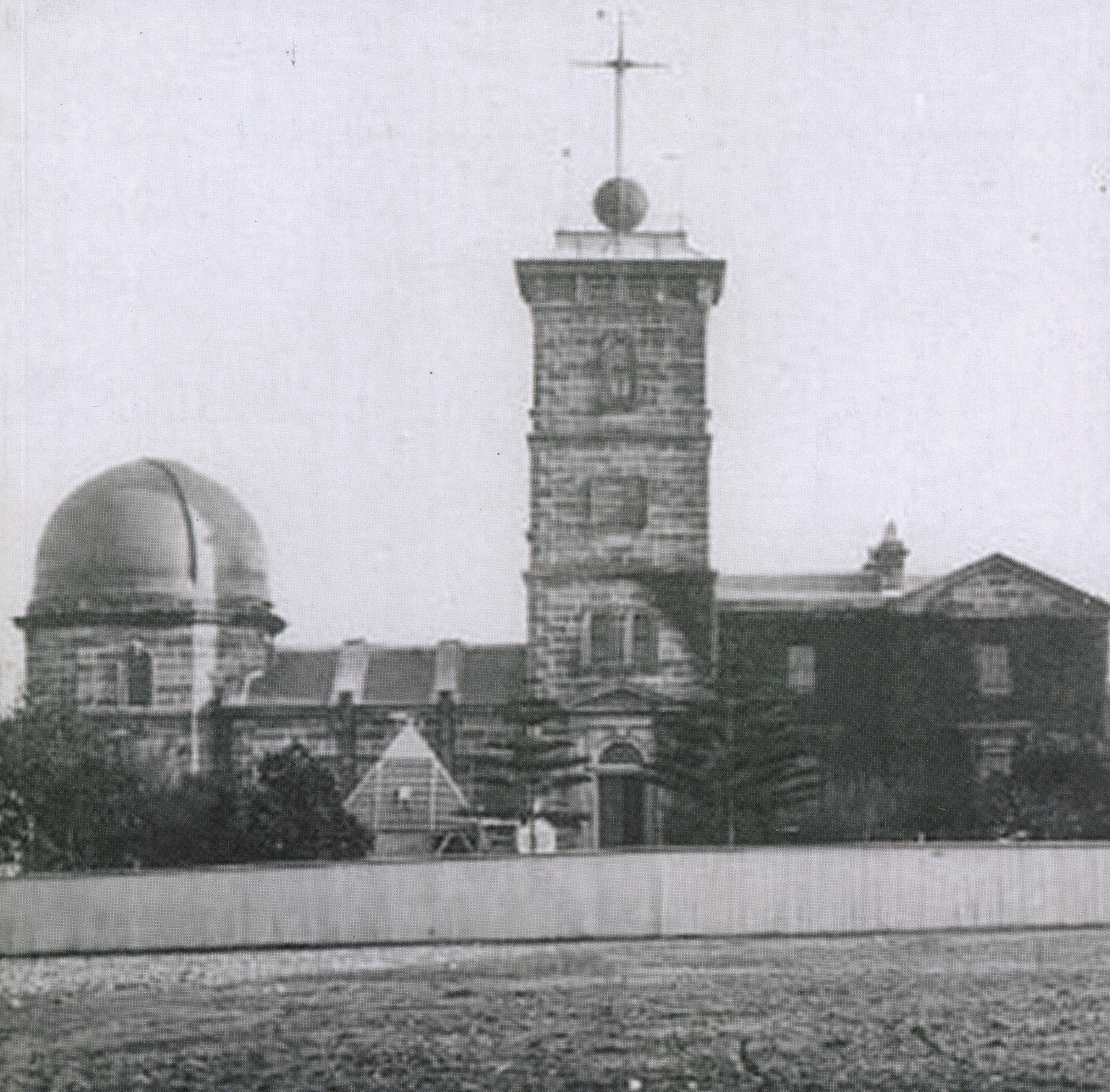
JOURNAL OF ASTRONOMICAL HISTORY AND HERITAGE



Vol. 12 No. 2 July 2009

JOURNAL OF ASTRONOMICAL HISTORY AND HERITAGE
ISSN 1440-2807

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The annual subscription rates for Volume 12 (2009) are:

AU$200:00 for institutions
AU$88:00 for individuals

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COVER PHOTOGRAPH

This nineteenth century photograph of Sydney Observatory (courtesy of the RAS Archives) shows (from left to right) the dome which housed an 11.5-in Schroeder refractor, spare transit shutters, the shutters associated with the 6-in Troughton and Simms transit telescope, the time ball tower, and the Government Astronomer's residence. Sydney Observatory was founded in 1858, primarily to provide meteorological data for the colony of New South Wales and to supply a local time-service. The Observatory owned a number of astronomical clocks and chronometers and these were regulated by means of transit telescope observations of 'clock stars'. Each day the time ball was dropped from the top of the mast at precisely 1pm, thereby providing an accurate time-service for local citizens, businessmen and ships in the port. The elevated location of the Observatory was purposely chosen so that it could be easily seen from the port and from Sydney town. The research paper by Roger Kinns on pages 97-108 in this issue of *JAH*^{2} compares and contrasts the time ball apparatus at Sydney Observatory with that found at the Lyttelton Time Ball Station near Christchurch, New Zealand, and places these two institutions in an international context.

JOURNAL OF ASTRONOMICAL HISTORY AND HERITAGE
ISSN 1440-2807
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Published by the
Centre for Astronomy, James Cook University, Townsville, Queensland 4811, Australia.
(www.jcu.edu.au/astronomy)

Journal of Astronomical History and Heritage, 12(2), 90-96 (2009).

MICHELL, LAPLACE AND THE ORIGIN OF THE BLACK HOLE CONCEPT

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Abstract: Black holes are fundamental to our understanding of modern astrophysics, yet the origin of this concept can be traced back to the writings of England's John Michell and France's Pierre-Simon Laplace in 1784 and 1796 respectively. Both independently postulated the existence of "non-luminous bodies", and while Michell used graphical methods to explain his concept, Laplace published a mathematical 'proof' in 1799.

Key Words: Michell, Laplace, black holes, missing mass, dark matter

1 INTRODUCTION

The concept of a black hole is now widely accepted in astronomy and is applied to a range of bodies, extending from extremely small primordial black holes formed during the Big Bang with masses less than the mass of the Earth, to stellar-remnant black holes with masses of 3-30 $M_\odot$ resulting from supernova explosions, up to supermassive black holes with masses of 10^6-10^9 $M_\odot$ at the centres of active galaxies. Such objects, defined by the common characteristic that their gravitational fields are so strong that light cannot escape from them, comprise a part of the baryonic component of dark matter in the Universe and are regarded as having their theoretical foundation in Einstein's General Theory of Relativity.

However, the concept of black holes has a much longer history, dating back to studies by Britain's Reverend John Michell and France's Pierre-Simon Laplace in the eighteenth century (see Hodges, 2007; Israel, 1987: 110, 201-203; Schaffer, 1979). In this paper we discuss their work, and also provide a modern version of Laplace's mathematical 'proof' of the existence of 'invisible bodies' such as black holes. It is important to recall that at that time light was believed to consist of corpuscles (rather than wave motion).

2 JOHN MICHELL

2.1 A Biographical Sketch

The Reverend John Michell was the son of the Rector at Eakring in central Nottinghamshire, and was born at the Rectory on Christmas Day in 1724 (Crossley, 2003). He was admitted to Queens' College, Cambridge, in 1742, graduating in mathematics as Fourth Wrangler in 1748. The following year he was elected a Fellow of Queens' College, where he taught arithmetic, geometry, Greek and Hebrew. He obtained an M.A. in 1752 and a B.D. in 1761, and was elected a Fellow of the Royal Society in 1760. In 1762 he was appointed Woodwardian Professor of Geology at Cambridge, but just one year later he became Rector of Compton, near Winchester, and spent the rest of his life as a clergyman. Later he moved to Yorkshire, where he carried out the astronomical studies that are the focus of this paper. John Michell died on 29 April 1793 (Hoskin, 2004).[1]

There is no known image of John Michell but we have a description of him which was recorded in Cole MSS XXXIII, 156, in the British Library:

> John Michell, BD is a little short Man, of a black Complexion, and fat; but having no Acquaintance with him, can say little of him. I think he had the care of St. Botolph's Church, while he continued Fellow of Queens' College [Cambridge], where he was esteemed a very ingenious Man, and an excellent Philosopher. (Cited in Crossley, 2003).

Although known as the 'father of modern seismology', Michell was a polymath and made important contributions in a number of fields of science (see Hardin, 1966), including geology and astronomy. Hughes and Cartwright (2007: 93; their italics) claim that Michell was "… the first *statistical* astronomer, and that he pioneered the application of probability theory to stellar distributions."

Jungnickel and McCormmach (1996: 301) also sing Michell's praises:

> … his publications in astronomy were—by default, it would seem—theoretical. In speculative verve he was Herschel's equal, and since he had mathematical skills equal to Maskelyne's and Cavendish's, he could develop his theoretical ideas farther. In breadth of scientific knowledge, Michell resembled William Watson … like Watson, Michell was knowledgeable in natural history as well as in natural philosophy.

As an astronomer, Michell was both an observer and a theoretician. During his life he made at least one telescope, a large reflector, in about 1780. Soon after Michell's death this instrument was described by his son-in-law in a letter to William Herschel:

> The dimensions & state of the telescope are nearly as follows. A Reflecting Telescope Tube 12ft long made of Rolled Iron painted inside and out, & in good preservation. The Diameter of the large Speculum 29 inches. Focal length 10 feet, its weight is 330 lbs it is now cracked. There are also 8 concave small mirrors of different sizes … and 2 convex mirrors … there are also [?] sets of eyeglasses in brass tubes & cells. The weight of the whole is about half a tun [*sic*] … (Turton, 1793).

Herschel went on to purchase this telescope, but this was his only association with Michell. Hutton (2006) has shown that there is no validity to the claim advanced by one of Michell's descendents in 1871 that it was John Michell who inspired Herschel to take up astronomy.

2.2 Michell's First Astronomical Publication

Michell's first paper was published by the Royal Society in 1767, and was concerned with the distances of stars based upon their parallaxes, and with the true nature of double stars. This paper was in response to Pierre Bouguer's *Traité d'Optique sur la Gradation de la Lumière* which placed importance on the distinction between the quantity and intensity of light. Michell applied a new approach to British sidereal astronomy, believing that the mass of a star determined the quantity of light it emitted. He based his argument upon a pioneering probability analysis, and demonstrated that nearly all double stars were binary systems and not chance alignments (i.e. optical doubles).

Michell proposed a purely dynamic procedure for determining the mass and density of binary stars, as summarised by McCormmach (1968: 139):

> According to gravitational theory, the period and greatest separation of a double star determine the relation between the apparent diameter and density of the central star. If the distance of the central star is somehow known, its apparent diameter can be converted into its true diameter. The mass and the surface can be calculated from the true diameter and density, and the star's total light and brightness are then referred to these magnitudes.

Hughes and Cartwright (2007) provide a succinct statistical examination of Michell's paper, which Hoskin (2004) has described as "… arguably the most innovative and perceptive contribution to stellar astronomy to be published in the eighteenth century."

When he began a search for new double stars in 1779, Herschel apparently was unaware of Michell's seminal paper of 1767, and in 1782 he published his "Catalogue of double stars" in the *Philosophical Transactions of the Royal Society* (Herschel, 1782a), along with a paper about stellar parallaxes (Herschel, 1782b).

2.3 Michell Introduces the Concept of Black Holes

Herschel's two 1782 papers, and especially the catalogue of double stars, provided Michell with the 'means' on which to base his second astronomical paper, which bears the exceedingly long and laborious title, "On the Means of Discovering the Distance, Magnitude, &c. of the Fixed Stars, in Consequence of the Diminution of the Velocity of Their Light, in Case Such a Diminution Should be Found to Take Place in any of Them, and Such Other Data Should be Procured from Observations, as Would be Further Necessary for That Purpose."

Michell completed this paper in May 1783 and sent it to his London-based friend, Henry Cavendish (Figure 1),[2] who at the time was regarded as the Royal Society's "… *scientifically* most eminent member." (Jungnickel and McCormmach, 1996: 249; their italics). Cavendish showed the paper to Maskelyne, Herschel, and other members of the Royal Society, and he read the paper—in three instalments—at the 11 and 18 December 1783 and 15 January 1784 meetings of the Society. This was a time when the Society was in turmoil as two opposing groups of members fought respectively to retain and unseat the President, Sir Joseph Banks, and Michell's paper was the only one read at the two December meetings (*ibid*.: 249-256). Apparently, Michell was in the habit of regularly making the long journey from Yorkshire to London in order to attend meetings (*ibid*.: 301), so it is strange that he decided not to present this important paper himself. Maybe the disruptive nature of the Society's meetings at this time prompted him to stay away from London. Alternatively, his paper was speculative, so perhaps he felt that it would gain greater acceptance by his peers if presented by his illustrious colleague.

Figure 1: Sketch of Henry Cavendish, 1731–1810 (after http//:en.wikipedia.org/wiki/File:Cavendish_Henry.jpg).

Be that as it may, Michell opens his discussion with the observation that Herschel had discovered a large number of double and triple stars. Referring to his own 1767 paper, Michell suggests that these stars would be affected by their mutual gravitational attraction, and that observations should reveal the period of revolution of the secondary components in some of these systems. In a binary system, if the diameter of the central component, the separation of the two components and the period of revolution of the secondary component are all known, then the density of the central component can be calculated. Knowing the density of any central body and the velocity any other body would acquire by falling towards it from an infinite height, then the mass and size of the central body can be calculated. Michell then suggests that particles (corpuscles) of light are attracted by gravitational forces (just like celestial bodies), so if any star of known density is large enough to affect the velocity of light issuing from it, then we have a means of calculating its actual size.

Michell then proceeds to carry out a geometrical analysis of the various velocities and forces that would apply. Referring to Figure 2, Newton's 39th proposition in *Principia* can be illustrated with respect to the velocity the body acquires falling towards the central body, C, by constructing perpendiculars, such as rd, to the directional line in proportion to the force applied at that point. The velocity acquired at that point is then proportional to the square root of the area described, for example AdrB.

If C is the centre of the central body attracting the falling body from infinity, A, then RD represents the force applied to the falling body at point D and the velocity acquired at D is the same as that acquired in falling from D to C under the force RD, where RD is inversely proportional to the square of DC, provided the area of the infinitely-extended hyperbolic space ADRB is equal to rectangle RDC.

The velocity of a falling body at the same distance from C will be proportional to the square root of the density of the central body, as the distance Cd will remain constant and rd will change in proportion to the density, and the rectangle rdC proportionally.

As the masses of different spheres of the same density are determined by their radii, the rectangles RDC and rdc will be increased or reduced in the square ratio of the radius CD and consequently the velocity in the simple ratio of CD.

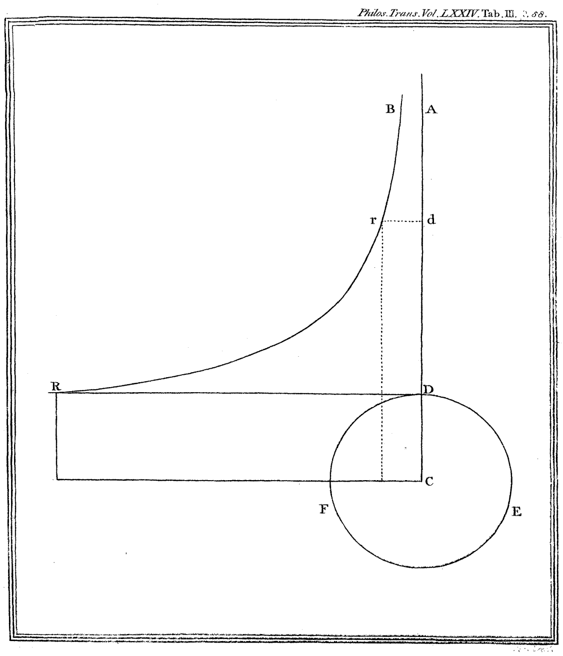

Figure 2: The explanatory diagram that accompanied Michell's 1784 paper.[3]

If the velocity of a falling body is the same when it reaches the surface of two different central bodies, then the rectangle RDC will remain the same. RD must be inversely proportional to CD, and the density is therefore inversely proportional to CD^2.

In modern parlance, Michell's diagram (Figure 2) is a graph of the gravitational force, $F = GMm/r^2$ between the falling body of mass, m, and the central attracting body of mass, M, as a function of the distance, r, from the central body. The area is the work done by the gravitational force, and is equal to the gain in kinetic energy of the mass, m. For an initially-stationary mass, m, free-falling from an infinite height, the work done (area AdrB) is GMm/r and the acquired velocity is given by $v^2 = 2GM/r$. At the surface of M, the area ADRB is GMm/R, the same as the rectangle RDC. If the central body is a sphere of density ρ, then $F = k\rho mR^3/r^2$, where $k = 4\pi G/3$, and the velocity of the falling body is $v^2 = 2k\rho R^3/r$, that is, v^2 is proportional to ρ at a fixed distance r. At the surface of M this becomes $v^2 = 2k\rho R^2$, and will be the same at the surfaces of different central bodies if ρR^2 is constant, that is, the density must be inversely proportional to CD^2.

Michell knew that the velocity of the falling body at the surface of the Sun is the same as a comet revolving in a parabolic orbit at the Sun's surface, but with a velocity 20.72 times the velocity of the Earth in its orbit of 214.64 times the Sun's radius. As the square of the velocity of the comet is twice the square of the velocity of a planet, the ratio of the squares of the velocities is 429.28:1, and the square root of 429.28 is 20.72.

Michell considered the speed of light to be 10,310 times the Earth's orbital velocity, which if divided by 20.72 gives approximately 497. This is the number of times the velocity of light would exceed the velocity of a body falling from infinity onto the surface of the Sun, and the ratio of an area whose square root should exceed the square root of area RDC, RD being the force of gravity at the surface of the Sun and CD the Sun's radius.

Therefore

> … if the semi-diameter of a sphere of the same density with the sun were to exceed that of the sun in the proportion of 500 to 1, a body falling from an infinite height towards it, would have acquired at its surface a greater velocity than that of light, and consequently, supposing light to be attracted by the same force in proportion to its vis inertiae, with other bodies, all light emitted from such a body would be made to return towards it, by its own proper gravity. (Michell, 1784: 42)

In this scenario, the central body would remain invisible, and using modern parlance we would refer to it as a black hole.

Michell then proceeds to comment that if the diameter of a sphere was < 497 times that of the Sun, light would escape, but at a very much reduced velocity.

He notes that it is difficult to determine the distance to individual stars and groups of stars that are at very large distances, except when these groups include double and triple stars to which his analysis can be applied. He suggests that it will be many years—even decades—before new double and triple stars will be found in sufficient numbers to test his theory. Since the revolution of some secondary components about their central stars takes many years, Michell expresses the hope that relevant observations of double and multiple stars will be made by future generations.

Michell (1784: 50) further suggests that

> If there should really exist in nature any bodies, whose density is not less than that of the sun, and whose diameters are more than 500 times the diameter of the sun, since their light could not arrive at us; or if there should exist any other bodies of a somewhat smaller size, which are not naturally luminous; of the existence of bodies under either of these circumstances, we could have no information from light; yet, if any other luminous bodies should happen to revolve about them we might still perhaps from the motions of these revolving bodies infer the existence of the central ones with some degree of probability, as this might afford a

> clue to some of the apparent irregularities of the revolving bodies, which would not be easily explicable on any other hypothesis …

It is interesting that this method is now widely used by contemporary astronomers to search for black holes. The X-ray sources Cygnus X-1, LMC X-3 and V404 Cygni were identified as stellar remnant black holes through observations of their optical binary companions, and the evidence for a 4×10^6 $M_\odot$ supermassive black hole at the centre of our galaxy comes from the analysis of short period stellar orbits about SgrA* (see Reid, 2009).

3 PIERRE-SIMON LAPLACE

3.1 A Biographical Sketch

Pierre-Simon Laplace (Figure 3) is considered one of France's greatest scientists (see Gillispie, 1997; Hahn, 2005). He was born on 23 March 1749 in lower Normandy where his father was a syndic of the parish. He began his education at the college at Beaumont-en-Auge, where his uncle taught, remaining there until he reached the age of sixteen. From this college students normally proceeded into the army or into an ecclesiastical vocation, and in 1766 Laplace moved to the University of Caen, where he matriculated in the Faculty of Arts after just two years.

During this two-year period Laplace discovered that he possessed mathematical gifts, so he abandoned his theological studies and in 1768 moved to Paris. There he came under the watchful eye of d'Alembert, a leading scientist in the French Academy, who obtained for him the appointment of Professor of Mathematics at the École Militaire. Laplace taught there from 1769 to 1776, and during this interval he presented thirteen papers on mathematics and the theory of probability to win election to the Academy of Science. One of the papers was on "The Newtonian theory of the motion of planets", which Laplace translated into Latin. He was elected to the Academy in 1773.

This was the era of the French Revolution (1789-1799), a period of political and social upheaval throughout France as it moved from an absolute monarchy with feudal privileges for the aristocracy and the Catholic clergy to a form based on the enlightenment principles of nationalism, citizenship and inalienable rights.

Laplace had remained at the Academy, and the fall of Robespierre and the Jacobin regime in 1794 saw a dramatic change in the education system which led to the institutionalization of modern French society. Various institutions of science emerged (including the Institute de France), but some of these fell by the wayside only to re-emerge at a later stage. In 1795 Laplace was elected Vice-President of the Institute of France, and a year later was made President.

In this position he deferred from giving lectures at the Institute, and instead referred the auditors to a book he was preparing titled *Exposition du Système du Monde* which appeared in two volumes in 1796.

Pierre-Simon Laplace died on 5 March 1827, just two and a half weeks short of his 78th birthday.

3.2 Laplace Independently Introduces the Concept of Black Holes

In the sixth chapter of *Exposition du Système du Monde* Laplace introduced speculation as to the origin of the Solar System and the nature of the Universe.

The Sun lies in the centre of the Solar System and spins on its axis every twenty-five and a half days and its surface is covered with 'oceans' of luminous matter spotted with dark patches. The atmosphere above this extends beyond recognition. Around the Sun spin the seven planets in almost circular orbits. However, Laplace did not consider comets to be part of the Solar System as some travelled in highly eccentric orbits, and while they moved into the Sun's domain they also moved far beyond the planetary sphere.

Figure 3: Pierre-Simon Laplace, 1749–1827 (after http://en.wikipedia.org/wiki/Pierre-Simon_Laplace #References).

In describing the Solar System Laplace (1796: 305) makes another conjecture:

> The gravitation attraction of a star with a diameter 250 times that of the Sun and comparable in density to the earth would be so great no light could escape from its surface. The largest bodies in the universe may thus be invisible by reason of their magnitude.[4]

Laplace stated this possibility in a merely qualitative way—almost in passing—without any mathematical proof, and he only proceeded to provide the latter when asked to do so by F.X. von Zach. This was subsequently published in the German journal, *Allgemeine Geographische Ephemeriden* (Laplace, 1799),[5] which von Zach edited.

3.3 Laplace's Mathematical 'Proof'

Laplace's (1799) proof of the existence of 'invisible bodies' (or black holes) took the form of an essay, which we summarise below.

For non-uniform motion, the velocity v over the time interval dt must be taken as

$$v = \frac{dr}{dt} \tag{1}$$

where dr is the distance travelled.

A continuously working force will strive to change the velocity. This change in velocity, namely dv, is therefore the most natural measure of the force. But as any force will produce double the effect in double the time, so we must divide the change in velocity dv by the time dt in which it is brought about by the force P (see Note 6), namely

$$P = \frac{dv}{dt} = \frac{d}{dt}\left(\frac{dr}{dt}\right) = \frac{d^2r}{dt^2} \tag{2}$$

The attractive force between a body M and a particle of light at a distance r is proportional to $-M/r^2$ (also see Note 6). The negative sign occurs because the action of M is opposite to the motion of the light. Equating P with $-M/r^2$ and integrating gives

$$v^2 = 2C + 2Mr^{-1} \tag{3}$$

where v is the velocity of the light particle at the distance r.

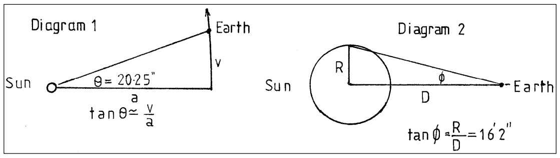

Figure 4: Diagrams used to help explain Laplace's concept of 'black holes'.

To determine the constant C, let R be the radius of the attracting body, and a the velocity of the light at the distance R. Hence on the surface of the attracting body one obtains

$$2C = a^2 - 2M/R \tag{4}$$

so that

$$v^2 = a^2 - \frac{2M}{R} + \frac{2M}{r} \tag{5}$$

Let R' be the radius of another attracting body with attractive power iM. The velocity of light at a distance r will be v',

$$v'^2 = a^2 - \frac{2iM}{R'} + \frac{2iM}{r} \tag{6}$$

As the distance of the fixed stars is so large, one can make r infinitely large, and one obtains

$$v'^2 = a^2 - \frac{2iM}{R'} \tag{7}$$

Let the attractive power of the second body be so large that light cannot escape from it; this can be expressed analytically as the velocity $v' = 0$ at an infinitely large distance. This gives

$$a^2 = \frac{2iM}{R'} \tag{8}$$

To determine a, let the first attracting body be the Sun; then a is the velocity of the Sun's light on the surface of the Sun. The gravitational force at the surface of the Sun is so small that its effect on the velocity of light leaving that surface can be neglected in the context of this discussion.

Laplace (1796) uses his assumption made on page 305 in *Exposition du Système du Monde* (*Part 11*), that $R' = 250R$. Since the mass changes as the volume of the attracting body multiplied by its density and therefore as the cube of the radius, then, if the density of the Sun is 1 and that of the second body is ρ,

$$M : iM = 1R^3 : \rho R'^3 = 1R^3 : \rho 250^3 R^3 \tag{9}$$

or

$$i = (250)^3 \rho \tag{10}$$

Substitution of the values of i and R' in the equation (8) gives

$$\rho = \frac{a^2 R}{2(250)^2 M} \tag{11}$$

for the density of the body from which light cannot escape. To obtain ρ, one must still determine M. The force of the Sun is equal at a distance D to M/D^2. If D is the average distance of the Earth and V the average velocity of the Earth, then this force is also equal to V^2/D (see Lalande 1792, Volume 3: 3539). Hence

$$M/D^2 = V^2/D \tag{12}$$

or

$$M = V^2 D \tag{13}$$

Substituting this into equation (11) gives

$$\rho = \frac{8}{(1000)^2}\left(\frac{a}{V}\right)^2\left(\frac{R}{D}\right) \tag{14}$$

From the phenomena of aberration, it appears that the Earth travels 20.25″ in its path while light travels from the Sun to the Earth. Referring to Figure 4, the ratio a/V, the velocity of light divided by the velocity of the Earth, is given by

$$a/V = 1/\tan 20.25'' \tag{15}$$

R/D is the absolute radius of the Sun divided by the average distance of the Sun, and is equal to the tangent of the average apparent angular radius of the Sun, which is tan 16′ 2″ (see Figure 4).

Hence the required density is given by

$$\rho = 8 \tan 16' 2'' / (1000 \tan 20.25'')^2 \tag{16}$$

which is approximately 4, or about that of the Earth.

4 DISCUSSION

It is important to note that Michell's reference to what we would now call a 'black hole' was merely a by-product of his 1784 paper and not the main focus of that paper. The paragraph containing the description of a black hole developed out of his theory about the distance to and relative sizes of double stars, although it is worth pointing out that on page 50 Michell (1784) also describes the perturbations of stars by "… bodies of a somewhat smaller size, which are not naturally luminous …"

As we have seen, just twelve years later the Frenchman, Laplace, followed up Michell's work by independently proposing the existence of 'black holes' and three years on he provided the mathematical proof of these. However this would appear to be a remarkable coincidence as there was little scientific contact between England and France during this extremely troubled time in French history. Thorne (1994), amongst others, has suggested otherwise: that upon hearing of Michell's theory that gravity could prevent light from emerging from a star, Laplace immediately proceeded to provide the mathematical proof. Furthermore, Thorne (*ibid.*) has stated that the reason that Laplace did not include the proof in the original edition of his book, *Exposition du Système du Monde*, and excluded it from several subsequent editions was that he did not believe in the existence of 'black holes'.

The first of these claims is not substantiated by Laplace's biographer, Charles Coulston Gillispie (1997) and Laplace's 1799 paper. The latter paper leaves no doubt that it was von Zach who requested that Laplace provide a mathematical proof to the simple statements made in his 1796 book.

Our British colleague, Emeritus Professor David W. Hughes (pers. comm., 2009), has made the following pertinent comment:

> It is interesting that Michell and Laplace both 'backed the wrong horse' when it came to predicting what stellar black holes might be like. Looking at the formula for the escape velocity one can see that one can have a black hole if you have a star of solar density that is very large. Or you can have a black hole if you have a star that is a bit more massive than the Sun but has a very small size and thus a very high density.
>
> Both Michell and Laplace went for the 'big star' option. But this was wrong. The black holes that have been found are all very small size and very high density.
>
> Why did they get it wrong? Maybe it was just down to the physics of the day. The most dense material at the time was gold and having substances much more dense than this was probably thought to be impossible. When it came to stellar size they had only one point on their graph, the diameter of the Sun. No other stellar sizes were known. They thought that there might be stars bigger than the Sun but seemed reluctant to consider the possibility that there might be much smaller ones. Let's face it, the physics of white dwarfs must have been surprising in the late 19th century, just as the physics of black holes is today.

Finally, it is of interest to reflect on the similarity in the lives of Michell and Laplace. While both studied theology with a view to entering the church, their interests turned towards mathematics and particularly the laws of probability. Indeed, it was the probability that non-luminous bodies should exist that led the two scientists quite independently to the concept of a 'black hole'. Having said that, it is important to realise that the non-luminous bodies postulated by Laplace were much larger than those suggested by Michell. The Laplacian body had a radius of 250 $R_\odot$, a density four times that of the Sun, and consequently a mass of $4 \times (250)^3\ M_\odot$, about 10^5 times the 500 $M_\odot$ body considered by Michell.

5 CONCLUDING REMARKS

The talented English scientist turned clergyman, John Michell, was the first to postulate the existence of a black hole in 1784 when he published a paper in the *Transactions of the Royal Society* which dealt with the distances of double stars and the relative sizes of their components. By a strange twist of fate, France's Pierre-Simon Laplace independently postulated the existence of black holes in his book, *Exposition du Système du Monde*, which was published in 1796, and three years later he published the necessary mathematical proof—not in response to Michell's earlier paper, but because the noted German astronomer F.X. von Zach specifically requested it.

6 NOTES

1. Note that Hodges (2007) gives Michell's date of death as 21 April rather than 29 April, but we have opted for the latter date.
2. According to Jungnickel and McCormmach (1996: 139),

   > Michell and Cavendish's acquaintanceship, if not their friendship, began no later than … 1760. That year, at Cavendish's first dinner as a member of the Royal Society Club, Michell was present as a guest, and in later years Cavendish often brought Michell as his own guest. In 1760, Michell and Cavendish were both elected Fellows of the Royal Society …

   Michell and Cavendish often took the opportunity to discuss their different philosophies on the appearance of the inverse square law in nature (Hardin, 1966). As early as 1750 Michell had stated the mathematical properties of magnetic force and in 1771 Cavendish established the laws of electrical attraction and repulsion, both related to the inverse square law (Jungnickel and McCormmach, 1996).
3. This figure appeared in the published version of Michell's 1784 paper, but is missing from the MS of the paper in The Royal Society's Archives. We are pleased to report that as a result of a dedicated search on behalf of the first author, Joanna Corden, the Archivist and Records Manager at The Royal Society, recently found the missing figure bound by mistake between the first and second pages of a meteorological paper by John Atkins which immediately follows Michell's paper in the *Philosophical Transactions*. Subsequently, a further copy of this diagram was found at the Cambridge University Library in the William Herschel Papers.
4. It should be understood that the word 'magnitude' is used here in its eighteenth century sense to refer to that which "… can be compared by the same common feature …" (Bailey, 1737), and therefore differs significantly from our current usage of the term.
5. An English translation of Laplace's 1799 paper appears in Hawking and Ellis (1973: 365-368) as Appendix A.
6. Note that P and M, as used here, are respectively the force per unit mass and the mass of the body multiplied by the Newtonian constant, G.

7 ACKNOWLEDGEMENTS

We wish to thank Joanna Corden, Archivist and Records Manager at The Royal Society (London), for finding the missing Michell Diagram Tab. III; The Royal Society for permission to publish the diagram and the extracts from Michell's paper; Rita Bisley, Librarian at James Cook University, for obtaining a copy of the original Michell paper and a further copy of Diagram Tab.111 from Cambridge University; and Sandra Ricketts, Librarian at the Anglo-Australian Observatory (Sydney) and Professor Hilmar Duerbeck (Centre for Astronomy, James Cook University) for their assistance. Finally, we wish to thank Professor Duerbeck, Professor Ken Freeman (Mount Stromlo and Siding Spring Observatories), Emeritus

Professor David W. Hughes (University of Sheffield) and Professor Joe Tenn (Sonoma State University) for reading and commenting on the manuscript.

8 REFERENCES

Bailey, N., 1737. *The Universal Etymological English Dictionary*. London, Printed for Thomas Co.

Crossley, R., 2003. Mystery at the Rectory: some light on John Michell. *Yorkshire Philosophical Society, Annual Report for the Year 2003*, 61-69.

Gillispie, C.C., 1997. *Pierre-Simon Laplace-1749-1827*. Princeton, Princeton University Press.

Hahn, R., 2005. *Pierre-Simon Laplace 1749-1827: A Determined Scientist*. Cambridge, Harvard University Press.

Hardin, C.L., 1966. The scientific work of John Michell. *Annals of Science*, 22, 27-47.

Hawking, S.W., and Ellis, G.F.R., 1973. *The Large Scale Structure of Space-Time*. Cambridge, Cambridge University Press.

Hoskin, M., 2004. Michell, John (1724/5–1793). In Matthew, H.C.G., and Harrison, B. (eds.). *Oxford Dictionary of National Biography*. Oxford, Oxford University Press. Pp. xx-xx.

Herschel, W., 1782a. Catalogue of double stars. *Philosophical Transactions of the Royal Society*, 72, 112-162.

Herschel, W., 1782b. On the parallax of the fixed stars. *Philosophical Transactions of the Royal Society*, 72, 82-111.

Hodges, L., 2007. Michell, John. In Hockey, T., et al. (eds.). *The Biographical Encyclopedia of Astronomers. Volume II M-Z.* New York, Springer. Pop. 778-779.

Hughes, D.W., and Cartwright, S., 2007. John Michell, the Pleiades, and odds of 496,000 to 1. *Journal of Astronomical History and Heritage*, 10, 93-99.

Hutton, E., 2006. The Reverend John Michell: a letter from his great-grandson. *The Antiquarian Astronomer*, 3, 65-68.

Israel, W., 1987. Dark stars: the evolution of an idea. In Hawking, S.W., and Israel, W. *Three Hundred Years of Gravitation*. Cambridge, Cambridge University Press. Pp. 199-276.

Jungnickel, C., and McCormmach, R., 1996. *Cavendish*. Philadelphia, The American Philosophical Society.

Lalande, J., 1792. *Traité d'astronomie*. Third Edition. Three volumes. Paris.

Laplace, P.S., 1796. *Exposition du Système du Monde. Part 11*. Paris (English translation by Rev. H. Harte, Dublin, 1830).

Laplace, S., 1799. Beweis des Satzes, dass die anziehende Kraft bey einem Weltkörper so gross seyn könne, dass das Licht davon nicht ausströmen kann. *Allgemeine Geographische Ephemeriden*, 4, 1-6.

McCormmach, R., 1968. John Michell and Henry Cavendish: weighing the stars. *The British Journal for the History of Science*, 4, 126-155.

Michell, J., 1767. An inquiry in to the probable parallax, and magnitude of the fixed stars, from the quantity of light which they afford us, and the particular circumstances of their situation. *Philosophical Transactions of the Royal Society*, 57, 234-264.

Michell, J., 1784. On the means of discovering the distance, magnitude, &c. of the fixed stars, in consequence of the diminution of the velocity of their light, in case such a diminution should be found to take place in any of them, and such other data should be procured from observations, as would be farther necessary for that purpose. *Philosophical Transactions of the Royal Society*, 74, 35-57.

Montgomery, C., 2009. From Michell to MACHOS: Changing Perspectives on our Understanding of 'Dark Matter'. Unpublished Ph.D. Thesis, Centre for Astronomy, James Cook University.

Read, Mark J., 2009. Is there a supermassive black hole at the center of the Milky Way? *International Journal of Modern Physics D*, 18 (in press). Preprint arXiv:0808.2624v1 [astro-ph].

Schaffer, S., 1979. John Michell and black holes. *Journal for the History of Astronomy*, 10, 42-43.

Thorne, K.S., 1994. *Black Holes and Time Warps*. New York, W.W. Norton. Editor, Lewis Thomas.

Turton, T., 1793. Letter to William Herschel dated 1 July. Original in the RAS Archives: Herschel W.1/T10(1).

Wikipedia essay about Henry Cavendish: http//:en.wikipedia.org/wiki/File:Cavendish_Henry.jpg).

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Journal of Astronomical History and Heritage, 12(2), 97-107 (2009).

TIME-KEEPING IN THE ANTIPODES: A CRITICAL COMPARISON OF THE SYDNEY AND LYTTELTON TIME BALLS

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Abstract: Maudslay, Sons & Field built the time ball apparatus for Sydney, New South Wales (NSW) in 1855, and to hoist the ball they used a rack and pinion that was developed from the mechanism found at Edinburgh and Deal. Sydney's time ball became operational in 1858, following completion of Sydney Observatory (which included a time ball tower). Henry Russell, the NSW Government Astronomer, modified this apparatus to a limited extent during the 1870s, but most principal features were retained. The apparatus for Lyttelton, New Zealand, was ordered in 1873 and shipped from London in 1874 by Siemens Brothers. It, too, had to await completion of the necessary tower, and became operational in 1876. Both Antipodean time balls were still working in 2009. In this paper it is demonstrated that the apparatus at Lyttelton is a replica of the 1855 design used in Sydney, despite the long interval between their dates of supply. The only surviving note in Maudslays' records about an 1873 time ball indicates provision for the Cape of Good Hope and an association with Siemens. A time ball was installed at Alfred Docks in Cape Town during 1873, but available evidence indicates that it was unlikely to have been built by Maudslays. It is suggested that Maudslays' 1873 apparatus was instead sold to Siemens Brothers who installed it at Lyttelton. No Siemens records showing the supply of time balls to other locations at this time have been found.

Keywords: time balls, Maudslays, Siemens, Sydney Observatory, Lyttelton Timeball Station, Cape of Good Hope

1 INTRODUCTION

The time balls at Sydney (Australia) and Lyttelton (New Zealand) are two landmarks that are famous locally, and they provide a reminder of maritime history when precise measurement of time using ships' chronometers was critical to determination of longitude. Their mechanisms, both fine examples of Victorian engineering, are still working. The aim of this paper is to explore why they are almost identical, despite supply by two different companies in England with an interval of nineteen years between shipments; Maudslay, Sons & Field (abbreviated to Maudslays in the following discussion) built the apparatus for Sydney in 1855, while Siemens Brothers shipped the apparatus to Lyttelton in 1874. Records of both companies concerning time balls are sparse, but recent work has thrown light on their contributions and business activities at the time of supply. Histories of the Sydney and Lyttelton time balls are outlined, based upon historical sources.

Kinns and Abell (2009) sought to establish the influence of Maudslays on the development of time balls in Australia. A brief history of Henry Maudslay and the company he founded is given in a Maudslay Society brochure, published in 1949 and amended in 1956. A letter from Henry Russell (1899), the NSW Government Astronomer, to Sir Charles Todd in Adelaide was thought to be the only surviving evidence in Australia of Maudslays' supply to Sydney. Confirmation has now been found in the Todd correspondence, archived in Adelaide (Todd, 1899a; 1899b). The Sydney time ball became operational on 5 June 1858, following completion of Sydney Observatory. Henry Russell, the NSW Government Astronomer, modified this apparatus to a limited extent during the 1870s, but most principal features, including the rack and pinion mechanism and the casing, were retained (Russell, 1899). The Sydney design provided the basis for the apparatus that was installed in the new Customs House at Newcastle, NSW. It became operational on 21 February 1878 and incorporated Russell's Sydney modifications and other improvements, which included an open structure for the mechanism casing. It was manufactured by Potter & Sons of Sydney in 1877 (Kinns and Abell: 78-81).

The history of the Lyttelton time ball station is described in an informative booklet, published by the New Zealand Historic Places Trust in 1979. According to this booklet, Siemens Brothers shipped the apparatus for Lyttelton from London in July 1874, following an order placed in March 1873 (Bremner and Wood, 1979: 15). Siemens had become a principal supplier of telegraphic equipment, with heavy commitments to supply and install telegraph cables at the time. The Lyttelton time ball also had to await completion of the necessary tower and it became operational on 23 December 1876 (*ibid*: 23). It was restored faithfully during the 1970s.

The Sydney and Lyttelton time balls are both included in the 1898 list of time signals for mariners. The Sydney ball was specified as having a diameter of 5 ft. and a drop of 10 ft. (List of time signals, 1898: 26-27), but although the corresponding parameters for Lyttelton were not indicated (List of time signals, 1898: 28-29) they were in fact the same. The two time ball mechanisms are remarkably similar, especially when known modifications to the Sydney apparatus after 1870 are taken into account. Drawings, photographs and other records are compared in this paper. The similarity suggests strongly that Siemens bought the apparatus for Lyttelton from Maudslays. It also suggests that no significant design development in time balls had taken place at Maudslays during the nineteen years that elapsed between the supply of the Sydney and Lyttelton time balls.

Maudslays' company records were largely destroyed after liquidation of the firm at the end of the nineteenth century (Maudslay Society, 1956: 20). There is, however, an indication that there was a relationship with Siemens for time ball supply in 1873. Possible options for this relationship are explored.

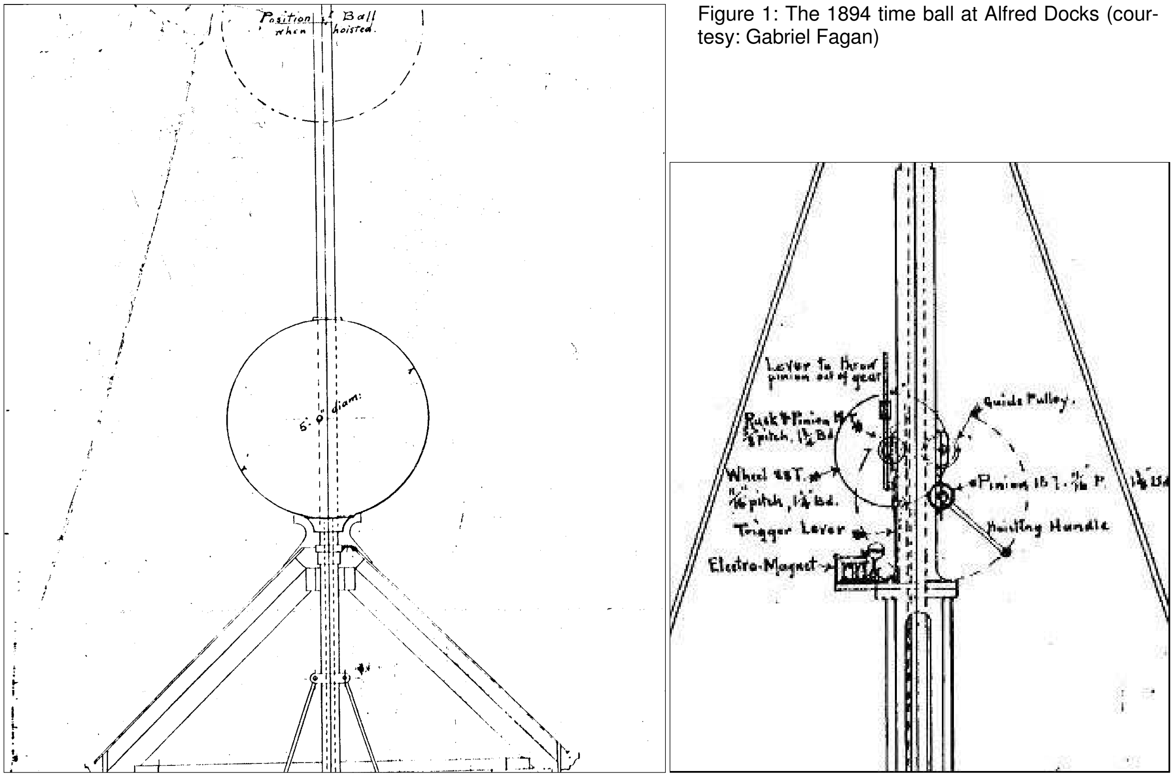


Figure 1: The 1894 time ball at Alfred Docks (courtesy: Gabriel Fagan)

2 TIME BALLS SUPPLIED BY MAUDSLAY, SONS & FIELD

Maudslays developed a wide-ranging general engineering business (Petree, 1934), which complemented the main work of marine steam engine supply. Petree (1967) drew heavily on twelve notebooks dating between 1842 and 1883 by Charles Sells, who was Maudslays' chief draughtsman for forty-eight years. The only reference to time balls is a list on the final page of the last note-book (Sells, 1878-1883):

Greenwich	1833
Edinburgh	1852
S Foreland (Deal)	1853
N. S. Wales (Sydney)	1855
C of Good Hope (Siemens)	1873

The time ball at Greenwich used a chain hoist, but those at Edinburgh, Deal and Sydney used rack and pinion hoists. Although it was planned originally that the Deal time ball would be installed on the South Foreland lighthouse, Astronomer Royal George Biddell Airy decided that it would be better located at the semaphore tower at Deal. The above dates are of construction, rather than first operation. Interpretation of the final entry for 1873 is key to this paper.

The need for a heavy ball and development of appropriate arrangements for controlling deceleration, in order to ensure reliability and availability in all but extreme weather, were described by Charles Piazzi Smyth in an 1853 paper concerning the Edinburgh time ball (Smyth, 1853). Piazzi Smyth (1819–1900) was the second Astronomer Royal of Scotland, and served in that capacity from 1846 to 1888 (Brück and Brück, 1988). He was responsible for provision of the time ball on top of the Nelson Monument at Calton Hill in Edinburgh, a location that allowed it to be seen easily from Leith Docks. This was Maudslays first apparatus to use a rack and pinion hoist for the ball, followed by Deal and then Sydney.

Sir Charles Todd (1899b) wrote that he saw the Sydney apparatus under construction in Maudslays' workshops before he left for Adelaide in 1855, and he also noted that it was modelled on the Deal apparatus. The systems at Deal and Sydney use the same principles of operation, but there are design differences, described later, which show development between 1853 and 1855. The original drawings for Sydney have been lost, so the original design has to be inferred from knowledge of later alterations.

2.1 Time Balls at the Cape of Good Hope

Maudslays contract list includes a time ball for the Cape of Good Hope in 1873, with a reference that suggests Maudslays had an arrangement with Siemens. The first time ball at the Cape Observatory had been erected in 1836 (Bartky and Dick, 1981); a second became operational on 14 October 1853 (Notice to Mariners, 1853), constructed because the original was no longer readily visible from Table Bay. The first time ball had been established by Thomas Maclear (1794–1879), Director of the Royal Observatory at the Cape from 1834 to 1870 (Gill, 1913). It had a diameter of 5 ft. and slid upon a rope projecting from a flagstaff. It was said to have had a probable error that had been reduced to 0.1 sec by 1852 (Maclear, 1852). Maclear (*ibid.*) was defensive about its availability, feeling obliged to point out that the signal had failed on only seven occasions between 1 January and 7 July 1852: four due to weather, two while the transit instrument was being repaired and one "… because the establishment was engaged upon a more urgent duty." Gill (1913) records the introduction of other time signals after the electric telegraph came into use: "… a time ball was dropped at the Docks in Cape Town; a Disc at the end of an arm was dropped at Simons Town, and similar Discs at the Light House, Port Elizabeth and at East London." The 1898 list of time signals indicates that there was still a disc at Simons Town, but by this time there were time balls at Port Elizabeth, Port Alfred, East London and Durban, as well as at Alfred Docks.

The Sells notebook entry for 1873 was interpreted by Petree to imply that Siemens might have supplied the electrical components for Maudslays' apparatus. The electromagnets operating the trigger were, however, a small part of the main apparatus and the telegraphic equipment was external to it. It may have been decided after the order was placed to use a simpler, lighter apparatus at Cape Town; clearly, there was a well-established capability for time ball operation at the Cape Observatory (Gill, 1913), which may have been exploited in local design of replacement systems. Maudslays' 1873 apparatus may then have been sold to Siemens Brothers who shipped it to Lyttelton in 1874 (Kinns and Abell, 2009). Another interpretation of the Sells notebook entry is that Maudslays built two systems in 1873, one for the Cape and one for Siemens. Either possibility would explain the remarkable similarity between the 1855 design for Sydney and the later Lyttelton apparatus.

A time ball was installed on a North Quay warehouse at Alfred Docks in Cape Town during 1873 (Spencer Jones, 1993); this is the only time ball that is known to have been installed in Cape Colony at that time. Cape Town is notoriously windy, so a heavy ball would have been essential for provision of a reliable service (private communication, Jonathan Spencer Jones, 27 February 2009). The Alfred Docks site was redeveloped during the 1890s and "In 1894 a new time ball was erected in a much more conspicuous position near the Resident Engineer's Office of the Cape Town Docks." (Gill, 1913). Its elevation was increased later, by extending the tower. There do not appear to be any surviving records of the 1873 arrangement (private communication, Gabriel Fagan, 17 March 2009). It was, however, the principal time ball for Table Bay in the first and second editions of the Admiralty list of time signals (1880 and 1888). It was listed as having a drop of 6 ft., the diameter being unspecified; its latitude and longitude were 33^{o} 54′ 27″ S and 18^{o} 25′ 15″ E (List of time signals, 1880: 8-9). According to the 1898 list, the 1894 time ball retained the 6 ft. drop, but there was a small adjustment or correction to its latitude: 33^{o} 54′ 24″ S and 18^{o} 25′ 15″ E (List of time signals, 1898: 22-23).

2.1.1 The 1894 Time Ball at Alfred Docks

The mechanism for the 1894 system no longer exists, but original drawings are available and a replacement system was designed by the Department of Mechanical Engineering at the University of Cape Town and was commissioned in November 1997 (Victoria and Alfred Waterfront, website). The overall restoration of the waterfront site was undertaken by Victoria and Alfred Waterfront (Pty.) Ltd., with Gabriel Fagan as the architect.

Figure 1 shows the design of the 1894 apparatus, from drawings made in 1898 (drawings used to restore the tower and construct the new time ball apparatus for the Waterfront site were received from Gabriel Fagan on 21 March 2009). The time ball clearly had a diameter of 5 ft. and a drop of 11 ft. The drawings expose an ambiguity in the Admiralty lists of time signals: the reported time ball drop can mean either the vertical drop of the ball centre from its raised to its rest position, or the distance from the bottom of the ball in its raised position to the top of the ball in its rest position. Thus the drop is recorded as 6 ft. at Alfred Docks, using the second definition, while it is recorded as 10 ft. at Sydney using the first, more intuitive, definition. Compilers of the Admiralty lists were probably unaware of the ambiguity. The second definition is likely to have been used for all time balls in Cape Colony, so the 1873 time ball is also likely to have had a drop of 11 ft.

The drawings of the 1894 mechanism show that it was similar in principle to that supplied for Deal in 1853, but it was of lighter construction. The rack and 18-tooth pinion had a pitch of only 16 mm whereas Maudslays' systems used a 10-tooth pinion and 24 mm pitch. It used a single guide wheel opposite the pinion, as at Edinburgh and Deal. This design was changed for Sydney, with a pair of guide wheels on each side of the rack. The small pitch and tooth size for the rack at Alfred Docks suggests that the ball and rack would have been considerably lighter than those at Edinburgh, Deal and Sydney. The descent was cushioned using an air-filled cylinder with an escape valve to provide damping, as in all Maudslays' mechanisms.

If the 1873 apparatus had been supplied by Maudslays, it would have been based on the 1855 design for Sydney, not the earlier design for Edinburgh and Deal. It would be surprising in those circumstances if the 1894 apparatus had then reverted to the earlier design.

3 TIME BALLS SUPPLIED BY SIEMENS

The principal biographies of Sir William Siemens and Siemens Brothers (Pole, 1888, and Scott, 1958) do not include any mention of time balls. Time ball supply would have been a minor business activity in relation to design, supply and installation of submarine telegraph cables. Siemens Brothers submitted a proposal in April 1873 to the governments of New South Wales, Queensland and New Zealand for provision and operation of telegraph cables between Singapore and Normantown and from Sydney to New Zealand (*Nelson Examiner and New Zealand Chronicle*, 1873), but this does not appear to have been accepted. The main preoccupations of Siemens Brothers during 1873 and 1874 were supply of the Direct United States and ill-fated Platino-Brasiliera cables, and commissioning of the cable-laying ship *Faraday* (Scott, 1958: 37-39). These major projects carried huge financial risk, with the future of the company depending on a successful outcome. It would not be surprising in these circumstances if Siemens decided to subcontract provision of a time ball apparatus to an established manufacturer, electing to act as systems integrator for their client. Maudslays was the obvious choice.

