a novelty not listed by Duboscq—a "Foucault telescope – M. Bourbouze's arrangement" with an accessory achromatic lens (Table 4).[61] In various ways this 'Swiss-army-knife' instrument could serve as projector, refractor, microscope (using the eyepiece assembly) or photographic camera! At about the same time Lutz sent potential customers a printed letter advertising a "New model" 10½-cm Foucault *télescope* with a pasted-on photograph (Figure 89).[62] In modified forms, this telescope appeared in later catalogues produced in 1882 and c.1890 (Tables 3 and 4). Figure 90 shows the associated engraving. At the Paris Exposition Universelle in 1878 Lutz showed a Foucault-type mirror. (At the same exhibition the Radiguet company exhibited an equatorial *télescope* with a mirror finished by one of the Henrys (Garnault, 1878: 475).) In 1890 Lutz gave one of his 16-cm reflecting telescopes to the Société astronomique de France (Armelin, 1890). Lutz died in 1895 (Registre d'État Civil, 1895), and subsequently similar 15-, 13- and then 10-cm instruments were offered in catalogues dated from 1907 to 1928 by Les Fils d'Émile Deyrolle, a firm better-known for biological supplies (Figure 90; 1907: 72; 1910: 110; 1928: 105).[63] Figure 91 shows what appears, on account of the longer collar fixing the altitude trunnions to the tube, to be a surviving Lutz instrument in Athens.

The previously-mentioned Bardou firm was founded in 1819 (see Table 3, 1899 catalogue) and towards the end of the century became an important supplier of small refractors, advertising frequently in Flammarion's monthly *Astronomie* magazine in the years around 1890.[64] Advertisements in 1888 and 1890[65] announced the availability of a catalogue, which I have not been

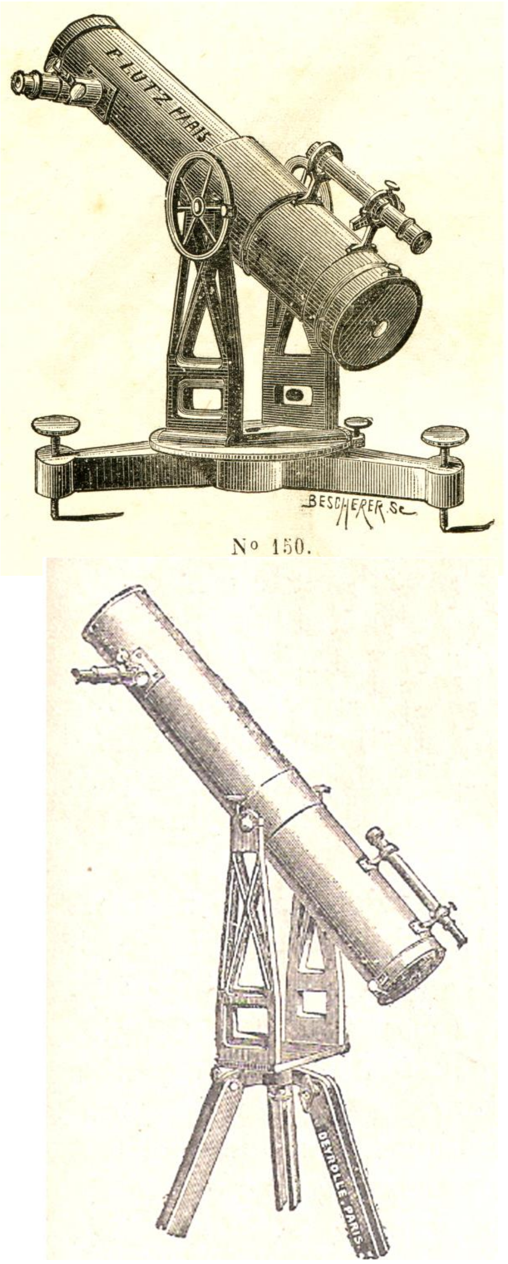


Figure 90: (Top) Engraving of Lutz Foucault-system telescopes from the firm's 1882 and c.1890 catalogues (Table 3). (Bottom) A similar style of telescope offered by the Deyrolle firm in the early twentieth century (after: Les Fils d'Émile Deyrolle, 1928: 105; courtesy: P. Brenni).

Figure 91: Remnants of what is probably a Lutz 4-*pouce* reflector (courtesy: Museum of Science and Technology, University of Athens).

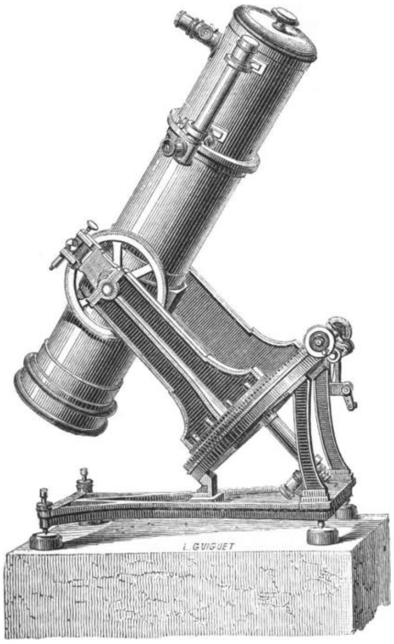


Figure 92: Woodcut of equatorially-mounted 10- to 20-cm reflecting telescopes printed in the 1892 Bardou catalogue (Tables 3 and 4) (after: Towne, 1896: 287; courtesy: Google Books).

Figure 93: A 20-cm reflector, conserved by the Istituto Leone XIII in Milan which from comparison with Figure 92 appears to have been supplied by the Bardou company. The Istituto was founded in 1893, so the telescope perhaps dates from after then (courtesy: P. Brenni).

able to find, with “Télescopes à miroir Foucault” as a category. A Bardou catalogue dated 1892 offered 10-, 16- and 20-cm alt-azimuth and equatorial *télescopes* (Tables 3 and 4), illustrated with woodcuts. For the alt-azimuth instruments, Secretan’s original xylograph from 1865 was reproduced (i.e. Figure 51), though recut by another engraver, Louis Guiguet, who also provided the equatorial illustration shown in Figure 92. (These two woodcuts were also printed in practical astronomy books written by Gélion Towne (1890; 1896).) Figure 93 shows what is no doubt a 20-cm example of such a Bardou equatorial in Milan, though the instrument is unsigned. Figure 94 shows an ~f/7 alt-azimuth with an 108.7 ± 0.2 mm full-diameter mirror (i.e. essentially 4 *pouces*) stamped “A. BARDOU, PARIS”. Denis Albert Bardou (b. 1841) says he took over from his father in 1865 (Légion d’honneur, 1892) and the instrument presumably dates from between then and his death in 1893 (Registre d’État Civil, 1893). Although the optical layout is basically the same as for a Foucault-Secretan telescope, the mounting does not conform to that illustrated in Figure 51 and the Bardou catalogues. The tube has a prominent brass ring at its mouth and is attached to the elevation axis by two plates rather than an encircling band. The Bardou stamp is surprisingly discreet compared to the exuberant signatures found on many A. Bardou refractors, raising the question of whether the Figure 94 telescope really was made by Bardou or on-sold from another manufacturer. However the form of its prism mount (Figure 95) is the same as for the Milan instrument, supporting the Bardou firm as the manufacturer of both telescopes. Nevertheless, why do the 1892 and 1899 catalogues illustrate the Secretan mount from 1865? Was this to save engraving fees, or did the firm just on-sell Secretan telescopes in the 1890s? After Albert Bar-

Figure 94: 4-*pouce* telescope belonging to the Lycée Janson de Sailly in Paris. The inset shows A. Bardou’s name stamped at centre rear of the mirror cell (author’s photographs).

dou's death the firm was taken over by J. Vial, and by 1899 (Tables 3 and 4) had ceased offering equatorial *télescopes*.

Ducretet & Lejeune (1893) and Ducretet (1905) offered a 10-cm instrument with cast iron mounting, tripod, four eyepieces, finder and solar filter for 600 fr. A direct-vision spectroscope and equatorial mount were available as extras.

We have seen that R. Mailhat left the Secretan business to set up independently in 1894. His c.1908 catalogue and the c.1913 catalogue of his successor Francis Mouronval[66] (1881–1954) both reprint Figure 51 and offer a range of alt-az and equatorial silvered-glass reflectors with surprisingly-small size increments (Table 4). An advertisement from c.1913 offers a telescope which looks in many ways similar to Figure 51, except that it has an equatorial mount which is adjustable in latitude (Figure 96; Mouronval, 1911). A wood-mounted telescope at the Musée des Confluences in Lyon is attributed to Mailhat, with the date range 1857–1868 (Figure 97; Musée des Confluences, 2009: 50). The date range is improbable, but not the attribution since the c.1913 catalogue adds "We also make … telescopes with a simplified mount, with a wooden mount, etc." (Mouronval, c.1913: 17).

Figure 95: Prism arm of the Janson de Sailly 4-*pouce* telescope. The arm in the Milan telescope (Figure 93) is similar, and provides a distinguishing feature from Secretan instruments (e.g. Figures 17, 46 and 57) (author's photograph).

Individual amateur astronomers also made silvered-glass telescopes, which in general are easy to identify because they do not match authenticated Foucault-Secretan designs. However, opticians sold mirrors on their own, which could then be mounted by amateurs. Secretan furnishes examples in 1874 (Appendix 2) as well as 1878a, c.1898, 1906a and 1915 (Table 1). A certain L. Cotessat ran an advertisement in 1890 offering 29-cm parabolized silvered-glass mirrors for 125 fr (Cotessat, 1890). Silvered-glass mirrors were also offered by Apoil (1904),[67] Mailhat (c.1908), and Mouronval (c.1913). An example of a self-mounted mirror is provided by the lunar

At^{rs} R. MAILHAT

MOURONVAL
Ancien élève de l'École Polytechnique
GRANDS-PRIX PARIS 1900, BRUXELLES 1910
Ex-Directeur et Acquéreur des Anciens Ateliers SECRÉTAN
10, Rue Émile-Dubois, 10 — PARIS (14^{e} arr^{t})

Fournisseur de tous instruments pour Observatoires, Facultés, Missions scientifiques, Amateurs et Débutants
Avec Références dans le Monde entier

OBJECTIFS (visuels et photographiques)
MIROIRS (plans, sphériques et paraboliques)
Oculaires tous types

Réfracteurs (lunettes), **Réflecteurs** (télescopes) avec tous genres de montures, azimutales et équatoriales, depuis les plus simples jusqu'aux plus complète.

Cercles méridiens — **Lunettes murales** — **Dipleidoscopes** — **Lunettes démontables** pour voyages — **Hélioscopes** — **Micromètres** — **Chronographes** — **Cœlostats** — **Sidérostats** **Héliostats** — **Cadrans solaires.**

SPECTROSCOPIE
tous genres.
PRISMES ou RÉSEAUX
avec ou sans fente,
avec ou sans mesures.
Spectrographie,
Mesureur de clichés.
Chambres astrophotographiques
avec ou sans agrandissement
Obturateurs
Châssis métalliques
Mouvements d'horlogerie
Enregistreurs
Instruments de laboratoire
Instruments de géodésie

Coupoles et Abris
tous genres.
Météorologie — Magnétisme
Anémomètres
RÉPARATIONS ET REPRISE D'INSTRUMENTS
Appareils nouveaux
Travaux pour Inventeurs

Catalogue, Renseignements, Projets, Devis, etc. sur demande

Figure 96: Mailhat-Mouronval advertisement showing a Newtonian reflector on a variable-latitude mount (cf. Table 4). The tube and fork resemble the Foucault-Secretan design from 1865 (Figure 51) (after: Mailhat and Mouronval, c.1913; courtesy: Google Books).

Figure 97: Wooden-tubed telescope attributed to "Ateliers R. Mailhat 1857–1868". The dates are improbable, because though similar to Foucault-Secretan wooden tubes, there are differences of detail (such as the round wooden mirror cell and the form of the fork) and the Mailhat firm dates from 1894 (after: Musée des Confluences, 2009: 50).

observer Casimir Marie Gaudibert (1823–1901; Obituary, 1901) who in about 1871 bought a 216-mm (8-*pouce*) primary mirror and an elliptical secondary mirror from an "... optician of the first rank ..." (who might or might not have been Secretan, given the focal ratio of *f*/7.6) and mounted it himself (Gaudibert, 1886: 375). Another example is furnished by Troubetzkoy (1917) who mounted or remounted a 10-*pouce* Secretan-Henry mirror (Figure 98). The possibility thus exists that a non-Secretan mount might contain a Secretan or even a Foucault mirror.

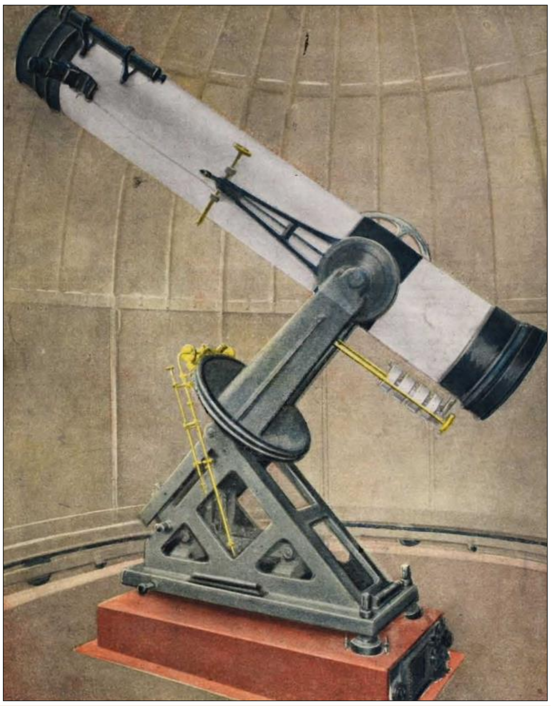


Figure 98: Equatorial Newtonian telescope incorporating a 10-*pouce* Henry-Secretan mirror. Troubetzkoy (1917) says he mounted the mirror himself, and the base is similar to a variable-latitude one invented by him (Troubetzkoy, 1919). However the tube and declination controls show many similarities with Foucault-Secretan instruments (cf. Figures 51 and 82) (after: Troubetzkoy, 1917; courtesy: introni.it).

11 HOW MANY TELESCOPES?

According to Babinet (1858), *Le Magasin Pittoresque*, the magazine that published the engraving of Foucault's first commercial telescope (Figure 9) had a circulation of 90,000. How many sales of non-professional telescopes may have resulted?

The disappointing answer is, not many. Taking the first design of 4-*pouce* mirrors mounted in a square wooden tube, the known serial numbers range from 2 to 42 (Table 6). For 10-cm mirrors in metal mountings the range is 13–236, and since the values for larger diameters fall within this range too, it seems that there may be only one sequence of numbers for metal mounts (Table 9). These serial numbers are to be compared with those on Secretan refractors, which towards the year 1900 could reach 2,306 (Wolf, 2014: FRA4), and even as high as 3,700 (Marine et Instruments Scientifiques, 2012). We can therefore expect sales of some tens for the first design and the low hundreds for metal-mounted silvered-glass *télescopes* compared to the several thousand refractors sold by the Secretan company.

Corroboration for these low numbers of reflectors comes from enumerations of public and private observatories published by Flammarion. In 1877, only the Marseilles 80-cm is listed explicitly as "... built by Foucault ..." (Flammarion, 1877a). The characterization "... Foucault *télescope* ..." applies to instruments in private hands: two 16-cm telescopes, one owned by Hippolyte Barnou, the architect of Flammarion's future observatory at Juvisy-sur-Orge, who used it to help Flammarion produce a corrected edition of Dien's *Atlas Céleste* (Flammarion, 1877b), and the other, equatorially-mounted, by a former naval officer, a Monsieur Le Roux de Villars; Flammarion's own telescope at his then-home on the Avenue de l'Observatoire, described as a 20-cm instrument (i.e. not the 16-cm seen in Figure 71), and another of the same size belonging to Dr E.M. Lescarbault (1814–1894) of Vulcan notoriety;[68] and a 40-cm instrument belonging to the wealthy Ghent sugar-refiner Adolphe Neyt (1830–1892).[69] Soon afterwards, Flammarion noted that "... several ..." 10-cm telescopes had been mounted as "... highly precise ..." equatorials (Flammarion, 1882: 685) and signalled a 10-cm Foucault reflector at the newly-founded Zacatecas Observatory (Flammarion, 1884). By 1890, Lescarbault was listed as also having a 30-cm Foucault *téléscope,* Flammarion said he owned both 16- and 20-cm ones, and a Monsieur D. Raffard in Gien possessed a 10-cm one (Flammarion, 1890: 858–861). A 135-mm Lutz reflector was owned in Bayonne by Émile Daguin (1844–1930), son of the aforementioned P. A. Daguin (Section 6.2; Flammarion, 1930). A handful of other *télescopes* is listed without mention of origin, although at least the two belonging to Jules Thore of Dax were of Secretan manufacture: the 30-cm Henry reflector mentioned in Section 9.1, and a claimed "... $0^m.15$ ... " instrument (no doubt 16 cm, Table 9), both now at the Observatoire de Dax (Soulu, pers. comm., 2016). The original dust cap has survived for the latter, and attaches via a pair of rotating fingers, as seen also for Flammarion's 16-cm telescope (Figure 71, right).

I have no information as to whether instruments produced in the twentieth century were numbered. The 1942 Secretan catalogue uses an engraving to illustrate the available reflectors (the same one as Figure 86, centre). Refractors are illustrated with photographs, so the lack of a photograph of a *télescope* suggests it was some time since one had been made.

12 TWO CASE STUDIES

I now apply the findings of this paper to evaluate two *télescopes* recently advertised by dealers.

12.1 Cambi Casa d'Aste, Genoa

Figure 99 shows a reflecting telescope put up for sale in 2006 by an Italian auction house (Asta di Strumenti Scientifici, 2006). The instrument was described as a Herschel-type Newtonian telescope scope with a glass mirror and original multi-coloured cardboard dust cap, and a circular plane mirror to direct light to the eyepiece. The tube outer diameter and length were given as 18 and 98 cm, respectively; and the telescope was ascribed an English or French origin in the late eighteenth or early nineteenth century.

The optical arrangement is clearly Newtonian and not Herschelian. The presence of a glass mirror shows it must postdate 1857. The equatorial mount shows similarities with those shown in Figures 31 and 44, so I feel its author must have read Foucault's description of his procedures in the Paris Observatory *Annales* as well as Drion and Fernet's *Traité*. This makes the early 1860s the earliest possible date for its construction, and perhaps favours a French origin. However the difference in detail of the fork, mirror cell, brasswork etc., and the use of a secondary mirror show that it was not made by the Secretan company. Corroborating this conclusion is the ~*f*/8 focal ratio suggested by the ~12-cm size of the aperture, which is too slow for a Foucault mirror. The dust cap may be old, but given such items' propensity to damage and replacement, I am agnostic about its originality.

Figure 99: Telescope offered for sale by the Cambi Casa d'Aste auction house in 2006. For an assessment, see Section 12.1. Now in the collection of Fausto Casi, Arezzo (courtesy: Cambi Casa d'Aste, Genoa).

12.2 Galérie Liova, Paris

Figure 100 shows a *télescope* offered by a Parisian gallery in 2012–2013, and more recently auctioned at the Hôtel Drouot, where I was able to inspect it. It was described as built on Dobsonian principles, attributed to Marc Secretan, and dated to around 1840 (Joron-Derem, 2015: 55).

The telescope has an alt-azimuth mount and Newtonian optics, which are features of the ideas of John Dobson (1915–2014) for large, inexpensive, transportable amateur reflectors, but the association is anachronistic because Dobson's ideas date from the second half of the twentieth century and the instrument does not incorporate pyrex, teflon and other modern materials (e.g. Dobson, 1991; Sinnott and Dobson, 1980).

The telescope is unsigned, and I am unaware of any Secretan advertisement for alt-azimuth telescopes in octagonal wooden tubes, but there can be no doubt it originated in the Secretan work-

Figure 100: The telescope auctioned at the Hôtel Drouot in November 2015. For an assessment, see Section 12.2. (Top) Overall view. The base measures 360 × 362 mm. Unlike the de Romilly telescope (Figure 38), the slats composing the octagonal tube have no decorative step. Their exposed length is 930 mm. Now in the collection of Vivek Hira, New York (courtesy: galerie-liova.com). (Bottom left) Mirror cell and (bottom right) mirror dust slide (author's photographs).

shop, because of numerous similarities with signed instruments. Perhaps the lack of a name indicates the instrument was first purchased through the intermediary of another Parisian instrument maker.

The optical arrangement is standard, with a prism and eyepiece assembly incorporating relay lenses. The mirror has a convex rear. Its full diameter is 160 ± 1 mm, but the effective aperture is probably 154 ± 1 mm, defined by the wooden circle at the front of the octagonal tube. A few small bubbles are visible within the glass, which has a slight green tint that is particularly evident because of a large chip in the mirror back. The centre of the prism is located approximately 89 cm from the pole of the mirror. Plausibly the focal length is a centimetre or two more, suggesting a focal ratio of ~*f*/5.7 for the full mirror and ~*f*/5.9 in practice. The eyepiece and prism assembly are held in place in the same way as for the Paris Observatory 20-cm telescope with a substantial circular brass plate and three knurled knobs (cf. Figure 45).

The polished brass and wood is reminiscent of the Worms de Romilly telescope (Figure 38) and of the equatorial mounts—Figure 50—still advertised in 1874. Unlike the de Romilly instrument, however, the brass mirror cell extends to the back of the square wooden plate in which it is inserted (Figure 100, bottom left, cf. Figure 42). In this it resembles the Paris Observatory 40 cm (Figure 28). A pair of threaded holes and marks on the brass show that a bar, now lost, once supported the mirror, as for the de Romilly and 40-cm telescopes. The dust cap is similar in conception to the Paris Observatory 20- and 40-cm telescopes (e.g. Figure 29) except that the round wooden disc, which is fragile in these instruments, has been strengthened between the struts with additional quarter-circles of wood. Also following the 40-cm conception is a mirror dust-slide held in position against the front of the mirror cell by lateral springs (Figure 100, bottom right). The finder is similar if not identical to the one on the No. 13 10-cm telescope (Figure 54).

All these features suggest an earliest possible date of about 1860, inferred from the 20- and 40-cm telescopes. However, the metric mirror diameter shows the telescope dates from after the introduction of metric sizes. When was this? Certainly by 1865 (Section 8), but perhaps earlier since the No. 42 4-*pouce télescope* has a metric diameter. In addition, the focal ratio suggests a date before standardization on *f*/6. But if a date within a few years of, say, 1863, seems plausible, it must be remembered that Secretan built instruments to order, and the absence of such a *télescope* from the 1874 catalogue does not necessarily exclude construction considerably later under the stewardship of Auguste or even Georges Secretan.

13 CONCLUDING REMARKS

We see some general and unsurprising influences in the story of the Foucault-Secretan telescope. Turner (1993: 26) has identified delight, luxury, ostentation, and scientific need as some of the "... essential aspects ..." involved in the development of a scientific instrument. Scientific need and, no doubt, delight drove Foucault to develop the silvered-glass reflector. We can compare the simple woodwork of prototypes and professional telescopes (e.g. Figures 4, 26 and 45) with the luxury of models made for amateurs (e.g. Figures 38 and 100) and the ostentation of an owner's arms engraved thereon (Figure 70). We can also see how the design for amateurs moved from the original, wooden, table-top model of 1857 (Figure 9) to a wide range of more practical—but more expensive—metal-tubed ones with alt-azimuth and equatorial mounts in the 1860s and 1870s (Figures 51 and 78), followed by a retrenchment of the range, possible difficulties in maintaining an *f*/6 focal ratio, and the introduction of a cheaper, simplified model in 1903 (Figures 84 and 85), which nevertheless was later improved with fine adjustments (Figure 86, centre). An expansion of the range of available apertures in 1915 unsurprisingly did not persist.

The microscope-style eyepiece assembly also evolved (Figures 18 and 58), and finally was (presumably) abandoned when a secondary mirror substituted for the prism for larger apertures in the 1940s (Table 2). Table 11 reports the barrel diameters for certain instruments. For the smaller apertures the value was standardised at about 23.9 mm until at least the 1860s, but later lost half a millimetre. There is no optical reason for the bigger diameter found in the Paris Observatory 20-cm telescope. Perhaps the reason was mechanical, to provide firm support for the micrometer used during the 1860 eclipse expedition, Wolf and Rayet's photographic plates in 1865, etc.

The Secretan company signed its wares in a variety of ways (Figures 12, 27, 41, 55, 59, 63 and 68).[70] This surprises in the modern epoch of registered trade marks. Also variable was the presence of a date. Serial numbers were only applied to non-professional production models, for which there is no unequivocal example of an un-numbered instrument (Tables 6 and 9). An un-numbered instrument might indicate one on-sold by another supplier, such as Chevalier or Negretti & Zambra.

The end of Newtonian-reflector production by Morin-Secretan was no doubt related to the amalgamation with SRPI in about 1967, and not because of competition from the Schmidt-Cassegrain design, which although it had appeared commercially, only really bloomed from the

Table 11: For five Foucault-Secretan telescopes, outside diameters of the part of the eyepiece assembly that slips into the focusing mechanism (or retaining ring for the 20-cm instrument), and outside diameters of the eyepieces alone. Barrels are not completely round, so the measured range is reported. The measurements show that variations of ~0.1 mm produce close fits, which provides a criterion for judging whether differences between instruments are significant, which they are not for Nos 4, 13 and 18. Measurements of a simplified achromatic microscope are given for comparison, which confirm that the eyepiece assembly of the 4-*pouce* wood-mounted telescopes was an adaptation and not a direct copy of the microscope design.

Telescope	Figures (this paper)	Assembly diameter (mm)	Eyepiece diameter (mm)
4-*pouce* wood-mounted (Secretan No. 4, Wolf TRE16)	10, 69	23.78–23.87	24.76–24.77
20-cm wood-mounted (Paris Observatory)	45, 46	35.8	
10-cm metal-mounted (Secretan No. 13)	53, 54	23.75–23.80	24.70–24.75
16-cm metal-mounted (Secretan No. 18, Wolf TRE17)	67, 69	23.87–23.92	1: 24.70–24.72 2: 24.62–24.64 3: 24.68–24.70 4: 24.70–24.71
10-cm metal-mounted (Secretan No. 236, Wolf FRE1)	62, 64, 69	23.40–23.45	50x: 23.58–23.62 80x: 23.60–23.62 150x: 23.72–23.74 200x: 23.70–23.72
Simplified achromatic microscope	19		24.85–24.90

1970s onwards (Manly, 1994).

This paper contains many uncertainties. It is only a start to research on Foucault-Secretan telescopes and their heritage, but one which I hope provides a structure for further work. The history of individual professional instruments could be extended. For instruments outside Paris, the use of both local and Parisian archives is essential. As an example, the accounting and other material in the Paris Observatory archives has revealed additional details concerning the Marseilles 80-cm reflector beyond what I presented in Tobin (1987). Extensive material is available for an instructive history of the ill-fated Eichens-Martin 120-cm telescope from its origins under Foucault and Le Verrier to its rebirth at Saint Michel.

The evolution of the mechanical design could be studied. Did declination supersede north polar distance on setting circles, and if so, when? (At the end of the nineteenth century Baillaud (1896: 5) was still writing that declination is "... often replaced by the *north polar distance*, its complement.") Questions remain concerning amateur instruments. For example, Schechner and Launie (2014) have made a detailed study of three 4-inch refractors made by the Alvan Clark firm all dating from 1871, and found surprising differences in every measurable dimension, revealing a production that was more workshop-based than industrial. How standardized were Foucault-Secretan products? The 4-*pouce* instruments show variations in their eyepieces and finders which appear to be original but unadvertised purchase options. The 10-cm telescopes show differences in dust-cap design and eyepiece offerings. Is the millimetre difference in eyepiece diameters and half-millimeter difference in overall assembly diameters between telescopes Nos 13 and 236 (Table 11) indicative of a wider revision of dimensions? Telescopes' optical performance would also merit investigation, as has been done, for example, for telescopes made by William Herschel (e.g. Mills and Hall, 1983, and references therein). When exactly did optical dimensions become metricated and the focal ratio standardize to *f*/6, and how rigid was this standardization? The design of the Foucault-Secretan 1865 10-cm telescope (Figure 51) influenced many other makers (e.g. Table 4, Figures 89 and 98) and it would be interesting to understand if this was simple emulation or whether subcontracting was involved —or even intervention by Foucault, as claimed by Lutz, whose products and relationship with Duboscq merit deeper investigation.

To answer these questions it would be desirable to find more telescopes, both by Secretan and other makers. Since a number of the known instruments derive from religious and/or teaching institutions (La Flèche, Quebec, Digne, Milan...), the storerooms of such establishments may be fertile territory for discoveries,[71] but many others may languish in private attics or cellars. Most of the known Foucault-Secretan *télescopes* date from the 1870s or before. It is obviously desirable that more recent instruments be discovered, especially from the twentieth century, and that examples should enter public collections. A fuller study of trade literature and advertising would be instructive,[72] as would a comparison with the production of reflecting telescopes and their uptake by British makers such as Henry Cooper Key (1819–1879), George With (1827–1904), George Calver (1834–1927) and John Browning (c.1831–1925)—whose *Plea for Reflectors,* first published in 1867, makes no mention of Foucault!

This paper was possible, in part, because Léon Foucault's invention of the silvered-glass telescope coincided with the mass introduction of woodcut illustrations in magazines and books in the nineenth century; and because of the easy inclusion of numerous images in a purely-electronic journal in the twenty-first. We can only agree with Foucault when he wrote (1853) "... let us loudly proclaim the importance of the service rendered to science by the publication of illustrated works ..."

14 NOTES

1. The date comes from an advertisement dated October 1911, nine months after Épry's acquisition of the firm, mentioning "... the new illustrated catalogue ..." (Épry, 1911b; a similar advertisement and another from earlier in the year are reproduced by Andrews, 1996: 92). The catalogue's "Avant-propos" notes "The present catalogue does not mention all the instruments that we can supply to the public. The Astronomy catalogue should be consulted." Presumably the 1906 catalogue is meant (Table 1, 1906a).
2. The catalogue is undated but an accompanying letter from the Secretan firm indicates it was published in 1924. It is rubber-stamped with the date "MAR 1929" and 30% price increases. On commercial web-sites such as fleaglass.com, ars-longa.fr and eBay.com I have seen copies with claimed dates of 1924, 1926 and 1929.
3. Date determined from the legal deposit stamp on the Bibliothèque Nationale copy, 10 July 1942.
4. Within a month of the grant of Drayton's first patent in England (1843) a French patent application was deposited in the name of Joseph Brown (1844). The processes were identical, so Brown was presumably an agent. According to Kopp (1859), the essential oils used in the solutions caused reddish-brown spots to appear on the silver surface after a while, which led to revisions in the process (Drayton, 1848a; 1848b). Additions to the Brown patent show that by 1851 Power was acting as representative for the holder of the 1844 patent. Note also the bibliography by Kanthack (1920).
5. With this last sentence and an accompanying footnote Foucault acknowledges that in the previous spring the Munich optician Carl Steinheil (1801–1870) had announced in a newspaper that he had produced a similarly-sized (4-inch) reflector using Liebig's silvering process, though the instrument only supported a magnification of 100× (Steinheil, 1856; see also Steinheil, 1858). According to Kopp (1859) Steinheil compensated the spherical aberration of his mirrors with a negative lens incorporated in the eyepiece. However, in his 1860 price list Steinheil advertised 4-, 6-, 9- and 12-inch parabolic mirrors with focal ratios *f*/6, *f*/6, *f*/10 and *f*/9 respectively. The three largest sizes were available made up as telescopes in the 1860s (Steinheil, 1860; 1867). Brachner (1987: 4) writes "As far as I know not one of these interesting Steinheil-Liebig mirror telescopes has survived." Unmounted parabolic mirrors with the offer to mount them according to the purchaser's wish appeared in the Steinheil firm's catalogue as late as 1907 (Steinheil Söhne, 1907).
6. Foucault's note to the Académie (1857b) referred to his mirror and telescope in the singular, but a fortnight later Babinet referred to mirrors and telescopes in the plural (Babinet, 1857a). In planning the Paris Observatory expedition to Spain to observe the 1860 total solar eclipse, Le Verrier (1860a) proposed taking, inter alia, "Two little reflectors of $0^{m}.10$" which "... [already] exist, at least for one of them ..." In the event, it was just "A $0^{m}.11$ reflector in its box ..." that was taken (Énumeration des objets, 1860). This suggests that in early 1857 Foucault had figured two 10-cm mirrors of acceptable quality, but only had a single tube in which to test them as a Newtonian telescope.

   The telescope mirror is now inventoried by the Paris Observatory as No. 250, and the tube and rectangular transport box as No. 251. Previously the identification was IA-19-63b for the tube and box, which were catalogued as having been donated by a "prof. Nughes" of the École Centrale des Arts et Manufactures. Foucault considered that he had privately financed the development of his small telescopes, and perhaps his first instrument was amongst the residue of scientific apparatus bequeathed to his friend Jules Regnauld (1820–1895). 'Prof. Nughes' is no doubt Émile Nugues (1870–1963), who graduated from the École Centrale in 1894 and taught there until 1941 (Obituary, 1964). He would be a later owner. Perhaps the items were gifted to the Observatory around 1950 when Nugues gave translations made by him of optical works by Karl Schwarzschild and Sigfried Czapski to the Observatory Library (Ms 1039 and Ms 1040). No provenance is given for the mirror, IA-19-63a, which was catalogued as having a diameter of 112.5 mm (i.e. 4 *pouces* 2 *lignes*), which actually corresponds to the inner diameter of the lip against which it abutted. In fact, the full diameter of the mirror is 4 *pouces* 6 *lignes*, and it is just too tight a fit to slip into the wooden mirror cell. Perhaps this is due to shrinkage of the wood over 150 years, but one must consider that it might be one of several of this size polished by Foucault. Nughes was an amateur telescope maker, but the non-metric diameter makes it seem unlikely that it could be one of his mirrors.

On the outside of the lid of the transport box there are the illegible remains of a label which according to catalogue details is a shipping label to the Royal Astronomical Society (RAS) in London. Foucault took his telescope with him when he talked about his telescope at the meeting of the British Association for the Advancement of Science in Dublin during the summer of 1857 (Foucault, 1858c) and visited Sir John Herschel in Kent on his way home. Perhaps the telescope went to the RAS then, but more plausibly it was sent without its creator when Warren De la Rue (1815–1889) presented Foucault's work to the Society in March 1859 (Foucault, 1859b). The presence of a transport box is not in conflict with this being the instrument taken to Spain in 1860.

7. That Foucault took a telescope with him is confirmed by Babinet (1857b) and British Association (1857: 168), where it is reported that Foucault's presentation of his telescope in Dublin was "... warmly applauded … [and provoked] an animated discussion ..." Some of these comments (from G.J. Stoney, T. Grubb and Rev. T.R. Robinson) are reported by Wells (1858: 224). Foucault, however, felt crowded out by Lord Rosse's Leviathan. See Tobin (2003: 204).
8. The Lissajous pamphlet carries no date, but the *Journal Générale de l'Imprimerie* (1858a) indicates that it was published on 14 August 1858. The focal length given for the 216-mm aperture is 162 cm, which is presumably more accurate than the 160 cm correction seen in Figure 5.
9. The 250 fr price is confirmed implicitly by a British source which 4 years later quoted £10 (The Great Foucault Telescope, 1862). (The conversion rate was 25 francs/pound—see Note 14.) In the scientific papers that were inventoried after Foucault's death (see Tobin, 2003: xii), cote 4ème pièce 429 records that the Emperor Napoléon III paid 300 fr for a small telescope: "Lettre de Mr Thélin envoyant 300 f pour prix d'un petit télescope construit pour l'Empereur." Charles Thélin (1801–1880) helped Louis-Napoléon escape from imprisonment in Ham in 1846 and was later his private treasurer.
10. The earliest invoice that I have found written on a billhead vaunting Foucault's telescopes is dated 1 February 1859 (Secretan, 1859a). The workshops were at 73, Rue du Faubourg Saint Jacques. In the first half of 1860 they moved to 13 Rue Méchain; in 1862 their address was 9 Rue Méchain (cf. Figure 6). A billhead from 1887 still mentions Foucault telescopes (seen on todocoleccion.net). The workshops were then at 54 Rue Daguerre.
11. This illustration disappeared from the 8th edition of Ganot's *Cours* (1881). In the 9th edition, reworked by Maneuvrier (1887), the Worms de Romilly telescope (Figure 40) was inserted, to be replaced in the following edition (Ganot-Maneuvrier, 1904) by a woodcut of the Paris 120-cm reflector. The 120-cm reflector first appeared in the *Traité* in 1894 (Maneuvrier, 1894).
12. Note that on page 91 of this publication a photograph of Hippolyte Fizeau is misidentified as representing Léon Foucault.
13. Seven round shims cut from newspaper have been inserted between the mirror of Wolf No. 4 and the wooden back of the mirror cell. I have been unable to identify the newspaper, but the shims carry advertisements for books published in 1858 as well as legal notices concerning Largentière in the Ardèche. Use of a newspaper from the south of France, far from Paris, suggests the shims are an addition after purchase.
14. That the 4-*pouce* telescopes were imported at the beginning is explicitly stated by Webb (1863). One might wonder if Negretti & Zambra later made replicas themselves, but the next line in their 1887 catalogue refers to other reflecting telescopes "... constructed to order", so "Supplied to order ..." strongly implies brought-in goods. In 1879 the price was 18 guineas (Negretti and Zambra, 1879). The Negretti & Zambra catalogues carry no dates. I adopted those from Anderson et al. (1990) for 1859, from the British Library catalogue for 1879, and the evidence of a review (Recent Publications, 1887: 181) for 1887. I used an exchange rate of 25 fr/£ (Bureau des Longitudes, 1858), a value which had not changed significantly three decades later, being based on gold (Bureau des Longitudes, 1887).
15. One might think this was a 15-*pouce* disc (≡ 406 mm), were it not that at about this time Moigno (1857b: 653) wrote of Foucault having crossed "... the distance which separates a 4-*pouce* from a 7-*pouce*, a 7-*pouce* from a 17-*pouce*, etc.", in which case '40-cm' was considerably rounded (17 *pouce* ≡ 460 mm). To add to the confusion,

Foucault himself later referred to the repeated failure of a 42-cm mirror (Foucault, 1859a: 198), but I think this is another disc (see Section 5).

16. Moigno (1858a) describes this mirror as a 35-cm one. Probably it was actually of 13 *pouce*s diameter (≡ 352 mm), which Foucault, with his penchant for even numbers, might have described as 36 cm. The 32-cm mirror was perhaps actually 12 *pouces* (≡ 324.8 mm) in diameter.
17. Elsewhere, Foucault reported that the two mirrors had a 25-cm diameter, showing that he did not always favour even numbers (Foucault, 1858d). Presumably their size was actually 9 *pouces* (≡ 243.6 mm).
18. Ganot (1859b: 442) reports that the 33-cm telescope was built by "... Froment and Secretan …". Perhaps Froment's contribution was limited to the test grid; but it seems more plausible that he was also involved in the mounting, as for the École Poytechnique instrument (Section 2.3.1). Foucault's Louis-Napléon account book shows that from January 1857 he made frequent payments to Froment, usually of 100 fr, totalling 1,400 fr by August 1858, after which they became sporadic, adding only 344.50 fr more by the end of 1859. The first payment was explicitly ascribed "... for supplies" (Foucault, 1852–1865). As an inventive physicist Foucault may well have been using Froment's constructional skills for a variety of other projects at this time which have not come down to us, but presumably any telescope work was included in these amounts.
19. Towards the end of the century, Baillaud (1893: 127) inversed Foucault's definition of the optical power and claimed that "... Foucault showed that it is about 1″ for a 13-cm objective." Foucault's optical power is of course different from the Rayleigh-criterion 'power', $D/1.22\lambda$, because of the striped nature of the target and the eye's spectral sensitivity. Scrutiny of Baillaud's text shows that actually he is referring to the Rayleigh-criterion resolution, $1.22\lambda/D$, for which the quoted value corresponds to a wavelength λ = 520 nm and a Foucault-style power of 16,000 per centimetre. In fact, Foucault claimed a *pouvoir optique* of "... 150,000 units per 0^{m}.10 of diameter." (1859a: 220). Based on his announced values for the 24/25-cm, 33-cm, 40-cm and Worms de Romilly mirrors, I obtain 12,000 per centimetre.
20. In November 1859 it was reported that Bulard was "... provided with ... two silvered speculum reflecting telescopes" (Miscellaneous Intelligence, 1859). In describing observations of the 1860 total solar eclipse with this instrument, Bulard wrote

    > Except for the mirror, it is the same instrument that I used to observe Donati's comet in 1858. For the eclipse, I had to use a non-silvered mirror, of M. Foucault's system. (Moigno, 1861: 328).

    If Bulard was meaning that the telescope was not 'the same' because of the removal of the silver from its mirror, it seems odd to specify that the unsilvered mirror was 'of M. Foucault's system.' Further support for there having been two mirrors comes from the fact that it is not until after 1874 that Bulard had the capacity to resilver a desilvered mirror (Soulu, pers. comm., 2014). A second 33-cm mirror is preserved in Algiers in addition to the one shown in Figure 25, but from its metal mounting with a surviving trunnion, it would appear to be the flat heliostat mirror installed in 1883 for solar photography (Trépied, 1884).
21. I measured 410 mm for the inner diameter of the mirror retaining ring seen in Figure 28, so the mirror diameter must be near 42 cm. The circular aperture at the sky end of the tube is warped. When in the meridian, its vertical and horizontal diameters are 404 and 408.5 mm respectively. The horizontal diameter of the mirror-cell aperture is 395 mm. (All dimensions ±1 mm.) With a ~2.5 m tube, these figures indicate an unvignetted field-of-view of about 15 arcmin. The 1859 and 1860 Secretan bills were for 1798.50 and 2730 fr respectively. There is no charge for *retouches locales*, which Foucault no doubt did as part of his Observatory duties.
22. When the 40-cm (and 20-cm) telescopes were shipped to Spain in 1860, the packing list detailed "... two rubber cushions" (Enumération des objets, 1860). In early 1868 Eichens invoiced for modifications to the 40-cm mirror cell to provide three support points and a three-pronged spring with adjustment screw (Eichens, 1868).
23. The telescopes were the Algiers 50-cm (Lagrula, 1932) and the Marseilles 80-cm (Tobin, 1987). One must wonder if similar problems did not occur when Stephan replaced the 40-cm's prism by a flat mirror for the 1905 eclipse, since he does not address the issue in his report (Stephan, 1911).
24. Exactly when is not clear. Secretan billed for having made openings in the "... bois blanc ..." tube in 1861, and again in 1865 for having "... remis en place l'ancien corps ..." into which six holes had been cut "... garnis de toile métallique ..." with an "... encadrement en cuivre", which sounds very like the surviving arrangement (Secretan,

1861a; 1865a; one of six vents is visible in Figure 26). Were initial vents enlarged, or was the chain-mount tube also used on the equatorial mount?