Maudslays and Siemens Brothers would have been well aware of each other's capabilities; indeed, Maudslays' Joshua Field, FRS, had been a proposer in the successful recommendation for William Siemens' fellowship of the Royal Society during 1862 (Pole, 1888: 129). Siemens does not have any record of time ball supply by either the British or German companies, other than for Lyttelton (private communication, Alexandra Kinter, January-March 2009).

Table 1: Time balls extant in 1898, having a diameter of 5 ft and a drop of 10 ft.

Country	Place	Location
Great Britain	Greenwich	Royal Observatory
Great Britain	Deal	Semaphore Tower
Great Britain	Edinburgh	Nelson Monument, Carlton Hill
Australia	Sydney	Sydney Observatory
Australia	Newcastle	Customs House
New Zealand	Lyttelton	Time Ball station
Germany	Wilhelmshaven	East Tower of Observatory
Germany	Bremerhaven	SW of lighthouse
Germany	Bremen	Harbour Office Tower
Germany	Cuxhaven	E of lighthouse
Germany	Hamburg	Kaiser Quay
Germany	Swinemunde	120 yds E of tower of New Navigation House
Spain	Cadiz	San Fernando Observatory

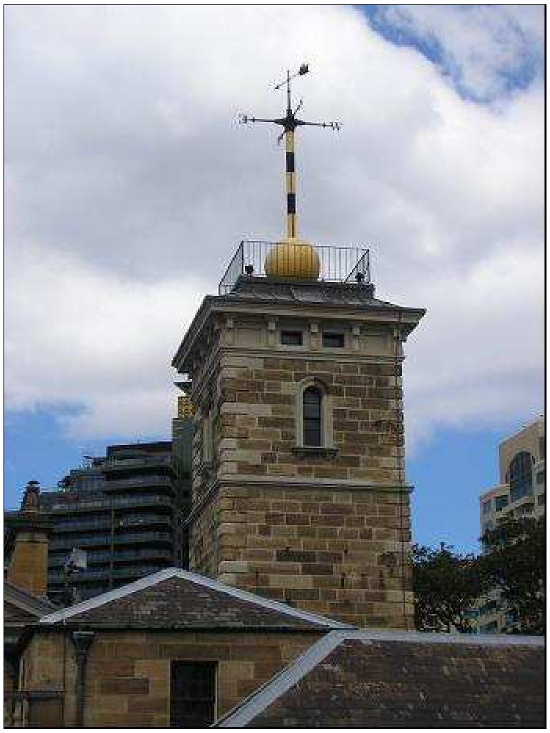


Figure 2: The tower and ball at Sydney on 27 March 2007.

4 ADMIRALTY LISTS OF TIME SIGNALS

The 1898 Admiralty list of time signals has 154 entries, including 94 time balls. In most cases, the list gives the diameter and drop of the ball, but as we saw when considering the 1894 design at the Alfred Docks in Cape Town there is ambiguity in the meaning of 'drop'. Other time balls existed in 1898, but were excluded from the list if they were not useful to mariners, because of location or accuracy. Various other devices were listed, including chronometers held in shore establishments that could be accessed for calibration, discs and moving arms, as well as guns that provided audible signals. All dimensions are given in the original Imperial units. This list formed the basis of a study by the New Zealand Historic Places Trust to show the status of time signals and to provide additional information about their origin (see Wright, 2007).

4.1 Accuracy of Data

The 1880 list has fewer entries, but can be used to judge the accuracy of the specified latitude and longitude, as well as other information such as the time ball drop distance. There are many corrections between the 1880 and 1898 lists, those for Sydney and Lyttelton being typical of locations remote from Greenwich. The actual time ball location was not changed in either case. In the 1880 list, the latitude and longitude of the Sydney time ball are given as 33° 51′ 54″ S and 151° 12′ 42″ E (List of time signals, 1880: 12-13), whereas in the 1898 edition they are 33° 51′ 41″ S and 151° 12′ 23″ E (List of time signals, 1898: 26-27). The corresponding data for Lyttelton are 43° 36′ 40″ S and 172° 44′ 17″ E (List of time signals, 1880: 14-15) and 43° 36′ 42″ S and 172° 44′ 50″ E (List of time signals, 1898: 28-29). The changes in listed latitude and longitude are 13″ and 19″ at Sydney and 2″ and 33″ at Lyttelton. The currently-accepted values for Sydney and Lyttelton are 33° 51′ 34″ S and 151° 12′ 16″ E and 43° 36′ 24″ S and 172° 43′ 35″ E respectively. Not surprisingly, changes between 1880 and 1898 are much smaller for facilities in Great Britain: 3″ and 2″ at Deal; and 3″ and 0″ at Edinburgh.

The time ball diameter and drop are often listed, but not always correctly. For example, the Lyttelton drop is given as 16 ft. in 1880, but is unspecified in 1898, yet it was always 10 ft. The first entry may be a typographical error, '10' and '16' being easily confused. The 5 ft. diameter is not specified in either edition. The Lyttelton time ball is listed as being at "The Custom House" in 1880, but at "The Observatory" in the 1898 list. The terms Signal Station or Time Ball Station were also used to describe the same location (Wright, 2007).

4.2 Time Balls of 5 ft Diameter and a Drop of 10 ft

Time balls supplied by Maudslays all had a diameter of 5 ft. and a drop of 10 ft. After 1852, they used heavy rack and pinion mechanisms, which required installation in a substantial building. Many other time balls in the 1898 list had similar diameters and drop heights. The time ball at Lyttelton had a diameter of 5 ft. and a drop of 10 ft., although these parameters are not stated in the 1898 list. The diameter of the Edinburgh ball is also not stated in the list, but it was 5 ft; the 10 ft. drop is stated.

Time balls in the 1898 list that are known to have had a diameter of 5 ft. (1.5 m) and drop of 10 ft. (3 m) are included in Table 1. Many were in Germany.

4.3 Time Balls at German Ports

The first time ball in Germany was at Cuxhaven in 1875 (Lexikon, 1888). The time ball at Kiel had a diameter of 5 ft., but the drop was listed as 11 ft. There was another 5 ft. diameter ball at Neufahrwasser, but with a reduced drop of 7 ft. (List of time signals, 1898: 36-39). Other German time balls used a drop of 10 ft. and are therefore included in Table 1. The only location outside the British Empire and Germany that is known to have used a 5 ft. diameter ball with a 10 ft. drop was Cadiz.

It was decided in 1873 to use a standard time ball apparatus for German ports (The time ball column at the Alte Liebe, website). The ball diameter of 5 ft and preferred drop of 10 ft were probably chosen in the light of British experience. The balls were all listed as black in 1898. The time ball drop in Germany was triggered using an electric telegraph signal. The apparatus for German ports was designed by Hugo Lentz, Leiter der Cuxhavener Wasserbauinspektion, who received a patent for the design. That appears to rule out design, and probably supply, of German time ball systems by Siemens, explaining the absence of any company records to that effect.

5 THE TIME BALL AT SYDNEY OBSERVATORY

Figure 2 shows a photograph of the Sydney Observatory tower and ball, taken on 27 March 2007. The ball was originally black, but was painted yellow for the Millennium celebrations. The ball itself is not the original design; it was changed during the 1870s.

5.1 The Letters Between Russell and Todd

A letter written by Henry Russell (Director of Sydney Observatory) to Sir Charles Todd (Director of Adelaide Observatory) includes criticisms of the original apparatus in Sydney and a brief description of the principal modifications that Russell made to it during the 1870s (Russell, 1899). These were: (1) Replacing the original ball, which had zinc plate nailed to wooden ribs, with a new one made of Muntz metal; (2) Replacing the wooden shaft which supported the rack with an iron shaft; and (3) Changing the trigger mechanism to make it direct acting.

Russell (*ibid.*) also remarks that

> The one we have in Newcastle was made in Sydney and is much better than the original in every way. The cast iron bore was replaced by four wrought iron corner pieces which leave the machinery all open and reduces the cost. It has been nearly 20 years in its place and has never cost anything for repairs.

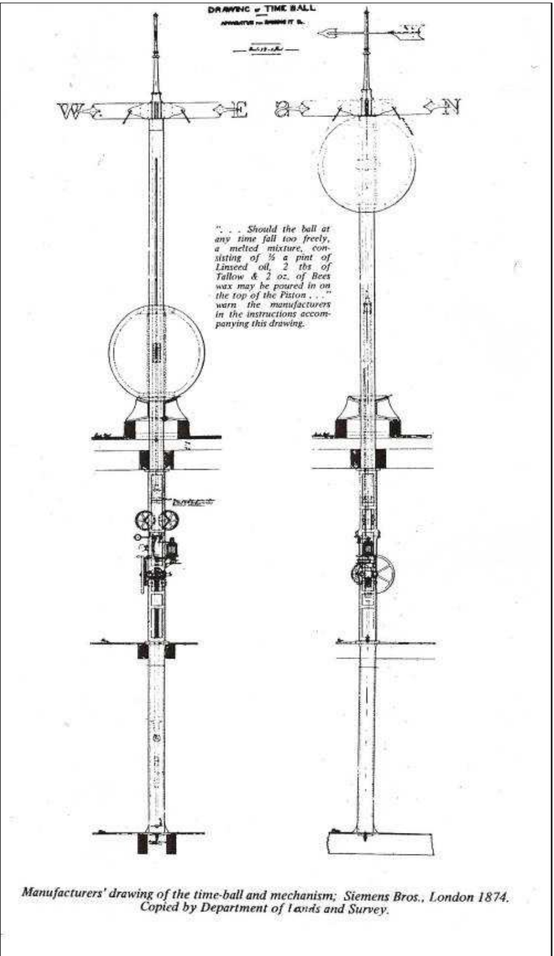
The Newcastle time ball had actually been in operation for over twenty years at the time the letter was written. In his response Todd (1899b) commented:

> It may interest you to know that I very carefully inspected the Time Ball at Maudsleys (*sic*) in 1855 before I came out to Australia. It was then considered a very fine piece of work; but I quite recognised the objections you mention from its being too much closed in.

The present Sydney mechanism retains the features mentioned in Russell's letter. Not surprisingly, there have been various repairs and additions since the letter was written more than a century ago. For example, the pinion has been replaced on more than one occasion, because the teeth were stripped when it was not withdrawn correctly before release. Sydney now has a modern electric motor drive to raise the ball, but the underlying arrangement was not altered and the capstan can still be used.

5.2 Costs of Time Ball Systems

Todd (1899a) recalled that the 1855 Sydney apparatus had cost £500, while Russell (1899) thought that the 1877 apparatus for Newcastle, which was made in Sydney, had cost £400. Russell (*ibid.*) also thought that £200 would have been sufficient in 1899. Todd (*ibid.*) mentioned the relatively low cost of the apparatus for Semaphore in 1875, which served Port Adelaide. That apparatus, with a chain hoist, is likely to have been built in Adelaide to Todd's design (Kinns and Abell, 2009).



". . . Should the ball at any time fall too freely, a melted mixture, consisting of ½ a pint of Linseed oil, 2 lbs of Tallow & 2 oz. of Bees wax may be poured in on the top of the Piston . . ." warn the manufacturers in the instructions accompanying this drawing.

Manufacturers' drawing of the time-ball and mechanism; Siemens Bros., London 1874. Copied by Department of Lands and Survey.

Figure 3: The 1874 Siemens drawing for Lyttelton (courtesy: NZ Historic Places Trust).

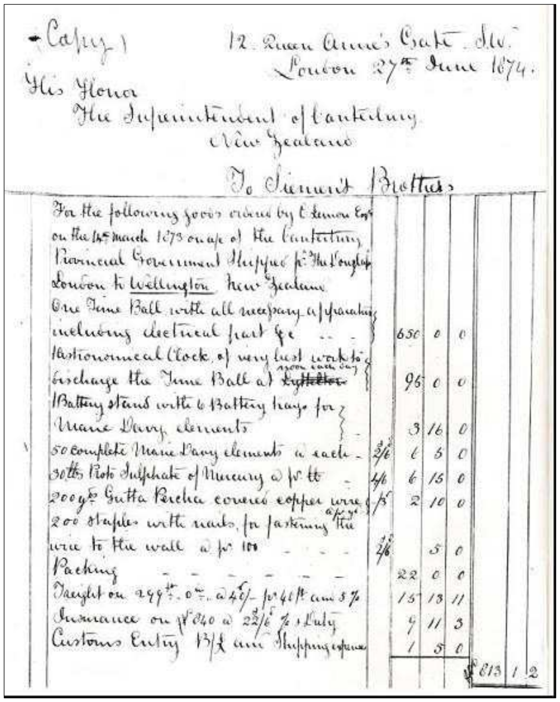
6 THE TIME BALL AT LYTTELTON, NEW ZEALAND

Booklets about the Lyttelton time ball were published by The New Zealand Historic Places Trust in 1979. Two versions are available, both entitled *The Lyttelton Time-Ball Station ...* The preliminary version contains the manufacturer's drawing, reproduced in Figure 3. The second, longer version (Bremner and Wood, 1979) includes several photographs and also a three-dimensional sketch of the mechanism in place of the drawing. The following quote from Bremner and Wood (1979: page 15) shows how the project came to fruition:

> Canterbury's time-ball project was backed by two Australians in the Provincial Council, who had a long-term interest in shipping. Businessman and farmer J.T.

> Peacock was the son of a Sydney shipowner who had a fleet of ships in Lyttelton, and Henry Webb, Provincial Secretary, had come to Lyttelton initially to take control of the Peacock shipping business. The old Sydney time-ball would have been a familiar sight to both of them.
>
> At a Council session in November 1870, Peacock proposed: 'That a respectful address be presented to His Honour the Superintendent requesting him to place upon the Supplementary Estimates a sum sufficient to erect a time-ball and tower at the port of Lyttelton.' The motion was passed, and Webb contacted the Telegraph Department in Wellington who requested a quotation from London for a ball and its machinery and also a special clock: the ball was to drop automatically, released by an electric current which was to be switched on at the correct time by an astronomical clock. Electricity was one of Webb's many interests – he had demonstrated the first electric light in Lyttelton.

Webb's interests in lighting and telegraphy would have made him aware of the important contributions by Siemens Brothers in these areas.



(Copy) 12 Queen Anne's Gate S.W.
London 27th June 1874.

His Honor
The Superintendent of Canterbury
New Zealand

To Siemens Brothers

For the following goods ordered by C. Lemon Esq on the 14th March 1873 on acc of the Canterbury Provincial Government Shipped p. "The Douglas" London to Wellington New Zealand				
One Time Ball with all necessary apparatus including electrical part &c		650	0	0
1 Astronomical Clock, of very best work to discharge the Time Ball at noon each day ~~Lyttelton~~		95	0	0
1 Battery stand with 6 Battery trays for Marie Davy elements		3	16	0
50 complete Marie Davy elements a each	2/6	6	5	0
30 lbs Proto Sulphate of Mercury a pr lb	4/6	6	15	0
200 yds Gutta Percha covered copper wire a pr yd	/3	2	10	0
200 staples with nails, for fastening the wire to the wall a pr 100	2/6		5	0
Packing		22	0	0
Freight on 299 ft. 0 in. a 40/- pr 40 ft and 5%		15	13	11
Insurance on £840 a 22/6 % + Duty		9	11	3
Customs Entry B/L and Shipping expenses		1	5	0
		£813	1	2

Figure 4: The 1874 invoice from Siemens Brothers (courtesy: NZ Historic Places Trust).

6.1 Cost of the Lyttelton Time Ball

The Telegraph Department in Wellington ordered "… one time-ball with all necessary apparatus and one astronomical clock …" from London on behalf of the Canterbury Provincial Council. Fifteen months later, in June 1874, the Council voted £750 to pay for them. The complete apparatus was supplied by Siemens Brothers to the Superintendent of Canterbury, NZ, as shown in the invoice that is reproduced in Figure 4.

The time ball apparatus was ordered on 14 March 1873 and invoiced on 27 June 1874. A shipping advice note bears the same date and "One Time Ball with all necessary apparatus including electrical parts" cost £650. The "Astronomical Clock of very best work to discharge the Time Ball at noon each day" cost £95. Other items brought the total to £813-1s-2d.

The original quotation had been for "… about £500". Interestingly, that is Todd's (1899a) recollection of the cost of the 1855 mechanism for Sydney, supplied by Maudslays. The apparatus and clock, which was made by Edward Dent & Co., London, were shipped by the *Douglas* in July 1874. Siemens' invoice for £813-1s-2d was sent to Canterbury's London agent who was shocked at the price, but paid promptly nevertheless.

The apparatus was unpacked in April 1876 and installed in the new tower at Lyttelton in September of that year. The Lyttelton time ball finally became operational on 23 December 1876. It was the third time ball in New Zealand, those at Wellington and Dunedin having become operational in 1864 and 1868. The time ball at Dunedin (Otago) provided a weekly service only and was of secondary importance. Only the Lyttelton apparatus has survived in New Zealand.

6.2 Restoration of the Lyttelton Time Ball Tower and Apparatus

The Lyttelton time ball service was discontinued in 1934. The building and apparatus fell into disrepair, but a group of local enthusiasts was formed in 1969 to restore the famous landmark. They suffered an early setback when vandals damaged the mechanism, smashing the manual gearwheels and stealing the electromagnet. The electromagnet was never recovered, but the Siemens Brothers nameplate was found in nearby scrub; it has since disappeared again. A replica of the electromagnet was made using a photograph of the original. Some new parts for the mechanism were made during the restoration by local engineering firms and it was possible to raise the ball again in December 1969. Restoration of the tower was a difficult and ultimately very expensive challenge; in the meantime, the restored mechanism was protected against corrosion. The project was finally completed in 1978. Figure 5 shows the ball in its raised position on 14 March 2009.

7 THE WELLINGTON TIME BALLS

It has been noted that the design of the apparatus which used to exist at Wellington was identical to that for Lyttelton (Clibborn, 1975), so it would also have been identical to that found in Sydney. The plan seen by Clibborn was probably for the 1888 Wellington time ball.

The first Wellington time ball became operational on 9 March 1864 and was installed on the roof of the Wellington Custom House, next to the Provincial Observatory (Ward, 1928; cf. Eiby, 1977). Ward records that the ball was black and made of metal. Early press notices gave its location as 41° 17′ 01″ S and 174° 49′ 15″ E (e.g. *Evening Post*, 1866). The Custom House ball was stated in the 1880 edition of the list of time signals to be red and white, with a drop of 12 ft.; the diameter was not specified. Its latitude and longitude were given as: 41° 17′ 15″ S and 174° 47′ 45″ E (List of time signals, 1880: 12-13). These co-ordinates should be more authoritative, but differ significantly from those given in earlier local press notices. The difference in longitude is particularly marked. A photograph taken in the late 1860s and now in the H.N. Murray Collection in the Alexander Turnbull Library in Wellington suggests that the ball drop was considerably larger than 12 ft., possibly because the alternative definition favoured at the Cape of Good Hope was used; it also shows that the ball was then a dark colour. By 1873, the apparatus had become worn and the service was unreliable, so repairs had to be made after less than ten years (Stock, 1873). The time ball was relocated in 1888 (Wellington's Maritime Heritage Trail, website).

The second Wellington time ball was listed as being on a "Staff on square tower at inner end of Railway Wharf." Its latitude and longitude were then 41° 16′ 50″ S and 174° 46′ 55″ E (List of time signals, 1898: 28-29), which should be about 750 m north and 1130 m west of the Custom House location given in the 1880 list. There may, however, be a significant longitude error in one or both locations specified in the Admiralty lists. The ball diameter, colour and drop height were not stated. This second Wellington time ball was destroyed by fire in 1909 (Wright, 2007). A photograph entitled "Wellington's latest Conflagration. - The Last of Captain Edwin's Tower and Time Ball" (*New Zealand Free Lance*, 1909) shows the exposed framework of the tower and an apparent rack and pinion system. It was not replaced and the apparatus is now lost.

8 COMPARISONS OF THE SYDNEY AND LYTTELTON TIME BALLS

Table 2 shows a comparison of some principal mechanism components at Sydney and Lyttelton. It includes dimensions of: the rack and pinion, the upper and lower guide wheels, and the casing. Dimensions are all to the nearest mm.

The rack at Lyttelton has a pitch of 24 mm and a width of 38 mm with a 10-tooth pinion. The rack at Sydney was re-backed with an iron shaft by Russell, replacing the original wooden shaft which is still extant at Lyttelton. The Sydney 10-tooth pinion is known to have been replaced on several occasions. The rack dimensions are the same to 1 mm accuracy. A precise measurement showed that the Lyttelton rack has 24.3 mm pitch, exactly as at Edinburgh (private communication, Bruce Carr, 18 April 2009).

The Sydney and Lyttelton time ball mechanisms have cast iron casings. Each casing has a square section, with the same breadth and depth of 270 mm (10⅝ in.). The arched apertures for access to the rack and pinion also have similar dimensions. The aperture at Lyttelton is now covered by a modern perspex window, which can be removed when necessary.

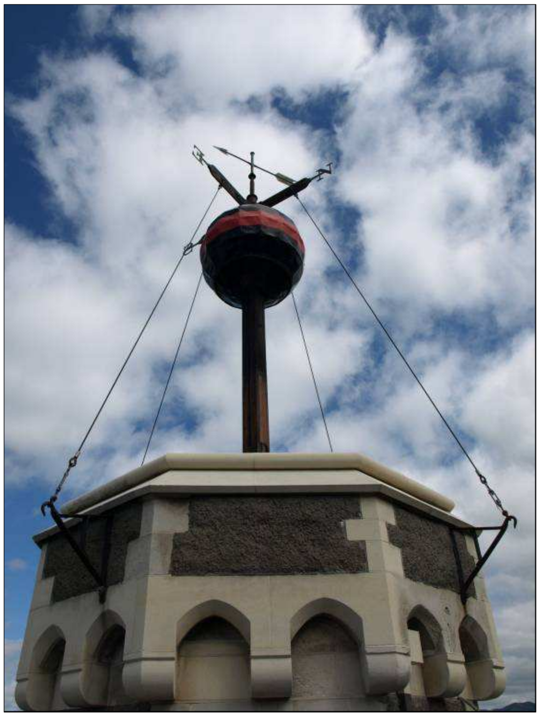


Figure 5: The time ball at Lyttelton on 14 March 2009 (courtesy: Ken Philpott).

The upper and lower guide wheels at Sydney and Lyttelton are identical, given small tolerances in manufacture and measurement. The inner width of the guide wheels is 84 mm ($3\frac{5}{16}$ in.).

Pairs of photographs allow comparisons of particular design features. Figure 6 shows the layout of the gears, Figure 7 the trigger mechanisms and Figure 8 the upper guide wheels. The compass arms on top of the mast are compared in Figure 9.

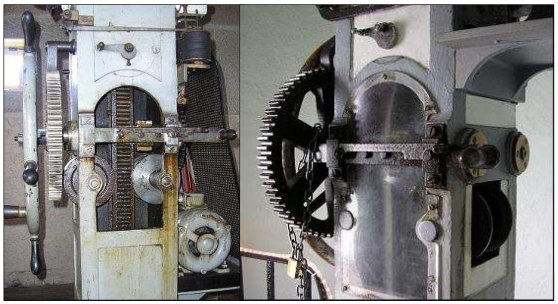


Figure 6: The Sydney (left) and Lyttelton (right) gears, clutch and aperture.

Table 2: Key dimensions at Sydney and Lyttelton (courtesy: Nick Lomb, Bruce Carr and Ken Philpott).

	Sydney				Lyttelton		
Component	Dimensions in mm			Component	Dimensions in mm		
	No. of teeth	Width	Diameter		No. of teeth	Width	Diameter
Pinion on rack	10	40	80	Pinion on rack	10	40	80
		Width	Pitch			Width	Pitch
Rack		39	24	Rack		38	24
		Width	Diameter				
Upper guide wheels	Outer	99	332	Upper guide wheels	Outer	103	330
	Inner	84			Inner	84	
Lower guide wheels	Outer	100	150	Lower guide wheels	Outer	97	149
	Inner	84			Inner	84	
		Width	Depth			Width	Depth
Main casing		270	270	Main casing		270	270

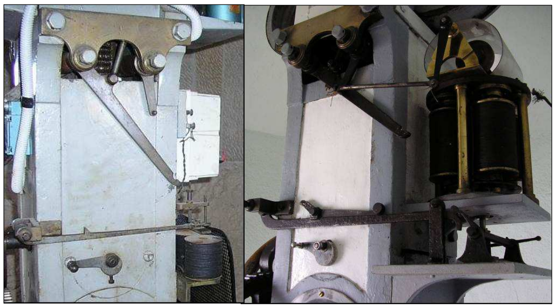


Figure 7: The Sydney (left) and Lyttelton (right) trigger mechanisms.

The rack and pinion arrangement is the same, but the outer gears and capstan differ in detail. The outer gearwheel and pinion have 80 and 15 teeth at Sydney, but have only 62 and 10 teeth at Lyttelton. The Lyttelton gears have the same number of teeth as at Edinburgh and Deal, so Sydney is the exception. The 6-spoked capstans differ in detail, that in Sydney having radial handles as well as a handle on one of the spokes. The original Lyttelton drawing shows a handle at the capstan periphery, now positioned on one of the spokes. The capstan at Edinburgh does not have radial handles, while that at Deal is similar to Sydney. Clearly, details like this are easily changed to suit the operator and may have been modified during the working life of the system. The electric motor, drive belt and gear for hoisting the ball are modern additions at Sydney, but the hand capstan can still be used.

Figure 8: The Sydney (left) and Lyttelton (right) upper guide wheels.

The sliders for the rack pinion, which act as simple clutches at Sydney and Lyttelton, are identical. This applies also to the brass plates on the back and front of the casing that support the trigger levers and roller catches for the rack. The pinion is engaged with the rack in the Lyttelton photograph, but is withdrawn to the right at Sydney, prior to the drop (see Figure 6).

Figure 9: The Sydney (left) and Lyttelton (right) compass arms (Lyttelton photograph courtesy Ken Philpott).

The trigger mechanisms (Figure 7) are significantly different. The Lyttelton mechanism is more complicated, with an extended series of levers between the electro-magnets and the ball release catches. This is likely to be the original arrangement at Sydney that was criticised by Russell (1899) as being "… complicated and clumsy in the extreme." His modifications to the Sydney apparatus give a much more direct link between the electromagnets and the release catches. A link from the right hand roller catch lever to the upper electromagnet contacts is still present at Lyttelton, but the link has been disconnected at Sydney.

The E-W and N-S compass bearing indicators are remarkably similar (see Figure 9). The arms themselves are more substantial at Lyttelton, but the letters and their fittings to the arms appear to be the same. The ball at Lyttelton still has a wooden frame and zinc plating, as supplied to Sydney in 1855, whereas Sydney now has a Muntz metal ball. This wooden frame is noted in the most recent documentation about Lyttelton (New Zealand Historic Places Trust, website). Ball construction of zinc plate on a wooden frame was used previously at Edinburgh and Deal.

The arrangement of the piston in the vertical cushioning cylinder below the casing is not visible, but the Sydney design was inspected when the time ball at the Newcastle, NSW customs house was being restored (McDonald, 2000). The 0.3m diameter piston is made of 0.1m thick rubber and is fitted with a bleeder valve to adjust the rate of descent. The bottom of the cylinder is filled with 7 litres of soapy water to act as a buffer and, presumably, to provide lubrication for the rubber (Kinns and Abell, 2009: 75). The use of a rubber piston and soapy water may have been Russell innovations. The arrangement at Lyttelton is generally similar, but the piston is made of metal with a leather cap seal and there is no apparent provision for water at the bottom of the cylinder in Figure 3.

The present slotted mast at Sydney is made of metal and has a circular section, while the slotted mast at Lyttelton is made of wood with a square cross-section. Russell probably modified the Sydney mast at the time the ball was changed; early photographs show a mast with a square cross-section (Pickett and Lomb, 2001: 20). The mast at Lyttelton is similar to that at Edinburgh.

9 TIME BALL DEVELOPMENT FROM EDINBURGH TO SYDNEY AND LYTTELTON

There were substantial changes in the detailed arrangements for the rack and pinion hoists from Edinburgh and Deal to Sydney, which can be seen in the surviving mechanisms.

The casings at Edinburgh and Deal were made of wrought iron, with corner pieces and bolted plates. The casing at Sydney was cast as an integral structure, presumably to give greater rigidity. That applies also to Lyttelton. Many features of the mechanisms at Edinburgh and Deal were changed for the Sydney apparatus. One of the most significant changes was to the guide arrangement for the wooden shaft. Other changes to the trigger and catch arrangements are also obvious.

9.1 Deal and Edinburgh

Figure 10 shows photographs of the Edinburgh and Deal casings and mechanisms. The designs are similar, although the capstan is on the opposite side of the casing to the external gears at Deal, with differences in the capstan handles that are not unlike those between Sydney and Lyttelton. The mechanism at Deal is no longer used for hoisting the ball, but it can still be seen in the Deal museum following restoration; a modern mechanism is now used to operate the ball. The original electric trigger at Edinburgh has been substituted by a manual rope pull, smoke from the Edinburgh Castle gun having replaced the time ball as the primary signal. The Edinburgh tower and apparatus, including the ball, are undergoing restoration in 2009; some parts of the apparatus are in poor condition, but it is essentially complete in its original form.


Figure 10: The Edinburgh (left) and Deal (right) mechanisms and wrought iron casings (courtesy Allan Marshall and Michael Kinns respectively).

A single guide wheel opposite the pinion was used for the rack at Edinburgh and Deal, as shown in Figure 11. This was changed at Sydney and Lyttelton to a design that used two pairs of guide wheels, one either side of the rack (see Figure 8). Another important change was in the catches for the rack. These were linked using gear segments at Deal and Lyttelton, but this arrangement was changed to lever-linked roller catches at Sydney and Lyttelton. The Edinburgh and Deal quadrants are shown in Figure 12, together with a photograph of one of the catches engaged with the wooden shaft at Edinburgh. The inspection holes for the catches are below the gear segments.

The Edinburgh casing is narrower than at Sydney and Lyttelton, with 251 mm sides. The capstan has the same diameter, with a single handle at the periphery as in the original Lyttelton drawing in Figure 3. The manufacturer's plates can still be seen at Edinburgh and Deal, but the plate at Sydney is absent. The plates shown in Figure 13, both indicating an 1853 date, suggest that Maudslays received a Royal Warrant between the deliveries to Edinburgh and Deal.

Allowing for tolerances in measurement and manufacture, the bronze rack at Edinburgh has the same 24.3 mm pitch ($^{23}/_{24}$ in.) and 38 mm tooth width as at Sydney and Lyttelton. It is backed by a wooden shaft, having a width and depth of 64 mm with bevelled corners that engage with the single guide wheel. The metal base for the teeth extends the full width of the shaft and is 13 mm thick. The rack itself is made in sections; the wooden shaft and its metal rod extensions connect the ball to the piston. The same basic rack design was used for Sydney and Lyttelton.


Figure 11: The Edinburgh guide wheel (courtesy: Allan Marshall).

10 CONCLUSIONS

Maudslay, Sons & Field built the time ball apparatus for Sydney in 1855, and used a rack and pinion mechanism to hoist the ball. It became operational in 1858, following completion of Sydney Observatory with its time ball tower. Maudslays' mechanisms and casings at Edinburgh and Deal are similar to each other, but the design was developed further for Sydney. Henry Russell, the NSW Government Astronomer, modified the Sydney apparatus during the 1870s, but most principal features were retained.


Figure 12: The Edinburgh (top) and Deal (bottom) gear segments and catches (courtesy Allan Marshall and Michael Kinns respectively).

The apparatus for Lyttelton, NZ was ordered in 1873 and shipped from London in 1874 by Siemens Brothers. It, too, had to await completion of the necessary tower and became operational in 1876. It has been demonstrated that the apparatus for Lyttelton is a replica of the original 1855 design for Sydney, prior to Russell's modifications, suggesting strongly that Siemens Brothers bought it from Maudslays in 1873. There are no Siemens records of time ball supply at any time, other than to Lyttelton, so it was not an ongoing business for the company. In 1873 and 1874 Siemens was heavily involved in supplying submarine cables and commissioning the cable-laying ship *Faraday*, so it would have been easier for them simply to buy an existing time ball apparatus from another company with an established record of production.

Figure 13: The Edinburgh (top) and Deal (bottom) Maudslay, Sons & Field plates (courtesy Allan Marshall and Michael Kinns respectively).

The only surviving reference to a Maudslays 1873 time ball is in the last notebook of Charles Sells, and indicates provision for the Cape of Good Hope and an association with Siemens. The first time ball at Alfred Docks in Cape Town was installed on a North Quay warehouse in 1873. Admiralty lists of time signals published in 1880 and 1888 show that the Alfred Docks installation was then the official time ball for Table Bay, and was operated by an electric telegraph signal from the Cape Observatory. It was superseded in 1894 by a new system after site redevelopment; this later design was similar to that used at Deal, but of lighter construction. When the site was developed again during the 1990s, it was possible to design and build a working system based on the 1894 drawings. Unfortunately, no records relating to the 1873 design have survived in South Africa, but it would be surprising if the design for Sydney had been used, when the 1894 design is essentially a reversion to the design for Deal.

The available evidence indicates that one time ball system is likely to have been built by Maudslays in 1873, using the 1855 design for Sydney. It may have been intended originally for Alfred Docks in Cape Town, but a lighter system was probably preferred and Maudslays' apparatus was no longer needed there. Instead, it was bought by Siemens Brothers of London who installed it at Lyttelton, New Zealand. Thus, the apparatus at Lyttelton is an 1873 reproduction of the original 1855 Sydney design, whereas the present apparatus at Sydney includes later modifications.

The rack and pinion mechanisms built by Maudslays between 1852 and 1874 have all survived.

11 ACKNOWLEDGEMENTS

Many gave freely of their time and energy to assist with this investigation. Bruce Carr and Jan Titus of Lyttelton (NZ) gave unstinting support throughout. Ken Philpott of Christchurch (NZ) measured the Lyttelton apparatus and some of his photographs feature in this paper. Measurements by Dr Nick Lomb, Curator of Astronomy and Timekeeping at the Sydney Observatory, allowed a full comparison of the two mechanisms. Alexandra Kinter, archivist at Siemens, conducted searches of company records which showed that the Lyttelton supply was not part of ongoing Siemens business in either England or Germany. Jonathan Spencer Jones and Gabriel Fagan supplied valuable information about the history of the Alfred Docks time ball in Cape Town. David McDonald of Edinburgh World Heritage and Alan Wilson of James Ritchie & Son (Clockmakers) Ltd. provided key information about the first rack and pinion mechanism and ball to be supplied by Maudslays. Allan Marshall took many informative photographs of the Edinburgh time ball apparatus, some of which are reproduced in this paper. Dr Michael Kinns visited the Deal Museum and photographed the apparatus there. Their help is greatly appreciated.

12 REFERENCES

Astronomical Society of Southern Africa, Historical Section: http://www.saao.ac.za/assa/html/his-astr-maclear_t.html

Bartky, Ian R., and Dick, Steven J., 1981. The first time balls. *Journal for the History of Astronomy*, 12, 155-164.

Bremner, J., and Wood, F.L.W., 1979. *The Lyttelton Timeball Station: An Account of its History, Operation and Restoration.* Wellington, Historic Places Trust.

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

Clibborn, D.H., 1975. Letter to J.R.S. Daniels (Director, NZ Historic Places Trust), dated 1 August.

Eiby, G., 1977. The New Zealand Government time service: an informal history. *Southern Stars*, 27, 15-34.

Evening Post, 17 March 1866. Page 2 notice. The same notice was repeated on various dates between 1865 and at least 1867.

Gill, D., 1913. *History and Description of the Royal Observatory at the Cape of Good Hope*. London, Her Majesty's Stationery Office.

H.N. Murray Collection. Alexander Turnbull Library, National Library of New Zealand (PAColl-0824-1).

Kinns, R., and Abell, L.J., 2009. The contribution of Maudslay, Sons & Field to the development of time balls in Australia. *International Journal for the History of Engineering & Technology*, 79, 59-90.

Lexikon, 1888. Zeitball 845-846: http://www.peter-hug.ch/lexikon/Zeitball/16_0845

List of Time Signals, Established in Various Parts of the World: Compiled for the Use of Seamen, as an Aid for Ascertaining the Errors and Rates of Chronometers. Printed for the Hydrographic Department, Admiralty. 1st edition, 1880 (compiled by Captain Pender, RN). 2nd edition, 1888 (compiled by Captain Pender, RN). 5th edition, 1898 (compiled by Captain T.H. Tizard, RN)

Maclear, Thomas, 1852. The Observatory time ball - Cape of Good Hope. *The Nautical Magazine*, 21, 611-612.

Maudslay Society, 1956. *Henry Maudslay, 1771-1831: and Maudslay, Sons & Field, Ltd.* Commemorative booklet to mark the establishment of the Maudslay Scholarship, originally published in 1949, and reprinted with amendments in 1956. Now available on CD from the Kew Bridge Steam Museum.

McDonald, Brian and Associates, March 2000. *Newcastle Customs House: A Plan for its Conservation and Management.* [A note concerning the Sydney mechanism is on page 65.]

Nelson Examiner and New Zealand Chronicle, 16 April 1873. Article headed "Offers for Telegraph to Australia and New Zealand" on Page 2.

New Zealand Free Lance, Volume IX, Issue 454, 13 March 1909, Page 11. "Wellington's latest Conflagration. - The Last of Capt. Edwin's Tower and Time Ball." - Zak, Photo.

New Zealand Historic Places Trust: http://www.historic.org.nz/Register/ListingDetail.asp?RID=43&sm=advanced

Notice to Mariners No.153. *Establishment of an Additional Time Ball at the Cape of Good Hope*. Issued by the Hydrographic Office, 13 December 1853.

Petree, J. Foster, 1934. Maudslay, Sons & Field as General Engineers, with written discussion. *Transactions of the Newcomen Society*, 15, 39-61.

Petree, J. Foster, 1967. Some reflections on engineering biography. *Transactions of the Newcomen Society*, 40, 147-158.

Pickett, Charles, and Lomb, Nick, 2001. *Observer & Observed; A Pictorial History of Sydney Observatory and Observatory Hill.* Sydney, Powerhouse Publishing,

Pole, William, 1888. *The Life of Sir William Siemens*. Reprinted and published by Siemens Ltd., 1986.

Preliminary version of '*The Lyttelton Time-ball Station'* available about 1979.

Russell, H.C., 1899. Letter to C. Todd, dated 21 March. Sydney Observatory. Transcribed as Appendix 2 in Kinns and Abell, 2009.

Scott, J.D., 1958. *Siemens Brothers, 1858-1958: An Essay in the History of Industry*. London, Weidenfeld and Nicholson.

Sells, Charles, 1842, 1847. Notebook 1842, also 1847. Original in the Science Museum Library, Swindon.

Sells, Charles, 1842-1849. Notebook April 1842 to 1849. Original in the Science Museum Library, Swindon.

Sells, Charles, 1849-1853. Notebook January 1849 to June 1856 [*sic*.]. Original in the Science Museum Library, Swindon.

Sells, Charles, 1853-1855. Notebook June 1853 to December 1855. Original in the Science Museum Library, Swindon.

Sells, Charles, 1856-1859. Notebook January 1856 to March 1859. Original in the Science Museum Library, Swindon.

Sells, Charles, 1859-1861. Notebook March 1859 to November 1861. Original in the Science Museum Library, Swindon.

Sells, Charles, 1861-1865. Notebook November 1861 to May 1865. Original in the Science Museum Library, Swindon.

Sells, Charles, 1865-1867. Notebook May 1865 to December 1867. Original in the Science Museum Library, Swindon.

Sells, Charles, 1867-1871. Notebook December 1867 to January 1871. Original in the Science Museum Library, Swindon.

Sells, Charles, 1871-1875. Notebook January 1871 to May 1875. Original in the Science Museum Library, Swindon.

Sells, Charles, 1875-1878. Notebook May 1875 to April 1878. Original in the Science Museum Library, Swindon.

Sells, Charles, 1878-1883. Notebook April 1878 to March 1883. Original in the Science Museum Library, Swindon.

Sir William Siemens, a Man of Vision. Siemens (1993).

Smyth, C.P., 1853. Remarks on the erection of the time-ball of the Royal Observatory, Edinburgh. *Monthly Notices of the Royal Astronomical Society*, 14, 23-25.

Spencer Jones, Jonathan, 1993 (?). Time and the sailor. *Waterfront Review*, 26-27.

Stock, A, 1873. Letter to the Editor of the *Evening Post*, dated 26 November.

The time ball column at the 'Alte Liebe': http://www.lentz-familie.de/r/zeitballe.html

Todd, Sir Charles, 1899a. Letter to W.E. Cooke, dated 23 March, State Records of South Australia (SRSA), GRG 31/1 0001, vols. 1-5, 343-344. Transcribed as Appendix 3 in Kinns and Abell, 2009.

Todd, Sir Charles, 1899b. Letter to H.C. Russell, dated 29 March, SRSA GRG 31/1 0001, vols. 1-5, 345-346. Transcribed as Appendix 4 in Kinns and Abell, 2009.

Victoria and Alfred Waterfront: http://cybercapetown.com/CapeBigSix/waterfront.php

Ward, Louis E., 1928. *Early Wellington*. (Section: Post office Time Ball Service). Wellington, Whitcombe and Tombs.

Wellington's Maritime Heritage Trail: http://www.wellington.govt.nz/services/heritage/pdfs/maritimetrail.pdf

Wright, Gareth, 2007. *A Compilation of World Time Signals, Past and Present, Based on the List of Time Signals (5th edition, Lords of the Admiralty, 1898).* Compiled for the New Zealand Historic Places Trust - Lyttelton Time Ball Station, 14 April 2003. Revised 29 June 2003 and 12 November 2007.

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Journal of Astronomical History and Heritage, 12(2), 108-118 (2009).

FROM FRAGMENTS TO A MUSEUM DISPLAY: RESTORATION OF A GAUTIER MERIDIAN CIRCLE

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Abstract: The *Museu de Astronomia e Ciências Afins* (MAST), which opened to the public in 1985, is a research institute of the Brazilian Ministry of Science and Technology. One of its main activities is to preserve its collections, especially the most important one, its collection of scientific instruments, which grants MAST its identity as a museum of science and technology. Among the 2,000 objects in the collection there is a Gautier meridian circle that has a 190-mm diameter objective lens and a focal distance of 2,400mm, with its axis aligned east-west. It should be noted that this instrument was at great risk of being lost to the collection, as it had been left dismantled since the 1960s, and the top part of the dome that sheltered it had been demolished in the 1980s, leaving just a vestibule and the base of the dome, which was in danger of completely collapsing. The intervention philosophy applied was not to put the instrument back in working order, but to allow it to be viewed and understood by the public within a coherent display space. As for the dome, a shelter was built for the instrument using a metal cover of a similar volume and appearance to the original, but with a different function, i.e. it is no longer designed to permit astronomical investigations, but rather to protect the exhibition space and merge harmoniously with the rest of the listed architectural complex. This paper presents information about the history of this meridian circle and its restoration, as well as about the Imperial Observatório do Rio de Janeiro/Observatório Nacional where this instrument was originally used.

Keywords: Gautier meridian circle, restoration, scientific instruments, museum of science and technology

1 INTRODUCTION

Restoration, in the terms used by the International Council of Museums (ICOM) Committee for Conservation (2001), is a physical intervention designed to lengthen an object's lifespan by ensuring its continued material, aesthetic and functional integrity. An appropriately-restored object reverts as closely as possible to its initial state. Using intervention techniques, restorers conserve and make functional those objects that are likely to be presented and related to a particular theme or historical period.

A key starting point is to clarify what it means to restore a scientific instrument. Miniati (1991) draws parallels with certain aspects of art restoration, in that many instruments, especially the oldest ones, have aesthetic, decorative and material features whose treat ment is analogous to that applied to works of art. Others are quite different.

Interventions should be performed on historical scientific instruments only when absolutely necessary for the survival and future conservation of the object. It is easy to understand how people who are unfamiliar with museological issues might have trouble understanding why a hydraulic pump or a microscope should have its integrity conserved to the utmost, and that any new element will be added only if it ensures its integrity, and this should bear a permanent physical mark aside from the record of the intervention in the paperwork pertaining to the piece. To draw a parallel, it would be difficult for a mechanic who deals with industrial parts to learn to give due value to many such cultural heritage objects (Sebastian, 1995).

Independent of the practical work involved, the restoration of a scientific object also demands an in-depth study to find out about its function, its manufacturer, and its time period. In other words, the idea is to obtain as much information as possible about it, and especially about the physical principles upon which the instrument was based.

Once a decision is taken to restore an object, the curator and restorer should carry out extended research to identify the correct restoration method, especially in the case of lost parts to be replaced or the repair of previously damaged parts. Access to newspapers from the time and specialized journals is an invaluable research asset.

In the view of André (1999), the guidelines for an ethics of restoration should be as follows:

(1) gather ample documentary evidence before beginning any intervention;

(2) always bear in mind the principle of minimum intervention;

(3) respect the integrity of the object, preserving as many original elements as possible without adding new elements; and

(4) make sure that the intervention is reversible.

In practice it is not always possible to follow all of these principles. One of the most important points is to understand the object, and further, should it be used for exhibition, to understand how it will be presented to the public.

Many issues have been raised concerning reversibility, especially about what actually constitutes a reversible intervention. Meehan (1999) addresses this point at length within the specific context of industrial collections. Dismantling is a reversible stage which generates a great deal of knowledge about such instruments but which is not an option for most other historical artefacts. However, many examples described by Meehan show that reversible procedures are often either not feasible or not even appropriate. An action must be guided by the principle of minimum intervention with a view to preserving the original components of the object in the long term. Perhaps the guiding principle is not to undertake reversible interventions, since no act is totally reversible in itself.

2 CURRENTS IN THE RESTORATION OF SCIENTIFIC INSTRUMENTS

Scientific instrument restoration practices follow different currents, much as is the case for other objects of cultural value. There are two clear lines of thought with somewhat different perspectives. The first one, advocated by scientists interested in the historical aspects of science, considers making the instrument functional again the primary aim of any restoration. The goal is to get the object to work just as it did when it was manufactured, provided this is the feature that differentiates it from other museum objects. This often implies quite major interventions which sometimes alter some of the object's features. The second school, led by science historians and art restorers, takes as its fundamental aim the preservation of the historical evidence contained within the object, which often means that the object will still not work after it has undergone the intervention.

Many arguments can be put forward to support the first approach, the best formulated of which, from the literature consulted, is by Mann (1994), of the Science Museum, London. In his paper, he takes as his starting point the governing ethic in most museums (of art, archaeology, ethnography, history, etc.), whose primary aim is the preservation of historical evidence, and concludes that this is not the case for science museums. As he sees it, a new ethic is required for such museums, which has actually already been practiced by its defenders until current times, though it has not been set out explicitly. This new ethic is primarily concerned with exploiting artefacts for the benefit of the public and to the detriment of the mere preservation of material evidence. Such a change in the overriding purpose is based, in turn, on the shift in the concept of artefacts as material evidence to also include functional evidence.

Still following Mann's line of argument, the scope of a museum of science and technology could permit one type of evidence to be destroyed so that another, of greater value, could be revealed to the public by sectioning the pieces and putting the instruments and machines to work. In this way, such museums become quite different from others because their primary aim is to explain how things work rather than to keep a collection of artefacts. In other museums, even if the objects have a functional nature, they are not collected because of this nature but rather because of their aesthetic features or historical properties.

According to this school of thought, the practices of many science and technology museums the world over, where machines and instruments have been sectioned to show their working parts or are displayed in action, are correct in that they help the visiting public understand these pieces. Yet Mann disregards the fact that scientific objects are also collected for their historical interest, for they make it possible for people to evaluate and reflect upon the development of science and technology.

Still in the UK, there is a more conservative viewpoint expressed by Newey (2000), who defends the use of replicas as the most suitable way of showing the public the information they seek, rather than actually putting the historical artefacts themselves to work.

The restoration of scientific instruments is a recent practice that does not have a strong, established tradition (Brenni, 1999). More often than not, such restoration work has paid greater attention to technical issues than to the instruments' historical value. The literature produced around the world is limited and the few existing treatises simply provide information on how to repair instruments. While collectors, technical experts and physicists favour the in-depth restoration of objects based on the overriding priority of regaining their functionality, art restorers tend to defend a very limited restoration with no parts replaced or any actual repairs made to the object. Both attitudes seem extreme and both have undesirable consequences, leading either to over-restoration or under-restoration. The former is more common in the attempt to restore the object back to its original state, but no restoration can wipe out the action of time even if it so desires, and it may end up removing the marks left by time, which may be very important for a better understanding of the object and its history. The second type of intervention, which is far rarer, attempts not to turn the clock back, but to stop it, interrupting the life of the object artificially.

Undoubtedly, sectioning an artefact or leaving it running and thereby causing more wear and tear could compromise such evidence and should not be permitted in most cases. This argument is concise and logical, yet is based upon the belief that the overriding aim is to preserve evidence and that this is of a purely material nature. If these underpinnings change, as put forward by Mann (1994), one would need to alter the ethic for such conservation.

It might be more fruitful to take the middle ground. When the object was manufactured as part of a series and more than one example still exists, or where the object's historical importance *per se* is minimal, it could be justified to carry out a deeper intervention, trying to get the object working again. However, in the case of very special items imbued with historical content, or unique objects, a better course would be to conserve the object preventively and use replicas to give the visiting public a better understanding of its appearance and function.

Any procedures, work or type of action that may alter the principle of the basic design, shape, appearance, style, basic idea and details of the object should be avoided. In particular, any addition should be scrupulously avoided, because this could be construed as a forgery. The only parts that can be replaced by new ones are those about which there is absolute certainty as to their shape, size, relative position, movements, appearance and other details, so that they correspond exactly to the original, or those that may pose an obvious risk to people's safety.

Finally, in 2002, a presentation was made of the summarized findings of a study that was carried out by a group set up by the *Direction des Musées de France* in 1996 to discuss and reflect upon a definition of conservation and restoration methodologies for scientific, technical and industrial artefacts (Rolland-Villemot, 2002). The working group set down seven points to be considered before any conservation or restoration should be carried out on such objects:

(1) the status of the object (whether unique, a proto-

type, a mock-up, an object produced in series, a teaching object), which is decisive in the choice of the restoration procedure;
(2) the diagnosis (a precise evaluation of its state of conservation and integrity);
(3) a scientific and cultural project regarding the object: the object must first be studied from all possible perspectives, even should one or another of these be given precedence later for museological or technical reasons;
(4) the setting up of an interdisciplinary team;
(5) the drafting a list of responsibilities with a precise definition of all the interventions to be made on the object;
(6) the sequence of the tasks and the precise nature of the roles of each participant (matrixes);
(7) the paperwork that must be gathered for a precise understanding of the object to be reached, and to assist in the restoration tasks.

The restoration of scientific instruments requires a high level of training in materials, which range from wood to a broad range of metals, glass, etc.; a profound knowledge of and sensitivity to history, allowing for a highly-attuned interaction with science historians; in-depth knowledge of the peculiarities of the object; familiarity with mechanical construction techniques, enhanced by examinations of different examples of the same type and contact with scientists; and highly developed manual dexterity so that, if necessary, the missing pieces of whatever type can be recreated in a historically-appropriate and technically-efficient way (Bonsanti, 1999). A multidisciplinary team must be set up to cover this range of prerequisites since a single person could hardly be expected to be skilled in all the different areas required.

All restoration work must be detectable, though not necessarily immediately visible nor even visible upon closer inspection. It should, rather, be detectable by an observant non-expert equipped with a magnifying glass and left alone with the object for five minutes (Ashley-Smith, 1994).

3 CONSERVATION AND RESTORATION OF SCIENTIFIC INSTRUMENTS AT THE MUSEU DE ASTRONOMIA E CIÊNCIAS AFINS IN BRAZIL

The *Museu de Astronomia e Ciências Afins* (MAST) in Rio de Janeiro, Brazil, opened to the public in 1985, and is a research institute in the Brazilian Ministry of Science and Technology. One of its main activities is to preserve its collections, especially the most important one, its collection of scientific instruments, which grants MAST its identity as a museum of science and technology. The museum is located in the grounds of the old National Observatory, and occupies a number of buildings belonging to that facility. These historic buildings, as well as the collections that originated within them, are preserved by a Federal Law that was passed in 1986 (IPHAN). MAST's main building, which was recently restored, houses the museum's technical store, where much of the collection of historical scientific instruments is kept.

The MAST collection, which contains 2000 objects, is one of the most important of its kind in Brazil. Around 1700 of these objects originally belonged to the old National Observatory, and were used in service and research of great importance to the country, such as determining and broadcasting the official time in Brazil, forecasting the weather, observing astronomical phenomena, determining Brazil's borders, and magnetically mapping Brazilian soil. Most of these instruments date back to the nineteenth and early twentieth centuries, though some of the more aesthetically-interesting pieces, like the quadrant by J. Sisson and the G. Adams theodolite, are from the 1700s. It is an extremely diverse collection, and can be compared with the great collections of this kind around the world (Brenni, 2000). Many of the objects are connected to astronomy, topography, geodetics, geophysics, meteorology and optical measurements. They are typical of this kind of institution, but the collection also touches on other scientific areas, such as electricity, magnetism and chemistry.

The great variety and high quality of the objects in the collection merit a special word. Together with instruments that can be found in similar institutions and museums (telescopes, theodolites, meridian circles, transits, precision clocks, magnetometers, meteorology instruments etc), MAST also preserves some very peculiar, rare pieces. These include a Kelvin tide-predicting machine, an Henrici analyser, a Salmoiraghi instrument for determining a personal equation, instruments to install cross-threads in reticules and other special instruments. At least one instrument at MAST is unique: an altazimuth from the end of the nineteenth century, invented by the astronomer Emanuel Liais and manufactured at the Hermida Passos workshops in Rio de Janeiro. This instrument won a number of awards in different exhibitions in Brazil and Europe.

About 98% of the objects in the MAST collection are in a good or satisfactory state of conservation. The remaining 2% are forty items that could be evaluated as to their need for restoration. Most of the collection only requires periodic cleaning which is being done at a rate of one cleaning per object every two years.

Concerning restoration, four instruments have already passed through interventions: a theodolite, made by Brunner Frères; an equatorial telescope with a 32 cm objective lens, made by Thomas Cooke and Sons; a meridian circle, made by Paul Gautier; and a Metron star finder, made by C. Baker. The first three were made in the late 1800s, while the fourth was made in the early twentieth century. They were selected according to the following criteria:

(1) the items' historical potential, as they could have been used in important research work at the Observatory;
(2) their makers, who are known to have produced objects of scientific quality using great technical skill;
(3) the deterioration of the metal surfaces, which were highly oxidized, with the loss of part of the original lacquer; and
(4) the absence of some parts of the instruments, in the case of the theodolite and the meridian circle, which would allow one of the more critical parts of the process to be done: the replacement of parts.

In all these interventions the same procedure was used. First, historical research was undertaken to gather information about the item to be restored, including how it worked. Next, the instrument was completely dismantled and the parts were mechanically cleaned. The parts to be restored were then separated from the rest. The corrosion was removed by mechanical means only, and then cleaned with ethyl alcohol and trichloroethylene. Finally, most of the parts were protected by lacquer or paint, depending on the original treatment they received. A meridian circle manufactured by Gautier was selected from the set of restored objects to present in greater detail the work carried out.

4 THE IMPERIAL OBSERVATORY OF RIO DE JANEIRO

During the eighteenth century, the Portuguese Government did little to encourage scientific activity in Brazil. It was only after Dom João VI arrived in the country, fleeing Napoleon's invasion of Portugal, and later under the rule of Dom Pedro I, that this situation took a turn for the better. Rudimentary astronomical observations were made during the early nineteenth century at the Escola Militar (Military School) in Rio de Janeiro, but it was only on 15 October 1827 that the Emperor decreed the creation of an astronomical observatory with the purpose of producing astronomical and meteorological data, as well as giving courses in astronomy to students from the military and naval academies (Morize, 1987).

For various reasons, the Observatory only began its work in the middle of the century. It was first based at the Escola Militar under the Directorship of Soulier de Sauve, who died a year later. It was then transferred to a more suitable location on Castelo hill, Rio de Janeiro, in an unfinished Jesuit church.

In 1846, the observatory was given its official name, Imperial Observatório do Rio de Janeiro, in a decree that also established the work it should undertake (Videira, 2002). Not only would it be responsible for astronomical and meteorological observations and training students from the Escola Militar and the Academia da Marinha (Naval Academy), but it would also publish an astronomical yearbook and supply accurate time for ships docked in the port.

In 1858 and 1865, the new Director, Antonio Manuel de Melo, organised observations of solar eclipses and published some astronomical tables. The largest instrument from this period of which there is mention was a Dollond refractor telescope with an aperture of 7 cm. Figure 1 shows a picture of the Imperial Observatory on Castelo hill.

After the Paraguay War (1870), Emperor Dom Pedro II, who was keen on astronomy, reorganised the Observatory and appointed the French astronomer Emmanuel Liais (1826−1900) as its Director. This was the beginning of a period during which much research was produced at the Observatory and was presented by Liais at European academies. According to a study of the period by Christina Barboza (1994), the Observatory was held in higher regard than any of the other Brazilian scientific institutions of the day. An indication of this is the invitation it received to take part in a major event organised by the French to observe the 1874 transit of Venus across the solar disk. Under Liais' Directorship, the Imperial Observatory became a hotbed of scientific activity, yet little of the knowledge acquired was actually applied. Liais managed to split the observatory off from the Escola Militar, but his administration was also dogged by many controversies, until he was finally dismissed in 1881 (Videira, 2002).

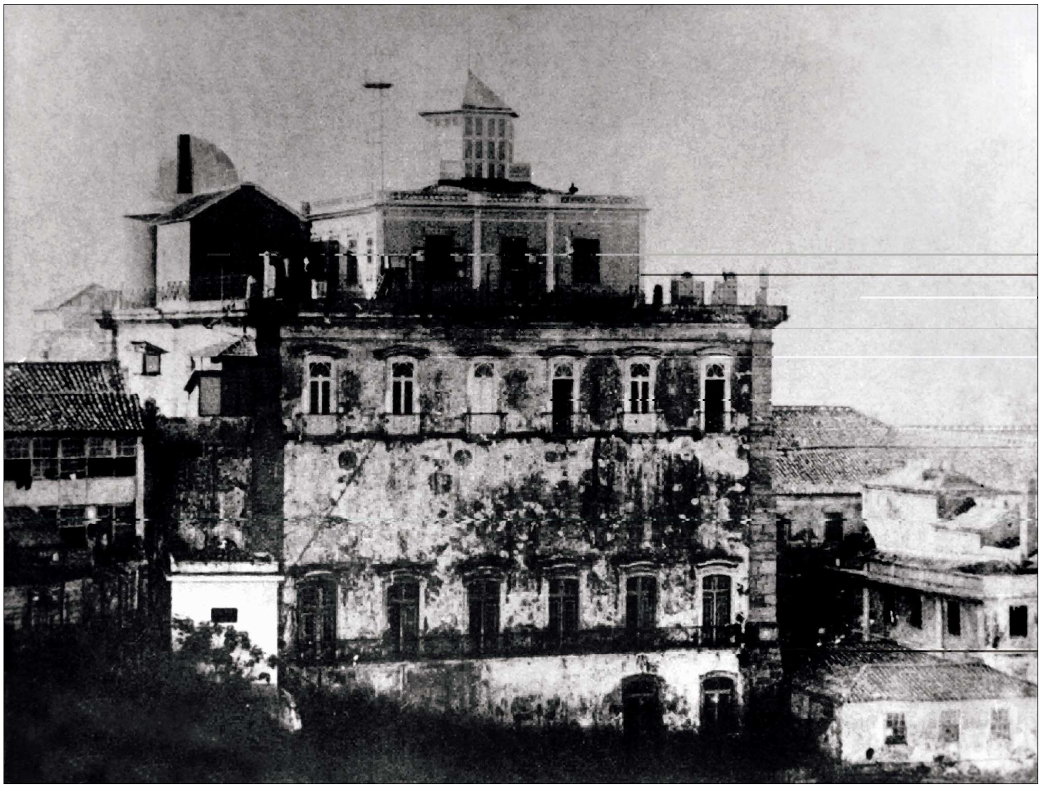

Figure 1: Photograph of the Imperial Observatory on Castelo hill taken in the second half of the nineteenth century (courtesy: MAST archives).

Liais was succeeded by his main collaborator, a Belgian engineer named Luís Cruls (1848−1908). Under his Directorship a number of scientific expeditions were undertaken: to Punta Arenas to observe the 1882 transit of Venus; to the Central plateau to demarcate the Brasilia quadrilateral, the site of the future capital city of the nation (1890); and to the border with Peru and Bolivia to determine the exact location of the source of the Javari river, which was crucial in the conflict between the countries (1898) (*Relatório* …, 1898b). At the same time, in 1887, the Observatory was invited to take part in another major international event also organised by France: the Carte du Ciel project which involved photographically mapping the entire celestial sphere (see Turner, 1912). The standard scientific instrument needed for this project, a 33-cm equatorially-mounted astrograph with 26-cm guide scope, was even purchased, but the political upheavals surrounding the proclamation of the Republic in 1889 prevented the Observatory from actually taking part in the project and the instrument was never installed in its intended dome.

With Brazil now a republic, the Observatory was renamed the Observatório do Rio de Janeiro, and then in 1909 the Observatório Nacional (National Observatory), which continues to be its name to this day. At the time, it was entrusted with organising a national meteorological service, much against the wishes of its then Director, Henrique Morize (1860−1930). Many meteorology instruments were acquired by the Observatory and these are now part of the MAST collection.

The location of the observatory on Castelo hill had been the subject of much debate since the mid-1800s. Reports by its Directors had repeatedly pointed to the unsuitability of the site because the land (composed of decomposing gneiss) was unstable, which severely limited its activities and made the use of large-scale astronomical instruments unfeasible. A mixture of political factors and plans to modernise the city were instrumental in the decision to find a new site for the Observatory. After several sites were considered, Morro de São Januário hill in the aristocratic district of São Cristóvão in suburban Rio de Janeiro was finally selected (Morize, 1987).

Work on the new architectural complex was begun in 1913 and completed in 1920, and in the following year the Observatory was moved there (see Figure 2). Meanwhile, demolition work that was underway in the centre of the city, including at the Castelo, inspired rumours that treasures hidden by the Jesuits were to be found there.

The tasks of the observatory included the following technical and research activities: determining the official time for the nation; weather forecasting; construction of astronomical tables; demarcation of the Brazilian borders; systematic observations of solar eclipses from Brazilian territory; and magnetic mapping of Brazilian soil (Barreto, 1987). Many different scientific instruments were used for these tasks, and they now make up a varied collection which includes some high quality instruments.

Figure 2: Photograph of the main building of the National Observatory on São Januário hill taken in 1922 (courtesy: MAST archives).

At this time, several institutional and financial hurdles stood in the way of the acquisition and functioning of these instruments. There are cases of instruments that took years to be repaired or years to be delivered. Naturally, this meant the set of instruments needed for research could not be kept up-to-date. Also, the number of people employed by the observatory was minimal, so much so that there was a shortage of technical staff, while the scientific personnel were often underqualified. One example of how this affected the work at the Observatory was an intended study of latitude variations. A programme was prepared for the project, but it had to be abandoned because there were not enough staff members to do the calculations (Morize, 1987).

These two factors illustrate a characteristic feature of the early Republican years: the absence of 'institutionalised' research activity. This only developed in the second half of the twentieth century, after the instruments needed for such work had been obtained.

Almost all the Directors made an effort to ensure that the Observatory was supplied with the latest equipment. This culture was passed down from the very first Directors during the Imperial era, who had managed to assure the effective engagement of the work carried out at the Observatory with the international astronomical community. The Directors were fully aware of the institutional and financial restricttions, and what was needed for the practice of astronomy, but there were countless difficulties to be overcome.

The instruments in the MAST collection and the uses to which they were put give us a good picture of what kind of institution the National Observatory was: what role was envisaged for it, and what its activities actually were. An analysis of these instruments shows us what could be done and allows us to draw inferences about the development, or in some cases the stagnation, of the methods used. The National Observatory is an active research centre to this day, and still stands on the same historic site in new premises inaugurated in 1985.

5 RESTORATION OF THE MERIDIAN CIRCLE

A meridian circle is a kind of telescope designed to determine the position of stars to a high degree of accuracy (Herbst 1996). It was crucial for determining the coordinates (right ascension and declination) of celestial bodies, which were used to prepare catalogues of the position of stars. The Gautier meridian circle in the MAST collection has a 190 mm diameter objective lens and a focal distance of 2,400 mm.

When we began the restoration process in 2003, this instrument was at great risk of being lost to the collection as it had been left dismantled since the 1960s, and the top part of the dome that sheltered it had been demolished in the 1980s, leaving just a vestibule and the base of the dome, which was in danger of completely collapsing. The intervention philosophy applied was not to put the instrument back in working order, but to allow it to be viewed and understood by the public within a display space in the Museum. As for the dome, a shelter was built for the instrument using a metal cover of a similar volume and appearance to the original, but with a different function, i.e. it is no longer designed to permit astronomical investigations, but rather to protect the exhibition space and merge harmoniously with the rest of the listed architectural complex.

During the second half of the nineteenth century, the top European and American makers were capable of producing high precision instruments for metrological, geodetic and astronomical measurements. One of the leading French makers was Paul Ferdinand Gautier (1842–1909), who, alongside the Brunner family, became the foremost representative of the French precision industry in the second half of the nineteenth century (Brenni, 1996). However, a refractor he designed to be shown at the Paris Universal Exhibition in 1900—the biggest instrument of its kind in his day—contained a design flaw, and the failure of this instrument ultimately drove Gautier to financial ruin and his brilliant career was cut short.

Ten years before this tragedy, Gautier received a commission from the Rio de Janeiro Observatory[1] to build a precision scientific instrument: a meridian circle with a 7" diameter objective lens (*Relatório* ..., 1891: 25). The late 1800s were a time when a meridian circle was crucial for the work of any serious professional observatory, and it was also the period when the Rio de Janeiro Observatory was at the height of its activities.

The instrument was finished in 1893 (*Relatório* ..., 1894: 19) and ended up with a 7.5 inch (19-cm) objective lens. However, it was still in boxes five years after delivery because there was no one at the Observatory who could assemble it (*Relatório* ..., 1898: 125). In those days, the Observatory was in downtown Rio de Janeiro, on land which was not stable enough for large-scale astronomical instruments. Even so, in 1900 the meridian circle was installed there in a makeshift wooden shelter (Morize, 1987: 129), but the conditions were far from suitable and the instrument could not be used correctly.

In 1913, after the move of the Observatory to its new site on Morro de São Januário hill, Carl Zeiss (MAST, 1913) was commissioned to build a wooden shelter and an observatory dome with an iron structure to house the meridian circle. The masonry structure for the dome was built in 1915 by the contractor João de Mattos Travassos Filho (MAST, 1915), but a number of faults were discovered, including leaks, which meant that rainwater even splashed onto the transit telescope. The necessary repair work was done, and a document was then sent from the Observatory to the Ministry of Agriculture, Industry and Trade (MAST, 1928) stating that on 30 March 1928 the meridian circle was put into service to catalogue the stars, which would allow a more accurate Brazilian time-service to be maintained.

The oldest known photographs of the meridian circle (e.g. see Figure 3) date from after it was installed at Morro de São Januário inside the Zeiss dome.

Alongside the meridian circle, other supplementary instruments were installed in the dome, including a synchronized pendulum, manufactured by L. Leroy & Cie., and a recording chronograph, by the Gaertner Precise Instrument Company of Chicago. These instruments were needed for the measurements made using the meridian circle.

As some of the activities at the National Observatory were gradually phased out, the pendulum and some of the meridian circle's accessories started to be used in other areas. According to a former Observatory employee, the circle was dismantled in 1962. One year later, the anteroom to the dome was stripped of its panelling because it was infested with termites. The neglect of the dome, the deplorable oxidation of the metal parts and the deterioration of the wooden parts led to its demolition between 1980 and 1985, leaving only the masonry vestibule and the base of the instrument mounting. The opening between the vestibule and the instrument room was bricked up and the room was left to its process of decline.

After the Museu de Astronomia e Ciências Afins was established in 1985 the ruins of the instrument room came under its protection, while the vestibule was to be safeguarded by the National Observatory. The architectural complex, as already mentioned, was listed, and it includes both of these parts of the dome.[2]

Most of the parts of the meridian circle were deposited in a ground floor room in the Museum's main building, while a few components were kept in other parts of the campus. As of 1997, the restoration of this instrument was adopted as one of the primary goals of the Museum. The reasons for this were that it (1) was the only surviving object of this kind and by this maker in Brazil; (2) was the only large-scale instrument not to have been installed in its own shelter on the campus; and (3) was at risk of being lost forever because it had been dismantled. In 2003, the restoration of the meridian circle was begun through a partnership with the Fundação VITAE, which also included the restoration of the shelter.

Before the restoration of any instrument commences there must be a moment when it is questioned whether this process is really worthwhile, bearing in mind the expense and time involved. Miniati and Brenni (1993: 55) discuss this issue at length and suggest an artefact's rarity, age, complexity and origin are useful factors that must be considered. However, they also note that instruments can take on different meanings depending upon their context. For instance, an electrostatic machine, the type of which was produced by the thousands and was very commonplace in the late nineteenth century, could be earmarked for intensive restoration work if it were part of a homogeneous, comprehensive collection of equipment of this kind, because its loss would leave a conspicuous gap in the collection.

From this perspective, the MAST's Gautier meridian circle is indeed a rare piece, as the only one of its kind in Brazil, and the fact that it was listed by the Brazilian cultural heritage agency, IPHAN, and its Rio de Janeiro state equivalent, INEPAC, is also important. Added to this, the meridian circle was the only large astronomical instrument at the Observatory that was not installed in its own shelter.

Having decided this instrument was worth restoring, the next step, as is the case for most cultural objects, was to make a detailed diagnosis of its state of conservation to define the type of intervention to be carried out. In this particular case, at this important initial stage in the restoration process, there was no single object to consider, but rather a set of objects (i.e. the instrument's constituent parts). And to make matters worse, it was impossible to tell whether all of the parts, or at very least those needed to reassemble the meridian circle, still existed. Thus, prior to any discussion on how to restore the instrument, we contacted observatories and science and technology museums in Algeria, Australia, France, Germany and the USA which might have similar instruments by the same manufacturer, in the hope of gathering data that could help us identify the various parts in MAST's technical store.

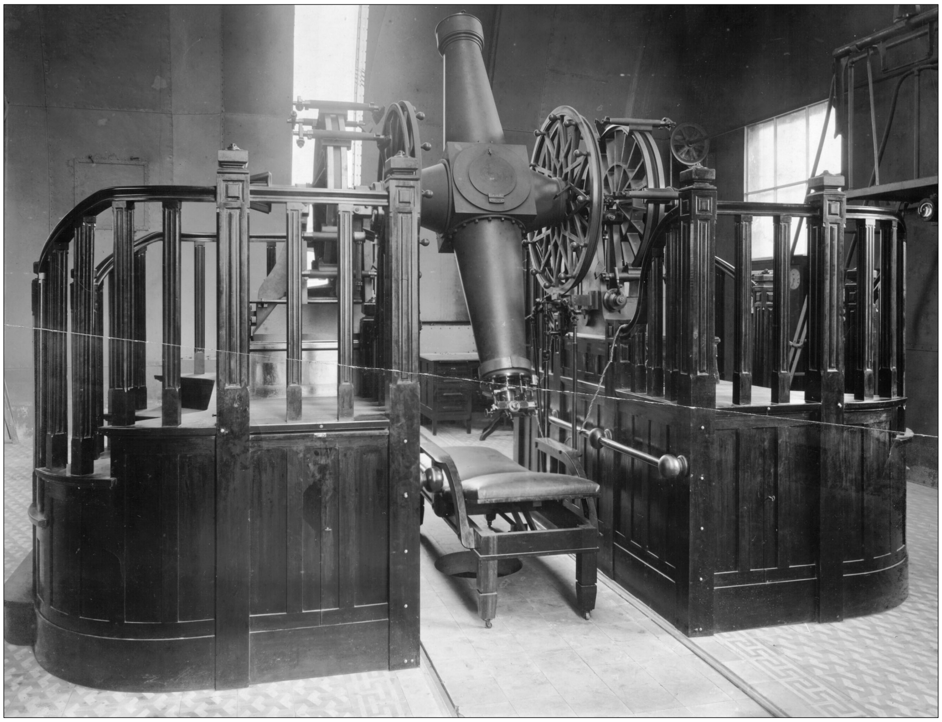

Figure 3: The Gautier meridian circle in its original position at Morro de São Januário (MAST archives).

This effort bore fruit, as the Besançon and Toulouse Observatories in France and the Algiers Observatory in Algeria all had Gautier meridian circles dating from the same period. These instruments had been acquired in 1885 (Besançon), 1888 (Algiers) and 1891 (Toulouse), and the first two had the same size objective lens (19-cm) as the MAST instrument and similar focal lengths (2370mm and 2400mm, respectively). Both the Algiers and the Toulouse meridian circles were acquired for the Carte du Ciel project.[3]

The conclusion drawn from the many digital images received from these institutions was that it would be possible to reassemble the Brazilian meridian circle, but that some parts were indeed missing. Details of some of these missing parts were obtained from the French observatories.

Armed with the information from the foreign observatories, the next stage ensued: a search of the MAST and Observatory campus for the instrument's missing parts. All the drawers, storerooms and rooms in the Museum were checked, and many professionals from the Observatory were contacted to help identify whether the items that were found during this search belonged to the meridian circle. Key finds were two brass shafts with a support at one end, which were linked to the brake system; two iron bars to support the counterweights, with pins to keep them in place; two square brass sheets; and a number of screws.

After recording all the information gathered and organising and grouping the various parts, we had to decide which parts required intervention treatment. Only four parts needed no restoration: the two cones from the system of mirrors, the Gautier micrometer and the micrometer manufactured by Édouard Bouty. The remaining parts were in an extremely poor state. Some had lost all their original varnish, many were painted in a colour different from the original and this paintwork was damaged, and there were large areas of metal that were badly rusted or had some mechanical damage.

The original Gautier micrometer supplied with the meridian circle must have been faulty because another micrometer, manufactured by Edouard Bouty (Paris), was acquired in 1923 (*Relatório* ..., 1923) and used for research from 1928. A decision was therefore made to install the Bouty micrometer on the restored meridian circle, and to display the original micrometer in a showcase inside the dome as part of the overall exhibition. The Gautier micrometer did not need restoration because it was in a good state of repair, but the Bouty micrometer did require treatment.

Upon analysing the Bouty micrometer its circular base was found to contain the inscription "Gautier 1893 Edouard Bouty 1923", revealing that this part was originally from the Gautier micrometer and was adapted to the new micrometer in 1923. After it was cleaned, the piece was mounted inside the optical tube using the original screws.

All of the remaining components of the micrometer then had their surfaces and mechanical parts cleaned, after which the restoration philosophy was discussed. As already mentioned, two lines of thought about the restoration of scientific instruments have prevailed for many years. One of them favours a comprehensive restoration of the object with the primary aim of getting the instrument to work again. It should be added here that many studies regard science and technology objects as different from other cultural objects in that they have a functional dimension, and that this should prevail over all other considerations in any restoration work.

The opposing restoration philosophy defends a more selective restoration, whereby the parts should not be replaced nor the object be repaired. Miniati and Brenni (1993: 53-54; my translation) clearly explain this less radical course of action:

> Lost parts often do have to be replaced. When we are sure about the original state of the instrument, we can reconstruct the object or parts that are missing. We do not share the view concerning old materials that one should not tamper with the "dust of time", which is normally just dirt, being satisfied to conserve a virtually useless relic.
>
> Obviously, each intervention should be reversible and recorded in detail on a restoration form. Also, mistakes and confusion can be prevented by marking the replacement part to make it easily identifiable.

At the time this text was written, certain conservation measures were still thought to be reversible, although the precepts of contemporary conservation theory would now argue that no action on a cultural object can be reversed, not even the simple act of cleaning using brushes (see Viñas, 2005). Strictly speaking, nothing is reversible. A corollary to this concept is the current principle of minimum necessary intervention for achieving the desired goal based on the guiding principle of the object's communication potential.

Other authors have also discussed the issue of making instruments from museum collections work again, including Mohen (1999), who is particularly interested in technology and music museums. He believes such institutions could be tempted to revert the objects to their initial function, like a clock that chimes on the hour or a violin played in a concert. He warns that it is illusory to think that one can recreate the conditions in which an object was originally used, such as medieval musical instruments for recreating old music, since the instruments themselves will have changed over the years, as will the music they play and the audiences themselves. You cannot recreate the past.

Turning to the Gautier meridian circle in the MAST collection, the guiding principle for its restoration was not to use it for educational or experimental purposes, which meant it would not be put to work as an example for the visiting public to see. Instead, it would be a museological and educational element in the new exhibition space and would never be used in practical demonstrations. Thus, there would be no intervention to make it work again.

Large instruments like the meridian circle discussed here have a great number of screws, and one of the first things to be assessed is the replacement of lost screws. It is a great temptation to just put in a new screw, even if this means remaking the hole, but depending on the alterations needed to do so, the result may be ethically unsound. Wheatley (1986) states that if screws must be replaced, the replacements must be identical to the originals. In the present restoration work, only a few screws needed to be replaced. Others that were missing did not affect the structural integrity and stability of the instrument so were not replaced.

Only when it was absolutely necessary were screws replicated, but in such instances the existing holes were used, so that no new holes had to be drilled.

Figure 4: The meridian circle parts before intervention began (author's photo).

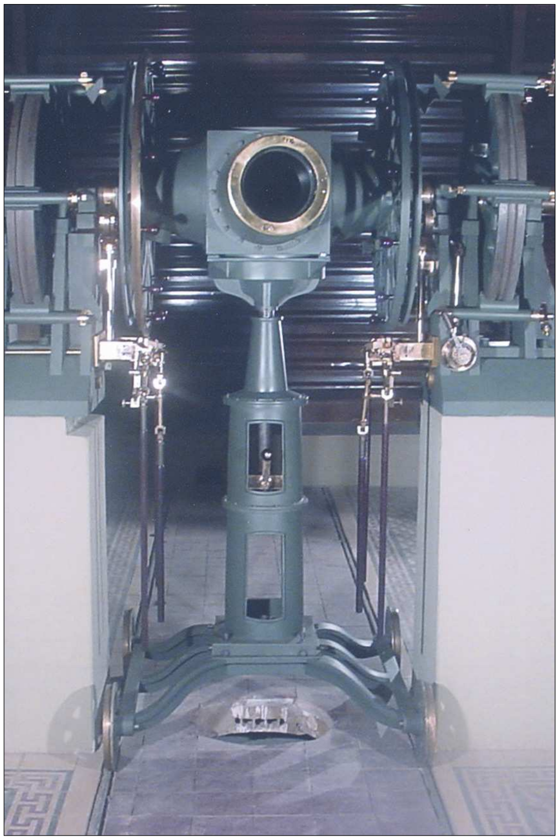

Figure 5: The meridian circle during the intervention process (author's photo).

Moving on to the third phase of the intervention process on scientific instruments, namely dismantling, the circumstances of this particular object were exceptional, in that it was already in pieces (see Figure 4). To compound matters, it was dismantled in the 1960s without any recourse to the modern precepts of conservation, meaning that the process was not recorded or documented. As far as screws are concerned, Keene (1999: 61) notes:

> Even the seemingly innocent action of dismantling an instrument in order to clean and reassemble it can cause damage. For example, in removing screws, many people would not appreciate that in scientific instruments each screw was specially made for its hole … It is essential to record the position of each one when dismantling an object. The screw slots are often specially shaped. A skilled and knowledgeable conservator will make a screwdriver to exactly fit the screw head - otherwise the heads can be torn, as they often have been, and the surface of the instrument damaged.

Thus, the meridian circle had to be reassembled carefully after its parts were restored, yet even the greatest of care could not rule out some divergence from the original, because it was impossible to tell exactly where each screw should be. Even so, the members of the group were unanimous in their decision to carry on with the restoration.

The procedures used in the interventions were similar to those employed on other instruments from the MAST collection (Granato, et al., 2005a, 2005b). When the restored parts still had some remaining varnish, they were cleaned with a methylene chloride solution, then rinsed thoroughly in water to remove all traces of the solution and dried. The oxidized parts were treated to remove the layers of oxidization products using mechanical processes, such as polishing pastes and fine sandpapers. For the finishing, 320# and 400# grit sandpaper was used. Finer grades (600# or 720#) were not used because they would result in a very shiny surface, which would be very different from the finished surface on the original instrument. Throughout the mechanical process, the surface of the parts was cleaned periodically with cotton to remove the suspension of oil and oxidation products. A scalpel was also used wherever there was pit corrosion on specific areas, where treating the entire surface of the piece was not necessary.

The parts which were originally produced using a mechanical lathe and originally bore machining marks had their layers of rust removed using a lathe, which also reproduced the concentric circles typical of this process.

Once the corrosion products had been removed, the unvarnished parts were degreased using trichloroethylene and then protected with a coating of microcrystalline wax. All the parts that were treated and protected with varnish were also degreased and then immediately had a new coat of varnish applied using an airbrush.

The right paint for the parts that were originally painted was chosen by studying areas of original paintwork that were revealed when the parts were dismantled. Their outside parts were then painted in a mixture of three synthetic gloss paints (brand: CORALMUR), at a ratio of around 38% green (code no. 9159), 38% grey (code no. 9152) and 24% blue (code no. 9295). When necessary, the inner parts were painted matt black (optical tubes, central shaft and objective lens protector), replicating how they were originally painted (see Figure 5). The final result is shown in Figure 6.

The most complex restoration work to have been undertaken at MAST was the meridian circle and rehabilitation of its pavilion. The whole project was carried out by a multidisciplinary team and was based on historical research into the object and its shelter over a period of three years. It was accompanied by an exhaustive photographical account of each stage of the work, covering the diagnosis of the instrument's state of conservation, its restoration, the rehabilitation of the pavilion and the return of the instrument to its original position, as well as a museological account of the area, providing the visiting public with information about the restoration work carried out.

6 FINAL CONSIDERATIONS

Over the past three years, different Brazilian and Latin American institutions have approached MAST for assistance in the conservation and restoration of their scientific instruments. It would appear that we are witnessing a ‘discovery’ of museum instruments of historical value on this continent, which means that some of them will need conserving and occasionally restoring. Being aware of the need to contribute to the preservation of these collections, MAST is in the process of setting up a new laboratory for the conservation of scientific instruments, which will be opened in 2009. It is hoped that it will then be able to meet the demand for training and services which has grown steadily in recent years.

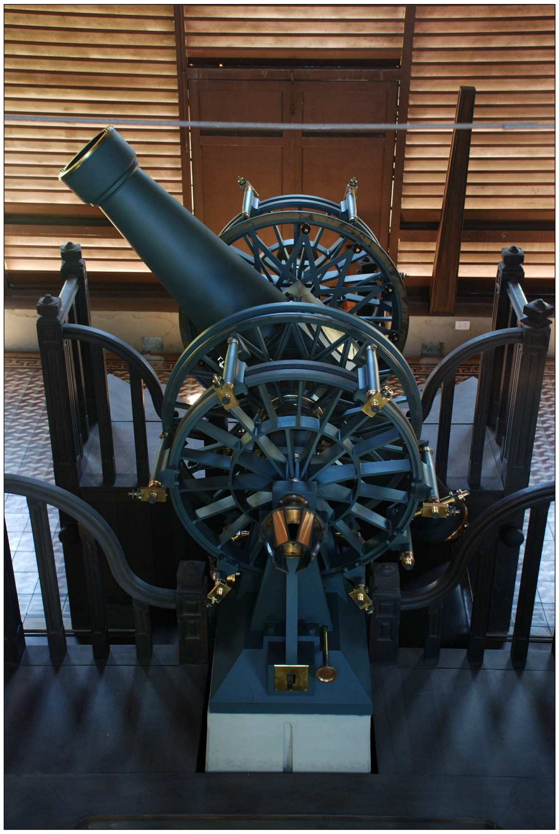

Figure 6: The fully-restored Gautier meridian circle.

7 NOTES

1 The Imperial Observatory of Rio de Janeiro was renamed the Rio de Janeiro Observatory on 31 May 1890 after the country was declared a Republic, and was included under the auspices of the Ministry of War (1891 Report).

2. The listing of the complex was in recognition of the uniqueness of its features, where the instruments had not been modernized and were still in their original sites.

3. This was an international project to photographically map the positions of all stars brighter than the 11th or 12th magnitude. Devised and initiated in 1887 by the Director of the Paris Observatory, Admiral Ernest Mouchez, it initially included the following observatories: Greenwich, Rome, Catania, Helsinki, Potsdam, Oxford, Bordeaux, Toulouse, Algiers, San Fernando, Tacubaya, Santiago, La Plata, Rio de Janeiro, Cape Town, Sydney and Melbourne (see Lamy, 2009; Turner, 1912).

8 REFERENCES

André, L. 1999. Scientific instrument restoration: problems and practice at the Musée des arts et Metiers and in France. In: *Proceedings of the Workshop The Restoration of Scientific Instruments*. Florence, Le Lettere. Pp. 23-30..

Ashley-Smith, J., 1994. The ethics of conservation. In Knell, Simon (ed.). *Care of Collections*. London, Routledge. Pp. 11-20.

Barboza, C.H.M., 2004. *O Encontro do Rei com Vênus. 1994.* Masters thesis, Instituto de Ciências Humanas e Filosofia, Universidade Federal Fluminense, Niterói.

Barreto, L.M., 1987. *Observatório Nacional*: *160 anos de história.* Rio de Janeiro, Observatório Nacional.

Bonsanti, G., 1999. Once again on the restoration of scientific instruments. In *Proceedings of the Workshop The Restoration of Scientific Instruments*. Florence, Le Lettere. Pp.51-56.

Brenni, P., 1996. 19th century French scientific instrument makers: the Brunners and Paul Gautier. *Bulletin of the Scientific Instrument Society*, 49, 38.

Brenni,, P., 1999. Better than new? Scientific instrument restoration in Italy. In *Proceedings of the Workshop The Restoration of Scientific Instruments.* Florence, Le Lettere. Pp. 89-97.

Brenni, P., 2000. Instruments in South America: the collection of the Museu de Astronomia e Ciências Afins of Rio de Janeiro. *Bulletin of the Scientific Instrument Society*, 65, 25-28.

Granato, M., Santos, L.R. dos, and Miranda, L.R.M. de, 2005a. Restauração de um teodolito astronômico da coleção do Museu de Astronomia e Ciências Afins - MAST- (Brasil). In Granato, M. (ed.). *Anais do II Congresso Latino-Americano de Restauração de Metais, 2005*. Rio de Janeiro, MAST. Pp. 273-295.

Granato, M., Duarte, I., and Suzuki, C., 2005b. Restauração do Pavilhão, Cúpula Metálica e Luneta Equatorial de 32cm - Conjunto Arquitetônico do Museu de Astronomia e Ciências Afins MAST. Anais do Museu Paulista. *São Paulo: Museu Paulista da USP*, 13, 273-314.

Herbst, K.-D. 1996. *Die Entwicklung des Meridiankreises 1700-1850*. Diepholz, GNT-Verlag.

ICOM Committee for Conservation, n.d. *Code of Ethics*. http://www.icom-cc.org

Keene, S., 1999. Instruments of history: appearance and evidence. In *Proceedings of the Workshop The Restoration of Scientific Instruments*. Florence, Le Lettere. Pp.57-68.

Lamy, J., 2009. The role of the conferences and the *Bulletin* in the modification of the practices of the Carte du Ciel. *Journal of Astronomical History and Heritage*, 12, 119-124.

Mann, P.R., 1994. *Working Exhibits and the Destruction of Evidence in the Science Museum*. London, Routledge. Pp. 35-50.

Meehan, P.M., 1999. Is reversibility an option when conserving industrial collections? In *Reversibility – Does it Exists?* London, British Museum (British Museum Occasional Paper, 135). Pp. 11-15.

Miniati, M., 1991. Il restauro degli strumenti scientifici. *Il coltello di Delfo*, 19, Setembre, 13-18.

Miniati, M., and Brenni, P., 1993. Restauro di strumenti storico-scientifici e filosofie di intervento. In Bitelli, L.M. (ed.). *Restauro di Strumenti i Materialli: Scienza, Musica, Etnografia*. Florence, Nardini Editore. Pp. 51-59.

Mohen, J.-P., 1999. *Les Sciences du Patrimoine*: *Identifier,* *Conserver, Restaurer*. Paris, Odile Jacob.

Morize, H., 1987. *Observatório Astronômico: Um Século de História (1827-1927)*. Rio de Janeiro, MAST/Salamandra.

Museu de Astronomia e Ciências Afins. Department of Documentation and Archives. Archives of the History of Science. Arcive: Observatório Nacional, Ofício n. 200, date 03 May 1913.

Museu de Astronomia e Ciências Afins. Department of Documentation and Archives. Archives of the History of Science. Archive: Observatório Nacional, date 07 July 1915.

Museu de Astronomia e Ciências Afins. Department of Documentation and Archives. Archives of the History of Science. Archives: Observatório Nacional, Ofício n. 177, date 30 March 1928.

Newey, H., 2000. Conservation and the preservation of scientific and industrial collections. In Roy, A., and Smith, P. (eds.) *Tradition and Innovation: Advances in Conservation. Contributions to the Melbourne Congress* … Melbourne, International Institute for Conservation of Historic and Artistic Works. Pp. 137-139.

Relatório do Ministerio da Guerra. Rio de Janeiro, Imprensa Nacional (1891).

Relatório do Ministerio da Guerra. Rio de Janeiro, Imprensa Nacional (1894).

Relatório do Ministerio da Industria, Viação e Obras Publicas. Rio de Janeiro, Imprensa Nacional (1898a).

Relatório do Ministério das Relações Exteriores – 1898. Rio de Janeiro, Imprensa Nacional (1898b).

Relatório do Ministerio da Agricultura, Industria e Commercio. Rio de Janeiro, Imprensa Nacional, (1923).

Rolland-Villemot, B., 2002. Une méthodologie pour la conservation et la restauration du patrimoine industriel, scientifique et technique. In *Proceeedings* of the *13th Triennial Meeting ICOM-CC, Rio de Janeiro*. London, James & James Science. Pp. 187-191.

Sebastian, A., 1995. Hacia una arqueología de la ciencia: problemas de conservación y restauración del patrimonio científico e industrial. *Pátina*, 7, 118-129.

Turner, H.H., 1912. *The Great Star Map, Being a Brief General Account of the International Project Known as the Astrographic Chart*. London, Murray.

Videira, A.A.P., 2002. *Os 175 Anos do Observatório Nacional*. Rio de Janeiro, Observatório Nacional.

Viñas, S.M., 2005. *Contemporary Theory of Conservation*. London, Butterworth-Heinemann.

Wheatley, C.J., 1986. Conservation and storage: scientific instruments. In *Manual of Curatorship. A Guide to Museum Practice.* London, Butterworths. Pp. 319-322.

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Journal of Astronomical History and Heritage, 12(2), 119-124 (2009).

THE ROLE OF THE CONFERENCES AND THE *BULLETIN* IN THE MODIFICATION OF THE PRACTICES OF THE CARTE DU CIEL PROJECT AT THE END OF THE NINETEENTH CENTURY

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Abstract: Launched in 1887, the Carte du Ciel was an international project aiming at photographing the entirety of the celestial vault. Tasks required for this huge undertaking were divided among eighteen observatories around the globe. Instruments were standardized, and a series of international conferences established operating modes and prescribed norms to be followed everywhere. In each observatory, however, the drive toward uniformity ran into a variety of minor technical and practical problems. In this paper, we examine the strategies mobilized by observers to tinker with stated rules and adapt them to their own experience as astronomers. To underscore the tension between normative prescriptions and individual practices, we consider the *Bulletin du Comité International Permanent de la Carte du Ciel* as an informal forum where various queries raised and arrangements adopted were shared among the scientific community.

Keywords: astronomy, Carte du Ciel project, scientific practices, Ernest Mouchez, David Gill

1 INTRODUCTION

The Carte du Ciel, initiated by Ernest Mouchez of the Paris Observatory and David Gill, Director of the Observatory at the Cape of Good Hope, mobilized eighteen observatories throughout the world. The goal of this international scientific program was to map the sky using photography (Jones, 2000; Lankford, 1984: 29-32). In fact, by employing recent developments in photography, the Carte du Ciel combined at the end of the nineteenth century a traditional astronomical theme (inventory of the sky) and a recent technology (photography). The Carte du Ciel required co-operation on a world scale. It was founded on the definition of common rules for all the astronomers. In this paper I will examine the ways in which the scientific co-operation between the observatories participating in the Carte du Ciel project was organized. I will also detail the role of the international conferences, which were held in Paris in 1887, 1889 and 1891. Then I will study the *Bulletin* of the Permanent International Committee for the execution of the Carte du Ciel, in order to understand how practices coordinated with one another.

2 THE CARTE DU CIEL PROJECT

In 1880 Mouchez, Director of the Paris Observatory, was particularly interested in the development of photography for astronomical applications. In the United States, William C. Bond undertook work on astronomical photography beginning in 1850 (Mouchez, 1887: 12) and in England, Warren De La Rue experimented with astronomical photography starting shortly afterwards (Chinnici, 1999: 3-4). In France Léon Foucault and Hippolyte Fizeau obtained photographs of the Sun of very good quality in 1844 and 1845 (Tobin, 2002: 53-54).

In 1879 Mouchez created a photographic laboratory at the Paris Observatory (Baillaud, 1935: 34), then he encouraged the brothers Paul and Prosper Henry, opticians and astronomers at the Observatory, to build photographic equatorials. They started by developing a camera with an objective of 16 cm. Then, in 1885, the two brothers delivered a camera with an aperture of 33 cm (Mouchez, 1887: 26). Mouchez was filled with enthusiasm by the quality of the instrument. He considered that the photographic objective of the Henry brothers "… goes far beyond all that were made up to now in France or abroad for the photography of the stars." (Mouchez, 1887: 6; my translation).

At the Cape of Good Hope, David Gill, impressed by the images of stars on photographs he took of the Great Comet of 1882, also considered the possible applications of photography to charting the stars. Catalogs of southern stars were few. Mouchez and Gill communicated and conceived an ambitious celestial cartographic project. Their objective was to use photography, not to reproduce the aspect of the stars, but to determine their positions. Mouchez (1887: 8; my translation) spoke about a "… geography of the sky." He wanted the Carte du Ciel to enable the study of "… the distribution of stars in space ... [so that the work of Herschel] will be exceeded and made useless." (Mouchez, 188: 6; my translation). Mouchez insisted on the transformation of the astronomical practice which photography allowed. He noticed that the photographic plate had a greater sensitivity than the human eye: it can distinguish several hundreds of stars where the eye saw only a single compact mass of stars. The astronomer no longer observed directly any more; he simply examined photographic plates with a microscope. Thus it was possible to transport the image of the sky "… into the study." (Mouchez, 1887: 48; my translation). Plates could also be reproduced at will and circulated among interested astronomers. This ambitious project thus rested on the search for a high degree of accuracy and as well on the mechanization of the operations. It should be possible to obtain the positions of more than two million stars in ten or twenty years.

Mouchez wanted to gather together astronomers interested in this project, so he contacted the Royal Astronomical Society in 1885 (Baillaud, 1935: 37) and wrote to Gill and the Directors of the observatories at Harvard, London, Rio and Pulkovo (Chinnici, 1999: 4-5). The reception he received was uniformly favorable. Gill was enthusiastic, and he even proposed to add to the photography of the sky the construction of a catalog of positions of the stars. He also urged Mouchez to organize an international conference.

Table 1: Attendees at the 1887 conference.

Foreign members	
A. Auwers	Prussian Academy of Sciences, Berlin
H.G. Van de Sande Bakhuyzen	Director, Leiden Observatory
F. Beuf	Director, La Plata Observatory
W. Christie	Astronomer Royal, Greenwich Observatory
A.A. Common	Royal Astronomical Society
L. Cruls	Director, Rio de Janeiro Observatory
A. Donner	Director, Helsingfors Observatory
N.C. Dunér	Lund Observatory
J.M Eder	Polytechnic School, Vienna
F. Folie	Director, Brussels Observatory
E. Gautier	Director, Geneva Observatory
D. Gill	Director, Cape of Good Hope Observatory
H. Gyldén	Director, Stockholm Observatory
B. Hasselberg	Pulkovo Observatory
J.C. Kapteyn	Groningen University
E.B. Knobel	Royal Astronomical Society
A. Krueger	Director, Kiel Observatory
O. Lohse	Potsdam Observatory
F.A. Oom	Director, Lisbon Observatory
J.A.C. Oudemans	Director, Utrecht Observatory
C.F. Pechüle	Copenhagen Observatory
J.P. Perry	Director, Stonyhurst College Observatory, Clitheroe, England
C.H.F. Peters	Director, Hamilton College Observatory, Clinton, NY, USA
C. Pujazon	Director, San Fernando Observatory, Cadiz, Spain
I. Roberts	Director, Private Observatory, Maghull (near Liverpool), England
H.C. Russell	Director, Sydney Observatory
E. Schönfeld	Director, Bonn Observatory
A. Steinheil	Instrument Maker, Munich
O. Struve	Director, Pulkovo Observatory
P. Tacchini	Director, Roman College Observatory, Rome
J.F. Tennant	Royal Astronomical Society
T.N. Thiele	Director, Copenhagen Observatory
H.C. Vogel	Director, Potsdam Observatory
E. Weiss	Director, Vienna Observatory
A.G. Winterhalter	U.S. Naval Observatory
French members	
J. Bertrand	Academy of Science
A. Bouquet de la Grye	Academy of Science
A. Cornu	Academy of Science
H. Faye	Academy of Science
H. Fizeau	Academy of Science
J. Janssen	Academy of Science
M. Lœwy	Academy of Science
E. Mouchez	Academy of Science
F. Perrier	Academy of Science
F. Tisserand	Academy of Science
C. Wolf	Academy of Science
B. Baillaud	Director, Toulouse Observatory
G. Rayet	Director, Bordeaux Observatory
C. Trépied	Director, Algiers Observatory
Paul Henry	Paris Observatory
Prosper Henry	Paris Observatory
P. Gautier	Instruments Maker, Paris
G.C. Cloué	Bureau des Longitudes
A. Laussedat	Museum and College of Applied Sciences, Paris
L. Liard	Public Instruction Ministry

3 TESTING INTERNATIONAL SUPPORT: THE PARIS CONFERENCE OF 1887

Mouchez heeded Gill's advice and an inaugural meeting was held in Paris in April 1887, attended by 56 astronomers from 38 nations (see Table 1). After a week of discussions, the objective was laid down:

> … to note the general state of the sky at the current time [and] to obtain data which will make it possible to determine the positions and the magnitudes of all stars up to an order of magnitude … (*Congrès Astrophotographique* …, 1887: 7).

Paris Observatory was at the center of a world-wide network of eighteen observatories. The first question to be settled concerned the distribution of the zones of the sky to be photographed by each observatory. William H. Christie, Director of the Greenwich Observatory, noticed that the observatories of the southern hemisphere (fewer than in the northern hemisphere) would have to take more photographs (*Bulletin* …, 1890: 340).

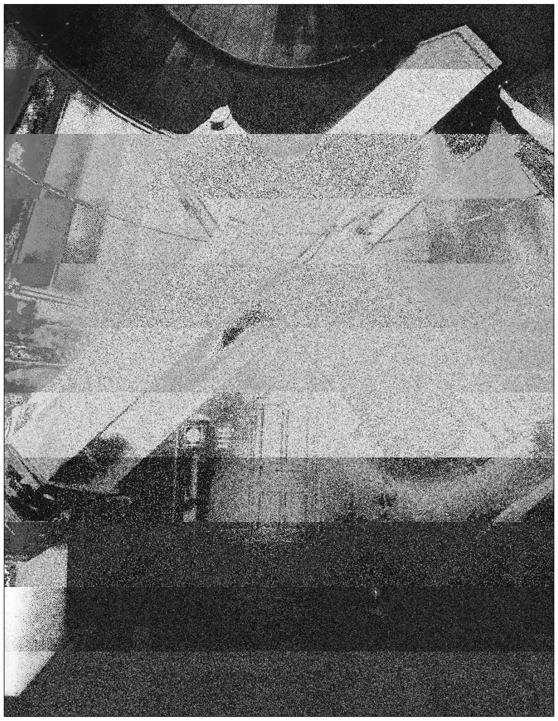


Figure 1: The Carte du Ciel astrograph at the Toulouse Observatory, ca. 1900 (courtesy: Archives of the Observatoire Midi-Pyrénées).

In 1891, the observatories received the co-ordinates of their zones of observation. Almost all the observatories received identical photographic equatorials, each with an objective of 33 centimeters diameter (Figure 1).

The Carte du Ciel required three distinct operations: (1) measuring the positions of stars with a meridian instrument; (2) taking the celestial photographs and processing them; and (3) determining the positions of the stars on the plates. The very large numbers of stars to be measured prevented the astronomers from carrying out all of the calculations themselves, so some observatories created separate computational departments (see Figure 2), while other institutions (e.g. Paris Observatory) entrusted these calculations to female employees.

The Carte du Ciel was one of the first major international scientific projects (Turner, 1918).

3 THE CONFERENCES: THE 'PARLIAMENT' OF THE CARTE DU CIEL

Mouchez (1888; my translation) asked that "… the final and uniform bases of the Carte du Ciel …" be fixed, so the execution, development and measurement of the photographs was thus framed and each operation was detailed. For example, in 1889, a resolution indicated the manner of ordering and of filing the photographic plates (Trépied, 1892: 43). The organizers of the Carte du Ciel required standardization and uniformity of practices. In particular, that applied to the calibration of the observers, and the personal equation of each of them was measured for the evaluation of the sizes of the stars on the plates (Baillaud and Baillaud, 1906: 329).

The first recommendations of the Carte du Ciel project were very prescriptive. This organization of scientific activity falls under a broader movement of transformation of the observatories into scientific factories. The industrial model became dominant at the end of the 19th century, with division of labor, the definition of the tasks and the standardization of the instruments.[1]

However, this regulation of the practices within the framework of the Carte du Ciel quickly caused resistance. For example, the exposure time was fixed at 40 minutes, but some climates did not allow such long exposures (Baillaud, 1929: 644). Some astronomers were skeptical about the possibility of following all of the rules. Thus, Henry Andoyer, from Toulouse in France, preferred to call upon "… the experience of the observer." (Baillaud, 1891; my translation), and estimated that daily experience with the astrograph enabled him to develop a more adequate know-how (see Andoyer, 1891). George Rayet (1901), Director of the Bordeaux Observatory, recognized that certain theoretical considerations for the measurement of star positions were "… impracticable in the reality of things." There was thus a strong tension between a system of standards and local and individual practices.

The organizers of the Carte du Ciel became aware of the danger of maintaining rules that were too strict and limiting. Felix Tisserand, Director of Paris Observatory in 1895, recognized that "… to want to do best, one is sometimes likely to miss the good." (*Bulletin* …, 1895: 344; my translation).

As a result, Mouchez and Gill set up a policy of flexibility, which involved easing the rules and the standards by taking individual situations into account. Two forums for dialogue, distinct but complementary, opened then for the participants of the Carte du Ciel project.

The first related to the international conferences. Initially, they were not supposed to reconsider a decision, but in 1890 Mouchez recognized that it was not a question of a "… absolute law …" (*Bulletin* …, 1892: 290; my translation). It then became possible to revise inapplicable rules or those that were too complex. Thus, at the 1891 meeting several astronomers disputed a resolution which envisaged making only one exposure for each area (Trépied, 1892: 40), proposing three exposures instead, which would make it possible to identify false stars more easily. The discussion was animated, with some astronomers maintaining that the risks of confusion were great in areas of the sky that were very rich in stars. Agreement seemed impossible, and so a technical commission was appointed to examine this issue. It proposed to persevere with single exposures, but to allow certain observatories to take three exposures.

The international Conferences of 1887, 1889 and 1891 defined a whole set of rules to be followed in practice. Thus the Conferences became a 'Parliament' of the Carte du Ciel, in which confrontation and debates were numerous. It was always a matter of seeking a democratic consensus through negotiation.

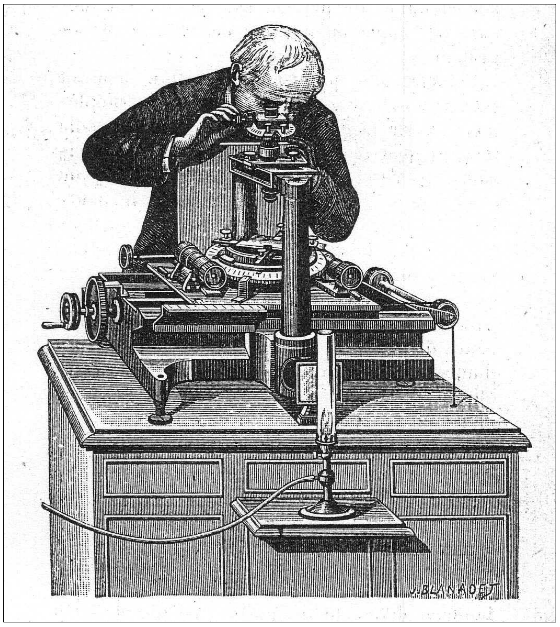


Figure 2: Measuring one of the Carte du Ciel plates (after Mouchez, 1887: 42).