25. It is sometimes unclear for his test targets whether Foucault was referring to individual line widths or their double, the pattern repeat distance. By stating that 1/6-mm spacing at 80 m corresponds to an optical power of 480,000 and a splitting of 0.4″ it is clear that he is referring to the pattern repeat distance.
26. The draft incorporates a note by Foucault who estimated 21,200 fr for the cost of the telescope proper, of which 2,000 fr were for the mirror blank and glass ball for working the initial spherical surface, 1,000 fr for working the surface, 500 fr for the prism-eyepiece assembly, 600 fr for silvering expenses, and 5,000 fr for the motor drive. The contract with Secretan was signed on 15 September (Le Verrier and Secretan, 1860). Major invoices followed on 1 November (Sautter, 1861: 1,977 fr, but see Note 27), 31 December (Secretan, 1860b), 30 July 1861 (Secretan, 1861b) and 14 July 1862 (Secretan, 1862a) totalling 12,831.45 fr.
27. On 22 October 1859 Foucault paid Sautter an advance of 1,000 fr for the provision of two "... big 80^c discs." (Foucault, 1852–1865). On 10 February 1860 he paid a Sautter bill of 1,927 fr for two discs "... of 0.80^c and of 0.85^c", which sum was reimbursed by the Education Ministry in March 1861 (Foucault, 1852–1865). This must be reconciled with an invoice issued by Sautter (1861) on 19 January 1861. It is a duplicate of an original dated 1 November 1860, for the casting and lathing of 80- and 85-cm discs, in execution of an order passed on 12 October 1860. The invoiced amount is 1,977 fr, almost the same as Foucault's payment in February 1860. Although the invoice was approved by Le Verrier, and is annotated with inventory numbers, Sautter has not countersigned indicating receipt of payment. Paperwork can often postdate action, so perhaps this invoice just reflects Paris Observatory officialising Foucault's original order and justifying reimbursement. In any case, Foucault's initial payment of 1,000 fr was presumably ultimately actually used for other purposes.
28. Sautter's bill (1861) indicates that both discs had a concave face "... doucie ..." i.e. fine ground, ready for optical polishing. The reverse faces were convex, left rough for the 85-cm disc but polished for the smaller disc, which also had a furrow cut in its edge for attaching ropes to facilitate manipulation (see Figure 33 and Tobin, 2003: Plate XIX).
29. In Tobin (1987) I quote 788 mm for the mirror diameter and 4.54 m for its focal length. The 788-mm diameter has recently been confirmed by Caplan and Ruiz (pers. comm., 2015). The radius of curvature of the convex surface is approximately 1.2 m.
30. The mirror Inv. 14050 was given to the Musée des Arts et Métiers in 1907 by the microscope-manufacturer Alfred Nachet (1831–1908). This tends to support an attribution to Foucault, because Nachet had collected other items indubitably associated with Foucault—daguerreotypes now in the Museum of the History of Science in Oxford and in the Optisches Museum in Jena, and microscopes made or owned by Foucault (Nachet, 1929). As displayed, the mirror is protected by an octagonal pane of glass. This made measuring the mirror difficult, but its diameter and thickness do not differ by more than a millimetre or so from 330 mm and 28 mm respectively. The poor optical quality of the protective pane made it difficult to check whether the 229 cm focal length claimed on a paper label visible in Figure 36 is accurate, but the points at which (i) my own image inverted and (ii) one of my fingers showed little parallax with its image in the mirror suggest that the focal length might be half a metre greater. The Musée des Arts et Métiers holds another mirror, acquired in 1975 from a deceased anonymous donor who attributed it to Foucault (Inv. 22507, dossier d'oeuvre). The attribution to Foucault is highly improbable since the mirror is made of metal. I measured its diameter as 252 ± 1 mm and thickness as 30 ± 1 mm. I could not determine the focal length, but it is greater than 5½ m, which suggests the object may not even be a telescope mirror.
31. At the end of 1862 Sautter billed for cutting to size a 801-mm glass disc with a 9.60-m radius concave surface and a 1.80-m radius convex surface (Sautter, 1862). Buoyed by the success of the 80-cm mirror completed at the beginning of the year, did Foucault and Le Verrier have the unused 85-cm disc cut to shape for another mirror of similar size? From the masses quoted in an earlier bill (Sautter, 1861) it would seem the disc would have been quite thick enough.
32. Shreds of evidence indicate the relationship. On 2 December 1852 (the day of Louis-Napoléon Bonaparte's coup d'état), Worms de Romilly took his friend (and later French Prime Minister) Émile Ollivier (1825–1913) to vist Foucault, where discussion centered on Foucault's "... beautiful experiments on

the motion of the Earth" (Ollivier, 1961: 136). Three years later Worms de Romilly wrote to Ollivier about lunching with "... le Foukmann ...", adding "So there's my man who's putting down more and more roots at the Observatory through his own forcefulness despite the lofty Blond [i.e. Le Verrier]" (de Romilly, 1855). About the same time, Worms de Romilly corresponded with Foucault concerning his (Foucault's) induction machine (Inventaire Des Diverses Cotes, n.d.: Cote 11ème, pièce 11 "Letter on an induction experiment (draft)", pièce 12 "ditto", pièce 13 "Monsieur de Romilly's reply (same subject)"). On "Saturday 20 August …" in a later year, which is probably 1859 but might be 1864, Worms de Romilly's wife, Elisa (1834–1880) wrote to Foucault thanking him for his intervention in some affair, inviting him for the afternoon, and noting that "Félix was enchanted with the letter you wrote him, because it shows him that you liked his parrot." (de Romilly, n.d.). Finally, a funeral oration for de Romilly mentions "... his friend Léon Foucault ..." (Mascart, 1903).

33. Lambert also commented on the informality, longer hours and Sunday working in French workshops compared to Irish ones, as well as greater opportunities for self-improvement in Paris than Dublin. "With such opportunities … can we wonder that the French workmen have acquired for themselves so high a reputation for intelligence and skill?" (Lambert, 1879: 478).
34. The stabilising rod was subsequently broken but has recently been repaired. The finder telescope has also disappeared. It had a 27-mm diameter and was a later addition, being installed by Eichens after the Siege of Paris (Eichens, 1871a).
35. A summary of the 20,000-fr expedition expenditure is provided by Le Verrier (1861). Purchase of the 20-cm telescope is not mentioned, but presumably was included in the sum of 4295.50 fr paid to Secretan "... for the construction of instruments."
36. The Paris Observatory conserves a 212 ± 1 mm diameter mirror (inv. 259) which the inventory speculates might be from the 20-cm telescope. It has many of the characteristics of a Foucault mirror—a polished, curved back, green-tinted glass, and a furrow around the edge. However, the furrow is deep, the edges are bevelled and the mirror is accompanied by a note "Mirror belonging to me, C. Wolf." I do not think this is the original Foucault mirror, but perhaps it is a substitute used by Wolf. It would be enlightening to measure its focal length. Could it be the 21-cm mirror made by Martin for the 1868 solar eclipse (Note 37 and Janssen, 1868)?
37. Two French expeditions observed the 1868 eclipse. The mission to the Malay peninsula took a 20-cm reflector while the one to India took a 21-cm instrument (Janssen, 1868; Stephan, 1868). Both mirrors were parabolized by Martin (see Section 7). Doubtless it was this 20-cm telescope that was used on the return journey to observe a transit of Mercury from Marseilles (Figuier, 1869).
38. The text was reprinted in at least three other publications with 'Rayet' corrupted to 'Reiset' (Astronomie photographique, 1866; Lacroix, 1865; Schnaiter, 1865). Modestly, Rayet does not mention this work in his history of astronomical photography (Rayet, 1887). The brass plateholder, rack and 24 glass plates for photography cost 55 fr and a new prism 12 fr (Secretan, 1866a; 1866b). Another special eyepiece had been procured when the telescope was taken to Spain.
39. Musée de la Civilisation accession No. 1993.3. Nadeau (1943: 237) notes that the telescope is signed "Secrétan à Paris, 1867". I am surprised by the 'é'. The mirror has a pale green tint. Not appreciating the reason, Nadeau finds it "... fairly bizzare ..." that the back of the mirror is curved. The eyepiece assembly is a "... veritable compound microscope ..." The base of the foot is like that of the 20-cm (Figure 45).
40. The incident involved a note presented to the Académie by Duboscq (1862) concerning Foucault's heliostat for photographic enlargements. In fact the note had been written by Foucault, as indicated by a draft in his handwriting (Foucault, 1862c). In reporting the presentation for *Cosmos*, Moigno innocently referred to "... their heliostat ..." (1862b: 470). Annoyed, Foucault prepared a letter (1862d) that Duboscq sent to *Cosmos* protesting the amalgam between scientist and constructor (Moigno, 1862a).
41. The 10,000 fr were given on 17 February 1852. On 29 September 1855 the Emperor's aide-de-camp wrote that having heard of Foucault's electrical experiments, Louis-Napoléon had decided to fund his future work (Favé, 1855). However, it was not until 4 November 1856 that Foucault took up this offer, receiving 2,000 fr. Subsequent payments were 1,500 fr and 2,000 fr on 18 February and 1 September 1858, and 3,000 fr on 1 February 1860. A week after the 1852 payment Foucault paid Froment's outstanding bill for the Panthéon demonstration (which was only 887 fr). A

week after the September 1858 payment he paid a Secretan bill for 890.40 fr. Nine days after the 1860 payment he paid a Sautter bill for 1,927 fr (see Note 27). It would seem Foucault sought out Louis-Napoléon whenever short of cash! After 1860 the telescopes were bringing in money, as perhaps were his electric arc and heliostats developed with Duboscq, and the Emperor's subventions ended.

42. This letter is a copy, in someone else's hand, in a subfolder entitled "1. Lettre rélative à des recherches d'optique. Recettes et dépenses." In order, the letter is followed by the account book (Foucault, 1852–1865) and a bill (Martin, 1867). The date of the letter invalidates my suggestion (Tobin, 2003: 265) that Foucault's relation with Martin may have begun in 1865.

43. These sums are roughly proportional to the surface areas of the mirrors. The receipt details work on two 10-cm, two 16-cm and one 50-cm mirror. Only half the price of the 50-cm was owing to Martin, presumably because Foucault contributed to its polishing. The inventory after Secretan's death mentions two 10-cm telescopes "... in the hands of the workmen …" and one 16-cm instrument on display at the Exposition Universelle, but there is no mention of a second 16-cm or 50-cm mirror (Sebert, 1867–1868). Perhaps they had already been sold, or had not yet been delivered.

44. In the hope that the agreement might have been registered, I searched the records of the following Paris notaries without success: Études XXIX and XLIX (Foucault notaries), and Études XLIV and XCVII (Secretan notaries). In the scientific papers that were inventoried after Foucault's death (see Tobin, 2003: xii) cote 11ème pièces 121 à 124 record "Projet de Traité avec Secretan." Is this the contract referred to by Rayet in 1868 (see Section 1)?

45. The stand carries a plate indicating "LANGLOIS SGDG rue de Bondy, 70". Alexandre-Eugène Langlois patented his camera foot in 1856 (Catalogue des Brevets, 1857). He was still in business in May 1868 (Langlois, 1868). The mirror and its cell are missing in Figure 71 (right) because they were being renovated (Fuentes, pers. comm., 2015). The mirror is the one announced as "Property of Camille Flammarion" exhibited at the 2011 Rencontre Transfrontalière d'Astronomie in Hendaye (www.astrosurf.com/rtaa/rtaa_images/expo/mirfouc160_1880053.jpg). It is dated to 1866 with focal length 960 mm (i.e. *f*/6) and has a convex rear. The slow-motion mechanisms are undersized and fragile (Fuentes, pers. comm., 2015). An engraving showing the telescope appears in Flammarion (1868: 301).

46. Measured by placing a pin adjacent to its image at the centre of curvature, the mirror's focal length was found to be 595.3 ± 1.0 mm, in which case the prime focus would lie within the reflecting prism, which is not impossible. The focal length was also obtained from mechanical dimensions and by relaxed-eye focusing of the telescope on a cross 1.02 km away and measurement of the position of R_1 (Figure 58) with respect to the exit plane of the prism. I assumed a crown glass prism of refractive index 1.5 and the position of the entrance plane of the eyepiece shown in Figure 58, which agrees to 0.25 mm with a value measured directly. A focal length of 605.7 ± 1.5 mm was found with the whole mirror illuminated, and 601.7 ± 1.5 mm with the mirror masked down to a 20-cm circle which gave a markedly better image. Has the glass slumped? Has the mirror been reworked, inexpertly? Or perhaps the modern aluminium coating is irregular because though the Sun can be seen through a small, sausage-shaped region towards the centre, elsewhere the coating is too thick to transmit any light.

47. Magnifications of 59× and 110× are given for the long and short terrestrial eyepieces, respectively. The lower row of celestial eyepieces are numbered, from left, 6, 8 and 5, with magnifications 300×, 350× and 150×. Missing are eyepieces numbered 2 and 4 with magnifications 70× and 112×.

48. It is strange that when the 80-cm mirror was silvered in 1862 it was Eichens personally who billed for the service, rather than the Secretan firm (Eichens, 1862). Was private work the point of discord? Eichen's address was 7 Rue Méchain, next-door to the Secretan workshops.

49. The notaries making the inventory after Marc Secretan's death turned to the Exposition Universelle on 20 September 1867. Only four astronomical items were on display: a 16-cm reflecting telescope with metal equatorial mount, and 95-, 135- and 160-mm astronomical objectives (Sebert, 1867–1868).

50. As well as on the title page, the year 1868 appears on the legal deposit stamp on the copy in the Bibliothèque Nationale. However, the publication does not appear in either the 1867 or 1868 *Bibliographie de la France*.

51. Martin's work on telescopes, daguerreotype photography on silvered glass, and sidero-

stat mirrors during 1872–1873 for the Transit of Venus expeditions is described in Commission du Passage de Vénus (1877). With Eichens he also built a 40-cm Foucault-style siderostat for Lord Lindsay's Transit of Venus expedition (André and Rayet, 1874; Brück, 2004). See also Note 37.

52. The 1874 catalogue does not appear in the *Bibliographie de la France*. The publication date derives from a review published in March (Dufour, 1874).
53. For the Digne and Coimbra telescopes the location of the declination clamp differs from other comparable instruments (Figures 70 and 77 vs. Figures 45, 50 and 67). For the Digne instrument, at least, I suspect this is the result of inexpert reassembly at some juncture. The 180°–0°–180° scale on its declination axis is inappropriate for declination and the clamp index mark is misplaced by a few degrees from the equator. If the clamp were in the usual location the scale would read polar distance.
54. Because of the poor image quality, Gully did not realise that he had seen the (super) nova S Andromedæ. Libert (1902) (and the Rouen Observatory web-page www.astrosurf.com/obsrouen) claim that Gully used the 16-cm reflector for this missed discovery, but that Gully's instrument was a different one seems confirmed by several different references to its 20-cm size (Gully, 1885; 1893; Venus le jour de sa conjunction, 1887).
55. Mailhat (c.1908: 3) says he was "... called ..." to head Secretan's workshops in 1888, which is not incompatible with his actually taking charge on 1 January of the following year. Afterwards Secretan advertisements mentioned his name as workshop director (e.g. Secrétan, 1890; 1893). Albert Rellstab was a later workshop head (e.g. Présentations et admissions, 1897).
56. Mailhat (1909) gives 30, Faubourg Saint-Jacques as the Secretan workshop address in 1889. An advertisement from the previous year has it at 54, Rue Daguerre, hardly much further from the Observatory (Secrétan, 1888). The evidence for expropriation comes from Épry (1911a: inside cover) and the date from Secretan (1915: 5). Mailhat's new premises were plausibly opposite the expropriated ones, because an advertisement from the early 1900s gives as address "41–42, Boulevard Saint-Jacques ... (opposite: 30, Faubourg Saint-Jacques)" (Andrews, 1994: 196).
57. Presumably the ~0.5-μm layer of celluloid varnish tried at Meudon Observatory by Perot (1909), the efficaciousness of which is perhaps attested by the reprinting of the method in *L'Astronomie* (Pérot, 1911 'Gelatine bichromate' had earlier been used on the 33-cm and perhaps 80-cm Foucault telescopes in Toulouse (Izarn, 1894).
58. Google Books snippet views reveal such advertisements from 1949 to 1963. Advertisements through 1948 make no mention of Prin, nor do ones following the takeover by Morin in 1964.
59. Morin-Secretan continued to appear in *L'Astronomie* cover-page listings of "Informations, adresses utiles" until early 1968, i.e. a little after the merger with SRPI, but perhaps these insertions were arranged prior to the fusion with SRPI.
60. In a form filled in for the 1878 Exposition Universelle, Lutz states the firm was founded in 1828 and that he "Took possession ..." of it in 1862 (Lutz, 1878), which is the year of A.S. Bertaud's death. However, the firm traded under Bertaud's widow's name as late as 1870 (e.g. Dupin, 1870: 123). To add to the confusion, H. Duplouich (in L'Industrie Française des Instruments de Précision, 1901–1902: 154) claims that the firm was founded by Berthaud (with an 'h') in 1848, and that he, Duplouich, took over in 1896. This latter claim seems likely since Lutz died on 1 October 1895 (Registre d'État Civil, 1895). In 1847 an almanach refers to "Bertaud ...", which by 1855 had become "Bertaud j[eun]e ..." (Almanach-Bottin, 1855: 965; Annuaire générale, 1847: 539). Perhaps between 1847 and 1855 A. S. Bertaud took over from a father or brother.
61. P. Fuentes (pers. comm., 2015) owns an *f*/6 Lutz reflector with a useful diameter of 125 mm but a 135-mm mirror with a convex rear. Is this a 125-mm instrument as advertised in Lutz's catalogue? Jean-Gustave Bourbouze (1825–1889) was a talented physics technician at the Sorbonne. He devised and manufactured a host of demonstration apparatus. I have no evidence that would corroborate the claim by the notoriously unreliable Louis Figuier (1890) that Barbouze collaborated with Foucault.
62. The letter is bound in the same volume as the 1858 Secretan catalogue 'Addition' (Table 1), but is not digitized at hathitrust.org. Lutz's 1882 and c.1890 catalogues equate 105 mm with 4 *pouces*, so the 10½-cm designation may or may not have indicated a change from the 108 mm advertised in the 1872 catalogue (Table 4).
63. The 1928 catalogue describes the instrument as having a 10-cm mirror and 80-cm

length, which is plausible when compared to the 85-cm length stated for the Lutz 10½-cm instrument (Figure 89). Apart from the diameters, the entries in the 1907, 1910 and 1928 catalogues are identically-worded, but 80-cm lengths would imply very fast focal rations for 13- and 15-cm mirrors. Misprints in diameters and/or lengths seem probable.

64. Harvard University Library holds volumes 1–9 (1882–1890) and 11–13 (1892–1894) of *L'Astronomie: Revue Mensuelle d'Astronomie Populaire, de Météorologie et de Physique du Globe.* The covers of the individual monthly issues have been retained in the bound volumes which are available (with difficulty) via Google.
65. Every issue in 1888 except December, for which the cover is missing, and July 1890. I have been unable to examine covers for 1891 (see Note 64).
66. "Mouronval" bought the firm in 1909 (Ventes de fonds de commerce, 1909: 1117). I have found references in 1911 and 1913 to the firm as "Mailhat & Mouronval Frères" so it appears that Francis Edmond's twin brother Pierre Paul (1881–1956) was associated with the firm, at least briefly (Adresses relatives aux appareils décrits, 1911; Mailhat and Mouronval Frères, 1913). The Mouronvals advertise their training at the École Polytechnique; the matriculation registers available at bibli-aleph.polytechnique.fr confirm that no other Mouronvals attended the school.
67. A copy of this rare pamphlet is preserved in the Paris Observatory Archives (Ms 1133-2 Frères Henry. Échanges avec des fabricants d'optique).
68. Lescarbault and Foucault may plausibly have been acquainted with each other, since in their medical studies both passed *externe* in the same year, 1843. Of the 124 candidates passed, Foucault was ranked 18th, Lescarbault 124th (Conseil Général des Hospices Civils de Paris, 1842).
69. If Flammarion intended to signpost Foucault-Secretan telescopes, I suspect he is mistaken concerning Neyt, whose famous lunar photographs—which admittedly date from a decade earlier—were taken with Browning-With silvered-glass reflectors of 9¼ and 10¼ English-inch clear aperture (e.g. De Vylder, 1877; Neyt, 1869).
70. From photographs it appears that a "SECRETAN A PARIS" signature was even applied *along* the length of the tube of a 16-cm metal-mounted alt-azimuth instrument offered recently by a fraudulent Uruguayan seller (Petrunin, pers. comm., 2015). This telescope is not included in Table 9.
71. For example, Moigno (1859c) states that he facilitated the acquisition of a Foucault telescope by the fabulous Bancker collection in Philadelphia (e.g. Simpson, 1995). What became of this instrument? It is presumably not the Smithsonian Institution telescope (Table 6), which was purchased in October 1979 from a dealer in Paris (Roux-Devillas, 12 Rue Bonaparte – S. Turner, pers. comm., 2015).
72. For an example of what might be done, see Hill (2005). The scientific papers inventoried after Foucault's death (see Tobin, 2003: xii) cote 11ème pièce 118 record "Secretan circular concerning his new model of reflecting telescope." Possibly this document advertised the 10-cm metal-tubed telescope.

15 ACKNOWLEDGMENTS

This paper would not have been possible without the help generously and graciously provided by a host of persons. Apologies to any omitted from the following list. From Paris Observatory, I thank Josette Alexandre, Frédérique Auffret, Laurence Bobis, Emilie Kaftan and Dominique Monseigny, as well as James Lequeux and Patrice Barrose for measuring respectively dimensions and the focal length of the telescope shown in Figure 4. For details of other telescopes I am indebted to Guy Artzner, Morgane Bauer and Alain Le Rille (Lycée Janson de Sailly), Dominique Bernard (Université de Rennes 1), Paolo Brenni, James Caplan (Observatoire de Marseille), Luc Chanteloup (Prytanée National Militaire), Philippe Dupouy (Observatoire de Dax), Patrick Fuentes, Gerhard Hartl (Deutsches Museum), Kevin Johnson (Science Museum), Jean-François Logeais (Lycée Louis le Grand), Jérôme Lamy, Françoise Le Guet Tully (Observatoire de la Côte d'Azur), Lionel Ruiz (Observatoire de Marseille), Frédéric Soulu, Guillaume Trap (Palais de la Découverte), Anthony Turner, and Steven Turner (Smithsonian Institution). From the Musée des Arts et Métiers I thank Ludéric Dubuisson, Cyrille Foasso, Lily Hibberd, Thierry Lalande, Jérôme Méneret and Isabelle Taillebourg. For numerous leads, I am grateful to Francis Gires (Association de Sauvegard et d'Études des Instruments Scientifiques et Techniques de l'Enseignement). I also thank the late Gilbert Auzet, Peter Baetes (Erfgoedbibliotheek Hendrik Conscience), Guy Barbel ('astr-rétro'), Peter Brougham, Dominique Collin, Jacques Dunkan, William P. Flatt, Marc Heller, Vivek Hira, Sergio Ilovaisky (Observatoire de Haute Provence), Jim Lattis, Takis Lazos (Hellenic Archives of Scientific Instruments), Patrick Mill (for measurements of his microscope achromatique simplifié), David Miller, Nadine Gomez Passamar, Alex Peck, Yuri Petrunin, Xavier Plouchard, Guy Pouget, Sara Schechner, Ronald Smeltzer, Albert Theberge (NOAA Central Library) and Marie-Christine Thooris (École Polytechnique). Lastly, I must especially thank Edward Wolf (www.wolftelescopes.com) for the many measurements made and details provided of his three Foucault-Secretan telescopes. Among on-line resources, this research has made use of NASA's Astrophysics Data System, the Google Books Project, the Internet Archive and Gallica.

16 REFERENCES

Prefix symbols before a reference indicate free, on-line availability as follows:

§ from the Archives de Paris (canadp-archivesenligne.paris.fr/archives_etat_civil);
* via the Bibliothèque Nationale de France gallica.bnf.fr);
+ from the Biodiversity Heritage Library (www.biodiversitylibrary.org);
† from the Conservatoire Numérique des Arts et Métiers (cnum.cnam.fr);
¶ from Google Books or the Google Books Library Project, though geographical restrictions may apply (books.google.com);
♦ from the Hathi Trust, though geographical restrictions may apply (hathitrust.org);
= from the Internet Archive (archive.org);
× from the Portail Documentaire of Méteo France (bibliotheque.meteo.fr);
° via the SAO/NASA Astrophysics Data System (adsabs.harvard.edu); and
from the Smithsonian Libraries' Instruments for Science Collection (www.sil.si.edu/DigitalCollections/Trade-Literature/Scientific-instruments).

Acloque, P., 1987. Pli cacheté No 2426 du 24 février 1868, ouvert le 12 novembre 1987. *La Vie des Sciences*, 4, 614–615.

†Adresses relatives aux appareils décrits. *La Nature, Supplément*, 1975, 143 (1911).

**Almanach-Bottin du Commerce de Paris*. Paris, Bureau de l'Almanach (1855).

Anderson, R.G.W., Burnett, J., and Gee, B., 1990. *Handlist of Scientific Instrument-Makers' Trade Catalogues 1600–1914.* Edinburgh, National Museums of Scotland.

André, C., and Rayet, G., 1874. *L'Astronomie Pratique et les Observatoires en Europe et en Amérique. Deuxième Partie. Écosse, Irlande et Colonies Anglaises.* Paris, Gauthier-Villars. On-line at www.bodleian.ox.ac.uk .

°Andrews, A.D., 1994. Cyclopaedia of telescope makers. Part 3 (K–N). *Irish Astronomical Journal,* 21, 167–249.

°Andrews, A.D., 1996. Cyclopaedia of telescope makers. Part 5 (Sae–Sim). *Irish Astronomical Journal,* 23, 57–117.

¶Angot, A., 1881. *Traité de Physique Élémentaire.* Paris, Hachette.

**Annuaire Générale du Commerce et de l'Industrie*. Paris, Firmin Didot (1847).

Apoil, C., 1904. *Optique – Miroirs – Objectifs*. Paris Imprimérie des Beaux-Arts.

°Armelin, G., 1890. Société Astronomique de France. Séance du 5 novembre. *L'Astronomie*, 9, 456–459.

Asta di Strumenti Scientifici. Martedì 14 Novembre 2006. Genova, Cambi Casa d'Aste (2006).

*Astronomie photographique. *Bulletin de la Société Française de Photographie,* 12, 80–81 (1866).

Auflage, D., 1983. Groβe Forscher und Erfinder Leben und Werk. Schätze im Deutschen Museum. Düsseldorf, VDI-Verlag.

*Babinet, [J.,] 1857a. Bulletin scientifique. *Journal des Débats Politiques et Littéraires,* February 26.

*Babinet, [J.,] 1857b. Bulletin scientifique. *Journal des Débats Politiques et Littéraires,* November 4.

*Babinet, [J.,] 1858. Bulletin scientifique. *Journal des Débats Politiques et Littéraires,* March 11.

Bach, A., Bernard, C., Bordes, F., et al., 2002. *Ils Observaient les Étoiles ...* Toulouse, Archives municipales.

¶Baillaud, B., 1893. *Cours d'Astronomie à l'Usage des Édudiants des Facultés des Sciences. Première Partie.* Paris, Gauthier-Villars.

¶Baillaud, B., 1896. *Cours d'Astronomie à l'Usage des Édudiants des Facultés des Sciences. Seconde Partie.* Paris, Gauthier-Villars.

°Baillaud, B., 1899. Introduction. *Annales de l'Observatoire Astronomique, Magnétique et Météorologique de Toulouse,* 3, vii–xvi.

Bardou, A., 1892, 1899. See Table 3.

¶Barnard, F.A.P., 1869. Machinery and processes of the industrial arts and apparatus of the exact sciences. In Blake, W.P. (ed). *Reports of the United States Commissioners to the Paris Universal Exposition, 1867.* Volume III. Washington, Government Printing Office. Pp. 1–669.

Bennett, J., 2009. Anthony Turner, Après Gassendi. *Annals of Science,* 66, 565–566.

¶Bontemps, G., 1868. *Guide du Verrier.* Paris, Librairie du Dictionnaire des Arts et Manufactures.

♦Boutan, A., and d'Almeida, J. Ch., 1861. *Cours Élémentaire de Physique.* Paris, Dunod.

Brachner, A., 1987. C.A. Steinheil, a Munich instrument maker. *Bulletin of the Scientific Instrument Society*, 12, 3–7.

Brasseur, R., 2010. Quelques scientifiques ayant enseigné en classe préparatoire aux grandes écoles. *Bulletin de l'Union des Professeurs de Spéciales*, 229, 12–21. On-line at sites.google.com/site/rolandbrasseur .

♦Breen, J., 1863. The telescope. *Popular Science Review,* 2, 466–474.

Brenni, P., 1989. The illustrated catalogues of scientific instrument-makers. In Blondel, Ch., Parot, F., Turner, A., and Williams, M. (eds.). *Studies in the History of Scientific Instruments.* London, Rogers Turners. Pp. 169–178.

Brenni, P., 1994. 19th century French scientific instrument makers. III: Lerebours et Secretan. *Bulletin of the Scientific Instrument Society,* 40, 3–6.

Brenni, P., 1996a. 19th century French scientific instrument makers. XI: The Brunners and Paul Gautier. *Bulletin of the Scientific Instrument Society,* 49, 3–8.

Brenni, P., 1996b. 19th century French scientific instrument makers. XIII: Soleil, Duboscq, and their successors. *Bulletin of the Scientific Instrument Society,* 51, 7–16.

Brenni, P., 2002. Who made what? The dilemma of signed instruments. In *XVIII International Scientific In-strument Symposium, Moscow-St. Peter[s]burg. Proceedings.* Moscow, Engineer. Pp. 50–64.

British Asssociation for the Advancement of Science. *The Engineer,* September 4, 165–170 (1857). On-line at www.gracesguide.co.uk .

Brown, J., 1844. *Perfectionnements dans l'Étamage des Glaces et Autres Verres au Moyen d'une Couche d'Argent.* French patent No. 16105. On-line at bases-brevets19e.inpi.fr .

Browning, J., 1867. *A Plea for Reflectors, being a Description of the New Astronomical Telescopes with Silvered-Glass Specula; and Instructions for Adjusting and Using Them.* London, Francis. On-line at www.bl.uk .

Brück, H.A., and Brück, M.T., 1988. *The Peripatetic Astronomer. The Life of Charles Piazzi Smyth.* Bristol, Hilger.

°Brück, M.T., 2003. An astronomer calls: extracts from the diaries of Charles Piazzi Smyth, *Journal of Astronomical History and Heritage,* 6 (1), 37–45.

Brück, M.T., 2004. Lord Lindsay's expedition to Mauritius in 1874. In Kurtz, D.W. (ed.). *Transits of Venus: New Views of the Solar System and Galaxy.* Cambridge, CUP (IAU Colloquium No. 196). Pp. 138–145.

*Bureau des Longitudes, 1858. *Annuaire pour l'An 1858.* Paris, Mallet-Bachelier.

*Bureau des Longitudes, 1887. *Annuaire pour l'An 1887.* Paris, Gauthier-Villars.

Caplan, J., 2012. Following the stars: clockwork for telescopes in the nineteenth century. In Morrison-Low, A.D., et al. (eds.). *From Earth-Bound to Satellite: Telescopes, Skills and Networks.* Leiden, Brill. Pp. 155–176 and colour plate XI.

**Catalogue des Brevets d'Invention pris du 1^{er} Janvier au 31 Décembre 1856.* Paris, Bouchard-Huzard (1857).

Chacornac, [J.,] 1860a. Undated letter to the Minister of Public Instruction and eclipse report. Archives Nationales, Pierrefitte-sur-Seine (F^{17}22785).

×Chacornac, [J.,] 1860b. Description des objets lumineux observés par M. Chacornac en dehors du disque solaire pendant l'Eclipse total de cet astre du 18 juillet 1860 avec un télescope en verre argenté de quarante centimètres de diamètre. *Bulletin de l'Observatoire Impériale de Paris*, September 4, 5, 6, 7 and 8.

Chanteloup, L., 2004. *Les Trésors du Prytanée National Militaire de La Flèche.* Le Mans, La Reinette.

Chevalier, A., 1860. See Table 3.

†Chevalier, A., 1860–1861. *Catalogue Explicatif et Illustré des Instruments de Physique Expérimentale, d'Optique Expérimentale, Chimie, Astronomie, Minéralogie, Chirurgie, etc.* Paris, Bonaventure & Ducessois. [Dates differ between cover (1860) and title page (1861).]

Christie's, 2008. *Travel, Science and Natural History, Wednesday 24 September 2008*. London, Christie's.

*Clerc, A., c.1882. *Physique et Chimie Populaires.* Tome 2. Paris, Rouff.

Cohen, I.B., 1993. Newton's description of the reflecting telescope. *Notes and Records of the Royal Society,* 47, 1–9.

Commission du Passage de Vénus, 1877. Procès-verbaux des séances. In Académie des Sciences (ed.). *Recueil de Mémoires, Rapports et Documents Relatifs à l'Observation du Passage de Vénus sur le Soleil*. Tome 1, 1ère Partie. Paris, Firmin-Didot. On-line at iris.univ-lille1.fr .

**Congrès Astrophotographique International Tenu à l'Observatoire de Paris pour le Levé de la Carte du Ciel.* Paris, Gauthier-Villars (1887).

Conseil Général des Hospices Civils de Paris. Procès verbal de la séance du 21 décembre 1842. Archives de l'Assistance Publique-Hôpitaux de Paris (CGH CLXXIII, No. 93049, ff. 611–612).

×Cornu, A., 1876. Études de photographie astronomique. *Bulletin International de l'Observatoire de Paris,* July 18.

♦Cotessat, L., 1890. Objectifs et miroirs astronomiques. *L'Astronomie,* January issue, inside front cover.

¶Cotton, A., 1905. Présentation du téléscope de Foucault légué par M. de Romilly. *Bulletin des Séances de la Société Française de Physique,* Année 1905, 44*–46*.

*Cristal, M., 1875. Curiosités astronomiques. *Musée Universel, Revue Illustrée Hebdomadaire*, 6, 66–67.

Crosse, M.-F., 1868. Inventaire après le décès de M. Foucault. Archives Nationales, Paris (MC/ET/XLIX/1504, item 202).

*Daguin, P.A., 1862. *Traité Élémentaire de Physique Théorique et Expérimentale.* 2ème édition, Tome 4. Toulouse, Privat.

*Daguin, P.A., 1863. *Cours de Physique Élémentaire avec les Applications à la Météorologie.* Toulouse, Privat.

Danjon, A., and Couder, A., 1935. *Lunettes et Télescopes. Théorie, Conditions d'Emploi, Description, Réglage.* Paris, Éditions de la Revue d'Optique Théorique et Instrumentale.

Darius, J., and Thomas, P.K., 1989. French innovation in clockwork telescope drives. In Blondel, Ch., Parot, F., Turner, A., and Williams, M. (eds.). *Studies in the History of Scientific Instruments.* London, Roger Turner, Pp. 144–154.

†de Gramont, A., and Peigné, P., 1902. *Musée Rétrospectif de la Classe 15 Instruments de Précision à l'Exposition Universelle Internationale de 1900 à Paris. Rapport du Comité d'Installation.* Saint-Cloud, Belin.

*De l'astronomie observatrice et du télescope. *Le Magasin Pittoresque,* 26, 310–312 (1858).

Delaunay, Ch., 1876. *Cours Élémentaire d'Astronomie, 6ème Édition Revue et Complétée par M. Albery Lévy*. Paris, Masson. On-line at cd.dgb.uanl.mx .

¶de Parville, H., 1865. *Causeries Scientifiques.* 4ème Année. Paris, Savy.

¶de Parville, H., 1869. *Causeries Scientifiques.* 8ème Année. Paris, Rothschild.

de Romilly, E., n.d.. Letter to L. Foucault, dated Saturday 20 August. Foucault family collection.

de Romilly, H.F.L., 1855. Letter to É. Olliver, dated 3 October. Archives Nationales, Pierrefitte-sur-Seine (542/AP/17, item 208).

*Desbeaux, E., 1891. *Physique Populaire*. Paris, Marpon & Flammarion.

♦D[e] V[ylder], G., 1877. Notre gravure. *Bulletin de l'Assocation Belge de Photographie,* 3, 167–172.

+[Diderot, D., and D'Alembert, J. le R.], 1767. *Recueil de Planches sur les Sciences, les Arts Libéraux et les Arts Méchaniques, Quatrième Livraison*. Paris, Briasson, David & Le Breton. Optique

Plate IV, Figure 45 No. 2.

Dobson, J.L., 1991. *How and Why to Make a User-Friendly Sidewalk Telescope.* Oakland, Everything in the Universe.

¶d'Ocagne, M., 1904. Les instruments de précision en France. *Revue des Questions Scientifiques*, 55, 353−417.

Drayton, T., 1843. *Silvering Glass for Mirrors, &c.* British patent No. 9968.

Drayton, T., 1848a. *Silvering Glass and other Surfaces.* British patent No. 12358.

Drayton, T., 1848b. *Perfectionnements dans l'Étamage à l'Argent des Glaces et Autres Surfaces.* French patent No. 7780. On-line at bases-brevets19e.inpi.fr .

Drion, C., and Fernet, Ém., 1861. *Traité de Physique Élémentaire Suivi de Problèmes.* Paris, Masson.

*Duboscq, [J.,] 1862. Sur un héliostat de grande dimension. *Comptes Rendus Hebdomadaires des Séances de l'Académie des Sciences*, 55, 644−645.

Duboscq, J., 1864, 1867, 1870, 1876, 1885. See Table 3.

Ducretet, E., 1905. See Table 3.

Ducretet, E., and Lejeune, L., 1893. See Table 3.

Dufour, L., 1874. Arts, science & lettres. *Gazette de Lausanne*, March 3. Page 3. On-line at www.letempsarchives.ch .

†Dupin, C., 1870. Distribution de médailles. *Bulletin de la Société d'Encouragement pour l'Industrie Nationale*, 2ème Série, 17, 86−123.

Eichens, W., 1862. Undated invoice. Paris Observatory Archives (Ms 1060-I-A, Comptabilité, Exercice 1861 Crédit extraordinaire, Bordereau No. 28, dated July 25).

Eichens, W., 1866. Letter to Le Verrier dated August 29. Bibliothèque de l'Institut de France, Paris (Ms 3711, Eichens envelope, item 4).

Eichens, W., 1867a. Undated invoice. Paris Observatory Archives (Ms 1060-I-A, Comptabilité, Exercice 1867, Bordereau No. 9, dated August 1867).

Eichens, W., 1867b. Undated invoice. Paris Observatory Archives (Ms 1060-I-A, Comptabilité, Exercice 1867, Bordereau No. 14, undated).

Eichens, W., 1868. Undated invoice. Paris Observatory Archives (Ms 1060-I-A, Comptabilité, Exercice 1867, Bordereau No. 24, dated March 1868).

Eichens, W., 1871a. Undated invoice. Paris Observatory Archives (Ms 1060-I-A, Comptabilité, Exercice 1871, Bordereau No. 2).

Eichens, W., 1871b. Undated invoice. Paris Observatory Archives (Ms 1060-I-A, Comptabilité, Exercice 1870, Bordereau No. 31, dated July 1871).

Eichens, W., 1872. Undated invoice. Paris Observatory Archives (Ms 1060-I-A, Comptabilité, Exercice 1871, Bordereau No. 21, dated 15 January 1872).

Enumération des objets renfermés dans les caisses faisant partie de l'envoi de l'Observatoire impériale de Paris en Espagne, 1860. MS dated July 1. Archives Nationales, Pierrefitte-sur-Seine (F^{17}3726).

Épry, C., 1911a. See Table 1.

♦Épry, C., 1911b. Astronomie-Géodésie-Topographie. *Bulletin de la Société Astronomique de France*, 25, October issue, supplementary page VIII. [University of California copy.]

Etablissements H.Morin-Secretan, 1964. Display advertisements, *L'Astronomie*, 78, inside cover pages.

*Exposition Secretan. *L'Exposition Populaire Illustré*, 316−318 (1867).

*Faits divers. *Le Temps*, May 18, page 2 (1874).

Favé, [I.,] 1855. Letter to Foucault, dated 29 September. Foucault family collection.

Favé, [I.,] 1858. Letter to the Ministre de l'Instruction publique, dated 23 July. Archives Nationales, Pierrefitte-sur-Seine (F^{17}20758).

*Faye, [H.,] 1858a. Seconde série des dessins de M. Bulard sur la comète de Donati. *Comptes Rendus Hebdomadaires des Séances de l'Académie des Sciences,* 47, 619−621.

*Faye, H., 1858b. La comète de Donati. *Revue Contemporaine,* 40, 760−785.

¶Fernet, E., 1875. *Cours de Physique pour la Classe de Mathématiques Spéciales.* Paris, Masson.

*Figuier, L., 1869. Passage de Mercure. *L'Année Scientifique et Industrielle,* 13, 14−17.

*Figuier, L., 1890. Bourbouze. *La Science Illustrée*, 5, 214−215.

*Fizeau, H., 1862. Recherches sur les modifications que subit la vitesse de la lumière dans le verre et plusieurs autres corps solides sous l'influence de la chaleur. *Annales de Chimie et de Physique*, 66, 429−482.

*Fizeau, [H.,] and Foucault, L., 1844. Recherches sur l'intensité de la lumière émise par le charbon dans l'expérience de Davy. *Comptes Rendus Hebdomadaires des Séances de l'Académie des Sciences,* 18, 746–754.

*Flammarion, C., 1867. Les sciences à l'Exposition. I. Instruments astronomiques. *Le Siècle*, May 14, page 3.

*[Flammarion, C.,] 1868. Mercure et sa conjunction récente avec Vénus et Jupiter. *Magasin Pittoresque*, 36, 299−303.

¶Flammarion, C., 1870. *Contemplations Scientifiques*. Paris, Hachette.

Flammarion, C., 1874a. Lausanne. [Auguste Secretan]. *Gazette de Lausanne*, October 20, page 3.On-line at www.letempsarchives.ch .

*Flammarion, C., 1874b. *Études et Lectures sur l'Astronomie,* 5, 246−265.

*Flammarion, C., 1877a. *Études et Lectures sur l'Astronomie,* 8, 246−299.

Flammarion, C., 1877b. *Atlas Céleste Comprenant Toutes les Cartes de l'Ancien Atlas de Ch. Dien, Rectifié, Augmenté et Enrichi.* Paris, Gauthier-Villars. Extracts on-line at www.atlascoelestis.com/20.htm .

*Flammarion, C., 1882. *Les Étoiles et les Curiosités du Ciel.* Paris, Marpon & Flammarion.

°[Flammarion, C.,] 1884. Nouvel observatoire au Mexique. *L'Astronomie*, 3, 310−312.

♦Flammarion, C., 1890. *Astronomie Populaire.* Paris, Marpon & Flammarion, edition printed by same.

°F[lammarion], G.C., 1930. Émile Daguin. *L'Astronomie*, 44, 289−290.

°F[lammarion], G.C., 1939. Gustave Jacquelin (1879–1939). *L'Astronomie*, 53, 417−418.

*Foucault, L., 1845. Académie des Sciences. *Journal des Débats Politiques et Littéraires*, August 27.

*Foucault, L., 1852. Académie des Sciences. *Journal des Débats Politiques et Littéraires,* May 21.

Foucault, L., 1852–1865. Notebook accounting for monies given to him by Louis-Napoléon. Archives Nationales, Paris (MC/ET/XXIX/1521).

*Foucault, L., 1853. Académie des Sciences. *Journal* *des Débats Politiques et Littéraires,* May 19.

Foucault, L., 1857a. Physique. Seven-sheet handwritten report. Paris Observatory Archives (Ms 1060 III-B-11).

*Foucault, L., 1857b. Note sur un télescope en verre argenté. *Comptes Rendus Hebdomadaires des Séances de l'Académie des Sciences,* 44, 339–342.

+Foucault, L., 1857c. Séance du 31 janvier 1857. *Société Philomathique de Paris. Extraits des Procès-verbaux des Séances pendant l'Année 1857,* 15.

¶Foucault, L., 1857d. Séance du 31 janvier 1857. *L'Institut,* 1ère Section, 25, 38.

=Foucault, L., 1857e. Sur un nouveau télescope en verre argenté. *Cosmos,* 10, 186–189.

+Foucault, L., 1858a. Séance du 1 mai 1858. *Société Philomathique de Paris. Extraits des Procès-verbaux des Séances pendant l'Année 1858,* 47–48.

¶Foucault, L., 1858b. Séance du 1 mai 1858. *L'Institut,* 1ère Section, 26, 151.

+Foucault, L., 1858c. On a telescope speculum of silvered glass. In *Report of the 27th Meeting of the British Association for the Advancement of Science, Dublin, August-September 1857. Notices and Abstracts of Miscellaneous Communications to the Sections.* London, Murray. Pp. 6–8.

=Foucault, L., 1858d. Télescopes en verre argenté. Miroirs à surfaces ellipsoïde et paraboloïde de révolution. Évaluation numérique des pouvoirs optiques. *Cosmos,* 13, 162–168.

+Foucault, L., 1858e. Séance du 8 mars 1858. *Société Philomathique de Paris. Extraits des Procès-verbaux des Séances pendant l'Année 1858,* 41.

¶Foucault, L., 1858f. Séance du 8 mars 1858. *L'Institut,* 1ère Section, 26, 161.

+Foucault, L., 1858g. Séance du 15 mai 1858. *Société Philomathique de Paris. Extraits des Procès-verbaux des Séances pendant l'Année 1858,* 49–50.

¶Foucault, L., 1858h. Séance du 15 mai 1858. *L'Institut,* 1ère Section, 26, 186.

+Foucault, L., 1858i. Séance du 3 juillet 1858. *Société Philomathique de Paris. Extraits des Procès-verbaux des Séances pendant l'Année 1858,* 51–52.

¶Foucault, L., 1858j. Séance du 3 juillet 1858. *L'Institut,* 1ère Section, 26, 221.

*Foucault, L., 1858k. Télescopes en verre argenté; miroirs à surfaces ellipsoïde et paraboloïde de révolution; application au ciel. *Comptes Rendus Hebdomadaires des Séances de l'Académie des Sciences,* 47, 205–207.

*Foucault, L., 1858l. Description des procédés employés pour reconnaître la configuration des surfaces optiques. *Comptes Rendus Hebdomadaires des Séances de l'Académie des Sciences,* 47, 958–959.

=Foucault, L., 1858m. Description des procédés employés pour reconnaître la configuration des surfaces optiques. *Cosmos,* 13, 749–752.

*Foucault, L., 1859a. Mémoire sur la construction des télescopes en verre argenté. *Annales de l'Observatoire Impérial de Paris, Mémoires*, 5, 197–237 and plate. English translation at bobmay.astronomy.net .

°Foucault, L., 1859b. Description of an improvement in the making of large reflecting telescopes with silvered glass specula. *Monthly Notices of the Royal Astronomical Society,* 19, 186–189.

°Foucault, L., 1859c. Description of various processes made use of for finding out the configuration of optical surfaces. *Monthly Notices of the Royal Astronomical Society,* 19, 284–287.

*Foucault, L., 1859d. Essai d'un nouveau téléscope parabolique en verre argenté. *Comptes Rendus Hebdomadaires des Séances de l'Académie des Sciences,* 49, 85–87.

*Foucault, [L.,] 1861. Le procédé de M. Willeme. *Bulletin de la Société Française de Photographie*, 7, 150.

*Foucault, L., 1862a. Note sur un nouveau télescope de l'Observatoire Impérial. *Comptes Rendus Hebdomadaires des Séances de l'Académie des Sciences,* 54, 859–861.

Foucault, L., 1862b. Note estimating costs, dated April 30. Paris Observatory Archives (Ms 1060-I-A, Correspondence administrative 1861–1867).

Foucault, L., 1862c. Draft of Duboscq (1862). Archives Nationales, Paris (MC/ET/XXIX/1521).