4 THE *BULLETIN*: THE CIRCULATION OF OPINIONS

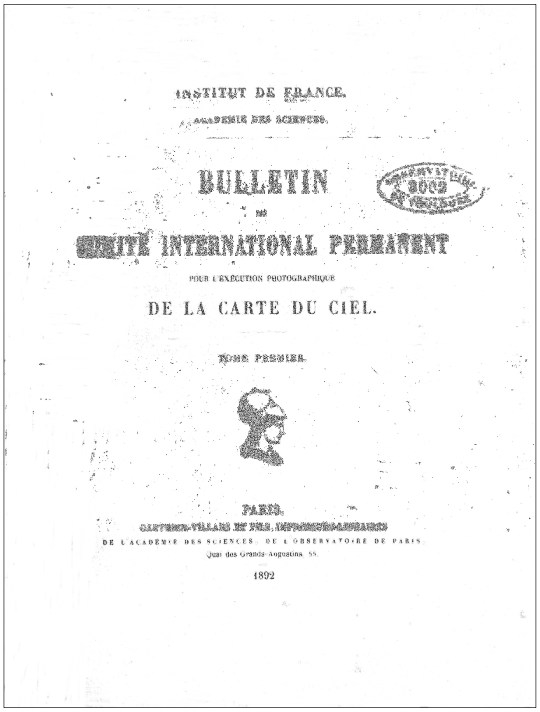
The *Bulletin du Comité International Permanent pour l'Exécution Photographique de la Carte du Ciel* (Figure 3) was the second forum for dialogue, which appeared in 1892 and 1895. I would like to describe in detail the role and contents of the *Bulletin*. The first volume was published in 1892, and in the Introduction Mouchez specified that the *Bulletin* must contain information that will be useful to astronomers taking part in the Carte du Ciel project (*Bulletin* …, 1892: 1).

A section of the *Bulletin* was devoted to correspondence, and contained letters from astronomers concerning their practical suggestions or their difficulties. Mouchez ensured that the discussions were always open and that the objective was to obtain "… a final general opinion …" (*Bulletin* …, 1895: 329; my translation). The *Bulletin* disseminated information and discussion in order to obtain a broad agreement among the astronomers involved in the project. It therefore served to supplement the work of the international Conferences.

We can distinguish three major sets of themes in the first *Bulletins* of the Carte du Ciel project.

The first relates to the examination of the instruments used to take the photographs. The astronomers conducted tests, then published their results in the *Bulletin*. In 1888 Franz Renz (from the Pulkovo Observatory) inspected the photographic plates taken by the Henry brothers and commented on their quality, which met the desired level of precision (*Bulletin* …, 1892: 275).

In the same manner, the astronomers described their first experiments with the camera. In 1891, Charles Trépied, Director of the Algiers Observatory, assured his readers that after four months of use and tests, the photographic equatorial functioned well (*Bulletin* …, 1892: 372).



INSTITUT DE FRANCE.
ACADÉMIE DES SCIENCES.

BULLETIN
DU
COMITÉ INTERNATIONAL PERMANENT
POUR L'EXÉCUTION PHOTOGRAPHIQUE
DE LA CARTE DU CIEL.

TOME PREMIER.

PARIS,
GAUTHIER-VILLARS ET FILS, IMPRIMEURS-LIBRAIRES
DE L'ACADÉMIE DES SCIENCES, DE L'OBSERVATOIRE DE PARIS,
Quai des Grands-Augustins, 55.

1892

Figure 3: Cover of the first volume of the *Bulletin du Comité international permanent pour l'Exécution Photographique de la Carte du Ciel* (1892).

Among the technical studies, the comparisons between different materials played an important part. For example, the astronomers devoted considerable time to the collective evaluation of the screens intended for the calibration of the image sizes. The various points of view and technical tests made it possible to obtain a consensus and to better determine the limits of the instruments.

Exchanges with the manufacturers were also important if the astronomers were to understand the operation of the equipment and avoid possible practical difficulties. The *Bulletin* allowed these discussions between scientists and manufacturers. Hermann Vogel, Director of the Potsdam Astrophysical Observatory, wrote a letter in July 1890 about the grid which made it possible to locate the position of stars. He noticed that too much pressure between the photographic plates and the grid led to notable misreadings (*Bulletin* …, 1892: 366). The manufacturer, Paul Gautier, who was responsible for constructing the grids, provided an answer for Vogel. He explained that the frame took into account characteristics of the plates and avoided placing too much tension on the glass (*Bulletin* …, 1892: 367).

The second topic which one finds in the *Bulletin* relates to the division of the experiments. The astronomers described their difficulties, the problems which they encountered and solutions that they implemented. In 1895, the *Bulletin* published several remarks in connection with the grid, which contained a very fragile layer of silver. Layers became uneven at different places, which could create false stars on the photographic plates. The *Bulletin* (1895: 123) outlined the method adopted by the majority of the astronomers to solve this: the regular use of a brush to remove dust from the grid in order not to produce false stars. These exchanges made it possible to understand the limits of the rules fixed at the beginning of the project.

From the same point of view, the *Bulletin* revealed the differences in methods between countries. Thus, there was a difference of opinion between the French and Finnish astronomers concerning the scale of the sizes of the star images. The French used a single multiplying coefficient between the exposure time and the size of stars (*Bulletin* …, 1895: 107), while the Finns gradually varied this coefficient according to the size of stars (*Bulletin* …, 1895: 109). Each side presented their arguments by publishing long reports in the *Bulletin*. The French astronomers considered that the method used by the Finns was not very reliable (*Bulletin* …, 1895: 113).

The *Bulletin* allowed a greater circulation of the experiments and the methods used in connection with the Carte du Ciel project. It forced astronomers to detail their practices and to compare them with those of their colleagues. It also started an international discussion on the methods of observing and of using photography in astronomy.

The third important topic that one finds in the *Bulletin* is the complaints that the rules were too constraining. Certain astronomers clearly acknowledged that they did not follow the resolutions of the Conferences. For example, Robert Ellery, Director of the Melbourne Observatory, explained that he did not take photographs each evening, as requested (*Bulletin* …, 1895: 449), since the Melbourne sky was too variable to allow this.

The resolutions voted in the Conferences were sometimes called into question. Thus, Gill recognized in 1892 that it is perhaps not necessary to require fixed exposure times. Instead it was left to the observer, whose experience would enable him to be the best judge of the appropriate exposure time (according to the transparency of the atmosphere, the stability of the images and the sensitivity of the plates) (*Bulletin* …, 1895: 119). Thus, the know-how of the astronomers sometimes replaced the initial rules. In the long term, this desired uniformity threatened the success of the Carte du Ciel project: too many constraints and requirements could paralyze proceedings.

The Carte du Ciel organizers accepted that each observatory had its own measuring machine for the plates. Certain astronomers used machines allowing for faster but less precise measurements. The important thing for the organizers was that the various techniques were properly documented.

The *Bulletin du Comité International Permanent pour l'Exécution Photographique de la Carte du Ciel* was an effective means of adjusting practices and coordinating activities. In particular, through the *Bulletin* it was possible to correct the system when it was too rigid. The circulation of the memoirs and letters transformed the scientific practices in the participating observatories. Technical remarks, different scientific traditions adopted by the participating countries and concrete solutions all appeared in the *Bulletin*, which was used to negotiate and build collective rules of work.

5 CONCLUSION

The beginnings of the Carte du Ciel project were marked by an important transformation in the organization of scientific activity. The organizers of the project initially imposed a very strict system of rules to coordinate work of all the participating observatories. This step is characteristic of the regimes of knowledge which were set up in the West in the second half of the nineteenth century. The observatories were simply scientific factories. The industrial model was characterized by the division of labor and the standardization of instruments. With regard to the Carte du Ciel project, this scientific policy quickly became ineffective due to differences between observers and local observing conditions. So the organizers of the Carte du Ciel project modified the rules of the work. Two forums of dialog developed: the international conferences and the *Bulletin du Comité International Permanent pour l'Exécution Photographique de la Carte du Ciel*. Collectively, they made it possible to find a balance between universal standards and local demands and practices. The adjustment of the practices was initially a collective work of negotiation.

In conclusion, I want to propose an explanation for the radical transformation of the diffusion process of the rules and conventions within the framework of the Carte du Ciel project. Several studies in the history of science (e.g. Biagilo, 1993; Détienne, 1965; Vernant, 1968; and Shapin and Schaffer, 1986) underline the powerful bond which links a mode of political organization at a precise moment and conventions which govern the scientific community and its practices at that time.

In the case of the Carte du Ciel project, the astronomers were careful to underline the major role to be played by France. In 1887, Otto Struve, the Director of Pulkovo Observatory, recognized that the initiative of the project was entirely that of France (Baillaud, 1929: 644). For their part, the French authorities—as stated by Louis Liard (1886), Director of Higher Education in the Ministry of Education—demanded that France play a major part in this important scientific project. One can link this insistence on establishing the prominent role to be played by France with the emergence of a new political regime which was set up with the Third Republic. The French Parliament was at the center of the democratic system (Berstein and Milza, 1996: 395), and at the same time the laws on freedom of the press allowed the expression and the circulation of opinions and ideas (Terrou, 1972).

The Carte du Ciel project was marked by the French republican and liberal political regime, which emerged after 1870. For the political world, just as for the scientific world, research by consensus emerged by the installation of democratic rules and the possibility of free expression. Benjamin Baillaud, Director of the Toulouse Observatory from 1878 to 1907, recognized the existence of a powerful link between the organization of the Carte du Ciel project and the new political orientation that emerged after the destruction of the Second Republic by the Prussians in 1870. He ensured, in 1899, that the "… decentralization of scientific work and resources … [wished by the republican government, was done] for the benefit of Science and Homeland." (Baillaud, 1899: 1).

However, the originality of the Carte du Ciel project lies less in the convergence of the political and scientific forms of organization than in the will of the French scientific community to diffuse, on a world scale, the new principles of government, set up by the republican system. The Carte du Ciel project constitutes from this point of view, for France, a first experiment in the propagation of a model of research organization.

6 ACKNOWLEDGMENTS

I wish to thank Danielle Briot and Emmanuel Davoust for help in the translation of this paper, and Suzanne Débarbat for her invaluable advice.

7 NOTES

1. In this context, Osterbrock et al. (1988) refer to W.W. Campbell as "The Creative Scientist Who Became a Factory Manager" in a chapter of their book on the history of the Lick Observatory.

8 REFERENCES

Andoyer, H., 1891. Report for the year 1891. Municipal Archives of Toulouse, 2R 95.

Baillaud, B., 1891. Letter to Ernest Mouchez, dated 11 September. Archives of the Paris Observatory, Ms 1060 V.

Baillaud, B., 1899. *Discours Prononcé à la Séance Générale du Congrès des Sociétés Savantes le Samedi 8 Avril 1899.* Paris, Imprimerie Nationale.

Baillaud, B., 1935. *Pour l'Histoire de l'Astronomie Stellaire de Position*. Toulouse.

Baillaud, B., and Baillaud, J., 1906. Sur une erreur systematique à craindre dans l'emploi des échelles de grandeurs photographiques stellaires. *Mémoires de l'Académie des Sciences, Inscriptions et Belles-Lettres de Toulouse*, 7, 328-332.

Baillaud, J., 1929. L'entreprise de la Carte du Ciel. Son organisation, son état actuel, son avenir. *Revue Scientifique*, 21, 641-655.

Berstein, S., and Milza, P., 1996. *Histoire du XIXe Siècle*. Paris, Hatier.

Biagioli, M., 1993. Le prince et les savants. La civilité scientifique au 17e siècle. *Annales E.S.C.*, 1417-1453.

Bulletin du Comité International Permanent pour l'Exécution de la Carte du Ciel. Paris, Gauthier-Villars (1890).

Bulletin du Comité International Permanent pour l'Exécution Photographique de la Carte du Ciel. Volume I Paris, Gauthier-Villars (1892).

Bulletin du Comité International Permanent pour l'Exécution Photographique de la Carte du Ciel. Volume II Paris, Gauthier-Villars (1895).

Chinnici, I., 1999. La Carte du Ciel. Correspondance inédite conservée dans les archives de l'Observatoire, Paris, Observatoire de Paris.

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

Détienne, M., 1965. En Grèce archaïque: géométrie, politique et société. *Annales E.S.C.*, 425-441.

Gill, D., 1888. Letter to E. Mouchez, dated 1 March. APO, Ms 1060 V.

Jones, D., 2000. The scientific value of the Carte du Ciel. *Astronomy & Geophysics*, 41, 16-20.

Lankford, J., 1984. The impact of photography on astronomy. In Gingerich O. (ed.). *The General History of Astronomy, vol. IV, Part. A: Astrophysics and twentieth-century astronomy to 195*0. Cambridge, Cambridge University Press. Pp. 16-39.

Liard, L., 1886. Letter to C. Trépied, dated April. APO, Ms 1060 IV-A-2.

Mouchez, E., 1887. *La Photographie Astronomique à l'Observatoire de Paris et la Carte du Ciel*. Paris, Gauthier-Villars.

Mouchez, E., 1888. Letter to B. Baillaud, dated 8 June. MAT, 2R 107.

Osterbrock, D.E., Gustafson, J.R., and Unruh, W.J. S., 1988. *Eye on the Sky: Lick Observatory's First Century*. Berkeley, University of California Press.

Rayet, G., 1901. Letter to B. Baillaud, dated 25 February. MAT, 2R 142.

Shapin, S., and Schaffer, S., 1986. *Leviathan and the Air Pump: Hobbes, Boyle, and the Experimental Life*. Princeton, Princeton University Press.

Terrou, F., 1972. L'évolution du droit de la presse de 1881 à 1940. In Bellanger C., Godechot, J., Guiral, P., and Terrou, F. (eds.). *Histoire Générale de la Presse Française. T. III: 1871-1940*. Paris, Presses Universitaires de France. Pp. 7-57.

Tobin, W., 2002. *Léon Foucault. Le Miroir et le Pendule*. Les Ulis, EDP Sciences.

Trépied, C., 1892. *Commentaires des Décisions Prises par les Conférences Internationales qui se Réunirent à l'Observatoire de Paris en 1887, 1889 et 1891, pour l'Exécution Photographique de la Carte du Ciel*. Paris, Gauthier-Villars & fils.

Turner, H.H., 1912. *The Great Star Map. Being a General Account of the International Project Known as the Astrographic Chart.* London, Murray.

Vernant, J-P., 1968. Structure géométrique et notions politiques dans la cosmologie d'Anaximandre. *Eirene*, 7, 5-23.

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Journal of Astronomical History and Heritage, 12(2), 125-140 (2009).

EARLY INFRARED ASTRONOMY

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Abstract: I present a short history of infrared astronomy, from the first scientific approaches of the 'radiant heat' in the seventeenth century to the 1970's, the time when space infrared astronomy was developing very rapidly. The beginning of millimeter and submillimeter astronomy is also covered. As the progress of infrared astronomy was strongly dependent on detectors, some details are given on their development.

Keywords: infrared, detector, bolometer, photometry, Sun, Moon, planet, star, William Herschel, Macedonio Melloni, Hippolyte Fizeau, Léon Foucault, Claude Pouillet, Samuel P. Langley, Ernest F. Nichols, Charles V. Boys, Laurence Parsons (4th Earl of Rosse), William W. Coblenz, Edison Pettit, Seth B. Nicholson, Gerard P. Kuiper, Peter Fellgett, Madeleine Lunel, Harold Johnson, Vassili Ivanovitch Moroz

1 INTRODUCTION

Infrared astronomy had a slow and somewhat erratic early development, which is only partially covered in the literature. Sinton (1986) and Rieke (2009) are the only modern authors to give some elements of this history, but they start in 1869 while there were interesting earlier observations, and their coverage of developments in Europe is incomplete. Developments after 1970 are well documented thanks to these papers as well as those of Jennings (1986), Price (1988), Dolci (1997), Storey (2000), Low et al. (2007) and Léna (2007, 2008), which were useful in preparing this review. Interesting information can also be found in the books by Smith et al. (1968) and Allen (1975).

The present paper includes points not discussed extensively by Sinton (1986) and by Rieke (2009), and the period covered extends only to the early 1970's in order to avoid redundancies. I include early infrared observations of the Sun which are often neglected in the literature. Finally, I briefly describe early developments of millimeter and submillimeter astronomy.

2 THE INFRARED BEFORE HERSCHEL

Officially, infrared radiation was discovered in 1800 by William Herschel (1738–1822). However, some interesting work was done earlier. In 1833, François Arago (1786–1853) wrote an obituary for Joseph Fourier (1768–1830), which contains historical information on what Fourier called the 'calorique rayonnant' (radiant heat):

> The famous academicians del Cimento [in Florence] found, almost two centuries ago, that this 'calorique' can be reflected like light; like light, it can be concentrated at the focus of a concave mirror. Replacing hot bodies by snow balls, they even proved that one can form frigorific focuses by reflection.
>
> A few years later, Mariotte, member of the French Academy of Sciences, discovered that there are different kinds of 'calorique rayonnant'; that which accompanies the solar rays [the near infrared] traverses all transparent media as easily as light; that which emanates from a heated, but still dark material, as well as that which is mixed with light rays from a slightly incandescent body [the far- and mid-infrared], are stopped almost completely by the most transparent glass plate. (Arago 1836: CIV; my translation).

Arago went a little too far, as we will see. Here is what we find in a description of experiments made in 1667 by the Academia del Cimento (Anonymous, 1684: 103):

> The Ninth Experiment of Reflected Cold. We were willing to try, if a Concave Glass [actually, a concave mirror] set before a mass of 500 l. of Ice made any sensible repercussion of Cold upon a very nice Thermometer of 400 deg. placed in its Focus. The truth is, it immediately began to subside, but by reason of the nearness of the Ice, 'twas doubtful, whether the direct, or reflected rays of Cold were more Efficacious: upon this account, we thought of covering the Glass, and (whatever may be the cause) the Spirit of Wine did indeed presently begin to rise; for all this we dare not be positive; but there might be some other cause thereof, beside the want of reflection from the Glass; since we were deficient in making all the Trials necessary to clear the Experiment.

Figure 1 is a nineteenth century representation of this experiment, which looks rather faithful. Presumably, the experimenters were so surprised by their result that they had doubts about it.

Figure 1: The experiment of reflected cold presented to Duke Ferdinand II by the Academia del Cimento, fresco by Gaspero Martellini (1785–1857) at the Tribuna di Galileo, Florence (Italy), dated 1841. The mass of ice is placed in a vessel and its radiation is concentrated by a concave mirror on a long vertical thermometer. An assistant is covering the mirror with a piece of canvas or cardboard (Wikipedia Commons).

In another account, written in French, we find the following note by Petrus van Musschenbroek (1692–1761), probably relating to an experiment made by himself:

> The heat from a charcoal fire placed out of an evacuated vessel, but nearby, passes easily through this vessel, and raises the thermometer placed at the center of this vessel. (Anonymous, 1755: 27; my translation).

Musschenbroek also cites a French experiment in which a piece of butter in a vacuum is melted when exposed to an external source of heat. As to Edme Mariotte (1620–1684), all we could find from him is the following account:

> M. Mariotte made some remarks and experiments on heat, in particular that the heat from a fire reflected by a concave mirror is noticeable at its focus: but if one inserts a piece of glass between the mirror and its focus, the heat becomes undetectable. (Anonymous, 1733a: 344; my translation).

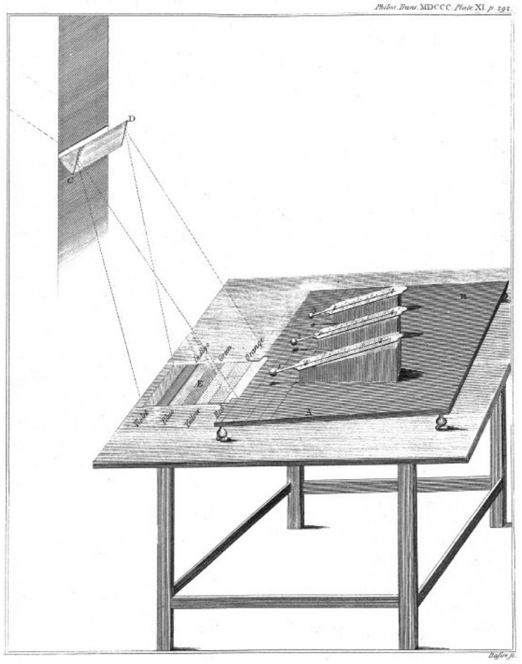

Figure 2: Herschel's experiment to study radiant heat in the solar spectrum. Three thermometers on a movable plate are placed in parallel at different places in the solar spectrum.

In 1682 Mariotte wrote a remarkable *Essay on cold and heat* (Mariotte, 1717; my English translation) in which he showed that cold does not exist by itself, but is only a lack of heat; for him, heat corresponded to an internal agitation in the heated bodies (a very modern idea, which however was not universally accepted as we will see later). A contemporary account summarizes his work as follows:

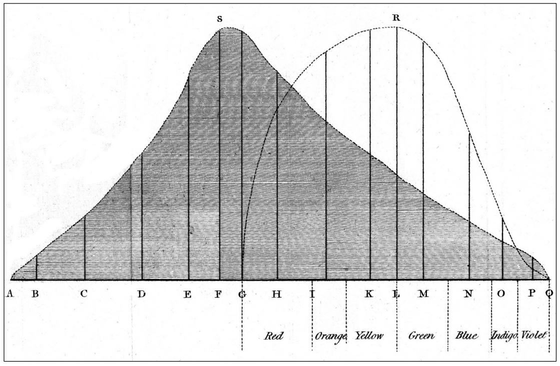

Figure 3: Herschel's attempt to display of the spectral energy distribution of light (R) and 'radiant heat' (S) in the spectrum of the Sun. The distribution of light mainly reflects the sensitivity of the eye. That of radiant heat, which would be expected to peak in the yellow, is in fact strongly displaced towards the infrared due to the variation of dispersion of the prism with wavelength: the thermometer receives a broader range at longer wavelengths.

> He did not find any positive cause for cold. A perfect cold would be a complete lack of motion in the bulk of bodies; but we think that this complete lack cannot be found in nature. (Anonymous, 1733b: 268; my translation).

It seems that Arago extrapolated what these authors have said in the light of the knowledge of his time, especially as far as Mariotte was concerned. They only produced interesting but fragmentary observations and theories, which were not placed in a coherent context. William Herschel was the first to achieve this goal.

3 WILLIAM HERSCHEL AND THE NATURE OF RADIANT HEAT

In 1800, while projecting onto a screen the spectrum of the Sun produced by a prism, Herschel had the idea of placing blackened thermometers at different places in this spectrum. He observed a strong heating in the red, which weakened when going to the violet side of the spectrum, and concluded:

> I must now remark, that my foregoing experiments ascertain beyond a doubt, that the radiant heat, as well as light, whether they be the same or different agents, is not only refrangible, but is also subject to the laws of dispersion arising from its different refrangibility ... May not this lead us to surmise, that radiant heat consists of particles of light of a certain range of momenta,[1] and which range may extend a little farther, on each side of refrangibility, than that of light? (Herschel, 1800a: 271).

Thus Herschel suspected that radiant heat and light were identical, or similar in nature. He was obviously troubled by the fact that the maximum of heat in the spectrum did not coincide with the maximum of light. Placing now his thermometers beyond the red side of the spectrum, he still saw heating and concluded that

> In this case, radiant heat will at least partly, if not chiefly, consist, if I may be permitted the expression, of invisible light; that is to say, of rays coming from the sun, that have such a momentum as to be unfit for vision. (Herschel, 1800a: 272).

His next research paper contains the famous plate describing his experiment, reproduced here as Figure 2. Herschel (1800b: 291) was still hesitant about the nature of radiant heat:

> To conclude, if we call light, those rays which illuminate objects, and radiant heat, those which heat bodies, it may be enquired, whether light be essentially different from radiant heat? In answer to which I would suggest, that we are not allowed, by the rules of philosophizing, to admit two different causes to explain certain effects, if they may be accounted by one.

A third paper by Herschel (Herschel, 1800c) is titled "Experiments on the solar, and on the terrestrial Rays that occasion heat; with a comparative View of the Laws to which Light and heat, or rather the Rays which occasion them, are subject, in order to determine whether they are the same, or different." It shows that the radiant heat from the Sun, from a candle, from a piece of iron red hot or sufficiently cold to stay dark (the 'invisible culinary heat'), etc., are all reflected by a mirror. In his fourth and fifth papers, Herschel (1800d; 1801) studies quantitatively the transmission, reflection and diffusion by a variety of substances of total sunlight, of sunlight dispersed by a prism, and of the different sorts of radiant heat described in the previous paper. This is a beautiful work, but there are no new conclusions about the nature of radiant heat. Paper 4 contains a plate comparing in a semi-quantitative way the spectral distribution of radiant heat and of light in the solar spectrum (see Figure 3). It is one of the very first attempts to display data using a graph instead of a table.

This figure must have perplexed Herschel and his contemporaries. Was the difference due to different refractive indices of the prism for light and radiant heat? Looking at this graph, it is hard to believe that radiant heat and light are one and the same thing, and that the difference is due to the sensitivity of the eye. No one, with the exception of Thomas Young (1773–1829), understood that radiant heat is the prolongation of the optical radiation. For example, Jean-Claude Delamétherie (1743–1817), relating Herschel's discovery in his *Journal de Physique*, flatly pretends that Herschel concluded that "… light differs from heat." (Delamétherie, 1801: 8; my translation). Joseph Fourier (1768–1830) speaks of "… rays of invisible heat mixed with the light of the Sun …" (Fourier, 1823: LXXV; my translation). To complicate the matter, Johannes Wilhelm Ritter (1776–1810) in Germany and Francis Wollaston (1731–1815) in England independently discovered in 1801 that the Sun also emits 'invisible rays', also called 'chemical rays', that darken silver chloride. Scientists were very puzzled.

In 1835, André-Marie Ampère (1775–1836), with considerable insight, proposed a new concept (cited by Melloni, 1835: 503; my translation):

> It consists in considering radiant heat as a series of undulations excited in ether by the vibrations of the hot bodies. These undulations would be longer than the waves which make light if the calorific source is dark.[2] But in the case of those sources that are at the same time calorific and luminous, there would always be a set of waves which possess simultaneously the two properties of heating and illuminating. Thus, in this view, no essential difference would exist between radiant heat and light.

However, in spite of his numerous experiments on reflection, refraction and polarisation of radiant heat, the greatest specialist of the time, Macedonio Melloni (1798–1854), the 'Newton of heat' (Langley, 1880: 501), still believed two years later that light and heat are of a different nature, although they have much in common (Melloni, 1837). For him, as for many of his contemporaries, radiant heat was comparable to the 'calorique', that kind of fluid which propagates slowly inside bodies, the very heat studied by Fourier. However, in 1842, Melloni changed his mind and rallied to Ampère's support (Melloni 1842: 454; my translation):

> Light, heat and chemical reactions [i.e. in fact the ultraviolet which produces these reactions] are three manifestations of the undulations of ether which make solar radiations. The dark undulations responsible for chemical or calorific actions are perfectly similar to luminous undulations; they only differ from them by wavelength.

This was confirmed five years later, for the near infra-red, by the superb experiments of interference and diffraction of Hippolyte Fizeau (1819–1896) and Léon Foucault (1819–1868) (Fizeau and Foucault, 1847). Room is lacking here to describe these rather complex experiments, and we will only show the spectral distribution of solar radiation that they obtained in the same way as Herschel, but now with a good wave-length calibration (Figure 4). An interesting feature of their device is that they used, apparently for the first time, a permutation method in order to eliminate the effect of the temperature variations in the enclosure containing the detector, in this case a thermometer: the signal was periodically chopped by an obturator, and they read the temperature difference between the 'on' and 'off' positions of this chopper.

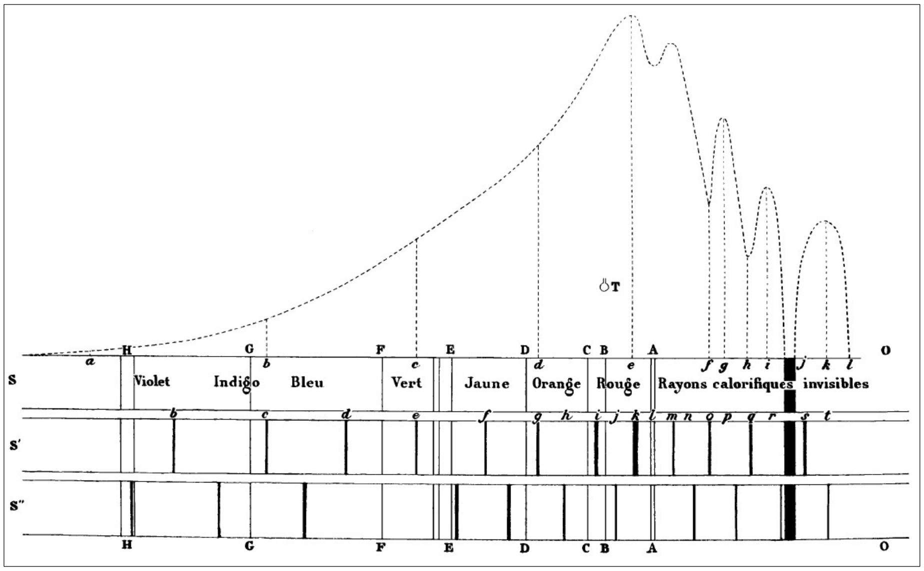

Figure 4: The spectrum of the Sun from the violet to the near infrared obtained by Fizeau and Foucault in 1847 with a glass prism. As for Figure 3, the spectrum, which would be expected to peak in the yellow, is in fact strongly displaced towards the infrared due to the variation of dispersion of the prism with wavelength. Fizeau and Foucault observed the infrared absorption bands due to the Earth's atmosphere, but they were not recognized as such by them. The vertical lines in S are the main Fraunhofer lines. The broad infrared bands were already suspected in 1843 by John William Draper (1811–1882) and also by John Herschel, but with no wavelength measurements.[3] In S′ and S″, the bold vertical lines mark the positions of interference fringes obtained using chromatic polarization, which are equidistant in wavelength. For the first time, they allowed the establishment of a wavelength scale in the near infrared.

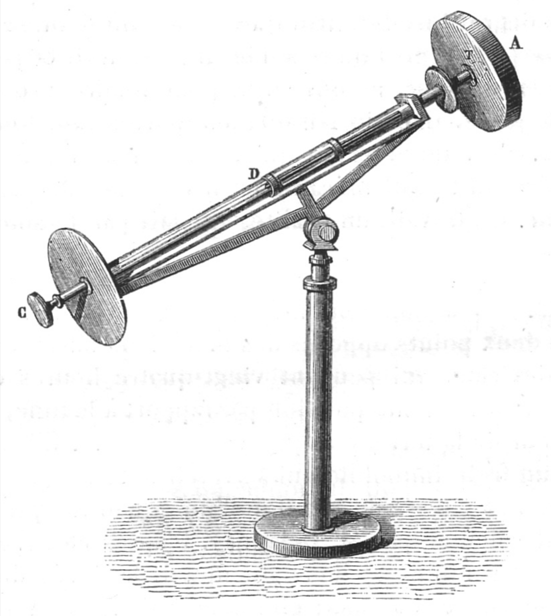

Figure 5: Pouillet's pyrrheliometer. A blackened surface A is directed normally to the direction of the Sun, using its shadow which has to be centred on the disk on the rear. It covers a metal box full of water, silvered on the outside to minimize radiative heat exchange. This box can be rotated upon itself in order to equalize the water temperature. This temperature is measured with the thermometer TD. The measurement consists in noting the temperature increase due to solar radiation during a given time (5 minutes). The temperature change in 5 minutes before and after the measurement is also noted in order to correct for it.

However, it seems that these experiments have been largely ignored. They are not mentioned in the lectures in physics given in the 1860s at the École Polytechnique by Jules-Célestin Jamin (1818–1886), who is still speaking of the "… *probable* identity of heat and light". (Jamin, 1858-1866; my translation and italics).

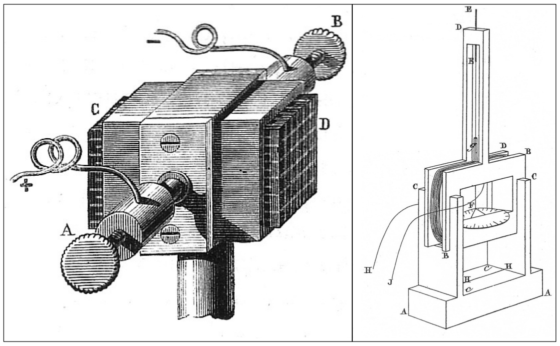

Figure 6: Left: the 'thermomultiplicateur' of Nobili and Melloni (ca. 1835); right: a 'multiplicateur' built by Christian Œrsted (1777–1831) in 1822 or 1823. The thermomultiplier is made of 36 antimony-bismuth thermocouples in series, separated by thin insulating foils. The front surface is covered with carbon black, and the device measures the temperature difference between the front and the back. It is connected to a 'multiplier', a galvanometer consisting of a magnetized needle inside a number of turns of conducting wires. The name of the multiplier comes from the fact that the first galvanometers had only a single loop, and that using several turns of wires multiplies the effect accordingly. Similarly, the infrared detector used several thermocouples instead of one, hence its name.

4 THE FIRST DETERMINATION OF THE SOLAR CONSTANT

Attempts to measure the total power received from the Sun per unit surface perpendicular to its direction at a distance of 1 A.U.—the solar constant—were made by Horace Bénédict de Saussure (1740–1799), then by William Herschel. Both were unsuccessful. The first successful measurement was that of the French physicist Claude Pouillet (1790–1868) (Pouillet, 1838). For this, he built a simple instrument that he named a 'pyrrhéliomètre' (see Figure 5).

Pouillet assumed that the black surface of his instrument entirely absorbed the incoming radiation. He also assumed that he could correct his result for absorption in the Earth's atmosphere using a method due to Pierre Bouguer (1698–1758): observing the Sun under stable conditions at different zenith distances, calculating the thickness e of the atmosphere for each direction, and supposing that the absorption is proportional to a^e, a being a transmission coefficient; an extrapolation to zero thickness allows one to calculate the incoming radiation at the top of the atmosphere. However, the carbon black on the surface did not fully absorb the radiation, and Bouguer's method was only valid if the absorption was unsaturated, which was not true for the main atmospheric absorption bands in the near-infrared. Both assumptions led to an underestimate of the solar constant, although by a relatively small amount. Pouillet obtained 1,230 watts per square meter, while the modern value measured by satellites is 1,367 watts per square meter.[4] This is a remarkably good result given the difficulties of this apparently simple experiment.

Pouillet's pioneering work was probably forgotten because the solar constant was measured again at the beginning of the twentieth century in the USA by Samuel P. Langley (1834–1906), who made a mistake in his reduction, then by Charles G. Abbot (1872–1973), whose result is not much better than the value obtained by Pouillet.

If Saussure did not succeed in measuring the solar constant, he was the first to observe in detail around 1780 the greenhouse effect using his 'héliothermomètre', a wooden box with a black bottom and a lid made of four successive glass layers. He even suggested that, like glass, the Earth's atmosphere could retain heat. This was confirmed and elaborated on by Fourier (1824). However, the main causes of atmospheric absorption in the infrared, hence for the glasshouse effect—water vapor and carbon dioxide—were only recognized spectroscopically in 1861 by John Tyndall (1820–1893) (Tyndall 1861).

5 THE FIRST INFRARED DETECTORS AND THEIR ASTRONOMICAL APPLICATIONS

The blackened thermometer is not a very sensitive infrared detector, and it is not surprising that no astronomical observation other than those of the solar spectrum and solar constant could be performed successfully with it. For example, Arago tried in vain to detect limb darkening of the solar disk in 'calorific rays' by letting the solar image produced by the lens of the Observatory's mèridienne (a gnomon) cross a thermometer. Fortunately, better detectors could be built using the thermoelectric effect discovered in 1821 by the physic-cist Thomas Johann Seebeck (1770–1831).

In Italy, Leopoldo Nobili (1784–1835) soon came up with the idea of placing in series numerous thermocouples, and Melloni connected this device (Figure 6) to a galvanometer, building what he called a 'thermomultiplicateur'. The device was sensitive enough to detect the radiation of the hand at a distance of one meter. Melloni made many experiments with it,[5] including a new spectral decomposition of solar radiation with a prism made of rock salt (natural sodium chloride), which, unlike glass, absorbed little in the infrared.

Father Angelo Secchi (1818–1878) from the Vatican Observatory succeeded where Arago failed by using the thermomultiplicateur to measure limb darkening of the Sun in the infrared (Secchi, 1875-1877). Various versions of this detector were in use until the beginning of the twentieth century.

Photographic techniques were also applied to the infrared, by staining photographic plates with various phosphorescent dyes. But the sensitivity remained low although wavelengths as long as 9,200 Å were commonly reached before 1912.[6] At this date, only the spectrum of the Sun could be photographed in the infrared. The first infrared photographs of stellar spectra up to 9,000 Å were obtained in the 1930s in the USA by Paul Willard Merrill (1887–1961).

In the 1880s, four new detectors appeared. The most famous of them is the 'bolometer' invented in 1880 by Langley (1900a). One of the several versions of this instrument, which uses the variation with temperature of an electrical resistance, is displayed in Figure 7. It was considerably more sensitive than the previous thermocouples, especially when connected to of the excellent galvanometers made by William Thomson (Lord Kelvin, 1824–1907).

In 1875, William Crookes (1832–1919) invented the 'radiometer', a well-known device in which the action of light on blackened surfaces moves a little mill in a partial vacuum. Initially, Crookes believed that radiation pressure was doing the job, but it was soon demonstrated by George Johnstone Stoney (1826–1911), an Irish scientist, that the pressure on the black surface was due to momentum transfer from the molecules of the gas heated by this surface. James Clerk Maxwell (1831–1879) and Osborne Reynolds (1842–1912) produced the complete theory of this apparatus.

Ernest Fox Nichols (1869–1924) built on this principle a very sensitive radiometer (Figure 8) that he used for laboratory and astronomical measurements (Nichols et al., 1901). This instrument had a very stable response but could not be moved, thus the radiation of the observed astronomical object had to be sent to it via a siderostat.

The third new detector was invented around 1878 by Thomas Edison (1847–1931): the 'tasimeter' (see Eddy, 1972). This device, which derives from his carbon telephone transmitter, consisted of a strip of some material sensitive to heat whose expansion changed the pressure on a carbon button. The resistance of the carbon was modified accordingly and was measured by a Wheatstone bridge and a galvanometer. The tasimeter was very sensitive but also was very unreliable (see for example Raynard, 1878), and it soon faded into obscurity.

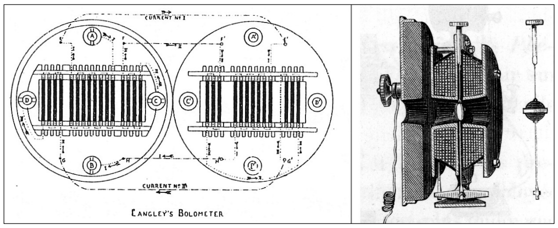

Figure 7: Left: a version of Langley's bolometer (after Rosse, 1895: 10); right: a Thomson galvanometer. The bolometer is composed of two superimposed gratings of very thin (4 µm) blackened metal, here represented deployed; each strip is 0.5 mm wide and the two planes, here represented side by side for clarity, are separated by 1 mm. For each grating, the strips are connected in series. The central gratings of 6.5 x 6.5 mm, formed of seven strips each, are inserted electrically in the two sides of a Wheatstone bridge, for a differential measurement of their resistance. The radiation is sent on the upper grating, with a chopping device. The lateral gratings of three strips each are parts of another circuit in order to detect accidental disturbances. The whole detector is placed in an enclosure where water circulates for thermal stability. It was generally connected to a Thomson galvanometer, which consists of a small magnet glued to a mirror, inserted in a coil; a pencil beam of light falls on the mirror, the deflection is read on a screen.

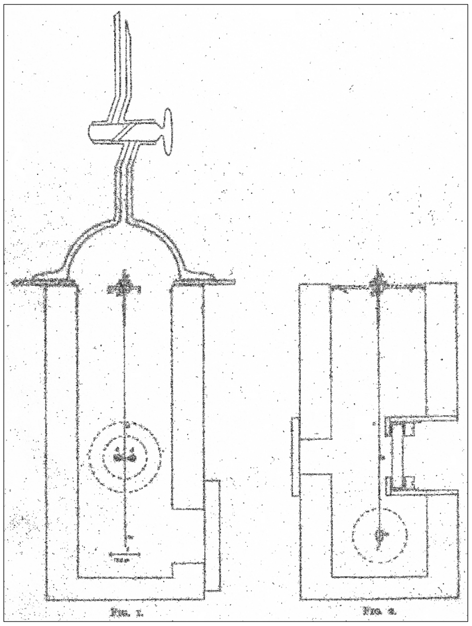

Figure 8: Nichols' radiometer (1898). Two 2-mm diameter mica disks blackened on one face are supported by a light cross-arm on either side of a thin glass rod, supported by a very thin torsion fiber of quartz in a partial vacuum. For astronomical observation of an object, both disks are submitted to the radiation of the sky through a fluorite window at the focus of a concave mirror illuminated by a siderostat, and the image of the object is focused on one of these disks. The rotation of the system is measured by reflection on a small flat mirror attached to the bottom of the rod.

Finally, Charles V. Boys (1855–1944) in England invented the 'radiomicrometer' (Boys, 1890), a combination thermocouple-galvanometer inserted between the poles of a permanent magnet (Figure 9). This instrument was used for high-resolution infrared spectroscopy by Exum Percival Lewis (1863–1925), who encountered severe difficulties in operating it (Lewis, 1895).

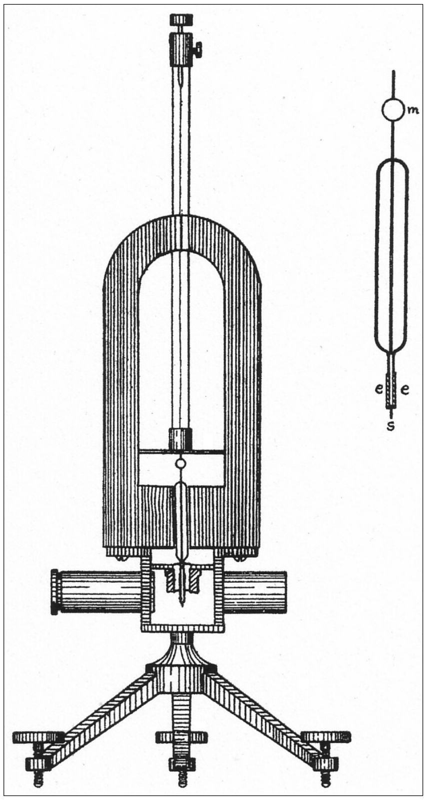

Figure 9: The radiomicrometer of Boys (after Lewis 1895: 9). Two blackened thermocouples *ee* are connected in opposition to an elongated rectangular electric circuit consisting of one or several loops. This ensemble is suspended from a torsion wire and placed between the poles of a permanent magnet. The heating of one of the thermocouples by the incoming thermal radiation produces a current in the circuit which is then deflected by the magnetic field. The small mirror *m* allows the observer to measure this deflection by reflection of a light beam. This set-up derives from the mobile-coil galvanometer invented in the early 1880's by Arsène d'Arsonval (1851–1940) and Marcel Desprez (1843–1918).

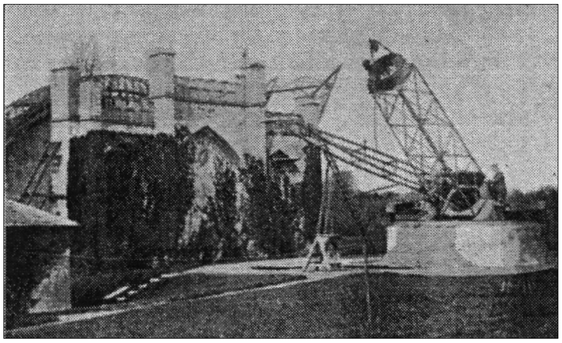

Figure 10: The 3-ft telescope of Lord Rosse at Birr Castle (Ireland), with the focal device illustrated in Figures 11 and 12.

Various detectors were used in attempts to detect the thermal radiation of the solar corona. The nature of the corona which was seen to surround the disk of the Sun during total eclipses was then a complete mystery, and it was hoped that detection of its thermal emission would help astronomers understand it. It is no surprise that the first attempts were made during total eclipses. Luigi Magrini (1802–1868), a pupil of Nobili, claimed to have detected the heat of the corona with a 'Rumford thermoscope' during the eclipse of 9 July 1842, but since he could not detect the heat of the full Moon with the same apparatus doubts were expressed about this observation (e.g. Hale, 1895: 327). During the eclipse of 29 July 1878, Langley made an unsuccessful attempt with an inadequate thermopile, while the thermal radiation from the corona was saturating Edison's tasimeter, at least if we can believe his account (see Fernie, 2000)! George Ellery Hale (1868 –1938) was optimistic about the possibility of a detection even outside eclipses, using a bolometer and a sensitive galvanometer (Hale, 1895). Langley and Abbot, and Henri Deslandres (1853–1948), were first to definitely detect the corona, during the total eclipse of 28 May 1900. Langley and Abbot used a bolometer and no filter (Langley, 1900b), while Deslandres employed a Melloni thermopile and a glass prism spectroscope which eliminated radiation outside the range 1.0-1.8 μm. Deslandres (1900) also succeeded in detecting infrared radiation from the corona outside of eclipse using another thermopile built by Heinrich Rubens (1865–1922). None of these researchers was able to draw a conclusion about the nature of the corona, which was generally believed at this time to be some electric phenomenon similar to a glow discharge. Since this discharge radiated very little heat, the faintness of the infrared radiation was considered an argument against it being thermal emission. However, in 1908 Abbot observed near-infrared emission from the corona during another eclipse and concluded that it was probably not an electrical phenomenon (Abbot 1908). He proposed that this emission was due to scattering of the solar emission by dust particles, an explanation confirmed later by polarization studies of the corona; the thermal emission of these particles starts to dominate in the mid-infrared.[7]

As can be expected, the next target for infrared astronomy was the Moon. Attempts to observe radiant heat from the Moon date from the seventeenth century.[8] The goal of these observations was obviously to see if the Moon is able to radiate some heat to the Earth at night. There are claims of a detection of lunar thermal radiation in 1685 by Geminiano Montanari (1633–1687), a member of the *Academia del Cimento* in Florence where the thermometer was developed, but this is probably spurious since subsequent attempts were unsuccessful. In 1845 or 1846, Melloni placed his thermomultiplicateur at the focus of a 1-m diameter Fresnel lens and made the first definite detection (Melloni, 1846). He used a Fresnel lens instead of an ordinary lens, a good idea because the glass thickness is considerably less and its absorption is limited; but the glass wavelength cut-off makes it impossible in this way to detect anything other than reflected solar radiation.

Confirmations were obtained in 1856 in Teneriffe by Charles Piazzi Smyth (1819–1900), the godson of Giuseppe Piazzi (1746–1826) who discovered the first asteroid. At the focus of a mirror, Charles Piazzi used a thermomultiplier "… with the ordinary cone of polished metal …" to concentrate the radiation. In 1869, Hippolyte Marié-Davy (1820–1893) in Paris also detected lunar heat with Edmond Becquerel's 'pile thermo-électrique', a bismuth-antimony/bismuth-cadmium thermocouple; he used permutation by alternatively covering and opening the objective of his 9-inch refractor (Marié-Davy, 1869). Another detection was made at the same time in France (Baille, 1869).

The most extensive set of infrared lunar observations is due to Laurence Parsons, the 4th Earl of Rosse (1840–1908), and his assistants. Laurence was the son of William Parsons, 3d Earl of Rosse (1800–1867), who built the famous reflecting telescope nicknamed 'The Leviathan', but also the more manageable 3-foot diameter reflector used by his son for the lunar observations (Figure 10).

For his first observations of 1868-1873, Rosse used a thermopile of four elements directed alternately towards the Moon and the nearby sky, but he soon replaced it by the differential device displayed in Figures 11 and 12. The whole disk of the Moon was imaged on one of the thermopiles, directly or through a sheet of glass which was known to absorb infrared radiation. In this way, Rosse could obtained by subtraction the infrared flux from the Moon. The electric signal was detected with a Thomson galvanometer (see Figure 7). Rosse (1973) observed the Moon at different phases, reducing the observed flux to outside the atmosphere using Bouguer's method. He found this flux to follow the optical flux (the 'phase-curve') rather well, and reached the following conclusions about the radiation:

> As the phase-curve descended on each side almost to zero on approaching New Moon, it was clear that little or none of the heat we were measuring came from the interior of the Moon. It was heat derived directly from the Sun ...
>
> From the fact that 8 to 17 per cent. of the heat (being greatest towards Full Moon) was transmitted by the glass, while some 90 per cent. of the sun's rays passed through the same sheet of glass, it was, we think, clearly established that the heat, which we had already concluded, as stated above, to be directly derived from the Sun was not reflected sun-heat, but heat absorbed and afterwards emitted by the lunar surface.

Rosse compared his lunar deflections with those from blackened cans containing water at different temperatures. This was the only wise thing to do given the knowledge at this time: Josef Stefan (1835–1893) published his fourth-power of the absolute-temperature law only in 1879, and little was known about atmospheric extinction. After some attempt to correct for this extinction, Rosse obtained a temperature of the full Moon in reasonable agreement (by chance!) with the present value.

Rosse, or rather the German astronomer Otto Boeddicker (1853–1937) whom he put in charge of his observatory, also observed two total eclipses in 1884 and 1888, and found that there was, as expected, some delay in the heat radiation with respect to the light in the eclipses (Anonymous, 1892a; Rosse, 1895). In both cases the flux took 1h 40m after the last contact to reach the original level. These were the last observations, and although Rosse (1905) later proposed a network of stations to observe lunar eclipses this was never realized.

One of the weak points in these observations was that they only measured the global flux of the Moon. The first to explore several points of the lunar disk was the American astronomer Frank W. Very (1852–1927) (Anonymous, 1892b), who in 1889 used Langley's bolometer. Langley himself also made many observations of the Moon.

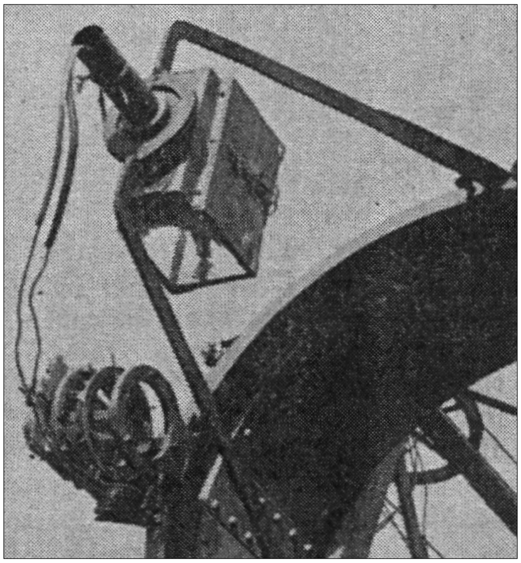

Figure 11: The focal equipment at the focus of the 3-ft telescope shown in Figure 10.

Observing the radiant heat from the stars and planets turned out to be considerably more difficult. Claimed detections in 1869 of the heat from bright stars by Sir William Huggins (1824–1910) (Huggins, 1878) and Edward James Stone (1833–1897) (Stone, 1870), who used a differential technique similar to Rosse's, were later shown to be spurious. Nor was Boys able to detect infrared radiation from stars when he carried out observations with his radiomicrometer[9] in 1888-1890. The first detections were secured in 1898 by Nichols and two collaborators who used a radiometer that was twelve times more sensitive (Nichols et al., 1901): Arcturus, Vega, Capella, Altair and a number of other stars were detected, although somewhat marginally. Nichols also obtained for the first time a detection for Jupiter and Saturn; in this case, it is obvious that he could only observe solar radiation scattered by the atmospheres of these planets, since they were too cold for their own radiation to be detected easily from the ground, especially through the fluorite window used by Nichols, which cuts the radiation off at 9 μm.

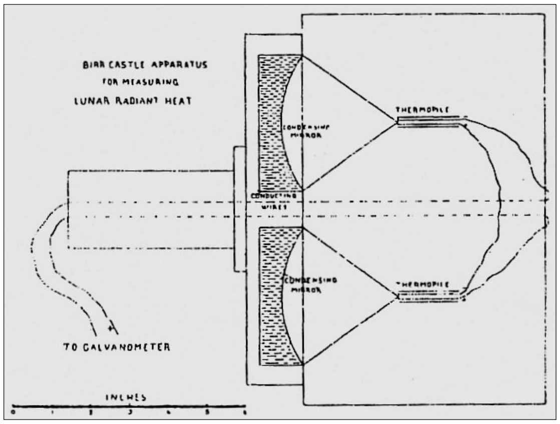

Figure 12: Principle of the infrared detection system at the focus of the 3-ft telescope (see Figures 10 and 11). Two detectors of four thermocouples each, mounted in opposition, are placed in a box at the foci of two small concave mirrors for a differential temperature mea-surement.

6 TOWARDS QUANTITATIVE MEASUREMENTS

All the measurements discussed in the previous section were qualitative: the signals were generally quite weak, no photometric system existed in the infrared, and the observers only compared the galvanometer deflections with those given by a candle at some specified distance. For example, in reporting on new observations by Nichols, Hale (1899) writes:

> In view of the smallness of the deflections, and the uncertainty which arises from rapid fluctuations in the atmosphere, Professor Nichols does not greatly rely upon the quantitative value of the results.

Atmospheric absorption was very important, even for the candle, and almost impossible to correct for, in spite of the investigations made with a rock-salt prism by Langley and Very (1889), who unfortunately used an incorrect wavelength scale. Anyway, the spectral range of the observations was either poorly-defined or not defined, with the notable exception of Deslandres' observations of the solar corona. All this made any reasonable astrophysical interpretation of the measurements impossible, a fact honestly acknowledged by the observers themselves. The 'ball' was now in the camp of the physicists, who were actively exploring the mid- and far-IR and were trying to bridge the gap between the optical-infrared range and the radio waves discovered by Heinrich Rudolf Hertz (1857–1894) in 1889.

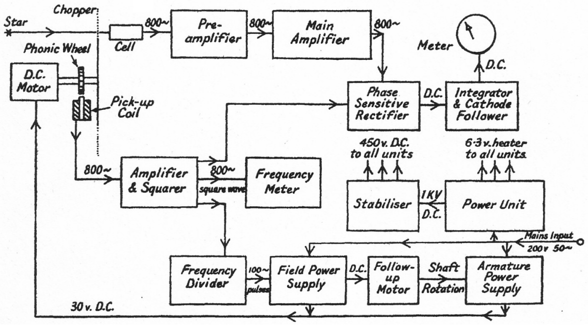

Figure 13: The electronics of Fellgett's infrared photometer. The synchronous detection (here at 800 Hz) is typical for all ground-based infrared detectors after WWII.

The first thing to do was to measure wavelengths. Most spectroscopic observations being done with glass or rock salt prisms, so it was necessary to calibrate their dispersion, either using a grating as Langley or Friedrich Paschen (1865–1947) did, or by modulating the spectrum by an interference pattern (Rubens), the method invented by Fizeau and Foucault but now attributed to Henri Becquerel (1852–1908)! In 1896, the wavelengths could be calibrated up to 9.4 μm, a range soon to be extended to much longer wavelengths.[10] Langley (1900a: 183) obtained a spectrum of the Sun up to 5.5 μm, discovering many spectral lines and obtaining simultaneously the position of the main absorption bands of water vapor. Other work on atmospheric absorption was done in 1898 by Rubens and his assistant Emil Aschkinass (1873–1909) who extended the measurements of absorption by H_2O and CO_2 to 24.4 μm (Rubens and Aschkinass, 1898). They concluded:

> The observations now communicated show that the Earth's atmosphere must be wholly opaque for the rays of wave-length 12^{μ} to 20^{μ} as well as for those of wave-length $24^{\mu}.4$. In fact Langley's observations on the spectrum of the Sun and Moon only extend to ... an extreme wave-length of from 10^{μ} to 11^{μ}.

All this was the basis of the quantitative theory of the 'greenhouse effect' of the terrestrial atmosphere, developed by Svante Arrhenius (1859–1927) after 1896.

In 1900, Max Planck (1858–1947) announced his theory of blackbody radiation. By a superb series of experiments, Rubens and Ferdinand Kurlbaum (1857–1927) in Berlin verified Planck's formula for blackbodies in a large range of temperatures and wavelengths (Rubens and Kurlbaum, 1901). It then became possible to interpret observations in the infrared in terms of temperature of the emissive body; all previous attempts were completely unreliable.

Now infrared astronomical observations could become quantitative. Most of them were done in the USA. In 1914, at the Lick Observatory, William W. Coblentz (1873–1962) made the first attempt to measure stellar radiation at all wavelengths accessible from the Earth (Coblentz, 1914). He then extended his measurements at a higher altitude site, the Lowell Observatory in Flagstaff, Arizona (Coblentz, 1922). With a very sensitive, tiny thermocouple in a vacuum, he detected twenty-seven stars, the radiation being blocked above various wavelengths by combining red glass, quartz and a water cell. Coblentz believed that he had also detected radiation from some of these stars between 4 and 10 μm, but this was probably spurious. He also observed Venus and Mars. From his measurements, he was able to determine the effective temperatures of stars:[11]

> In this manner the distribution of energy in the spectra of sixteen stars was determined, and thus was obtained for the first time an insight into the intensities of radiation in the complete spectrum of a star ... It was found that in the stars of type B and A the maximum intensity of radiation lies in the ultra-violet (0.3 μ to 0.4 μ) while in the cooler stars of types K and M the maximum emission lies at 0.7 μ to 0.9 μ in the infrared. From this it appears that the black-body temperature (i.e., the temperature which a black body would have to attain in order to emit a similar distribution of relative spectral energy) varies from 3000°C. for red M stars to 9000° or 10,000°C. for blue B stars. (Coblentz 1922: 21).

For many years, observations of stars in the infrared stopped at 4 μm. Independently of Coblentz, in the 1920s Abbot (1929) obtained at the coudé focus of the Mount Wilson 2.5 m telescope the spectral energy distribution of eighteen stars and of two planets (Mars and Jupiter) from the visible to 2.2 μm. He used a flint prism as a disperser and a radiometer in a low-pressure hydrogen enclosure, whose sensitive elements were blackened flies' wings, but difficulties with this equipment prevented him from obtaining accurate results. This was first achieved by Edison Pettit (1889–1962) and Seth B. Nicholson (1891–1963), who observed with their excellent vacuum thermocouples (Pettit and Nicholson, 1922) 124 stars from 1922 to 1928, also at the Mount Wilson Hooker telescope, but this time at its Newtonian focus (Pettit and Nicholson, 1928). They determined the effective temperature and the bolometric absolute magnitude for a number of these stars, and separated dwarfs from giants. Other systematic near-infrared observations of a larger sample of 347 stars, obtained at the Loomis telescope of the Yale University Observatory, were published in 1934 by

John Scoville Hall (1908–1991). He used, probably for the first time in astronomy, a caesium oxide photoelectric cell, cooled to −40°C to reduce the dark current.

Another important result was obtained in 1924 by Pettit and Nicholson: this was the detection of thermal radiation from the dark hemisphere of Venus in the 8-14 μm atmospheric window (Pettit and Nicholson, 1924). Their observations were carefully calibrated against stars they had measured and set as standards. The temperature of Venus was correctly estimated to be about 0°C. This is actually the temperature of the top of the thick clouds which surround the planet. Coblentz and Carl Otto Lampland (1873–1951) also extensively observed planets, particularly Venus, but little of their work was published (for details see Sinton 1986: 247-248). Finally, Arthur Adel (1908–1994) conducted observations of atmospheric transmission in the 8-14 μm window and discovered another window around 20 μm (Adel, 1942; details are in Sinton, 1986: 248-250).

Most of this pioneering work was largely ignored by other astronomers, even in the USA. More could have been done with the existing detectors, but more promising ones were appearing. The lead sulfide photoconductive cell was the first of these new detectors, developed by the Germans for military purposes during and after World War II.[12] It was first used in astronomy by Gerard P. Kuiper (1905–1973), one of the pioneers of infrared astronomy, who discovered, through their infrared bands, CO_2 and CH_4 in the atmospheres of Mars and Titan respectively (Kuiper, 1947). Equipped with a chopper, it was also used for photometry by Albert Edward Whitford (1905–2002) in order to extend the interstellar extinction curve to 2.4 μm, the longest wavelength accessible with a PbS cell (Whitford, 1948a). Whitford (1948b) also made with this cell the first photoelectric infrared survey, of the Sagittarius region. Soon after, Peter Fellgett (1922–2008) used an uncooled PbS cell with a preamplifier, chopper and synchronous detector (Figure 13) to measure 51 stars in two infrared colors, reviving in this way infrared astronomy in the United Kingdom (Fellgett, 1951). Similar innovative work was carried out in France a few years later by Madeleine Lunel (1926–1998), who was careful to use filters selecting the atmospheric transparency windows and made good corrections for atmospheric transmission (Lunel, 1960). Unfortunately, there was no interpretation in these two papers, and they remained relatively unnoticed.

Still, they marked the beginning of a new era in infrared astronomy. But there was no standardization in the photometry until Harold Johnson (1921–1980) in 1962 introduced a stellar photometric system for the near- and mid-infrared. The availability of square interference filters was of crucial importance for this work and all the future efforts. Johnson (1962) added to the classic bands UBVRI[13] three new bands, JKL, corresponding to atmospheric windows with respective effective wavelengths of 1.3, 3.6 and 5.0 μm. Eric Becklin later introduced a fourth one, H. at 2.2 μm. Johnson's observations were made first with PbS cells, then with an InSb photovoltaic detector cooled by liquid nitrogen. His photometric system was later extended to 20 μm with three other bands, MNQ, as it was known since the work of Adel in 1942 that observations were sometimes possible in very good sites up to 24 μm, and an excellent spectrum of the Sun was obtained in 1951 between 16 and 24 μm by Marcel V. Migeotte (1912–1992) and L. Neven at the Jungfraujoch (Migeotte and Neven, 1952). For observing near 10 μm, two new detectors were used: a mercury-doped germanium photoconductor cooled by liquid hydrogen by Robert L. Wildey (1934–1998) and Bruce C. Murray (Wildey and Murray, 1964), and a bolometer cooled by liquid helium by Frank J. Low (1933–2009) (Low and Johnson, 1964). These were to give another new impulse to infrared astronomy; moreover, thanks to the success of radio astronomy, astronomers were slowly opening their interest to new wavelength ranges and to new techniques. However, as remarked by Low et al. (2007), the new start in infrared astronomy was led almost entirely by experimental physicists, not by astronomers.

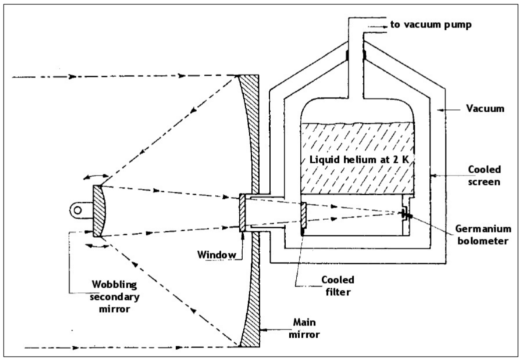

Figure 14: Low's bolometer (1961) at the focus of a Cassegrain reflector. The bolometer itself is a piece of doped germanium connected with two fine wires which carry the current and act as heat leaks. It is inside a liquid helium dewar.

7 THE GLORIOUS SIXTIES

The doped germanium photoconductive detector was classified and unavailable to astronomers; however, it was possible to purchase the material from the Eagle Picher Company and to stick contacts on it, but this was not too easy. As to the cooled bolometer, Low's own company, IR Laboratories Inc., produced it from 1968 in quantities quite insufficient to meet demand. This made it difficult, especially for non-Americans, to work in infrared astronomy, except with PbS cells. In order to remedy this situation some efforts were made in Australia, England, France and Germany to build competitive instruments, in particular helium-cooled bolometers, but these were not available before the 1970s. Impressive infrared work was done in the USSR by Vassili Ivanovitch Moroz (1931–2004) and his collaborators, with PbS and germanium cells obviously developed for military purposes (e.g. see Moroz et al., 1968). Their observations of the Crab Nebula (Moroz, 1964) were particularly interesting. However their work was largely overlooked by the rest of the world.

It was fully understood for a long time that cooling the detectors and their surroundings would give great advantages in increasing their response and reducing thermal noise (see Jones, 1934), so why one had to wait until the 1960s to see a cooled bolometer is difficult to explain. The first one, Low's bolometer (Figure 14), is perfectly designed and all later ones were in one way or another derived from it.

Thanks to these superb instruments, the time was finally ripe for infrared astronomy: evidence of this is the Liège colloquium titled "The Infrared Spectra of Stars" (English translation), the proceedings of which were published in Volume 9 of the *Mémoires de la Societé Royale des Sciences de Liège*. Most astronomers active in infrared research were present, and although many speculations were presented at this colloquium there were few results.

After that, discoveries occurred at a rapid pace. It is impossible to list all of them, and I give only a few examples. Murray, Wildey and James Wesphal (1930–2004) at Caltech and at the Mount Wilson and Palomar Observatories observed for the first time thermal emission from the dark Moon and from Jupiter and its satellites (Murray et al., 1964a; 1964b), while Low (1965) observed Saturn, Jupiter and Mars in the mid-infrared. Near- and mid-infrared emission from galactic sources buried in molecular clouds and located at the Galactic Center was discovered by Eric E. Becklin and Gerald Neugebauer at Caltech (Becklin and Neugebauer, 1968). D.E. Kleinmann and Low found a low-temperature nebula in Orion, the first protostar ever observed (Kleinmann and Low, 1964). Observations of various objects like the Crab Nebula and the quasar 3C 273 (Low and Johnson, 1965) were also reported, showing in both cases that synchrotron emission was responsible for their infrared radiation. They were strong indications that some galactic and extragalactic sources emit most of their energy beyond 25 μm (Figure 15), pointing to the need for observations made above the atmosphere (see Low, 1969).

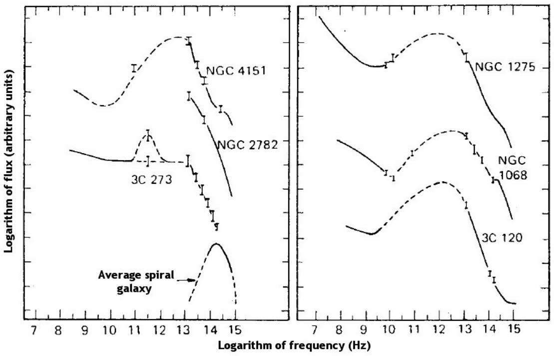

Figure 15: The spectral energy distribution (SED) of some active galaxies and quasars obtained by Low and collaborators from ground-based observations before 1969. The bars are observations, and the dotted lines are interpolations in the far-IR/submillimeter range. The tentative SED for an 'average spiral galaxy' is wrong, because it contains only the radiation from the stars: later observations have shown that the far-infrared radiation of interstellar dust is also very strong so that the SED has another peak around 2×10^{12} Hz.

A near-infrared survey (IRC) in the K band (2.2 μm) was started in 1960 on Mount Wilson and later on White Mountain in California by Neugebauer and a Caltech physicist, Robert Leighton (1919–1997), who built for this purpose the first specialized infrared telescope, a lightweight parabolic mirror of 1.6-m diameter obtained by rotating liquid epoxy during hardening. The corresponding catalogue (Neugebauer and Leighton, 1969) contains 5,612 objects, mostly cool or strongly-reddened stars. This proved a 'gold mine' for future research, and was probably the main cause of the explosion in infrared astronomy during the late sixties.

The 1960s also saw the birth of Fourier transform spectrometry. The possibility of doing spectrometry with Michelson interferometers was first discussed by Albert A. Michelson (1852–1931) and by Lord Rayleigh (1842–1919), but practical applications had to await the development of electronic computers. The spectrum is the Fourier transform of the signal obtained by moving the reflecting mirror of one of the two arms of the interferometer.[14] Fourier transform spectrometry was developed more or less independently by Pierre Jacquinot (1910–2002) (Jacquinot, 1958), then by Pierre and Jeanine Connes (1966) in France**,** by Fellgett (1973) in England, by Donald M. Hunten (1968) in the USA, and also by L. Delbouille, Ginette Roland and H.A. Gebbie (Delbouille et al., 1964) in Belgium and in England. Its main advantages are:

- the high throughput which allows extended objects to be studied with a very high wavelength resolution;[15]
- the possibility of reaching this resolution with a relatively small telescope;
- the possibility of measuring wavelengths with high accuracy; and finally
- the high sensitivity resulting from the 'multiplex' property: if the sensitivity is limited by the detector noise and not by the photon noise of the signal, for a given observation time the signal-to-noise ratio in a spectrum with N independent spectral elements is $N^{1/2}$ times larger than if a one-channel spectroscopic scanning technique was used. This advantage was a feature of the detectors at this time, although it disappeared later when detectors like CCDs became limited by photon noise, and when detector mosaics could be constructed.

Fourier transform spectrographs became favorite tools for molecular spectroscopists and spectacular astronomical results were obtained. For example, observations of Venus by Delbouille et al. reached 25 μm as early as 1964, but with a relatively low wavelength resolution. In 1967-1968 very high resolution observations of planetary atmospheres (Connes et al. 1967, 1969; Maillard et al. 1973) and cool stars (Connes et al. 1968) were obtained in the near infrared at the Haute Provence Observatory, giving a new impulse to their study.

Some observations were also made with Fabry-Perot interferometers, but these instruments turned out to be more useful in space.

Finally, after the discovery of the maser and laser, several astronomers had the idea of applying heterodyne techniques to the mid-infrared, using a CO_2 laser at 11 μm as the local oscillator. Very high wavelength resolutions could then be obtained, but due to the limited wavelength range this technique was mainly of interest in the study of line intensities and profiles of Martian CO_2 (Peterson et al., 1974). M.A. Johnson, A.L. Betz and Charles H. Townes in Berkeley succeeded in building a spatial interferometer at this wavelength using two telescopes separated by 5.5 m, the common local oscillator being a CO_2 laser (Johnson et al., 1974). They obtained interference fringes on Mercury, then on several cool stars. Similar work was done in France at the CERGA Observatory near Grasse (de Batz et al., 1973; Gay and Journet, 1973). Unfortunately, the small available band at the intermediate frequency limited strongly the sensitivity in the continuum, so that only very bright objects could be observed. Consequently, this type of interferometer proved a dead end. Direct interferometry, although more difficult to implement, had a much brighter future and is presently extremely active in the infrared.

8 THE BEGINNING OF SPACE INFRARED ASTRONOMY

The Earth's atmosphere is so troublesome in the infrared that observations from space are not only much better than observations from the ground in the transparency windows, but absolutely necessary in the various water vapor absorption bands; the atmosphere is almost completely opaque in the far-infrared. It is not surprising that as soon as they became technically feasible astronomical observations were started in the infrared from high-altitude sites, aeroplanes, balloons, rockets and satellites. As an example, Figure 16 shows the best estimates obtained in 1968 of the zenithal atmospheric transmission in the submillimeter range for typical conditions in a low-altitude observatory, in a high-altitude one and from a balloon at 30 km altitude (Turon-Lacarrieu and Verdet, 1968).

Techniques were mature, thanks to recent developments in detectors and spectrometers, but also to the laboratory work done since the beginning of the twentieth century in the far-IR: lenses and mirrors, *Reststrahlen* filters using selective reflection by various materials (e.g. see Porter, 1905), grid filters, transmission filters made of various materials, beamsplitters, etc. They only had to be adapted to the conditions in space vehicles.

Balloons were particularly suited to observations in the far-infrared. The first observations from balloons were made in 1964 in the USA: the Stratoscope II observations of some stars and planets were very influential (Woolf, 1964). Our new infrared group at the Paris-Meudon Observatory used a pointed gondola to obtain for the first time the spectral energy distribution of the Sun in the 50-200 μm range (Gay et al., 1968; Gay, 1970). We used a Michelson interferometer and a Golay pneumatic detector. This detector, which is particularly robust but not very sensitive, consists of a gas container with a dark bottom absorbing the incoming radiation (for a description see Golay, 1947). The expansion of the gas so heated exerts pressure on a foil whose deformation is measured either by an optical system or, as in the system we used for the balloon flight, by the variation of a capacitance. The equipment worked well, but the result was not very accurate. Simultaneously, in the USA, a series of photometric far-infrared balloon observations was initiated at the NASA Goddard Space Flight Center, with Low's bolometer (Hoffmann et al., 1967). The most interesting result was the detection of strong far-infrared emission from the Galactic Center, due to thermal emission from interstellar dust grains (see Hoffmann and Frederick 1969; Lequeux, 1970). For many years, balloons continued to be used with success for far-infrared astronomy, especially in the Netherlands, France, Japan and the United Kingdom, and results included measurements of the solar spectrum between 12 and 24 μm (Baluteau, 1971), detection of various far-infrared sources (Furniss et al., 1972a; 1972b), and surveys of the Galactic Plane (Maihara et al., 1978; 1979). However, many flights were technical failures, so aeroplanes were often preferred when available.

At the end of the 1960s NASA decided to equip two aircraft, a Convair 990 and a Lear jet, with telescopes for astronomical infrared studies. From 1968 the Convair was used by John A. Eddy, Pierre J. Léna and Robert M. MacQueen to measure solar emission at around 300 μm (Eddy et al., 1969), but unfortunately it crashed in April 1973 with eleven persons on board. Meanwhile, Low and his collaborators used the Lear jet with great success in 1969 and 1970, confirming in particular the idea that the spectra of several galactic and extragalactic sources peak in the far-infrared; however, with the exception of the Galactic Center, the origin of this radiation had yet to be elucidated. The first far-infrared interstellar fine structure line, that of [OIII] at 88 μm, was discovered in M17 using the Lear jet.

In 1971, another aeroplane, a Lockheed C141 Starlifter, was equipped with a relatively large telescope, 91-cm in diameter. Christened the 'Kuiper Airborne Observatory' (KAO), it began scientific flights in 1975. During the twenty years it contributed to infrared research the KAO surpassed most astronomers' expectations. Amongst the early results obtained with the KAO I will only cite three: some observations of far-infrared fine structure lines (Baluteau et al., 1976); a very high resolution spectrum of Jupiter obtained at around 80 μm (Baluteau et al., 1978); and the discovery of the rings of Uranus (Elliot et al., 1977).

Amongst the first to use rockets for infrared astronomy were groups from the US Air Force and the Center for Radiophysics and Space Research at Cornell University. From 1970 to 1974 the US Air Force conducted a mid-infrared rocket survey in order to be able to distinguish Soviet missiles from celestial sources. This survey, known as the AFGL Survey and the supplementary ground-based survey, were made with doped silicon detectors cooled by liquid neon and extended to 24-30 μm; the results were published by Stephan D. Price and R.G. Walker in 1976.

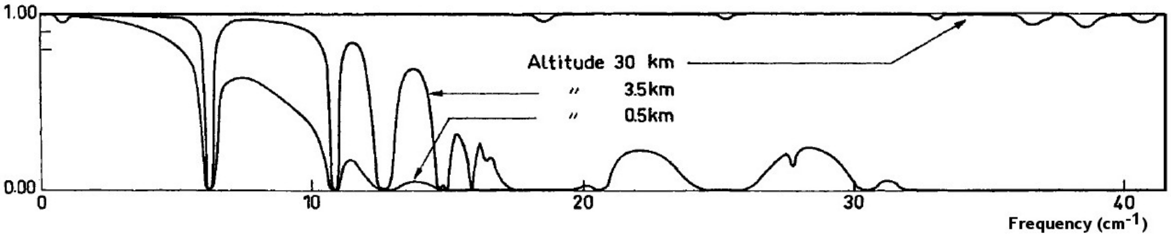

Figure 16: Estimated atmospheric transmission at the zenith in the submillimeter range for typical conditions at various elevations. This transmission is calculated from the laboratory spectrum of water vapor of S.A. Zhevakin and A.P. Naumov, and smoothed to a resolution of 0.5 cm^{-1}. Absorption by molecular oxygen is not included.

The Cornell group used a helium-cooled, rocket-borne telescope and an InSb bolometer and detected an unexpectedly high diffuse flux of about 5 10^{-9} W cm^{-2} sr^{-1} between wavelengths of 0.4 and 1.3 mm in various regions of the sky, some remote from the Galactic Plane (Shivanadan et al.; 1968; Houck and Harwit, 1969). This raised considerable interest and a lot of controversy until it became clear that this high flux was spurious (Houck et al.; 1972). During these flights, Harwit and his collaborators discovered thermal emission from interplanetary dust in the mid-infrared (5-23 μm).

Satellites for the mid- and far-infrared were more difficult to build because they must have giant helium dewars containing the cooled telescope, optics and detectors. After earlier activity by the US Air Force, NASA, the UK and the Netherlands finally collaborated to launch IRAS in 1983, and this space telescope proved a great success. The first European mid-infrared spectrometer with passive cooled detectors was on board the Soviet probe Vega 1, launched in 1984, and gave many valuable results when it was directed at Comet 1P/Halley (e.g. see Combes et al., 1986). This period also saw the appearance of infrared detector arrays. A new era was opening in infrared astronomy, but this is another story.

9 EARLY MILLIMETER AND SUBMILLIMETER ASTRONOMY

During the development of radio astronomy in the 1950s, there was a natural impulse to observe at increasingly shorter wavelengths. Some of the relevant techniques at millimeter waves were available long before, thanks to scientists like Jagadis Chandra Bose (1858–1937) in Calcutta (Emerson, 1998), but the main problems were the observing sites and the detectors. Several studies of high-altitude sites were conducted in the 1960s in order to evaluate the atmospheric transmission at submillimeter wavelengths, for example in the 350 μm window (e.g. see Biraud et al., 1969). The conditions for millimeter waves were less restrictive, and most of the early observations were performed in existing mid-altitude observatories, with optical telescopes. The first specialized millimeter-submillimeter radio telescopes appeared in the sixties: in 1965 two 4.9-m radio telescopes were erected, one at the McDonald Observatory of the University of Texas and the other one at the Aerospace Corporation in the USA. In 1968, the 11-m infrared telescope at Kitt Peak (Arizona) was turned to radio astronomy by NRAO. For their part, in 1959 Soviet astronomers started to carry out observations at 8 mm wavelength with the 22-m diameter radio telescope at Pushchino near Serpukhov, followed in 1966 by a similar one at Simeis in Crimea. The Kitt Peak instrument was by far the most productive of these. Then around 1976 several 14-m radio telescopes and a number of smaller instruments were constructed around the world. The first millimeter interferometer, an experimental instrument devoted to solar studies at 8 mm wavelength, was constructed at the Bordeaux Observatory in France at the end of the 1960s (Delannoy et al., 1973).

Initially, the observers used broad-band detectors like Golay cells, Low's germanium bolometer or InSb bolometers cooled at liquid helium temperature. With them, the millimeter and submillimeter thermal emission from the Sun and the Moon was observed as early as 1954 in the USSR (Salomonovich, 1958; Salomonovich et al., 1958),[16] then in the USA (Low and Davidson, 1965)[17] and finally in England (Bastin et al., 1964). However, these detectors were not suited to spectroscopy or to interferometry.

At the beginning of the 1960s, radio astronomers started to build heterodyne receivers at millimeter wavelengths. This was a difficult task because the mixers were not very reliable and required a lot of power for the local oscillator, which could only be obtained as harmonics of a cm-wave klystron (e.g. see the observations of the Sun by Tolbert and Straiton, 1961). After radio line emission from interstellar molecules at centimeter and decimeter wavelengths was discovered in 1963, many efforts were devoted to the construction of such receivers because more molecular lines were expected to be observable at millimeter and submillimeter wavelengths. The best was that built by Arno A. Penzias and R. Wilson at the Bell Telephone Laboratories, and in 1970 it allowed them to discover several interstellar molecules with the Kitt Peak radio telescope.[18] This opened a new era in radio astronomy.

The submillimeter range was even more difficult to observe. Spectroscopic observations could be carried out with the InSb bolometer, but the bandwidth was rather narrow, of the order of 1 MHz, which allowed the profile of a spectral line to be explored by tuning the bolometer through a change of magnetic field. The real progress came when Tom G. Phillips and K.B. Jefferts (1973) at the Bell Telephone Laboratories developed an heterodyne receiver with a InSb bolometer as a mixer, requiring little power from the local oscillator. This allowed the Caltech group to discover the interstellar line of atomic carbon at 610 μm using the KAO (Phillips et al. 1980). Since then, progress has been spectacular, leading to the heterodyne instrument on board the Herschel satellite, launched in 2009.

10 CONCLUSION

Infrared astronomy is an older science than is usually believed: good detectors were directed at the sky as early as 1845, while the first measurement of the solar constant dates to 1838. Better detectors became available at the end of the nineteenth century, but apart from the Sun and the Moon the targets were too faint even for these instruments and progress initially was slow. Lack of interest from the astronomical community contributed to this. Solid-state, cooled detectors and helium-cooled bolometers which appeared after WWII offered good possibilities, opening a new era in infrared astronomy. The same occurred for millimeter and submillimeter heterodyne detection. Interest in infrared and submillimeter astronomy grew rapidly, fostering the construction of specialized telescopes and space vehicles, and culminating recently in the Herschel and Planck space missions.

11 NOTES

1. As with most of his contemporaries, Herschel adhered to the corpuscular theory of light developed by Newton, in which light was supposed to be made of particles with a mass.
2. Ampère was one of the strongest proponents of the undulatory theory of light, which had then almost

replaced the corpuscular theory thanks to Augustin Fresnel and Arago.

3. For details, see Lewis (1895).
4. Pouillet and his successors, including Father Secchi, expressed the solar constant through the thickness of ice that the solar radiation would melt in a year. Note that the equivalence between heat and work was poorly known in 1838.
5. Some of Melloni's experiments are described by Jamin (1858–1866).
6. For a detailed history see Burns (1912).
7. With considerable insight, William Thomson (Lord Kelvin) proposed in 1860 that "… the hot dust around the Sun must produce radiant heat of such colour as that of a hot stone or metal not at bright red heat …", but his suggestion apparently remained unnoticed (Hale, 1895: 328).
8. For historical information see Volpicelli (1869) and Zantedeschi (1869).
9. The validity of the claimed detections by Huggins and by Boys is discussed by Nichols et al. (1901: 102). These authors also mention a detection of Arcturus by Edison with his tasimeter, but they do not seem very confident of the result.
10. For a detailed history see Lewis (1895; 1896).
11. This was not the first determination of the effective temperatures of stars. Previous ones were made independently in Postdam (Wilsing and Scheiner, 1909) and in Paris (Nordmann, 1909), by comparing visually the fluxes of the stars at several wavelengths with that of black bodies.
12. A German laboratory developing PbS cells was moved to the Paris Observatory after WWII, complete with equipment and people! I carried out my military service in this laboratory from 1957 to 1959.
13. In 1945 Joel Stebbins (1878–1966) and Whitford added the R (red) and I (near infrared) bands to Johnson's original UBV system.
14. Other devices, like the Mock interferometer, also give the Fourier transform of the spectrum and were used effectively in astronomy, particularly by Laurence Mertz and his associates (1962).
15. This also allowed poor images and hence a low-quality telescope to be used. In Meudon, Pierre Connes started to build a large-diameter, low-quality mosaic telescope for Fourier transform spectroscopy, but this was never completed.
16. Whether their detector, a 'modulation radiometer', was an ordinary radiometer or an heterodyne receiver is not clear.
17. Combined observations in the mid-IR and at 1.2 mm yielded for the first time a good picture of the heating and cooling of the lunar surface.
18. See the many papers published by them and their collaborators in 1970 and 1971 in the *Astrophysical Journal*.
19. This paper is of particular interest for astronomy students as it gives an extensive description of the equipment and observing procedures.
20. This special issue contains many interesting papers in French on interference spectroscopy and astronomical applications.
21. This very interesting paper gives many details on the state-of-the-art infrared techniques useful for astronomy.

12 ACKNOWLEDGEMENTS

I thank Pierre Léna and George Rieke for interesting comments on the first version of this paper. I am also grateful to the Bibliothèque Nationale de France and to the Astrophysics Data System for providing free Internet access to a very large number of original papers. Finally, I wish to thank the two referees for their interesting comments and suggestions.

13 REFERENCES

The original documents available freely through http://gallica2.bnf.fr are indicated by a * sign, while those from http://cdsads.u-strasbg.fr are labelled with a ° sign.

°Abbot, C.G., 1908. A bolometric study of the solar corona. *Publications of the Astronomical Society of the Pacific*, 20, 86-90.

°Abbot, C.G., 1929. Energy spectra of the stars. *Astrophysical* Journal, 69, 293-311.

°Adel, A., 1942. The extension of the prismatic solar spectrum from 14μ to 24μ, through a new atmospheric window in the infrared. *Astrophysical Journal*, 96, 239-241.

Allen, D.A., 1975. *Infrared, the New Astronomy.* Keith Reid Shaldo, Keith Reid.

Anonymous [Lorenzo Magalotti], 1684. *Essays of Natural Experiments Made in the Academy del Cimento … Englished by Ric. Waller*. London, Benj. Alsop. Accessible on http://fermi.imss.fi.it/rd/bd?Ing=en

*Anonymous, 1733a. *Histoire de l'Académie Royale des Sciences. Volume 1*. Physics in 1682.

*Anonymous, 1733b. *Histoire de l'Académie Royale des Sciences. Volume 1*. Physics in 1679.

Anonymous, 1755. *Collection Académique: Essais d'Expériences Physiques faites dans l'Académie del Cimento de Florence*. Dijon, François Desventes, et Auxerre, François Fournier, Volume 1. Accessible on http://fermi.imss.fi.it/rd/bd?Ing=en

°Anonymous, 1892a. Lunar radiant heat. *Monthly Notices of the Royal Astronomical Society*, 52, 284-285.

°Anonymous, 1892b. The distribution of the Moon's heat. *Monthly Notices of the Royal Astronomical Society*, 52, 285-286.

*Arago, F., 1836. Éloge historique de Joseph Fourier. *Mémoires de l'Académie des Sciences*, 14, lxix-cxxxviij; see also Barral, J.-A., 1854, **Œuvres Complètes de François Arago.* Paris, Gide, Volume 1, 295-369.

*Baille, J.-B., 1869. Sur la chaleur réfléchie par la Lune. *Comptes Rendus de l'Académie des Sciences*, 69, 960-961.

°Baluteau, J.P., 1971. Solar brightness measurements between 12 and 24 microns. *Astronomy & Astrophysics*, 14, 428-438.

°Baluteau, J.P., Bussoletti, E., Anderegg, M., Moorwood, A.F.M., and Coron, N., 1976. Infrared line emission from the Orion Nebula – detection of [S III] (18.71 μ) and [0 III] (88.35 μ). *Astrophysical Journal*, 210, L45-L48.

°Baluteau, J.P., Marten, A., Bussoletti, E., Anderegg, M., Moorwood, A.F.M., Beckman, J.E., and Coron, N., 1978. Observations of Jupiter around 80 μm at high spectral resolution. *Astronomy & Astrophysics*, 64, 61-65.

Bastin, J.A., Clegg, P.E., Gear, A.E., Jones, G.O., and Platt, C.M., 1964. Lunar brightness distribution at 1.5 mm wavelength. *Nature*, 203, 960-961.

°Becklin, E.E., and Neugebauer, G., 1968. Infrared observations of the Galactic Center. *Astrophysical Journal*, 151, 145-161.

°Biraud, Y., Gay, J., Verdet, J.P., and Zéau, Y, 1969. Transmission atmosphérique et spectroscopie solaire en ondes submillimétriques. *Astronomy & Astrophysics*, 2, 413-418.

*Boys, C.V., 1890. On the heat of Moon and stars. *Proceedings of the Royal Society of* London, 47, 480-499.

°Burns, K., 1912. Infra-red photography. *Publications of the*

Astronomical Society of the Pacific, 24, 251-255.

°Coblentz, W.W., 1914. Note on the radiation from stars. *Publications of the Astronomical Society of the Pacific*, 26, 169-178.

°Coblentz, W.W., 1922. New measurements of stellar radiation. *Astrophysical Journal*, 55, 20-23.

Combes, M., Moroz, V.I., Crifo, J.F., Lamarre, J.M., Charra, J., Sanko, N.F., Soufflot, A., Bibring, J.P., Cazes, S., Coron, N., Crovisier, J., Emerich, C., Encrenaz, T., Gispert, R., Grigoryev, A.V., Guyot, G., Krasnopolsky, V.A., Nikolsky, Yu.V., and Rocard, F., 1986. Infrared sounding of Comet Halley from VEGA 1. *Nature*, 321, 266-268,

Connes, J., and Connes, P., 1966. Near-infrared planetary spectra by Fourier spectroscopy. I. Instruments and results. *Journal of the Optical Society of America*, 56, 896-910.

Connes, P., Connes, J., and Maillard, J.-P., 1969. *Atlas des Spectres dans le Proche I.R. de Vénus, Mars, Jupiter et Saturne*. Paris, Editions du CNRS.

°Connes, P., Connes, J., Benedict, W.S., and Kaplan, L.D., 1967. Traces of HCl and HF in the atmosphere of Venus. *Astrophysical Journal*, 147, 1230-1237.

°Connes, P., Connes, J., Bouigue, R., Querci, M., Chauville, M., and Querci, F., 1968. Sur les spectres d'étoiles rouges M et C entre 4000 et 900 cm^{-1} (2,5 à 1,1 μ) I. Description générale. *Annales d'Astrophysique*, 31, 485-492.

de Batz, B., Granès, P., Gay, J., and Journet, A., 1973. Heterodyne detection of Arcturus at 10.6 μm. *Nature Physical Science*, 245, 89.

Delamétherie, J.-C., 1801. Discours préliminaire; de la physique. *Journal de Physique*, LII (nivôse an IX = 1801), 8-14.

°Delbouille, L., Roland, G., and Gebbie H.A., 1964. Actual possibilities of astronomical infrared spectroscopy by interferometry and Fourier transformation. *Astronomical Journal*, 69, 334-338.

Delannoy, J., Lacroix, J., and Blum, E.-J., 1973. An 8-mm interferometer for solar radio astronomy at Bordeaux, France. *Proceedings of the IEEE*, 61, 1282-1284.

*Deslandres, H., 1900. Premiers résultats des recherches faites sur la reconnaissance de la couronne solaire en dehors des éclipses avec l'aide de rayons calorifiques. *Comptes Rendus de l'Académie des Sciences*, 131, 658-661; translation in *Astrophysical Journal*, 12, 366-369 (1900).

Dolci, W.W., 1997. *Milestones in Airborne Astronomy: from the 1920's to the Present.* Reston, American Institute of Astronautics and Aeronautics.

Eddy, J.A., 1972. Thomas A. Edison and infra-red astronomy. *Journal for the History of Astronomy*, 3, 165-187; see also Anonyme, 1878. Micro-tasimètre d'Edison. *La Nature*, 135, accessible on http://cnum.cnam.fr .

°Eddy, J.A., Léna, P.J., and MacQueen, R.M., 1969. Far infrared measurements of the solar minimum temperature. *Solar Physics*, 10, 330-341.

Elliott, J.L., Dunham, E., and Mink, D., 1977. The rings of Uranus. *Nature*, 267, 328-330.

Emerson, D.T., 1998. *The Work of Jagadis Chandra Bose: 100 Years of mm-wave Research*. http://www.tuc.nrao.edu/~demerson/bose/bose.html

°Fellgett, P., 1951. An exploration of infra-red stellar magnitudes using the photo-conductivity of lead sulfide. *Monthly Notices of the Royal Astronomical Society*, 111, 537-559.[19]

°Fellgett, P., 1973. Origins of multiplex spectroscopy. *The Observatory*, 93, 210-211.

Fernie, J.D., 2000. Eclipse vicissitudes: Thomas Edison and the chickens. *American Scientist*, 88(2), 120-121.

*Fizeau, H, and Foucault, L., 1847. Recherches sur les interférences des rayons calorifiques. *Comptes Rendus de l'Académie des Sciences*, 25, 447-450; see also Foucault, L., 1878. *Recueil des Travaux Scientifiques de Léon Foucault*. Paris, Gauthier-Villars, new edition 2001, Paris, Librairie Albert Blanchard, 135-160 and 161-162; see also Tobin, W., 2002. *Léon Foucault.* Cambridge, Cambridge University Press (Chapter 6).

*Fourier, J., 1823, published in 1827. Éloge historique de sir William Herschel. *Mémoires de l'Académie des Sciences*, 6, lxj-lxxxj.

*Fourier, J., 1824, published in 1827. Mémoire sur les températures du globe terrestre et des espaces planétaires. *Mémoires de l'Académie des Sciences*, 7, 569-604.

Furniss, I., Jennings, R.E., and Moorwood, A.F.M., 1972a. Infrared astronomy – observations of M 42, NGC 2024 and M 1. *Nature Physical Science*, 236, 6.

°Furniss, I., Jennings, R.E., and Moorwood, A.F.M., 1972b. Detection of far-infrared astronomical sources. *Astrophysical Journal*, 176, L105-L108.

°Gay, J., 1970. Balloon observations in the submillimeter region: an absolute measurement of the brightness of the Sun and the transparency of the stratosphere above 25 km. *Astronomy & Astrophysics*, 6, 327-348.

Gay, J., and Journet, A., 1973. Infrared astronomy - interferometric measurement of solar diameter. *Nature Physical Science*, 241, 32.

Gay, J., Lequeux, J., Verdet, J.P., Turon-Lacarrieu, P., Bardet, M., Roucher, J., and Zeau, Y., 1968. Balloon observations of the far-infrared spectrum and brightness temperature of the Sun. *Astrophysical Letters*, 2, 169-172.

Golay, M.J.E., 1947. A pneumatic infrared detector. *Review of Scientific Instruments*, 18, 357-362.

°Hale, G.E., 1895. On a new method of mapping the solar corona without an eclipse. *Astrophysical Journal*, 1, 318-334.

°Hale, G.E., 1899. Heat radiation of the stars. *Astrophysical Journal*, 9, 360-362.

°Hall, J.C., 1934. Photo-electric photometry in the infra-red with the Loomis telescope. *Astrophysical Journal*, 79, 145-182.

Herschel, W., 1800a. Investigation of the powers of the prismatic colours to heat and illuminate objects … *Philosophical Transactions of the Royal Society*, 90, 255-283.

Herschel, W., 1800b. Experiments on the refrangibility of the invisible rays of the Sun. *Philosophical Transactions of the Royal Society*, 90, 284-292.

Herschel, W., 1800c. Experiments on the solar, and on the terrestrial rays that occasion heat … *Philosophical Transactions of the Royal Society*, 90, 293-326.

Herschel W., 1800d. Experiments on the solar and on the terrestrial rays that occasion heat … (2^{d} part). *Philosophical Transactions of the Royal Society*, 90, 437-538.

Herschel, W., 1801. Additional observations tending to investigate the symptoms of the variable emission of the light and heat of the Sun … *Philosophical Transactions of the Royal Society*, 91, 354-362.

°Hoffmann, W.F., and Frederick, C.L., 1969. Far-infrared observation of the Galactic-Centre region at 100 microns. *Astrophysical Journal*, 155, L9-L13.

Hoffmann, W.F., Woolf, N.J., Frederick, C.L., and Low, F.J., 1967. Far-infrared surveys of the sky. *Science*, 157, 187-189.

°Houck, J.R., and Harwit, M., 1969. Far-infrared nightsky emission above 120 kilometers. *Astrophysical Journal*, 157, L45-L48.

°Houck, J.R., Soifer, B.T., Harwit, M., and Pipher, J., 1972. The far-infrared and submillimeter background. *Astrophysical Journal*, 178, L29-L33.

°Huggins, W., 1878. Heat of the stars. *Astronomical Register*, 16, 309; see also *Huggins, W., 1868-1869. Note on the heat of the stars. *Proceedings of the Royal Society*, 17, 309-312.

Hunten, D.M., 1968. Fourier spectroscopy of planets. *Science*, 162, 313-318.

Jacquinot, P., 1958. Caractères communs aux nouvelles méthodes de spectroscopie interférentielle; Facteur de mérite. *Journal de Physique et Le Radium,* 19, 223-229.[20]

*Jamin, J.-C. 1858-1866. *Cours de Physique de l'École Polytechnique*. Three volumes. Paris, Mallet-Bachelier.

Jennings, R.E., 1986. History of British infrared astronomy since the Second World War. *Quarterly Journal of the Royal Astronomical Society*, 27, 454-461.

°Johnson, H.L., 1962. Infrared stellar photometry. *Astrophysical Journal*, 135, 69-77; for photometry at 10 μm see also Low and Johnson, 1964.

Johnson, M.A., Betz, A.L., and Townes, C.H., 1974. 10-μm heterodyne stellar interferometer. *Physical Review Letters*, 33, 1617-1620.

°Jones, R.V., 1934. Modern methods of infra-red spectroradiometry. *The Observatory*, 57, 300-308.[21]

°Kleinmann, D.E., and Low, F.J., 1967. Discovery of an infrared nebula in Orion. *Astrophysical Journal*, 149, L1-L4.

°Kuiper, G., 1947. Infrared spectra of planets. *Astrophysical Journal*, 106, 251-254.

°Langley, S.P., 1880. Solar physics, Part 1. *The Observatory*, 3, 501-506.

°Langley, S.P., 1900a. The absorption lines in the infra-red spectrum of the Sun. *Annals of the Astrophysical Observatory of the Smithsonian Institution*, 1, 5-265 and plates.

°Langley, S.P., 1900b. The heat radiation of the corona. *Astrophysical Journal*, 12, 370-371.

Langley, S.P., and Very, F.W., 1889. *The Temperature of the Moon, from Studies at the Allegheny Observatory.* New Haven, J.D. and E.S. Dana.

Léna, P., 2007. L'astronomie infrarouge 1. Le temps des pionniers. *L'Astronomie*, 121, 70-76.

Léna, P., 2008. L'astronomie infrarouge 2. L'envol. *L'Astronomie*, 122, 8-15.

°Lequeux, J., 1970. The nature of the far-infrared radiation of the Galactic Center. *Astrophysical Journal*, 159, 459-462.

°Lewis, E.P., 1895. The measurements of some standard wave-lengths in the infra-red spectra of the elements I. *Astrophysical Journal*, 2, 1-25.

°Lewis, E.P., 1896. Recent researches bearing on the determination of wave-lengths in the infra-red spectrum. *Astrophysical Journal*, 3, 63-77.

°Low, F.J., 1965. Planetary radiation at infrared and millimeter wavelengths. *Lowell Observatory Bulletin*, 6, 184-187.

Low, F.J., 1969. Infrared astrophysics. *Science*, 164, 501-505; French translation: Low, F.J.. 1970. Astrophysique en lumière infrarouge. *L'Astronomie*, 84, 11-22.

°Low F.J., and Davidson, A.W., 1965. Lunar observations at a wavelength of 1 millimeter. *Astrophysical Journal*, 142, 1278-1282.

°Low, F.J., and Johnson, H., 1964. Stellar photometry at 10μ. *Astrophysical Journal*, 139, 1130-1134.

°Low, F.J., and Johnson, H.L., 1965. The spectrum of 3C 273. *Astrophysical Journal*, 141, 336-338.

Low, F.J., Rieke, G.H., and Gehrz, H.D., 2007. The beginning of modern infrared astronomy. *Annual Review of Astronomy and Astrophysics*, 45, 43-75.

°Lunel, M., 1960. Recherches de photométrie stellaire dans l'infrarouge au moyen d'une cellule au sulfure de plomb. *Annales d'Astrophysique*, 23, 1-61.

°Maihara, T., Oda, N., and Okuda, H., 1979. A balloon observation of diffuse far-infrared emission from the Galactic Plane. *Astrophysical Journal*, 227, L129-L132.

°Maihara, T., Oda, N., Sugiyama, T., and Okuda, H., 1978. 2.4-micron observation of the galaxy and the galactic structure. *Publications of the Astronomical Society of Japan*, 30, 1-20.

°Maillard, J.P., Combes, M., Encrenaz, Th., and Lecacheux, J., 1973. New infrared spectra of Jovian planets from 12000 to 4000 cm^{-1} by Fourier transform spectroscopy. I. Study of Jupiter in the $3\nu_3$ CH_4 band. *Astronomy & Astrophysics*, 25, 219-232.

*Marié-Davy, H., 1869. Note sur les radiations lunaires. *Comptes Rendus de l'Académie des Sciences*, 69, 705-706.

Mariotte, E., 1717. Discours sur le froid et le chaud. *Oeuvres de M^{r}. Mariotte*. Two volumes. Leiden, Pierre Van der Aa, Volume 1, 183-194. Accessible on http://num-scd-ulp.u-strasbg.fr:8080

*Melloni, M., 1835. Observations et expériences relatives à la théorie de l'identité des agents qui produisent la lumière et la chaleur rayonnante. *Comptes Rendus de l'Académie des Sciences*, 1, 503-509.

*Melloni, M., 1837. Polarisation de la chaleur. *Comptes Rendus de l'Académie des Sciences*, 5, 530-537.

*Melloni, M., 1842. Sur l'identité des diverses radiations lumineuses, calorifiques et chimiques. *Comptes Rendus de l'Académie des Sciences*, 15, 454-460.

*Melloni, M., 1846. Sur la puissance calorifique de la lumière de la Lune. *Comptes Rendus de l'Académie des Sciences*, 22 , 541-544.

Mertz, L., Young, N.O., and Armitage, J., 1962. Mock interferometry. In Habell, K.J. (ed.). *Optical Instruments and Techniques*. London, Chapman and Hall. P. 51f.

°Migeotte, M., and Neven, L., 1952. High-dispersion solar spectrograms between 15 μ and 24 μ. *Astrophysical Journal*, 115, 326.

°Moroz, V.I., 1964. Infrared observations of the Crab nebula. *Soviet Astronomy*, 7, 755-763.

°Moroz, V.I., Vasil'chenko, N.V., Danilyants, L.B., and Kaufman, S.A., 1968. Experimental observations at 8-14 μ with a photoconductive cell cooled by liquid helium. *Soviet Astronomy*, 12, 150-153.

°Murray, B.C., and Wildey, R.L., 1964a. Surface temperature variations during the lunar nighttime. *Astrophysical Journal*, 139, 734-750.

°Murray, B.C., Wildey, R.L., and Westphal, J.A., 1964b. Observations of Jupiter and the Galilean satellites at 10 microns. *Astrophysical Journal*, 139, 986-993.

Neugebauer, G., and Leighton, R.B., 1969. *Two-micron Sky Survey: A Preliminary Catalog*. Washington, NASA (SP 3047).

°Nichols, E.F., Colton, A.L., and St. John, C.E., 1901. On the heat radiation of Arcturus, Vega, Jupiter and Saturn. *Astrophysical Journal*, 13, 101-141.

*Nordmann, C., 1909. Nouvelle approximation dans l'étude des températures effectives des étoiles. *Comptes Rendus de l'Académie des Sciences*, 149, 1038-1041.

Peterson, D.W., Johnson, M.A., and Betz, A.L., 1974. Infrared heterodyne spectroscopy of CO_2 on Mars. *Nature*, 250, 128-130.

°Pettit, E., and Nicholson, S.B., 1922. The application of vacuum thermocouples to problems in astrophysics. *Astrophysical Journal*, 56, 295-317.

°Pettit, E., and Nicholson, S.B., 1924. Radiation from the dark hemisphere of Venus. *Publications of the Astronomical Society of the Pacific*, 36, 227-228.

°Pettit E., and Nicholson, S.B., 1928. Stellar radiation measurements. *Astrophysical Journal*, 68, 279-308.

Phillips, T.G., and Jefferts, K.B., 1973. A low temperature bolometer heterodyne receiver for millimeter wave astronomy. *Review of Scientific Instruments*, 44, 1009-1014.

°Phillips, T.G., Huggins, P.J., Kuiper, T.B.H., and Miller, R.E., 1980. Detection of the 610 micron (492 GHz) line of interstellar atomic carbon. *Astrophysical Journal*, 238, L103-L106.

°Porter, J.T., 1905. Selective reflection in the infra-red spectrum. *Astrophysical Journal*, 22, 229-248.

*Pouillet, C., 1838. Mémoire sur la chaleur solaire, sur les pouvoirs rayonnants et absorbants de l'air atmosphérique, et sur la température de l'espace. *Comptes Rendus de l'Académie des Sciences*, 7, 24-65.

Price, S.D., and Walker, R.G., 1976. *The AFGL Four Color Infrared Sky Survey: Catalog of Observations at 4.2, 11.0, 19.8 and 27.4 Micrometers*. Hanscom Air Force Base, Interim Report Air Force Geophysics Lab.

*Raynard, A.C., 1878. Edison's Tasimeter. *Astronomical Register*, 16, 309.

Rieke, G.H., 2009. History of infrared telescopes and astronomy. In *400 years of Astronomical Telescopes*. Berlin, Springer-Verlag, in press.

Rosse, (Laurence Parsons, 4th Earl of), 1873. On the radiation of heat from the Moon, the law of its absorption by our atmosphere, and its variation in amount with her phases. Bakerian Lecture, London; *abstract in 1873. *Proceedings of the Royal* Society, 21, 241-242.

Rosse, (Laurence Parsons, 4th Earl of), 1895. The radiant heat from the Moon during the progress of an eclipse. *Royal Institution of Great Britain, meeting of Friday, May 31, 1895*, London, 3-16.

°Rosse, (Laurence Parsons, 4th Earl of), 1905. Researches on lunar heat. *The Observatory*, 28, 409-414.

°Rubens, H., and Aschkinass, E., 1898. Observations on the absorption and emission of aqueous vapor and carbon dioxide in the infra-red spectrum. *Astrophysical Journal*, 8, 176-192.