Foucault, L., 1862d. Draft of letter sent by Duboscq to A. Tremblay, owner of *Cosmos*, reproduced by Moigno (1862b). Archives Nationales, Paris (MC/ET/XXIX/1521).

Foucault, L., 1862e. Draft case prepared for Le Verrier. Bibliothèque de l'Institut de France, Paris (Ms 3711, Eichens envelope, item 7).

Foucault, L., 1863. Copy of letter to A. Martin, dated April 29. Archives Nationales, Paris (MC/ET/XXIX/1521).

Foucault, L., 1864a. Pièce C 'Construction d'un miroir de télescope en verre argenté, de 1^{m},20^{c} de diamètre' accompanying a letter from Le Verrier dated January 20. Archives Nationales, Pierrefitte-sur-Seine (F^{17}3730).

Foucault, L., 1864b. Letter to Le Verrier, dated September 20. Paris Observatory Archives (Ms 1060 III-B-11, Télescope de 0^{m}80).

Foucault, L., 1865. Handwritten *Proposition relative à l'application d'un oculaire tournant au télescope de Marseilles* and associated order dated November 14. Paris Observatory Archives (Ms 1060 III-B-11, Télescope de 0^{m}80).

*Foucault, L., 1869. Sur la construction du plan optique. Note trouvée dans les papiers de Léon Foucault. *Comptes Rendus Hebdomadaires des Séances de l'Académie des Sciences*, 69, 1101–1102.

*Foucault, L., 1878. Microscope catadioptrique avec miroir en verre argenté. In Gariel, C.-M. (ed.). *Receuil des Travaux Scientifiques de Léon Foucault.* Paris, Gauthier-Villars. Pp. 285–286.

*Ganot, A., 1859a. *Cours de Physique Purement Expérimentale à l'Usage des Gens du Monde. [Première Édition.]* Paris, l'Auteur-Éditeur.

Ganot, A., 1859b. *Traité Élémentaire de Physique Expérimentale et Appliquée et de Météorologie. Huitième Édition.* Paris, l'Auteur-Éditeur.

¶Ganot, A., 1860. *Traité Élémentaire de Physique Expérimentale et Appliquée et de Météorologie. Neuvième Édition.* Paris, l'Auteur-Éditeur.

Ganot, A., 1862. *Traité Élémentaire de Physique Expérimentale et Appliquée et de Météorologie. Dixième Édition.* Paris, l'Auteur-Éditeur.

Ganot, A., 1880. *Traité Élémentaire de Physique Expérimentale et Appliquée et de Météorologie. Dix-huitième et Dernière Édition.* Paris, l'Auteur-Éditeur.

Ganot, A., 1881. *Cours de Physique Purement Expérimentale et sans Mathématiques. Huitième Édition.* Paris, l'Auteur-Éditeur.

Ganot-Maneuvrier, 1904. *Petit Cours de Physique Purement Expérimentale et sans Mathématiques. Dixième Édition.* Paris, Hachette.

†Garnault, E., 1878. Les instruments de précision, de physique et de navigation. In Lacroix, E. (ed.). *Études sur l'Exposition de 1878*, Volume 7. Paris, Lacroix. Pp. 433–512.

°Gascoigne, S.C.B., 1996. The Great Melbourne Telescope and other 19th-century reflectors. *Quarterly Journal of the Royal Astronomical Society,* 37, 101–128.

°Gaudibert, C.M., 1886. Comment je me suis construit un télescope. *L'Astronomie,* 5, 375–382.

*Gaudin, 1867. Nécrologie. *Le Siècle,* July 5, page 3.

¶Gordon, [M.M.,] 1869. *The Home Life of Sir David Brewster.* Edinburgh, Edmonston & Douglas.

*Guillemin, A., 1864. *Le Ciel.* Paris, Hachette.

=Guillemin, A., 1874. *Les Applications de la Physique aux Sciences, à l'Industrie et aux Arts.* Paris, Hachette.

=Guillemin, A., 1882. *Le Monde Physique*. Tome 2. Paris, Hachette.

°Gully, L., 1885. Nova Andromedæ. *Ciel et Terre*, 6, 355.

°Gully, L., 1893. Éruptions solaires. *L'Astronomie*, 12, 406–408.

♦Hastings, C.S., 1891. Optical instruments and optical materials. In *Reports of the United States Commissioners to the Universal Exposition of 1889 at Paris.* Volume II. Washington, Government Printing Office. Pp. 213–237.

♦Herschel, J.F.W., 1860. The telescope. In *The Encyclopædia Britannica, 8th edition.* Volume 21. Edinburgh, Black. Pp. 117–145.

Hill, R., 2005. *A Myopic View of the History of Criterion Mfg. Co.* On-line at www.lpl.arizona.edu/~rhill/DYNASCOPE/criterion.html .

¶Hussey. W.J., 1914. A general account of the Observatory. *Publicaciones, Observatorio Astronómico de la Universidad Nacional de La Plata,* 1, 1–64.

Inventaire des Diverses Cotes renfermant les Papiers de la Succession Scientifique de L. Foucault. Manuscript, Foucault family collection, n.d.

*Izarn, 1894. Application nouvelle de la gélatine bichromatée. *Comptes Rendus Hebdomadaire des Séances de l'Académie des Sciences*, 118, 1314–1315.

*Jamin, J., 1866. *Cours de Physique de l'École Polytechnique*. Tome 3. Paris, Gauthier-Villars.

*Jamin, J., 1870. *Petit Traité de Physique.* Paris, Gauthier-Villars.

*Janssen, [J.,] 1868. Rapport sur l'éclipse de soleil du 18 août 1868. *Archives des Missions Scientifiques et Littéraires,* 2ème série, 5, 295–304 and plate.

*Janssen, J., 1873. Rapport sur l'éclipse de 12 Décembre 1871 observée a Schoolor (Indoustan). *Archives des Missions Scientifiques et Littéraires,* 3ème série, 1, 103–124.

*Janssen, J., 1896. Description de l'Observatoire. *Annales de l'Observatoire d'Astronomie Physique de Paris, sis Parc de Meudon,* 1, 67–87 and plates.

*Jeunesse, A., 1865. Les causeries scientifiques. *La Science Pittoresque*, 6, 486–489.

Joron-Derem, C., 2015. *Vente aux Enchères Publiques. Vendredi 27 Novembre 2015 a 13h.* Paris, Hôtel des Ventes Drouot. On-line at www.joronderem.com .

**Journal Général de l'Imprimerie et de la Librairie – Bibliographie de la France,* 2ème série, 2, 428 (1858a).

**Journal Général de l'Imprimerie et de la Librairie – Bibliographie de la France,* 2ème série, 2, 502 (1858b).

**Journal Général de l'Imprimerie et de la Librairie – Feuilleton Commercial,* 2ème série, 2, 477 (1858c).

**Journal Général de l'Imprimerie et de la Librairie – Bibliographie de la France,* 2ème série, 2, 573 (1858d).

**Journal Général de l'Imprimerie et de la Librairie – Feuilleton Commercial,* 2ème série, 2, 581 (1858e).

**Journal Général de l'Imprimerie et de la Librairie – Bibliographie de la France,* 2ème série, 4, 121 (1860a).

**Journal Général de l'Imprimerie et de la Librairie – Bibliographie de la France,* 2ème série, 4, 288 (1860b).

**Journal Général de l'Imprimerie et de la Librairie – Feuilleton Commercial,* 2ème série, 4, 389 (1860c).

=Kanthack, R., 1920. *Survey of the Bibliography on metallic deposition on glass* and *Bibliography.* In Physical Society of London and Optical Society, *A Discussion on the Making of Reflecting Surfaces.* London, Fleetway. Pp. 1–5 and 6–10.

Khantine-Langlois, F., 2006. *Un Siècle de Physique à travers un Manuel à Succès: le Traité de Physique de Ganot.* On-line at www.societechimiquedefrance.fr/fr/resume-et-article.html .

King, H.C., 1955. *The History of the Telescope.* London, Griffin.

Kœnig, R., 1873. *Catalogue des Appareils d'Acoustique Construits par Rudolph Kœnig*. Paris, [Kœnig]. On-line (see Table 1).

Kopp, E., 1859. Sur l'argenture des glaces. *Moniteur Scientifique,* 2, 385. On-line at www.bsb-muenchen.de .

†Kwal, B., and Lesage, M., 1937. La physique au Palais de la Découverte. L'Optique. *La Nature,* 3008, 230–238.

*Lacroix, E., 1865. Photographie astronomique. *La Science Pittoresque,* 10, 384.

°Lagrula, J.-L., 1932. Le Télescope Foucault de l'Observatoire d'Alger. *Journal des Observateurs,* 15, 167–170.

¶Lambert, M., 1879. Report on optical instruments. In Society of Arts (ed.), *Artisan Reports on the Paris Universal Exhibition of 1878.* London, Sampson Low, Marston, Searle & Rivington. Pp. 473–478.

Lamy, J., 2008. The chaotic genesis of a scientific instrument: The 80-cm Telescope at Toulouse Observatory. *Bulletin of the Scientific Instrument Society,* 99, 2–8.

Langlois, [A.-E.,] 1868. Advertisment. *Bulletin de la Société Française de Photographie*, May issue, inner front cover. On-line at e-corpus.org .

*Laurent, L., 1878. *Instruments de Précision.* Paris, Laurent.

*Laussedat, [A.,] 1875. *Sur la télégraphe optique*. In l'Assocation Française pour l'Avancement des Sciences, Compte rendu de la 3ème Session, Lille, 1874. Paris, L'Association. Pp. 1267–1291.

*Laussedat, A., 1901. *Recherches sur les Instruments, les Méthodes et le Dessin Topographiques.* Tome II. Paris, Gauthier-Villars.

Lecouturier, [H.,] 1859. Télescopes en verre argenté par M. Léon Foucault. *Le Musée des Sciences,* 3, 299−300.

Légion d'honneur, 1862. Eichens file, LH/892/49, On-line at www.culture.gouv.fr/public/mistral/leonore_fr .

Légion d'honneur, 1892. Bardou file, LH/114/21, On-line at www.culture.gouv.fr/public/mistral/leonore_fr .

Legros, J., and Boyelle-Morin, H., 1963. Circular letter dated March 12. On-line at www.compassmuseum.com .

Le Guet Tully, F., Sadsaoud, H., and Heller, M., 2003. La création de l'Observatoire d'Alger. *Musée des Arts et Métiers – La Revue,* 38, 26−35.

Lemay, D., 1979. Letter. *Sky & Telescope*, 58, 426.

Lequeux, J., 2009a. *Le Verrier: Savant Magnifique et Détesté.* Les Ulis, EDP Sciences.

Lequeux, J., 2009b. The great nineteenth century refractors. *Experimental Astronomy,* 25, 43−61.

*Le Rebours, [N.,] 1915. Séance du lundi 20 avril 1818. *Procès-verbaux des Séances de l'Académie,* 6, 309.

¶Lerebours, [N.M.P.,] and Secretan, [M.,] 1853. *Catalogue et Prix des Instruments d'Optique, de Physique, de Chimie, de Mathématiques, d'Astronomie et de Marine.* Paris, Lerebours & Secretan.

Les Fils d'Émile Deyrolle, 1907. *Catalogue Méthodique. Physique, Instruments de Précision, Materiel de Laboratoire.* Paris, Les Fils d'Émile Deyrolle. On-line at www.astropa.unipa.it .

Les Fils d'Émile Deyrolle, 1910. *Catalogue Méthodique. Physique, Instruments de Précision, Materiel de Laboratoire.* Paris, Les Fils d'Émile Deyrolle. On-line at www.museocabrerapinto.es/blascabrera .

Les Fils d'Émile Deyrolle, 1928. *Physique Génerale Expérimentale, Instruments de Précision.* Paris, Les Fils d'Émile Deyrolle.

Le Verrier, U.J., 1859. Letter to the Minister of Public Instruction, dated 31 January. Archives Nationales, Pierrefitte-sur-Seine (F^{17}20758).

Le Verrier, U.J., 1860a. Instruction sommaire concernant l'observation de l'éclipse du 18 Juillet 1860. MS dated April 20. Archives Nationales, Pierrefitte-sur-Seine (F^{17}3726).

Le Verrier, U.J., 1860b. Draft of a letter to the Minister of Public Instruction, dated January 18. Paris Observatory Archives (Ms 1060-I-A, Correspondence administrative 1816−1860).

*Le Verrier, U.-J., 1860c. Observations faites aux instruments méridiens en 1856. *Annales de l'Observatoire Impérial de Paris, Observations*, 12, 1−140 and [1]−[347].

Le Verrier, U.J., 1861. Draft and fair copy of letter to the Minister of Public Instruction, dated August 20. Paris Observatory Archives (Ms 1060-I-A, Correspondence administrative 1861–1867).

Le Verrier, U.J., 1862. Draft of letter to the Minister of Public Instruction, dated April 30. Paris Observatory Archives (Ms 1060-I-A, Correspondence administrative 1861–1867).

Le Verrier, U.J., 1867. Draft of letter to the Minister of Public Instruction, dated January 26. Paris Observatory Archives (Ms 1060-I-A, Correspondence administrative 1861–1867).

*Le Verrier, U.J., 1868a. M. Le Verrier exprime son profond étonnement. *Comptes Rendus Hebdomadaires des Séances de l'Académie des Sciences*, 66, 393−396.

Le Verrier, U.J., [1868b]. *Observatoire Impérial. Notes Administratives.* Paris, Bonaventure.

Le Verrier, U.J., and Secretan, M., 1860. Contract dated September 15. Paris Observatory Archives (Ms 1060 III-B-11, Télescope de 0^{m}80).

°Libert, L.-L., 1902. Observatoires populaires & privés. *Annales de Mon Observatoire*, 1 (4), 67–75.

*L'incendie de la nuit dernière. *Le Gaulois*, May 18, page 3 (1874).

L'Industrie Française des Instruments de Précison. Paris, Syndicat des Constructeurs en Instruments d'Optique & de Précision (1901–1902). On-line (see Table 1).

¶Lissajous, J., [1858]. *Instruction Pratique Relative à l'Emploi des Instruments d'Acoustique de M. Lissajous.* Paris, Secretan.

†Lissajous, [J.,] 1868. Instruments d'astronomie, de géodésie, de topographie, de marine, d'optique et d'acoustique. In Chevalier, M. (ed.). *Exposition Universelle de 1867 à Paris. Rapports du Jury International.* Tome 2. Paris, Dupont. Pp. 446−484.

°L'Observatoire de Juvisy. *L'Astronomie*, 6, 321−330 (1887).

¶Lœwy, M., 1891. *Enquêtes et Documents Relatifs à l'Enseignement Supérieur. XLIII. Rapport sur les Observatoires Astronomiques de Province.* Paris, Imprimerie Nationale.

Lutz, E., 1872. See Table 3.

Lutz, E., 1878. Réponses. Archives Nationales, Pierrefitte-sur-Seine (F^{12}3362).

Lutz, E., 1882, c.1890. See Table 3.

Mailhat, R., c.1908. See Table 3.

Mailhat, R., 1909. *Notice sur les Principaux Instruments et Appareils Construits par M. R. Mailhat.* Paris, Schaeffer.

♦Mailhat, R., and Mouronval, c.1913. Advertisement. In Flammarion, C., *Annuaire Astronomique et Météorologique pour 1913*. Paris, Flammarion. End page iv.

°Mailhat, R., and Mouronval Frères, 1913. Advertisement. *Bulletin de l'Observatoire de Lyon*, 1(1), August issue, outer back cover.

*Maison Secretan, 1876. Advertisment in *L'Explorateur*, *Journal Géographique et Commercial*, No. 80, August 17, outer back cover.

Maneuvrier, G., 1887. *Cours de Physique Purement Expérimentale et sans Mathématiques par A. Ganot. Neuvième édition.* Paris, Hachette.

=Maneuvrier, G., 1894. *Traité Éléméntaire de Physique par A. Ganot. Vingt-unième édition*. Paris, Hachette.

Manly, P.L., 1994. *The 20-cm Schmidt-Cassegrain Telescope.* Cambridge, Cambridge University Press.

Marine et Instruments Scientifiques, 2012. Sold 25 February. On-line at www.cannes-encheres.com/lots.php?speciality=60 .

*Marion, F., 1867. *L'Optique.* Paris, Hachette.

Martin, A., 1852. *Photographie Nouvelle. Procédé pour Obtenir des Épreuves Positives Directes sur Glace.* Paris, Chevalier.

*Martin, A., 1853. Méthode pour obtenir des épreuves photographiques positives et directes sur des planches de nature quelconque. *Comptes Rendus Hebdomadaires des Séances de l'Académie des Sciences*, 36, 703−704.

*Martin, [A.,] 1861. Les moyens propres à éviter les accidents ordinaires dans le procédé de collodion humide. *Bulletin de la Société Française de Photographie*, 7, 142–147.

×Martin, A., 1863a. Sur un procédé d'argenture à froid du verre, par l'emploi du sucre interverti. *Bulletin Quotidien de l'Observatoire Impérial de Paris*, June 4.

*Martin, A., 1863b. Sur un procédé d'argenture à froid du verre, par l'emploi du sucre interverti. *Comptes Rendus Hebdomadaires des Séances de l'Académie des Sciences*, 56, 1044–1045.

¶Martin, A., 1863c. Description d'un procédé d'argenture à froid du verre par l'emploi du sucre interverti. *Les Mondes*, 1, 472–473.

Martin, A., 1867. Compte de M. Martin, dated July 26. Archives Nationales, Paris (MC/ET/XXIX/1521).

*Martin, A., 1868a. Dépôt d'un pli cacheté. *Comptes Rendus Hebdomadaires des Séances de l'Académie des Sciences*, 66, 1058–1059.

¶Martin, A., 1868b. Argenture du verre par le surce interverti, pour les instruments et les expériences d'optique. *Les Mondes*, 18, 615–619.

*Martin, A., 1868c. Argenture du verre par le sucre interverti. *Annales de Chimie et de Physique*, 4ème série, 15, 94–100.

*Martin, A., 1869. Observations sur la Note précédente. *Comptes Rendus Hebdomadaires des Séances de l'Académie des Sciences*, 69, 1102–1107.

*Martin, A., 1870a. Sur la méthode suivie par L. Foucault, pour reconnaître si la surface d'un miroir est rigoureusement parabolique. *Comptes Rendus Hebdomadaires des Séances de l'Académie des Sciences*, 70, 389–392.

*Martin, A., 1870b. Méthode d'autocollimation de L. Foucault; son application à l'étude des miroirs paraboliques. *Comptes Rendus Hebdomadaires des Séances de l'Académie des Sciences*, 70, 446–448.

Martin, A., 1870c. Invoice dated December 31. Paris Observatory Archives (Ms 1060-I-A, Comptabilité, Exercice. 1870, Bordereau No. 22, dated 15 March 1871).

=Martin, A., 1875. Argenture du verre par le sucre interverti pour les instruments et les expériences d'optique. *Κοσμοσ-Les Mondes*, 37, 285–288.

¶Mascart, E., 1903. Discours prononcé par M. Mascart. *Bulletin des Séances de la Société Française de Physique, Année 1903*, 70*–72*.

*Mesnard, J., [1868]. *Les Merveilles de l'Exposition Universelle de 1867.* Tome 2. Paris, Lahure.

Mills, A.A., and Hall, R., 1983. The production of a plane surface, as illustrated by specula from some early Newtonian telescopes. *Notes and Records of the Royal Society*, 37, 147–166. On-line via www.jstor.org .

°Miscellaneous Intelligence. *Monthly Notices of the Royal Astronomical Society,* 20, 24 (1859).

=[Moigno, F.,] 1857a. Nouvelles de la semaine. *Cosmos,* 11, 368.

=[Moigno, F.,] 1857b. Académie des sciences. *Cosmos,* 11, 652–653.

=[Moigno, F.,] 1858a. Nouvelles de la semaine. *Cosmos,* 12, 590.

=[Moigno, F.,] 1858b. Académie des sciences. *Cosmos,* 13, 159.

=[Moigno, F.,] 1858c. Nouvelles de la semaine. *Cosmos,* 13, 326.

=[Moigno, F.,] 1858d. Nouvelles de la semaine. *Cosmos,* 13, 411.

=[Moigno, F.,] 1858e. Variétés. *Cosmos,* 13, 464.

=[Moigno, F.,] 1858f. Nouvelles de la semaine. *Cosmos,* 13, 328.

=[Moigno, F.,] 1858g. Académie des sciences. *Cosmos,* 13, 743.

=[Moigno, F.,] 1858h. Nouvelles de la semaine. *Cosmos,* 13, 782.

=[Moigno, F.,] 1859a. Faits de science. *Cosmos,* 14, 32–33.

¶Moigno, F., 1859b. Essai d'un nouveau télescope à miroir en verre argenté. *Cosmos,* 15, 138–140.

=[Moigno, F.,] 1859c. Nouvelles de la semaine. *Cosmos*, 14, 557–558.

¶Moigno, F., 1861. Académie des Sciences. *Cosmos,* 19, 326–329.

¶M[oigno], F., 1862a. Rectification. *Cosmos,* 21, 476–477.

¶Moigno, F., 1862b. Académie des Sciences. Séance du lundi 20 octobre 1862. *Cosmos,* 21, 470–472.

¶[Moigno, F.,] 1864. Nouveaux grands instruments de l'Observatoire impérial. *Les Mondes*, 6, 487–492.

¶Moigno, [F.,] 1865. Nouveau télescope à miroir argenté, par M. Secretan fils. In *Cours de Science Vulgarisée, Résumé Oral du Progrès Scientifique. Conférence d'Octobre 1865.* Paris, Giraud. Pp. 234–236.

¶[Moigno, F.,] 1867. Secrétan. Télescope à miroir en verre argenté, à monture équatoriale. *Les Mondes*, 14, 242–247.

¶Monckhoven, D.V., 1863. *Traité Général de Photographie*. Paris, Masson.

♦Mouronval, [F.,] 1911. Présentation d'un télescope à latitude variable. *Bulletin de la Société Astronomique de France*, 25, 192.

Mouronval, [F.,] c.1913. See Table 3.

Musée des Confluences, 2009. *Dossier de Presse. Collections [Acquisitions 2008].* Lyon, Musée des Confluences.

*Nachet, A., 1929. *Collection Nachet. Instruments Scientifiques et Livres Anciens*. Paris, Petit.

°Nadeau, P.H., 1943. Examen d'un miroir parabolique de 40 cm d'ouverture. *Journal of the Royal Astronomical Society of Canada*, 37, 237–240.

°Nadeau, P.H., 1944. The Quebec Centre of the Royal Astronomical Society of Canada. *Journal of the Royal Astronomical Society of Canada*, 38, 313–319.

Negretti and Zambra, [1859]. *An Illustrated Descriptive Catalogue of Optical, Mathematical, Philosophical, Photographic and Standard Meteorological Instruments.* London, [Negretti & Zambra]. On-line at bl.uk .

#Negretti and Zambra, [1879]. *Encyclopædic Illustrated and Descriptive Reference Catalogue.* London, [Negretti & Zambra].

+Negretti and Zambra, [1887]. *Encyclopædic Illustrated and Descriptive Reference Catalogue.* London, [Negretti & Zambra].

*[Newton, I.,] 1704. *Opticks: or, a Treatise on the Reflexions, Refractions, Inflexions and Colours of Light.* London, Smith & Walford.

Neyt, A., 1869. *Atlas Photographique de la Lune.* [Ghent], [Neyt]. On-line at lib.ugent.be .

Obituary: Emile Nugues (1870–1963). *Arts et Manufactures,* 138, 44 (1964).

♦Obituary: G. Secrétan. *Bulletin de la Société Astronomique de France*, 20, 505–506 (1906).

°Obituary: Le Pasteur Astronome Gaudibert. *Bulletin de la Société Astronomique de France,* 15, 337–338 (1901).

Observation du Passage de Mercure sur le Soleil du 14 novembre 1907. Paris Observatory Heritage Collection, Inv. I.610. On-line at alidade.obsmp.fr .

Ollivier, E., 1961. *Journal, Tome I, 1846–1860.* Zeldin, T. (ed). Paris, Julliard.

Orchiston, W., and Soonthornthum, B., 2017. French observations of the total solar eclipse of 1868 from Thailand. In Nakamura, T., and Orchiston, W. (eds.). *The Emergence of Astrophysics in Asia: Opening a New Window on the Universe*. Cham, Springer.

Orchiston, W., Clark, B.A.J., Frew, D., and Andropoulos, J., 2017. The development of astronomy and the foundations of astrophysics in Australia. In Nakamura, T., and Orchiston, W. (eds.). *The Emergence of Astrophysics in Asia: Opening a New Window on the Universe*. Cham, Springer.

Pellin, Ph., 1889, 1900. See Table 3.

Pérolle, J.-N., n.d. *Le Grand Télescope de Toulouse de 83 centimètres de Diamètre*. On-line at sap toulouse.net/observatoire/instruments/telescope-t83 /SAP_T83.pdf .

*Perot, A., 1909. Protection de l'argenture des miroirs. *Comptes Rendus Hebdomadaires des Séances de l'Académie des Sciences*, 149, 725.

°Pérot, A., 1911. Protection de l'argenture des miroirs. *L'Astronomie*, 25, 127.

°Petit, F., 1863. Annales de l'Observatoire de Toulouse. *Annales de l'Observatoire de Toulouse,* 1, 1–13.

Picart, A., 1874. See Table 3.

¶Présentation de nouveaux sociétaires. *Bulletin de la Société Astronomique de France*, 16, 493–495 (1902).

°Présentations et admissions. *Bulletin de la Société Astronomique de France*, 11, 183–187 (1897).

°Prin, G., 1942. Le nouveau télescope de l'Observatoire d'astrophysique de Saint-Michel, en Haute-Provence. *L'Astronomie*, 56, 7–8.

¶Rayet, G., 1868. Revue des instruments d'astronomie et de physique à l'Exposition Universelle. In Dehérain, P.-P. (ed.). *Annuaire Scientifique. Les Progrès des Sciences en 1867.* Paris, Masson. Pp. 230–246.

°Rayet, G., 1887. Notes sur l'histoire de la photographie astronomique. *Bulletin astronomique,* 4, 165–176, 262–272, 307–320, 344–360 and 449–456.

¶Recent Publications. *Quarterly Journal of the Royal Meteorological Society*, 13, 179–188 (1887).

§*Registre d'État Civil, 5ème Arrondissement, Paris. Décès. 1862.* Archives de Paris (V4E 518).

§*Registre d'État Civil, 10ème Arrondissement, Paris. Décès. 1893.* Archives de Paris (V4E 8913).

§*Registre d'État Civil, 10ème Arrondissement, Paris. Décès. 1895.* Archives de Paris (V4E 8962).

Registre d'État civil, Caen. Décès. 1896. Archives départementales du Calvados, Caen (2 Mi EC). On-line at archives.numerisees.calvados.fr .

°Report of the Council to the fortieth Annual General Meeting of the Society. *Monthly Notices of the Royal Astronomical Society,* 20, 109–149 (1860).

Rouget, L.E., 1869. Inventaire après décès de Marie Jeanne Eugénie Espanet, dated January 8. Archives Nationales, Paris (MC/ET/CVIII/1256).

Rutten, H.G.J., and van Venrooij, M.A.M., 2002. *Telescope Optics.* Richmond, William-Bell.

*Saint-Claire Deville, H., 1868. Observations sur les derniers travaux de M. Léon Foucault. *Comptes Rendus Hebdomadaires des Séances de l'Académie des Sciences*, 66, 338–342.

Sautter, L., 1861. Invoice reissued January 19 of a lost original dated 1 November 1860, and letter dated January 24. Paris Observatory Archives (Ms 1060-I-A, Comptabilité, Exercice 1860, Bordereau No. 20, dated February 9).

Sautter, L., 1862. Invoice dated December 29. Paris Observatory Archives (Ms 1060-I-A, Comptabilité, Exercice 1862 Crédit extraordinaire, Bordereau No. 22, dated 7 March 1863).

Schechner, S.J., and Launie, K.J., 2014. More a workshop than a factory: a look at Alvan Clark & Sons. In *XXXIII Scientific Instruments Symposium. Book of Abstracts.* Tartu, University of Tartu Museum. p. 14. On-line at iuhps.org .

¶Schnaiter, C., 1865. Chronique de la semaine – Astronomie photographique. *Cosmos,* 2ème Série, 2, 649–651.

†Sebert, [H.,] 1896. Rapport fait sur … les titres de M. Adolphe Martin. *Bulletin de la Société d'Encouragement pour l'Industrie Nationale*, 5ème série, 1, 940–943.

Sebert, L.E., 1858. Contrat de mariage entre M. Secretan et Mad^{elle} Moncharmont, dated December 29. Archives Nationales, Paris (MC/ET/XLIV/1074).

Sebert, L.E., 1865. Procuration par M. Secretan à son fils, dated March 1. Archives Nationales, Paris (MC/ET/XLIV/1126).

Sebert, L.E., 1867–1868. Inventaire après le décès de M. Secretan, commenced 29 July 1867. Archives Nationales, Paris (MC/ET/XLIV/1148).

Secretan, 1858. See Table 1.

Secretan, 1859a. Invoice dated 1 February. Paris Observatory Archives (Ms 1060-I-A, Comptabilité, Exercice 1859, Bordereau No. 2, dated 8 February 1859).

Secretan, 1859b. Invoice dated 22 June. Paris Observatory Archives (Ms 1060-I-A, Comptabilité, Exercice 1859, Bordereau No. 20, (mis)dated 12 August 1879).

Secretan, 1860a. Invoice dated 2 February. Paris Observatory Archives (Ms 1060-I-A, Comptabilité, Exercice 1859, Bordereau No. 43, dated 10 April 1860).

Secretan, 1860b. Invoice dated 31 December. Paris Observatory Archives (Ms 1060-I-A, Comptabilité, Exercice 1860 Crédit extraordinaire, unnumbered bordereau).

Secretan, 1861a. Undated invoice. Paris Observatory Archives (Ms 1060-I-A, Comptabilité, Exercice 1861, Bordereau No. 7, dated 25 July 1861).

Secretan, 1861b. Two undated invoices. Paris Observatory Archives (Ms 1060-I-A, Comptabilité, Exercice 1860 Crédit de 85.000, Bordereau No. 31, dated July 30).

Secretan, 1862a. Undated invoice. Paris Observatory Archives (Ms 1060-I-A, Comptabilité, Exercice 1861 Crédit extraordinaire, Bordereau No. 26, dated July 14).

†Secretan, 1862b. *Catalogue et Prix des Instruments*

d'Optique, de Physique, de Chimie, de Mathématiques, d'Astronomie et de Marine qui se Trouvent ou s'Exécutent dans les Magasins et Ateliers de Secretan. Chimie. Galvanoplastie. Minéralogie. Paris, [Secretan].

Secretan, 1863. Undated invoice. Paris Observatory Archives (Ms 1060-I-A, Comptabilité, Exercice 1863 Crédit extraordinaire, Bordereau No. 10, dated July 23).

Secretan, 1864. Undated invoice. Archives Anciennes de l'Observatoire de Marseille, available on-line at www.e-corpus.org under 132 J 203, frame 36.

Secretan, 1865a. Undated invoice. Paris Observatory Archives (Ms 1060-I-A, Comptabilité, Exercice 1865, Bordereau No. 13, dated December).

¶Secretan, A., 1865b. Nouveau télescope à miroir argenté. *Les Mondes*, 9, 272–273.

Secretan, 1865c. Undated invoice. Paris Observatory Archives (Ms 1060-I-A, Comptabilité, Exercice 1865, Bordereau No. 13, dated December).

Secretan, 1866a. Undated invoice. Paris Observatory Archives (Ms 1060-I-A, Comptabilité, Exercice 1866, Bordereau No. 7, dated August 13).

Secretan, 1866b. Undated invoice. Paris Observatory Archives (Ms 1060-I-A, Comptabilité, Exercice 1866, Bordereau No. 10, dated October 11).

Secretan, 1868. See Table 1.

¶Secretan, [A.], 1871. Ravages causés par le bombardement. *Les Mondes*, 24, 374.

Secretan, 1874, 1878a, 1878b, 1885. See Table 1.

Secrétan, G., 1888. Advertisement, *Supplément à la Revue d'Astronomie*, January issue. On-line at oncle-dom.fr .

*Secrétan, G., 1890. Advertisement. In Towne, G., *Traité d'Astronomie Pratique*. Paris, Bertaux. Endpapers.

¶Secrétan, G., 1893. Advertisement. *L'Astronomie*, December issue, endpapers, p. iv. (University of Michigan copy).

Secretan, P., 1895. Letter to a Henry brother ordering a 5-*pouce* lens, dated May 3. Paris Observatory Archives (Ms 1133-2, Frères Henry. Échanges avec des fabricants d'optique).

Secretan, P., 1896. Letter to the Henry brothers accompanying a payment, dated July 23. Paris Observatory Archives (Ms 1133-2, Frères Henry. Échanges avec des fabricants d'optique).

Secretan, c.1898, 1901–02, 1906a. See Table 1.

♦Secretan, G., 1906b. Les réflecteurs et leur rôle dans l'astronomie. *Bulletin de la Société Astronomique de France*, 20, 414–428.

Secretan, 1911, 1915, 1924, 1942. See Table 1.

+Silvered mirror telescopes – Their merits and disadvantages. *The Intellectual Observer*, 11, 176–180 (1867).

Simon, J., 2009. Circumventing the 'elusive quarries' of popular science: The communication and appropriation of Ganot's *Physics* in nineteenth-century Britain. In Papanelopoulou, F., Nieto-Galam, A., and Perdiguero, E. (eds). *Popularising Science and Technology in the European Periphery, 1800–2000.* Aldershot, Ashgate. Pp. 89–114.

Simon, J., 2011. *Communicating Physics: The Production and Appropriation of Ganot's Textbooks in France and England, 1851–1887.* London, Pickering & Chatto.

Simpson, A.D.C., 1995. 'La plus brillante collection qui existe au monde': A lost American collection of the nineteenth century. *Journal of the History of Collections*, 7, 187–196.

Sinnott, R.W., and Dobson, J., 1980. Have telescopes, will travel. *Sky & Telescope,* 59, 338.

♦Société Française de Physique. Séance du 3 mai 1903. *L'Électricien, Revue Internationale de l'Électricité,* 25, 399 (1903).

Steinheil, C.A., 1856. Eröffnung der optischen und astronomischen Werkstätte. *Allgemeine Zeitung, Beilage zu Nr. 84,* March 24, 1337–1338.

°Steinheil, [C.A.,] 1858. Aus einem Schreiben des Herrn Ministerialsraths Steinhel an den Herausgeber. *Astronomische Nachrichten,* 48, 145–150. Translated as: °Steinheil, [C.A.,] 1858. On the advantages to be derived from the use of silver mirrors for reflecting telescopes, and of a novel method of mounting such instruments. *Monthly Notices of the Royal Astronomical Society,* 19, 56–60.

°Steinheil, C.A., 1860. Preis-Courant der optischen und astronomischen Werkstätte. *Astronomische Nachrichten,* 52, 205–208.

Steinheil, C.A., 1867. Preis-Courant der Optischen und Astronomischen Werkstätte. München, Straub.

#Steinheil Söhne, C.A., 1907. Price-List of Astronomical and Physical Instruments. Munich, Steinheil Söhne.

*Stephan, E., 1868. Rapport sur l'observation de l'éclipse de soleil du 18 août 1868. *Archives des Missions Scientifiques et Littéraires,* 2ème série, 5, 535–610 and plate.

*Stephan, [E.,] 1884. Note sur les nébuleuses découvertes a l'Observatoire de Marseille. *Bulletin Astronomique*, 1, 286–290.

*Stephan, E., 1911. Rapport sur l'observation de l'éclipse totale de soleil du 30 août 1905. *Annales du Bureau des Longitudes*, 8, L1–L17 and plates.

♦Stone, E.J., 1873. *The Cape Catalogue of 1159 Stars.* Cape Town, Solomon.

Tableau de l'Inflation en France avec Inflateur Cumulé depuis 1901, 2015. On-line at www.france-inflation.com .

Tandeau de Marsac, G. J., 1861. Procuration par M. Secretan, dated June 13. Archives Nationales, Paris (MC/ET/XCVII/976).

Tandeau de Marsac, G. J., 1864. Procuration par M. Secretan, dated May 11. Archives Nationales, Paris (MC/ET/XCVII/994).

†Teisserenc de Bort, L., 1891. Class 15, Instruments de précision: Rapport du jury international. In Picard, A. (ed.). *Exposition Universelle de 1889 à Paris. Rapports du Jury International. Groupe II, 2ème partie.* Paris, Imprimerie Nationale. Pp. 609–699.

¶Terquem, [A.,] 1866. Session générale tenue à Metz les 19, 20 et 21 avril 1866. *Bulletin Mensuel de l'Association Scientifique de France,* 1(14), 209–231.

+The Great Foucault Telescope. *Intellectual Observer,* 1, 380–381 (1862).

Thiac, J.B.E., 1858. Decharge par Mr Lerebours à Mr Secretan, dated January 16. Archives Nationales, Paris (MC/ET/XCVII/959).

Thiot, A., 1995. Rétrospective astronomique. *L'Astronomie,* 109, 161–167.

Thoday, A.G., n.d. Silver-on-glass telescope mirror and platinised glass by L. Foucault, and other items in file T/1943/55, Documentation Centre, Science

Museum, London.

×Tisserand, F., 1876. Observations faites à l'Observatoire de Toulouse avec le grand télescope Foucault. *Bulletin International de l'Observatoire de Paris,* April 28.

Tobin, W., 1987. Foucault's invention of the silvered-glass reflecting telescope and the history of his 80-cm reflector at the Observatoire de Marseille. *Vistas in Astronomy,* 30, 153–184.

Tobin, W., 1993. Toothed wheels and rotating mirrors: Parisian astronomy and mid-nineteenth century experimental measurements of the speed of light. *Vistas in Astronomy,* 36, 253–294.

Tobin, W., 1998. Léon Foucault. *Scientific American*, 279, July issue (pagination varies with edition).

Tobin, W., 2003. *The Life and Science of Léon Foucault. The Man who Proved the Earth Rotates.* Cambridge, Cambridge University Press.

°Tobin, W., and Holberg, J.B., 2008. A newly-discovered accurate early drawing of M51, the Whirlpool Nebula. *Journal of Astronomical History and Heritage*, 11, 107–115.

Tobin, W., Lequeux, J., and Lalande, T., 2007. Les pendules de Foucault. *Musée des Arts et Métiers – La Revue,* 48, 63–69.

♦Touchet, E., 1903. Société Astronomique de France. Séance du 6 Juin 1903. *Bulletin de la Société Astronomique de France,* 17, 312–320.

*Towne, G., 1890. *Traité d'Astronomie Pratique pour Tous.* Paris, Bertaux.

¶Towne, G., 1896. *Astronomie, Astrophysique, Géodésie, Topographie et Photogrammétrie Pratique.* Tome 1. Paris, Bertaux.

Trap, G., and Tobin, W., 2014. Télescope de Foucault: Stupeur dans le collimateur. *Découverte, Revue du Palais de la Découverte,* 393, 42–49.

♦Trépied, C., 1884. Notice sur l'Observatoire d'Alger. *Bulletin Astronomique,* 1, 214–216.

Troubetzkoy, [A.,] 1916. Istrumenti astronomici. II. Tempi moderni. *La Scienza per Tutti*, 23 (16), 255–260. On-line at introni.it .

Troubetzkoy, [A.,] 1917. Istrumenti astronomici. V. Osservatorî. *La Scienza per Tutti*, 24 (4), 50–54 and front cover. On-line at introni.it .

°Troubetzkoy, [A.,] 1919. Modèle de monture équatoriale à latitude variable. *L'Astronomie*, 33, 82–84.

Turner, A.J., 1993. Interpreting the history of scientific instruments. In Anderson, R.G.W., Bennett, J.A., and Ryan, W.F. (eds.). *Making Instruments Count.* Aldershot, Variorum. Pp. 17–26.

Turner, A., 2006. *Après Gassendi: son Influence et sa Réputation, Essai: avec l'Histoire des Collections Scientifiques et un Catalogue des Instruments et Appareils Concernant les Sciences Exactes Appartenant au Musée Gassendi à Digne-les-Bains.* Digne-les-Bains, Musée Gassendi.

=Turner, H.H., 1912. *The Great Star Map.* London, Murray.

°Variétés. Observatoire de Haute Provence. *Annales d'Astrophysique*, 7, 187 (1944).

*Ventes de fonds de commerce. *Archives Commerciales de la France*, 36, 1109–1117 (1909).

*Ventes de fonds de commerce. *Archives Commerciales de la France*, 38, 68–74 (1911).

°Venus le jour de sa conjunction. *L'Astronomie*, 6, 386–387 (1887).

¶Webb, T.W., 1863. Silvered glass specula. *Intellectual Observer,* 3, 126–130.

Weld, C.R., 1868a. Report on philosophical instruments and apparatus for teaching science (Class 12). In (By Command) *Reports on the Paris Universal Exhibition, 1867.* Volume 2. London, HMSO. On-line at www.bodleian.ox.ac.uk .

+Weld, C.R., 1868b. The philosophical instruments in the Paris Exhibition. *The Intellectual Observer*, 12, 425–434.

Wells, D.A., 1858. *Annual of Scientific Discovery: or, Year-Book of Facts in Science and Art for 1858*. Boston, Gould & Lincoln. On-line at www.bodleian.ox.ac.uk .

Wilson, R.N., 1996. *Reflecting Telescope Optics. I. Basic Design Theory and its Historical Development.* Berlin, Springer.

Wolf, C., and Martin, Ad., 1874. Projet d'appareil photographique pour l'observation du passage de Vénus. In Académie des Sciences (ed.). *Recueil de Mémoires, Rapports et Documents Rélatifs à l'Observation du Passage de Vénus sur le Soleil.* Paris: Firmin Didot. [This compendium was republished in 1876 as Tome I, 2ème partie of an identically-titled 3-volume work. On-line at iris.univ-lille1.fr .]

×Wolf, C., and Rayet, G., 1865. *Bulletin International de l'Observatoire Impérial de Paris,* November 25, 4.

*Wolf, C., and Rayet, G., 1867. Spectroscopie stellaire. *Comptes Rendus Hebdomadaires de l'Académie des Sciences,* 65, 292–296.

Wolf, E., 2014. *Wolf Telescopes. A Collection of Historical Telescopes.* At www.wolftelescopes.com .

°Woolley, R.v.d.R., and Symms, L.S.T., 1937. Two visual binary orbits. *Monthly Notices of the Royal Astronomical Society,* 97, 438–453.

*Zurcher, F., 1862. Les télescopes. *L'Ami des Sciences,* 8, 417–420.

17 APPENDICES

17.1 Appendix 1 – English Translation of Instructions Accompanying the Smithsonian Institution 4-*Pouce* Telescope

The instructions are lithographed from handwriting and occupy the front and back of a single sheet (Figure 11). Recto, they are marked with an oval stamp "LEREBOURS ET SECRETAN – 13, PONT-NEUF, PARIS" and at lower left the lithographer's name ("Lith. V. Janson 18r Dauphine").

[recto]

Instructions for Telescopes with silvered-glass mirrors

---

1. Setting up the Telescope

The instrument having been placed on the table which will act as its support, one begins by pushing to the back the small movable board or rake which runs in the notches placed in the foot; one will remove the tube of the instrument from the foot in which it is stored; for that insert the right hand in the round opening placed at one end of the tube, one will lift this latter by pushing it at the same time on the closed end with the other hand, one will free it easily. That done one will undo the hooks which retain the board pierced with a hole & that was referred to above; this board removed, one will slide out from the inside of the tube the box which is there & which contains the telescope accessories; one will take from this box the thin rod with a knob, the nut and thread, and the eyepiece furnished with its adjustment screw. The nut will be placed in the hole that is located in the rake of the foot such that the knurled knob is underneath. This screw acts to give the slow movement in height to the telescope. Next one will install the small triangular feet which by means of bolts and nuts attach at either side of the base and give it greater stability; after that, one will run the rake along the notches to the point at which the first folding board is approximately horizontal, then taking the telescope, one will place it on this plane in such a way that the fasteners fixed to the tube align with those fixed on the board; one inserts the thin rod with a knob that we have already spoken of in the said fasteners and the telescope will be attached to its base. The tube must be placed in such a way that its opening is on the same side as the claws of the rake which runs on the notches. One will then screw in the eyepiece and one will put back the board pierced with a circular hole that was removed at the beginning.

2. Use of the Telescope

The instrument being thus set up, to make use of it, one will withdraw the little hatch located above and towards the closed end of the telescope. This hatch removed exposes a slit and a metal hook which one will seize in order to remove a little black slide that acts as a shutter for the mirror. Bring the eyepiece towards oneself, one will focus on the objects that by chance are in the field of view. The focus will be made more accurately with the knurled knob attached to the eyepiece support.

The two parts of the finder located on the side of the tube will be unfolded from their bases & by looking through the spyhole one will see if the object that appears in the telescope is centred in the circle which forms the other half of the finder. If it is not, one centres it with the screws which adjust the spyhole. For

[verso]
the preceding operation, it will be wise first to remove one of the lenses to have at the same time both more field & more light.

In this state the instrument can serve to observe either terrestrial objects or celestial bodies. Movements in the horizontal direction are effected by moving the base on the table and movements in height by raising the tube by its open end to the appropriate height, which makes the rake run along the notches after which it stays fixed. The final adjustment is made by turning the screw fixed to the rake with the right hand. When a celestial body is nearly at the zenith the weight of the telescope can tip it over backwards if, in this very rare circumstance, one has not been careful to use a hand to keep the rake engaged in the notches, while with the other one turns the screw which adjusts the height.

3. Precautions to take to preserve the Telescope

1. When removing and replacing the accessory box be careful not to knock the small prism which is in the tube nor the strut which holds it. When you see by moving the eyepiece that there is dust on the surfaces of this prism clean it with a piece of suede inserting your hand carefully into the tube; besides, the prism needs to be very dirty before the effect of the telescope is noticeably diminished.

2. If the lenses of the eyepiece are covered with dust, or they have been dulled by whatever cause, wipe them in the same way.

3. So to speak never touch your mirror & each time you have made use of the instrument be careful to replace the little shutter.

When looking down the telescope tube you perceive that through lack of care the mirror is covered with dust, you will remove the hatch, the shutter, undo the hooks which attach the base containing the mirror & you will remove this dust using a very fine shaving brush with very little pressure. If there are marks on the mirror, it is best to leave them because one can only make them disappear by removing the silvering itself. In addition, they need to be very numerous and very extensive to harm the optics of the instrument.

4. It is not enough that the mirror be sheltered from dust, it must also be kept in a dry place, above all salty vapours are to be feared. When you look at your mirror, fear touching it with your fingers & spluttering the least drop of saliva, it will produce indelible stains.

17.2 Appendix 2 – English Translation of Extracts from Secretan's 1874 Catalogue

[Page 76]

Reflecting Telescopes with Silvered-Glass Mirrors

379 Newtonian telescope, with 10-cm diameter glass mirror, parabolized and silvered by the methods of Léon Foucault, mounting in cast iron, additional 6-lath stand for observing stand-

ing up; four eyepieces magnifying from 60 to 200 times, dark glass for the Sun; a finder (Fig. 73 [*this paper's Figure 51*])

500 francs

380 The same, with a mirror of 160-mm aperture; five eyepieces, maximum magnification 350 times; same accessories as previously.

1200 francs

[Page 77]
381 The same, with a mirror of 200-mm aperture; six eyepieces; maximum magnification 400 times; same accessories as previously.

2000 francs

[Page 94]

Equatorial Reflecting Telescopes

METAL MOUNTINGS

427 Telescope with silvered-glass mirror of 16-cm aperture, 1-metre focal length, equatorial mounting entirely in metal, hour-angle circle of 37-cm diameter, declination circle of 20-cm diameter, divided on brass; lighting apparatus; maximum useful magnification 320 times; a finder.

1800 francs

428 The same, with clockwork drive and isochronous governor.

2500 francs

[Page 95]
429 The same with mirror of 20-cm aperture, 1m20 focal length, 47-cm hour-angle circle, 33-cm declination circle; maximum useful magnification 400 times.

4500 francs

430 The same with mirror of 30-cm aperture, 1m80 focal length, 75-cm hour-angle circle, 45-cm declination circle; maximum useful magnification 600 times.

9000 francs

431 The same with mirror of 40-cm aperture, 2m40 focal length, 1-m hour-angle circle, 60-cm declination circle; maximum useful magnification 800 times; two finders.

18000 francs

432 The same with mirror of 50-cm aperture, 3-m focal length, 1m50 hour-angle circle, 80-cm declination circle; maximum useful magnification 1000 times.

35000 francs

WOODEN MOUNTINGS
(FIG. 86 [*this paper's Figure 50*])

We still give prices in our catalogue for telescopes with equatorial mountings in wood, although this option is far inferior to that of numbers 427 to 432.

[Page 96]
Their lower price means they may still be chosen by institutions whose budgets are too limited to envisage metal mountings. The dimensions of the circles, the magnifications, the focal lengths and all accessories are the same as in the previous numbers.

433 Telescope with silvered-glass mirror, 16-cm aperture, wooden equatorial mounting, brass hour-angle and declination circles.

1650 francs

434 The same with clockwork drive and isochronous governor.

2350 francs

434bis The same, mirror of 20-cm aperture.

4000 francs

435 The same, mirror of 30-cm aperture.

6000 francs

[Page 97]
436 The same, mirror of 40-cm aperture.

9000 francs

437 The same, mirror of 50-cm aperture.

13000 francs

438 The same, mirror of 80cm aperture, 5-m focal length, 2-m diameter hour-angle circle, reading directly to 20s in time, 1m12 declination circle reading to 15" via verniers; 8 astronomical eyepieces; maximum useful magnification 1600 times (Fig. 87 [*this paper's Figure 34*]).

29000 francs

In 1864 we built a similar instrument for the Marseilles Observatory; in 1874 we supplied one to the Toulouse Observatory.

[Page 109]

Silvered Mirrors

481 Concave glass mirrors, silvered and parabolized by Foucault's procedures. The price for every ten centimetre square contained within the square circumscribing the circumference of the mirror is

150 francs

482 Glass mirrors that are rigorously flat, silvered by the same procedures, able to serve as an artificial sky for collimation. Same price as concave mirrors number 481.

We re-silver telescope mirrors at the following prices.

Mirror of	$0^{m}.10$	4 francs 50 centimes
	$0^{m}.16$	7 francs 50 centimes
	$0^{m}.20$	20 francs
	$0^{m}.30$	40 francs
	$0^{m}.40$	50 francs
	$0^{m}.50$	70 francs

For mirrors of greater diameter, prices will be set by mutual agreement.

Dr William Tobin was for many years on the academic staff of the Department of Physics & Astronomy at the University of Canterbury, Christchurch, New Zealand, where he introduced CCD detectors at Mount John University Observatory, which he used (*inter alia*) to make observations of eclipsing binary stars in the Magellanic Clouds. He has now retired to Brittany. His work on Foucault has won several prizes: the Arthur Beer Memorial Prize 1991–1993, the *Prix spécial du jury* of the *Prix du livre de l'astronomie–Haute Maurienne-Vanoise 2003*, and the Informa Healthcare Award 2006. In 2012 William was the opening lecturer in the Transit of Venus Lecture Series at the National Museum of New Zealand-Te Papa Tongarewa in Wellington. Following this, he prepared a profusely-illustrated paper on "Transits of Venus and Mercury as Muses" about ways in which these transits have inspired artistic creation of all kinds, and subsequently this paper was *published in this journal (Volume 16, Number 3, pages 224–249, 2013).*

Journal of Astronomical History and Heritage, 19, 185–194 (2016).

THE EARLY HISTORY OF LOW FREQUENCY RADIO ASTRONOMY IN AUSTRALIA. 6: MICHAEL BESSELL AND THE UNIVERSITY OF TASMANIA'S RICHMOND FIELD STATION NEAR HOBART

Martin George, Wayne Orchiston
National Astronomical Research Institute of Thailand, 191 Huay Kaew Road,
Suthep District, Muang, Chiang Mai 50200, Thailand,
and University of Southern Queensland,
Toowoomba, Queensland, Australia.
Emails: martingeorge3@hotmail.com; wayne.orchiston@narit.or.th

Bruce Slee
CSIRO Astronomy and Space Sciences, Sydney, Australia.
Email: Bruce.Slee@csiro.au

and

Richard Wielebinski
Max-Planck-Institut für Radioastronomie, Bonn, Germany, and University
of Southern Queensland, Toowoomba, Queensland, Australia.
Email: rwielebinski@mpifr-bonn.mpg.de

Abstract: Following some initial research in Tasmania between 1955 and 1957, notably by Graeme Ellis and Grote Reber, low frequency radio astronomy became a significant activity of the University of Tasmania from the early 1960s, with the main aims being to study the radio Milky Way and Jupiter's decametric emissions. Although locations very close to Hobart Airport were to see the majority of this work, in the early to mid-1960s low frequency antenna arrays were set up and used by the University at nearby Penna and Richmond. This paper describes the erection and use of the Richmond arrays, which in 1962–1963 operated at a site 1 km north of the town of Richmond, and at frequencies of 2.35, 1.55 and 1.03 MHz.

Keywords: Radio astronomy, Tasmania, Richmond, Michael Bessell, Graeme Ellis

1 INTRODUCTION

Initial research in low frequency (<30 MHz for the purpose of this series of papers) radio astronomy in Tasmania in the mid-1950s generated considerable interest in this field, largely buoyed by the successful observations made by Grote Reber (1911–2002) and Graeme Reade Anthony (Bill) Ellis (1921–2011) at Cambridge in 1955 (see Reber and Ellis 1956), and subsequent observations, such as those by Ellis and Gordon Newstead (1917–1987) that were also conducted near Hobart (Ellis and Newstead, 1957).

The 1955 research had come about largely as a result of Reber's decision to concentrate on low frequency observations, although in Australia work at relatively low frequencies had begun some years earlier at Hornsby Valley, near Sydney, under the auspices of the CSIRO's Division of Radiophysics (see Orchiston et al. 2015b).

Ellis was absent from Tasmania from late 1957 until October 1960 (Elizabeth Ellis, pers. comm., 2008) during which time he took posts in Queensland and New South Wales. He then returned to Hobart in order to accept the Chair of Physics at the University of Tasmania, and his interest in low frequency radio astronomy quickly led to a blossoming of activity in this field of research.

Ellis was instrumental in selecting sites for the various arrays, and locations to the east and north-east of Hobart became the centres for the construction of several of them. The area near Hobart Airport (Llanherne) contained large expanses of suitable flat land, and this location will be discussed in a future paper in this series. Meanwhile, other sites were identified that were suitable for array construction.[1] One of these was 1 km north of the historic town of Richmond (see Figure 1), where Michael Bessel carried out research for his B.Sc. Honours degree in Physics. This paper discusses Bessell's work at the University of Tasmania's short-lived Richmond field station.[2]

2 A BIOGRAPHICAL NOTE

Michael S. Bessell (Figure 2; b. 1942) entered the University of Tasmania in 1959 with an interest in science, particularly physics, and teaching, for which he had received a teacher studentship. He graduated with a major in Physics in 1961, and with Graeme Ellis as supervisor undertook his Honours degree studies in 1962, preferring radio astronomy rather than theoretical research. Bessell's Honours thesis details his use of three low frequency radio astronomy arrays that were erected at Richmond (Bessell, 1963).

After completing this radio astronomy project, Bessell never returned to radio astronomy, concentrating instead on optical astronomy. He satisfied the requirement to begin a teaching career in 1963, but was awarded a scholarship to undertake a Ph.D. in astronomy, which he commenced in 1964 at the Australian National University in Canberra, studying variable stars under Professor Bart Bok (1906–1983).

Bessell's career in astronomy then saw him involved in many pursuits, including significant advances in photoelectric photometry, a topic in which he became a world authority (e.g. see Bessell, 2005).

Mike Bessell was appointed to a professorship at the Australian National University in 1988.

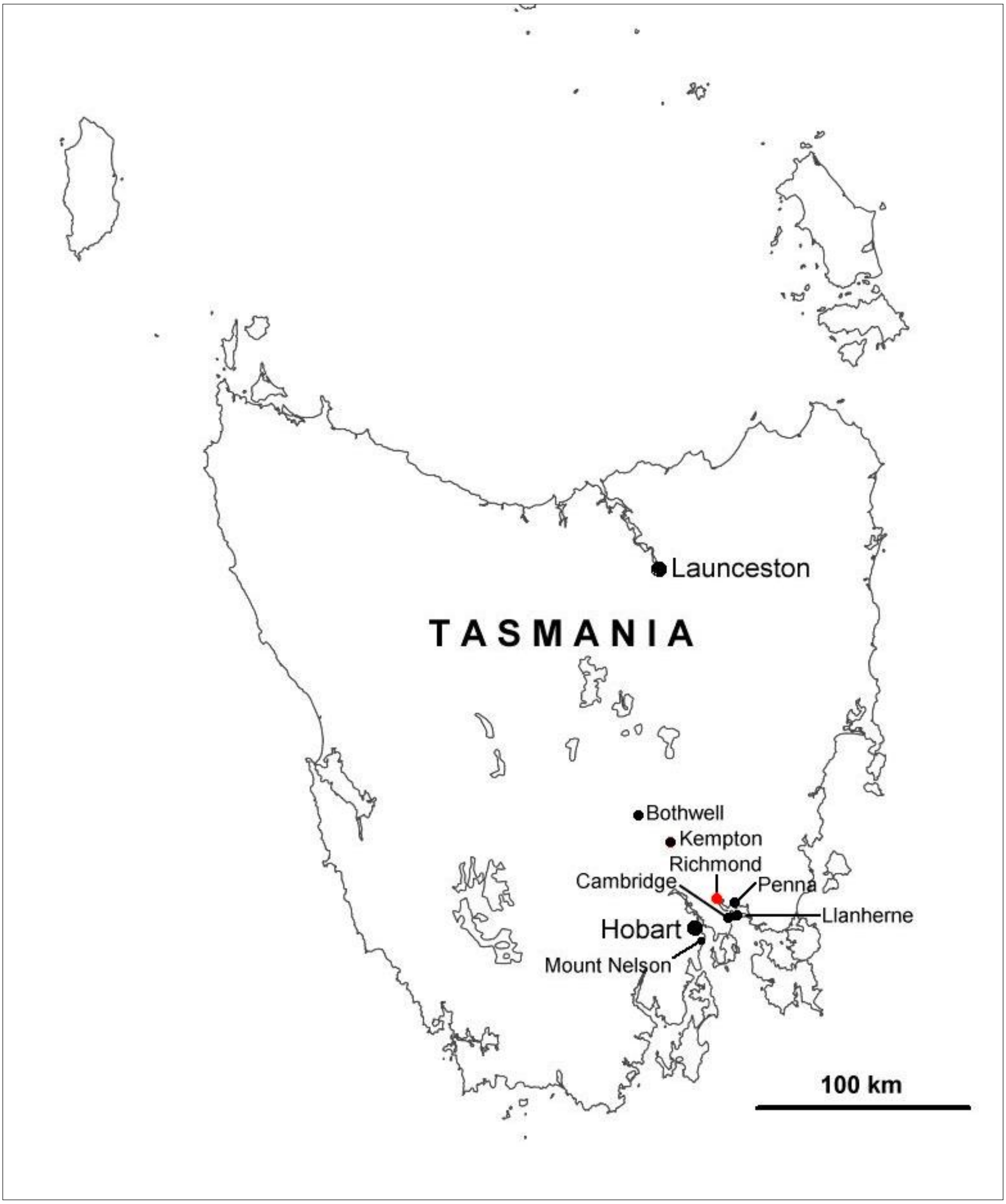


Figure 1: Key radio astronomy sites in Tasmania. This paper discusses the University of Tasmania arrays at Richmond, to the north-east of Hobart.

3 INSTRUMENTATION

The setup at Richmond was erected, beginning in early 1962, on a plot of land within a property known as 'Daisy Bank' (Figure 3), after permission was given by the owner, John Jones, who was a family friend of Bill Ellis and his wife Helen. Using an aerial photograph of the site taken in 1965 (Figure 4) which, when enlarged, shows the shadows of some poles that were then still standing (Figure 5), we have identified the centre of this plot as being at longitude 147° 25′ 48″, latitude −42° 43′ 26″ (WGS84). For decades this piece of land has been known colloquially as the 'pole paddock' (Ben Jones, pers. comm., 2016).[3]

The section of the property that was used was approximately rectangular, with dimensions of about 900 m × 280 m, and with its long axis oriented towards azimuths 280° and 100°.

The arrays were erected parallel to the long axis of this rectangular area, and therefore were not oriented exactly east-west.

Bessell (1963) describes the layout of the arrays:

> Each array consisted of three centre fed full wave dipoles supported about 23 ft above the ground. The dipoles were separated by about half a wavelength and fed in phase so as to give vertical reception. The 4.8 Mc/s dipoles were aligned in an E-W direction at Llanherne (long 147.2° E, lat 42.9° S) and the 2.35, 1.5 and 1 Mc/s arrays were in a S.E. - S.W. direction at Richmond about 5 miles away.

Figure 2: Michael Bessell in the early 1960s (courtesy M. Bessell).

Clearly, Bessell had intended to write "S.E. - NW. direction", but even this is not strictly correct, because the arrays were almost certainly oriented toward azimuths of 280° and 100°, as mentioned above.

With all three arrays, lattice networks were used to transform the impedance of the antennas so that they matched the 70 Ω coaxial transmission cables. (ibid.)

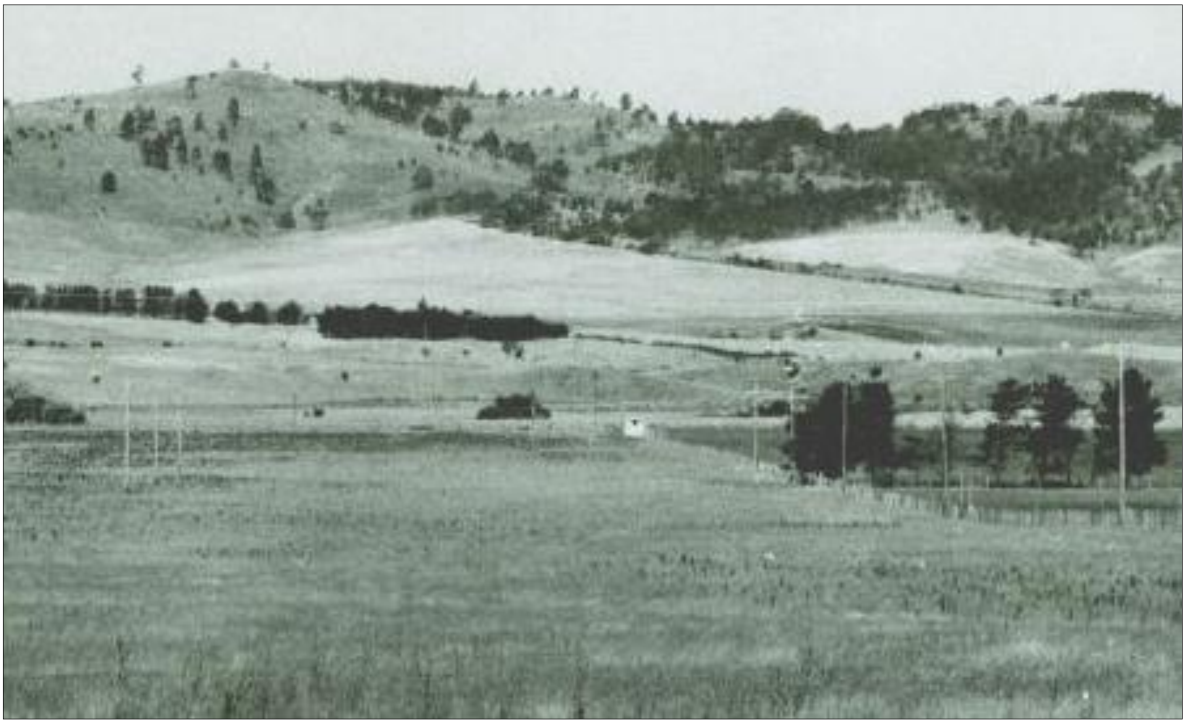


Figure 3: A panoramic view looking east south east showing parts of the Richmond arrays (the three poles on the left and the five poles along the fence-line on the right), and the hut (just right of centre) containing the receiving equipment (after Bessell, 1963).

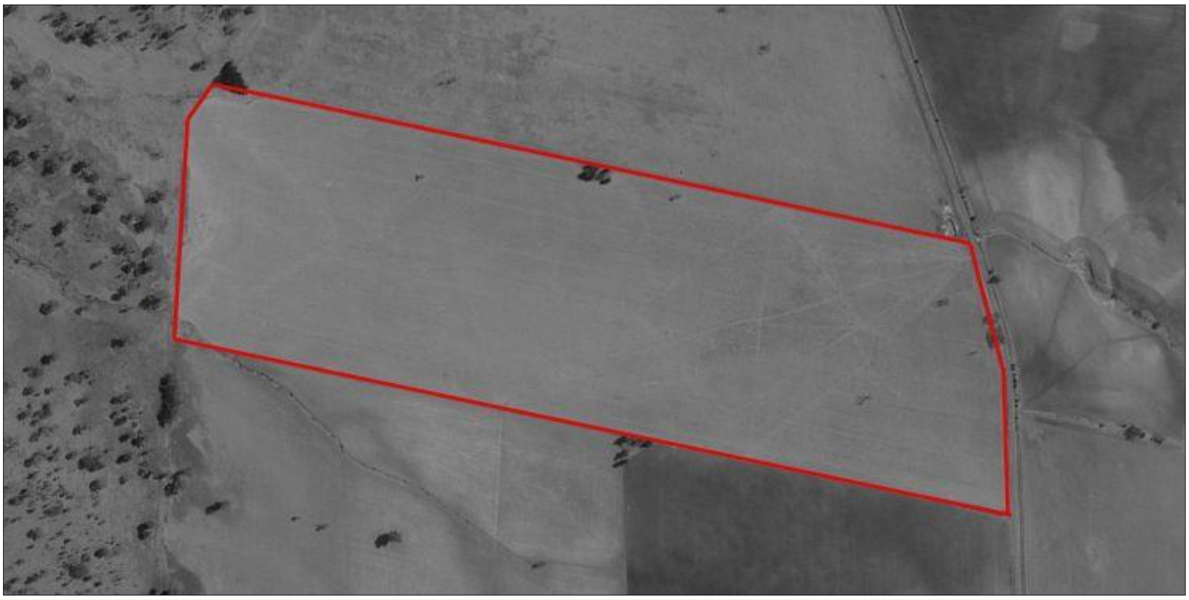


Figure 4: A 1965 aerial view of the site of the arrays at Richmond, delineated in red. North is uppermost. (Adapted from an image provided by TASMAP (www.tasmap.tas.gov.au), © State of Tasmania).

The 4.8 Mc/s dipoles to which Bessell refers were located adjacent to Hobart Airport, but were included as a mention in his Honours thesis because the results at the lower frequencies at Richmond were to be compared with the somewhat higher frequency results from Llanherne.

The poles that were used at Richmond were telegraph poles.[4] Bessell (pers. comm., 2011) recalls that as part of his work toward his Honours degree, he was required to visit the Hydro-Electric Commission at Glenorchy,[5] or the Postmaster General's Department, to purchase the cross sections for the tops of the poles.

Bessell (pers. comm., 2011) remembers:

> We made the antennas out of aluminium clothesline. We had a plastic extruder so we put plastic chips in and they got heated up and you put different moulds on them and could make whatever kind of shape needed ... [The aluminium] was in long rolls. It was essentially aluminium, multitwisted. It looks like steel, but it's just the stuff that goes on aluminium clotheslines. It's quite strong. It's easy to bend but you can't bend it more than once. If you have to bend it again, it breaks. They worked out a way that you could easily attach it so it wouldn't come unstuck. It all went together rather easily.

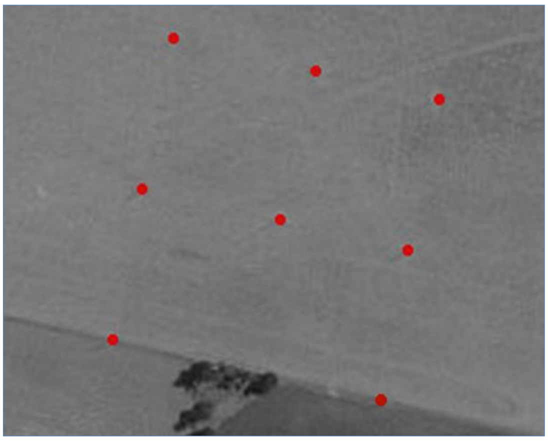


Figure 5: A close up of part of the aerial view in Figure 4, showing the bases of some poles (red dots) that were still standing in 1965, as indicated by their shadows (adapted from an image provided by TASMAP (www.tasmap.tas.gov.au), © State of Tasmania).

The arrays at Richmond originally were designed for use at 2.4, 1.6 and 0.9 MHz (Bessell, 1963). This corresponds to wavelengths of 125, 188 and 333 metres, respectively. Clearly, the losses through insufficient antenna height were considerable and we shall return to this point in the Section 5, below.

Bessell (1963) does not comment on the resolution of the arrays. Although a different resolution for each would be expected, Ellis and Hamilton (1964) state that the resolution was 32° × 40° at both 2.35 MHz and 1.66 MHz. (See Section 5 for comments on evidence that 1.66 MHz observations were carried out in 1963.)

A small timber shed (see Figure 3) was erected to house the receiving equipment. While Mike Bessel (pers. comm., 2011) recalls that it was purchased rather than built by the Physics Department, Kevin Parker (pers. comm., 2009) remembers it being constructed in the Carpenters' Shop at the University. Evidently the shed had been removed by the time the 1965 aerial photograph was taken, but it appears in two of Bessell's images. Curiously, the photographs show that it appears to have been placed near the south-eastern corner of the plot of land. This may have been to allow road access, or possibly because its position related to one or more of the arrays. Whether it was moved at any stage is not recorded.

Bessell (pers. comm., 2011) describes the contents of the shed (cf. Figures 6 and 7):

> [There were] a couple of benches. This was all done by Gordon [Gowland] and Kevin [Parker].[6] There was RAAF [Royal Australian Air Force] surplus equipment which they had large numbers of. They put these mechanical sweeps on, which gave us better data in order to get rid of these spikes.

The use of 'mechanical sweeps', to which Bessell refers, was a way of countering a major problem faced in low frequency radio astronomy: interference from local, national and international AM radio stations. The method was to sweep through a range of frequencies to find one at which the interference was minimised. As Bessell recalls (ibid.),

> When there weren't Chinese broadcasts coming in, we could pick up the Galaxy going through.

The sweeps were effected by slowly driving the rotor of a variable capacitor (Figure 7), resulting in slight changes in the resonant frequency of the receiver.[7]

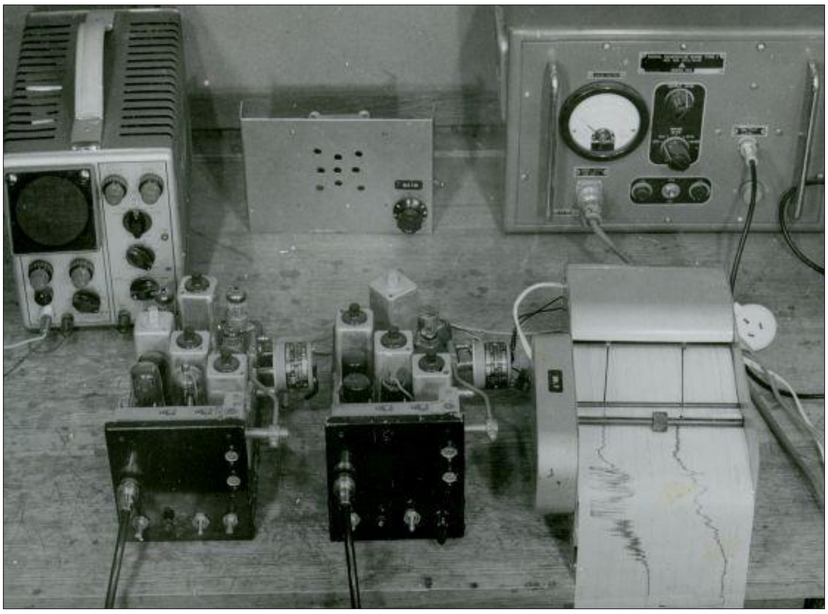


Figure 6: Equipment used in the shed at Richmond. The chart recorder can be seen at right (after Bessell, 1963).

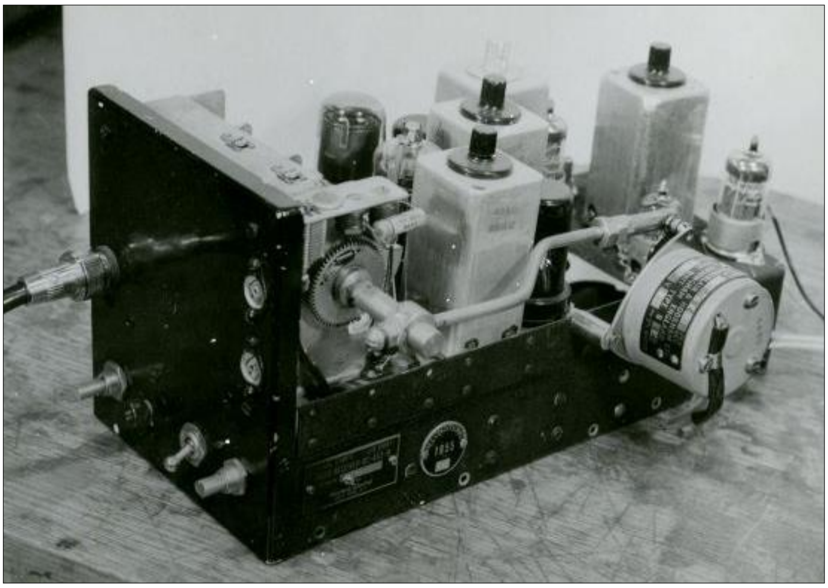


Figure 7: A receiver with a mechanical sweep, used at Richmond. The motor that was used to drive the motions of the rotor for the variable capacitor can be seen at right (after Bessell, 1963).

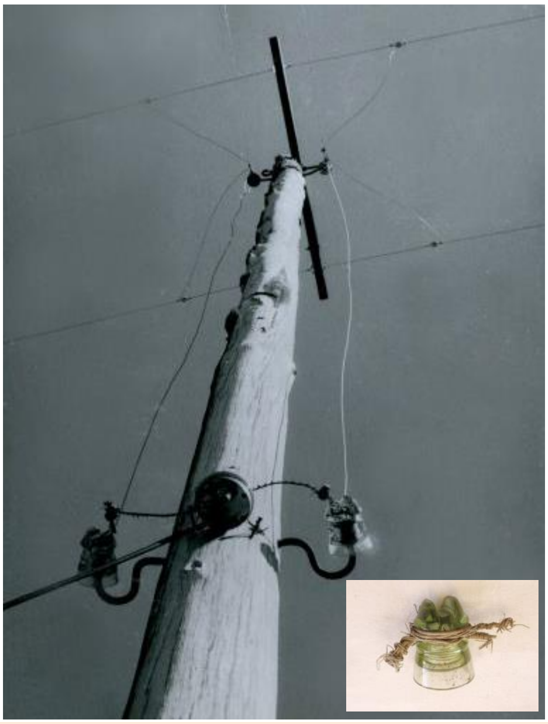


Figure 8: One of the telegraph poles at Richmond, with a close up of an insulator shown in the inset photograph (after Bessell, 1963).

Bessell (ibid.) also commented that because of the low frequencies at which he was working there were atmospheric spikes—which were to be expected. These were countered by having a minimum reader circuit on the input, which revealed any steady or slowly varying background.

This use of a 'minimum reader' method, often in combination with a suitable time constant to avoid the problem of atmospherics, was commonly used by low frequency researchers and was superior to simply identifying an apparently-empty channel and remaining at that exact wavelength.

4 THE OBSERVATIONS

Observations at Richmond were conducted over the winter and spring of both 1962 and 1963, at the three frequencies 2.35 MHz (July-October 1962 and June-October 1963); 1.55 MHz (July to October 1962, and June to October 1963); and 1.03 MHz (late July to late August 1962). There also is evidence (Ellis and Hamilton, 1964) that some results at ~1.66 MHz were obtained during 1963; Bessell (1963) referred to some observations at this frequency in that year even though no details are presented.

Figure 9: Some artefacts retrieved from the ground at the Richmond site in 2016 (Photograph: M. George).

Observations were carried out without phasing of the dipoles, resulting in the peak sensitivity being in the vertical direction toward declination –42° for all measurements. The receiver swept a bandwidth of 10 kHz each second, using the mechanical apparatus described in Section 3.

As would be expected, the 2.35 MHz observavations were the most successful. Bessell (ibid.) commented that 78 records were obtained in 1962 and 20 in 1963, but in 1963 only five nights produced observations that were "… useable for absolute measurement." At 1.55 MHz, 61 records were obtained in 1962 and 75 in 1963, but only 12 in 1963 were 'acceptable'. At 1.03 MHz, 31 records were obtained in 1962, but Bessell (ibid.) described these as "… very poor."

The 1.55 MHz observations were the only results presented graphically in Bessell's thesis (see Figure 10), where just three nights of observations are included: 22 July, 6 August and 31 August.

It is unclear whether these graphically-reproduced records were made in 1962 or in 1963, but it is highly likely that these were all 1962 observations, as Bessell (Ibid.) commented:

> The 1963 observations were affected by unexpected sunspots (~79 in July equal to solar max). These interfered with all observations but mainly at 1.5 Mc/s. Of 75 records obtained only 12 were taken as being good enough, however the profiles matched with the 1962 ones.

This comment is interesting, as it conflicts with records of sunspot numbers (see, e.g., Meeus, 1983; NASA Website, 2016) which, although they show a slight resurgence in solar activity during parts of 1963, indicate the sunspot numbers to have been only about 25% that of a typical solar maximum. However, the data show only the mean for the month, and it is possible that the figure may have been unusually high for part of July.

Bessell (ibid.) also made comments about the state of the ionosphere, mentioning that

> During July 1962 there appeared to be about six clear hours. During August 1962 there were two records unaffected for 4 hours and there were 7 others with one or more clear hours just before dawn. During September 1962 the ionosphere had effectively closed up.

These varying ionospheric conditions may explain the cut-off levels at different right ascen-

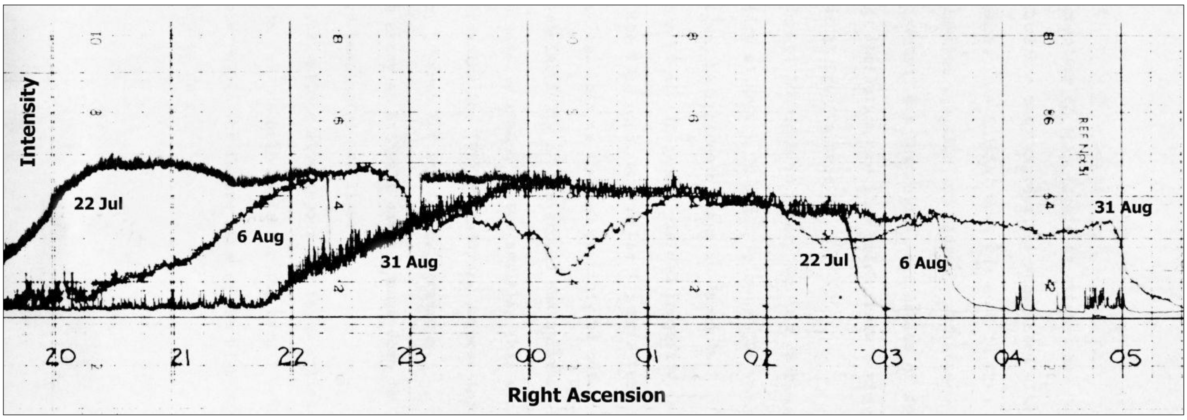


Figure 10: 1.55 MHz observations made by Bessell (adapted from a diagram in Bessell, 1963).

sions which are a pronounced feature of Figure 10.

The observations, including those at 9.8 and 4.8 MHz made at Llanherne in 1961 (see Waterworth, 1961), were combined in a paper in which the dependence of intensity on frequency below 10 MHz was plotted and discussed (Ellis et al., 1962). These results were compared with those obtained in 1955 by Reber and Ellis (1956) at Cambridge, and showed good agreement with these earlier observations.

Comparison between the 1961–1962 observations and those of the late 1950s, however, suggested that the former revealed a steeper drop in intensity than expected near the lower end of the frequency range, below 2 MHz. The authors attributed this to the earlier observations being made under "… rather unusual ionospheric conditions." (Ellis et al., 1962: 1079). They also noted that the highest maximum intensity occurred around 19h right ascension and the lowest maximum around 4h right ascension, with the maximum around 19h being around 7 MHz and around 4h being around 5 MHz. These differences were attributed to absorption of the radiation in interstellar ionised gas (Ellis et al., 1962), which was discussed at considerable length by Cambridge University's Fred Hoyle (1915–2001) and Ellis in an important paper published the following year.[8]

The Hoyle and Ellis (1963) paper derived equations relating to the radiation from the galactic disc and halo, respectively, and showed that at high galactic latitudes the frequency of maximum intensity was expected to be a factor of 1.45 higher for disc radiation when compared with halo radiation, closely matching the factor of 1.4 that was observed.[9]

5 DISCUSSION

Although Bessell's research followed by several years the initial observations made by Reber and Ellis at Cambridge at similar frequencies, the Richmond effort nevertheless represented quite serious early work at frequencies in the 1–2 MHz range.

Despite this, the importance of the Richmond site is not widely recognised. Perhaps this is because Mike Bessell was the only researcher who used this site, and the arrays only were utilised during 1962 and 1963. The 'field station' clearly had fallen into disarray by 1965 with many poles having been removed or fallen, while the nearby array at Penna, operating firstly at 4.7 MHz and later 10 MHz, continued to operate until 1967.

Although Bessell (ibid.) comments that the losses due to the ground were not significant, a major problem with low frequency dipole arrays is that with decreasing frequencies it becomes increasingly difficult to avoid significant losses caused by inadequate height above the ground plane. At Richmond, the dipoles were supported only 7 metres (23 feet) above the ground, whereas the ideal height of one-quarter of a wavelength would see them placed at heights of 32, 48 and 73 metres, in decreasing order of frequency.[10] Because the received power factor is the square of this quantity, the loss was considerable. Bessell calculated these losses, including losses in the feeder lines, to be 15.7 dB at 2.35 MHz and 14.8 dB at 1.50 MHz.

Could the Richmond array, rather than being allowed to fall into disuse, have been utilised to produce further results, thus providing improved definition of the intensity-frequency curve? We consider that the reasons for this not happening are likely to have been a combination of the increased efforts at the much larger array at Penna, and the difficulties of observing at such low frequencies, even at time close to solar minimum. Bessell (1963) also commented:

> The narrow beam array at Bothwell can be tuned down to 1.5 Mc/s and this will produce more meaningful profiles. The satellite observations also appear now to be reliable and these should provide good data for the halo region in the band 1-10 Mc/s.

The Bothwell array, however, produced results only at 2.085 MHz (Reber, 1968).

6. CONCLUDING REMARKS

The results at Richmond produced important points at the low frequency end of the intensity-frequency curve and served to clarify the dependence of the former on the latter, showing that the intensity dropped off more rapidly than had been suggested by the 1955 observations (see Reber and Ellis, 1956).

Although the Richmond arrays were operating for a relatively short time, they played an important role in the progress of low frequency radio astronomy in Tasmania, which blossomed in the 1960s under the leadership of Graeme Ellis.

This was not the only time that observations would be carried out in Tasmania at frequencies <2 MHz; successful 1.6 MHz work was undertaken at Llanherne in 1985 and 1986 (Ellis and Mendillo, 1987). However, the results from Richmond certainly contributed to the study of the intensity-frequency relationship, improving on existing knowledge of the relationship at these very low frequencies and even assisting in the interpretation of Reber and Ellis' 1955 results.

Meanwhile, it is interesting that when he enrolled for a Ph.D. Mike Bessell chose to pursue research in optical astronomy rather than radio astronomy, even though it is likely that he could have enrolled in and completed an ANU radio astronomy Ph.D. in association with the CSIRO's Division of Radiophysics, utilising the 64-m (210-ft) Parkes Radio Telescope.

7 END NOTES

1. Ellis also considered the use of an area of land near Bothwell, to the north of Hobart. However, this site ended up being used by Reber instead. The Bothwell field station will be discussed in a future paper in this series.
2. This is the sixth paper in a series, all published in this journal, which documents the early development of low frequency radio astronomy in Australia. The first two papers presented overviews of CSIRO initiatives near Sydney and Tasmanian research (Orchiston et al., 2015a; George et al., 2015a respectively), and were followed by three detailed case studies. These examined the Cambridge field station near Hobart (George et al., 2015b), the Hornsby Valley field station near Sydney (Orchiston et al., 2015b) and the Kempton field station in Tasmania (George et al., 2015c).
3. Historical studies of this type can often be frustrating because research papers only mention approximate locations of the observing sites. Thus, 'Hobart' has been used in reference to at least three distinct sites of antenna arrays (Llanherne, Penna and Richmond), the first two of which will be described in future papers in this series. The precise location of the observations at 2.35, 1.55, and 1.03 MHz discussed in this paper was discovered through personal communications with Elizabeth Ellis, Mike Bessell and Ben Jones, and finally was confirmed by the aerial photographs taken in 1965.
4. 'Telegraph Pole' is a term used to describe a wooden pole used to carry overhead cables. The term dates from the use of the telegraph system in Australia. It is still in occasional use to describe poles that carry cables supplying electricity, even though the telegraph system no longer exists.
5. The Hydro-Electric Commission was the name given in 1929 by the State Government to the former Hydro-Electric Department. It was a Government Commission charged with the operation of hydro-electric power stations and the construction of their associated dams. It is now called Hydro Tasmania.
6. Gordon Gowland and Kevin Parker both began working at the University of Tasmania in 1961, and were responsible for some of the construction and many of the technical installations for the University's low frequency radio astronomy arrays.
7. A 'variable capacitor', of the type used with these arrays, consists of two sets of parallel closely-spaced plates, each normally forming a semicircle, which mesh together. One is rotatable, thereby changing the overlapping area of the two sets, and thereby changing the capacitance of the device. It is sometimes called a 'tuning capacitor', because of its use to change the resonant frequency of a circuit.
8. This paper resulted from a visit that Hoyle made to Tasmania, where he met Ellis and they discussed the University of Tasmania's low frequency radio astronomy program (see Delbourgo and McCulloch, 2013).
9. Hoyle and Ellis' estimate of the mass of our galaxy, 5×10^8 solar masses, is about three orders of magnitude less than the currently-accepted value (excluding dark matter). However, this does not sensibly affect the explanation of the relative frequencies of maximum radiation.
10. The received energy is maximised when

    $\sin(2\pi h/\lambda) = 1$

    where h is the height of the dipole and λ is the wavelength.

8 ACKNOWLEDGEMENTS

We wish to thank Michael Bessell, Elizabeth Ellis, Susan Blackburn, Gordon Gowland, Philip Hamilton, Ben and Hana Jones, Peter McCulloch, Kevin Parker, the late Michael Waterworth for their assistance, and Peter Robertson for bringing information in Note 8 to our attention. We also thank the Department of Primary Industries, Parks, Water & Environment (Tasmania) for kindly supplying the 1965 aerial photograph that was used to generate Figures 4 and 5.

9 REFERENCES

Bessel, M., 1963. *Low Frequency Galactic Radio Emission.* B.Sc. Honours Thesis, University of Tasmania, Hobart.

Bessell, M., 2005. Standard photometric systems. *Annual Review of Astronomy and Astrophysics*, 43, 293–336.

Ellis, G.R.A., and Newstead, G., 1957. Discrete sources of cosmic radio noise at 18.3 and 10.5 Mc/s. *Journal of Atmospheric and Terrestrial Physics*, 10, 185–189.

Ellis, G.R.A., Waterworth, M. and Bessell, M., 1962. Spectrum of the galactic radiation between 10 Mc/s and 1.5 Mc/s. *Nature*, 196, 1079.

Ellis, G.R.A., and Hamilton, P., 1964. Absorption of radio waves in the galaxy. *Nature*, 204, 272–273.

Ellis, G.R.A., and Mendillo, M., 1987. A 1.6 MHz survey of the galactic background radiation. *Australian Journal of Physics*, 40, 705–708.

George, M., Orchiston, W., Slee, B., and Wielebinski, R., 2015a. The history of early low frequency radio astronomy in Australia. 2: Tasmania. *Journal of Astronomical History and Heritage*, 18, 14–22.

George, M., Orchiston, W., Slee, B., and Wielebinski, R., 2015b. The history of early low frequency radio astronomy in Australia. 3: Ellis, Reber and the Cambridge field station near Hobart. *Journal of Astronomical History and Heritage*, 18, 177–189.

George, M., Orchiston, W., Wielebinski, R., and Slee, B., 2015c. The history of early low frequency radio astronomy in Australia. 5: Reber and the Kempton field station in Tasmania. *Journal of Astronomical History and Heritage*, 18, 312–324.

Hoyle, F., and Ellis, G.R.A., 1963. On the existence of an ionized layer about the galactic plane. *Australian Journal of Physics*, 16, 1–7.

McCulloch, P., and Delbourgo, R., 2013. Graeme Reade Anthony ('Bill') Ellis 1921–2011. *Historical Records of Australian Science,* 24, 96–108. [Obituary. A pioneer in the area of low-frequency radio observations.]

Meeus, J., 1983. *Astronomical Tables of the Sun, Moon and Planets*. ISBN 0-943396-02-6. Richmond, Willman-Bell.

NASA Website, 2016.
http://solarscience.msfc.nasa.gov/greenwch/SN_m_tot_V2.0.txt. Retreived May 2016.

Orchiston, W., George, M., Slee, B., and Wielebinski, R., 2015a. The history of early low frequency radio astronomy in Australia. 1: The CSIRO Division of Radiophysics. *Journal of Astronomical History and Heritage*, 18, 3–13.

Orchiston, W., Slee, B., George, M., and Wielebinski, R., 2015b. The history of early low frequency radio astronomy in Australia. 4: Kerr, Shain, Higgins and the Hornsby Valley field station near Sydney. *Journal of Astronomical History and Heritage*, 18, 285–311.

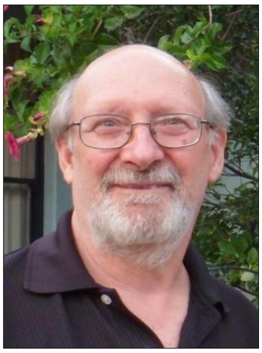
Reber, G., and Ellis, G.R.A., 1956. Cosmic radio-frequency radiation near one megacycle. *Journal of Geophysical Research*, 61, 1–10.