°Rubens, H., and Kurlbaum, F., 1901. On the heat-radiation of long wave-length emitted by black bodies at different temperatures. *Astrophysical Journal*, 14, 335,-348.

°Salomonovich A.E., 1958. Radio emission of the Moon at 8 millimeters. *Soviet Astronomy*, 2, 112-118.

°Salomonovich, A.E., Pariiskii, Iu.N., and Khangil'Din, U.V., 1958. Observations of the total solar eclipse of June 30, 1954, at millimeter wavelengths. *Soviet Astronomy*, 2, 612-614.

*Secchi, A., 1875 and 1877. *Le Soleil*. Two volumes. Paris, Gauthier-Villars (see Volume 1, 121-138).

Shivanadan, K., Houck, J.R., and Harwit, M., 1968. Preliminary observations of the far-infrared night-sky background radiation. *Physical Review Letters*, 21, 1460-1462.

°Sinton, W.M., 1986. Through the infrared with logbook and lantern slides: a history of infrared astronomy from 1868 to 1960. *Publications of the Astronomical Society of the Pacific*, 98, 246-251.

Smith, R.A., Jones, F.E., and Chasmar, R.P., 1968. *The Detection and Measurement of Infra-red Radiation.* Second Edition. Oxford, Clarendon Press.

°Soifer, B.T., Houck, J.R., and Harwit, M., 1971. Rocket infrared observations of the interplanetary medium. *Astrophysical Journal*, 168, L73-L78.

*Stone, E.J., 1870. Approximate determination of the heating-powers of Arcturus and Alpha Lyrae. *Proceedings of the Royal Society*, 18, 159-165.

°Storey, J.W.V., 2000. Infrared astronomy: in the heat of night. *Publications of the Astronomical Society of Australia*, 17, 270-274.

°Tolbert, C.W., and Straiton, A.W., 1961. Solar measurements at millimeter wavelengths. *Astrophysical Journal*, 134, 91-95.

°Turon-Lacarrieu, P., and Verdet, J.-P., 1968. Quelques données sur l'absorption atmosphérique de 50 μ à 1 mm. *Astronomy & Astrophysics*, 31, 237-243.

*Tyndall, J., 1861. On the absorption and radiation of heat by gases and vapours, and on the physical connexion of radiation, absorption and conduction. *Philosophical Transactions of the Royal Society*, 151, 1-36.

*Volpicelli, P., 1869. Sur la chaleur des radiations lunaires. *Comptes Rendus de l'Académie des Sciences*, 69, 920-922.

°Whitford, A.E., 1948a. An extension of the interstellar absorption-curve. *Astrophysical Journal*, 107, 102-105.

°Whitford, A.E., 1948b. An infra-red survey of the Sagittarius region at wave length 2 μ. *Astronomical Journal*, 53, 206-207.

°Wildey, R.L., and Murray, B.C., 1964. 10-μ photometry of 25 stars from B8 to M7. *Astrophysical Journal*, 139, 435-441.

°Wilsing, J., and Scheiner, J., 1909. Temperaturbestimmung von 109 helleren Sternen aus spektralphotometrischen Beobachtungen. *Astronomische Nachrichten*, 183, 97-108; see also the review of this paper by C.G. Abbot in *Astrophysical Journal*, 31, 274-278 (1910).

°Woolf, N.J., 1964. Infra-red spectra of stars, planets and the Moon from Stratoscope II. *IAU Symposium 23*, 267-273; this paper is reproduced in *Annales d'Astrophysique*, 28, 218-224 (1965).

*Zantedeschi, F., 1869. Sur l'action calorifique des rayons de la Lune. *Comptes Rendus de l'Académie des Sciences*, 69, 1070-1071.

Dr. James Lequeux started research in radio astronomy as a student in 1954, and spent most of his career as a radio astronomer. In parallel, he became interested in the infrared during his military service in 1956-1959, which was carried out in a military infrared laboratory, and in 1966 he and a few colleagues founded the first infrared laboratory at the Paris-Meudon Observatory. He was active in the scientific preparation of the Infrared Space Observatory (ISO) and was an Associate Scientist for this European satellite. His post-retirement interests turned to the history of astronomy. He produced several research papers and three books in this field. James is now affiliated with the LERMA Department at the Paris Observatory.

Journal of Astronomical History and Heritage, 12(2), 141-152 (2009).

GENESIS OF THE 1000-FOOT ARECIBO DISH

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Abstract: The giant radar/radio astronomy dish near Arecibo, Puerto Rico, was conceived by William E. Gordon in early 1958 as a back-scattering radar system to measure the density and temperature of the Earth's ionosphere up to a few thousand kilometers. Gordon calculated the required size of the antenna by using the Thomson cross-section for scattering by the electrons, and assuming that the elementary scattered waves would be incoherent. During the summer and autumn of 1958 Gordon led a study group that published a design report in December 1958. The report showed that a dish 1000 feet in diameter would be required, and described a limestone sinkhole in Puerto Rico that would make a suitable support for such a dish. Meanwhile, in November 1958, Kenneth L. Bowles performed an ionospheric radar experiment that showed that the Gordon calculation for the scattered power was roughly correct, but that the calculated spectral width was too big. The consequence of these results was that a dish substantially smaller than 1000 feet could have satisfied the original goals for the radar. However, from the spring of 1958 the value of 1000 feet had been in the minds of the study team, and a large suite of important experiments that such a dish could do had been identified. These apparently became the *raison d'être* for the project, and the possibility of shrinking the dish to accomplish only the original goals seems to have been ignored. The project was sold to a new federal funding agency, the Advanced Research Projects Agency (ARPA), which was interested, in part at least, because ballistic missiles traveled through the ionosphere and it was important to fully understand that environment. Gordon's original calculation contained a remarkably beneficial error. Without it, it is doubtful that such a large dish would have been built.

Keywords: Arecibo, space radar, plasma physics, incoherent scatter, radar astronomy, radio astronomy

1 INTRODUCTION

The giant radar/radio astronomy dish near Arecibo, Puerto Rico (Figure 1), was conceived in 1958 as a back-scattering radar system to measure the density and temperature of the ionosphere up to a few thousand kilometers above the Earth's surface. The scattered signal was calculated to be weak and a large antenna would be required to measure it; the dish would have to be around 1000 feet in diameter.

However, six months after the project began to be studied in earnest, it was shown that the characteristics of the echo are different from those assumed, and that a much smaller dish could successfully measure the signals. Nonetheless, the project continued on its original track, and the dish was built with a diameter of 1000 feet. This paper describes the project and how the much larger goals allowed by the large diameter became the *raison d'être* for the project.[1]

Figure 1: Recent view of part of the 1000-ft Arecibo dish, and the prime focus facility (courtesy: Cornell University).

Figure 2: William E. Gordon (1918–) ca 1963 (courtesy: Cornell University Archives).

The ionosphere of the Earth consists of ionized gas starting at about 60 km above the Earth; its density generally rises to a peak called the F region, typically near 300 km, and it slowly decreases above that. The electron density at the peak is around 10^6 cm^{-3} although with large variations, and the corresponding plasma frequency is about 9 MHz (the plasma frequency = $\nu_p \approx 9 \times 10^3 n_e^{1/2}$ Hz, with n_e the electron density per cm^3).

The ionosphere has been studied since the 1920s (Appleton and Barnett, 1925) with 'ionosondes', swept-frequency radars that receive echoes from successively higher layers of the ionosphere as the frequency is raised, and the local plasma frequency is reached. But when the frequency goes above the highest plasma frequency of the F region, the wave penetrates the entire ionosphere, and there are no echoes from higher levels. Rocket experiments to study the high ionosphere were being made in the 1950s (Friedman, 1959); and whistler (Helliwell and Morgan, 1959) and other experiments also gave 'top-side' information. However, these were all episodic, or otherwise limited.

The shortcomings of the traditional experiments led William E. (Bill) Gordon (Figure 2),[2] early in 1958, to investigate the possibility of seeing the weak 'incoherent scatter' from the top-side of the ionosphere. Incoherent scatter (IS) refers to the weak scattering of high-frequency radio waves by the electrons in an ionized gas, and is in distinction to the strong scattering, or reflection, seen when the wave frequency becomes equal to the plasma frequency. The term 'incoherent' implies that the elementary waves back-scattered by the electrons have no fixed phase relationship, and thus that the total scattered power is the sum of the individual powers. In fact this can be in error by up to a factor of 2 or somewhat greater, as discussed below.

Gordon (1979: 7-12; 1994: 2-5) was led to the IS problem by his prior experience with 'scatter' communications. This refers to long-distance radio propagation, around the curve of the Earth, by scattering on irregularities in the atmosphere. In 1950 Gordon wrote an important paper with Henry Booker (Booker and Gordon, 1950) that explained over-the-horizon communication by means of radio wave scattering on irregularities in the troposphere. The irregularities were described in terms of fluctuations in the dielectric constant of air, a formalism first used by Einstein (1910). Booker and Gordon (1957) then successfully investigated the possibilities of scattering in the stratosphere, which allows for communications at a greater range. Gordon (1979) continued this work by asking if the upper ionosphere could support scatter communications; this would give yet more range if it were possible. He concluded that in this case the scattered signal would be too weak to be useful in any practical system. However, it was then a straight-forward step to ask if incoherent back-scattering could be used to study the ionosphere itself. Figure 3 shows how 'forward scattering' for communications can conceptually lead to incoherent back-scattering.

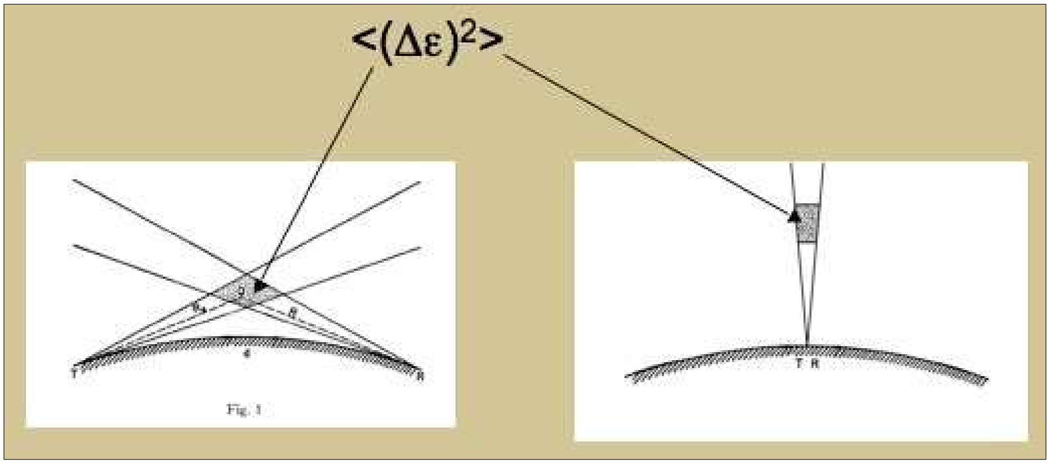


Figure 3: Simple illustration of how moving the transmitting (T) and receiving (R) antennas together takes an over-the-horizon communication system to an incoherent scatter ionosphere radar. $<(\Delta\varepsilon)^2>$ is the mean square fluctuation in the dielectric constant. Left panel after Booker and Gordon (1950: 407).

Modelling the ionosphere encountered a theoretical difficulty, however. Gordon had earlier used the fluctuations in dielectric constant arising from turbulence in the lower neutral atmosphere. What were the corresponding fluctuations in the ionosphere, an ionized gas? An answer to a simplified version of this question had been given by Pines and Bohm (1952), who calculated the thermal fluctuations for the fictitious case where the positive charge is smoothed out. This eliminates the electrostatic forces between electrons and ions, and the effect is to greatly reduce the fluctuations at the length scales that affect the radar backscatter. Gordon (2008) apparently did not know of the Pines and Bohm result. However, if he had used it, with the assumption that it actually did provide a good approximation to the ionosphere, then he would have found that the echoes, say at 500 km height, would be far too small to be useful. Gordon instead assumed that the echo would be due to Thomson scattering by the individual electrons, acting incoherently. With this assumption the echo would be weak, too weak for practical communications. However, with a large enough antenna, it would be adequate for backscattering experiments, to measure ionospheric electron density and temperature.

The IS idea may have been ‘in the air’ at the time. According to Gillmor (1986: 126), Henry Booker thought of it in the 1930s, but dismissed the idea as impractical (which it would have been, in the ’30s). Kenneth Bowles (Figure 4)[3] told the author that he independently thought of the IS idea (Bowles, 2007), and his first IS paper begins as follows:

> The possibility that incoherent scattering from free electrons in the ionosphere, vibrating independently, might be observed by radar techniques has apparently been considered by many workers although seldom seriously, because of the enormous sensitivity required (Bowles, 1958: 454).

At the time there was a great deal of interest in the ionosphere, fueled by the IGY (1957-1958) and the launch of the *Sputnik* and *Explorer* satellites. More than 75 ionosondes were operating world-wide during the IGY. Rocket and propagation experiments using the satellites were part of the IGY program, and the idea of top-side sounding from a satellite was widespread. Several meetings on the topic may be noted: in October 1958 a meeting at Cornell University brought together ionospheric physicists to discuss the possibilities of satellite experiments (Forsyth, 2002; Franklin, 1993). A symposium entitled “The Upper Atmosphere Above F2-Maximum” was held in Paris, France, in May 1959 (Bowles, 1959a), and another was held at the URSI meeting in Washington, D.C. in May 1960. A good report of the state of knowledge at that time is provided by the “Summary of the Proceedings” for the URSI meeting (see Hines, 1960).

There also was military interest in the ionosphere, because satellites and missiles travel in the ionosphere and understanding the disturbances they make, and detecting them, was a high priority. In addition, the effect of high-altitude nuclear explosions on the ionosphere, and on radio propagation in the ionosphere, was of interest.

Sections 2 and 3 may be skipped by the non-technical reader. The essential result is contained in Figure 5, where the echo spectrum (i.e. the distribution in frequency of the signal that scatters from the ionosphere and returns back to the radar) is shown. The black curve shows the spectrum calculated by Gordon and used to find the required diameter of the radar dish. The top red line shows the result of a more accurate calculation. The red curve is narrower and higher than the black curve, and that means that a smaller, less-sensitive dish could have been used to accommodate the original goal, the measurement of density and temperature in the ionosphere to a height of 1000 km.

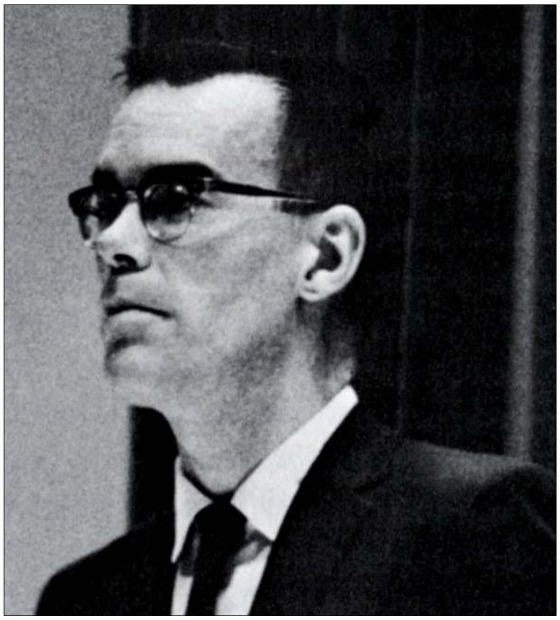


Figure 4: Kenneth L. Bowles (1929–). This photograph appeared in *Engineering: Cornell Quarterly*, 1(3): 14 (Fall 1966).

2 THE GORDON CALCULATION AND THE BOWLES CONFIRMATION

Gordon (1958b) used a beam-filled formulation of the radar equation (Battan, 1973: 31-33) to calculate the power received from a slab of the ionosphere:

$$P_r \propto P_t A h (\sigma n_e)/r^2 \qquad (1)$$

where P_r and P_t are the received and transmitted powers, respectively, A is the effective area of the antenna, $h = c\tau$ is the pulse length in space (c is the velocity of light and τ is the pulse width in time), σ is the scattering cross-section of an electron, n_e is the number of electrons per unit volume, and r is the height. This assumes that the electrons are randomly spaced and independent, and each undergoes Thomson scattering. The total scattered power is the sum of the elementary scatterings from all the electrons in the appropriate volume. Each elementary scattered wave has a Doppler shift given by the electron’s vertical component of velocity, and the total scattered signal has a Gaussian spectrum; this also assumes that the electrons are in equilibrium at temperature T_e. The half-power width of the spectrum (in kHz) is

$$\Delta\nu = 122 (T_e/100)^{1/2} (\nu_{MHz}/200) \qquad (2)$$

where ν_{MHz} is the radar frequency in MHz. Gordon justifies these assumptions by assuming that collisions are unimportant and that $L < s$, where L is the effective scale for backscattering ($L = \lambda/2$, where λ is the radar wavelength) and s is the mean-free-path of the electrons in their thermal motion. This formulation ignores the electrostatic effect of the ions, which produces changes in both the scattered power and spectrum in some circumstances, as discussed later.

The received power in Equation (1) must be compared to the expected noise. The noise power, N_r, in watts, can be expressed as

$$N_r = kT_{eff}B \qquad (3)$$

where T_{eff} is the effective noise temperature of the receiving system, including radiation from the ground and the sky, and internal noise from the receiver itself. B is the receiver bandwidth in Hertz and k is Boltzmann's Constant.

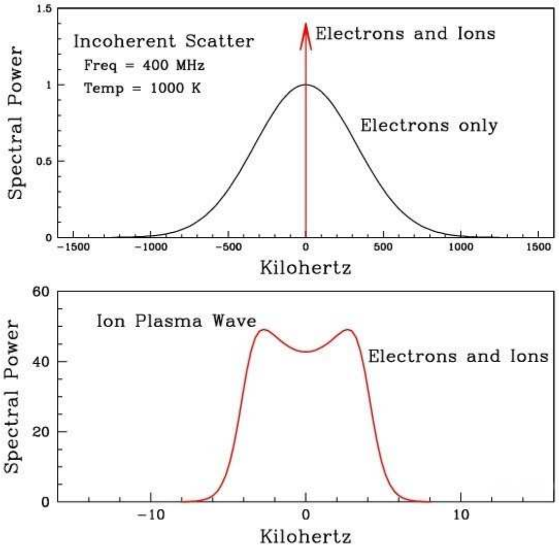


Figure 5: Spectrum of the incoherent scatter from the electrons in a plasma at a temperature of 1000K, with the incident wave at 400 MHz. Note the change in scales between the top and bottom panels. Bottom: wavelength large compared with the Debye length. The shoulders are due to heavily damped ion waves. Top: The red curve is a rescaled copy of the bottom curve. The black curve is for the case where the wavelength is small compared to the Debye length, and is the result obtained for any wavelength if the ions are simply ignored.

The ratio P_r / N_r (the signal-to-noise ratio, SNR) for a single pulse is usually well below unity, so one pulse by itself cannot be measured. But when many pulses are averaged together, the SNR is improved by the square root of the number of pulses. In his paper, Gordon assumed that 10,000 pulses would be averaged, giving an improvement of a factor of 100 in the SNR. Other factors affecting the SNR are the bandwidth, B, which Gordon chose as 100 kHz, and the pulse width, τ, which controls the vertical scale in the ionosphere that can be explored, as the height resolution is $h/2 = c\tau/2$. Gordon considered values of τ from 0.1 to 10 ms, corresponding to resolution from 15 to 1,500 km. However, τ and B are not independent, since the condition $B\tau > 1$ must hold. With $B = 10^5$ Hz, τ must be greater than 10^{-5} s, comfortably below the smallest values considered. This point will arise later, when we consider the effect of the ions, which can give spectral widths of order 1 kHz.

Gordon assumed that the transmitter and receiver both would use readily-available components, with $P_t = 10^6$ W and $T_{eff} = 600$ K at a few hundred MHz. He found that a 1000-foot dish, with 60% aperture efficiency and a feed loss of 2 db, could explore the ionosphere from 100 to 3000 km. He noted that at the lower heights a smaller antenna could be used, but the full 1000 feet is needed for experiments at 1000 km. In addition, the full-sized dish allows planetary radar measurements to be made, and also allows for sensitive radio astronomy observations.

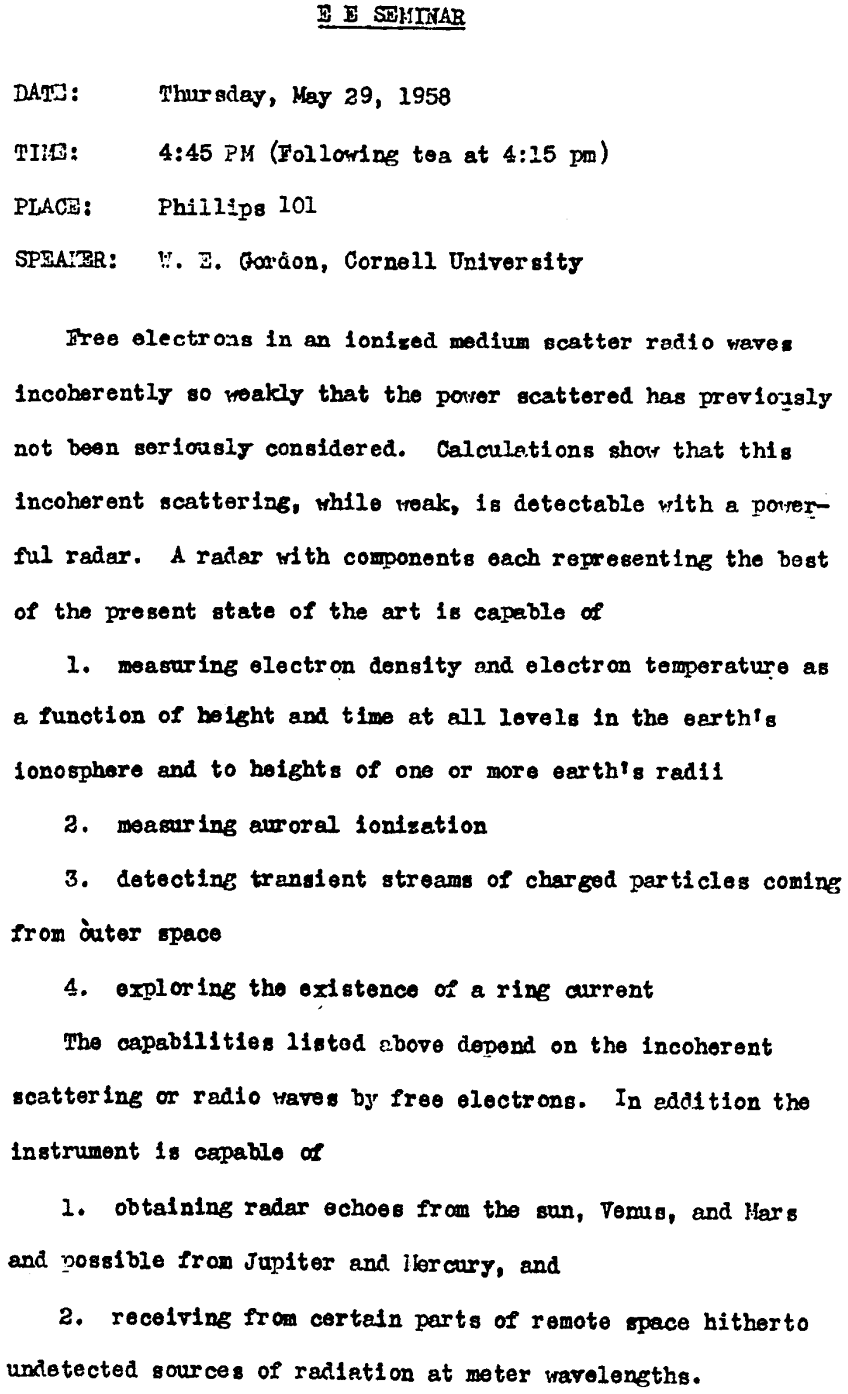
Gordon developed these ideas early in 1958, first described them in April at the weekly seminar of the ionosphere research group in the School of Electrical Engineering at Cornell, and then presented them at a Departmental Seminar (Figure 6) on 29 May 1958 (Farley, 2007; Gordon, 1958a; 2007a; 2007b). Gordon's first paper (1958b) was received at the *Proceedings of the Institute of Radio Engineers* on 11 June 1958 and was published in November, 1958.

A former Cornell graduate student, Kenneth Bowles, heard about Gordon's work and set out to test the IS idea. Bowles was working at the National Bureau of Standards in Boulder, Colorado, and was able to adapt a new 41-MHz transmitter that was being installed at the NBS station in Long Branch, Illinois, for a test. On 21 and 22 October 1958 Bowles made vertical radar experiments that showed a weak signal consisting of excess noise at a range of about 200-400 km (Bowles, 1958). He interpreted this excess as incoherent scatter. His figures definitely show the excess noise, and the peak density region of the ionosphere, the F layer, was known to be at about 200-400 km. However, the signal appeared to have a much narrower spectrum than predicted by Gordon. At the time there probably was little doubt that he had actually seen the IS, and thus had generally confirmed Gordon's calculations. Bowles submitted a paper to *Physical Review Letters* in early November, and this was published on 15 December 1958 (Bowles, 1958).

Gordon (1994: 20-21; 2007a) relates that at an URSI meeting at Pennsylvania State University in October 1958, he received a telephone call from Bowles informing him of the 41-MHz results. Gordon then announced it at the meeting. The word probably spread quickly in the ionosphere community. The echo power was roughly as calculated for incoherent scattering, and a large ground-based radar could be used to monitor the topside of the ionosphere.

Bowles did not quantify his result, and it is difficult to estimate the strength of the echoes he received from the parameters given in his first paper. We can say that there is agreement with Gordon's calculation, to within an order-of-magnitude. But Gordon also calculated the width of the spectrum of the echo, and here Bowles gives a strong hint that his measurement disagrees with the theory. He used bandwidths of 10 and 15 kHz, which for the F region should have been much smaller than the half-width of the spectrum, since the temperature of the F region is about 1500 K and the spectrum should have been at least 100 kHz wide. Bowles (1958: 455) includes this intriguing sentence: "Reception at frequencies slightly separated from the transmitted frequency indicated little thermal broadening (F-region line broadening of the order of 100 kc/sec is expected for incoherent electron scatter)." He did not take the next step and calculate a limit to the spectrum width, even though earlier in the paper he discussed different scattering regimes and how a narrow spectrum could result in some cases.

Bowles' measurements were confirmed in 1960 by Pineo, Kraft, and Briscoe (1960a; 1960b) with experiments conducted at Lincoln Laboratory in Westford, Massachusetts. Pineo et al. used an 84-foot diameter paraboloid at 440 MHz, and were able to study the ionosphere up to about 800 km. At 315 km they measured a spectrum width of 11 kHz, "... 5 to 10 per cent of that predicted by Gordon [1958] on the basis of Doppler broadening by thermal motion of free electrons." (Pineo, et al., 1960a: 1621). In fact, with a pulse width of 500 microseconds, and bandwidths as narrow as 2.3 kHz, they had values of $B\tau$ near unity, and so, as they note, their value for spectrum width is an upper limit.



E E SEMINAR

DATE: Thursday, May 29, 1958

TIME: 4:45 PM (Following tea at 4:15 pm)

PLACE: Phillips 101

SPEAKER: W. E. Gordon, Cornell University

Free electrons in an ionized medium scatter radio waves incoherently so weakly that the power scattered has previously not been seriously considered. Calculations show that this incoherent scattering, while weak, is detectable with a powerful radar. A radar with components each representing the best of the present state of the art is capable of

1. measuring electron density and electron temperature as a function of height and time at all levels in the earth's ionosphere and to heights of one or more earth's radii

2. measuring auroral ionization

3. detecting transient streams of charged particles coming from outer space

4. exploring the existence of a ring current

The capabilities listed above depend on the incoherent scattering or radio waves by free electrons. In addition the instrument is capable of

1. obtaining radar echoes from the sun, Venus, and Mars and possible from Jupiter and Mercury, and

2. receiving from certain parts of remote space hitherto undetected sources of radiation at meter wavelengths.

Figure 6: Announcement of the seminar by William E. Gordon on 29 May 1958 in the School of Electrical Engineering at Cornell University. This copy was provided by Mrs. Elizabeth Gordon, from material left by her late husband, Professor Ralph Bolgiano, of the School of Electrical Engineering at Cornell University.

Pineo et al. (1960b) had an independent measure of the electron density in the F region, from a nearby ionosonde, and so they could estimate the scattering cross-section of the particles. They found $\sigma_{scatt} = 5 - 8 \times 10^{-26}$cm^2, a factor 10 less than the Thomson cross-section for electrons. But their estimate of received power probably was a lower limit, again because the Bτ product was small, and thus their published value is in fair agreement with the Thomson cross-section, 6.65×10^{-25} cm^2. Pineo et al. confirmed Bowles' two results: the Thomson cross-section could be used to (roughly) predict the strength of the echo, and the spectral width of the scattered signal was much less than the value given by thermal motion of electrons.

3 ACCURATE SCATTERING CALCULATIONS

The Bowles result showed the need for a more complete theory for incoherent scatter. Some of the resulting theoretical papers started with the work by Pines and Bohm (1952), who investigated motions in an electron gas neutralized by ions spread into a uniform background, and calculated the spectrum of the fluctuations in density of the electrons. This spectrum could be used to calculate the radar echo, but first the restriction to a smooth background had to be eased. Following Pines and Bohm (1952), Bowles (1959a; 1959b) heuristically argued that the ion motions would control the electron density fluctuations. This explained the measured narrow spectrum; it was connected to the ion thermal velocity.

Bowles' discussion was qualitatively correct, but needed a rigorous basis. Four such papers appeared the following year, by Fejer (1960), Salpeter (1960a; 1960b) and Dougherty and Farley (1960). These analyses proceeded differently but all assumed that the plasma was in thermodynamic equilibrium with no magnetic field. (Salpeter allowed for different temperatures for the ions and electrons.) The common result was that the strength and spectrum of the scattered signal depends on the ratio $L/4\pi D$, where $L = \lambda/2$ is the scale for scattering and D is the Debye length, $D = (kT_e/4\pi n_e e^2)^{1/2} = 6.9(T_e/n_e)^{1/2}$, where T_e is the plasma temperature in Kelvins, and n_e the electron density in cm^{-3}. The Debye length is the 'screening distance' around an ion. At sufficiently high radio frequencies, the fluctuation scale for scattering is small and $L/4\pi D \ll 1$. This is the case that Gordon implicitly used; the electrons are independent and his calculation for the strength and spectrum of IS is correct. However, for ionosphere experiments below a few thousand kilometers the opposite is true: $L/4\pi D \gg 1$, and the scattering, crudely speaking, is mostly from electron clouds moving with the ions. The total strength of the back scattering is reduced by one half (or more, if the electron temperature is greater than the ion temperature), and the spectrum is not Gaussian but is roughly flat-topped and narrow, with the width given by the ion thermal velocity. In addition, as shown by Salpeter and by Dougherty and Farley, the spectrum contains two narrow features, the 'plasma' lines, at frequencies $\nu = \nu_o \pm \nu_p$, where ν_o is the frequency of the incident wave, and ν_p is the plasma frequency. These plasma lines subsequently have proved useful in diagnostics of laboratory plasmas, in addition to the ionosphere.

Figure 5 shows the theoretical spectrum of the IS echo. At top is the Gaussian used by Gordon and originally expected by Bowles; it is calculated from the Doppler shift on electrons with a Maxwell-Boltzmann distribution of velocities, and no interaction with the ions. At bottom is the spectrum obtained when the ions are included and $L/4\pi D \gg 1$. The low peaks on the spectrum are due to heavily damped ion acoustic waves. Note the different scales of both the abscissa and the ordinate on the two graphs. The ion curve (red) is shown on the top as the arrow. It is too narrow for its shape to be recognized, and is far off-scale in power. This readily illustrates that the signal is much narrower and stronger than originally assumed.

The important ion in the F region is singly-ionized oxygen, with atomic weight 16 and mass 14,500 times the mass of an electron. Its rms thermal velocity is smaller by a factor of 120, and the spectral width of the electron echo is similarly 120 times smaller than the value estimated from the electron thermal velocities.

In 1961 five papers including the magnetic field appeared: Farley et al. (1961), Salpeter (1961), Fejer (1961), Hagfors (1961) and Renau et al. (1961). These showed that the field has little effect on the scattering except near perpendicularity between the field and the incident wave vector. When close to perpendicular, the echo splits into lines separated (approximately) by multiples of the ion gyro frequency. Salpeter calculated the spectrum in considerable detail. This flurry of activity continued over the next years, especially with calculations of non-equilibrium effects. Five years later the theory appeared in a plasma physics text (Bekefi, 1966: 260ff).

4 GENERAL INTEREST IN THE HIGH IONOSPHERE (1957-1958)

The International Geophysical Year (IGY) lasted through 1957 and into mid-1958. It was timed to include the period of maximum solar activity, and studies of the ionosphere were included from the start of planning in 1953. One of the programs, for example, was the establishment of more than 75 ionosondes, to measure density and other properties of the ionosphere, up to the level of maximum electron density (IGY Observations ..., 1956). Another was the launching of a number of research rockets. In February 1959 the *Proceedings of the Institute of Radio Engineers* published a special issue on the ionosphere (Morgan, 1959) containing many articles summarizing what was then known.

On 4 October 1957, as part of the IGY, the Soviet Union launched a satellite, *Sputnik 1*, and then a month later launched *Sputnik 2*. On 31 January 1958 the US launched *Explorer 1*, which discovered the Van Allen Belts, the first major scientific discovery from a satellite. *Sputnik 1* was unexpected in the US and startled everyone (York, 1987: 100); it prompted the founding of both the Advanced Research Projects Agency (ARPA, now DARPA, the Defense Advanced Research Projects Agency) in February 1958 (*ibid*: 137) and the National Aeronautics and Space Agency (NASA) in October 1958 (*ibid*: 154). Thus, Bill Gordon's studies for an incoherent scatter radar in early 1958 grew out of an ambience of strong interest in the high ionosphere; and, as described in the Introduction, also grew out of his own earlier work on scatter propagation.

The military also was deeply interested in the ionosphere, not least because of the emerging threat of ballistic missiles. Intercontinental ballistic missiles travel in the ionosphere, and everything about this environment was of interest. In the summer of 1958 the US performed the Argus experiment, consisting of three high-altitude nuclear explosions (*Defence's Nuclear Agency* …, 2002: 143-147). Argus was prompted by some calculations by Nicholas Christofilos, a scientist at Lawrence Livermore National Laboratory. Christofilos had a strong reputation as an original thinker. Prior to the launch of *Explorer 1* and its discovery of the Van Allen Belts, Christofilos had predicted the existence of bands of particles supported by the Earth's magnetic field. He suggested that a series of nuclear bombs exploded at a high altitude would produce a band of particles that might interfere with a ballistic missile, and perhaps even disarm it (York, 1987: 128-132). In the event, Argus showed that there would be negligible interference with a missile, but that communications could be affected.

5 THE STUDY PHASE

The IS radar was enthusiastically supported at Cornell, and Bill Gordon started to sell the idea to funding agencies sometime in the spring of 1958. Gordon's contract with Office of Naval Research (ONR) for radio astronomy research provided funds at first (Gordon, 1979: 18-19), but neither the ONR nor the National Science Foundation could support a detailed study. In principle the Air Force was interested in the ionosphere; this is indicated by a *Guide for Preparation of Contract Proposals* dated August 1958, and an accompanying form letter signed by Morton Alperin, who was Director of Advanced Studies for the Air Force (Alperin, 1958). The letter states: "New knowledge of the extra-atmospheric environment is of particular interest." and "Studies concerning ion density, [and the] ... earth's magnetic field ... are important ..."

So Gordon had to circulate through the Washington agencies, until he finally got the attention of ARPA. This Agency had been founded in February 1958 to coordinate and promote research and development by the different military services, especially on projects related to missiles and space. ARPA was new, well-funded and encouraged new projects; the match between ARPA and the radar was excellent. It was a new idea, and would investigate some aspects of the ionosphere, which was ARPA's 'turf'. ARPA was an agency of the Department of Defense; but its charter also included pure civilian research on subjects related to space and other topics (York, pers. comm., 2008). Gordon's timing was excellent and he was encouraged to study the project, but many trips to Washington and other places were required before ARPA was finally convinced that the big radar would actually work (Gordon, 1994: 11-15).

A preliminary study of the radar was made during the summer and autumn of 1958, and the results were published in a report issued by the School of Electrical Engineering on 1 December 1958 (Gordon, et al., 1958). The report was addressed to the Wright Air Development Center at Wright-Patterson Air Force Base, Ohio, and presumably became the basic document describing the project when the next funding steps were undertaken.

The report was issued only a month after Bowles' demonstration of the narrow nature of the echo spectrum, and before his paper appeared in *Physical Review Letters*. Nearly all the work in the report must have been done with the wide spectrum in mind. There is no reference to Bowles' work in the report, and the funding agencies may not have known about it when they received the report. However, the agencies, where many atmospheric scientists worked, would have learned about Bowles' work soon afterwards.

The primary criterion for the radar was to obtain a useful echo from 1000 electrons cm^{-3} at a height of 1000 km in one second, with a height resolution of 150 km, using readily available components (Gordon, et al., 1958: 2). This leads to an antenna diameter of about 1000 feet. There is some, but not much, arbitrariness in the numbers and hence in the required dish diameter. Based on what was known of the ionosphere at that time, the diameter could not be substantially smaller than 1000 feet without seriously weakening the radar as a scientific instrument.

From the first discussion of a powerful radar in a 1000-foot dish, it was obvious that important scientific programs in addition to the ionosphere could be undertaken. Surfaces of the Moon and planets could be studied (Cohen, 1959), and it was clear that the planets out to Jupiter could be detected with the radar. The inferior conjunction of Venus with the Earth provided an excellent potential target, and the conjunction of 2 May 1961 was picked as a date for completion of the radar (Gordon, et al., 1958: 21). In fact that date was missed by several years.

The Sun provided another possible target, although it was not known if any echoes could be detected from its plasma atmosphere. At that time there was general interest in the topic of solar echoes (Coles, 2004), with the first positive result coming in 1959, at 25 MHz (Eshleman et al., 1960). The solar radio astronomy program at Cornell provided additional interest, including theoretical studies of the possibility of enhanced echos from magnetized regions of the Sun, or from shock waves (Cohen, 1960; Petrosian, 1963). All this led to the first requirement on motion of the radar beam: it had to be at least ±2° from the zenith, to allow for the round-trip travel time between the Earth and the Sun (Gordon, et al., 1958: 5). Radio astronomy possibilities with the dish were less specific than for Solar System radar, but confirmation and extensions of the surveys made in England and Australia were recognized as useful observations, and if the dish surface were accurate enough, studies at the 21-cm line of atomic hydrogen had great potential value. A later report, *Scientific Experiments for the Arecibo Radio Observatory* (1960: 28), also discussed the study of missile wakes, which was an important topic for ARPA.

5.1 Picking the Site

From the beginning it was clear that the radar should be in the tropics, so that the Sun, Moon and planets would go overhead. However, at the urging of the Air Force, some attention was also given to sites in Texas and northern New York, where infrastructure was already in place. In the latter cases the axis would be tilted so that the beam itself would go out close to the Earth's equator. However, the Texas and New York sites were not competitive in cost with the site ultimately chosen, and the New York site also had weather problems (Mason and McGuire, 1958: 26, 34).

A site search was made by the firm of Donald J. Belcher Associates, which was led by Donald Belcher, a Professor of Civil Engineering at Cornell University and a specialist in aerial photographic interpretation (Donald J. Belcher ..., 1958). The choice quickly narrowed to karst regions, limestone areas where underground caves had collapsed, leaving large depressions, or 'sinkholes', in the ground. If the sinkhole roughly fitted the desired shape, the excavation cost could be greatly reduced. For geographic and political reasons Puerto Rico was the region of choice, and three good possibilities were found. These sites were presented to a meeting at Cornell on 12 August 1958, only about six months after Gordon first conceived of the radar. At that meeting two sites were selected for detailed field studies. The optimum site was in the northwest part of the island, in the town of San Sebastian, about 60 miles from San Juan.

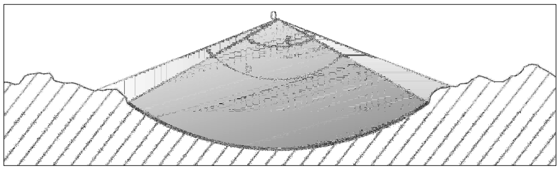


Figure 7: Schematic diagram of the 1000-foot spherical reflector. The primary feed is at point O, the paraxial focus located half-way from the vertex to the center of curvature. The transmitted energy goes out from the feed into the cone of opening angle a. When the feed is aimed off axis, into the angle b, some of the transmitted power is wasted on the ground. This off-axis vignetting, or reduction in the size of the effective aperture, exists for reception also.

Later in 1958, before a specific design was started, a decision was made to find a larger bowl, one that could hold a 1500 foot dish. This diameter was connected with the idea of using a spherical, rather than paraboloidal, dish, so that the beam could be swung off the vertical. With a 1000-foot dish the primary beam starts to hit the ground as it is swung off the vertical, as shown in Figure 7. This leads to a reduction of sensitivity. But if the dish is 1500 feet in diameter, while the primary beam illuminates only 1000 feet, there is no 'vignetting' until the swing reaches 20°, the desired maximum (Gordon, 1959). In a report submitted to the Wright-Patterson Air Force Base in mid-1959, Gordon (1959: 1-2) says "... we propose ... a total size (diameter) of the aperture of 1000 feet ... but located at a site where a future increase in reflector size can be accommodated." Donald J. Belcher Associates returned to the study of Puerto Rican karst topography and found one acceptable site, south of the city of Arecibo, where the observatory was later built (Donald J Belcher ..., 1959). ARPA did not approve the suggestion that the dish should be 1500 feet in diameter (Gordon, 2007a), and the dish as built at 1000 feet has been the largest such structure in the world for forty-six years. However, it will some day be eclipsed by a new structure in China, where radio astronomers have started to build the FAST project, a 500-meter (1640 feet) dish, in a limestone sinkhole (Nan, 2006; Hvistendahl, M., 2009).

5.2 From Paraboloid to Sphere

As originally conceived, the dish was to be a paraboloid with a vertical axis, an aperture 1000 feet in diameter, and the feed at the focal point, 500 feet above the vertex (Gordon, et al., 1958). The feed is supported on a vertical tower and moves on a horizontal structure about 7 meters in radius, so that the beam can swing up to 2° off the vertical. This gives enough motion to follow the Sun during the round-trip flight of the radio waves, during a solar radar experiment. The beam degrades as the feed is moved off-axis, and the degradation gets worse as the frequency is raised. At 400 MHz, the highest frequency considered, the loss in sensitivity is 7 db more than it is at 200 MHz (Gordon et al., 1958). This reduction in sensitivity is lessened if the focus is moved higher, but that increases the height of the tower, leading to an increase in cost. The compromise between cost and performance was complex and involved many variables. The vertical paraboloid was analogous to the 218-foot dish constructed at Jodrell Bank, England, in 1946-1947. This had a tiltable tower mounted at the vertex, and at 160 MHz the beam swing could be as much as 15° (Hanbury-Brown and Lovell, 1958: 192).

Many programs in addition to ionosphere experiments were considered as soon as the dish diameter was calculated as 1000 feet. The inner planets and the Sun were obvious radar targets, and could be studied with a beam swing of 2°. But much more could be done if the swing could be increased. The planet Jupiter, for example, at closest approach, requires about 15°. Note from Figure 6 that Jupiter was considered as a possible target from essentially the beginning of the project. With a 15° swing, observations of more than half of the northern sky could be made, and, importantly, selected targets could be tracked for more than an hour. Further, the ionosphere work could be enhanced, for example by changing the angle to the magnetic field, and by tracking traveling waves.

Gordon learned at ARPA that the Air Force Cambridge Research Laboratories (AFCRL) had been working on spherical reflectors for a decade. All lines through the center of a sphere are equivalent, meaning that a spherical-section antenna fixed to the ground could still look in all directions equally well, except for the 'spillover' or 'vignetting' that occurs when the main beam is moved off-axis and the primary beam is partly aimed at the ground (Figure 7). Gordon credits Ward Low at the Institute for Defense Analyses (IDA) and ARPA for his knowledge and help with spherical dishes, and for connecting him with AFCRL (Butrica, 1996: 89; Gordon, 1979: 26; 1994: 13).

ARPA and AFCRL both were enthusiastic about the large spherical dish. A study published in August 1959 (Gordon, 1959) produced the final shape for the dish: radius 870 feet, aperture diameter 1000 feet, and a maximum off-axis beam swing of 20°. A short 7-page proposal to Air Force Cambridge Research Center dated 30 October 1959 (*Proposal* …, 1959) described the system and its capabilities in broad terms and proposed "... to design build and operate the radar in Puerto Rico." Funding to start this work was obtained in November 1959. A further proposal dated 30 April 1960 (*Proposal* …, 1960) to provide money for construction was approved in June 1960. Excavation at the Arecibo site started in September 1960. A good description of the project and the construction phase can be found in the Final Construction Report to the Air Force Cambridge Research Laboratories dated 30 November 1963 (*Construction* ..., 1963).

The Arecibo Ionospheric Observatory (its then-name) was dedicated in November 1963 (Figure 8). The interval from conception of the project to completion was less than 6 years—a remarkable achievement. There is an extraordinary contrast between the speed of the Arecibo project and the painfully slow pace of a large science project today. A great deal of the speed can be credited to ARPA and the Cold War rivalry, but the dedication and enthusiasm of Bill Gordon and his team were central.

6 CODA

As described in Section 2, the dish was over-designed by a large factor for its original task, which was the measurement of ionospheric electron density and temperature up to a few thousand kilometers. This came about because Gordon used an incorrect assumption for the density fluctuations in the plasma, and this led to the 1000 feet diameter of the dish. People then began thinking about a 1000-foot reflector, and the remarkable power of that swamped the original task when the error was discovered less than a year later. Apparently, neither the designers nor the funding agency looked back. No discussion on this point is in any of the Cornell reports available to me. The reports published in 1958 and 1959 do not make reference to Bowles' 1958 paper, although the result was known to the Cornell people and must have been known at ARPA. The entire program remained focussed on the 1000-foot dish, with all the enhanced possibilities that entailed. It appears that ARPA, whose interest centered on studying missile wakes, found the 1000-foot dish interesting and worth funding, whereas a 100-foot dish was not interesting (York, 2008).

Gordon's assumption was an extraordinarily beneficial error. Because of it, we have had the world's largest reflector for forty-five years. It is interesting that a somewhat analogous situation developed in England at The Jodrell Bank Experimental Station (now the Jodrell Bank Observatory). In 1941 P.M.S. Blackett and A.C.B. Lovell (1941) published an article on radio echoes from cosmic ray (CR) air showers, and showed that they should be readily detectable. Two months later, however, T.L. Eckersley wrote to Blackett pointing out that collisions of the electrons with air molecules might greatly reduce the echo strength (Lovell, 1993: 124). This letter was forgotten during the War but surfaced again in 1945, and Lovell returned to the CR echo problem. By early 1946 it was clear that Eckersley was right: collisions were important and the echoes would be seen only if the CR spectrum extended to very high energies, and a very large antenna was used. But by this time the Jodrell Bank Experimental Station had been set up, to do CR experiments based on the 1941 article. That work shifted to studying meteors, but the realization that a large dish would be needed to see the CR echoes helped to support later decisions to build first the stationary 218-foot paraboloid, and then the moveable 250-foot dish. Lovell (1993: 119) states

> Evidently if we had been able to give attention to Eckersley's letter in 1941, the incentive for the proposed post-war research would have vanished and Jodrell Bank would not exist today.

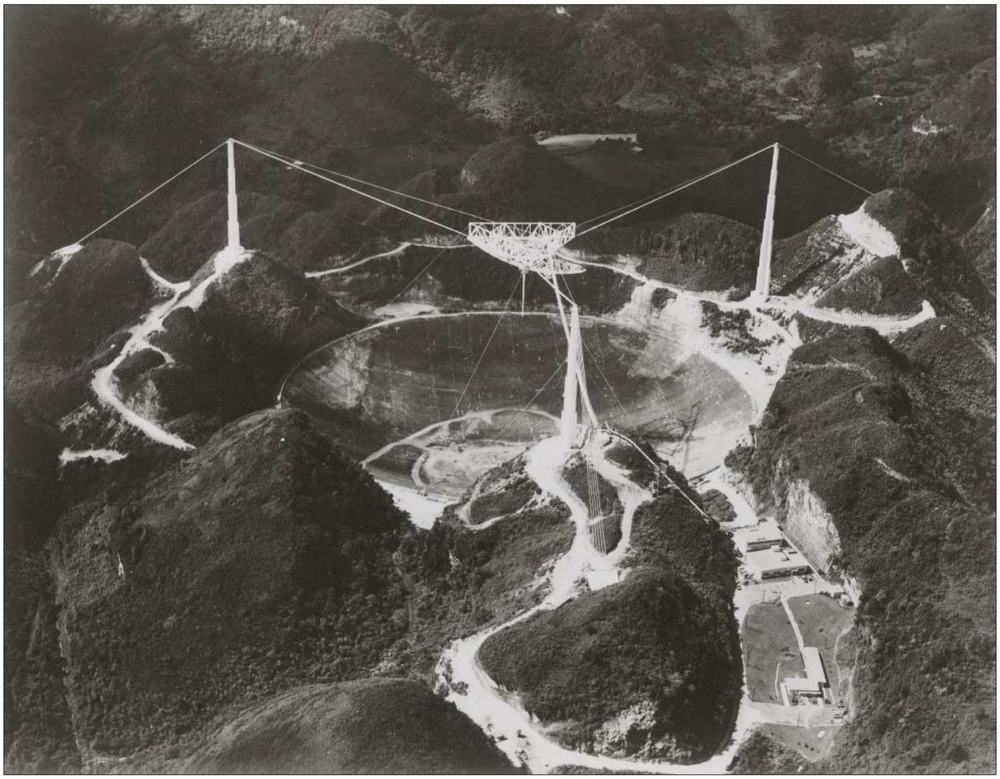


Figure 8: Aerial photograph showing the newly-completed Arecibo Ionospheric Observatory and the surrounding karst terrain (courtesy: Cornell University).

The Arecibo system has made remarkable advances in radar and radio astronomy, as well as in atmospheric and ionospheric physics. An important early result was the surprising determination that the rotation period of Mercury is 59 ± 5 days, two-thirds of the orbital period (Pettengill and Dyce, 1965). Another important result was the 1974 discovery of a pulsar that orbited another neutron star (Hulse and Taylor, 1974). Long-term monitoring of this binary system showed that gravitational radiation caused the pulsar's orbit to change in a manner consistent with Einstein's General Theory of Relativity. Hulse and Taylor were awarded the 1993 Nobel Prize in Physics for this discovery.

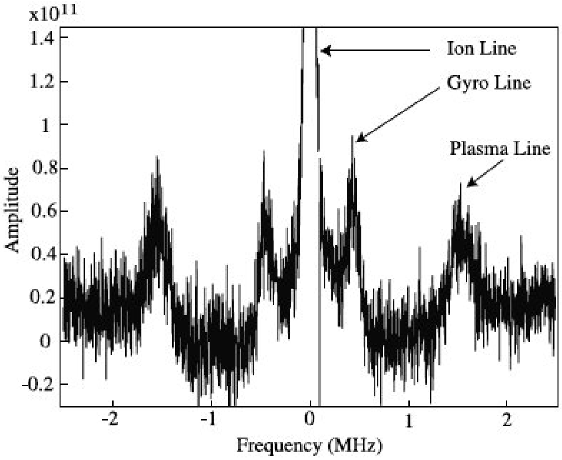


Figure 9: Spectrum of ionosphere echo obtained at sunrise at Arecibo on 15 August 2004. The central high peak corresponds to the red curve in Figure 5. The close-in peaks are offset, approximately, by the electron gyro frequency times the cosine of the angle between the wave vector and the magnetic field; and the outer peaks are offset, approximately, by the electron plasma frequency. With information like this, the strength of the field and the electron density can be tracked with height (after Aponte et al., 2007: Figure 3).

The Arecibo radar has also done far more in ionospheric research than could have been planned in 1958. As an example, Figure 9 shows a recent IS spectrum with three lines, each connected to a type of wave in the magnetized plasma (after Aponte, et al., 2007). The ion line corresponds to the red curve in Figure 5, and arises from scattering on ion acoustic waves. The gyro and plasma lines correspond to the lower and upper hybrid resonances (Stix, 1962: 32). These lines offer powerful diagnostics of the plasma and its magnetic field. The great sensitivity of the 1000-foot dish makes measurements like this possible. As the largest dish in the world, with ever-increasing versatility, the Arecibo radio telescope has the potential to continue to make fundamental discoveries for years to come.