Reber, G., 1968. Cosmic static at 144 meters wavelength. *Journal of the Franklin Institute*, 285, 1–12.

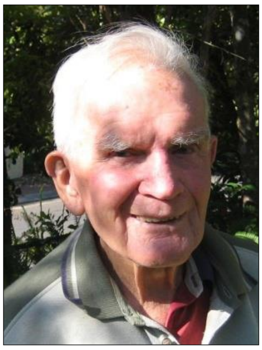
Waterworth, M., 1961. *Cosmic Radio Emission at 4.85 Mc/s and 9.7 Mc/s.* B.Sc. Honours Thesis, University of Tasmania, Hobart.

Martin George is the Collections and Research Manager at the Queen Victoria Museum and Art Gallery in Launceston, Tasmania, and also is responsible for the Museum's planetarium and astronomy collections. He is a former President of the International Planetarium Society. Martin has a special research interest in the history of radio astronomy, and is completing a part-time Ph.D. on the development of low frequency radio astronomy in Tasmania through the University of Southern Queensland, supervised by Professors Wayne Orchiston and Richard Wielebinski (and originally also by Professor Bruce Slee). Martin is the Administrator of the Grote Reber Medal for Radio Astronomy, and is a member of the IAU Working Group on Historic Radio Astronomy.

Professor Wayne Orchiston was born in New Zealand in 1943 and works as a Senior Researcher at the National Astronomical Research Institute of Thailand and is an Adjunct Professor of Astronomy at the University of Southern Queensland in Toowoomba, Australia. In the 1960s Wayne worked as a Technical Assistant in the CSIRO's Division of Radiophysics in Sydney, and forty years later joined its successor, the Australia Telescope National Facility, as its Archivist and Historian. He has a special interest in the history of radio astronomy, and in 2003 was founding Chairman of the IAU Working Group on Historic Radio Astronomy. He has supervised six Ph.D. or Masters theses on historic radio astronomy, and has published papers on early radio astronomy in Australia, England, France, Japan, New Zealand and the USA. He also has published extensively on the history of meteoritics, historic transits of Venus and solar eclipses, historic telescopes and observatories, and the history of cometary and asteroidal astronomy. Early in 2016 Springer published his latest book, *Exploring the History of*



New Zealand Astronomy: Trials, Tribulations, Telescopes and Transits (733 pp.). He is the Vice-President of IAU Commission C3 (History of Astronomy), and is a co-founder and the current Editor of the *Journal of Astronomical History and Heritage*. In 2013 the IAU named minor planet 48471 Orchiston after him.



Dr Bruce Slee* was born in Adelaide, Australia, in 1924 and is one of the pioneers of Australian radio astronomy. Since he independently detected solar radio emission during WWII he has carried out wide-ranging research, first as a member of the CSIRO's Division of Radiophysics, and then through its successor, the Australia Telescope National Facility. After working with John Bolton and Gordon Stanley on the first discrete sources at Dover Heights, Bruce moved to the Fleurs field station and researched discrete sources with Bernie Mills using the Mills Cross, and radio emission from flare stars with the Shain Cross and the 64-m Parkes Radio Telescope. He also used the Shain Cross and a number of antennas at remote sites to investigate Jovian decametric emission. With the commissioning of the Parkes Radio Telescope he began a wide-ranging program that focussed on discrete sources and radio emission from various types of active stars. He also used the Culgoora Circular Array (Culgoora Radioheliograph) for non-solar research, with emphasis on pulsars, source surveys and clusters of galaxies, and continued some of these projects using the Australia Telescope Compact Array. Over the past two decades, he also has written many papers on the history of Australian radio astronomy, and has supervised a number of Ph.D. students who were researching the history of radio astronomy.

Professor Richard Wielebinski was born in Poland in 1936, and moved with his parents to Hobart, Tasmania, while still a teenager. Richard completed B.E. (Hons.) and M.Eng.Sc. degrees at the University of Tasmania. In his student days he met Grote Reber and was involved in the construction of a low frequency array at Kempton. After working for the Postmaster General's Department in Hobart he joined Ryle's radio astronomy group at the Cavendish Laboratory, Cambridge, and completed a Ph.D. in 1963 on polarised galactic radio emission. From 1963 to 1969 Richard worked with Professor W.N. (Chris) Christiansen in the Department of Electrical Engineering at the University of Sydney, studying galactic emission with the Fleurs Synthesis Telescope and the 64-m Parkes Radio Telescope. He also was involved in early Australian pulsar research using the Molonglo Cross. In 1970 Richard was appointed Director of the Max-Planck-Institute für Radioastronomie in Bonn, where he was responsible for the instrumentation of the 100-m radio telescope at Effelsberg. In addition, he built up a research group that became involved in mapping the sky in the radio continuum, studying the magnetic fields of galaxies, and pulsar research. Further developments were the French-German-Spanish institute for mm-wave astronomy (IRAM), and co-operation with the Steward Observatory, University of Arizona, on the Heinrich-Hertz Telescope Project. Richard holds Honorary Professorships in Bonn, Beijing and at the University of Southern Queensland. He is a member of several academies, and has been awarded honorary doctorates by three universities. After retiring in 2004 he became involved in history of radio astronomy research, and is currently the Chairman of the IAU Working Group on Historic Radio Astronomy.

* It is with great sadness that we report that our close friend and collaborator, Bruce Slee, died on 18 August 2016, just eight days after his 92nd birthday and one day after the very successful SleeFest Workshop was held in Sydney to commemorate his amazing 70-year contribution to radio astronomy. At that meeting I reported that the IAU recently named minor planet 9391 Slee in his honour.

Wayne Orchiston

Journal of Astronomical History and Heritage, 19(2), 195–202 (2016).

ARE SPACE STUDIES A SCIENTIFIC DISCIPLINE IN ITS OWN RIGHT?

Jérôme Lamy
Laboratoire PRINTEMPS, UMR CNRS 8085, Université de Versailles
Saint-Quentin-en-Yvelines, 47 Boulevard Vauban, 78047 Guyancourt, France.
Email: jerome.lamy@laposte.net

and

Emmanuel Davoust
IRAP, UMR CNRS 5277, Université de Toulouse, 14 Avenue
Edouard Belin, 31400 Toulouse, France.
Email: edavoust@irap.omp.eu

Abstract: In this paper we present a bibliometric analysis of the disciplinary composition of space studies, which specifically targets French participation in space research. We used as our database all the scientific papers resulting from space experiments that occurred between 1965 and 1990 in which French researchers were involved. Our aim is to characterize the disciplinary behaviour of participants in space studies, involved in a field in which instrumental specialization could provoke segmentation, if not relative cognitive autonomy. Our sample is compared to a reference sample of all the publications in the field of astronomy and astrophysics in 1980, and to a sample of publications in radio astronomy.

The editorial behaviour of the scientists involved in space studies is barely different from that of other astronomers or astrophysicists, except for the larger number of co-authors. The distribution of papers (as opposed to technical reports and conference proceedings) dealing with space studies in scientific journals does not differ significantly from that in the reference sample. To explain this disciplinary non-differentiation of space studies we propose that it is essentially a scientific area of transitory opportunity for astrophysicists and astronomers who want to use all the available frequency bands of the electromagnetic spectrum.

Keywords:space studies, discipline, instruments, journals

1 INTRODUCTION

The concept of a discipline is frequently discussed in social sciences. The debate is organized around three main theoretical suggestions.

The first consists in an *a priori* definition of a discipline. Functionalists like Rudolf Stichweh (1992) circumscribed the discipline within the contemporary era, arguing for a global logic in the distribution of knowledge. In contrast to this very restrictive definition, although still under the influence of an *a priori* analytical undertaking, Donald Kelley (2006) conceived of disciplines as fields of constituted knowledge, at least since the Middle Ages, in and through methods of transmission.

Another broad orientation for understanding the idea of discipline is organized around an empirical approach. A series of very fine studies centered on concrete practices of sharing knowledge define the salient features of disciplinary structuring. The structuring of specific places (laboratories, universities, observatories), the editorial density, the construction of exchange networks and the emergence of common organizational rules, provide the real outlines of a discipline (Findlen, 1999; Pantin, 2002). This theoretical proposal was subsequently reconstituted by several sociologists (Heilbron, 2006; Lamy and Saint-Martin, 2011; Shinn and Ragouet, 2005). Terry Shinn in particular emphasized the possible transformations of communities centered around stock instruments that can lead to a specific discipline. For example, Jesse Beams' ultracentrifuge led to the restructuring of biomedical research (Shinn and Ragouet, 2005: 174). This tool, a local spin-off of a generic instrument, allowed the organization and solidification of a community of practitioners. Bruno J. Strasser (2002) also showed how the concentration of a team of biophysicists in Geneva around an electron microscope (a real 'laboratory totem') after WWII led to the struc-turing of molecular biology as an autonomous and legitimate discipline.

Space studies, like radio astronomy (Edge and Mulkay, 1976) are a case study of these fields of knowledge that a technical transformation allows to emerge and grow. In fact, it is not so much the introduction of new instruments that define space research as the genesis of a new approach, i.e., reaching beyond the absorbing screen of the atmosphere. Researchers can thus access a very wide range of wavelengths—from the visible and radio centimetric-kilometric domain to the whole electromagnetic spectrum. Hence, for space research, a certain spontaneous sociology of scientists confirms a kind of obvious congruence between overcoming atmospheric perturbations (and the technical and methodological issues linked to them) and the identification of an autonomous discipline. James Lequeux (2005: 46) claims that the arrival of radio astronomy and space tools transformed the field of astrophysics, dividing it into fragmented sub-disciplines. Space and radioastronomical observations would therefore supposedly be better organized and better financed than the sub-disciplines restricted to traditional observatories.

The aim of this paper is to determine empirically whether space studies has become an autonomous discipline. Has the introduction of instruments enabling access to wavelengths unreachable from Earth (particularly X- and γ rays) led to the organization of a specific community centered around particular instruments? Has the particularly massive spatial infrastructure led to the development of one or several cognitive spheres that are autonomous within a hypothetical 'space discipline'? Above all, beyond studies on the exchanges between disciplines and cases of interdisciplinary studies (Larivière and Gingras, 2011; Sugimoto et al., 2011), we want to test the relevance of the (essentialized) link between discipline and instrumental matrix.

To answer the above questions, we have adopted the methods of bibliometry, which have already been applied to the field of astrophysics, with the pioneering studies of Abt (1981, 1982, 1987); our own study (Davoust and Schmadel, 1987) on the world production of papers in astronomy; and papers by Girard and Davoust (1997) on the role of references in the astronomical discourse, and Davoust et al.(1993) aimed specifically at the output of French astronomers.

We have determined the editorial behaviour of astronomers participating in space experiments by asking more specific questions: Do they publish like other astronomers and astrophysicists? Do they have recognizable areas of publication? Do they specifically organize the production and circulation of their results, independently of the rest of the astronomical community?

We have voluntarily limited our scope to publications with French authors or co-authors, considering that they are representative of the scientific community. They generally contribute ~5–10% of the publications in the field (Davoust, 1987). By'French astronomers' we mean all astronomers and astrophysicists in a French astronomical institute, whether an observatory, a CNRS laboratory or a university, regardless of their nationality.

2 METHODOLOGY

In order to gather the totality of publications with French contributors dedicated to space studies, we used as starting point Appendix VIII of the publication by Carlier and Gilli (1995: 333–334), which collects French space-borne experiments. We established the list of the programs they participated in, from 1965 (the first observations, carried out with American researchers on OGO2) to 1991 (the launch of ULYSSE and the closing of Carlier and Gilli's list [1995]). This first list brought together experi-ments in astronomy (as such), solar physics and external geophysics. These three themes do not of course cover the totality of fields of exploration covered by space astronomy. We left aside planetology, first of all because the recurrence of Martian and Venusian exploration, which have no equivalence in terrestrial astron-omy, would have prevented pertinent compari-sons, and secondly because this field covers the discipline of internal geophysics of the Earth. We were specifically interested in astronomy, also leaving aside scientific fields such as biol-ogy, in which French researchers were particu-larly active.

The period chosen—from 1965 to 1992—corresponds to the second part of the Cold War. This geopolitical context, in which geopolitical bipolarity organized global scientific space, is important for the proper understanding of the particular (but not exclusive) relations that French astronomers had with their Russian colleagues within the framework of agreements on space cooperation, signed in 1966 by France and the USSR. Links with American researchers were just as important during the same period. This scientific concentration around Soviet and American poles also had the corollary (at least at the beginning) of fewer collaborations with European researchers. The corpus of experiments (taken from Carlier and Gilli, 1995) is synthesized in Table 1.

We have located all the published papers relating to the experiments listed in Table 1 in which at least one French astronomer (i.e. attached to a French institute), was an author or co-author. The search was carried out using NASA's ADS database. Citations and references were extracted from the same database. This produced a total of 541 papers, 8,813 citations and 6,066 references. Each bibliographical entry consisted of a bibcode, a title, a list of authors, a journal name, year, volume and pages. The bibcode is the unique identifier of a paper that is used in the large astronomical databases.

As coherent reference points, we have extracted from NASA's ADS database all the papers (as opposed to papers in conference proceedings, book and technical papers) published in 1980. We have also compared our numbers with those of Davoust and Schmadel (1987) for the world community of astronomers.

3 RESULTS

The downloaded bibliographical database was processed in the following way: we associated each bibcode with an experiment, and then computed the number of papers, citations, references, etc. for each experiment. We also identified the dominant theme of each paper and each journal. The statistical treatment was done with small procedures in perl language or with commands or scripts under UNIX. We had to manually process a certain number of papers that included two references (the original article in Russian and the translation into English) and find by hand the page numbers of a certain number ofpapers when they were missing. We also corrected some errors in the ADS database (in particular, merging the bibcodes of some papers with multiple authors that had been classified under several distinct bibcodes).

Table 2 presents the results of the data extraction. It gives the number of papers, refereed papers, books, proceedings, the number of citations and references (the total and those published in a journal of space research) and dominant theme for the different space experiments in which French astronomers were involved.

In order to test the strength of our corpus, we globally compared the ‘publishing behaviour’ of the researchers in our sample with that of the authors of all the astronomical papers produced in 1980. For the sake of simplicity, we retained only actual papers, eliminating publications in proceedings of colloquia, technical notes, articles with no identified authors, books and a few single references to all the proceedings of a colloquium (which usually referred to the editors of the whole proceedings) in both the space science sample and the comparison sample. For the latter, we chose only one year because the volume of publications thus considered was sufficient. We chose 1980 because it is in the middle of the period under study. We thus created a comparison sample of 8,951 papers.

Table 3 highlights a difference in the number of authors per paper. The large number of authors in space studies simply reflects the fact that the teams are very large since, as in all scientific fields, the size of the teams is proportional to the financial investment.

The histogram of the number of authors (Figure1) shows a peak for 16 authors. This is neither an artifact nor an error. 56 articles were indeed co-signed by 8 French authors (4 from CESR, 4 from CEA) and 8 Russian authors. A Franco-Russian agreement on the publication of the results from SIGMA, on which the CEA and CESR had worked equally, stipulated a strict allocation of authors: 16 per article, 8 French and 8 Russian.

In total, for the space experiments we counted 4,071 author names, 1,568 of which were French, or 39%. We specify that this number of 1,568 is not the total number of different French authors, which is 342, but the total number of times a French name appears on a publication. When the number of publications is reduced to refereed (n = 413), the number of authors reaches 3,174, of whom 1,155, or 36%, are French. This proportion is nearly identical to that of the global corpus. The difference is not significant and indeed shows the structural homogeneity of French signatures for papers, whether they are refereed or not.

We then calculated the degree of French participation in the publications by counting the relative number of French names in each publication. This proportion is 52% for the 413 refereed papers. In other words, the proportion of French authors that is most frequent in A-level papers is ~50%. This is not the same as counting the total number of occurrences of French names, because in the present case, the degree of participation is weighed by the number of papers with the given proportion, and, as demonstrated below, that of 50% is the most frequent one.

Table 1: Vehicles and space experiments (1965–1990).

Vehicle	Launch year	Experiment
OGO-2	1965	
OGO-4	1967	
OGO-5	1968, 1969	
ESRO	1968	S72
HEOS A-1	1968	S72, S 79
HEOS A-2	1972	S 209
TD-1	1972	S 67, S 77, S 133
Skylab	1973	S 183
Prognoz 2	1972	Signe
Prognoz 6, 7	1977, 1978	Galactica
IUE	1978	IUE
ISEE-C	1978	ISEE-C
Venera 11, 12, 13	1978, 1981	Signe-2MS
HEAO-3	1979	HEOA-C
Saliout-7	1982	Piramig, Sirene
Spacelab-1	1983	Wide Field Camera
ACTION-A	1985	UFT
Spacelab-3	1985	FAUST
Phobos	1988	IPHIR, Lilas
Hipparcos	1989	
Granat	1989	Sigma
Gamma	1990	Gamma-1, Spectre-2
Ulysse	1990	KET, STP, HUS

Indeed, we find that 111 articles out of the 413 have a proportion of 50% French authors. When we remove articles with Russian researchers (for which the co-signature rule was strict andsomewhat constraining), there remain 32 papers where the proportion of French authors reached 50%. No other proportion of French authors appears so frequently, showing that French researchers participated 50% on the aver-

Table 2: The numbers of publications, citations, references and dominant themes for the different space experiments.

Space Experiment	Total No.	Total No. Space	No. ofPapers	No. of Refereed Papers	No. of Other Publ'ns (Proceedings, Books, Technical Reports)	No. of Citatns	No. of Citatns in Space Publns	No. of References	No. of References in Space Publns	Dominant theme*
ARCAD	18	3	17	17	1	79	12	58	9	GGG
FAUST	18	3	11	9	8	137	1	95	5	AAA
GALACTICA	5	1	2	2	0	18	0	42	1	AAA
GAMMA	18	8	16	15	2	88	4	41	7	AO-A-A
GRANAT-SIGMA	147	20	119	80	28	1727	99	1380	109	AAA
HEOS A1 and A2	24	0	6	5	18	71	3	82	1	AAA
HIPPARCOS-team	30	0	29	29	1	2760	38	956	75	AAA
HIPPARCOS	57	1	57	57	0	1789	29	1952	113	AAA
IPHIR	25	5	16	15	9	475	67	252	22	AAA
ISEE-C	44	?	33	29	11	713	?	301	?	?
IUE	48	13	20	20	28	391	24	220	12	AAA
Lilas	8	2	5	5	2	41	3	62	2	AAA
OGO	13	5	13	13	0	57	6	55	14	GGG
Piramig	2	1	2	2	0	14	0	8	0	AA?
SIGNE 2	18	3	14	14	4	112	10	112	3	AAA
S183	2	0	2	2	0	6	0	16	0	AA?
SIRENE	0	0	0	0	0	0	0	0	0	
SMM	15	2	12	12	3	514	20	170	2	AAA
Wide Field Camera	11	2	10	9	1	63	4	201	13	AAA
STEREO1	5	1	5	5	0	104	6	55	2	AAA
TD1	13	2	9	9	4	173	1	214	0	AAA
UFT	2	1	2	1	0	0	0	0	0	A?
Ulysse	5	0	5	2	0	51	0	19	0	AAA
VENERA-SIGNE	12	1	9	9	3	142	6	76	1	AAA
Total	541	497	413			8813	331	6066		75
% space studies		15%					3.7%		6.4%	

* Key: A: astrophysics, G: geophysics, O: oceanography and P: physics. The question marks correspond to samples of items too small to be significant and for which a dominant designation has no sense.

age, even though the standard was artificial with Soviet astronomers.

This global structure of space publications by French researchers allows us to understand the general behaviour of those who publish. It is nevertheless necessary to refine the identification of editorial practices to better define the characteristics of space publications.

We therefore classified the journals thematically. By theme we mean the cognitive subsets linked to a specific object (e.g. planets, the Sun) or to specific methodologies (e.g. optics, instrumentation). Because they cannot be reduced to strict disciplinary fragmentation, these themes require a wider level of analysis than the classic limits such as astrophysics, geophysics, physics, etc. They nonetheless provide a satisfactory approach for locating the papers concerning space studies in the disciplinary territory. We thus tried to determine the editorial choices made by researchers working on themes dealing with space research.

Table 3: The numbers of papers and authors.

Parameter	1980	Space Experiments
Number of Papers	8,951	413
Authors per Paper	2.27	7.66
Average Page	7.55	7.91

* Note that for the space experiments, the sample was 401 instead of 413 papers, because the database did not provide the number of pages for 12 of the papers.

Table 4 gives the number of different journals represented in each thematic field. The list is limited to fields with 5 journals or more. Hence are excluded from this list the following themes, which are less present in editorial surfaces: electronics, instruments, fluid mechanics, astroparticles, computer science, radiophysics, astrobiology, astronautics, climatology, cosmology, geochemistry, geodesics, nanotechnologies, physiology and spectroscopy, which each count between 1 and 4 journals. The overwhelming majority of papers are published in astrophysics, followed by physics.

Journals of 'space research' make up only 5.5% of the editorial surface (15 out of 271 journals). Of course, this very low percentage cannot tell us whether the bulk of publications transfer preferentially to astrophysics whose editorial

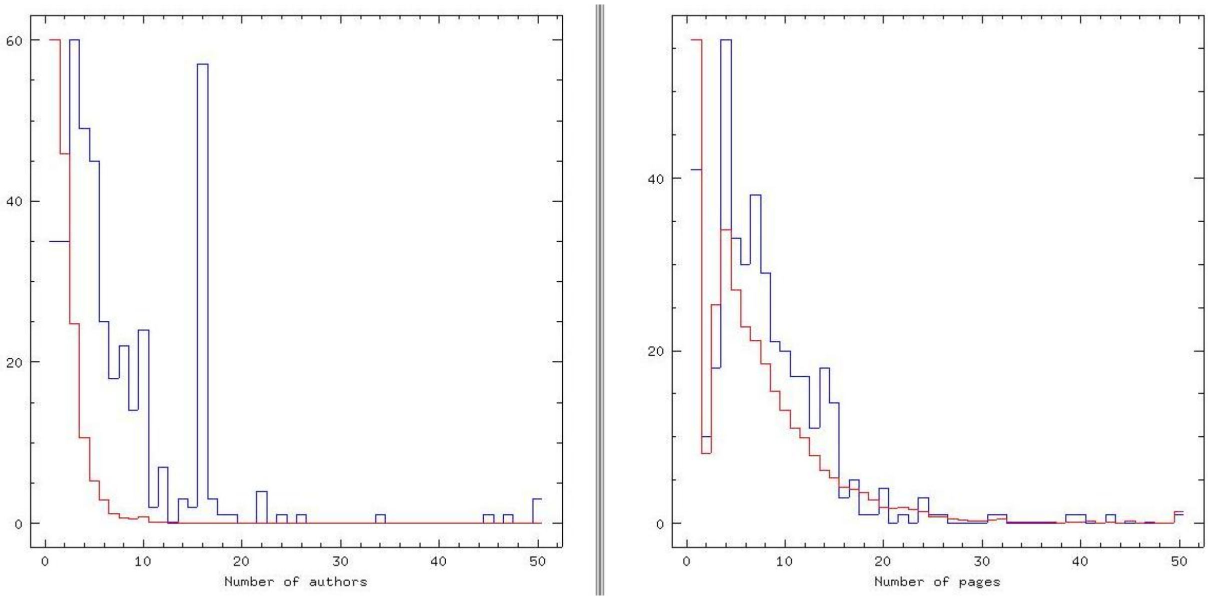


Figure 1: Plots showing the number of authors of the different papers and the lengths of the papers. The black and red histograms are for the space papers and the 1980 papers respectively. The vertical scale refers to the space data.

offer (42.8%) is huge. We can however note that there is no solid editorial core of space science. We must also note that while looking for the specifics of ‘space’, we assumed that the journals whose titles included the word ‘space’ represented this hypothetical discipline. But we did not consider the journal *Astrophysics and Space Science* as a journal dedicated to space studies, because of the absence of editorial policy and peer review during that period.

We then looked for more precise locations of publication of ‘space studies’ articles, the thematic origin of the publications, citations and references (see Table 1). We notice that the number of papers dealing with space studies published in journals whose theme is space science is low, but not negligible (15%). They take few references from journals dedicated to space studies (6.4%) and are even less frequently cited in these same journals (3.7%). Furthermore, we note that among all the experiments, not one concentrated its publications preferentially in space study journals. Astrophysics is a main theme, polarizing editorial offer and absorbing (with, to a lesser extent, geophysics) the greatest amount of publications dedicated to space experiments.

The structure of the editorial field in which publications are distributed thus seems to be globally organized around astrophysics. It is nevertheless necessary to refine this mapping of publications by examining the precise distribution of publications dedicated to space in scientific journals. By comparing this distribution to that of the totality of articles published in 1980 (our reference sample), we wanted to evaluate the behaviour within the editorial field of authors working in space studies. Although astrophysical polarity is undeniable, perhaps the publishing practices of space scientists studies is relatively different within astrophysics itself?

In Table 5, we listed the ten most frequent journals in which space science studies have published and the ten most solicited journals in 1980.

ApJ and A&A are the two central journals in the discipline of astronomy. From this point of view, space scientists do not behave differently from their other colleagues. These two journals polarize (to a great extent) publication intentions and dominate production. Similarly, for research in geophysics, the JGR remains the principal place of publication for the community. The main difference is first of all the emergence of AdSpR for specialists in space studies, showing an important orientation, but not essential, since it does not represent the preferred editorial choice. On the contrary, multidisciplinary journals (like *Nature*) do not accrete ‘space research’. We can therefore consider that editorial practices in space studies differ very little from those of astrophysicists in general: a more specialized sub-discipline and weakly polarized by a single specific emerging journal. The major trends of the discipline of astrophysics (through the two principal journals ApJ and A&A) quite

Table 4: The number of different journals represented in each thematic field.

Domain	Number of Journals
Astrophysics	116
Physics	62
Geophysics	26
Space Research	15
Optics	9
Multidisciplinary	6
Total	235

Table 5: The numbers of space research papers published in the different journals.

Editorial behaviour of space scientists		Behaviour of the astrophysical community in 1980	
Journals	Number of papers	Journals	Number of papers
A&A	115	ApJ	1138
ApJ	38	A&A	729
IAUC	36	JGR	435
AdSpR	32	MNRAS	361
A&AS	27	Natur	324
AstL	11	ApS&SS	296
JGR	10	Geo CoA	213
AnGeo	10	E&PSL	213
SoPh	8	AJ	205
P&SS	7	Metic	204

clearly predominate in the context of space study practices.

4 THE CASE FOR RADIO ASTRONOMY AS A DISTINCT COMMUNITY

Space science is not the only scientific community that might distinguish itself from the general astronomical community. Since radio astronomy essentially started with physicists and engineers after WWII, it was worth examining whether this other community had a different editorial behaviour. To that end, we proceeded along two different routes.

We first analysed the corpus of papers published by French radio astronomers associated with the three large radioastronomical institutes: IRAM (Institut de Radioastronomie Millimétrique), Laboratoire d'Astrophysique de Bordeaux and the Nançay radioastronomical station. We queried ADS with the keywords 'IRAM', 'Bordeaux' and 'Nançay' over the period 1965–1992, and removed irrelevant papers. For Nançay, we also queried ADS with the author names (Biraud, Bottinelli, G. Bourgois, Crovizier, P. Encrenaz, Guelin, Heidmann, Kazès, Lequeux, Rieu and Weliachew), because some French radio astronomy papers (mostly in French) are not in ADS. Thus we were able to identify all the papers of French radio astronomers who used the national radio astronomy instruments and IRAM. We did not consider the few papers by French radio astronomers who used radio telescopes in the USA, Australia or the UK. We ended up gathered 399 papers, 94 proceedings, 9 technical reports and 2 books.

In order to put the editorial policy of French radio astronomers in context, we then analysed in the same way the radio astronomers using the Very Large Array (VLA), by querying ADS with the keyword 'VLA' over the same period, and obtained 1,451 papers, 633 proceedings, 25 technical reports and 12 books.

Table 6 gives the distribution of papers of the French radio astronomers and of the users of the VLA, restricted to those journals with ≥5 papers, as well as the total number of papers in the respective journals in 1980, for comparison. It shows that the radio astronomers do not form a scientific community with a distinct editorial policy from the world astronomers. The VLA users and the world community both have a prefer-ence for ApJ and AJ. The explanation is that most VLA users and most astronomers are in the USA. The French radio astronomers have a different behaviour, in that they predominantly publish in the European journals A&A and A&AS. They also publish in SoPh, because Nançay radio observatory has a radioheliograph, which is used daily to monitor the solar corona, and in IAUC to announce new OH megamasers or radio detection of comets, two domains that are not relevant at the VLA.

We also found that only 14 proceedings (out of 633) and one technical report (out of 25) were on subjects of engineering, meaning that the radio astronomers are indeed astronomers, not engineers.

5 ANALYSIS AND DISCUSSION

Space instruments have opened a new window in the electromagnetic spectrum, particularly in the X-rays and the infrared. We could have expected a technical and cognitive structuring of a community of specialists, independent of other astrophysicists. But in fact, there are no astrophysical or astronomical journals that focus on particular wavelengths. The disciplinary distribution is therefore not associated with this reconfiguration of available spectral windows. In the fields of X-rays and γ rays new phenomena have been revealed, such as the emission of highly-energetic rays coming from the shearing of matter spiralling towards the black hole or the compact object in a binary star. We could legitimately have thought that these discoveries implied new conceptual tools and, associated with an *ad hoc* methodology, they would define an autonomous epistemological place (or at least about to become such a place). In this particular case, we have both concepts drawn from fluid mechanics and a specific instrumentation (special receivers). However, this field of research has not produced a specific community structured by its own techno-cognitive issues. Similarly for the infrared, thanks to space probes, it is pos-

Table 6: The distribution of papers for radio astronomers and other astronomers.

Journal	World 1980	French Radio Astronomers		VLA Users	
A&A	795	177	44.3%	156	10.8%
IAUC	317	41	10.3%	25	1.7%
SoPh	146	25	6.3%	27	1.9%
A&AS	174	22	5.5%	25	1.7%
ApJ	1245	16	4.0%	527	36.3%
AnAp	0	11	2.8%	0	0.0%
LAstr	57	9	2.3%	2	0.1%
P&SS	124	7	1.5%	0	0.0%
AdSpR	53	6	1.5%	13	0.9%
ApL	63	6	1.5%	3	0.06%
MNRAS	390	0	0.0%	114	7.9%
AJ	227	1	0.3%	224	15.4%
NRAON	0	1	0.3%	39	2.7%
Natur	156	3	1.0%	35	2.4%

sible to research the chemistry of dark clouds. Despite its proximity to classical organic chemistry, IR astronomy still presents distinctive features that could have separated it from its sister discipline.

The spread of knowledge relative to space research thus remains confined to astrophysics. We can of course note a ‘big science’ effect in the large number of signatures in space study articles. The technicalities of space research are visible in the low number of accounts in multidisciplinary journals. At the same time, a journal (AdSpR) is emerging that weakly polarizes the disciplinary sub-field, without however rivalling the principal journals, ApJ and A&A. This is not a new discipline emerging, but merely a specialization.

The disciplinary positioning of ‘space research’ is counter-intuitive compared to other disciplinary examples, as it is a sub-discipline that is subservient to the general framework of the discipline of astrophysics. Space instrumentation has not really had any effect on astrophysicists’ editorial practices.

Putting our results into perspective, we can consider that space studies constitute a cognitive field of opportunity that provisionally or temporarily brings together researchers interested in a specific object. The diffusion of information in the space studies field partly explains this disciplinary void. The small group of astrophysicists who developed an on-board instrument is assured of a certain amount of guaranteed observing time (which typically lasts from six months to a year) during which they have the exclusivity of the results obtained, but the data are subsequently available to a much wider community through requests for observing time or open archives. In the case of the so-called legacy surveys, the data are available almost immediately to the world community through an internet site. On the contrary, in the terrestrial field, the results of proprietary experiments can well remain the property of a group for a very long period, if not forever.

The specificity of space scientists is confirmed by the comparison with the community of radio astronomers. The latter overwhelmingly publish in classical astrophysics journals, and their editorial behaviour is similar to that of other astronomers. Contrary to space research, radio astronomy does not appear as an editorially-specialized field of research: it is definitely an integral part of astrophysics.

Scientists can seize the opportunities offered by spatial instruments through calls for proposals. But other opportunities (via terrestrial instruments) can follow a ‘space episode’, which explains the non-specificity of this type of research. Let us add that astrophysical phenomena are best understood by analysing them in the greatest number of wavelength bands possible. This necessity of panchromatic studies reinforces the spatial opportunism that can complement analyses in other parts of the spectrum.

6 ACKNOWLEDGEMENTS

We thank Arnaud Saint-Martin for his comments on previous versions of this paper, and the referees for their helpful suggestions.

7 REFERENCES

Abt, H., 1981. Some trends in American astronomical publications. *Publications of the Astronomical Society of the Pacific*, 93, 269–273.

Abt, H., 1982. Statistical publication histories of American astronomers. *Publications of the Astronomical Society of the Pacific*, 94, 213–220.

Abt, H., 1987. Are papers by well known astronomers accepted for publication more readily than others? *Publications of the Astronomical Society of the Pacific*, 99, 439–441.

Carlier, C., and Gilli, M., 1995. *Les Trente Première Années du CNES (1962–1992).* Paris, La Documentation Française.

Davoust, E., 1987. Les publications des astronomes Français depuis 1969. *Journal des Astronomes Français*, 29, 35–37.

Davoust, E., Bercegol, H., and Callon, M., 1993. L’astronomie, cartographie d’une discipline. *Cahiers de l’ADEST,* special number, 44–49.

Davoust, E., and Schmadel, L.D., 1987. A study of the publishing activity of astronomers since 1969.

Publications of the Astronomical Society of the Pacific, 99, 700–710.

Edge, D.O., and Mulkay, M.J., 1976. *Astronomy Transformed. The Emergence of Radio Astronomy in Britain*. London, John Wiley.

Findlen, P., 1999. The formation of a scientific community: natural history in sixteenth-century Italy. In Grafton, A., and Siraisi, N. (eds.). *Natural Particulars. Nature and the Discipline in Renaissance Europe*. Cambridge (Mass.), MIT Press. Pp. 369–400.

Girard, R, and Davoust, E., 1997. The role of references in the astronomical discourse. *Astronomy and Astrophysics*, 323, A1–A6.

Heilbron, J., 2006. *Naissance de la Sociologie*. Marseille, Agone.

Kelley, D., 2006. Le problème du savoir et le concept de discipline. In Boutier, J., Passeron, J.-C., and Revel, J. (eds.). *Qu'est-ce qu'une Discipline?* Paris, Editions de l'Ecole des Hautes Etudes en Sciences Sociales. Pp. 97–115.

Lamy, J., and Saint-Martin, A., 2011. Pratiques et collectifs de la science en régime. Note critique. *Revue d'Histoire des Sciences*, 64, 377–389.

Larivière V., and Gingras, Y., 2010. On the relationship between interdisciplinarity and scientific impact. *Journal of the American Society for Information Science and Technology*, 61, 126–131.

Lequeux, J., 2005. *L'Univers Dévoilé. Une Histoire de l'Astronomie de 1910 à nos Jours*. Les Ulys, EDP Sciences.

Pantin, I., 2002. L'astronomie et les astronomes à la Renaissance: les facteurs d'une mutation. *Nouvelle Revue du Seizième Siècle*, 20, 65–78.

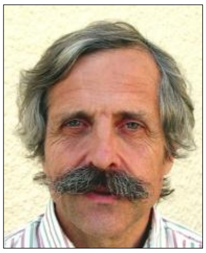
Shinn, T., and P., 2005, *Controverses sur la Science. Pour une Sociologie Transversaliste de l'Activité Scientifique*. Paris, Raisons d'Agir.

Stichweh, R., 1991. *Etudes sur la Genèse du Système Scientifique Moderne*. Arras, Presses Universitaires de Lille.

Strasser, B.J., 2002. Totems de laboratoires, microscopes électroniques et réseaux scientifiques: l'émergence de la biologie moléculaire à Genève (1945–1960). *Revue d'Histoire des Sciences*, 55, 5–43.

Sugimoto, C.R., Ni, C., Russell, T.G., Bychowski, B., 2011. Academic genealogy as an indication of interdisciplinarity: an examination of dissertation networks in Library and Information Science. *Journal of the American Society for Information Science and Technology*, 62, 1808–1828.

Dr Jérôme Lamy is a researcher at the Versailles Saint-Quentin-en-Yvelines Université (France). He is an historian and sociologist of science. His research interests include the relationships between science and politics, space research in the twentieth century and more generally, scientific institution. He is the author of more than fifty research papers.



Dr Emmanuel Davoust was a research scientist in astrophysics for 40 years, working mainly in the field of nearby galaxies, and more recently on stellar populations in galaxies and globular clusters, by medium-resolution spectroscopy with large telescopes and multivariate statistical analyses. He was involved in numerous public outreach activities, and published two books, one on the search for life in the Universe and one about the history of Pic du Midi Observatory. Since 2012, he has been an astronomer emeritus at Observatoire Midi-Pyrenees in Toulouse (France), participating in the many activities of the heritage commission of the Observatory: salvaging old instruments, and contributing to exhibitions, to conferences and talks, and to an astronomy museum project.

Journal of Astronomical History and Heritage, 19(2), 203−215 (2016).

HOW SUPERNOVAE BECAME THE BASIS OF OBSERVATIONAL COSMOLOGY

Maria Victorovna Pruzhinskaya
Laboratoire de Physique Corpusculaire, Université Clermont Auvergne,
Université Blaise Pascal, CNRS/IN2P3, Clermont-Ferrand, France; and
Sternberg Astronomical Institute of Lomonosov Moscow State University,
119991, Moscow, Universitetsky prospect 13, Russia.
Email: pruzhinskaya@gmail.com

and

Sergey Mikhailovich Lisakov
Laboratoire Lagrange, UMR7293, Université Nice Sophia-Antipolis, Observatoire
de la Côte d'Azur, Boulevard de l'Observatoire, CS 34229, Nice, France.
Email: lisakov57@gmail.com

Abstract: This paper is dedicated to the discovery of one of the most important relationships in supernova cosmology—the relation between the peak luminosity of Type Ia supernovae and their luminosity decline rate after maximum light. The history of this relationship is quite long and interesting. The relationship was independently discovered by the American statistician and astronomer Bert Woodard Rust and the Soviet astronomer Yury Pavlovich Pskovskii in the 1970s. Using a limited sample of Type I supernovae they were able to show that the brighter the supernova is, the slower its luminosity declines after maximum. Only with the appearance of CCD cameras could Mark Phillips re-inspect this relationship on a new level of accuracy using a better sample of supernovae. His investigations confirmed the idea proposed earlier by Rust and Pskovskii.

Keywords: supernovae, Pskovskii, Rust

1 INTRODUCTION

In 1998−1999 astronomers discovered the accelerating expansion of the Universe through the observations of very far standard candles (for a review see Lipunov and Chernin, 2012). In astronomy Type Ia supernovae (SNe) are used as standard candles. First, they are bright enough to be visible from cosmological distances. And second, their luminosity at maximum light is approximately the same. This last property derives from the fact that the Type Ia supernova (SN) phenomenon is an explosion of a carbon-oxygen white dwarf—an object with nearly a solar mass but a hundred times smaller in diameter. In this case we can calculate the brightness of a supernova at any distance within the framework of any cosmological model.

Thus, comparing the observations with theoretical predictions one determines the cosmological parameters of the Universe. Such measurements became possible with the development of observational tools and the emergence of major supernovae surveys (Dong et al., 2016; Gal-Yam et al., 2013; Lipunov et al., 2010; Rau et al., 2009).

From a theoretical point of view, the accelerating expansion of the Universe can be explained in Einstein's equations of General Relativity by the introduction of a cosmological constant, or more generally by an unknown form of energy with a negative pressure, so-called 'dark energy' (Einstein, 1917; 1997; McVittie, 1965). However, from the moment that Albert Einstein (1879−1955; Whittaker, 1955) introduced into the equations of the General Theory of Relativity a cosmological constant until the discovery of the accelerating expansion of the Universe, nearly 80 years would pass.

2 A BRIEF ACCOUNT OF SUPERNOVAE

A hundred years ago our concept of the Universe was remarkably different from the modern view. Estimations of the size of our galaxy ranged from 5×10^3 to 3×10^5 l.y.; the location of our Solar System within our galaxy remained an open question; and there was no agreement about whether spiral nebulae belong to our galaxy or not. These topics were discussed during 'The Great Debate' between Harlow Shapley (1885−1972; Trimble and Smith, 2014) and Heber Doust Curtis (1872−1942; Lindner and Marché, 2014) in 1920 (Shapley and Curtis, 1921). Objects which today are known as novae and supernovae were prominent characters in this dispute. However, at that time all new star-like bright objects that gradually faded over a period of several months were referred to as 'novae'.

The tradition to assign this name (novae) to such objects was established back in the sixteenth century by Tycho Ottesen Brahe (1546−1601; Moesgaard, 2014) in his work titled "Concerning the new and previously unseen star" (our English translation of the Latin original) about the famous object SN 1572, a supernova in our galaxy that was visible to the naked eye. At that time, of course, it was not called a 'supernova'.

As van den Bergh (1988) reminds us, prior to 1917 only two novae had been observed in spiral nebulae, S Andromedae in 1885 and Z Centauri in 1895, whereas dozens of novae had been recorded in our own galaxy.[1] The discovery of a new star in NGC 6946 by George Willis Ritchey (1864–1945; Cameron, 2014) in 1917 motivated many observatories to start a search for such objects in archival data. As a result, Shapley (1917) published a list of eleven 'temporary stars' in spiral nebulae—today we know that three of these were actually novae, while the remaining eight were supernovae. Curtis (1917) adopted mean values $<m_{\max}> \approx 5$ for galactic novae and $<m_{\max}> \approx 15$ for novae in spiral nebulae (van den Bergh, 1988). Therefore, novae in spiral nebulae were on average ~10 magnitudes fainter than other novae. This could be explained in one of two different ways: either novae in spiral nebulae were generally 10^4 times fainter, or novae in spiral nebulae were on average 100 times further away than other novae. Shapley doubted Curtis' idea that spiral nebulae were galaxies comparable in size to our own galaxy.[2] If one adopts this 'comparable galaxy theory', then distances to the spiral nebulae, estimated through their angular diameters, would be immense. Shapley noted among the points of agreement between himself and Curtis:

> If our galaxy approaches the larger order of dimensions, a serious difficulty at once arises for the theory that spirals are galaxies of stars comparable in size with our own: it would be necessary to ascribe impossibly great magnitudes to the new stars that have appeared in the spiral nebulae. (Shapley and Curtis, 1921: 180).

Curtis suggested that at most, spiral nebulae were ~10 times smaller than our galaxy. Thus, with this greatly-reduced scale of the Universe it was easier to accept the still impressively-great magnitudes of novae in spiral nebulae.

A few years after the Great Debate, a relationship between recessional velocity and distance to spiral nebulae was established. In 1927, Georges Henri-Joseph Edouard Lemaître (1894–1966; Kragh, 2014) published a work titled "A homogeneous Universe of constant mass and growing radius accounting for the radial velocity of extragalactic nebulae" (our English translation of the French original) in the *Annals of the Scientific Society of Brussels* (Lemaître, 1927). In this work he found dynamic solutions to Einstein's General Theory of Relativity equations. These solutions indicated that there was a linear relationship between the recessional velocity of a galaxy and its distance. Lemaître was the first to estimate the value of this parameter, linking the recessional velocity (v) and galaxy distance (D). Today this parameter is known as H_0 where

$$v = H_0 D \qquad (1)$$

Using redshift measurements of Vesto Melvin Slipher (1875–1969; Giclas, 2014) from Gustav Strömberg (1882–1962; Hockey and MacPherson, 2014) published in 1925 and distance estimations from Hubble (1926) for 42 galaxies, Lemaître obtained a value of 625 km/s/ Mpc. In a cited work, Hubble used a statistical expression for distance (D) in parsecs:

$$log(D) = 4.04 + 0.2m \qquad (2)$$

where m is the total apparent magnitude. Lemaître noted, however, that contemporary uncertainties in distances to galaxies were too high to show this linear relationship between velocity and distance. His value of H_0 is quite different from the modern $H_0 = 67.80 \pm 0.77$ km/s/Mpc (Planck Collaboration, 2014), but close to the value of 500 km/s/Mpc obtained by Hubble two years later (Hubble, 1929), where he used Cepheid variables to find distances to the galaxies. The main reason of their significant errors was incorrectly-determined distances to galaxies. To determine distances, Hubble used the period-luminosity relation for Cepheid variables in nearby galaxies and the brightest resolved stars as the most luminous individual locators for distant galaxies. In 1952 it was shown that there were two types of Cepheid variables (Baade, 1952; Thackeray, 1952), and Allan Rex Sandage (1926–2010; Lynden-Bell and Schweizer, 2012) summarized problems associated with both approaches (Sandage, 1958).