7 NOTES

1. Research for this paper began in the early 2000s, when the author realized that he had forgotten some of the details of his own involvement in the Arecibo project some forty-five years earlier. Rereading the early papers then led to the question implied in the first paragraph of the Introduction: "Why, after Bowles' measurements, did the dish continue to be 1000 feet in diameter?" This paper is an attempt to answer this question. Useful histories of the Arecibo Observatory have been written by Butrica (1996) and by Altschuler (2002). Butrica describes the origins of the radar and its relationship with other planetary radar systems at Lincoln Laboratory and the Jet Propulsion Laboratory; he also discusses the politics and early funding problems associated with the Observatory. Altschuler (2002) gives a brief history of the Observatory, including its origins, construction, and the upgrades, the first in 1974 to raise the operating frequency, and the second in 1997 to greatly increase the bandwidth and versatility of the system for radio astronomy.
2. William E. Gordon was born in Patterson, New Jersey, on 8 January 1918. He went to Montclair State Teachers College and received a B.A. degree in mathematics in 1939. During World War II he trained as a meteorologist at New York University, and spent much of the wartime studying the atmospheric refraction of radio waves. After the war he did atmospheric research at the University of Texas and in 1947 went to Cornell University, where he worked with Henry Booker on the mechanism of long-distance radio propagation (Booker and Gordon, 1950). He received a Ph.D. degree in 1953, and was a member of the Electrical Engineering faculty at Cornell from 1953 to 1965. In 1958 he conceived of the incoherent scatter radar technique for studying the ionosphere. He developed the Arecibo Observatory, and was its Director from 1960 to 1965. In 1965 he moved to Rice University as Dean of Science and Engineering, and in later years was Provost and Acting President. He retired from Rice in 1986 and currently lives in Ithaca, New York. Professor Gordon has received many honors and awards, and was active in many scientific and engineering societies (including a term as Foreign Secretary of the National Academy of Sciences).
3. Kenneth L. Bowles was born in Bronxville, N.Y., on 20 February 1929. He attended Cornell University, receiving a B.S. degree in Engineering Physics in 1951 and a Ph.D. in 1955 in Electrical Engineering, working with Henry Booker on radar studies of the Aurora Borealis. In July 1955 he joined the National Bureau of Standards where, in 1958, he successfully adapted a NBS transmitter to make the first measurements of ionosphere scatter echoes (Bowles, 1958). In 1960 he founded the Jicarmaca Radar Observatory, an equatorial ionospheric scatter radar near Lima, Peru, and was its Director from 1960 to 1964. In 1965 he joined the new Department of Applied Electrophysics at the University of California, San Diego (UCSD). His career-long interest in computing eventually resulted in widespread use of the programming language Pascal on personal computers. Professor Bowles retired in 1995 and currently lives in Del Mar, California. He has become an expert on California wildflowers and their identification with computers.

8 ACKNOWLEDGEMENTS

I am grateful to Ken Bowles, Don Farley, Ed Salpeter, Herb York and especially Bill Gordon for information and insight into the early days of the Arecibo idea, and to Don Farley, Paul Goldsmith, Dan Kevles, Gordon Pettengill and the two anonymous referees for comments on the manuscript. I thank Don Farley for his help in obtaining the early seminar notice (Figure 6), and other materials; the staffs of the Fondren Library at Rice University, the Archives of Cornell University and the NAIC office for their help in obtaining manuscripts and photographs; and Murph Goldburger and Dan McMorrow for assistance in obtaining lists of JASON reports from the 1960s. Not least, I thank the search engines of the internet, which gave me material ranging from declassified military reports to the photograph of Ken Bowles (Figure 4) that was on page 14 of an old Cornell magazine that was for sale on eBay.

9 REFERENCES

Alperin, M. 1958. Undated letter accompanying *Guide for Preparation of Contract Proposals*, dated August 1958, Directorate of Advanced Studies, Air Force Office of Scientific Research, Air Research and Development Command, Pasadena, California. Materials at the NAIC office, Cornell University. Attached to an email from Jill Tarbell to Don Farley, dated 1 November 2007, and forwarded to Marshall H. Cohen.

Altschuler, Daniel R., 2002. The National Astronomy and Ionosphere Center's (NAIC) Arecibo Observatory in Puerto Rico. In Stanimirovic, S., Altschuler, D.R., Goldsmith, P.F., and Salter, C.J. (eds.). *Single-Dish Radio Astronomy: Techniques and Applications*. San Francisco, Astronomical Society of the Pacific (ASP Conference Series, Volume 278). Pp. 1-24.

Aponte, N., Sulzer, M.P., Nicolls, M.J., Nikoukar, R., and Gonzalez, S., 2007. Molecular ion composition measurements in the *F*1 region at Arecibo. *Journal of Geophysical Research*, 112, A06322, doi:10.1029/2006JA012028.

Appleton, E.V., and Barnett, M.A.F., 1925. On some direct evidence for downward atmospheric reflection of electric rays. *Proceedings of the Royal Society A*, 109, 621-641.

Battan, L.J., 1973. *Radar Observations of the Atmosphere*. Chicago, University of Chicago Press.

Bekefi, G., 1966. *Radiation Processes in Plasmas*. New York, Wiley.

Blackett, P.M.S., and Lovell, A.C.B., 1941. Radio echoes and cosmic ray showers. *Proceedings of the Royal Society A*, 177, 183-186.

Booker, H.G., and Gordon, W.E., 1950. A theory of radio scattering in the troposphere. *Proceedings of the Institute of Radio Engineers*, 38, 401-412.

Booker, H.G., and Gordon, W.E., 1957. The role of stratospheric scattering in radio communication. *Proceedings of the Institute of Radio Engineers*, 45, 1223-1227.

Bowles, K.L., 1958. Observation of vertical-incidence scatter from the ionosphere at 41 Mc/sec. *Physical Review Letters*, 1, 454-455.

Bowles, K.L., 1959a. Incoherent scattering by free electrons as a technique for studying the ionosphere and exosphere: some observations and theoretical considerations. In Poeverlein, H. (ed.). *The Upper Atmosphere Above F2-Maximum*. Papers Presented at the Symposium of the Ionospheric Research Committee, AGARD Avionics Panel, Paris, France, 26-28 May, 1959, North Atlantic Treaty Organization, Advisory Group for Aeronautical Research and Development. Pp. 223-241.

Bowles, K.L., 1959b. Incoherent scattering by free electrons as a technique for studying the ionosphere and exosphere: some observations and theoretical considerations. *NBS Report 6070*, dated September 18.

Bowles, K.L., 1961. Incoherent scattering by free electrons as a technique for studying the ionosphere and exosphere: some observations and theoretical considerations. *Journal of Research of the National Bureau of Standards - D. Radio Propagation*, 65D, 1-14.

Bowles, K.L., 2007. Personal communication with the author. See, also, the email from KLB to Don Farley, Marshall Cohen, Bill Gordon, and Ben Balsey, dated 21 May.

Butrica, A.J., 1996. *To See the Unseen*. Washington, U.S. Government Printing Office (NASA History Series, NASA SP-4218). Pp. 88-105.

Cohen, M.H., 1959. *Radar Echo from a Rough Rotating Planet*. School of Electrical Engineering, Cornell University, Radio Astronomy Technical Report No. 1, dated 1 June (Research Report EE 428).

Cohen, M.H., 1960. High-frequency radar echoes from the Sun. *Proceedings of the Institute of Radio Engineers*, 48, 1479.

Coles, W.A., 2004. Solar radar. In Gary, D.E., and Keller, C.U. (eds.). *Solar and Space Weather Radiophysics*. Dordrecht, Kluwer. Pp. 335-354.

Construction of the Department of Defense Ionospheric Research Facility - VII, 30 November 1963. New York, Cornell University, Center for Radiophysics and Space Research (Research Report RS 55, prepared under the supervision of W.E. Gordon for Air Force Cambridge Research Laboratories, Office of Aerospace Research, United States Air Force, Bedford, Mass.).

Defense's Nuclear Agency 1947-1997, Defense Threat Reduction Agency. Washington, US Department of Defense (DTRA History Series), 2002.

Donald J. Belcher & Associates, 1958. *Site Locations for a Proposed Radio Telescope*. Prepared for the School of Electrical Engineering, Cornell University, and dated August 1958. This report also appears as Appendix C in Gordon, Booker, and Nichols (1958), op. cit.

Donald J. Belcher & Associates, 1959. *Site Selection for a Proposed Radio Telescope, Supplement No. 1*. Prepared for the School of Electrical Engineering, Cornell University, and dated March 1, 1959. This report appears as an Appendix in Gordon (1959), Research Report EE 435, op. cit.

Dougherty, J.P., and Farley, D.T., 1960. A theory of incoherent scattering of radio waves by a plasma. *Proceedings of the Royal Society A*, 259, 79-99.

Einstein, A., 1910. Theorie der Opaleszenz von homogenen Flüssigkeiten und Flüssigkeitsgemischen in der Nähe des kritischen Zustandes. *Annalen der Physik*, 33, 1275-1298. Translation by Anna Beck, 1993. The theory of the opalescence of homogeneous fluids and liquid mixtures near the critical state. In *Collected Papers of Albert Einstein Volume 3, The Swiss Years: Writings, 1909-1911*. Princeton, Princeton University Press. Pp. 231-249.

Eshleman, V.R., Barthle, R.C., and Gallagher, P.B., 1960. Radar echoes from the Sun. *Science*, 131, 329-332.

Farley, D.T., Dougherty, J.P., and Barron, D.W., 1961. A theory of incoherent scattering of radio waves by a plasma II. Scattering in a magnetic field. *Proceedings of the Royal Society A*, 263, 238-258.

Farley, D.T., 2007. Email to M.H. Cohen and W.E. Gordon, dated 16 May, 2007.

Fejer, J.A., 1960. Scattering of radio waves by an ionized gas in thermal equilibrium. *Canadian Journal of Physics*, 38, 1114-1133.

Fejer, J.A., 1961. Scattering of radio waves by an ionized gas in thermal equilibrium in the presence of a uniform magnetic field. *Canadian Journal of Physics*, 39, 716-740.

Forsyth, Peter, 2002, Comments at a meeting at the University of Western Ontario, 25 November 2002. URL: physics.uwo.ca/~drm/history/space/w_s10.html

Franklin, C.A, 1993. International Milestones in Engineering Ceremony, Shirley Bay, Ottawa, May 13, 1993. Excerpted from document NSSDC/WDC-A-R&86-09. URL: ewh.ieee.org/reg/7/millennium/alouette/alouette_franklin.html.

Friedman, H., 1959. Rocket observations of the ionosphere. *Proceedings of the Institute of Radio Engineers*, 47, 272-280.

Gillmor, C. Stewart, 1986. *Federal Funding and Knowledge Growth in Ionospheric Physics, 1945-81*. Social Studies of Science, Volume 16.

Gordon, W.E., 1958a. Announcement of the Seminar by William E. Gordon on 29 May 1958, School of Electrical Engineering, Cornell University. Copy provided by Mrs. Elizabeth Gordon, from the material left by her late husband Professor Ralph Bolgiano of the School of Electrical Engineering at Cornell University.

Gordon, W.E., 1958b. Incoherent scattering of radio waves by free electrons with applications to space exploration by radar. *Proceedings of the Institute of Radio Engineers*, 46, 1824-1829.

Gordon, W.E., 1959. *Antenna Beam Swinging and the Spherical Reflector*. Supplement to Gordon, W.E., Booker, H.G., and Nichols, B., 1958. *Design Study of a Radar to Explore the Earth's Ionosphere and Surrounding Space*. New York, Cornell University, School of Electrical Engineering (Research Report EE 435, dated 1 August 1959). (Also denoted by *Engineering Report No. 5*.)

Gordon, W.E., 1979. Self interview, dated March 1979. Copy received from Professor D. T. Farley, Cornell University, on 7 April 2008. A discussion of this self-interview is contained in the correspondence between W.E. Gordon and Joanna Rankin, March-June 1979, Rice University, Fondren Library (Papers of William E. Gordon, Box 10 No. 6).

Gordon, W.E., 1994. Transcript of an interview conducted by Andrew Butrica at Rice University on 28 November 1994. Copy received from Professor D. T. Farley, Cornell University, on 7 April 2008.

Gordon, W.E. 2007a. Email to M.H. Cohen and D.T. Farley, dated 10 May 2007

Gordon, W.E. 2007b. Email to M.H. Cohen and D.T. Farley, dated 16 May 2007

Gordon, W.E. 2008. Email to M.H. Cohen, dated 17 October 2008.

Gordon, W.E., Booker, H.G., and Nichols, B., 1958. *Design Study of a Radar to Explore the Earth's Ionosphere and Surounding Space*. New York, Cornell University, School of Electrical Engineering (Research Report EE 395, dated 1 December 1958). (Also denoted by *Engineering Report No. 3*.)

Hagfors, T., 1961. Density fluctuations in a plasma in a magnetic field, with applications to the ionosphere. *Journal of Geophysical Research*, 66, 1699-1712.

Hanbury-Brown, R., and Lovell, A.C.B., 1958. *The Exploration of Space by Radio*. New York, John Wiley.

Helliwell, R.A., and Morgan, M.G., 1959. Atmospheric whistlers. *Proceedings of the Institute of Radio Engineers*, 47, 200-208.

Hines, C.O., 1960. Symposium on the exosphere and upper *F* region. Summary of the Proceedings. *Journal of Geophysical Research*, 65, 2563-2569.

Hulse, R.A., and Taylor, J.H., 1974. Discovery of a pulsar in a binary system. *Astrophysical Journal Letters*, 195, L51-L53.

Hvistendahl, M., 2009. Radio astronomers go for high gain with mammoth telescope. *Science*, 324, 1508-1509.

IGY observations of the ionosphere, 1956. *Science*, 124, 1072 (1956).

Lovell, Sir Bernard, 1993. The Blackett-Eckersley-Lovell correspondence of World War II and the origin of Jodrell Bank. *Notes and Records of the Royal Society of London*, 47, 119-131.

Mason, R.E., and McGuire, W., 1958. *The Fixed Antenna for a Large Radio Telescope - Feasibility Study & Preliminary Cost Estimate*. Prepared for the School of Electrical Engineering Cornell University, November 1958.

Morgan, M.G., 1959. The nature of the ionosphere - an IGY objective. *Proceedings of the Institute of Radio Engineers*, 47, 131-132.

Nan, R., 2006. Five hundred meter aperture spherical radio telescope (FAST). *Science in China: Series G Physics, Mechanics, and Astronomy*, 49, 129-148.

Petrosian, V., 1963. On the Possibilities of Ultra-High Frequency Echoes from the Sun. Unpublished M.S. Thesis, Cornell University.

Pettengill, G.H., and Dyce, R.B., 1965. A radar determination of the rotation of the planet Mercury. *Nature*, 206, 1240.

Pineo, V.G., Kraft, L.G., and Briscoe, H.W., 1960a. Ionospheric backscatter observation at 440 Mc/s. *Journal of Geophysical Research*, 65, 1620-1621.

Pineo, V.G., Kraft, L.G., and Briscoe, H.W., 1960b. Some characteristics of ionospheric backscatter observed at 440 Mc/s. *Journal of Geophysical Research*, 65, 2629-2633.

Pines, D. and Bohm, D., 1952. A collective description of electron interactions: II. Collective vs idividual particle aspects of the interactions. *Physical Review*, 85, 338-353.

Proposal for the Radar Exploration of the Earth's Ionosphere and Surrounding Space (Radar Design, Construction and Operation, Analysis and Research). New York, Cornell University, School of Electrical Engineering. Prepared for the Air Force Cambridge Research Center, and dated 30 October 1959.

Proposal for the Continuation of Contract AF19(604)-6158 (Arecibo Radio Observatory) for the Construction Phase, Covering the Period 6/1/60 to 7/31/61. New York, Cornell University, Center for Radiophysics and Space Research. Prepared for the Air Force Command and Control Development Division, L.G. Hanscom Field, Bedford, Mass., and dated 30 April 1960.

Renau, J., Camnitz, H., and Flood, W., 1961. The spectrum and the total intensity of electromagnetic waves scattered from an ionized gas in thermal equilibrium in the Presence of a static quasi-uniform magnetic field. *Journal of Geophysical Research*, 66, 2703-2732.

Salpeter, E.E., 1960a. Scattering of radio waves by electrons above the ionosphere. *Journal of Geophysical Research*, 65, 1851-1852.

Salpeter, E.E., 1960b. Electron density fluctuations in a plasma. *Physical Review*, 120, 1528-1535.

Salpeter, E.E., 1961. Plasma density fluctuations in a magnetic field. *Physical Review*, 122, 1663-1674.

Scientific Experiments for the Arecibo Radio Observatory. New York, Cornell University, Center for Radiophysics and Space Research (Research Report RS 5, Scientific Report No. 2, dated 31 March 1960). Prepared for Electronics Research Directorate, Air Force Cambridge Research Center, Research and Development Command, United States Air Force, Bedford, Mass.

Stix, T.H., 1962. *The Theory of Plasma Waves*. New York, McGraw-Hill.

York, H.F., 1987. *Making Weapons, Talking Peace*. New York, Basic Books.

York, H.F., 2008a. Interview with MHC, dated 24 January.

York, H.F., 2008b. Email to MHC, dated 15 October.

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Journal of Astronomical History and Heritage, 12(2), 153-158 (2009).

STUDY AND ORIENTATION OF THE MT. OCHE 'DRAGON HOUSE' IN EUBOEA, GREECE

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Abstract: In southern Euboea, Central Greece, there are several megalithic buildings known as 'drakospita' (or dragon houses) whose builders and purpose are unknown. On 22 March 2002 and 4 July 2004 we visited the best-preserved of all drakospita on top of Mt. Oche, measured its dimensions and calculated its orientation based on the azimuth of sunset and moonrise. A Sirius-rise orientation corresponding to *ca* 1100 B.C., not inconsistent with previous archaeological dating based on artefacts found inside the structure, indicates a religious/astronomical purpose for the building. It could probably be argued that at least the famous drakospito at Mt. Oche was not only a place of worship but also an ancient astronomical observatory.

Keywords: Dragon-house, drakospito, Euboea, astronomical observatory

1 INTRODUCTION

The Dryopes were a Prehellenic ancient tribe, mentioned in Greek mythology by both Herodotus and Pausanias. Since their name is Indo-European, Dryopes are thought to belong to the Indo-European part of the Prehellenic racial substrate. Initially, they occupied the area between the mountains Oete and Parnassus, a dry land called Dryopis. They are thought to be related to Leleges, and they have been characterized as a tribe of bandits. The settlements of Leleges and Dryopes lasted until the end of the Neolithic Period, when the first Greek tribes started to appear. Pressed by them, the Dryopes supposedly immigrated to southern Greece, *ca* 1200 B.C. (Papamanoles, 1954), colonizing Euboea and the Cyclades islands. Herodotus (who is not always a reliable source, so the reader must be cautious) writes that during the period of the movements of the Greek tribes, Dryopes from Euboea colonized the island of Kythnos, which took the name Dryopis as a whole (Herodotus: 8, 46). On the island of Euboea the Dryopes settled in the southeast part of the island, mainly in Styra and Karystos (see Figure 1). Styra is a small town situated approximately 30 km to the northwest of Karystos and 90 km to the southeast of Chalkis, the capital of Euboea. The city of Karystos is built on the innermost point of a bay in the southern part of Euboea, under Mt. Oche. This mountain is the tallest mountain in this part of Euboea, and its highest peak, Prophet Elias, reaches an altitude of 1398 m.

Very near the top of Mt. Oche there is a megalithic building which is preserved in good condition (Figure 2) and is known as the 'drakospito' (i.e. house of the dragon). In general, in Euboea, 'drakospita' or 'dragà', are local names assigned to between twenty-three and twenty-six such stone buildings (depending on who you believe), or remnants of them. Their presence is restricted to the southeast third of the island, with about a dozen in the area around Styra. According to the local tradition, these structures were built by dragons and the king of the Cyclops resided here. The reason is simple: only giants, dragons or Cyclops were capable of transporting these huge rocks (Politis, 1904: I, 220-222).

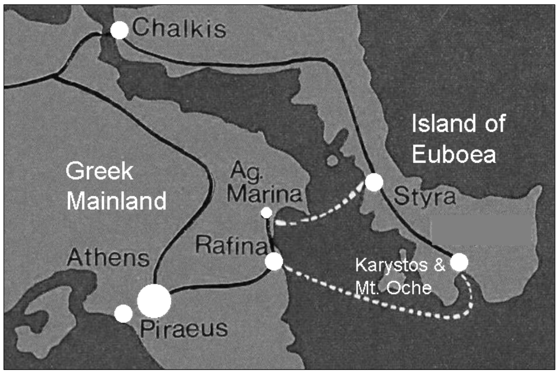

Figure 1: Localities mentioned in the text.

Today, the drakospita stand as a testimony to a distinct cultural phase in Euboean history, with the Dryopes as their most probable builders, provided that the approximate age of their construction is the one inferred by the present study.

2 PREVIOUS STUDIES OF THE DRAKOSPITA

The first modern reference to these buildings dates to 21 October 1797, and was recorded by the British geographer and geologist John Hawkins (1758–1841). He was the first to discover the drakospito on Mt.

Oche, and believed that it was an ancient temple. Other Greek and overseas researchers followed, including H.N. Ulrichs (1842), G. Welcker (1850), L. Ross (1851), M.J. Girard (1851), G. Bursian (1855) and, more recently, Th.G. Papamanoles (1954).

Three drakospita near Styra, known as Pálle-Lákka Dragò, are especially imposing, but most impressive of all is the drakospito on Mt. Oche. None of the others preserves the perfection of its construction.

Some archaeologists (see Ulrichs, 1842) consider the drakospita as sanctuaries of Teleia Hera, the 'legal' wife of Zeus and thus protector of marriage due to her holy union with the Father of the Gods, while others, (see Bursian, 1855), believe that they were places of worship of Hercules. Both these views connect drakospita with worship, and assign to them a well-defined religious importance.

The temple theory is also supported by Theodor Wiegand (1896: 11-17), who

> … was the first to point out that the Dragon-House of Mt. Oche was by no means Mycenaean – despite the similarity between its roof construction and the corbelling systems used at Mycenae and Tyrins. (Carpenter and Boyd, 1977: 1).

Franklin P. Johnson (1925) was the first to postulate a Karian derivation by noting the features shared by the so-called dragon-houses of Euboea and certain even less well-known structures in Karia (Asia Minor). J. Carpenter and D. Boyd (1977) also favour a religious usage.

In 1959 Professor Nikolaos K. Moutsopoulos studied the Mt. Oche drakospito and eleven similar buildings, and excavated the surrounding space in 1960 and 1978-1980. Inside the Mt. Oche building he discovered numerous pots, while outside the building he located an apothetes, i.e. a subterranean construction inside which some utensils and animal bones were found (probably relics of ritual sacrifices), as well as pottery fragments and inscriptions dating from the Preclassical Period to the Hellenistic Period; on one of the potsherds were inscriptions in an unknown kind of writing. These relics are now housed in a small archaeological museum at Karystos (inside the Yokaleio Cultural Foundation), where one can also see a couple of finds from other drakospita near Karystos and Styra.

The study of the Mt. Oche building, together with certain architectural details, persuaded Moutsopoulos that this megalithic monument was a temple of the Dryopes built some time before 700 B.C., a temple where sacrifices had taken place since the Archaic (Preclassical) Period. However, Moutsopoulos (1992) dates the pots found during the drakospito excavation to the early Hellenistic Period, that is third or second centuries B.C. The same dating is proposed by Carpenter and Boyd (*ibid*.). This cannot of course exclude a much older construction age for the building itself.

Carpenter and Boyd (*ibid*.) report the existence of an edifice on the western interior wall of the structure, which they considered probable evidence of sacrifices, together with a 50-cm diameter roof opening, a kind of primitive chimney for the smoke from the sacrifices. They also argue in favour of the existence of an altar in front of the edifice.

Ulrichs (1842) and Bursian (1855) independently reported the existence of a square table-like plate inside the building, probably for placing the offerings on. Moutsopoulos mentions, however, that during the 1960 excavations neither the edifice nor the square table-like plate was found, and during our recent investigations we also did not notice anything like an edifice on the western interior wall.

Figure 2: Photograph of the Mt. Oche drakospito looking northeast before sunset on 4 July 2004.

Most researchers who have studied the Mt. Oche drakospito focus either on the religious character of the building (sanctuary/temple of the Perfect Hera or Hercules), or on its archaeological or architectural significance. Carpenter and Boyd note (1977: 1) as archaeologists that, if the drakospito is regarded as a temple, then the placement of the entrance at the long side and the confinement of sacrifices inside it do not agree with the Greek modes of temple construction and usage, respectively; therefore, they conclude that most probably it was a sanctuary of Leleges or Karian slaves.

It should be noted that apart from southeast Euboea no other places in Greece have drakospita, if we exclude some markedly smaller similar constructions in Mane (southern Peloponnese) or, according to Carpenter and Boyd (*ibid.*), a solitary example on Mt. Hymettos in Attica. However, from a geological point of view we assert that the Hymettos construction can in no way be associated with the Mt. Oche drakospito.

In the Greek folklore, the drákoi (plural of drákos, the common Greek form of the word dragon) are large legendary monsters with the general form of a serpent, usually winged and gifted with supernatural powers. Such mythical monsters are to be found, with some variations, in all the mythologies or folklore of the world. However, in Greek the word drákoi means also humanoid creatures of larger-than-normal height, with muscular power exceeding the human measures. These creatures are thought to live inside caves on the mountains. Probably the legends about the humanoid drákoi are the succession of the Greek myths about Giants, Titans, Cyclops and Centaurs (Politis, 1904, II, 994-995). Out of these dragon legends much topographic nomenclature was created, and is used up to this day: drakotrypa (dragon hole), drakospelia (dragon cave), drakovouni (dragon mountain), drakolimne (dragon lake), etc.

3 OUR STUDY OF THE MT. OCHE DRAKOSPITO AND ITS ORIENTATION

We visited the Mt. Oche drakospito at both the time of the vernal equinox (22 March 2002) and around the time of the summer solstice (4 July 2004). We noticed the presence of ancient quarries on the slopes of the mountain, the source of the well-known marbles that secured wealth for ancient Karystos, the third largest city on ancient Euboea. According to some literature, the entrances of drakospita look towards the ancient quarries. In Kylindroi, in the vicinity of Karystos, one can see imposing marble columns from that period. In the Styra area there is an equally-impressive ancient quarry near Ai-Nikolas, and two others in the area of Kapsala (a village 2 km to the south of Styra). The southern Euboea area was known in antiquity for its quarries, as mentioned by Strabo (X 16). So, although the drakospita themselves are not made of marble, some researchers have hypothesized that they were the residences of the local quarry workers. Maybe the smaller ones could have been erected, or simply used, by such people, but this hypothesis seems improbable for the largest one of all, on Mt. Oche, because of its position on the very top of the mountain, a hard-to-reach and cold place.

The Mt. Oche drakospito lies at an altitude of 1386 m (4547 feet), on the tiny plateau formed between the twin peaks of the mountain. Access is rather difficult and requires some mountaineering ability, but not special climbing skills.

The geographical coordinates of the building, determined by using a hand-held GPS, are: latitude 38° 03′ 06″ North and longitude 24° 27′ 10″ East in the World Geodetic Reference System (WGS ’84). The area of the peaks is bare and precipitous.

The ancient building is an approximate rectangular parallelogram made of large blocks of rock, weighing up to 10 tons each, and the way in which the blocks fit together and the overall quality of the construction is impressive. We carefully measured the dimensions of the main building. The largest of the stone blocks is 4.0 × 2.0 × 0.4 m. All of the blocks of rock seem to have been extracted from the same area, and geologically they are amphibolites, rocks composed of silicate minerals. From the inside we could testify to the excellent state of preservation. Indeed, the strength of the construction and the feeling of safety offered by this megalithic monument prompted the people to think of it as the creation of supernaturally-strong beings, dragons or Cyclops. The lowest blocks are fitted into the natural rock substrate, while—where needed—cavities were filled with smaller stones. No trace of any connecting mortar, such as mud, was detected.

The entrance of the drakospito, visible in Figure 2, is made of three slate blocks (a trilithon) forming a Π shape, a common feature of all ‘dragon houses’.[1] It may be noticed that at least the entrance of the Mt. Oche dragon house resembles the dolmens of the Atlantic coast. The circular dolmens with corridors in Bretagne and Poitou date from the end of the fifth millennium B.C. (such as the ‘Table of the Merchants’ at Locmarie), or the beginning of the fourth millennium.

The top block on the Mt Oche drakospito measures 1.2 m × 2.3 m × 0.2 m and sits at a height of 2 m. The thickness of the walls is everywhere larger than or equal to 1.40 m (for comparison, one member of the Pálle-Lákka Dragò trilithon has average wall thickness of 1.17 m, and another one 1.05 m). The interior comprises just one room, which measures 9.80 m long and 4.90 m wide,[2] i.e. a 2:1 ratio, forming a space of about 48 m^2. The height of the walls is 3.45 m and that of the building approximately 4.5 m. The only wall with windows is the southern one, where two small windows exist, approximately 40 cm wide, one to each side of the door opening, allowing a small amount of light to enter the building (as is the case in most temples and churches, in order to create a proper atmosphere).

The construction method of the whole building appears to have solved serious structural problems. The construction of the roof follows the ecphoric method on all four sides, and not only on two sides, as is the case with the Mycenae megalithic monuments.

In order to construct a roof with this method or system, one needs both accurate calculations and good craftsmen. First, a large piece of slate is placed on the top of the wall, protruding a little towards the interior of the room. Upon this slate, a second one is placed, which extends towards the interior a little further than the first one, then a third piece of slate extends over the second, etc., until the uppermost slate supported by the one wall meets the uppermost slate supported by the opposite wall, thus closing the roof. The structural study must be accurate, because if the weights of the slates is not calculated correctly, the barycenter of the whole pile will exceed the edge of the supporting wall, and the roof will collapse. The unknown constructors of the ancient building, thinking cleverly, not only made very thick walls, but also used large rocks as counterweights placed upon the first slates on the parts that were resting on the thick wall. Also, the slates are not horizontal, but were slightly inclined, for the draining of rainwater.

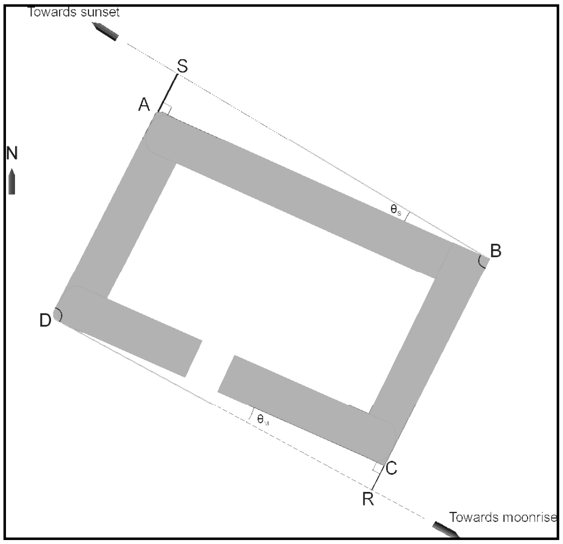

Figure 3: Diagram showing the method used to determine the orientation of the Mt. Oche drakospito.

The lengths of the exterior walls are: 12.70 m (north), 7.70 m (east), 12.60 m (south) and 7.75 m (west). It should be stressed that the structure and texture of the walls is such that the accuracy of the measurements can be no better than approximately 5 cm. The structure should be further studied in respect to its mathematical analogies, since the ratio of length to width (1.64) is very close to the 'golden ratio' or 'divine analogy' of $\Phi \approx 1.618:1$, a ratio that appears during the Classical Period mainly in the vertical plane to increase the aesthetic appeal to an external viewer.

During the 4 July 2004 expedition, measurements of the angle between the northern wall and the Sun's azimuth at sunset were obtained. The instrumentation used was a measuring tape and portable marking signs. The sunset is clearly visible from the northern side of the building at around the time of the summer solstice, and clearly visible from the southern side at the time of the vernal equinox: the altitude of the natural horizon as seen from the northeastern corner of the building is zero, i.e. the natural horizon from that point coincides with the mathematical horizon at the azimuth of the 4 July sunset. The situation is the same with the south wall, as the Moon was seen from the southwestern corner rising over the sea. This way it was possible to calculate the angles between the lines of the walls and the setting and rising azimuths by simply measuring the lengths (AS) and (CR) respectively in Figure 3 and using the length of the longer walls mentioned earlier.

Since (AS) = 1.45 ± 0.01 m and (AB) = 12.70 ± 0.04 m, the angle $\theta_S = 6° 31' \pm 5'$ (due again to the structure and texture of the walls, the error of the angles calculated is approximately 5′). Therefore, the azimuth of the northern wall was calculated to be 293° 25′ ± 5′, or 113° 25′ ± 5′ facing towards the east, as the azimuth of the setting Sun, derived from the *Cartes du Ciel 2.75* planetarium program, was 299° 56′ for the specific date and geographical position. Diffraction and altitude effects were taken into consideration. Figure 4 shows the azimuths obtained.

For the southern wall we have (CR) = 0.88 ± 0.01 m, thus the angle θ_M equals 3° 59′ ± 5′. Therefore, the azimuth of the southern wall, facing towards the east, was calculated to be 113° 09′, as the azimuth of the rising Moon, derived from the *Cartes du Ciel 2.75* planetarium program, was 117° 08′ for the specific date and geographical position. This represents a difference of just 16′ from the azimuth of the northern wall.

Trigonometric calculations based on the measured lengths of the walls yielded an angle for the northwestern corner of the building equal to 94° 27′; that of the south-western corner 85° 17′; the angle of the south-eastern corner 95° 29′ and of the north-eastern corner 84° 47′. The length of the exterior southeast-northwest diagonal was 14.25 m.

The habit of giving an astronomical alignment to religious buildings is common in Greece, both in ancient and mediaeval times, with the sunrise and sunset at certain dates being especially favoured, as reported by Pantazis et.al. (2004). Having excluded the sunrise and sunset at solstices and equinoxes, an obvious first choice was to check for possible astronomical alignments among the brightest stars, and especially Sirius, since the orientation towards the southeast was compelling. Indeed, by using two separate astronomical planetarium programs, *Redshift 5.1* and *Cartes du Ciel 2.75*, we discovered a rise of Sirius orientation of the southern wall for 1060 B.C. ± 30 years and of the northern wall for 1150 B.C. ± 30 years, the average for both walls being 1105 B.C. (the uncertainties correspond to the 5′ error mentioned above). The dating of the construction of the building at that time is not at odds with the archaeological evidence, as Moutsopoulos (1960) assigned this drakospito an eighth century B.C. date based upon artefacts found inside the building.

4 POSSIBLE USES OF THE OCHE DRAKOSPITO

If the Mt Oche drakospito does indeed date to the eighth century B.C., it may have been a watch-tower and residence of the observer, who from that height was observing the Aegean Sea and could use smoke signals to notify administrators in the nearby city of what he was seeing. However, it is unlikely that a squat building like this would have been constructed solely as a watch-tower. A more plausible hypothesis is that it served as a temple of Hera and at the same time as a 'watch-tower of the skies', i.e. an ancient astronomical observatory. The view had it had a religious function is supported by Girard (1851), Bursian (1855), Baumeister (1864) and Moutsopoulos (1992).

We know that many megalithic monuments in Europe were constructed for exactly this purpose. In the case of the Mt. Oche drakospito, an architecturalconstructional element supporting this view is, as was mentioned before, the 1.64 ratio of length to width in the case of the dimensions of the exterior walls, very close to the ‘golden ratio’.

Moreover, if this drakospito was dedicated to the goddess Hera, which is most probable, this leads to certain connotations. The continuous quarrels of the goddess with Zeus, according to Greek mythology, gave rise to the view that Hera was the symbolic personification of celestial/atmospheric disturbances. This view connects Hera with celestial phenomena. In accordance with the first view, since Hera had to do with celestial phenomena, we hypothesize that the so-called Mt. Oche drakospito was not only a place of worship, but in addition it was a Prehellenic observatory devoted to the stars and celestial phenomena.

Another line of argument comes from etymology. The ancient word ‘drakon’ (modern Greek: ‘drakos’, from which the modern term ‘drakospito’ was derived) can be traced back to the ancient Greek verb δέρκομαι, which means to see clearly, to watch, to observe. Indeed, the tenses of the verb are: δέρκομαι, εδρακόμην, δρέξομαι, έδρακον, δέδορκα and εδεδόρκην. We see that the root of the past tense (drak-) gives us the word dragon (δράκων), which in Greek means “… the one who observes”! A dragon is a creature with excellent vision … Therefore, the name drakospito is a paretymological term (i.e. where the word takes on a new meaning), and a substantial use of these megalithic monuments, as suggested by the ancient Greek verb δέρκομαι, was that of an ‘observatory’: either a watch-tower (for observing the Aegean Sea) or an astronomical observatory (for observing celestial phenomena and heavenly bodies). This seems especially true for the largest and best-preserved structure of this kind, the Mt. Oche drakospito.

5 CONCLUSIONS

In this paper, arguments have been presented in favour of a religious and/or astronomical function for the Mt. Oche drakospito, and this possibility needs to be carefully considered by any archaeologists or historians who wish to carry out further research on this site. Whatever their actual function, the distribution and the variety of these megalithic monuments is an indication of a certain level of continuity in the construction of cyclopean buildings in Greece. The use of monoliths and the exquisite manner of fitting the stone slabs together were true architectural challenges.

The uniqueness of the drakospita provides a challenge for future researchers who now need to carefully examine the two dozen or so surviving buildings in order to ascertain whether their construction reflects some astronomical orientation or mathematical rules. From houses of dragons and giants, and palaces for the kings of the Cyclops, they were abandoned or became sheep-folds and the residences of shepherds in recent centuries. Our hypothesis that at least one member of this group of monuments was originally used for astronomical observations could give new momentum to research, quite apart from the interest drakospita present from an archaeological and architectural point of view.

6 NOTES

1. Intriguingly, the three Pálle-Lákka Dragò drakospita form a Π shape as viewed from above.
2. By comparison, one of the Pálle-Lákka Dragò drakospita has walls measuring 10.85 m, 3.80 m, 9.90 m and 4.05 m., while in a second one, all four walls are approximately 4 m long.

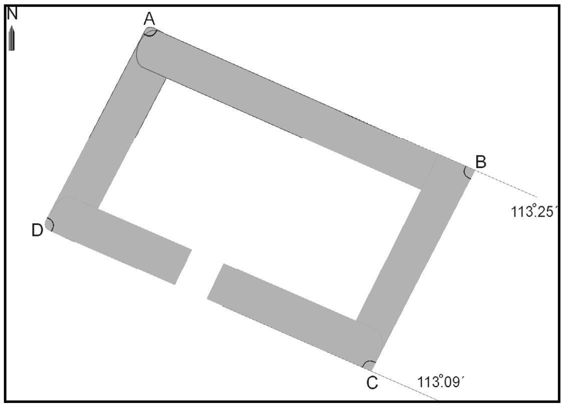

Figure 4: Diagram showing the orientation of the Mt. Oche drakospito.

7 REFERENCES

Baumeister, A., 1864. *Topographische Skizze der Insel Euboia.* Lübeck, Rathsbuchdruckerei (= Lübeck, Catharineum, Schulnachr. 1863-64).

Bursian, C., 1855. Die dryopische Bauweise in Bautrümmern Euboea’s. *Archaeologische Zeitung*, 13, 129-142.

Carpenter, J., and Boyd, D., 1977. Dragon-houses: Euboia, Attica, Karia. *American Journal of Archaeology*, 81, 179-215.

Diaries of Hawkins’ Servant James Thoburn. Unpublished diaries, Cornish Public Records Office, Truro: Hawkins family archive. [Hawkins kept a journal, but many of his papers were destroyed by one of his descendants in the early 1900s].

Girard, J., 1851. Mémoire sur l’île d’Eubée. *Archives des Missions Scientifiques et Littéraires*, 2, 708-714, 724-725, plate after p. 730.

Herodotus, *The History*. 1985 translation by David Grene, book 8, 43 and 8, 46. Chicago, University of Chicago Press.

Johnson, F.P., 1925. The Dragon-houses of southern Euboea. *American Journal of Archaeology*, 29, 398-412.

Moutsopoulos, N.K., 1960. The Oche Drakospito. *To Vouno*, 217, 147-169 [in Greek].

Moutsopoulos, N.K., 1978-1980. The drakospita of SE Euboea – Contribution to their architecture, classification and morphology studies. *Epistemoniki Epetirida Polytechnikis Scholis, Tmima Architectonon*, viii, 263-278 [in Greek].

Moutsopoulos, N.K., 1992. The drakospita. *Archaeologia*, 42, 47-54 [in Greek].

Pantazis, G., Sinachopoulos, D., Lambrou, E., and Korakitis, R., 2004. Astrogeodetic study of orientations of ancient and Byzantine monuments: methodology and first results. *Journal of Astronomical History and Heritage*, **7**, 74-80.

Papamanoles, Th.G., 1954. *Karystos*. Athens (in Greek).

Pausanias, *Messeniaka II*, Book IV, xxxiv, 9 (in: *Pausanias’ Guide to Ancient Greece*, 1985, translation by Christian Habicht, Berkeley, Berkeley University Press.

Politis, N.G., 1904. *Paradoseis: Meletai peri tou viou kai tis glossis tou ellinikou laou* (*Traditions*). Volume I, pp. 220-222 and Volume II, pp. 994-995. In the Series of the “Bibliothiki Marasli”, Ed. D. Sakellariou, Athens.

Ross, L., 1851. *Wanderungen in Griechenland im Gefolge des Königs Otto und der Königinn Amalie (Griechische*

Königsreisen), Volume 2. Halle, Schwetschke. Pp. 28-31.

Strabo: *The Geography of Strabo* by Jones, Horace L. (ed. and translator) 8 volumes, containing Books 1-17. Cambridge (USA), Harvard University Press, 1917-1932 (Book X, p. 16).

Ulrichs, H.N., 1842. Intorno il tempio di Giunone sul monte Ocha vicino a Carystos. *Annali dell' Istituto di Corrispondenza Archeologica*, XIV, 5-11.

Welcker, F.G., 1850. Der kleine Tempel auf der Spitze des Bergs Ocha in Euböa. *Kleine Schriften*, 3, 376-392, 553.

Wiegand, Th., 1896. Der angebliche Urtempel auf der Ocha. *Ath. Mitt.* [Mitteilungen des deutschen archäologischen Instituts (Athenische Abteilung), Atena], 21, 11-17.

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Journal of Astronomical History and Heritage, 12(2), 159 -166 (2009)

INVESTIGATING THE ORIENTATION OF ELEVEN MOSQUES IN GREECE

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Abstract: This paper investigates the orientation of eleven mosques situated in several regions of Greece. The aim of this work is to verify whether and how accurately the monuments have been constructed according to the Muslim tradition. As geodetic and astrogeodetic methods are used, the geometric documentation of each monument is carried out and its astronomical orientation is determined. The qibla for each monument is calculated by using geodetic equations. The mosques' main axis azimuths are determined by a precision of some arc minutes. Also, their orientation, relative to the Canopus star (Alpha Carinae)—which the tradition has closely related to Kaabah in Mecca—is examined. All the mosques seem to follow the religious rule.

Key words: geometric documentation, astrogeodetic observations, astronomical azimuth, mosque, Qiblah, Kaabah.

1 INTRODUCTION

Muslim tradition defines the orientation of the sacred buildings of Islam named mosques. Religious rulings require that Muslims must face Mecca during prayers. They must pray towards the Kaabah, the home of the holy black stone, in Mecca. The holy direction is named qibla. The qibla is the direction towards the Kaabah in Mecca, the sacred place of Islam. "The qibla is the direction that a human observer faces the Kaabah in Mecca." (Abdali, 1997).

The definition of qibla is the line of sight to a vertical line passing through the Kaabah. For example it is the direction in which an imaginary tower built over the Kaabah would appear or the line of sight of any observer on Earth who could see this tower. Many books, papers and studies had been carried out on this subject.

From the first Islamic centuries many astronomers and other scientists were occupied in computing this direction from many different places in the world. The fourteenth century astronomer Al Khalili produced a table where the qibla direction was calculated for any latitude between 10° and 56° North and longitudes between 10° and 60° East.

The most commonly-used methods for calculating the quibla direction are:

- Basic spherical trigonometrical formulae;
- Stellar observation; and
- Recording the solar shadow.

Depending upon whether the place in question was situated relatively east, west, north or south of Mecca, one of the eight cardinal directions of north, northeast, east, southeast, south, southwest, west and northwest was adopted for the qibla.

In the early ages of Islam, the qibla was also defined as the direction towards Jerusalem, where the Dome of the Rock, the other sacred Muslim place, is situated.

Over the centuries, different countries adopted different directions for the orientation of their mosques, as they calculate the qibla direction in different ways (see Saifullah et al., 2001).

The Kaabah itself has a specific orientation. The direction of its northeastern wall is almost perpendicular to the direction of the sunrise at the summer solstice, as its southeastern wall face towards the rising point of Canopus (Alpha Carinae) on the horizon of Mecca (Figure 1). So it is interesting to investigate the orientation of mosques in different countries.

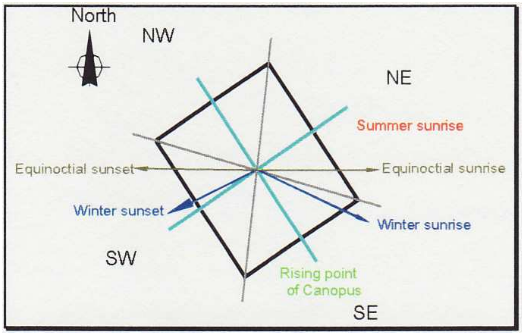

Figure 1: The orientation of the Kaabah (after Sailfullah et al, 2001).

The architectural construction of a mosque follows some basic rules. The main parts of a mosque are shown in Figure 2 and comprise:

- The main hall of the temple for praying, which is called the 'haram';
- The altar, which is called 'mihrab';
- The 'imber', which is a pulpit for the preaching;
- The minaret; and
- An open air hall which is called the'sahm'.

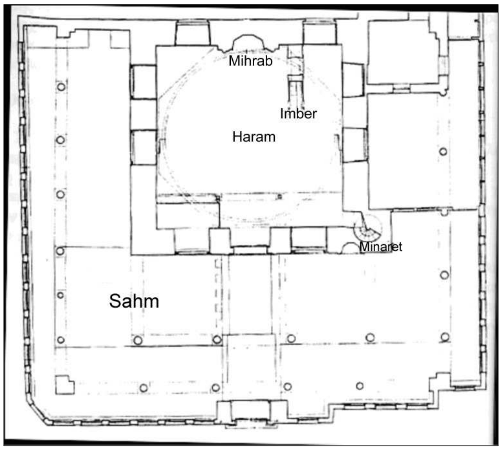

Figure 2: The main parts of a mosque.

In this paper, eleven mosques that were built in Greece between the fifteenth and nineteenth centuries are studied. They comprise

- The four remaining mosques in Ioannina (Epirus) (of the twelve that were originally built);
- Three mosques on the island of Chios;
- The Kursum mosque in Trikala town (in Thessalia, Central Greece);
- Two mosques in Nafplion town (Peloponnesus);
- A mosque in Argos town (Peloponnesus).

Their locations are shown in Figure 3.

2 HISTORICAL DATA

The Veli Pasha mosque (Figure 4) is a simple small construction. It was founded in the early seventeenth century at Ioannina. Its main hall is about 6m × 5m. The interior has a remarkable decoration of marble. Today the building is well conserved. It has an impressive octagonal dome but its minaret has not been preserved.

The Kaloutsiani mosque dates to the late fifteenth century, or to the second half of the seventeenth century according to different sources. It is maintained with its minaret (20.36m height) and its quadrangular main hall which is about 11.5m × 11.5m. The exterior of the mosque has been converted to shops (see Figure 5).

On the southeastern side of 'Its Kale' castle in Ioannina is the Fetiye mosque (Figure 6). It was constructed in 1597 or 1618 on the ruins of a Christian church that was dedicated to the archangel Michael. Its minaret is 20.8m high and its main hall is about 10m × 10m. It is a well-preserved monument.

The Aslan Pasha mosque (Figure 7) dates to 1600-1620 and is situated on the northwestern side of the Castle. It is an exceptional architecture monument. Its main hall is about 10m × 10m and 13m in height. Its dome contains remarkable works of art. Its minaret is 26.4m high and has one hundred steps leading from the ground floor to the top. Today it is used as museum.

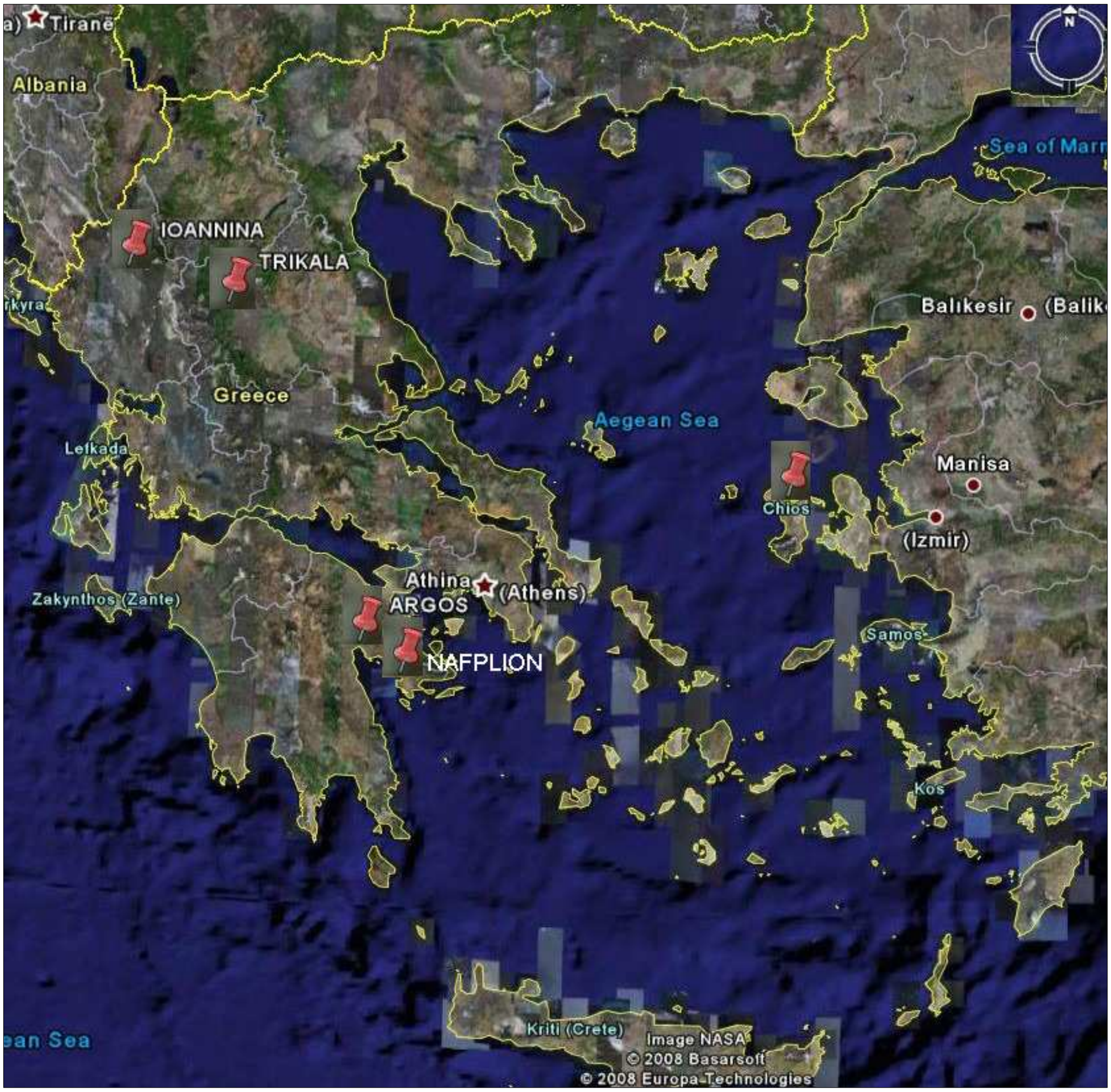

Figure 3: The geographical distribution of the Greek mosques discussed in this paper.

Figure 4: The Veli Pasha mosque.

Figure 5: The Kaloutsiani mosque.

Figure 6. The Fetiye mosque.

Figure 7: The Aslan Pasha mosque.

Figure 8: The Metzitie mosque.

Figure 9: The Osmanie mosque.

Figure 10: The Bairakli mosque.

Figure 11: The Kursum mosque.

Figure 12: The mosque in Argos.

Figure 13: The 'Trianon' mosque.

Figure 14: The Vouleftiko mosque.

The Metzitie mosque (Figure 8), situated in the center of Chios, is a large construction that was erected in 1843 by the Sultan Metzit. Today it is reconstructed and preserved with its minaret. It is used as a Byzantine museum and contains significant exhibits.

The Osmanie mosque (Figure 9), situated close to the center of Chios, was erected in 1893. It is a small and simple building with a minaret Today it is used as an exhibition place.

The Bairakli mosque (Figure 10) is located inside the old castle in Chios. Originally it was probably constructed as a Christian church, in about AD 1410, but later was converted into a mosque. Today it is almost abandoned; it is in ruins and it is used as a storehouse.

The Kursum mosque (Figure 11) in Trikala is situated at the southern entrance to the town. It is one of the larger Greek mosques, and in the central region of Greece is the only one that has been preserved up till the present day. Osman Sah Bey or Osman Pasha constructed this mosque in 1557. It has an impressive dome that is 22.5m high, many rows of windows for lighting the interior, and a minaret. Today the mosque is restored and is used as an exhibition hall.

The mosque in Argos (Figure 12) was founded between 1570 and 1600, and is the only Muslim monument in the town. It was abandoned and is almost in ruins today. In 1871 it was converted into a Christian church dedicated to Saint Constantine the Great.

The 'Trianon' mosque (Figure 13) is situated at the center of Nafplio. It is the oldest preserved building in the town, and dates to the late sixteenth century. It is a simple construction, and its minaret has not been preserved. Today it is used as a theatre.

The Vouleftiko mosque (Figure 14) was constructed in 1730 about a hundred meters from the 'Trianon' mosque. It is a building of remarkable architectural appeal with a rectangular main hall and an impressive dome. In 1825 it was used for the sessions of the first Hellenic Parliament. Today it is used as a special events center.

3 THE ORIENTATION OF THE MOSQUES

The determination of the astronomical orientations of the eleven mosques was carried out using a geodetic surveying method and astrogeodetic observations (see Pantazis, 2002; Pantazis et al., 2003).

The position of each monument, namely the φ and λ coordinates in the world's reference system, was calculated using GPS receivers. For the surveying of each monument a local arbitrary astronomically-oriented geodetic network was used.

The orientation of the network was determined by astrogeodetic observations of Polaris (α Ursa Minoris). The horizontal angle and the time of each observation of the star were registered (Lambrou et al., 2008). All the astrogeodetic and geodetic measurements were carried out using modern digital total stations. These instruments perform precise digital angular and distance measurements, using a visible laser beam which defined accurately the desired points on the monument's structure. The coordinates of each point in the 3-dimensional system were calculated. The points that were selected for measurement were characteristic ones, in order to draw the plan of each monument.

Generally, between 200 and 400 points were measured on each monument, depending upon the size and the complicity of the construction. The plans were drawn digitally. The coordinates have an accuracy (standard error) of ±5mm.

The orientation of each mosque was determined by calculating the astronomical azimuth of the main axis of the building, namely the longitudinal symmetrical axis of the building which passes through the center of the mihrab. Substantially, this axis reflects the direction that the believers are praying. In order to determine the main axis, the characteristic symmetrical points of the building were selected on the plan (e.g. the corresponding openings, the edges of the main entrance, the center of the mihrab) and the midpoint of each line, which joins them, was determined (see Figure 15). The main axis was calculated as the best fitting line to these selected points (1 to 8 in Figure 15) using the following equation:

$$y = \alpha x + b \qquad (1)$$

where x and y are the coordinates of the selected points in the local astronomically-oriented arbitrary reference system.

The least square method was used for the adjustment. The coefficients α and b of the line were determined, as well as their uncertainties (σ_α, σ_b). The astronomical azimuth A_A of this line was determined using the following equation:

$$A_A = 90° \pm \arctan(\alpha) \qquad (2)$$

as term arctan(α) defines the angle between the line and the x-axis, but the azimuth A_A is the angle between the line (the main axis of the mosque) and the y-axis (Figure 16).

The precision σ_{A_A} of the determination of the main axis azimuth is given by the equation:

$$\sigma_{A_A} = \pm\left|\frac{1}{1+\alpha^2}\cdot\sigma_\alpha\right| \qquad (3)$$

The precision achieved fluctuated from 1′ to 7′, and depended upon the size of the monument, the number of the points which were used for the adjustment and the condition of the building. Figure 17 presents the astronomically-oriented plans of the eleven mosques, with the main axes drawn.

4 THE CALCULATION OF THE QIBLA DIRECTION

In order to investigate the orientation of the mosques according to the traditional rules, the geodetic azimuths of the directions which defined each place and the Kaabah in Mecca, namely the qibla directions, must be calculated. This calculation is carried out via the Vicenty equations for the geodetic conversion problems. These equations provide adequate accuracy for distances longer than 1000km (Veis et al., 1995). The geodetic coordinates, φ and λ, of the Kaabah are equal to 21° 25′ 24″ N and 39° 49′ 24″ E (Abdali, 1997), and the coordinates of each mosque were determined by using GPS measurements.

The astronomical azimuth A_A between two points can be calculated by the geodetic one, A_G, via the Laplace equation (Bomford, 1972):

$$A_G = A_A - \eta \tan\Phi - (\xi \sin A - \eta \cos A) \tan \upsilon \qquad (4)$$

where η and ξ are the components of the deflection of the vertical, Φ is the astronomical latitude of the point, and υ is the altitude between the two points. The term $-(\xi \sin A - \eta \cos A) \tan \upsilon$ is of the order of 1″. For such long distances (thousands of kilometers) the value $\tan \upsilon$ is almost negligible, as the altitute υ is very small. Also, the term $-\eta \tan\Phi$ is of the order of a few arcseconds. As the precision of the calculated astronomical azimuths of the main axes of the mosques is of the order of some arcminutes, this correction can be ignored, and so $A_G = A_A$.

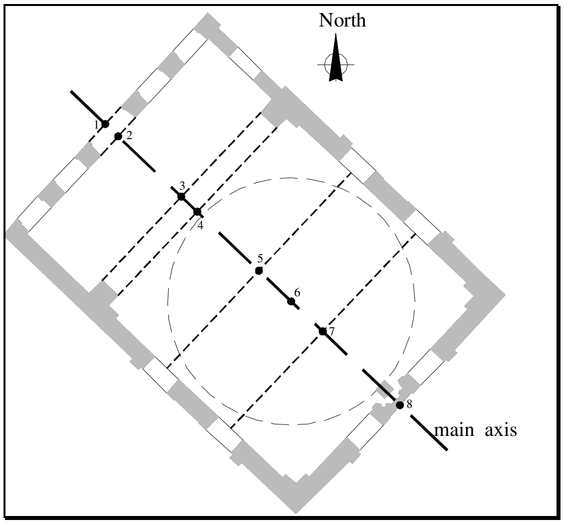

Figure 15: The calculation of the main axis of the building.

Table 1 presents the calculated Qibla direction for each mosque position and its astronomical orientation. Also, as the Kaabah is oriented towards the rising of Canopus in Mecca, that azimuth is determined via the virtual planetarium SkyMap Pro 10 [Marriott, 2001]. In the era that the mosques were erected the rising azimuth of Canopus in Mecca was about 148° 03′. It must be underlined that Canopus is invisible from Greece due to the latitude of that country and the declination (δ) of the star.

Figure 18 illustrates on a circular (mathematical) horizon the qibla direction, namely the azimuth of the direction from each mosque's position towards the Kaabah in Mecca relative to the astronomical orientation of each mosque. In addition, the direction of the rise of Canopus in Mecca and the azimuth from each place towards Jeru-salem are marked.

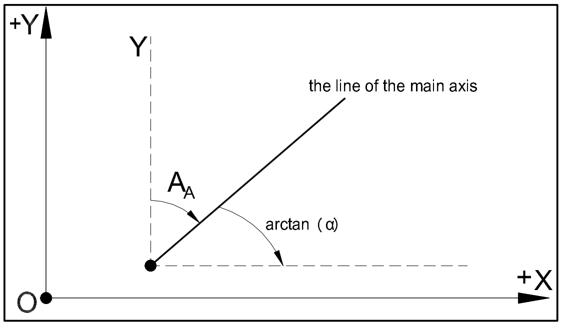

Figure 16: Calculation of the azimuth of the main axis

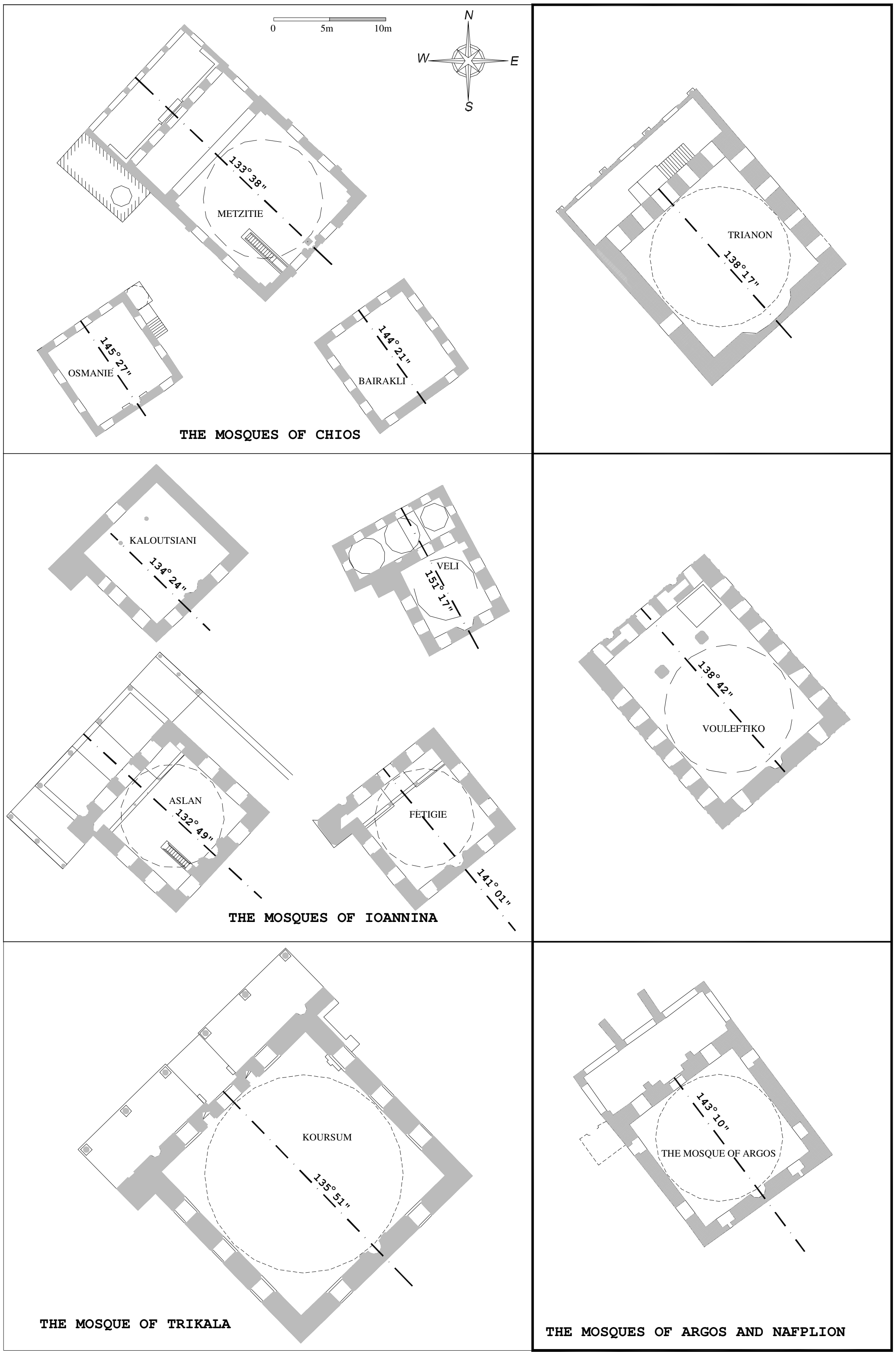

Figure 17: The oriented plans relative to the astronomical north.

Table 1: The astronomical orientation and the qibla directions of the mosques.

Region	Mosque	Qibla direction	A_A (of the main axis)	σ_{A_A} (′)	S (Km) Site - Mecca
IOANNINA	*Veli Pasha*	132° 44′	151° 17′	± 5′	2708.8
	Kaloutsiani	132° 42′	134° 24′	± 8′	2708.6
	Aslan Pasha	132° 43′	132° 49′	± 4′	2708.9
	Fetiye	132° 44′	141° 01′	± 1′	2709.3
CHIOS	*Metzitie*	141° 12′	133° 18′	± 5′	2291.0
	Osmanie	141° 11′	145° 57′	± 7′	2291.0
	Bairakli	141° 12′	144° 21′	± 2′	2291.1
TRIKALA	*Kursum*	134° 12′	135° 51′	± 1′	2643.0
ARGOS – NAFPLIO	*Argos*	132° 43′	143° 10′	± 4′	2435.8
	Vouleftiko	132° 44′	138° 42′	± 3′	2426.7
	Trianon	132° 44′	138° 17′	± 3′	2426.7

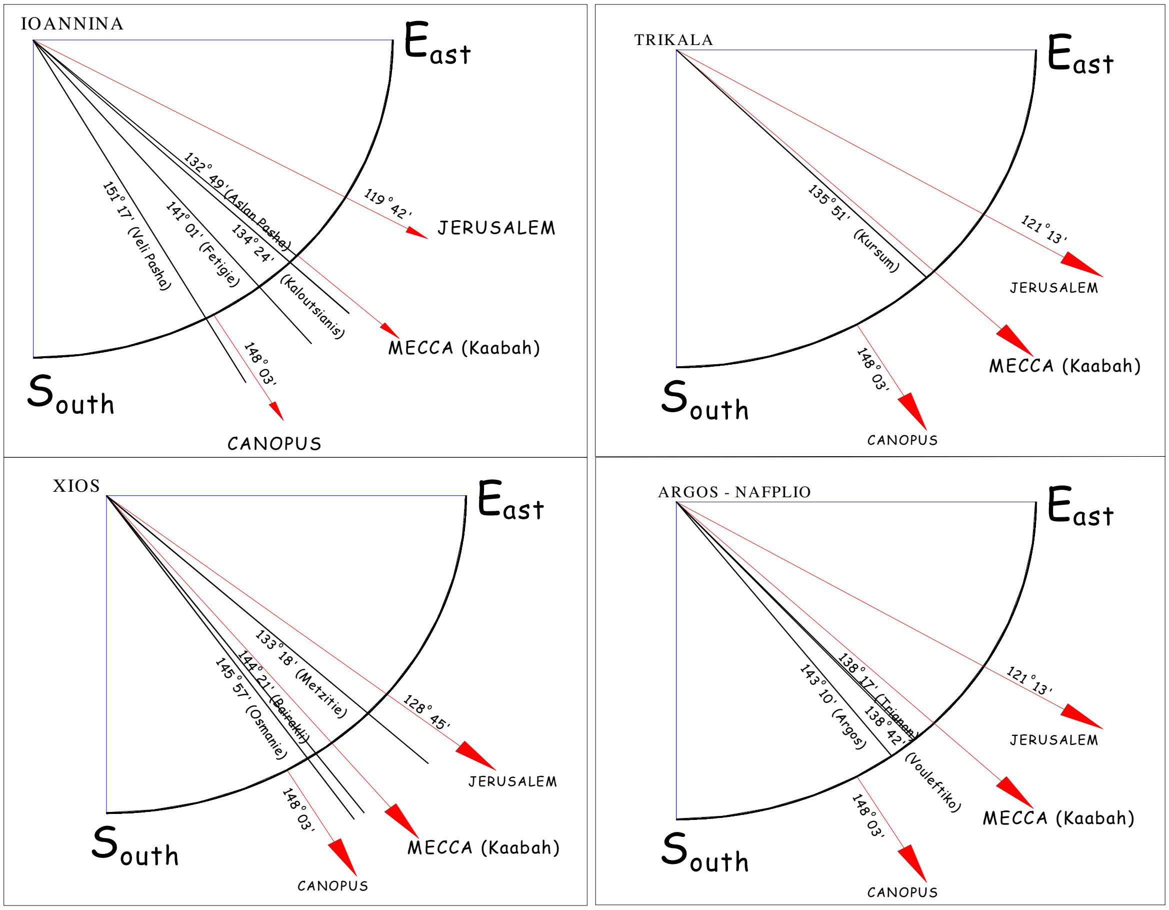

Figure 18: The astronomical azimuths and the qibla direction of each mosque and the rising azimuth of the Canopus star in Mecca.

5 CONCLUDING REMARKS

The results that emerge from the present investigation suggest that the scientific community, but particularly archaeologists, astronomers and archaeoastronomers, can expand their research on ancient mosques.

Firstly, the plans that we produced contain useful geometric data relating to the construction of the eleven mosques and their present-day condition. In addition, the astronomical orientation of each mosque was determined. The applied geodetic methodology provides adequate accuracy both for the geometric documentation and astronomical azimuth determination.

All of the mosques have a southeastern orientation, which varies from 132° 49′ and 151° 17′. It was verified that all of the founders of the mosques followed the Muslim tradition. The effort involved in gauging the right orientation for each mosque is obvious. The deviations that were observed range between 6′ and 10° for nine of the eleven investigated mosques. Given the limitations in making the qibla calculations during the periods when the mosques were built, errors of several degrees would seem justified.

The astronomical azimuths of the main axes of ten of the mosques were found to lie between the qibla direction, namely the direction that is defined between each site and the Kaabah in Mecca, and the rising azimuth of Canopus in Mecca. This agrees with the historical data presented in this paper, which indicates the devotional role of the qibla direction.

Furthermore, it should be noted that the Aslan Pasha mosque in Ioannina is exactly oriented towards the Kaabah in Mecca. According to the historical data, Aslan Pasha was a very significant person during that era, and following his orders scientists were invited to Ioannina in order to undertake the construction of the biggest mosque in the region. It is obvious that the founders had special knowledge, and they were able to make accurate calculations of the required orientation for the building. This is proven by our measurements.

The same conclusions apply to the Kursum mosque in Trikala and the Kaloutsiani mosque in Ioannina, which are also oriented towards Mecca with a deviation of <2°.

The Vouleftiko and Trianon mosques in Nafplio have almost identical orientations, with a difference of only 25′. These two mosques are situated within 100m of each other, and their founders probably followed the same rules and the same procedures when determining their orientations.

Finally, we found that none of the examined mosques was oriented towards Jerusalem.

In planning the eleven mosques, it is obvious that the founders paid special attention to their orientation during the laying of the foundations. It is remarkable how they managed this. How did they calculate their position on the Earth (the φ and λ coordinates), and how did they determine the qibla direction? Did they carry out astronomical observations of specific stars or did they use simpler methods?

6 REFERENCES

Abdali, S. Kamal, 1997. *The Correct Qibla*. PDF version at http://www.patriot.net/users/abdali/ftp/qibla.pdf.

Balodimos, D.-D., Papazissi, K., Lambrou, E., Pantazis, G., Mavrakis, S., and Proutzos, Th., 2004. Investigation on the orientation of the Islamic mosques in Ioannina by astrogeodetic methodology. *Proceedings at 4th Interdisciplinary Interuniversity Conference of the N.T.U.A, "Integrated development of Epirus"*. Metsovon (in Greek).

Bomford, G., 1972. *Geodesy. Third Edition.* Oxford, Clarendon Press.

Bouras, Ch., 1974. *Guides of Greece*. Athens, National Bank of Greece.

Chios: History and Art, the Monuments of Chios. Chios Prefecture (1988).

Krasanakis, G., 2007. *The Orientation of the Islamic Mosque of Koursum at Trikala.* Unpublished Diploma dissertation, School of Rural and Surveying Engineering, National Technical University of Athens (in Greek).

Lambrou, E., 2003. *Development of a Methodology for Astrogeodetic Determinations, using Digital Geodetic Instruments.* Unpublished Ph.D. thesis, School of Rural and Surveying Engineering, National Technical University of Athens (in Greek).

Lambrou, E., and Pantazis, G., 2003. On the date of early Christian basilicas (Central Greece). *Mediterranean Archaeology and Archaeometry* (Special Issue), 6, 49-56.

Lambrou, E., and Pantazis, G., 2008. Astronomical azimuth determination by the hour angle of Polaris using ordinary total stations. *Survey Review*, 40, 164-172.

Manioudi-Gavada, D., 2001. *The Castle of Chios.* Chios, Papyros.

Marriott, C., 2001. *Skymap Pro Version 10*.

Mavrakis, S., 2004. *The Orientation of the Islamic Mosques of Fetiye and Aslan Pasha in Ioannina*. Unpublished Diploma dissertation School of Rural and Surveying Engineering, Athens, National Technical University of Athens (in Greek).

Pantazis, G., 2002. *Investigation of Monuments Orientation using Geodetic and Astronomical methods: Application at Meteora*. Unpublished Ph.D. thesis, School of Rural and Surveying Engineers, National Technical University of Athens (in Greek).

Pantazis, G, and Balodimos, D.-D., 2003. Methodology for investigating the orientation of monuments. *Tech. Chron. Science Journal*, 23(3), 55-63.

Pantazis, G., and Papathanassiou, M., 2005. On the date of the Katholikon of Daphni monastery. A new approach based on its orientation. *Mediterranean Archaeology and Archaeometry*, 5, 63-72.

Proutzos, T., 2004. *The Orientation of the Islamic Mosques of Kaloutsiani and Veli Pasha in Ioannina*. Unpublished Diploma dissertation, School of Rural and Surveying Engineering, National Technical University of Athens (in Greek).

Saifullah, M.S.M., Ghonien, M., Squires, R., Hamman, M.A. and J., 2001. The Qibla of Early Mosques: Jerusalem or Makkah? Web site: http://www.islamic.awareness.org/History/Islam/Dome_of_the_Rock/qibla.html

Strobe, D., n.d. The Islamic Astrolabe: An Indicator of the Role of Islamic Astronomy during the Middle Ages. Web site: http://www.cod.edu/middle/history/astrolabe.pdf

Zolotas, G.I., 1921-1928. *History of Chios.* Three volumes. Athens, P.D. Sakellariou (in Greek).

Veis, G., Billiris, C., and Papazissi, K., 1995. *Higher Geodesy Notes.* National Technical University of Athens (in Greek).

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Journal of Astronomical History and Heritage, 12(2), 167-170 (2009).

COMET HALLEY IN 1910, AS VIEWED FROM A MALTESE PERSPECTIVE

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Abstract: Comet Halley's return in 1910 was keenly anticipated globally by scientists and the lay public alike. Although cometary science had progressed rapidly during the last quarter of the nineteenth century, superstition remained significant in different parts of the world and there were fears that people would die if the prediction that the Earth would pass through the comet's tail were correct.

Malta was a small British island colony in the Mediterranean, and the inhabitants there were no exception. Local newspapers reported concerns from their readers and from foreign sources, but they also included reassuring scientific information about comets. Under the patronage of the colonial government a local amateur astronomer named Francis Reynolds reassured the public through lectures that he delivered. Overall the local population appeared to have been calm about the impending return. The first recorded sighting from Malta was on 24 April 1910 and the first naked eye sighting occurred the following day. Accounts were published in the local newspapers and in private correspondence, suggesting a high level of public interest in this object. No photographs of the comet from Malta have been traced, but the aforementioned Mr Reynolds and a well-known Maltese artist, G. Cali, did make a number of paintings. On the night when the Earth was due to pass through the comet's tail many local people congregated around the bastions of the city under an overcast sky in the early hours of the morning, but no untoward events were experienced.

Keywords: Comet Halley, Malta, newspaper accounts of comets, paintings of comets, superstition and comets

1 INTRODUCTION

To the public, Comet Halley[1] is undoubtedly the best-known of all comets, and Stephenson and Yau (1985) have traced records of its apparitions back possibly to 240 BC. Depending upon the circumstances of each apparition, the appearance of the comet may be particularly impressive or of mediocre interest (see Hughes, 1985). After the spectacle created in 1835, the return of the comet in 1910 was expected to be an even more favourable event:

> What made the earth's encounter with Halley's Comet in 1910 so interesting and unusual was that our planet was positioned in such a manner that the comet passed precisely between the earth and the sun. At that time earth was closer to the comet but as the two swept by one another travelling in opposite directions, the comet passed directly in front of the sun … In addition, cyanogen, a poisonous gas, was discovered in its coma by spectroscopy. Needless to say, the prospect of cyanogen poisoning the earth, when the tail brushed the planet, caused consternation among nonscientists. Despite assurances that the comet posed no threat, numerous stories worldwide testify to the public's panic. (Olson and Pasachoff, 1998: 312).

The occupants of the islands of Malta[2] in the Mediterranean Sea were no exception, and this paper presents an account of the 1910 return of Comet Halley as experienced in Malta, based primarily upon contemporary newspaper reports.

2 MALTESE REPORTS OF COMET HALLEY IN 1910

At this time Malta featured English, Italian and Maltese language newspapers, each representing different political allegiances and aspirations. Between them, from the early spring of 1910 these newspapers covered the return of the comet in considerable detail. The local reporters certainly were familiar with the latest scientific knowledge regarding comets, and they had access to up-to-date information about the impending return of the comet. They also were aware of the fear with which some local people viewed comets.

As a result, a succession of articles appeared in the English-language newspapers *The Malta Herald* (1910a; 1910c; 1910e; 1910f and 1910h) and *The Daily Malta Chronicle* (1910c; 1910f; 1910i; 1910j and 1910n) explaining the true nature of comets, the specific dynamics of this return and the scientific observations being undertaken worldwide. There were also concerted attempts to reassure the readers that no harm would befall them. Similar articles appeared in the Maltese-language newspapers *In Nahla ta' A. Levanzin* (1910a; 1910b and 1910c) and *Malta Taghna* (1910b). The Italian-language press followed suit (e.g. see *Malta*, 1910b).

It is clear that there were individuals in Malta who were very familiar with the nature of comets. One of these was Francis J. Reynolds, Inspector of Elementary Schools, who on Saturday 16 April 1910 lectured to a capacity audience in the University Hall in Valletta (the capital of Malta). The lecture was advertised in the local newspapers, and interested persons were urged to collect their free tickets from the Office of Public Instruction (*The Daily* …, 1910a). The audience was described as intelligent, select and eager, and the lecture was introduced and concluded by the Honorable Professor Magro, Director of Public Instruction. Reynolds described the nature of comets as known at the time, and specifically traced the history of Comet Halley. He sought to reassure his audience that no harm would befall human beings even though the Earth was expected to pass through the tail of the comet. Reynolds was commended in the local press for presenting a potentially technical and tedious subject in a simple way which everyone could understand, as well as for the illustrations that he screened using an electric lantern. However, the correspondent bemoaned the fact that a bigger audience could not be accommodated (*The Malta Herald*, 1910b). Reynolds eventually repeated the lecture at the same venue on 19 April 1910 (*The Daily* …, 1910a), and it was suggested that he should publish his lecture and that A.M. Galea (no relation to the author), who was in the audience, could translate it into Maltese in order to make it available to a larger percentage of the local population (*The Malta Herald*, 1910b).

The timing of Reynolds' lectures was significant, for a few days later reports began reaching the local press of the impact the impending return of the comet was having upon populations around the world. Although cometary science had made remarkable progress during the second half of the nineteenth century (Guillemin, 1877) and especially since the advent of astronomical spectroscopy and photography (e.g. see Clerke, 1893: 109-133; 392-449), superstition and fear associated with the return of the comet abounded. The fact that the Earth was due to pass through the comet's tail on 19 May did not help any, for spectroscopic studies had revealed the presence of cyanogen, which when combined in a salt produces cyanide, a deadly substance even in small quantities. But as Sagan and Druyan (1985: 123) point out, it was not absolutely certain that the Earth would in fact pass through the comet's tail, and even if it did cometary tails were very tenuous objects and cyanogen was only a minor chemical component. Meanwhile, the local newspapers did their best to allay community fears.[3]

Nonetheless, reports soon surfaced of widespread concern for the welfare of the Earth's population. In Austria-Hungary, the comet was a source of great terror, and many peasants prepared to sell their property and indulge in one final wild act of debauchery. The government endeavoured to calm the population by means of priests and teachers (*The Daily* …, 1910b). A similar state of affairs was reported in France (ibid.). In Croatia, some sold off their possessions to pay for a final earthly indulgence (*Malta Taghna*, 1910a). In the American West, itinerant patent medicine vendors were selling comet pills to ward off its evil influence and cashing in on the gullible public (see Brown, 1985: 126). Reports from China suggested a population in fear of their lives (*The Daily* …, 1910d). Sustained national panic lasted weeks in Japan and Russia, residents of Chicago stuffed rugs under their doors, and Pope Pius X denounced the hoarding of oxygen cylinders in Rome. In Kentucky, people held all-night vigils in preparation of their impending demise. Some people took their own lives (see Sagan and Druyan, 1985: 123). In Nikolsk (Russia), the inhabitants fasted and prayed, and the day before the expected passage of the Earth through the comet's tail they solemnly took baths, donned clean linen and sat down beneath the icons in the corners of their rooms to await the end (*The Malta Herald*, 1910j).

In the British Empire, matters were not helped when King Edward VII suddenly passed away in London on 6 May 1910 (see Brown, 1985: 126). It was clear to the observant that not only did Comet Halley return but for the first time in many years Good Friday fell on Lady Day in 1910, therefore fulfilling the ancient saying "If Our Lord falls on our Lady's lap England shall have a great mishap." (*The Malta Herald*, 1910g).

Needless to say, there was certainly a measure of unease among the Maltese population regarding the impending approach of the comet. On 28 April 'E.N.P' wrote that he felt reassured by the report of a lecture delivered by Father Cortie S.J., in England, and that by reproducing this in the local newspaper he hoped that it would also reassure others (*The Daily* …, 1910g). The report was correct in its overall conclusion that passing through a comet's tail would not be harmful, but we now know that it was incorrect when it stated that it would still not have been dangerous if the Earth hit the comet's nucleus as this was a sandbank of particles—which would merely produce a meteor storm—and not a solid body. The available newspaper reports do not reflect a general state of panic amongst the Maltese population, so it would seem that Reynold's public intervention and various reassuring reports in the press were successful.

Cycil Leach from the University's meteorological station carried out a systematic search for the comet, and was the first person in Malta to publicly report a visual sighting of it, at 3:40 am local time on 24 April 1910. In the 25 April issue of *The Daily Malta Chronicle* (1910e) he described how he swept the skies with his field glasses and found the comet 20° to the left of and 5° below Venus. It became clearer between 4.00am and 4.20am, and its tail was broad and twice as long as the diameter of the Moon (i.e. 1°), with streams away and upwards to the right at an angle of forty degrees. The nucleus was discernable to the naked eye for a couple of minutes around 4.15 am. The comet grew fainter from 4.30am onwards, probably due to twilight, but could still be seen through field glasses until 4.45am. Despite these successful observations, Leach mentioned that the conditions were not ideal for cometary observing at the time. The next to sight the comet was W.B. Smith of Sliema, who claimed to have briefly seen the comet with the naked eye at 4.13am on 25 April, and pointed it out to others (*The Daily* …, 1910f).

On 27 April, shortly after the comet reaching naked eye visibility, Reynolds travelled to Gozo, the smaller sister island to Malta, and gave his Comet Halley lecture in English at the Elementary Schools in Victoria (the capital of Gozo), presided over by the Bishop of Gozo and W.C. Milliard, the Assistant Secretary to the Government. The report in *The Malta Herald* (1910d) once again commended Reynolds for successfully presenting a subject he was clearly familiar with in a simple manner, thereby keeping his audience engaged.

Comet Halley appears to have left a considerable impression on the Maltese population. Writing at the time of the 1985 return, A. Dougall claims to have heard from several old people who remembered seeing the comet in 1910, and were full of awe at its splendour, with its "… fiery peacock-shaped tail." (*The Times* …, 1985b). This is reflected in the following account, which was published in *The Daily Malta Chronicle* on 16 June 1910 (1910p): "Nearly every man and woman and most of the children, who are old enough to concern themselves with the things around them, have looked up for many nights …", some in wonder and others in scientific enquiry.

A compelling local eyewitness account of the 1910 return of Comet Halley was provided by Paul Mamo (b. 1898) in a letter addressed to The Astronomical Society of Malta and written on 13 September 1985. He recalled that in 1910 he was twelve years old and remembered going with other boys and his 10-year-old brother, John, to the Upper Barracca Gardens, a popular vantage point overlooking the Grand Harbour in Valletta which afforded an almost unimpeded view of the eastern sky. Paul Mamo described seeing the comet in the night sky over Fort St Angelo towards the fort of Ricasoli further north. He remembered the large crowd at the Barracca, and squeezing himself through so that he always managed to get a place by the railings on the gallery overlooking the harbour. It can be inferred from this letter that Paul Mamo made such observations on several occasions, and that the atmosphere he experienced was similar each time. The comet was beautiful and brilliant, and he stated that it was impossible to find the proper words to describe it. Mamo was 87 when he wrote the letter, and he expressed the hope that he would live to see the return of Comet Halley for a second time. Although his account was written from memory seventy-five years after the grand event, I believe that it provides a reasonably accurate indication of the general atmosphere that existed among those who went out in the middle of the night to view the comet.

There are no known photographs of the comet as seen from Malta in 1910, but its return was recorded by two artists. One of these was the well-known Maltese artist, Giuseppe Cali (1846–1930), and in 1985 Brigadier A. Sammut Tagliaferro stated how Cali knew his father very well and had presented him with a painting of the comet as a memento. Tagliaferro remembers the painting as being about 36 × 13cm and was drawn against a grey background, showing at the extreme left the Lower Barrakka gardens with Ball's monument in the foreground, then to the right Fort Ricasoli, Rinella, the Bighi Hospital, etc. The picture was described as a superbly-executed night scene with the comet itself displaying its magnificent tail, heading north-east, high above the Bighi area. During the fierce German evening bombing raid on Valletta on 7 April 1942 the Tagliaferro's third floor flat at 10 South Street, Valletta, was hit and practically demolished. The family lost everything, but one wall of the building survived in isolation and Cali's picture hung inaccessibly from that wall of what would have been the sitting room, forty feet above the ground. After this, Tagliaferro never saw the picture again (*The Times* …, 1985a).

In 1985 Dougall examined a similar painting by Cali measuring about 40 × 25cm in a private collection, which was about the same size as one bearing catalogue number 308 which was exhibited during Cali's centenary exhibition at the Palazzo De La Salle in Valletta, late in 1947. This exhibited painting was lent by a Mr E. Sammut Tagliaferro, and it is unclear whether this was the same painting referred to above or another one. After learning of this exhibition and talking with one of Cali's descendents Dougall (ibid.) concluded that Cali must have made quite a few replicas of the comet painting, of various sizes. Indeed, it would seem that E. Sammut Tagliaferro's picture was painted in 1912 (Bonnici-Cali, 1946: 46).

Apart from the aforementioned works, Cali is known to have donated a picture of the comet to the Royal University in 1910 (*Malta*, 1910a). A member of the Astronomical Society of Malta remembers seeing it at the meteorological observatory on the campus of the University in St Paul Street, Valetta, while studying in the late 1950s (*The Times* …, 1985c).

Mr T. Tanti of the Astronomical Society of Malta came into possession of a photograph of a postcard showing Comet Halley's 1910 return as seen from Malta, the original being in possession of Mr Graham Smeed of Ashford, England. The picture (Figure 1) is very similar to, if not a direct copy of Cali's painting of the comet over the Grand Harbour: the comet has the same appearance and orientation and there are the same landmarks in the background. Several stars are depicted in the night sky, some of which are shining through the comet's tail. A computer simulation (using Redshift 2) for 3.00am on 13 May 1910, the same time as the painting, indicates that some stars can be recognisable but that there is also a certain amount of artistic license as other stars are difficult to identify. The four stars creating a square shape just above the comet's head are likely to be the Great Square of Pegasus while the bright object to the lower right of the comet's head and just above the skyline corresponds to Venus (cf. *The Times* …, 1985c).

Figure 1: Giuseppe Cali's painting of Comet Halley over the Grand Harbour, Malta on 13 May 1910.

Another depiction of the comet, this time a watercolour, was painted at 3.00am on 13 May 1910 by the amateur astronomer, Francis Reynolds. This showed the comet set against background stars, with both Venus and the comet being reflected in the sea. Reynolds later painted two other watercolours, the first on 20 May showing the comet in the early evening just after twilight. The comet's nucleus is very clear, and the tail is split into two. In the other painting the comet and tail are smaller in size, and three arrows indicate the position of the comet on 7, 8 and 10 June (see Ventura, 2002: 219).

The climax of Comet Halley's 1910 return was expected on the night of 18/19 May when the Earth was supposed to pass through the tail. Local newspapers warned of no danger, and some raised the possibility of seeing atmospheric disturbances similar to the aurora borealis or a meteor storm (e.g. see *The Daily* …, 1910k), potentially the most impressive storm ever seen (*The Daily* …, 1910h). However, one report mentioned the probability of a tidal wave that would also cause difficulty with respiration due to the anticipated increased atmospheric pressure (*The Daily* …, 1910j). That night, while the streets of Paris were deserted, there was a carnival atmosphere in Milan. People in Naples, Palermo (*The Daily* …, 1910n) and Alexandria (*The Malta Herald*, 1910i) remained out all night in an ultimately futile anticipation of observing something, while fear appeared to be the predominant reaction in the United States (*The Daily* …, 1910m).

In Malta there was overcast weather, but in the early hours of the morning many people congregated on the bastions of Valletta in anticipation of seeing the comet, but nothing untoward was observed (ibid.). Later the *Malta Taghna* newspaper (1910c) expressed relief that the atmosphere had not been poisoned and that no hail of stones was experienced. However it reported that around twenty hours after the comet's passage the sky turned overcast and it started to drizzle gently and between 10.00 and 11.00pm snakes of fire (an aurora?) appeared silently in the sky! The correspondent wondered whether these natural phenomena could be related to the passing of the comet. Some people were of the same belief when a storm hit London in the early hours of that same night (see *The Daily …*, 1910m).

3 CONCLUDING REMARKS

The return of Comet Halley in 1910 was well publicised in Malta, and the nature of comets, the dynamics of the return and the events surrounding the potential passage of the Earth through the comet's tail were well explained in the local English, Italian and Maltese language newspapers with a view to reassuring the public that no harm would befall them. As a result, there was no sense of panic; instead, the comet was seen as an object of wonder, and many people made a point of observing it. It was also recorded in a series of paintings, but most of these no longer survive.

4 NOTES

1. The correct designation for this comet is 1P/Halley, but for the purposes of this paper I will simply refer to it throughout as 'Comet Halley'. There is some controversy over the pronunciation of the name 'Halley": should it rhyme with 'valley' or with 'poorly'? Cometary expert, Professor David W. Hughes (1983) discusses this and opts for the former pronunciation.
2. Malta (longitude 14.35° E and latitude 35.50° N) is an archipelago in the centre of the Mediterranean Sea made up principally of the islands of Malta and Gozo. Malta lies south of Sicily and north of Libya and is approximately equidistant between Gibraltar in the west and Alexandria in the east. The islands passed to Great Britain in 1800 and became a strategic military and trading post in the centre of the Mediterranean due to the quality of its main harbour. The islands were administered by a British Governor, and an expatriate community resided there.
3. They should also have pointed out that the Earth had earlier passed through the tail of the Great Comet of 1861 (C/1861 J1, Tebbutt), and despite considerable public apprehension, no ill effects were experienced (see Orchiston, 1998).

5 ACKNOWLEDGEMENTS

I would like to thank Mr Tony Tanti who provided a copy of G Cali's print and Dr Godfrey Baldacchino B.A., M.A., Ph.D., who provided helpful advice. Finally, I wish to thank Dr Wayne Orchiston (James Cook University) for revising the manuscript.

6 REFERENCES

Bonnici-Cali R, 1946. *Giuseppe Cali, Biographical Notes*. Malta, Empire Press.
Brown, P. Lancaster, 1985. *Halley and His Comet*. Poole, Blandford Press.
Clerke, A., 1893. *A Popular History of Astronomy During the Nineteenth Century. Third Edition*. London, Adam & Charles Black.
Guilllemin, A., 1877. *The World of Comets*. London, Sampson Low, Marston, Searle, & Rivington.
Hughes, D.W., 1983. How to say Halley. *Nature*, 304, 119-120.
Hughes, D.W., 1985. The position of Earth at previous apparitions of Halley's Comet. *Quarterly Journal of the Royal Astronomical Society*, 26, 513-520.
In-Nahla ta' A Levanzin, 7 May 1910, 700-701 (1910a).
In-Nahla ta' A Levanzin, 14 May 1910, 708-709 (1910b).
In-Nahla ta' A Levanzin, 21 May 1910, 716-718 (1910c).
Malta, 11 May 1910, 2 (1910a).
Malta, 16 May 1910, 2 (1910b).
Malta Taghna, 30 April 1910 (1910a).
Malta Taghna, 14 May 1910 (1910b).
Malta Taghna, 28 May 1910 (1910c).
Mamo, P., 1985. Letter to T Tanti, Secretary of the Astronomical Society of Malta, dated 13 September. Original in the ASM records.
Olson, R.J.M., and Pasachoff, J.M., 1998. *Fire in the Sky. Comets and Meteors, the Decisive Centuries, in British Art and Science*. Cambridge, Cambridge University Press.
Orchiston, W., 1998. Illuminating incidents in Antipodean astronomy: John Tebbutt and the Great Comet of 1861. *Irish Astronomical Journal*, 25, 167-178.
Sagan, C., and Druyan, A., 1985. *Comet*. New York, Random House.
Stephenson, F.R., and Yau, K.K.C., 1985. Far Eastern observations of Halley's Comet – 240 BC to AD 1368. *Journal of the British Interplanetary Society*, 38, 195-216.
The Daily Malta Chronicle, 12 April 1910 (1910a).
The Daily Malta Chronicle, 20 April 1910, 3 (1910b).
The Daily Malta Chronicle, 22 April 1910, 3 (1910c).
The Daily Malta Chronicle, 23 April1910, 6 (1910d).
The Daily Malta Chronicle, 25 April 1910, 3 (1910e).
The Daily Malta Chronicle, 26 April 1910, 3-5 (1910f).
The Daily Malta Chronicle, 28 April 1910, 7 (1910g).
The Daily Malta Chronicle, 29 April 1910, 2 (1910h).
The Daily Malta Chronicle, 10 May 1910, 3 (1910i).
The Daily Malta Chronicle, 16 May 1910, 3-4 (1910j).
The Daily Malta Chronicle, 18 May 1910, 3 (1910k).
The Daily Malta Chronicle, 19 May 1910, 6 (1910m).
The Daily Malta Chronicle, 24 May 1910, 5-6 (1910n).
The Daily Malta Chronicle, 16 June 1910, 4 (1910p).
The Malta Herald, 16 April 1910, 5 (1910a).
The Malta Herald, 18 April 1910, 3 (1910b).
The Malta Herald, 29 April 1910, 4 (1910c).
The Malta Herald, 3 May 1910, 3 (1910d).
The Malta Herald, 9 May 1910, 4 (1910e).
The Malta Herald, 14 May 1910, 5 (1910f).
The Malta Herald, 16 May 1910, 3 (1910g).
The Malta Herald, 30 May 1910, 4 (1910h).
The Malta Herald, 31 May 1910, 3 (1910i).
The Malta Herald, 15 June 1910, 3 (1910j).
The Times of Malta, 8 August 1985 (1985a).
The Times of Malta, 3 September 1985, 8 (1985b).
The Times of Malta, 13 September 1985, 7 (1985c).
Ventura, F., 2002. *L'astronomija F'Malta*. Independent publishers.

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Journal of Astronomical History and Heritage, 12(2), 171-172 (2009).

FILM AND BOOK REVIEWS

***Spiral Galaxy: De Melkweg Ontrafeld*, a film by Maarten Roos and Pieter-Rim de Kroon, on DVD, 2009. Dutch, with subtitled English and German versions. €22.95 (includes postage and packing).**

This 45-minute film traces the steps which led from the nineteenth century view of the cosmos (when the Milky Way was synonymous with the Universe), to the first 21-cm hydrogen map of our Galaxy which revealed its spiral structure. The story is related, in the main, by three astronomers and a technician who either participated in the early work, knew the key players and/or witnessed the events first hand as they unfolded (all four are over 80; Adriaan Blaauw recently celebrated his 95th birthday). Much of the filming was done at locations which formed the backdrop to the research effort: the old Leiden and Utrecht Observatories, and Radio Kootwijk where the early 21-cm observations were made. As one might guess from the sub-title (meaning *the Milky Way solved* [or *unravelled*]), it is a Dutch film which emphasizes twentieth century research on our Galaxy done in the Netherlands.

A narrator sets the scene by describing how sixteenth and seventeenth century scientists—Copernicus, Galileo, Kepler, Huygens—changed our world-view from geocentric to heliocentric. Blaauw then recounts Kapteyn's research, culminating in his model of the Milky Way with the Solar System near its centre. The narrative continues with the work of men like Shapley and Curtis (though neither is named) marking another shift in our location away from the centre of things, culminating in Oort's model of the Milky Way with the Sun well-removed from the nucleus. To penetrate the dust which obscures most of the Galaxy including its centre, light of a different colour was to be needed. Kees de Jager tells the story (which he witnessed from Utrecht) of Van de Hulst's 1944 prediction at a Leiden colloquium organized by Oort, that the 21-cm hydrogen line might be detectable. Hugo van Woerden discusses the early results obtained with the 7.5-m Würzburg antenna at Kootwijk, and Arie Hin, one of Kootwijk's first electronics technicians, describes how the observations were done.

The film is quite good in capturing the atmosphere and excitement of the early work. I particularly enjoyed seeing the setup Kapteyn used to measure over 450,000 stars (each twice!), and Van Woerden's demonstration of how hundreds of HI spectra were 'digitised' from chart records using a ruler and pencil (this should be required viewing for astronomy students who are used to seeing their data, calibrated and integrated, flow out of a computer). As history, however, the film is rather selective, mainly following the thread of Dutch research on the Milky Way. English and German versions (the Dutch original with subtitles) are available on the same DVD; the translations are quite faithful. There are a few factual errors (the number attending the 1944 colloquium may have been small, but it was more than double the six De Jager mentions—but then he wasn't there), and the odd technical flaw (an English sub-title creeps into the German version), but they are minor. The film was made in the context of IYA 2009, and will probably mainly appeal to schools and amateur groups in the Dutch-speaking world. For the historian there are few new facts, though the personal accounts should have lasting value. (The DVD has a bonus: additional reminiscences by Blaauw and Van Woerden.)

There is information on the film on the following web site: www.spiralgalaxy.nl

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***Inventar der historischen Sonnenuhren in Mecklenburg-Vorpommern,* compiled by Jürgen Hamel (Frankfurt am Main Verlag Harri Deutsch, 2007; *Acta Historica Astronomiae*, Volume 34), pp. 205, €19.80, 250 x 145 mm.**

This small book is a catalog of 188 sundials in the German federal state of Mecklenburg-Vorpommern, located on the Baltic (the major city is Rostok). Each dial is described in great detail, accompanied by a black-and-white photograph. The book, however, is only for the über-specialist, as the dials, with rare exception, are not at all attractive or notable. A majority are barely visible in the photos because they are medieval 'scratch dials', often found on churches in northern Europe as crude indicators for the times of mass. The hour lines on such dials, usually poorly preserved incisions in stone, show up only when the lighting is just right, and their gnomons have long rusted away. The remainder of the catalogued dials, of a more conventional nature from mainly the eighteenth and nineteenth centuries, are also mostly in very poor condition.

Such catalogs are nevertheless valuable as records of the architectural, artistic and time-keeping history of a region. But for some reason this region has not produced its share of the wealth of interesting and beautiful sundials that can be found throughout Europe. Or perhaps such dials once existed, but have not been preserved?

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***Cometography. A Catalog of Comets. Volume 4: 1933-1959* by Gary W. Kronk (Cambridge, Cambridge University Press, 2009), pp. xii + 616, ISBN 0-521-58504-X (hardcover), £150:00, 259 x 185 mm.**

It is a great pleasure to see the appearance of Volume 4 in the *Cometography* series (see Figure 1) so soon after the publication of its predecessor, and Gary W. Kronk is to be congratulated on providing cometary enthusiasts with yet another indispensible research tool.

Following the pattern of previous issues, Volume 4 details the progress of each comet, from its discovery through to its disappearance, along with supporting references. In addition, there is a 4-page Introduction, a 13-page Appendix listing "Uncertain Objects" (some of which are undoubtedly legitimate comets but have not been formally accredited because of a lack of adequate documentation), and a long "Person Index".

For me, this book has special appeal because it contains accounts of the first two naked eye comets I

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2009JAHH...12..1710

remember observing, back in 1957, under the dark skies of rural New Zealand. Within a span of five months, both Comet C/1956 R1 (Arend-Roland) and C/1957 P1 (Mrkos) captivated me, and—coupled with remarkable views of Mars during its close opposition of 1956—guaranteed that my youthful passion for astronomy would eventually translate into a career in this noblest of the sciences. But it was only when I carefully read Kronk's accounts of these two comets that I discovered that Mrkos was certainly at its best when I viewed it, whereas Arend-Roland—although still an impressive naked eye object—was well past its prime by the time it graced New Zealand skies.

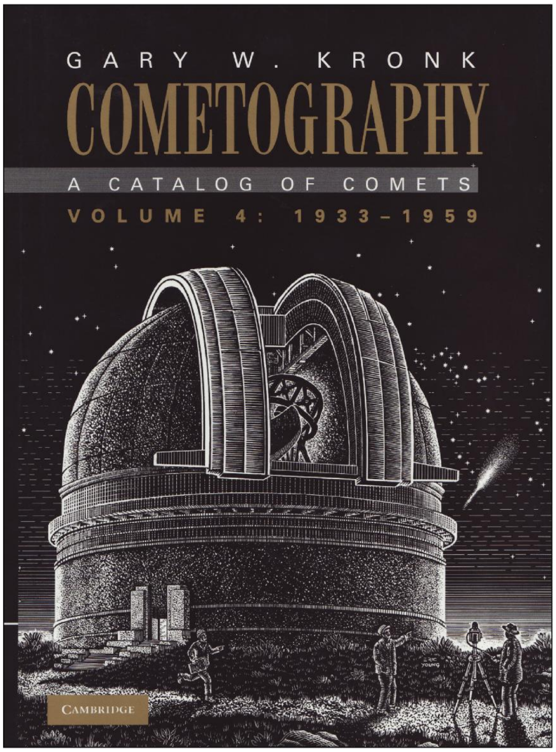

Figure 1: The attractive dust cover of *Cometography Volume 4* features Palomar Observatory.

Another feature of this book that is bound to reverberate with readers over the age of 60 is they will invariably meet up with old departed (and sometimes not yet departed) friends as they leaf their way through the accounts of the various comets in Kronk's portfolio. Soon after leaving school and beginning work as a Technical Assistant in the CSIRO's Division of Radiophysics in Sydney I accepted a part-time evening position at Sydney Observatory, where the then Director, Harley Wood, became a close friend and great source of inspiration to me. Harley began his own association with Sydney Observatory in 1943, and over the years he observed a number of different comets, recording their positions, describing their nuclei and tails, and from time to time photographing them with the Observatory's astrographs. His work is summarised on pages 128-133, 311 and 317.

Another old friend who features even more prominently is Albert Jones of Nelson, New Zealand, who has made more visual observations of variable stars than any other living astronomer (see Austin, 1994). But Albert has also discovered two comets, and made regular observations of many known comets. His cometary work between 1945 and 1959 (inclusive) is discussed on no fewer than 48 different pages in Kronk's book.

One feature of astronomy that particularly interests me is those cometary discoveries by southern astronomers that were not formally credited, either because of the 'tyranny of distance' in those long-past times before the introduction of intercontinental cables, or because of communication crises during major wars. Two Australian examples I have studied involved Frank Skjellerup (1875–1952) and Mark Howarth (1884–1971), who independently discovered Comets C/1941 B2 (de Kock-Paraskevopoulos) and C/1941 K1 (van Gent) respectively. Australia and the Pacific were in the throes of WWII at the time, and news of their discoveries took far too long to reach the northern hemisphere. In Orchiston (1977: 122) I make a compelling case for the renaming of these comets since "… communication issues conspired to deprive Australian astronomers of credit for the discoveries of the above comets." Kronk discusses these comets on pages 126-133 and 150-156 respectively, where the independent discoveries by Skjellerup and Howarth are recognised.

Like its predecessors, *Cometography Volume 4* is a beautifully-prepared and beautifully-presented book that will appeal to those with a passion for the history of cometary astronomy, but once again I fear that its relatively high price will prevent it from joining the bookshelves of some astronomers.

References

Austin, R.R.D., 1994. Albert Jones – the quiet achiever. *Southern Stars*, 36, 35-42.

Orchiston, W., 1997. The 'tyranny of distance' and Antipodean cometary astronomy. *Australian Journal of Astronomy*, 7, 115-126.

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Strom, Richard G., 2008. The origin and meaning of colourful descriptions in Chinese astronomical records. *Journal of Astronomical History and Heritage*, 11(2), 87-96.

During editing, rewording of one sentence has erroneously changed its meaning. At the beginning of the second full paragraph on page 93, the sentence which begins, "Firearms were invented…" should be replaced by:

The Chinese invention of gunpowder between 850 and 880 CE (Ronan, 1980: 50) was followed some centuries later by firearms. An early example unearthed near Harbin has been dated to 1288 (Needham et al., 1986: 293).

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