Once the distances to the hosts of novae had been determined, it became possible to estimate their absolute magnitudes. It turned out that some novae were orders of magnitude brighter than others, and astronomers realized that novae should be divided into two subclasses. This division occurred in 1934, when Fritz Zwicky (1898–1974; Knill 2014; Figure 1) and Walter Baade (1893–1960; Florence, 2014; Figure 2) suggested the term 'super-novae' for 'exceptionally bright novae'.[3] It then took a couple of years for the hyphen to disappear. In 1938 Baade noticed that supernovae were a more homogeneous class of objects than novae. He found the mean absolute magnitude at maximum light for 18 supernovae[4] to be -14.3^m, with a dispersion of $\sim 1.1^m$. Therefore, supernovae were considered as good distance indicators in the Universe (Baade, 1938; Wilson, 1939; Zwicky, 1939). In 1941 Rudolph Leo Bernhard Minkowski (1895–1976; Durham, 2014)[5] obtained and analyzed the first spectra of supernovae, dividing them into two main types (Minkowski, 1941). To Type I he attributed supernovae that had no hydrogen lines in their spectra, where the

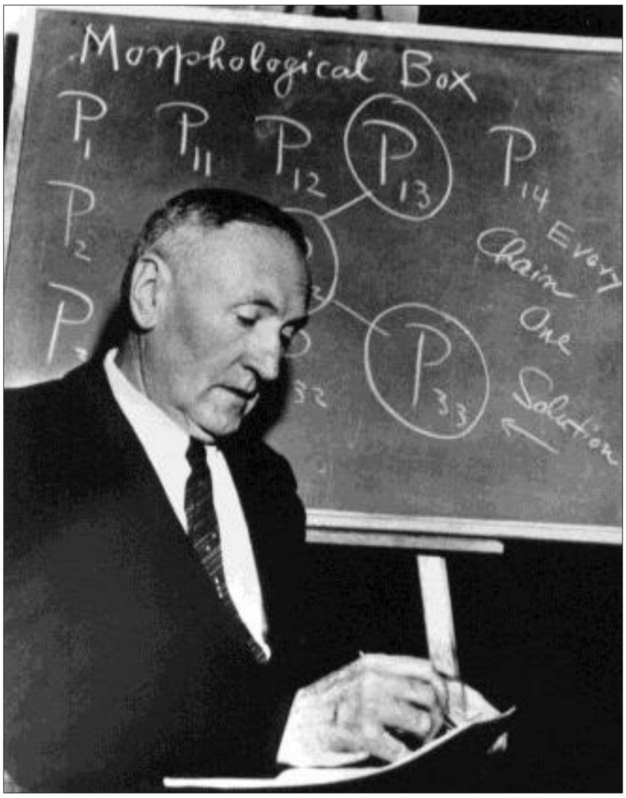


Figure 1: Fritz Zwicky (https://www.wikipedia.org)

Figure 2: Walter Baade (https://www.wikipedia.org)

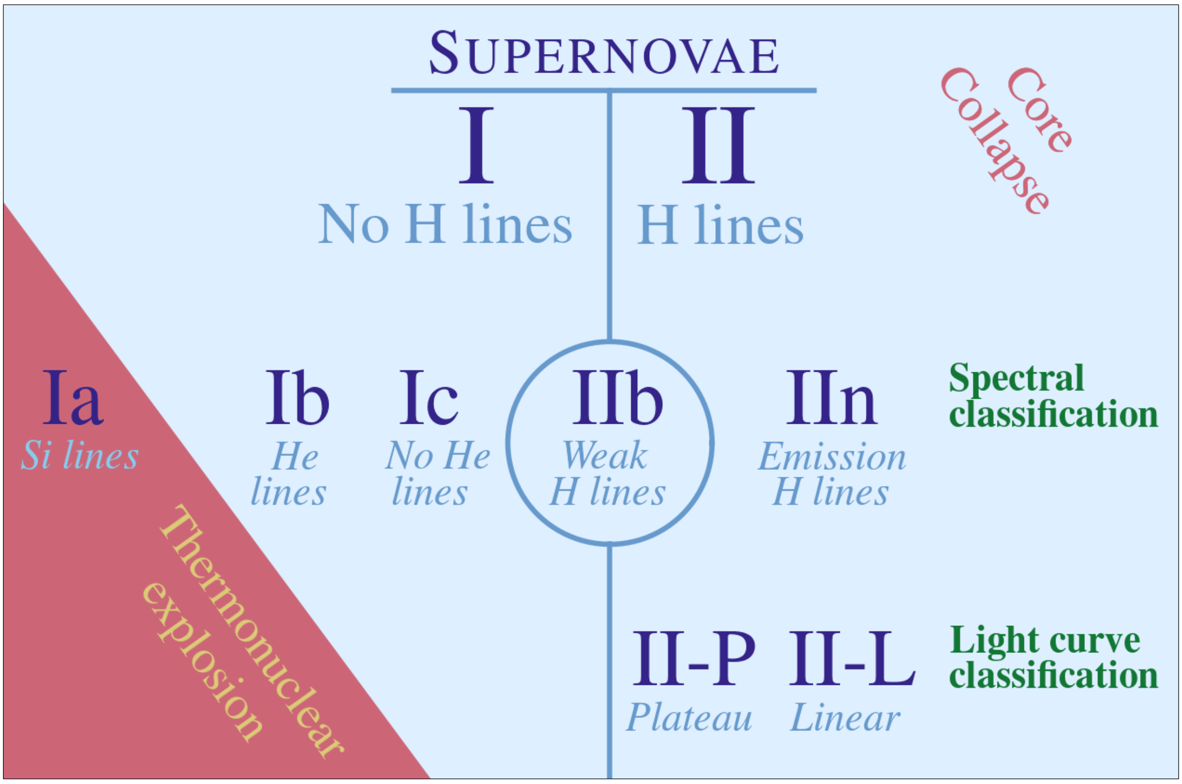


Figure 3: Supernova classification (drawn by authors)

entire spectrum consisted of broad maxima and minima that were not possible to explain.[6] Type II supernovae, on the contrary, showed the presence of hydrogen in their spectra. Over time, a more detailed classification appeared (see Figure 3). Type I supernovae were divided into three SN subtypes: Ia, Ib and Ic. It was found that the SN Ia phenomenon arises from the thermonuclear explosion of a white dwarf, and Type II SNe and SNe Ib/c from the core collapse of a massive star at the final stage of its evolution. Thus, SN Ia explosions differ in their origin from other supernovae.

As mentioned previously, the SN Ia phenomenon is an explosion of a carbon-oxygen white dwarf of nearly 1 $M_\odot$ but with a diameter hundred times smaller than the Sun. A thermonuclear explosion occurs when the mass of the white dwarf exceeds the Chandrasekhar Limit either by matter accretion from a companion star or by merging with another white dwarf. SNe Ia are highlighted by the presence in their spectra of absorption lines of singly-ionized silicon. During the explosion, ~0.5 $M_\odot$ of ^{56}Ni is produced. The radioactive decay $^{56}\text{Ni} \rightarrow {}^{56}\text{Co} \rightarrow {}^{56}\text{Fe}$ powers the maximum and post-maximum light curve of SNe Ia (Colgate and McKee 1969; Hoyle and Fowler, 1960).

To explain the spectra of core-collapse supernovae it is important to know which part of the envelope of the star is lost before the core collapse. If the stellar wind by which the star loses matter is not intense, the collapse occurs at the stage of the red supergiant. The radius of these stars can be several hundred times greater than the solar radius, and their extremely tenuous envelopes contain large amounts of hydrogen. Therefore, red supergiants are the progenitors of Type II SNe, in the spectra of which hydrogen lines are the most prominent.

More massive stars lose mass more efficiently by the stellar wind and end their lives losing all or part of the hydrogen envelope. Although having the same energy source, such core-collapse supernovae do not show hydrogen in their spectra (SNe Ib), or only show it in small quantities (SNe IIb). An even more effective stellar wind can ‘blow out’ not only the hydrogen but also the helium envelope. As a result, SNe Ic explode. Phenomenon of SNe Ib/c also may arise from an explosion in a binary system where the envelope is lost due to interaction with a companion star.

It was only when SNe were divided into Types and Subtypes that the most homogeneous SNe Ia could be identified and used as cosmological distance indicators.

Studies of supernovae led to one of the greatest discoveries in observational cosmology: the accelerating expansion of the Universe. In 1998–1999, two international teams of astronomers, one led by Brian Schmidt and Adam Riess and the other by Saul Perlmutter, reported that the cosmological expansion was accelerating.

The ‘Supernova Cosmology Project' started in 1988 under the leadership of Saul Perlmutter, with the aim of determining the cosmological parameters of the Universe using the relationship of ‘distance modulus−redshift’ for distant SNe Ia. The first results, obtained for seven supernovae at redshift of z ~0.4, gave a zero value for the cosmological constant. However, a more detailed analysis, including 42 cosmological supernovae with redshifts from 0.18 to 0.83, showed that in the case of a flat Universe ($\Omega_M + \Omega_\Lambda = 1$) the density of matter is $\Omega_M = 0.28$ +0.09/–0.08 (1-σ statistical error) +0.05/–0.04 (systematic error). The probability that the dark energy density is not equal to zero was 99.8% (Perlmutter et al., 1999).

Brian Schmidt's competing project, involving the ‘High-Z Supernova Search Team’, was launched in 1995. Their first attempts to detect the accelerating expansion also were unsuccessful due to large measurement errors. Only in 1998, using an expanded sample of 16 distant supernovae, were they able to show that in the case of a flat Universe $\Omega_M = 0.28 \pm 0.1$ (Riess et al., 1998).

It is noteworthy that most of the distant supernovae in both projects were discovered at the Cerro Tololo Inter-American Observatory with the 4-meter Blanco Telescope and nearby supernovae with z <0.1 were taken from the Calan/ Tololo supernovae survey. The spectra of distant supernovae were obtained with the Keck telescopes by Alex Filippenko who was a member of both teams. In 2011, for their discovery of the accelerating expansion of the Universe through observations of distant supernovae Saul Perlmutter, Brian Schmidt and Adam Riess were awarded the Nobel Prize in Physics (Figure 4).

However, this important discovery would not have been possible without another discovery: that there was a relationship between the peak luminosity of an SN Ia and the shape of its light curve.

3 THE ‘STANDARDIZATION’ OF A CANDLE

The SNe Ia light curves in most cases are very similar to each other (see Figure 5). Approximately at 15 days, the luminosity of an SN Ia reaches a maximum, which then lasts for a few days. At maximum light SNe Ia have on average an absolute magnitude in the *B*-band of the order of -19.5^m. At that moment, the luminosity of the star is comparable to the luminosity of the entire host galaxy! After reaching maximum light the luminosity of an SN Ia declines rapidly, by ~3^m in 25–30 days, following an almost linear increase of apparent magnitude, which corresponds to an exponential dimming of the luminosity (Tsvetkov et al., 2009). Nearby SNe Ia (e.g. SN 2011fe, SN 2014J) can be observed for about a year.

Figure 4: The Nobel laureates in Physics in 2011, Saul Perlmutter, Adam Riess and Brian Schmidt (from Wikipedia, Licensing: this work has been released into the public domain by its author, Ariess at English Wikipedia; this applies worldwide).

Despite the apparent similarities, the light curves of SNe Ia are different. The average dispersion on the Hubble Diagram for different samples of SNe Ia is $0.4-0.6^m$. In addition, some discovered SNe Ia are characterized by a red colour at maximum light and low luminosity. The first object with such characteristics was SN 1991bg, which exhibited a rapid decline after maximum light. SN 1991bg was about 2 magnitudes dimmer than other SNe Ia in the Virgo cluster, where the supernova host galaxy, NGC 4374, was located. Objects that are similar to SN 1991bg are called 'Type 1991bg supernovae'.

Some SNe Ia, on the contrary, have high-peak luminosities and slow declines after maximum light. The prototype for this class of supernovae is SN 1991T. The smallest Subclass is the peculiar SNe Iax with absolute magnitudes in the range of $-14.2^m \geq M_{V\,peak} \geq -18.9^m$ but having the same shaped light curves as normal SNe Ia (Foley et al., 2013).

Figure 6 shows the contribution of SN Ia subtypes in volume up to z = 0.08. This choice of volume is motivated by the fact that only for the nearby supernovae are there good spectral data, and selection effects are not significant. However, they cannot be completely avoided. For example, only about thirty SNe Iax were discovered because of their weakness, while it

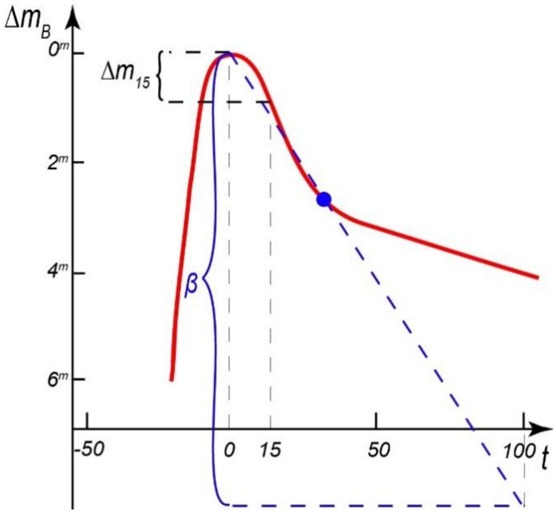


Figure 5: The typical light curve of an SN Ia in the *B*-filter. The β parameter introduced by Pskovskii and Δm_{15} parameter introduced by Phillips are shown. The blue point is the point at which the decline in brightness begins to slow down (Drawn by authors).

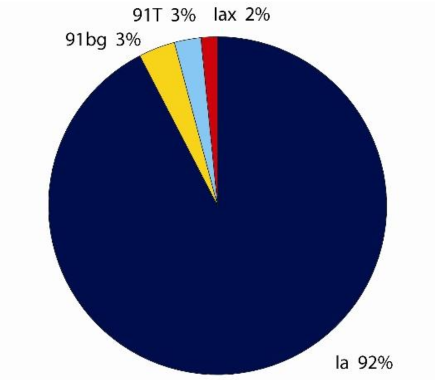


Figure 6: The distribution of SNe Ia subtypes in volume up to z = 0.08. The data are taken from the SAI supernovae catalog (Bartunov et al., 2007) and (Foley et al., 2013) (Drawn by authors).

is expected that there are 31 + 17/–13 for every 100 SNe Ia (Foley et al., 2013).

Thus, mass observations of SNe Ia raised questions about the universality of their light curves, and the ‘standard candle’ hypothesis was destroyed. But it turned out that there is a relationship between the physical characteristics and the parameters of the light curve of a supernova: the brighter the supernova is, the slower its luminosity declines after the maximum. Therefore, SNe Ia are ‘standardizable’ objects.

In the 1940s to describe the light curves of novae Dean Benjamin McLaughlin (1901–1965; Lindner, 2014) introduced the t_3 parameter—the time in days following the maximum light, during which the nova decreased in brightness by 3^m—and he found a connection between t_3 and the absolute magnitude of novae at maximum (M_{max}) (McLaughlin, 1945). To test the idea of Iosif Samuilovich Shklovsky (1916–1985; Gurshtein, 2014) about the absence of a qualitative difference between novae and supernovae, Ivan Mikheevich Kopylov (1928–2000) plotted the $t_3 - M_{max}$ relationship for supernovae (Kopylov, 1955a; 1955b). If Shklovsky had been right, this dependence for supernovae would have been simply a continuation of the dependence for novae. However, the supernovae and novae data points did not follow the same straight line, and the lines associated with each type had different inclinations (see Figure 7). Thus, Kopylov showed that novae and supernovae were two independent types of objects. In this work Kopylov did not divide supernovae by types. However, if one identifies the points on the graph with supernovae whose types were known at that time, an interesting detail is found: Type I SNe (the green line) are positioned differently to all other supernovae. Thus, had Kopylov divided his sample of SNe into Types I and II he would have been the first to find that bright Type I SNe decline more slowly after reaching peak luminosity.

In 1967 Yuri Pavlovich Pskovskii (Figure 8) began to explore similar dependencies for different types of SNe. As a main parameter characterizing the light curve shape, Pskovskii used β—the mean rate of decline in photographic brightness from maximum light to the point at which the luminosity decline rate changes. β is measured in magnitudes per 100-day intervals (see Figure 5, and Pskovskii, 1967). The point

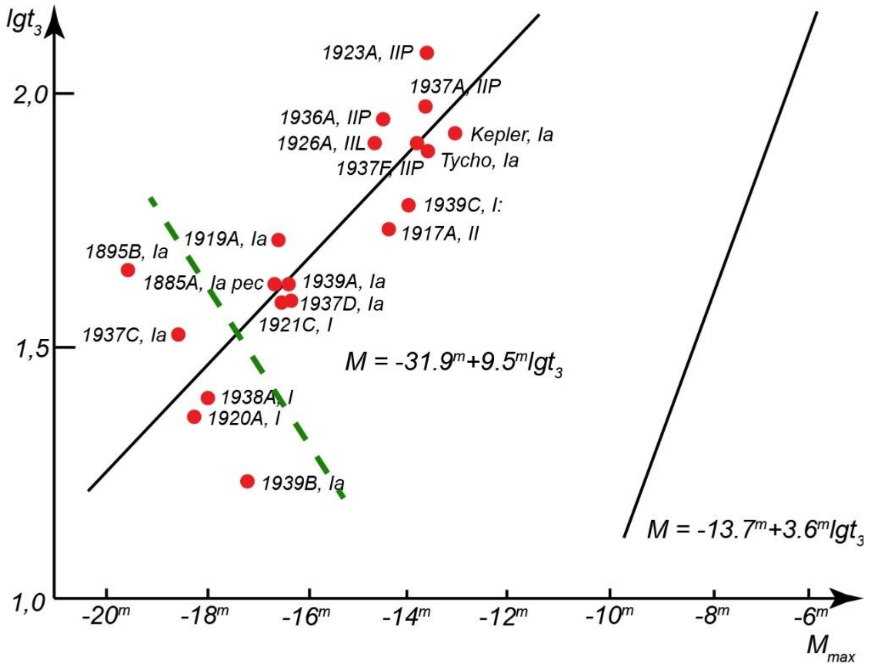


Figure 7: The dependence between the absolute magnitude in maximum light and the decline rate after maximum for SNe (left) and novae (right) (after Kopylov, 1955a; 1955b). The green dashed line shows the plot for SNe Ia. Kepler’s and Tycho’s historical SNe do not follow the common tendency due to the large uncertainty in their absolute brightness.

at which the luminosity decline rate changes, refers to the moment when the rapid luminosity decline is replaced by a slower one. It happens about 25–30 days after the maximum. Selection of this parameter is justified by the fact that, at that time, the probability of discovering a supernova before the maximum light, and obtain the full light curve, was small. Moreover, the existing light curves were mostly incomplete. On the other hand, to determine the decline after the maximum light was rather simple for most observed supernovae. However, first of all, by plotting the $\beta - M_{max}$ relationship Pskovskii, just as Kopylov had done earlier, sought to emphasize the difference between novae and supernovae. Second, upon analyzing Type I SNe, Pskovskii[7] showed that the majority of them has similar values of β, and therefore their light curves could effectively be considered as 'identical', so Type I SNe could serve as reliable distance indicators.

In 1973 Roberto Barbon and his collaborators subdivided Type I SNe into two classes, depending upon their decline rates: 'fast' and 'slow' (Barbon et al., 1973). 'Fast' Type I SNe were brighter at maximum than the 'slow' ones. In addition, Barbon et al. concluded that the existence of two subclasses of Type I SNe is physically justified because there was a connection between the SN subclass and the type of host galaxy: 'fast' Type I SNe avoided elliptical galaxies while 'slow' Type I SNe avoided irregular galaxies. Further, Barbon et al.'s studies (1975) showed that there was no significant difference between 'fast' and 'slow' Type I SNe.

In 1977 Pskovskii published a paper in which he proposed the introduction of a photometric classification of SNe based on the value of β: SNe with large values of β would be called 'senior' and those with small values of β 'junior' (Pskovskii, 1977). Photometric classes were denoted as follows: SN Type followed by the value of β after the decimal point; for example, photometric class I.10 means that the SN belongs to Type I and as β value of 10. In the same paper Pskovskii showed that there was a relationship linking the absolute magnitude at maximum for Type I SN with the β parameter. On the basis of 32 Type I SNe this relation was found to be

$$-21.3 + 0.11\beta = M_{pg} \pm 0.5 \tag{3}$$

where M_{pg} is the photographic magnitude (Pskovskii, 1977). Thus, Pskovskii came to the correct conclusion that supernovae with a slow decline rate were brighter than supernovae with a fast decline rate. Later, he confirmed this relation using an expanded sample of Type I SNe (Pskovskii, 1984).

Figure 8: Yury Pavlovich Pskovskii, 1 February 1926–21 July 2004 (http://www.astronet.ru/db/msg/1211317).

However, it should be noted that in 1974 the American statistician and astronomer Bert Woodard Rust (b. 1940; Figure 9) independently derived the correct relation between the peak luminosity and the light curve slope for Type I SNe in his Ph.D. thesis *The Use of Supernovae Light Curves for Testing the Expansion Hypothesis and Other Cosmological Relations.* To characterize the slope of the light curve Rust used the parameter

$$\Delta t_c = t(m_0 + 0.5) - t(m_0 + 2.5) \tag{4}$$

where m_0 is the supernova magnitude at maximum. To determine the absolute magnitude of SNe Rust (1974) used the following formula:

$$M_0 = (-18.5 \pm 0.68) - (0.0512 \pm 0.0359)\Delta t_c \tag{5}$$

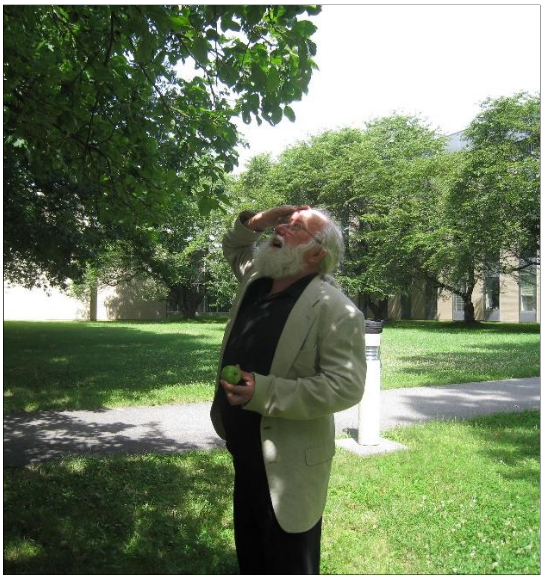
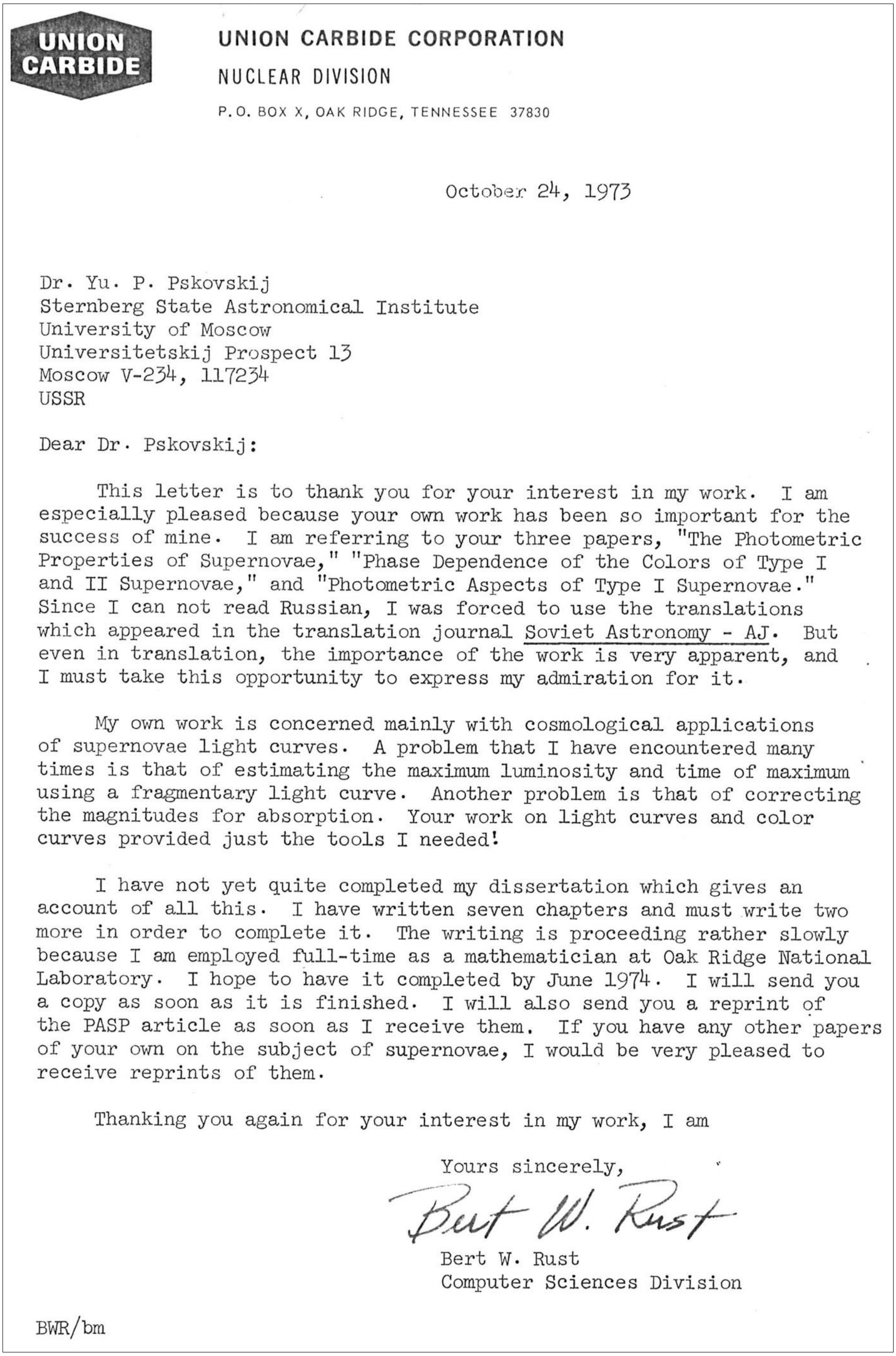


Figure 9: Professor Bert Woodard Rust, who works at the National Institute of Standards and Technology, in the USA (Photograph courtesy Professor Rust from his personal archive).



UNION CARBIDE CORPORATION
NUCLEAR DIVISION
P. O. BOX X, OAK RIDGE, TENNESSEE 37830

October 24, 1973

Dr. Yu. P. Pskovskij
Sternberg State Astronomical Institute
University of Moscow
Universitetskij Prospect 13
Moscow V-234, 117234
USSR

Dear Dr. Pskovskij:

This letter is to thank you for your interest in my work. I am especially pleased because your own work has been so important for the success of mine. I am referring to your three papers, "The Photometric Properties of Supernovae," "Phase Dependence of the Colors of Type I and II Supernovae," and "Photometric Aspects of Type I Supernovae." Since I can not read Russian, I was forced to use the translations which appeared in the translation journal Soviet Astronomy - AJ. But even in translation, the importance of the work is very apparent, and I must take this opportunity to express my admiration for it.

My own work is concerned mainly with cosmological applications of supernovae light curves. A problem that I have encountered many times is that of estimating the maximum luminosity and time of maximum using a fragmentary light curve. Another problem is that of correcting the magnitudes for absorption. Your work on light curves and color curves provided just the tools I needed!

I have not yet quite completed my dissertation which gives an account of all this. I have written seven chapters and must write two more in order to complete it. The writing is proceeding rather slowly because I am employed full-time as a mathematician at Oak Ridge National Laboratory. I hope to have it completed by June 1974. I will send you a copy as soon as it is finished. I will also send you a reprint of the PASP article as soon as I receive them. If you have any other papers of your own on the subject of supernovae, I would be very pleased to receive reprints of them.

Thanking you again for your interest in my work, I am

Yours sincerely,

Bert W. Rust

Bert W. Rust
Computer Sciences Division

BWR/bm

Figure 10: A 1973 letter from Bert Rust to Yuri Pskovskii, 1973 (courtesy Professor Rust from his personal archive).

Never having met in person, Rust and Pskovskii were in long-term scientific and friendly correspondence. In one of the letters to Pskovskii, Rust wrote that he was interested in the problem of determining the luminosity of supernovae at maximum light by using a fragmentary light curve (see Figure 10). Undoubtedly, Bert Rust was the first to discover this important relationship. However, as Rust noted in one of his letters, Pskovskii's work had a tremendous impact on his own research.

Unfortunately, at the time Rust's discovery went unnoticed by the astronomical community. This was partly due to the fact that Rust's publications on this topic were not in high-profile astronomical journals. Except in his Ph.D. thesis, Rust (1974) mentioned this correlation only once, in a conference abstract that was published in the *Bulletin of the American Astronomical Society* (Rust, 1975).

In 1981 David Branch studied the possibility of sub-classifying Type I SNe by photometric properties and showed that the light curve parameters of these SNe are distributed in a continuous manner, and do not form two subclasses as Barbon had claimed. In addition, Branch (1982) confirmed Pskovskii's conclusion that the absolute magnitude at maximum light is proportional to the decline rate after the maximum. However, further analyses of SNe Ia, conducted by Douglas L. Miller and David Branch (1990), did not reveal this relationship.

John R. Boisseau and J. Craig Wheeler (1991) then explored the question of how the background light from the host galaxies of SNe Ia may affect the observed changes in absolute magnitude at maximum light, and the decline rate. By adding a small amount of the background of the host galaxy to the photometric data, they noticed both an increase in the peak luminosity and a flattening of the light curve, in other words, the Rust-Pskovskii relationship. They showed that the contribution from the background becomes more significant for the faint objects. Thus, the correct background accounting is particularly important for the study of distant SNe Ia, because their light contains a large degree of contamination by the background light of the host galaxy. Boisseau and Wheeler (ibid.) came to the conclusion that the observed dispersion of parameter β is random, and that most SNe Ia have similar light curves.

As can be seen, the Rust-Pskovskii relationship repeatedly was subjected to inspection and criticism. But nowadays it is the most important relationship in observational cosmology that is based on the study of distant SNe Ia.

In the early 1980s CCD cameras appeared, and the number of SNe discoveries increased substantially. Moreover, the probability of discovering SNe before they reached maximum light and following their brightness evolution longer also increased. The first light curves of SNe Ia obtained using CCD photometry showed that some supernovae had faster decline rates than others. Later, the low luminosity SN Ia 1991bg with a fast decline rate was discovered. All this motivated the American astronomer Mark Phillips to revise the Rust-Pskovskii relationship using nine SNe Ia with well-known distances measured either using the Tully-Fisher Relation or the surface brightness fluctuation method for galaxies. Since the point where the luminosity decline rate changes (and therefore, the β parameter) is difficult to determine with high accuracy, as an alternative to the β parameter Phillips used Δm_{15}—a parameter that indicates how many magnitudes fainter the luminosity becomes in blue light during the first 15 days after maximum light (see Figure 5). Parameter Δm_{15} initially was proposed by George Jacoby, as Phillips (1993) noted in the acknowledgements in his paper. The relation between the absolute magnitude at maximum light in the *B*-band and Δm_{15}, derived by Phillips (ibid.) was

$$M_{Bmax} = -21.726(0.498) + 2.698(0.359)\ \Delta m_{15(\mathrm{B})} \qquad (6)$$

The use of Δm_{15} reduced the dispersion of M_{Bmax} by a factor of two. There is also a quadratic relation between the absolute magnitude at maximum light and the slope parameter Δm_{15}.

4 DISCUSSION

The existence of empirical relationships between the luminosity and light curve shape of SNe Ia is explained in some theoretical models (e.g. see Höflich and Khokhlov, 1996; Höflich et al., 1993; Livne and Arnett, 1995; Woosley and Weaver, 1994). It is now generally accepted that the SN Ia phenomenon arises from an explosion of a carbon-oxygen white dwarf with a mass close to the Chandrasekhar Limit. Different theoretical models include deflagration (subsonic combustion), detonation (supersonic combustion), delayed detonation, off-center detonation, pulsating delayed detonation etc. (Arnett, 1969; Khokhlov, 1991; Nomoto et al., 1976; Ruiz-Lapuente et al., 1993). There is also a model with a sub-Chandrasekhar mass white dwarf as a progenitor of an SN Ia, wherein an explosion occurs on the surface of the white dwarf due to the ignition of the helium layer accumulated as a result of the accretion. One possible explanation of the observed relationship is that the density at which the detonation combustion is replaced by deflagration affects the amount of ^{56}Ni (the decay of which is responsible for the light curve shape of SNe Ia) synthesized in the explosion (Blinnikov and Tsvetkov, 2009). If the change of combustion modes occurs relatively late, then the outer envelope is able to expand, reducing the amount of produced ^{56}Ni. This leads to a decrease in temperature of the expanding envelope and photospheric opacity decreases rapidly. Therefore, the photosphere becomes transparent earlier and the energy is released in a short period of time. Conversely, if the detonation replaces deflagration early enough, a large amount of ^{56}Ni is produced. The result is a bright hot supernova whose opaque envelope loses energy rather slowly, which explains the slow decline rate in the luminosity for the brightest supernova light curves.

Theoretical models of the SN Ia explosion only partly explain the heterogeneity of supernovae and the origin of the relationship between the peak luminosity of SNe Ia and their luminosity decline rate after maximum light. It remains to be seen whether all or some of the proposed theoretical models can be explained by the variations exhibited.

5 CONCLUDING REMARKS

It is generally believed that SNe Ia are good 'standard candles' and can serve as distance indicators in the Universe. However, their peak luminosity differs from one SN to another. The situation was saved by the discovery of a relationship between the luminosity of SNe Ia and their decline rate after the peak brightness–a slower decline corresponds to a brighter SN. This idea originally was proposed by Bert Rust and Yuri Pskovkii in the 1970s. However, at that time the number of well-studied SNe was small and their light curves were essentially incomplete. Probably this fact was the reason why Pskovskii used the β parameter to characterize the light curves of SNe. For the observed SNe, at that time it was easier to measure the initial decline in the light curve rather than catch a SN before it reached maximum light and plot the entire light curve.

In 1993 Mark Phillips used better observational data to revise the idea proposed by Rust and Pskovskii. In his method he successfully linked the absolute magnitude of SNe Ia with a parameter Δm_{15} which indicates how many magnitudes fainter luminosity becomes in blue light during the first 15 days after the maximum light. Phillips' study revealed the same trend as previous ones.

From this time, several different concepts of the 'standardization' of SNe Ia were developed: Δm_{15} (Phillips, 1993; Phillips et al., 1999); stretch-factor (Perlmutter et al., 1997; 1999); Multicolor Light Curve Shape (Jha et al., 2007; Riess et al., 1996;); PRES (Prieto et al., 2006); Spectral Adaptive Light curve Template for Type Ia supernova (Guy et al., 2005; 2007); Color-Magnitude Intercept Calibration (Wang et al., 2003), etc. All of these 'standardization' methods allowed the determination of the distance to SNe Ia based on the relationship between various parameters, depending on the distance (maximum brightness or the average difference in magnitudes between the observed light curve and the reference light curve) or parameters that did not depend on the distance (the Colour Index, stretch-factor or Δm_{15}). Applying standardization techniques for SN Ia light curve analysis produced an improved value for the cosmological constant.

The development of new, more accurate, standardization techniques in order to use SNe Ia as reliable distance indicators is still an important task, and one which the international astronomical community is addressing in current research.

6 NOTES

1. Today S Andromedae and Z Centauri are classified as supernovae SN 1885A and SN 1895B respectively.
2. This, however, was not a cornerstone in Shapley's theory. Unlike Curtis, he was correct in placing the Solar System far out from the center of our galaxy and in his suggestion that the size of our galaxy was much larger than previously estimated. Shapley's and Curtis' estimations, of $\geq 3 \times 10^5$ and $\leq 3 \times 10^4$ l.y. respectively, were almost equally erroneous in comparison to the modern value of 10^5 l.y.
3. Although Osterbrock (2001) states that this term was first used in print in 1933 in a publication by the Swedish astronomer Knut Emil Lundmark (1889–1958; Teerikorpi, 2014), according to Zwicky (1940) it had been used from 1931 in seminars and courses given by Zwicky and Baade at Caltech.
4. The average absolute magnitude is many times fainter than the currently-accepted value because Baade used H_0 = 500 km/s/Mpc.
5. Rudolph was a nephew of a famous mathematician Hermann Minkowski (1864–1909; Hall, 2014).
6. Type I SNe spectra were decrypted later by Soviet astronomer Yu.P. Pskovskii in 1969, however the first astronomer who tried to explain the minima in Type I SNe spectra as absorption lines was Dean McLaughlin, in 1963.
7. Subtypes Ia, Ib and Ic were identified later.

7 ACKNOWLEDGEMENTS

The authors thank Professor Bert Woodard Rust for providing material from his personal archives and especially for his useful comments and interesting discussion about cosmology. Maria Pruzhinskaya acknowledges Professors V.M. Lipunov and S.I. Blinnikov for their encouragement and D.Yu. Tsvetkov for his comments that helped improve the manuscript. We acknowledge Katharine Mullen for her support, comments and writing assistance. We also thank the referees for their corrections and suggestions and Professor P. Lundqvist.

M.V. Pruzhinskaya acknowledges the support of the Mechnikov Scholarship from the French Government for a 3-month research visit to the Observatoire de la Côte d'Azur where part of this work was completed. Sergey Lisakov is supported by the Erasmus Mundus Joint Doctorate Program by Grants Number 2013-1471 from the agency EACEA of the European Commission.

8 REFERENCES

Arnett, W.D., 1969. A possible model of supernovae: detonation of ^{12}C. *Astrophysics and Space Science*, 5, 180–212.

Baade, W., and Zwicky, F., 1934. On super-novae. *Proceedings of the National Academy of Science*, 20, 254–259.

Baade, W., 1938. The absolute photographic magnitude of supernovae. *Astrophysical Journal*, 88, 285–304.

Baade, W., 1952. *Transactions of IAU VIII (1952 Rome Meeting), Report to Commission 28*. Cambridge, Cambridge University Press. P. 397.

Barbon, R., Ciatti, F., and Rosino, L., 1973. On the light curve and properties of Type I supernovae. *Astronomy and Astrophysics*, 25, 241–248.

Barbon, R., Capaccioli, M., and Ciatti, F., 1975. Studies of supernovae. *Astronomy and Astrophysics*, 44, 267–271.

Bartunov, O.S., Tsvetkov, D.Yu., and Pavlyuk, N.N, 2007. Sternberg Astronomical Institute Supernova Catalogue, and radial distribution of supernovae in host galaxies. *Highlights of Astronomy*, 14, 316.

Van den Bergh, S., 1988. Novae, supernovae, and the Island Universe Hypothesis. *Publications of the Astronomical Society of Pacific*, 100, 8–17.

Blinnikov, S.I., and Tsvetkov, D.Yu., 2009. Supernovae. In Surdin V.G. (ed.), Stars. Moscow, Fizmatlit. Pp. 349–401 (in Russian).

Boisseau, J.R., and Wheeler, J.C., 1991. The effect of background galaxy contamination on the absolute magnitude and light curve speed class of Type IA supernovae. *Astronomical Journal*, 101, 1281–1285.

Branch, D., 1981. Some statistical properties of Type I supernovae. *Astrophysical Journal*, 248, 1076–1080.

Cameron, G.L., 2014. Ritchey, George Willis. In Hockey, 1834–1836.

Colgate, S.A., and McKee, C., 1969. Early supernova luminosity. *Astrophysical Journal*, 157, 623–643.

Curtis, H.D., 1917. Novae in the spiral nebulae and the Island Universe Theory. *Publications of the Astronomical Society of Pacific*, 29, 206–207.

Durham, I.T., 2014. Minkowski, Rudolph Leo Bernhard. In Hockey, 1491–1493.

Dong, S., Shappee, B.J., Prieto, J.L., Jha, S.W., Stanek, K.Z., et al., 2016. ASASSN-15lh: A highly superluminous supernova. *Science*, 351, 257–260.

Einstein, A., 1917. Kosmologische Betrachtungen zur allgemeinen Relativitätstheorie. *Sitzungsberichte der Königlich Preußischen Akademie der Wissenschaften* (Berlin), 142–152.

Einstein, A., 1997. *The Foundation of the General Theory of Relativity. The Collected Papers of Albert Einstein. Volume 6*. Princeton, Princeton University Press.

Florence, R., 2014. Baade, Wilhelm Heinrich Walter. In Hockey, 125–127.

Foley, R.J., Challis, P.J., Chornock, R., Ganeshalingam, M., Li, W., et al., 2013. Type Iax supernovae: a new class of stellar explosion. *Astrophysical Journal*, 767, 57–84.

Gal-Yam, A., Mazzali, P.A., Manulis, I., and Bishop, D., 2013. Supernova discoveries 2010–2011: statistics and trends. *Publications of the Astronomical Society of Pacific*, 125, 749–752.

Gurshtein, A.A., 2014. Shklovsky, Iosif Samuilovich. In Hockey, 2004–2006.

Guy, J., Astier, P., Nobili, S., Regnault, N., and Pain, R., 2005. SALT: a spectral adaptive light curve template for Type Ia supernovae. *Astronomy and Astrophysics*, 443, 781–791.

Guy, J., Astier, P., Baumont, S., Hardin, D., Pain, R., et al., 2007. SALT2: using distant supernovae to improve the use of Type Ia supernovae as distance indicators. *Astronomy and Astrophysics*, 466, 11–21.

Hockey, T. (eds.), 2014. *Biographical Encyclopedia of Astronomers. 2nd Editio*n. New York, Springer.

Hockey, T., and MacPherson, H., 2014. Strömberg, Gustav. In Hockey, 2084.

Höflich, P., Mueller, E., and Khokhlov, A., 1993. Light curve models for Type IA supernovae - physical assumptions, their influence and validity. *Astronomy and Astrophysics*, 268, 570–590.

Höflich, P., and Khokhlov, A., 1996. Explosion models for Type IA supernovae: a comparison with observed light curves, distances, H_0, and q_0. *Astrophysical Journal*, 457, 500–528.

Hoyle, F., and Fowler, W.A., 1960. Nucleosynthesis in supernovae. *Astrophysical Journal*, 132, 565–590.

Hubble, E.P., 1926. Extragalactic nebulae. *Astrophysical Journal*, 64, 321–369.

Hubble, E., 1929. A relation between distance and radial velocity among extra-galactic nebulae. *Proceedings of the National Academy of Sciences of the United States of America*, 15, 168–173.

Jha, S., Riess, A.G., and Kirshner, R.P., 2007. Improved distances to Type Ia supernovae with multicolor light-curve shapes: MLCS2k2. *Astrophysical Journal*, 659, 122–148.

Khokhlov, A.M., 1991. Delayed detonation model for Type IA supernovae. *Astronomy and Astrophysics*, 245, 114–128.

Knill, O., 2014. Zwicky, Fritz. In Hockey, 2432–2434.

Kopylov, I.M., 1955a. Comparison of morphological properties and spatial distribution of novae and supernovae. *Proceedings of the Crimean Astrophysical Observatory*, 15, 140–146.

Kopylov, I.M., 1955b. Novae. In *Proceedings of the IV Meeting on Cosmogony*. Moscow: Academy of Sciences of the USSR. Pp. 40–70.

Kragh, H., 2014. Lemaître, Georges Henri-Joseph Edouard. In Hockey, 1304–1305.

Lemaître, G., 1927. Un Univers homogène de masse constante et de rayon croissant rendant compte de la vitesse radiale des nébuleuses extra-galactiques. *Annales de la Société Scientifique de Bruxelles*, A47, 49–59.

Lindner, R.P., 2014. McLaughlin, Dean Benjamin. In Hockey, 1438–1440.

Lindner, R.P., and Marché, J.D., 2014. Curtis, Heber Doust. In Hockey, 488–492.

Lipunov, V., Kornilov, V., Gorbovskoy, E., Shatskij, N., Kuvshinov, D., et al., 2010. Master Robotic Net. *Advances in Astronomy*, article id. 349171.

Lipunov, V.M., and Chernin, A.D., 2012. The Nobel Laureates in Physics in 2011. *Priroda*, 1, 108–111 (in Russian).

Livne, E., and Arnett, D., 1995. Explosions of sub-Chandrasekhar mass White Dwarfs in two dimensions. *Astrophysical Journal*, 452, 62–74.

Lynden-Bell, D., and Schweizer, F., 2012. Allan Rex Sandage. 18 June 1926 – 13 November 2010. *Biographical Memoirs of Fellows of the Royal Society*, 58, 245–264.

McLaughlin, D.B., 1945. The relation between light-curves and luminosities of nNovae. *Publications of the Astronomical Society of the Pacific*, 57, 69–80.

McLaughlin, D.B., 1963. The spectrum of the supernova of 1954 in NGC 4214. *Publications of the Astronomical Society of the Pacific*, 75, 133–148.

McVittie, G.C., 1965. *General Relativity and Cosmology*. Urbana, University of Illinois Press.

Miller, D.L., and Branch, D., 1990. Supernova absolute-magnitude distributions. *Astronomical Journal*, 100, 530–539.

Minkowski, R., 1941. Spectra of supernovae. *Publications of the Astronomical Society of the Pacific*, 53, 224–225.

Moesgaard, K.P., 2014. Brahe, Tycho Ottesen. In Hockey, 297–301.

Nomoto, K., Sugimoto, D., Neo, S., 1976. Carbon deflagration supernova, an alternative to carbon detonation. *Astrophysics and Space Science,* 39, 37–42.

Osterbrock, D.E., 2001. Who really coined the word supernova? Who first predicted neutron stars? In American Astronomical Society Meeting Abstracts, *Bulletin of the American Astronomical Society*, 33, 1330.

Phillips, M.M., 1993. The absolute magnitudes of Type IA supernovae. *Astrophysical Journal Letters*, 413, 105–108.

Phillips, M.M., Lira, P., Suntzeff, N.B., Schommer, R.A., Hamuy, M., and Maza, J., 1999. The reddening-free decline rate versus luminosity relationship for Type IA supernovae. *Astronomical Journal*, 118, 1766–1776.

Perlmutter, S., Gabi, S., Goldhaber, G., Goobar, A., Groom, D.E., et al., 1997. Measurements of the cosmological parameters Ω and Λ from the first seven supernovae at z <= 0.35. *Astrophysical Journal*, 483, 565–581.

Perlmutter, S., Aldering, G., Goldhaber, G., Knop, R. A., Nugent, P., et al., 1999. Measurements of omega and lambda from 42 high-redshift supernovae. *Astrophysical Journal*, 517, 565–586.

Planck Collaboration; Ade, P.A.R., Aghanim, N., Alves, M.I.R., Armitage-Caplan, C., Arnaud, M., et al., 2014. Planck 2013 results. I. Overview of products and scientific results. *Astronomy and Astrophysics*, 571, 1–48.

Prieto, J.L., Rest, A., and Suntzeff, N.B., 2006. A new method to calibrate the magnitudes of Type Ia supernovae at maximum light. *Astrophysical Journal*, 647, 501–512.

Pskovskii, Yu.P., 1967. The photometric properties of supernovae. *Soviet Astronomy*, 11, 63–69.

Pskovskii, Yu.P., 1969. Identification of the absorption spectrum of the Type I supernova. *Soviet Astronomy*, 12, 750–756.

Pskovskii, Yu.P., 1977. Light curves, color curves, and expansion velocity of Type I supernovae as functions of the rate of brightness decline. *Soviet Astronomy*, 21, 675–682.

Pskovskii, Yu.P., 1984. Photometric classification and basic parameters of Type I supernovae. *Soviet Astronomy*, 28, 658–664.

Rau, A., Kulkarni, S.R., Law, N.M., Bloom, J.S., Ciardi, D., et al., 2009. Exploring the optical transient sky with the Palomar Transient Factory. *Publications of the Astronomical Society of Pacific*, 121, 1334–1351.

Riess, A., Press, W., and Kirshner, R, 1996. A precise distance indicator: Type Ia supernova multicolor light curve shapes. *Astronomical Journal*, 473, 88–109.

Riess, A.G., Filippenko, A.V., Challis, P., Clocchiatti, A., Diercks, A., et al., 1998. Observational evidence from supernovae for an accelerating Universe and a cosmological constant. *Astronomical Journal*, 116, 1009–1038.

Ritchey, G.W., 1917. Novae in spiral nebulae. *Publications of the Astronomical Society of Pacific*, 29, 210–212.

Ruiz-Lapuente, P., Jeffery, D.J., Challis, P.M., Filippenko, A.V., Kirshner, R.P., et al., 1993. A possible low-mass type Ia supernova. *Nature*, 365, 728–730.

Rust, B.W., 1974. *The Use of Supernovae Light Curves for Testing the Expansion Hypothesis and Other Cosmological Relations*. Ph.D. thesis, University of Illinois at Urbana-Champaign, Urbana, Illinois; Oak Ridge National Laboratory., TN, USA.

Rust, B.W., 1975. The use of supernovae for determining the Hubble Constant and estimating extragalactic distances. *Bulletin of the American Astronomical Society*, 7, 236.

Sandage, A., 1958. Current problems in the extragalactic distance scale. *Astrophysical Journal*, 127, 513–526.

Shapley, H., 1917. A faint nova in the nebula of Andromeda. *Publications of the Astronomical Society of Pacific*, 29, 213–217.

Shapley, H., and Curtis, H.D., 1921. The scale of the Universe. *Bulletin of the National Research Council*, 2, Part 3, No. 11, 171–217.

Stromberg, G., 1925. Analysis of radial velocities of globular clusters and non-galactic nebulae. *Astrophysical Journal*, 61, 353–362.

Teerikorpi, P., 2014. Lundmark, Knut Emil. In Hockey, 1362–1363.

Thackeray, A.D., 1952. *Transactions of IAU VIII (1952 Rome Meeting), Report to Commission 28*. Cambridge, Cambridge University Press. P. 397.

Trimble, V., and Smith, H.A., 2014. Shapley, Harlow. In Hockey, 1988–1992.

Tsvetkov, D.Yu. Supernovae, http://www.astronet.ru/db/msg/1175009 (in Russian).

Wang, L., Goldhaber, G., Aldering, G., and Perlmutter, S., 2003. Multicolor light curves of Type Ia supernovae on the color-magnitude diagram: a novel step toward more precise distance and extinction estimates. *Astrophysical Journal*, 590, 944–970.

Whittaker, E., 1955. Albert Einstein. 1879–1955. *Biographical Memoirs of Fellows of the Royal Society*, 1, 37–67.

Wilson, O.C., 1939. Possible applications of supernovae to the study of the nebular red shifts. *Astrophysical Journal*, 90, 634–636.

Woosley, S.E., and Weaver, T.A., 1994. Sub-Chandrasekhar mass models for Type IA supernovae. *Astrophysical Journal*, 423, 371–379.

Zwicky, F., 1939. On the theory and observation of highly collapsed stars. *Physical Review*, 55, 726–743.

Zwicky, F., 1940. Types of novae. *Reviews of Modern Physics*, 12, 66–85.

Maria Victorovna Pruzhinskaya (below, left) was born in Syktyvkar (Russia) in 1988. She graduated from Lomonosov Moscow State University with Honours in 2011 and received a Ph.D. from this University in 2014. As a Ph.D. student she has been working in the MASTER Global Robotic Net project (Mobile Astronomical System of TElescope-Robots, http://observ.pereplet.ru/). Her Ph.D. project "Supernovae, gamma-ray bursts and accelerating expansion of the Universe" and recent research cover several aspects of supernovae and gamma-ray burst theory and observations. Maria works at the Sternberg Astronomical Institute of Lomonosov Moscow State University and at the Laboratoire de Physique Corpusculaire de Clermont-Ferrand in France.

Sergey Mikhaylovich Lisakov (above, right) was born in Leninsk, Kazakh SSR in 1990. His father was a military specialist working at Baikonur Cosmodrome. In 1992 the family moved to Moscow (Russia), where Sergey graduated from the Astronomy Department in the Faculty of Physics at Lomonosov Moscow State University. In September 2013 he started his Ph.D. research on "Core-collapse supernovae and their progenitors" at the University of Nice Sophia Antipolis in France.

Journal of Astronomical History and Heritage, 19(2), 216–232 (2016).

ASTRONOMY OF THE KORKU TRIBE OF INDIA

M.N. Vahia
Tata Institute of Fundamental Research, Homi Bhabha Road, Navy Nagar, Colaba, Mumbai 400 005, India.
Email: vahia@tifr.res.in

Ganesh Halkare
Indrayani Colony, Badnera Road, Amravati, Maharashtra, India, 444 607, India.
Email: ganeshhalkare@gmail.com

and

Purushottam Dahedar
"Antariksh", Narsih Sarswati Nagar, Narsih Sarswati Nagar, Gopal nagar area, Amravati, Mharashtra, 444607, India
Email: dahedar@gmail.com

Abstract: The Korku are an ancient tribe of India believed to be of Austro-Asian origin. They trace their origin to the eastern Indian region of Chota Nagpur but large numbers of these people are settled in the forest reserves of central India. We visited twelve villages almost exclusively populated by Korku people in Northern Maharashtra about 200 km north of the city of Amravati, and focused on recording their astronomical beliefs. While living in the same Satpuda Mountain ranges, these groups differ in their astronomical beliefs from other tribes in the region. They focus on the Big Dipper (part of Ursa Major), and also show an understanding of some other aspects of the sky. They are particularly fascinated by eclipses (but treat solar and lunar eclipses the same) and have elaborate ways of measuring time. They also are aware of conjunctions of Mars and Venus and consider these to be of importance for marriages. They also are fascinated by Taurus.

In this paper we report on the astronomical beliefs of the Korkus and compare these with the astronomical beliefs of other tribes in the region that have already been reported.

Keywords: India, Korku tribe, astronomical beliefs, Ursa Major, Taurus, conjunctions of Mars and Venus

1 INTRODUCTION

The tribes of India consist of Indo-Tibetan (or Tibeto-Burman), Indo-European, Dravidian and Austro-Asiatic (including Andamanese) (Reich et al., 2009). The Indo-European tribes are conventionally thought to be the people who travelled from northern India to the south and settled in intermediate locations where they mixed with the earlier Dravidian population (Rosenberg, et al., 2002). This is also visibile in Y chromosome studies (Sengupta et al., 2006). These locations, largely in Vindhyachal and Satpuda Mountain ranges, divide the Indian Subcontinent into two distinct parts. These ranges have been the reason for distinct identities of South and North India in terms of ancient culture and language, which were magnified by access to the sea for people living in the southern part of the Peninsula. The mountain ranges are well served by multiple rivers and their tributaries, particularly the Tapi and the Narmada. However, due to the extreme weather, where the summer-to-winter temperature difference can be >40° C, the region has not been overrun by modernisation and is sparsely populated.

In recent years, large parts of this region have been declared forest reserves and tiger reserves, which has largely prevented people from other parts of India settling in this region. Meanwhile, the original Korku residents of the forests largely have been allowed to stay in their traditional villages–except in those regions declared as 'core tiger reserves'. Villagers from these latter regions have been resettled (*en masse*) to outer parts of the forest reserves, allowing them to continue their traditional lifestyle. Tribal schools, access to modern amenities and other signs of modern civilisation are luring these groups into greater integration with Indian society, but by and large the older generation continues to adhere to the traditional lifestyle, which offers many benefits.

In view of the onslaught of modernity, however, the original lifestyle of the Korku is changing and, more importantly, their traditional knowledge is being lost. Several anthropologists—but particularly Devgaonkar and Devgaonkar (1990)—have done an admirable job in recording aspects of the social and cultural live of members of the Korku Tribe.

For our part, we have focused on Korku astronomy. This is part of a larger study of ethnoastronomy in India, and elsewhere we have recorded the astronomy of the Gonds (Vahia

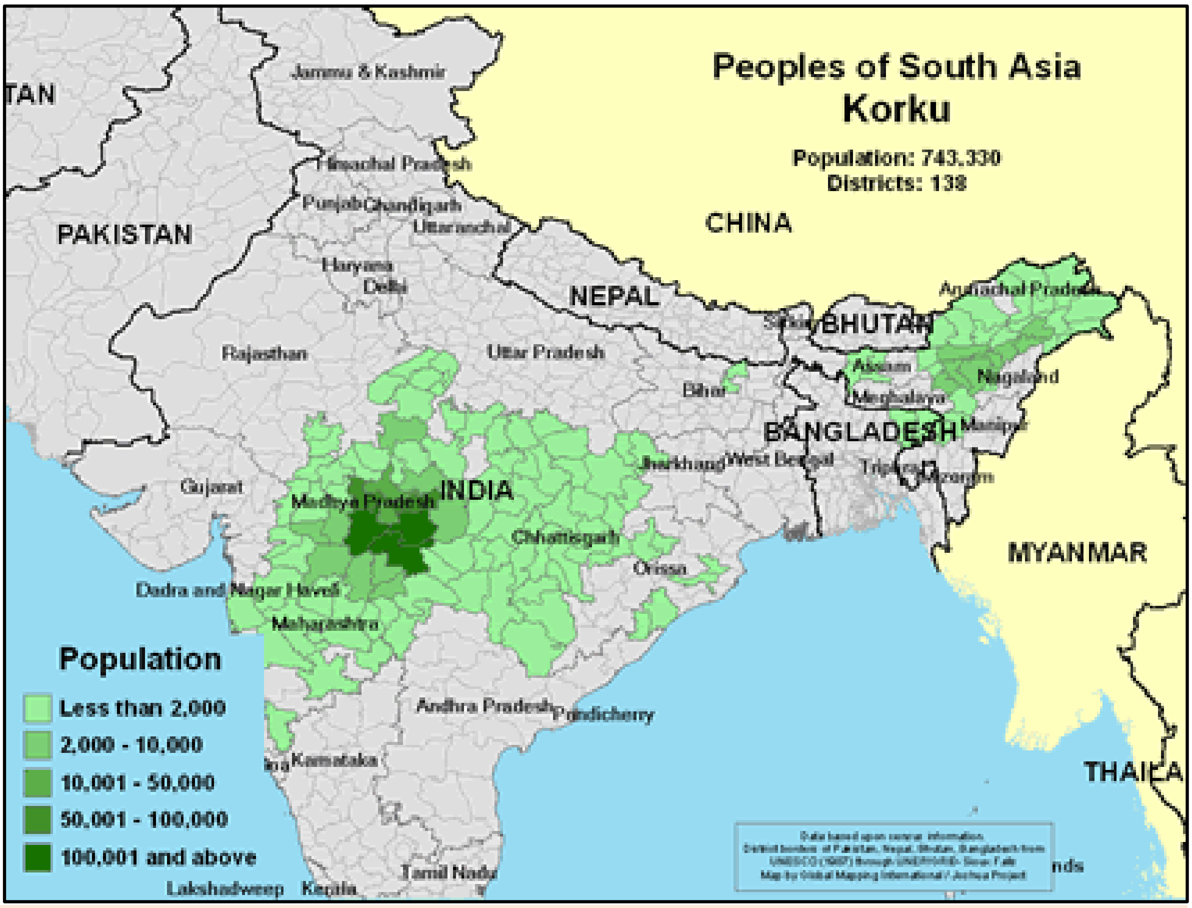


Figure 1: Geographical distribution of the Korku people (after joshuaproject.net/people_groups/17269/IN).

and Halkare 2013), the Kolams and the Banjaras (Vahia et al., 2016). In this paper we report on the astronomical beliefs of the Korkus.

2 THE KORKU TRIBE: A PROFILE

Devgaonkar and Devgaonkar (1990) have provided details of the Korku Tribe, and they have also been studied by Chaure (1987) and are briefly mentioned by Vaidyar (2008). Their currently geographical distribution is shown in Figure 1.

Although they now are largely concentrated in Central India, they have their roots in Eastern Orissa and in regions of north-eastern India (Nagaland and Arunachal Predesh) adjoining Myanmar. They belong to the Austro-Asiatic group of people, and as the earliest genetically-modern (*Homo sapiens sapiens*) 'out of Africa' migrants in the Indian sub-continent, are thought to have arrived in the region approximately 60,000 years ago (Rao et al., 2003, Reich et al., 2009, see also Chakravarti, 2009). Today, the Korku are geographically and culturally isolated from the mainstream population of India and have little contact with other groups or other tribal people (who may be of Dravidian or Indo-European origin). The Korku are by far the most western-situated of all Austro-Asians, and they belong to the Munda group of people who largely reside in Eastern India and Myanmar (Mukherjee and Chakravartti, 1964; Parkin, 1988). Another great Indian tribe, the Gonds (Deogaonkar and Deogaonkar, 1990), also live nearby in Central India.

The Korkus derive their name from the combination of the word 'koru', meaning 'man', and 'ku', which makes it plural, meaning 'tribal men' (Russell, 1916). Members of the Korku Tribe speak the Korku language, which is part of the Austroasiatic language family (Parkin, 1991). Currently, the Korku language is considered an endangered language (Sengupta, 2009). The Korku typically reside in small groups of no more than a few hundred people. Their houses are made from bamboo and other plant products and thatched with mud; in some cases cow dung is also used as a plaster.

The Korku live in a relatively arid region of India with forests and open plains. Originally they survived by scavengering and hunter/gathering, but within the last half century they have been introduced to agriculture and now live off farming and forest products. However, farming is marginal, and those who reside in forest reserves are no longer permitted to collect food from the forest, so they are forced to practise subsistence agriculture. To help compensate

Figure 2: Memorial stones for Korku people

for this ecologically-challenging existence, many Korku like to consume liquor made locally from the flowers of the *Mahua* tree.

According to a census conducted in 1991, the Korku tribe then numbered 452,149 (mptribalmuseum.com/tribes-korku.html), while the 2016 Joshua project website reports their current population as 1,015,000,000 (joshuaproject.net/people_groups/17269/IN).

The Korku bury their dead with the head to the south. This is because they believe that the gods are in the north so when the body springs to life in the presence of the gods it will look directly at the gods. The Korku erect a memorial pillar which is called *Munda*. A typical memorial for one of their dead is shown in Figure 2. These typically consist of a wooden staff with markings of gods and the dead (see Gordon, 1936 for further examples).

2.1 Genetic Data

In a recent study (Nayak and Das, 2015) showed that genetically the Korku are related to other Munda Austro-Asiatic tribes. Earlier, Rao et al. (2003) reported an extensive study of the genetic make-up of the Korku. They concluded that the Korku showed evidence of demographic expansion, consistent with a long history of migration and an origin in western Orissa (ibid.). Deora and Zade (2014) have studied the sickle cell disease amongst the Korku and suggested that this is a cause of the high infant mortality that typifies the tribe.

3 KORKU ASTRONOMY

In order to study Korku astronomy over a period of three days we travelled ~1,000 km within the region of northern Maharashtra, north of Amaravati city. Between 31 May and 4 June 2016 we visited ten villages where there was a pure Korku population that was not mixed with other communities. This was preceded by a survey study of two villages on 23 and 24 May 2016. Details of our visits, including the village names and other data, are given in the Appendix.

Details of Korku astronomical beliefs and the villages where these were recorded are listed in Table 1 below. The villages in the list are respectively Zingapur, Rani Tamboli , Kawadaziri ,

Table 1: A summary of the astronomical beliefs of the Korku tribe.

Belief	Village												
	1	2	3	4	5	6	7	8	9	10	11	12	total
Milky way													
As path	1	1		1	1	1		1	1	1		1	9
Story of Elder brother and younger man's wife					1	1		1				1	4
As council of gods	1												1
Big Dipper													
The quadrilateral of Big Dipper as Golden Cot	1	1	1	1	1	1	1	1	1	1	1	1	12
Three trailing stars of Big dipper as thieves	1	1	1	1	1	1	1	1	1	1	1	1	12
Deformation of bed					1	1			1	1			4
Servants on the cot		1						1					2
Water bearer in the middle of the trailing star	1					1		1		1	1		5
As clock in the night				1	1	1			1				4
Polaris													
name	1	1											2
Mythology		1											1
Orion													
Plough	1	1	1	1	1	1	1	1	1	1	1	1	12
Bullocks	1	1	1		1	1		1		1			7
Man								1		1			2
Eggs (Head of the Orion)				1	1	1							3
Knowledge about it is not seen April to October	1	1	1	1	1	1		1	1	1			9

Belief	Village											
Myth about why it is not seen April to October					1	1							2
Whip to scare the birds								1				1	2
Pleiades													
Earthworm	1												1
Minced meat of cow		1	1	1	1	1					1	1	7
As a tool to remove husk							1	1	1	1			4
Canis Minor													
Bird	1							1	1	1			4
Eggs	1							1		1			3
Tree										1			1
Auriga – Gemini													
Well	1		1					1	1			1	5
Ladies taking water from the well	1		1					1	1			1	5
As bird nest											1		1
Taurus													
Other identification	1												1
Aldebaran as cowherd		1											1
As a place for grinding								1	1				2
Family								1					1
Scorpius													
Scorpius in the lower part	1			1	1				1				4
Complete Scorpius								1		1			2
Crux													
Dagger	1												1
As *Mahua* tree									1				1
Have a story associated with it	1								1				2
Virgo													
Linga	1												1
Moon													
Have a name for name	1	1	1	1	1	1	1	1	1	1	1	1	12
Give importance to glow around the Moon	1	1	1	1		1		1	1	1			8
As monsoon predictor	1	1	1	1		1		1	1	1			8
Mythology		1			1			1					3
Sun													
Name	1	1	1	1	1	1	1	1	1	1	1	1	12
Mythology		1						1					2
Eclipse													
As myth	1	1			1	1		1	1	1	1	1	9
Tool to track eclipse using a shaft	1			1	1	1	1	1	1	1			8
Omen for Eclipse	1	1		1	1	1		1	1				7
Venus													
As morning star	1		1	1	1	1	1	1	1			1	9
As evening star					1	1	1	1	1				5
Venus as cowherd					1	1							2
Mars													
Name			1		1	1	1	1	1				6
Conjunction of Mars and Venus													
As a time for marriage					1	1	1	1	1				5
Comet													
Star with tail	1	1	1					1	1	1	1		7
As broom				1	1	1							3
Omen for Comet	1				1			1	1				4
Meteor													
As excreta of stars	1	1	1	1	1	1	1	1	1	1	1	1	12
As a falling star	1												1
As a reminder of death of some important person		1							1				2

Makhala, Raipur, Borata Kheda, Bela, Jamunala, Baghalinga, Gaulkheda Bazar, Hatida and Gadgabhandum. They appear in the same sequence in the Appendix. Of these villages, Bela, Jamunala, Baghalinga and Gaulkheda Bazar (7–10 respectively) are located on the plains, while the others are within forest reserves.

Here we discuss the major Korku beliefs that were recorded in several villages. We begin with the Milky Way and conclude with Solar System objects. The relative importance of each belief can be gauged from the number of villages that repeat a particular story (see Table 1).

The Milky Way is recognised as a path, but many villagers were uncertain about the travellers on this path. However, several villagers told us that the Milky Way had two paths. On the primary path a gentleman was walking and when he encountered the wife of his younger brother she had to change to a subordinate path. One village also told us about the Milky Way as the meeting place of the Gods, who decide on the allocation of all the human needs.

The most commonly-held belief is about the Big Dipper part of Ursa Major (Figure 3). As with many other cultures in Central India (see Vahia and Halkare, 2013; Vahia et al., 2014), the Korku identify the four primary stars of the Big Dipper (Dubhe, Merak, Phecda and Megrez) as a cot, and the following stars, Alioth, Mizar, Alkaid, as three people trying to steal the cot. However, the stories vary in detail. The cot is believed to be made of gold and it is acknowledged that it does go below the horizon (unlike the Gonds, who insist that the lady in the cot never sleeps as it does not go below the horizon; see Vahia and Halkare, 2013). Also, the occupants of the cot are different for the Korku. In most villages they are undefined, but in two villages they reportedly are servants who need to get up in the morning and start work. In five villages the Korku also identify the double star Mizar, and call it a water jug. They also recognise the 'deformed' nature of the bed, caused by its being tugged by the thieves.

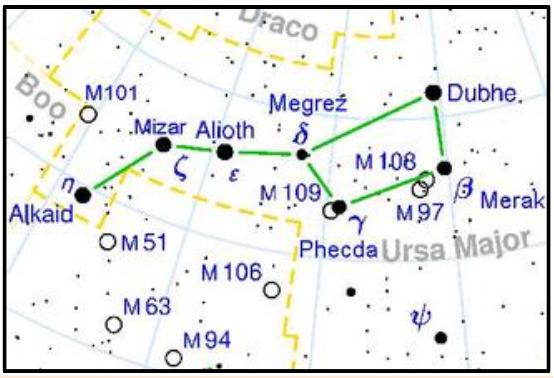


Figure 3: Big dipper part of Ursa Major (en.wikipedia.org).

The Korku also are fascinated by the Orion region. They identify the belt of Orion as the plough, and Rigel and Saiph as bullocks, even though their involvement in agricultural activities is a relatively recent phenomenon. Betelgeuse is identified with the man ploughing the field. They can see a whip in the fainter stars of Orion, near Bellatrix, while some villagers (all living in the forest) can see birds' eggs at the head of Orion (near Meissa). Many villages know that Orion is not visible (at all) from April to October, and a few of them suggested that this is because the gods do not want humans to copy the gods' own plough. Very few Korku identified Taurus, but the Pleiades were identified in seven forest villages as the location of minced cow meat, while four villages identified it as a tool for beating wheat to remove the husk.

One major surprise was the identification of Auriga, as well as Castor and Pollux (the brightest stars in the constellation of Gemini). The Korku identify Auriga as a well of water (to be used for the farming activites that are done by Orion) and Castor and Pollux as two ladies who bring water from the well.

Several villages were familiar with *Bichu*, and identified it as the local name for Scorpius or a region close to Scorpius (generally near the tail of the scorpion). Based on these and other descriptions, in Table 2 we list the names of various stars identified by the Korku, and their conventional names. The magnitudes in this table are taken from Stellarium.

As regards the Sun and Moon, the Korku have an interesting tale. They say that amongst all the gods who influence our lives (see the creation myth below), only the Sun and the Moon are visible. Both are sons of a common mother. At one time the mother sent her children to attend a religious festival where some food was distributed. She asked them to bring back some food for her. In one version, the Sun ate all the food he collected, stole the food saved by the Moon, and then presented this to their mother. The mother, unaware of the treachery, blessed the Sun with brightness while cursing the Moon and causing it to wax and wane. In another version, since the Sun did not bring back any food, it was cursed to be burning hot while the Moon lived a more soothing life. The Korku believe that the Sun and Moon, being the guardian gods of humans, absorb human sins and when these overflow, an eclipse occurs. Then a demon tries to eat the Sun or the Moon. In some villages, the demon eating the Sun or the Moon is recited without the accompanying that during an eclipse they must take a long wooden pestle used to grind food and put it on a

Table 2: Korku star names of and their Western equivalents.

Korku names for stars	Conventional names of stars	Apparent Magnitude
Southern Sky		
Dhanay	Rigil Kent (α Cen)	0.10
Charakhaya	Hadar (β Cen)	0.55
Bharada	ε Cen	2.25
Pechla	Menkent (θ Cen - 5 Cen)	2.05
Northern sky		
Dhur tara	Polaris (α UMi - 1 Umi)	1.95
Pahila chor (thief 1)	Aloth (ε UMa)	1.75
Dusara chor (thief 2)	Mizar (ζ UMa)	2.20
Kaseti or *Dhona* or *Ghanti* (bell) or *Kudapa* or *dadudi* (water jar)	Alcor (80 UMa) (binary to Mizar)	1.96
Tisara chor (thief 3)	Alkaid (η UMa)	1.85
Well and water		
Kunva (well)	Constellation Auriga	-
Reike (water bearer)	Castor (α Gem)	1.90
Chaike (water bearer)	Pollux (β Gem)	1.15
Farming scene		
Harnangar (plough)	Alnitak (ζ Ori), Alnilam (ε Ori) and Mintaka (δ Ori)	1.85, 1.65, 2.40
Doba 1 (bullock)	Rigel (β Ori)	0.15
Doba 2 (bullock)	Saiph (κ Ori)	2.05
Nangarnara manus (the person ploughing the field)	Betelgeuse (α Ori)	0.45
Arrangement for separating seeds from whey		
Circular ground for thrashing rice husk (*Khiryan*) beater using cow (*Khiryan*)	Aldebaran (α Tau), Ain (ε Tau), Hyadum II (δ1 Tau), Hyadum I (γ Tau)	0.85, 3.50, 3.75, 3.65
Michan (rope to control the bulls)	Tabit (η3 Ori) and stars around it	3.15
Miryan (Central pole)	θ2 Tau	3.40
Bird and eggs		
Pankheru (bird)	Sirius (α CMa)	–1.45
Bhori Aakom (eggs)	Meissa (λ Ori) and stars around it	3.50
Bhori Aakom (alternate)	Wezen (δ CMa) and Adhara (ε CMa)	1.80, 1.50
Family and gods		
Pati (husband)	κ1 Tau (just north of Aldebaran)	420, 4.25
Patni (wife)	μ Tau	4.25
Mulga (son)	72 Tau	5.50
Diya Gomez (god of the day)	Sun	
Rata Gomez (god of night)	Moon	
Pleiades		
Gai Jijulu, *Kuthali Ku*, *Gaikasai* (all implying minced meat of the cow)	Pleiades	-
Bhotmongari (tool to beat husk to remove husk)	Pleiades	-
Gugul gothu	Pleiades	-
Miscellaneous		
Kiding, *Clemp*	Tail of the Conventional Scorpius	-
Nangi	Corona Austrialis	-
Tree of *Mahua*	Constellation of Lupus	-
Devgan Panchayat, assembly of gods	In the Milky Way near Scorpius.	-

plate with water. As long as the eclipse is happening, they believe that this implement will remain upright on its own (see Figure 4). At the end of the eclipse it will fall, and some people believe that the direction in which it falls indicates the direction from which air-borne diseases will arrive.

Another interesting aspect of Korku astronomy is that many people are aware of Venus, both as an evening and a morning star. But they have an additional myth. They say that there is another nearly-stationary star of *equal brightness* (we suspect Mars) in the sky and Venus moves close to and away from this. When the two stars are close, it is a celestial suggestion that marriages may be arranged at this time. When they are far away, it is a bad time for marriage.

The Korku consider a comet to be a star with a tail, or a broom star, and have no strong feelings about it in terms of omens. They believe that a meteor is an stellar excreta. In two villages the people said that a meteor indicated that somewhere a good person had died.

The Korku are aware of the rainbow and have a variety of beliefs about it. They believe that at either end of the rainbow there is an anthill, and if the anthill is dug into you get small soft nuggets of great value. Some believe that if a rainbow is seen during the monsoon, the rains will halt.

Some of the common songs of the Korku also invoke the Sun and Moon gods, seeking their blessings (Fuch, 2000).

4 DISCUSSION

4.1 The Creation Myth

The Korku have a unique creation myth. They believe that when God wanted to create humans, he sent out a crow to get some soil. While getting the soil, the crow dropped some of it along the way and that became the Earth. From the remaining soil the Great God (*Mahadeo* or *Shiva*) fashioned a man and a woman. However, every time he made them, other beings would come at night and destroy them. So Shiva's wife (*Parvati*) created a dog that guarded the man and woman and hence dogs are man's best friend. Once they were given life, there was a dilemma since all humans were brothers and sisters and could not inter-marry. So the humans went back to God, and he created a massive storm and everyone hid behind different objects (e.g. rocks, rivers, trees, some crops, etc.). There were 12½ such objects (half for the neuter gender). When the storm abated, God decreed that each group would get a name based on the object they had hidden behind, and the people who had hidden behind different objects could marry one another but those who had hidden behind the same object could not (see also Fuchs, 1946).

Figure 4: A photograph showing the procedure adopted during an eclipse

There is another story, which justifies the Korku passion for alcohol and hallucinogens. *Shiva* was instructed by his wife that he must always knock before coming into the house. Once Shiva forgot and entered without knocking only to find *Parvati* lying naked on her bed. She was very angry and told him off. He then left, and went away determined not to return. *Parvati* regretted her outburst, and tried to make peace with *Shiva* by sending various emissaries. She sent a dog and a tiger, but both were rebuffed. She then sent a naked female wild ass. *Shiva* simply put a cloth around its waist and sent it back to *Parvati*. At this stage other gods offered to step in and help resolve the problem. They threw a big party with alcohol and hallucinogens. *Shiva* came to the party and was happy to join in, and peace was restored between *Shiva* and *Parvati*.

4.2 The Forest versus the Plains and Korku Astronomy

Until agriculture was introduced, the forest and the plains offered the Korku totally different ecological regimes, but this is not clearly reflected in the range of astronomical beliefs listed in Table 1. While some beliefs, such as eggs seen in Orion or the bird's nest seen in Auriga were only reported by forest villagers, and are easily associated with a forest environment, minced cow meat and cowherds—also reported only in forest villages—are not. These relate more to a pastoral existence, which was only introduced to the Korku with agriculture. Meanwhile, other typical forest elements, such as the bird and eggs seen in Canis Minor, were reported by forest and plains villagers.

On the other hand, given that agriculture is now the subsistence base of the Korku living on the plains, it is no surprise that there are clear agricultural associations with the tool used for removing the husk from wheat seen in the Pleiades and reported (only) by all four plains villages; the ploughsman in Orion claimed by two of the four plains villages; and a place in Taurus where grain is crushed—also noted by informants from two plains villages. But all other obvious references to agriculture (in Orion, Gemini, and during eclipses) were reported at forest *and* plains villages. This is unexpected given the recent introduction of agriculture (and pastoralism) among the Korku, and is best explained as a relic of ealier times when their Astro-Asian ancestors in Nagaland, Orissa and even further east in South East Asia practiced agriculture.

Finally, it is a little surprising that the *Mahua* tree (seen in Crux) was only reported by one village, which was located on the plains. Apart from the production of alcoholic beverage, the flowers were used for medicine and jam, while the fruit provided a skin cream, soap, detergent, vegetable butter and fuel oil. The seed cakes made excellent fertilizer, and the bark also had medicinal properties (see https://en.wikipedia. Org/wiki/Madhuca_longifolia). As elsewhere in

Central India, surely this remarkable multi-functional native tree was highly prized by the Korku, and was cultuivated both on the plains and in the forest.

5 CONCLUDING REMARKS

We have presented a summary of the most important astronomical beliefs of the Korku Tribe that now resides largely in forest reserves in Central India. The Korku are believed to be the western-most of the Austro-Asian group of people called Munda who largely reside in eastern parts of India. Other Austro-Asians are found further afield, in Myanmar and in pockets throughout South East Asia.

Apart from sharing some commonly-held beliefs found elsehwere in Central India about the Big Dipper, the Korku have an interesting visualisation of the Orion-Taurus-Auriga-Gemini region. They identify Auriga as a well, which is unusual, as is their identification of Castor and Pollux as two women taking water from the well. Yet these elements surely reflect the importance of water for successful agricultural production. The identification of mashed cow meat in the Pleiades by the Korku also is interesting. The Korku also recognise the existence of Venus but note that the distance between it and another object, which we identify as Mars, varies. A conjunction of these planets occurs about every 1.7 years, which marks the marriage season.

Finally, we can see that Table 1 reveals an interesting mixture of forest and plains elements, but the interpretation of these is not always straightforward if we simply view Korku astronomy in a contemporary context. It only makes sense when we see the Korku in a chronological light, and allow for the transmission of an ancestral astronomical knowledge base that was prevalent elsewhere in South East Asia and came to Central India when the Korku settled this region. This is comparable to the preservation of the Proto-Polynesian concept of an historic supernovae, which may be represented by the term *Mahutonga* in Maori astronomy (see Orchiston 2016: Chapter 3).

6 ACKNOWLEDGEMENTS

We wish to thank all of these villagers listed in the Appendix who kindly provided information for this study, and the referees for their helpful comments. We also are grateful to Professor Wayne Orchiston for his suggestions, and for kindly supplying Section 4.2 and part of Section 5.

7 REFERENCES

Baig, M.M., Khan, A.A., and Kulkarni, K.M., 2004. MItochndrial DNA diversity in tribal and caste groups of Maharashtra (India) and its implications on their genetic origin. *Annals of Human Genetics*, 68, 453–460.

Chakravarti, A, 2009. Tracing India's invisible threads. *Nature*, 461, 487–488

Chavan, R.R., and Surve, A.Y., 2015. Socio-economic status of the undergraduate and postgraduate scheduled tribe students in Khandesh region of Maharashtra State. *International Journal of Development Research*, 5, 3675–3680.

Chaure, N., 1987. *Korku janajati ka sanskrutik itihas.* Nagpur, Vishwa Bharati Prakashn (in Hindi).

Deogaonkar, S.G., and Deogaonkar, S.S., 1990. *The Korku Tribe*. New Delhi, Concept Publishing Company.

Deora, A.U., and Zade, S.B., 2014. Distribution of sickle cell gene in Korku tribe of central India. *National Journal of Community Medicine*, 5, 270–272.

Fuchs, S., 1946. What some tribes and castes of Central India think about God. *Anthropos*, 41/44, 883–887.

Fuchs, S., 2000. Thirty Korku dancing songs. *Asian Folklore Studies*, 59, 109–140.

Gordon, D.H., 1936. Korku memorial tablets. *Man*, 36, 17–19.

Jagtap, S.D., Deokule S.S., and Bhosle S.V., 2008. Ethnomedicobotanical uses of endemic and RET plants utilised by Korku tribe of Amravati district, Maharashtra. *Indian Journal of Traditional Knowledge*, 7, 284–287.

Mukherjee, D.P., and Chakravartti, M.R., 1964. A dermatoglyphic approach to the mundari ethnic problem. *Zeitschrift für Morphologie und Anthropologie*, 55, 32–45.

Nayak, J.K., and Das, P.K., 2015. Genetic diversity of Hill-Banda tribal population of Odisha with reference to ADH and ALDH2 gene variants. *European Journal of Molecular Biology and Biochemistry*, 2, 106–110.

Orchiston, W., 2016. *Exploring the History of New Zealand Astronomy: Trials, Tribulations, Telescopes and Transits*. Cham, Springer.

Parkin, R.J., 1988. Behaviour and feneration among the Munda of Eastern India. *Zeitschrift für Ethnologie*, 113, 67–85.

Parkin, R.J., 1991. *A Guide to Austroasiatic Speakers and their Languages.* Honolulu, University of Hawaii Press (*Oceanic Linguistics Special Publications*, 23).

Rahmann, R., 1959. Shamanistic and related phenomena in Northern and Middle India. *Anthropos*, 54, 681–760.

Rao, R., Thangaraj, K., Reddy, A.G., Sridhar, V., and Singh, L., 2003. Pairwise MtDNA-HVRII sequence differences and geographic maternal distances among Korku, an Austro-Asiatic tribe in Central India. *Indian Journal of Human Genetics*, 9, 25–28.

Reich, D., Thangaraj, K., Patterson, N., Price, A.L. and Singh, L. 2009, Reconstructing Indian population history. *Nature*, 461, 489–494.

Rosenberg, N.A., Pritchard, J.K., Weber, J.L., Cann, H.M., Kidd, K.K., Zhivotovsky, L.A., and Feldman, M.W., 2002. Genetic structure of human populations. *Science*, 298, 2381–2385

Russell, R.V., 1916. *Tribes and Castes of the Central Provinces of India. Volume III*. London, Macmillan.

Sengupta, P., 2009. Endangered languages: some concerns. *Economic and Political Weekly*, 44(32), 17–19.

Sengupta S, et al. [15 authors], 2006. Polarity and temporality of high-resolution Y-chromosome distributions in India identify both indigenous and exogenous expansions and reveal minor genetic influence of Central Asian pastoralists. *The American Journal of Human Genetics*, 78, 202–221.

Vahia, M.N., and Halkare, G., 2013. Aspects of Gond astronomy. *Journal of Astronomical History and Heritage*, 16, 29–43.

Vahia M.N., Halkare G, Menon K., and Calamur H., 2014. Astronomy of two Indian tribes: the Banjaras and the Kolams. *Journal of Astronomical History and Heritage*, 17, 65–84.

Vahia M.N., Ramachandran, V.S., Gangopadhyay, J., and Joseph, J., 2016. The Cholanaikkan Tribe of Kerala. Submitted to *Current Science*.

8 APPENDIX: KORKU VILLAGES NEAR AMRAVATI, MAHARASHTRA VISITED IN THE PRESENT STUDY

For the location of the study area in Central India see Figure 5 below.

Village 1: Zingapur

Post Popatkheda
Taluka Chikhaldara,
District Amravati,
Population: 375
How to reach: From Amravati go to Paratwada and then take the Paratwada Akot State Highway. On this road one comes to a junction called Divthana. From that junction, coming from Partwada, the town is on the right, about 11 km off the Highway.
GPS location 21° 13.218′ N; 77° 6.737′ E; ~310 meters above msl.
Date of visit: 31 May 2016

Name and age of persons interviewed:

1) Babulalji Baba Kasdekar – age 70 years
2) Raju Mula Gavate – age 70 years
3) Motiram Hore Chilatre – age 50 years
4) Madhukar Bhaku Chilatre – age 55 years
5) Sudhakar Madhukar Chilatre – age 35 years

Astronomical beliefs:

1) The first four stars of the Big Dipper are part of Ursa Major (see Figure 3) and are called *Sona Parkom* (i.e. the bed of gold). The three following stars are three thieves. The middle one (which is a binary) has a bell (called *Kasati*) and the last one has a little container made from a pumpkin for carrying water (called *Da dudi*).
2) They refer to Venus as *Suko.*
3) They refer to the Sun as *Diya Gomej* and the Moon as *Thendej* or *Rata Gomej.* *Gomej* means God; *Diya* means day; *Thandage* means darkness and *Rata* means night.
4) They call the Pole Star *Dhoor* (which is similar to the Sanskrit name for Polaris).
5) They refer to the belt of Orion as *Harnangar*—a plough with three blades.
6) They consider Auriga as a well, and they refer to the two main stars of Gemini, Castor and Pollux, as the two water-bearer ladies (*da Hinda*) taking water from the well. Their individual names are *Raike* and *Chaike*.
7) They consider the circle at the top of Virgo to be the place where the *Shivalinga* is placed.

Figure 5: Map showing the study area in Central India.

8) The first four stars of the Big Dipper are part of Ursa Major (see Figure 3) and are called *Sona Parkom* (i.e. the bed of gold). The three following stars are three thieves. The middle one (which is a binary) has a bell (called *Kasati*) and the last one has a little container made from a pumpkin for carrying water (called *Da dudi*).
9) They refer to Venus as *Suko.*
10) They refer to the Sun as *Diya Gomej* and the Moon as *Thendej* or *Rata Gomej. Gomej* means God; *Diya* means day; *Thandage* means darkness and *Rata* means night.
11) They call the Pole Star *Dhoor* (which is similar to the Sanskrit name for Polaris).
12) They refer to the belt of Orion as *Harnangar*—a plough with three blades.
13) They consider Auriga as a well, and they refer to the two main stars of Gemini, Castor and Pollux, as the two water-bearer ladies (*da Hinda*) taking water from the well. Their individual names are *Raike* and *Chaike*.
14) They consider the circle at the top of Virgo to be the place where the *Shivalinga* is placed.
15) They know the two main stars of Canis Minor as a bird and egg (while most people in the group agreed, a few of them had doubts about its exact location).
16) They refer to Taurus as *gai jijilu*—the mashed meat of the cow.
17) They know the Pleiades as *gugul gotho* (the earth worm).
18) They know Crux as a dagger (*katri*) with a lemon at the tip that is used in marriage ceremonies.
19) Among the Korku, the groom is required to pay the bride's family certain predecided money or perform labour for the bride's family in order to win the bride. In order to remind people of the importance of this payment, they have a story taken from the sky:

    > To the east of Crux they identify two couples, *Dhanaya* (a female identified with 0.1 magnitude Rigil Kent), who is married to *Bharada* (a male, identified with the Greater Coucal bird here on Earth and with ε Cen, a 2.25 magnitude star in the sky), and *Dhanaya's* younger sister *Charakhaya* (a female, identified with Hadar) who is married to *Pelcha* (identified with the Red Whiskered Bul-bul bird here on Earth) and with Men-kent, a 1.01 magnitude star in the sky. The story is that *Pechla* (Menkent) did not pay the amount he had to pay for his bride *Charakhaya* (Hadar) and hence *Charkhaya* ate a betel leaf (which gives a red colour to the mouth) and spat on *Pechla*. On earth *Pechla* is identified with the Bulbul which has a red vest. This essentially emphasizes the need to pay for the bride as promised, or face life-long consequences.

20) They identify Corona Australis (just south east of Scorpius) as the *kidding* (Scorpio and the classical Scorpius as the fang of the scorpion).
21) They consider the Milk Way as a crowded path (*Rahadari Kora*). The Milky Way near Scorpius and between Scorpius and Crux is considered a place where the Gods (*Devgan Panchayat*) hold their meetings to discuss issues of importance to the Earth. Various forces such as diseases, water, wind, etc. seek permission from the gathering to go to Earth and the Gods decide which should go.
22) They refer to a comet as a star with a tail (*churia ifil*) and are ambivalent about its nature but somehow consider it a bad omen.
23) They do not distinguish between solar and lunar eclipses. Eclipses brings poison to the Earth.
24) They consider a meteor simply as a fallen star, without any association.
25) They use the glow around the Moon to decide on the season–a compact, yellow ring close to the Moon is bad for the monsoon while a large white ring will bring rain.
26) They consider a conjunction of Mars and Venus as very important, and if they are close to each other one can expect a good marriage season.
27) They bury their dead in a north-south direction, with the legs to the north.
28) They sleep with their legs to the south.
29) For weddings they create a special wooden pillar with markings for the Sun and the Moon.

Village 2: Rani Tamboli

Post: Rani Tamboli
Taluka Dharni
District Amaravati
Population: About 1,300
How to reach: Amravati to Dharni is 168 km. From Dharani, to Titamba Road, Rani Tamboli is about 7 km away.

GPS location: 21° 30.052′ N; 76° 53.216′ E; 332 meters above msl.
Date of visit: 1 June 2016

Name and age of persons interviewed:

1) Loma Gopal Dhruve (Kasdekar) – age above 90 years
2) Movya Bhonya Jambekar – age above 90 years
3) Ramu Bhau Kasdekar – age 85 years
4) Surajlal Onkar Bhilavekar – 60 years

Astronomical beliefs:

1) They confirmed the story of the Big Dipper as the golden cot pursued by three thieves.
2) A servant couple (*Bhagya* and *Bhagini*) sleep in the quadrilateral in the Big Dipper and guard the cot. However, they need to get up to go and to collect *Mahua* (*Madhuca longifolia*) seeds when they see the Morning Star. But by then the Sun has risen in the sky and the thieves go away.
3) They confirmed that the Milky Way is a path (with an unspecified purpose).
4) The Milky Way has two paths on which the elder brother (*Jeth*) and the wife of his younger brother (*Bahu)* walk. Since, as per Kurku custom, she cannot cross *Jeth's* path, she has to go another way and hence the Milky Way is bifurcated.
5) They confirmed that the belt of Orion was the plough, but added that Rigel and Saiph are the two bullocks pulling the plough. They refer to these bullocks as *Doba*.
6) They identified the Pleiades as the minced meat of a cow (*gai jijilu*).
7) They identify Aldebaran as a cowherd (*bailmarya tara*).
8) They believe that there are many Gods, but when responsibilities were being distributed amongst gods, only the Sun and the Moon took responsibility for humans. Hence of all the Gods, only the Sun and the Moon are visible to humans.
9) They appreciate the fixed nature of Polaris and suggest that when a person can no longer see it, then he or she is on their deathbed.
10) They identify a small close circle around the Moon (called *Mandal*) as bad for rains, and a large outer ring as good for rains.
11) They consider a comet to be a star with a tail (*churya ifil*).
12) They consider a meteor (*ifil bocho*) as stellar excreta, and an indication that a good man has died somewhere on this Earth.
13) They consider eclipses (solar and lunar) as bad omens that bring epidemics.
14) They believe that at the base of a rainbow there exists an anthill and if this anthill is explored they will find small nuggets of great medical value.

Village 3: Kawadaziri

Post: Titambi
Taluka Dharni
District Amaravati
Population: 325
How to reach:
Amaravati to Dharani (150 km) then to Titamba (30 km) and from TItamba Kawadazili is 8 km.
GPS location: 21° 23.882′ N; 76° 54.881′ E; 462 meters above msl.
Date of visit: 1 June 2016

Name and age of persons interviewed:

1) Tumba Mithua Mavaskar - age 85 years
2) Babulal Dahalu Mavaskar - age 70 years
3) Mansaram Dahulu Mavaskar - age 65 years

Astronomical beliefs:

1) They confirm that the four stars of the Big Dipper that make a quadrangle are a bed of gold, with thieves following it.
2) They identify Orion with a plough and Rigel and Saiph as bullocks.
3) They identify Auriga as the well. They add that when it is seen in the west at sunset the monsoon will arrive.

4) They identify Castor and Pollux as two ladies taking water from the well.
5) They identify Venus (*Suko*) as a star and Mars as the Red Star (*Laal Suko*).
6) They identify the Pleiades as the minced meat of the cow.
7) They cannot identify Scorpius (*kiding*).
8) They identify rings around Moon and mention that the rings have different colours. A large circle implies a good monsoon, and a small ring a bad monsoon.
9) They are vague about meteors and comets, and indifferent to eclipses.

Village 4: Makhala

Post: Semadoh
Taluka: Chikhaldara
District: Amaravati
Population: ~900
How to reach: Amaravati to Semadoh and then 10 km from Semadoh is Makhala.
GPS location: 21° 31.7′ N; 77° 22.89′ E; 955 meters above msl.
Date of visit: 1 June 2016.

Name and age of persons interviewed:
1) Chandan Babu Bethekar - age 70 years
2) Wishram Babulal Kasdekar - age 65 years
3) Jajunu Babu Bethekar - age 65 years
4) Gunu Babanu Bethekar - age 65 years
5) Shivkali Sajju Selokar - age 45 years
6) R M Barde - age 57 years
7) Shankar Ringjuji Darsimbe - age 44 years

Astronomical beliefs:
1) They confirm that the first four stars of the Big Dipper are a golden cot that is being pursued by three thieves.
2) They recognise the belt of Orion as *Harnagar*—the plough.
3) They recognise the head of Orion as *Bhori Akkam*—the eggs of a bird.
4) They recognise the Pleiades as the minced meat of a cow.
5) They recognise the morning star (Venus) as *Suko.*
6) They identify a scorpion in the sky in the Scoprius-Corona Australis region and consider the classical Scorpius as its fang.
7) They recognise the Milky Way as the path (*Raha dando*) to heaven.
8) They interpret a comet as a broom star.
9) They consider meteors as excreta of the stars.
10) They recognise that a glow close to the Moon means poor rains while a wide ring around the Moon means good rain.
11) They have a custom of taking wooden pestle and putting it in water during an eclipse, and they insist that during the eclipse it will stand up by itself. Only when the eclipse ends will it fall, and airborne infections or epidemics will come from the direction in which it falls.
12) They also confirm that human burial is in the north-south direction, with the legs to the north.

Village 5: Raipur

Taluka: Chikhaldara
District: Amravati
Population: ~1,000
How to reach: Amravati to Semadoh (110 km) and then on Raipur Road (16 km)
GPS location: 21° 34.905′ N; 77° 16.068’ E; 553 meters above msl.
Date of visit: 2 June 2016

Name and age of persons interviewed:
1) Babu Bhau Semalkar - age 67 years
2) Motilal Dadu Dhande - age 65 years
3) Kande Bhau Semalkar - age 55 years
4) Manag Bhau Dhande - age 68 years
5) Sanu Bhurya Dhande - age 68 years
6) Manu Lala Sawalkar - age 70 years

Astronomical beliefs:
1) They confirm that the Big Dipper is golden cot with three thieves trying tosteal it. They suggest that the cot is not a rectangle since the first thief is trying to pull it.

2) They use the Big Dipper as a clock in the sky.
3) They confirm that the belt of Orion is the plough (*Harnangar*).
4) They recognise that Orion is not seen from April to September. This is because in April people plough the fields and if they see the heavenly plough they will imitate it. Hence the Gods hide the plough during these months.
5) They identify *Bhori Akkom*—bird eggs at the head of Orion.
6) They identify the conventional Scorpius as the true Scorpius.
7) They recognise the Pleiades as the minced meat of a cow.
8) They refer to Venus, the morning and evening star, as *Suko*. If it is seen in the morning, it marks the beginning of the day and if it is seen in the evenings then its appearance marks the time when shepherds return home.
9) They have a concept of a star of marriage (*lagin tara*). This is the time when Venus and Mars are in conjunction (Note: this will happen once every 1.7 years!). Hence there are more marriages every alternate year.
10) They suggest that the waxing and waning of the Moon is an indication to humans that their lives also will rise and fall with time.
11) They believe that eclipses occur when the Gods take on the of sins of mankind and a demon eats them up during the eclipse. After the eclipse, life moves on.
12) They recognise a comet as a broom star that brings illness.
13) They recognise the Milky Way as a path, and confirm the story of the elder brother and the wife of the younger brother.
14) Their Scorpio is below the conventional Scorpius.

Village 6: Borata Kheda

Taluka: Chikaldhara
District: Amaravati
Population: 300
How to reach: It is 10 km from Raipur.
GPS location: 21° 36.59′ N; 77° 14.055′ E; 493 meters above msl.
Date of visit: 2 June 2016

Name and age of persons interviewed:
1) Somaji Babanu Bedhkar – age 65 years
2) Hiraji Jirga Dhikar – age 63 years
3) Labu Bhura Dhikar – age 60 years
4) Tanu Raju Bethekar – age 64 years
5) Baby Sanu Sawalkar – age 55 years

Astronomical beliefs:
1) They confirm that the Big Dipper is a golden cot, but add that it is deformed (not a perfect rectangle) since it is being pulled by one of the thieves. The middle thief has a little pot of water with him called *da dudi* or *Kudapa*. This makes the outermost thief laugh. They also imagine that this laughter irritates the thief who is closest to the cot and wants to scold the outermost thief.
2) They recognise Orion as the plough and note that it is not visible in May. They have a story that Orion hides itself in May, the season of ploughing the field, to prevent the plough from being copied and does not appear until after harvesting, in October.
3) They recognise the head of Orion as bird eggs (*Bhori Akkom*).
4) They recognise the Pleiades as the minced meat of a cow.
5) They recognise Venus as rising at sunset and sunrise. The morning star is called *Suko* and the evening star *Bel Marya*.
6) They recognise that the Mars-Venus conjunction is a good time for marriage.
7) They recognise comets as broom stars but do not consider them to be an omen.
8) They think that meteors are star excreta.
9) They consider the rainbow as a good omen of the monsoon.
10) They consider the rings around the Moon in the conventional way, for predicting the monsoon.
11) During eclipses they put a staff in water.

Village 7: Bela

Taluka: Chikaldhara
District: Amaravati
Population: 295
How to reach: The village is on Amaravati Chikaldhara Road via Ghatang. About 80 from

Amravati, on this road is a village called Salona. Bela is in the interior about 5 km from this village.
GPS location: 21° 24.906′ N; 77° 25.765′ E; 830 meters above msl.
Date of visit: 2 June 2016

Name and age of persons interviewed:

1) Sonaji Bhima Kasdekar - age 65 years
2) Manang Moti Dahikar - age 63 years
3) Bansi Bhulji Jamunkar - age 55 years
4) Rajaram Bala Bhusum - age 55 years
5) Sonoji Sanu Dahikar - age 50 years.

Astronomical beliefs:

1) They recognise Ursa Major as a golden cot pursued by thieves.
2) They recognise the Pleiades as *Bhot Mangali*—a tool designed to beat wheat to remove husk.
3) They know that *Bhori Akkam* (eggs of birds) exists in the sky, but they do not know where.
4) They recognise the conjunction of Mars and Venus as a good omen for marriage.
5) They recognise comets.
6) They recognise the morning star.
7) They recognise eclipses but have no omen(s) attached to them.

Village 8: Jumunala

Taluka: Chikaldhara
District: Amaravati
Population: 371
How to reach: On Amaravati Chikaldhara Road, 85 km from Amaravati on this road is a village called Salona. Jumunala is 7 km off the road from this village.
GPS location: 21° 25.841′ N, 77° 23.552′ E; 874 meters above msl.
Date of visit: 2 June 2016

Name and age of persons interviewed:

1) Labu Shikari Belsare - age 70 years
2) Babulalji Budha Belsare - age 65 years
3) Ramchandra Muka Dhandekar - age 65 years
4) Moti Shikari Belsare - age 75 years
5) Shankar Ganu Kasdekar - age 65 years
6) Kalu Shikari Belsare - age 66 years
7) Surajlal Chotelal Kasdekar - age 48 years
8) Kalu Tambu Belsare - age 55 years
9) Lalji Kalu Belsare - age 42 years

Astronomical beliefs:

1) They confirm the Big Dipper as a golden cot with three thieves following it, including a water jar (*kudpa*) with the middle star (Mizar).
2) They confirm the plough as Orion’s belt.
3) They identify Rigel and Saiph as the bullocks used to pull the plough.
4) They identify Betelgeuse as the man using the plough.
5) In Lepus, around Arneb, they identify a whip thrown by the man to scare away the birds.
6) They identify Sirius as a (generic) bird (*pankharu*) and Adhara and Wezen as two eggs of the bird (*Bhori Akkom)*.
7) They identify the Pleiades as *Bhot Mungali* (*Mogari*)—a tool used to beat wheat to remove the husk.
8) In Taurus they see a family with a wife and children (presumably those of the man who is ploughing).
9) They identify Auriga as a well, and Castor and Pollux as two ladies taking water from the well.
10) They identify Scorpius with the conventional Scorpius.
11) They identify the Milky Way with the path. But within the Milky Way around Scorpius they notice two non-intersecting paths. On the larger one walks the family elder and on the smaller path walks the wife of the younger brother, and since she is not supposed to cross the path of the elder brother she turns away near Rigil Kent.
12) They identify the conjunction of Venus and Mars as *Lagin tara*.
13) They recognise a comet as a star with a tail and consider it a bad omen.
14) They consider meteors to be stellar ex-

creta.

15) During eclipse they put the pounding stick in water and insist that it will remain upright as long as the eclipse is on. They believe that eclipses occur when the Gods suffer for sins of humans and as a result a demon engulfs them during the eclipse.
16) They also accept the standard belief about the monsoon and the ring of light around Moon.
17) They believe that the Sun and Moon had a common God, a mother who sent them to get some food. The Moon ate a little of what he got but brought the rest back to his mother who was happy and blessed him saying that he will be in a cool (night) environment. The Sun, on the other hand, brought nothing back and his mother cursed him into eternal burning. (At another village we were told that the Sun stole food that the Moon was bringing back and upon giving it to his mother was blessed with brightness, while the Moon, who now had nothing left to bring back for his mother was forced into waxing and waning.)

Village 9: Baghlinga

Taluka: Chikhaldhara
District:Amravati
Population: 1,230
How to reach: From Amravati to Paratwada to Dhamangaon to Badnapur to Baglinga
GPS location: 21° 21.542′ N, 77° 20.907′ E; 582 meters above msl.
Date of visit: 3 June 2016

Name and age of persons interviewed:

1) Babulal Deba Dahikar - age 70 years
2) Hiralal Mukka Dhandekar - age 60 years
3) Shikari Mundu Kale - age 70 years
4) Channy Mangal Dhandekar - age 50 years
5) Batu Moti Dhandekar - age 45 years
6) Champalal Laxman Jhamarkar - age 60 years
7) Dadu Mansu Mavskar - age 55 years
8) Shyamlal Dadu Dahikar - age 60 years
9) Santu Manang Belsare - age 56 years
10) Lalji Laxman Kavalkar - age 60 years
11) Shivram Laxman Jhamakar - age 45 years
12) Harichandra Jhol Dhandekar - age 64 years

Astronomical beliefs:

1) They repeated the Ursa Major story and stated that they use its location for relative time measurement, especially when the Moon is not in the sky.
2) They also contend that Ursa Major looks after the world when the Sun and the Moon are not in the sky.
3) They recognise the conjunction of Venus and Mars, but insist that one of them is stationary and as bright as Venus (note that only Venus and Mars have an apparent magnitude of –3).
4) They recognise the plough in Orion but do not identify the bullocks.
5) They identify Sirius as the bird, but not its eggs.
6) They recognise the Pleiades as the tool used for beating the husk of the wheat.
7) They recognise Taurus. Aldebaran and stars to the north of Aldebaran are bullocks and the star at the tip of the 'V' shape of Taurus (Hyadum) is the pole around which they rotate when crushing grain.
8) They recognise Auriga as a well and the Pollux and Castor as two women drawing water from the well.

9) They recognise the tail of Scorpius as Scorpius.
10) In the southern sky, in Circinus they recognise Rigil Kent and Hadar as *Dhanay* and *Charka*.
11) In Lepus they see the *Mahua* tree (*Madhuca longifolia*).
12) They recognise the Milky Way as a path crowded with stars.
13) They have a vague memory of comets but have no opinion on it.
14) They subscribe to the rule of thumb that a ring around the Moon is linked to rain.
15) They believe that eclipses are a bad omen and bring illness.
16) They believe that lightening is an arrow thrown by the Gods.
17) This village also told us about the creation myth discussed in the text.

Village 10: Gaulkheda Bazar

Taluka: Chikhadhara

District: Amaravati
Population: 1,700
How to reach: Amaravati to Parsapur Junction is about 70 km, and from there Gaukheda Bazar is 10 km.
GPS location: 21° 20.064′ N, 77° 22.243′ E; 516 meters above msl.
Date of visit: 3 June 2016

Name and age of persons interviewed:

1) Zholu Khuda Belsary - age 80 years
2) Babulal Onkar Darsimbe - age 55 years
3) Babulal Mhating Savalkar - age 70 years
4) Shivram Sanu Kale - age 66 years
5) Tumla Zinguji Mavaskar - age 60 years

Astronomical beliefs:

1) They identify the Big Dipper as the golden cot that is deformed by attempts to steal it.
2) In Orion they recognise the plough (belt), the cows (Rigel and Saiph) and the ploughsman (Betelgeuse).
3) They identify the Pleiades as the tool used for removing husk of wheat.
4) They recognise Sirius as a bird and Adhara and Mirzam as its eggs.
5) The associate the whole of Scorpius with a scorpion.
6) They see a tree in Canis Minor.
7) They recognise a comet as a star, with tail but are indifferent to it.
8) They recognize shooting star as star excreta.
9) They suggest that there is an anthill at either end of a rainbow which may even host a snake. But they suggest that these anthills have nuggets of great medical value.
10) They recognise the 'standard' interprêtation of rings around the Moon.
11) They recognise the Milky Way as a path in the sky.
12) They recognise that an eclipse occurs when a demon is eating the Moon, and they have the concept of putting a stick in water to mark the end of the eclipse.
13) Their burial practices are standard.
14) They believe that the Earth sits on the head of a cobra.

Village 11: Hatida

Taluka: Dharani
District: Amaravati
Population: 300
How to reach: From Dharni to Dhakna Road, Bijudhavdi is situated 15 km from Dharni. From Bijudhavdi take a left to Hatida, which is 1.5 km in the interior.
GPS location: 21° 27.9′ N; 76° 58.68′ E.
Date of visit: 23 May 2016

Name and age of persons interviewed:

1) Rajaram Dadu Bhilavekar - age 60 years
2) Ravaji Sanu Bhilavekar - age 55 years
3) Sanu Kalu Darsimbe - age 70 years
4) Motiram Khanu Kasdekar - age 60 years
5) Sonaji Kalu Jambekar - age 60 years

Astronomical beliefs:

1) They know the Big Dipper as the golden bed. The second thief also carries a water jar.
2) They know of the plough in Orion.
3) They know the Pleiades as the minced meat of a cow.
4) They know Auriga as a bird's nest, with Capella as the bird and the southern stars as eggs.
5) They know comets as stars with tails, and consider them a bad omen.
6) They know the rainbow.
7) They refer to east as *Gomej ot*, West as *Gomej Namur Lagken*, North as *Dhola* and South as *Barad*.
8) They bury their dead with the head to the south.
9) They know of eclipses and consider them to be a bad omen.
10) Their month goes from full moon to full moon.
11) They know Venus as morning star.
12) They believe meteors are stellar excreta.

Village 12: Gadgabhandum

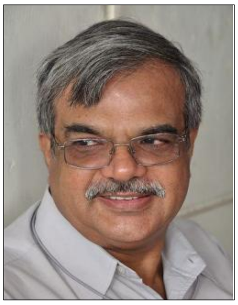
Taluka: Dharani
District: Amaravati
Population: 1,540
How to reach: From Dharni to Dhakna Road, 24 km from Dharni there is a junction. Take a right from there and at 2 km is the village of Gadgabhandum.
GPS location: 21° 26.68′ N ; 77° 0.46′ E.
Date of visit: 24 May 2016

Name and age of persons interviewed:

1) Shaligram Babnu Mavaskar - age 55 years
2) Kaluram Bhau Mavaskar - age 60 years
3) Budha Patel Kasdekar - age 65 years
4) Darasingh Raju Kasdekar - age 40 years
5) Patel Sakharam Dahikar - age 45 years
6) Sakharam Bhau Dahikar - age 80 years
7) Batu Dadu Kasdekar - age 60 years
8) Hira Batu Kasdekar - age 60 years

Astronomical beliefs:

1) They know the Big Dipper as the cot made of gold, with three thieves trying to steal it.
2) They know the belt of Orion as the plough.
3) They recognise the whip used to frighten off birds (Sirius).
4) They know the Pleiades as the minced meat of a cow.
5) They know Auriga as a well.
6) They know Castor and Pollux as two ladies taking water from the well.
7) They know the Milky Way as a pathway which separately marks the paths of an elder brother and the wife of a younger brother.
8) They believe that during an eclipse a demon eats the Sun—but don't have a custom of helping him.
9) They know of Venus as *Suko*.
10) Their month goes from new moon to new moon.



Mayank Vahia is a Professor in the Department of Astronomy and Astrophysics at the Tata Institute of Fundamental Research in Mumbai. He began his career making satellite-based astronomical instruments for high energy astrophysics. He was the Director of the Nehru Planetarium in Mumbai for a year in 2000–2001. He is currently the National Coordinator of the Astronomy Olympiad in India. In recent years he has become interested in the origin and growth of astronomy in the Indian subcontinent. He has been working on prehistoric records of astronomy in India and is deeply interested in documenting astro-nomical beliefs amongst Indian tribes. Mayank has published more than 200 papers in research journals, about 35 of which are on history of astronomy.

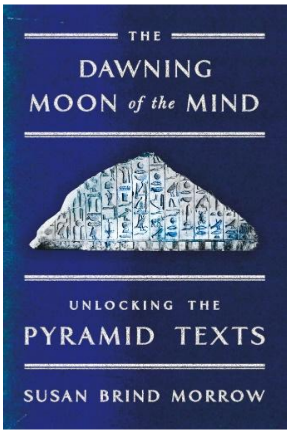
Ganesh Halkare is an advocate in Amravati, a town in Maharashtra. He is also a post-graduate degree holder in Archaeology and Anthropology from Nagpur University. He has a deep interest in tribal education, particularly in the removal of superstition among the tribe members. He is also deeply interested in tribal anthropology and is highly respected amongst the tribesmen for his work in ensuring that they are aware of and can exercise their rights within the nation state. He also has been a regular columnist on constitutional rights. Ganesh has published more than a dozen research papers on the archaeology of the Nagpur region in Indian journals and conference proceedings. He is now working on the astronomy of other tribes in the Nagpur region.

Purushottam Laxmanrao Dahedar is a teacher in a tribal school in Washim district. He holds a master's degree in archaeology and a post graduate diploma in anthropology and tribal development. He is the district coordinator, Center India Sky Watch Group, Chandrapur, and also works with anti-superstition groups. He has a special interest in painted rock shelters and has presented four papers on the subject at the Indian history congress. He is also an amateur astronomer and astronomical telescope maker. He is now involved in the study of astronomy of Indian tribes.

BOOK REVIEWS

The Dawning Moon of the Mind **by Susan Brind Morrow (New York, Farrar, Straus and Giroux, 2015), pp. 289. ISBN 978-0-374-20010-7, 160 × 235 mm, US$28.**

With this landmark book archaeologist and linguist Susan Brind Morrow has unlocked the hieroglyphs of ancient Egypt. Specifically, she has examined the Pyramid Texts in the pyramid of Unis, the oldest version of the work found to date. Unis was the last ruler of the Fifth Dynasty, and dates to the mid-24th century BCE.



Morrow gives us a completely different translation of the texts, upending more than a century of scholarly analysis. Until now, Egyptologists have said the beginning of the texts deal with the private parts of a baboon. Morrow reveals it is actually a description of the constellation Orion!! Maybe the fact the ceilings of the pyramid are covered in stars should have given earlier researchers a clue as to what the texts are about. The Pyramid Texts are in fact the oldest astronomical text in existence. Here is an excerpt from her description of the north wall of the antechamber in the pyramid:

> The north wall of this room presents a sequence of riddles encoding the visible features of the north side of the night sky. The first verse introduces the primary constellation of the north, the Big Dipper. The riddle lies in the mystery of what the Big Dipper is and what it does. The Dipper is the mechanism that turns the sky like the hand of a clock. Hence it is a paradox: it is the arm of the night, real and active, yet as a pattern of stars it is diffuse and nonmaterial. The night is not a goddess. It is the night.

Morrow goes on to explain the second verse on the north wall deals with the stars Sirius, the falcon and Canopus, the dog. The third verse "… presents this glittering stream of the marvelous sky as a ladder of souls, a word (*mkt*, ladder) that is a pun on the hieroglyphic name of the Milky Way (*mskt*)."

In this description we see the three primary elements that Morrow employs to great effect, elements no other reader of the hieroglyphs has ever done. Recognising the text contains paradoxes, riddles and puns, she reveals what has remained hidden for more than 4,000 years (she actually lists six linguistic devices the Egyptians used). Morrow places what we can now read here in dramatic terms:

> The verse is a return to the catalogue of celestial phenomena that began on the west wall of the entrance-way. It is as though one were in a planetarium, a miniature re-creation of the night sky. But the actual, accurate re-creation of the map of the night sky is effected not with a detailed visual imitation of it, as in Grand Central Station. It is done with iconographic riddles that contain not only the physical description of primary stars and specific constellations, but layers of deeper meaning that reveal their significance in the life of the universe.

Morrow gives us a full translation of the Pyramid Texts, wall by wall and room by room. Her discussion both before and after this translation is illustrated by specific hieroglyphs, which she explains, showing how they have been misinterpreted by previous scholars.

The name of the Dipper, for example, grows out of the word *ms*, "to give birth." Until now the hieroglyph was thought to represent three fox skins tied together by a tail. Morrow reveals it is a botanical illustration! The correct text reads "Great Night uncovers her arms …" but what does that mean? She explains:

> This is a coded line that means night reveals its secret. The secret is that the night sky is a clock. The arms are the Dippers, which swing around the North Star like the arms of a clock. This is at once an astute astronomical observation, a poetic conceit, and a practical measuring device. The monument is a metaphor for time: conception, gestation, and birth.

One feels almost giddy finally knowing what the Egyptians really meant. I read the canonical translation of the Pyramid Texts 30 years ago, but it did not make a whole lot of sense to me. Now I know why: it was wrong. "Hieroglyphs are not recondite or indecipherable …" writes Morrow.

There is clearly much work for archeoastronomers too, as Morrow links the texts to the pre-dynastic culture of Egypt. She specifically mentions a site on the Nabta Playa, a hundred miles west of Aswan, "… where stones are set up as an astronomical observatory."

Philosophers of the history of science and astronomy will also have much to consider here. The pyramid as a metaphor for time, coming from such a distant time in human history, must be integrated into the very bedrock of how and why man relates to the cosmos.

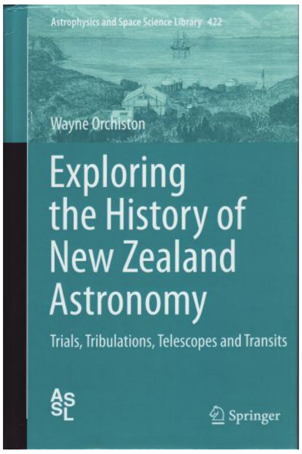
Dr Clifford J. Cunningham
National Astronomical Research Institute of

Thailand, Chiang Mai, Thailand
Email: asteroid4276@comcast.net

***Exploring the History of New Zealand Astronomy: Trials, Tribulations, Telescopes and Transits* by Wayne Orchiston (Cham, Springer International Publishing, 2016), pp. [xlv] + 688. ISBN 978-3-319-22565-4 (hardback), 161 x 241 mm, CHF146.50. Also ISBN 978-3-319-22566-1 (eBook), PDF and ePUB, CHF 117.00.**

This journal's founding editor, Professor Wayne Orchiston, has devoted a goodly part of his research life to the history of astronomy in the islands comprising the country now known as Aotearoa/New Zealand. As is inevitable in the history of science, Wayne has reported his work in a wide range of publications, some of which may be difficult to access, such as numerous conference proceedings, the now-defunct *Australian Journal of Astronomy*, and especially *Southern Stars*, the journal of the Royal Astronomical Society of New Zealand.

Exploring the History of New Zealand Astronomy thus performs a great service in summarizing some of this work in a single publication. The book is no mere rehash, however. Since many of Wayne's original papers were written new information has come to light, and the National Library of New Zealand's *Papers Past* project has appeared, digitizing and making text searchable many of the country's historic newspapers and periodicals. Wayne has incorporated numerous additional details which provide texture and deepen our knowledge of what happened.



The book is divided into an introduction followed by seven parts comprising in total 24 chapters. The introduction starts with a touching feature. Wayne recounts his life as an astronomer, which is highly appropriate since he is himself part of Kiwi astronomy, being Auckland-born and having served in the 1990s as Executive Director of the Carter Observatory in Wellington. His interest in astronomy was sparked in boyhood when his family moved to the "... simply stunning ..." dark skies of the small, South-Island town of Lincoln, and continued 'across the ditch' in Sydney, where, *inter alia*, he worked with radio astronomer Bruce Slee (b. 1924). Acquaintance with archives left by the Australian amateur John Tebbutt (1834–1916), who featured on the old Australian $100 note, redirected his research towards astronomical history. "... New Zealand astronomical history remains my sentimental favourite," writes Wayne, "hence this book." The paths to astronomy are many and surely provide grist to the mill for future astro-sociological research. Let me encourage all members of the *JAHH* Editorial Board to follow Wayne's example and put their own journeys as astronomers into print, perhaps in *JAHH*; and you too, dear reader.

The introduction goes on to stake out the book's boundaries—astronomy done in New Zealand, whether by navigators, amateurs or professionals, up to about the 1960s. So, for example, there is no discussion of the US Naval Observatory, Carter Observatory and JANZOS outstations on Black Birch, nor of the University of Canterbury's Mount John University Observatory, near Tekapo, nor of the flights of the Kuiper Airborne Observatory and its SOFIA successor. But space and time limitations have led to other exclusions too, such as the history of astronomical societies, the pioneering radar meteor astronomy undertaken by Cliff Ellyett (1915–2006) and Colin Keay (1930–2015), or discussion of astronomers who have already been the subject of biographies or autobiographies. Here I think of the charismatic Alexander Bickerton (1842–1929), author of the 'partial impact' theory of the formation of almost everything, and Frank Bateson (1909–2007), who for 77 years was director of the Variable Star Section of the Royal Astronomical Society of New Zealand, and was heavily involved in the early days of Mt John. Both fell foul of authorities at the University of Canterbury and receive only the briefest mention in *Exploring the History* ..., though I am sure there is no causal connection!

The book's seven parts treat pre-European astronomy, Cook-voyage astronomy, telescopes and observatories, the 1874 and 1882 transits of Venus, "stunning spectacles" (that is, observers of eclipses, comets and meteor showers), a clutch of additional North-Island astronomers, and pioneering New Zealand radio astronomy. Each component chapter is written as a research paper following a set format, beginning with an abstract and introduction, and ending with concluding remarks and references. This may seem strange, but in the shifting sands of academic publishing was a deliberate decision by the publisher so that a reader with a very specific interest can (for CHF 24.95) download an individual, pertinent, stand-alone chapter.

Wayne's doctorate is in environmental prehistory, through an Anthropology Department, which gives special importance to what he writes concerning the Māori astronomical world view. As he points out, 'Māori astronomy' really means Māori ethnoastronomy, and cannot be divorced from Polynesian ethnoastronomy. The problem with this field is that there had been many decades of widespread contact with European ideas before there was any large-scale investigation of Māori celestial lore by the ethnographer Elsdon Best (1856–1931); and in a culture which showed major regional variations, Best's research was mostly limited to only one part of the North Island. To summarize, Best reports lunar calendars and lore relating to stars, asterisms, planets, the Milky Way and the Magellanic Clouds as well as reflecting awareness of events such as lunar and solar eclipses, 22° solar haloes, comets, fireballs and stellar occultations, most of which were taken to portend terrestrial events. But the conclusion has to be that either the Māori were not overwhelmingly interested in the sky, or that Best's account is superficial. Wayne hopes for the latter, but I find it difficult to believe that the current renaissance of interest in Māori star lore, and particularly in the heliacal rising of *Matariki* (the Pleiades) as a new-year marker, will reveal much about Māori ethnoastronomy prior to European arrival in Aotearoa.

Many authors have written about Cook's three circumnavigations of the globe, but it is useful to have a summary of the New Zealand astronomical material in one place. Although celestial observations were made on the first voyage for navigational and cartographical purposes, notably of a transit of Mercury, it was on the second voyage, in 1773, that New Zealand "... gained its first genuine astronomical observatories …" when tent observatories were erected at Dusky Sound and Queen Charlotte Sound. An interesting chapter concerns the so-called 'Cook' telescope bought by the New Zealand Government in 1952 and now in The Museum of New Zealand/Te Papa Tongarewa in Wellington. This Gregorian telescope was made by the London instrument-makers Heath & Wing. Wayne traces its provenance. Revising an earlier opinion, he now believes that there is indeed a Cook connection, and that it is the telescope used by Daniel Solander (1733–1782), the naturalist on Cook's first voyage, to observe the 1769 transit of Venus from Tahiti.

A century was to pass before professional astronomy returned to New Zealand in the form of Stephen Carkeek (1815–1878), who as Controller of Customs played a key role in setting up a transit telescope and time ball on the Wellington waterfront to provide a time service for shipping and the city. In retirement, Carkeek built a private observatory. Its dilapidated remains are the country's oldest surviving observatory.

In 1869 the Colonial (formerly Provincial) Observatory set up by Carkeek was transferred from the waterfront to Wellington's Botanic Garden. The nominal Director of the Observatory was James Hector (1834–1907) who was perhaps the most influential nineteenth-century scientist in New Zealand, and behind the introduction of standard time throughout the country in 1868. However, most of the observations were the work of the enthusiastic Archdeacon Arthur Stock (1823–1901), who Wayne characterises as "... New Zealand's first professional astronomer (albeit a part-time one) ..." Stock, incidentally, suggested the idea of the solar coronograph eleven years before experiments with a similar idea were performed in London by William Huggins (1824–1910), and seventy years before such an instrument was built by Bernard Lyot (1897–1952) in France. The Colonial Observatory met an abrupt end when it was demolished on the day of the funeral to provide a grave and monument site for the just-deceased Prime Minister, 'King Dick' Seddon (1845–1906). (This is apparently politics trumping science, but I suspect there is more behind this event than meets the eye.) Happily the Botanic Garden proved fertile ground for observatories, and several others bloomed there—the Hector Observatory (whose observer resigned when the Government refused to triple his salary), the Dominion Observatory, the Thomas King Observatory, the Wellington City Observatory (colloquially known as the 'Green Tin Shed'), and finally the Carter Observatory, which for several decades was enshrined by legislation as the country's 'National Observatory', whatever that may mean. Wayne discusses these establishments and their equipment, as well as others set up or made by amateur astronomers in Thames, W(h)anganui, Dunedin, Auckland, and elsewhere, including the production of Joseph Ward (d.1927), a pioneer New Zealand telescope maker. On the subject of more recent optical production (and crossing the 1960s time boundary), it is nice to see photographs of the then-Department of Scientific & Industrial Research's optical designer Norman Rumsey (1922–2007) and optical fabricator Garry Nankivell (1929–2001), who were so important in providing instrumentation for Mt John. With the creation of Mt John in the early 1960s, the focus of professional astronomy moved from Wellington to the University of Canterbury in the South Island.

The 1769 transit of Venus was a seminal event in the European colonization of New Zealand, which was in full swing by the time of the next transits a century later. German, French, American and British teams came to make observations of the 1874 transit with high hopes that photography would provide observations of unprecedented quality. The British coordinated local observers. Only the Americans and Germans got much in the way of results, and photography was a deception. In 1882 just the Americans and British returned; they made visual observations only. Nevertheless, the transits of Venus represent a high point in nineteenth-century professional astronomical interest in New Zealand.

The 1880s was a time of high spectacle in the sky. Besides the transit of Venus, there were major comets in 1880, 1881 and 1882, and a widely-observed total solar eclipse in 1885 (a special train was laid on so that citizens of Napier could travel to within the path of totality). In the early 1880s British astronomy popularizer Richard Proctor (1837–1888) made a lecture tour of New Zealand. Wayne misses a link here—Proctor turned to writing and lecturing after he lost all his money in the collapse of a New Zealand bank.

Wayne breaks the 1960s time limit to consider all Kiwi comet discoveries, from one found by Stock in 1881, through those detected by John Grigg (1838–1920) from Thames in the first decade of the twentieth century and the cometary astro-photographer C.J. Westland (1875–1950), to the most recent comet discovery, Comet Gilmore in 2007. Photographs of the discoverers are a welcome feature. Westland is an example of what Wayne has dubbed an 'ATP'—an amateur turned professional—because after amateur astronomy on his farm he was employed by the Hector Observatory. Later, the process was reversed when he returned to farming and amateur astronomy—a 'PTA'.

Several chapters describe other Kiwi astronomers, including the Wellington-resident Robert Sheppard (1810–1896), William Mein Smith (1799–1869), and instrument-maker James Henry Marriott (1799 or 1800–1886), who advertised as a "Telescope manufacturer", but whose production may have been small, since only one example is known to survive. Also deserving mention are talented science-lecturer Henry Severn (1833–1883), whose attempt to observe the 1874 transit of Venus was thwarted by rain, and meteor tracker Ronald McIntosh (1904–1977). In 1959 McIntosh was appointed "Lecturer-Demonstrator" at the newly-opened Auckland Planetarium. Upon his retirement thirteen years later, he claimed to have given 310,000 lectures on astronomy over his life. Most must have been very short! McIntosh was also a key player in the founding of the Auckland Observatory, opened in 1967.

The final part of Wayne's book is devoted to the baby days of radio astronomy. Wayne highlights unjustly-forgotten war work by Dr Elizabeth Alexander (1908–1958), who as Director of the Radio Development Laboratory in Wellington identified non-thermal emission from the Sun in dawn and dusk recordings from radar stations in the South Pacific Command, and notably from Norfolk Island. (A biography of this arguably first woman radio astronomer by her daughter Mary Harris should be published imminently.) Alexander was followed by better-remembered work by John Bolton (1922–1993) and New Zealander Gordon Stanley (1921–2001), who were sent from Australia to make 'cliff interferometer' observations of the 'radio stars' Cygnus-A, Centaurus-A, Virgo-A and Taurus-A, while Wayne's mentor, Bruce Slee, carried out concurrent observations in Sydney. By setting their antenna on sea cliffs at Pakiri Hill and later Piha in Northland, they were able to make interferometric observations of the sources and their mirror images in the sea at both rising and setting, which led to accurate positions and optical identification of all but Cyg-A, and the realization that 'radio star' was a misnomer.

Exploring the History of New Zealand Astronomy is accurately titled. It is an exploration, because although the book brims with information, almost every topic invites further investigation; and there are myriad undiscussed subjects, some of which will be treated in an announced companion volume. Wayne has scoured New Zealand to find photographs, many of them previously unpublished, and the book is abundantly illustrated. It abounds with references too; and given the number of people whom Wayne thanks that have died, comes none too soon. I do have some minor gripes—a number of the illustrations, particularly the maps, should have been printed at higher resolution; and the index is not comprehensive, which is regrettable since material on some topics and astronomers is spread over several chapters, but only partially indexed, or not at all.

Does the history of New Zealand astronomy matter, some may ask? Well, it certainly does for people in Aotearoa as part of their national story, and for them and the country's libraries, this is a must-have volume. But New Zealanders (and others) often under-rate the importance of the Kiwi experience for the world's stage. Science at the periphery is an important thread in current history-of-science debate, and Wayne's work provides a solid base from which to attack wider questions such as why the history of professional astronomy has been so different in Australia compared to other lands of former British influence, like Canada and New Zealand. In a review of the history of Australian astronomy written by Haynes et al. (1996) I made the suggestion that visionary scientists who know how to influence the workings of government are of cardinal importance (Tobin, 1996). And what about amateur astronomers? An NZ-Oz comparison could be extended to include the UK, thanks to Allan Chapman's work on British amateurs (1998), and also South Africa, through an expansion of a paper that Wayne has already published in *Monthly Notices of the Astronomical Society of Southern Africa* (Orchiston, 2006). Scientists and historians of science, professionals and amateurs, we must all heartily congratulate the author for this impressive and weighty volume.

References

Chapman, A., 1998. *The Victorian Amateur Astronomer: Independent Astronomical Research in Britain, 1820–1920.* Chichester, Wiley-Praxis.

Haynes, R., Haynes, R., Malin, D., and McGee, R., 1996. *Explorers of the Southern Sky: A History of Australian Astronomy.* Cambridge, CUP.

Orchiston, W., 2006. Amateurs in the Antipodes: the common denominators of nineteenth and early twentieth century South African, Australian and New Zealand astronomy. *Monthly Notices of the Astronomical Society of Southern Africa*, 65, 148–159; 194–208.

Tobin, W., 1996. (Review of Haynes et al.) *Endeavour,* 20, 182.

William Tobin, Ph.D.
6 rue Saint Louis,
56000 Vannes, France.
Email: william@tobin.fr
orcid.org/0000-0002-0533-411X

***Galileo's Telescope: A European Story*, by Massimo Bucciantini, Michele Camerota and Franco Giudice, translated by Catherine Bolton (Cambridge, Harvard University Press, 2015), pp. [x] + 340. ISBN 978-0-674-73691-7, 160x240 mm, US$35.**

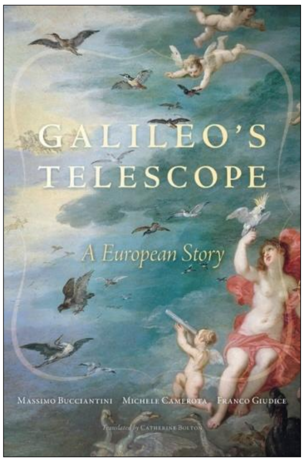
***Galileo's Idol: Gianfrancesco Sagredo & the Politics of Knowledge*, by Nick Wilding (Chicago, University of Chicago Press, 2014), pp. 200. ISBN 978-0-226-16697, 160x235 mm, US$35.**

These two excellent books on various aspects of the life and work of Galileo are complementary. Each has its unique strengths, and together they provide an insightful and remarkably detailed look at the astronomical world of the early 1600s.

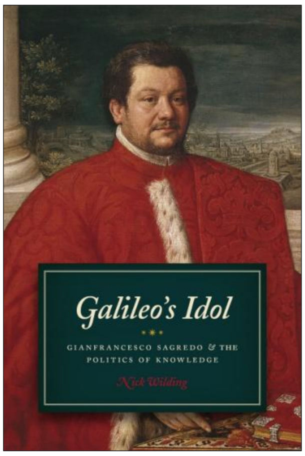
Until now historians of astronomy have concentrated on the contents of Galileo's 1610 book *Sidereus Nuncius* which contains the first astronomical observations made with a telescope. However, a close look at the title page reveals a hidden secret. Dominating the page is an image known as a printer's mark with a Latin inscription that reads "From Here True Religion". Printed below that is: Apud Thomam Baglionum.

The Bucciantini book states on page 77, "His *Sidereus nuncius* finally came off the press of Tommaso Baglioni on the night of Saturday, March 13." As Nick Wilding at Georgia State University conclusively proves in his book—in a masterful case of bibliographic detection work—this is not true.

It was believed for centuries that Thomas Baglioni was the publisher of Galileo's book, but Wilding shows that Baglioni did not have a press at that time; he actually used the press of Niccolò Polo. "His appearance on a title page was legally irregular, and it indicates some kind of impropriety …" writes Wilding on page 95. Even though the Bucciantini book has a publication date a year after the Wilding book, it does not include this new research. The reason is that the 2015 book is an English translation of a 2012 Italian book entitled *Il Telescopio di Galileo: Una Storia Europea*.



In my own study for a *Mercury* magazine history of astronomy column (see Cunningham, 2016), I looked at a book by Marco Antonio de Dominis, who is not mentioned in either of these Galileo books. The title page of his book bears the same printer's mark that appeared on Galileo's book the following year.



Giovanni Bartoli is named on the title page of Dominis' book as the editor, and his name does appear in both Galileo books under review here. He is merely mentioned by Wilding in passing as "… the Tuscan resident in Venice." But as the Bucciantini book reveals, he is a key source for our knowledge of the origins of the telescope in Venice. Here we learn he was "… secretary to Asdrubale Barbolani, the resident of the Grand Duke of Tuscany in Venice …", thus correcting Wilding's assertion he was the resident.

On 22 August 1609, Bartoli informed his masters in Tuscany of a remarkable event in Venice:

> … a person came here who wanted to give his lordship the secret to a spyglass or a cannon ... with which one can see even twenty-five

> and thirty miles away so clearly that they say it seems to be nearby ... in France and elsewhere this secret is known to all, and that it can be purchased cheaply. (pages 36–37).

On 27 March 1610, Bartoli wrote to a friend that Galileo's book *Sidereus nuncius* was being "… read by everyone …" in Venice, and

> With his spyglass, Galileo has found four other planets and seen another world on the Moon, and similar things that provide pleasant food for thought to the professors of those sciences. (page 86).

The Bucciantini book is superb in its richness of manuscript records, many of which have never before been published. The authors weave the story of the origins of the telescope throughout Europe (and even India and China), with some well-placed maps that show the dissemination of knowledge about this amazing invention. They describe this historiographical approach as "… our experiment in cartography and the cross-referencing of texts in an attempt to offer an overall vision of the circulation of the telescope." (page 169). Their experiment has succeeded admirably.

Likewise the Wilding book, with its focus on the little-known figure of Gianfrancesco Sagredo, opens up a new aspect of Galileo studies. Until now readers of Galileo's 1632 book *Dialogue upon the Two Main Systems of the World* regarded Sagredo as nothing more than, in Wilding's words, "… a Socratic midwife ... In the *Dialogue* Galileo narrates Sagredo's experiences and makes them stand in for experiments." As Wilding notes, "Sagredo left no published work, invented nothing, gave his name to no theory or law." Nonetheless he was a real person and a close confidant of Galileo, and this book brings him to life at long last. Letters he wrote still exist, and years of archival research have enabled Wilding to give us a convincing portrait of his life. Indeed, he was even able to identify previously-unknown portraits of Sagredo, one of which (at the University of Oxford) graces the cover.

The addition of these two books advances our understanding of Galileo and his world far beyond anything previous generations of scholars have attained. While Galileo's trial and scientific experiments are amply covered by other great scholarly books, these two books fill a critical gap in Galileo studies.

Reference

Cunningham, C.J., 2016. Of Moonbows and Galileo. *Mercury* 45(3), 7.

Dr Clifford J. Cunningham
National Astronomical Research Institute of
Thailand, Chiang Mai, Thailand
Email: asteroid4276@comcast.net

EDITORIAL NOTE

The March/April issue of *JAHH* included the following paper:

> Cuntz, M., Gurdemir, L., and George, M., 2016. Seasonal dating of Sappho's 'Midnight Poem' revisited. *JAHH*, 19(1), 18–24.

It has been brought to our attention that some of the biographical material about Sappho in this paper draws freely on text included in the Poetry Foundation and other web sites without giving due recognition or acknowledgement. We very much regret this, and have taken steps to ensure that henceforth the proper attribution of sources will be rigorously adhered to.

Meanwhile, we would like to stress that the authors of this paper never claimed (nor desired) to make an original contribution to the biography of Sappho herself, whereas their analysis of the astronomical content of the 'Midnight Poem' is an original contribution to scholarship.

Professor Wayne Orchiston
Editor