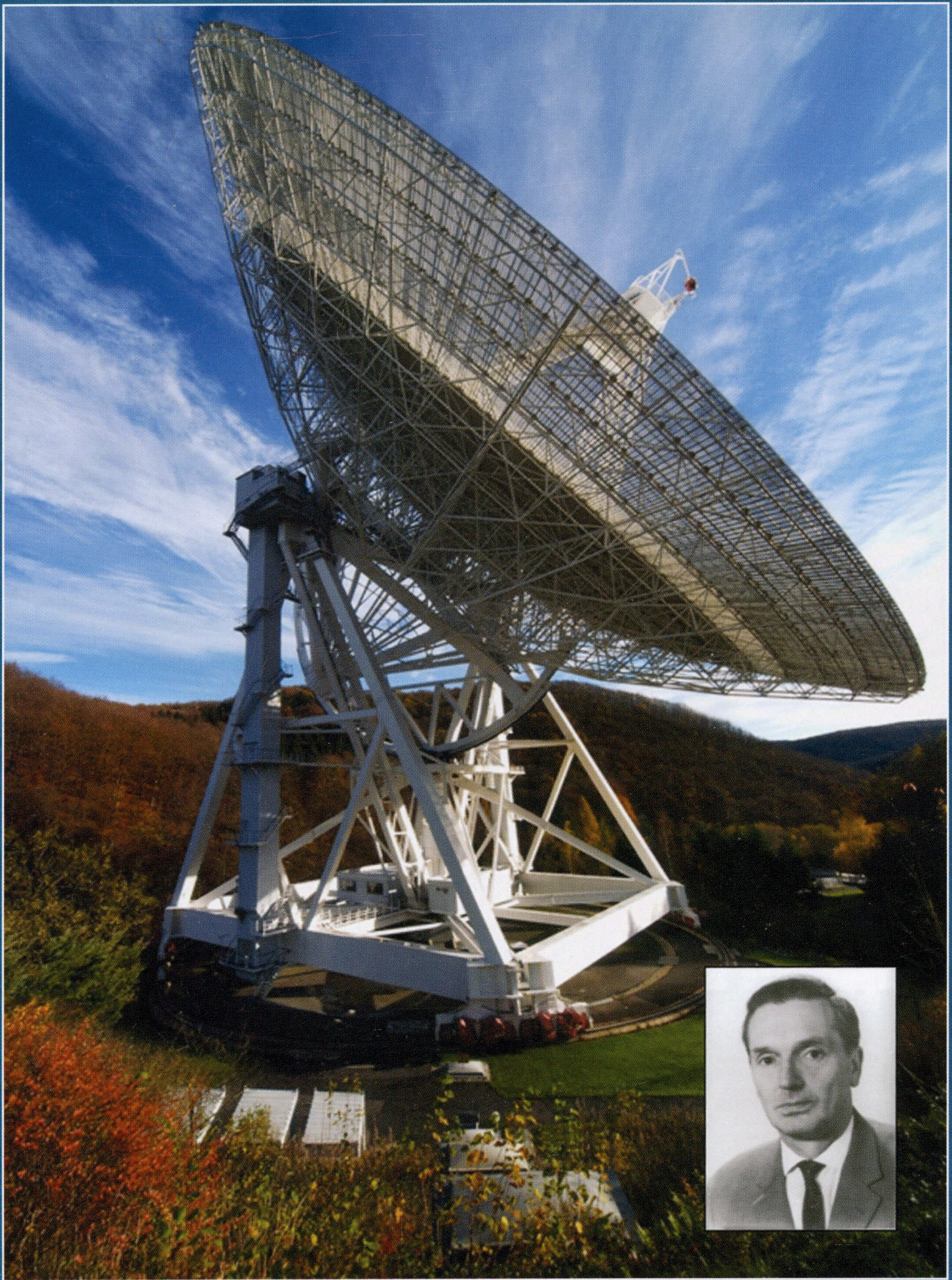
JOURNAL OF ASTRONOMICAL HISTORY AND HERITAGE



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COVER PHOTOGRAPH

This photograph shows the 100-m Effelsberg Radio Telescope in the valley of the Effelsberg Creek, in Germany (the photograph was taken by Mr N. Tacken and is reproduced here by courtesy of the Max-Planck-Institut für Radioastronomie). The planning, design and construction of this radio telescope occurred during the 1960s and early 1970s, with 'first light' occurring on 23 April 1971. The inset photograph shows the man behind this project and responsible for its fruition, Professor Dr Otto Hachenberg (photograph by courtesy of the Archiv der Max-Planck-Gesellschaft in Berlin-Dahlem). For information about this remarkable radio telescope, its links with the Max-Planck-Institut für Radioastronomie, and the important contribution it has made to astrophysical research over the past forty years see the paper by Richard Wielebinski, Norbert Junkes and Berndt Grahl on pages 3-21 in this issue of the journal.

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THE EFFELSBERG 100-M RADIO TELESCOPE: CONSTRUCTION AND FORTY YEARS OF RADIO ASTRONOMY

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Abstract: The Effelsberg 100-m dish represents a major breakthrough in the technology of radio telescope construction. Using new methods of computation a big step in the direction of improved surface accuracy for large structures was achieved. In conjunction with the decision to build the 100-m radio telescope the Max-Planck-Gesellschaft (MPG) founded the Max-Planck-Institute for Radio Astronomy (MPIfR) in Bonn. The MPIfR grew out of the Bonn University Astronomy Department to become one of the leading institutes for radio astronomy in the world. This new institute received strong support from the MPG in the form of new positions and operating funds. As a result, the 100-m radio telescope could be quickly opened up for astronomical observations. The technical divisions provided state-of-the-art receivers and astronomical software. Teams of astronomical researchers made inroads in several important directions of astronomical research. Over the years virtually all the observing methods of radio astronomy were implemented at Effelsberg. In later years the MPIfR became involved in mm, sub-mm and infrared astronomy research. However, the 100-m radio telescope remained the 'work horse' of the Institute. The Effelsberg Radio Telescope will celebrate its 40th anniversary of operations in May 2011 and is still going strong. The observations with the 100-m radio telescope have resulted in thousands of publications. It has served several generations of radio astronomers and has given hundreds of students the opportunity to complete doctoral degrees. The 100-m radio telescope has been upgraded continuously, is in excellent condition and can look to a further period as an important research instrument.

Keywords: Effelsberg 100-m Radio Telescope, Max-Planck-Institut für Radioastronomie, radio astronomy, observational results

1 INTRODUCTION

German radio astronomy started late compared to other European countries due to restrictions on radio research after World War II. At first, smaller radio astronomy observatories started observations in Kiel and Tübingen. The Heinrich-Hertz-Institut (HHI) in Berlin-Adlershof (Soviet zone) started operations in 1946. This institute became involved in solar radio astronomy research. In the 1950s, after restrictions were lifted in the Western zones, an initiative from the local government in the West German State of Nordrhein-Westfalen led to the funding of a 25-m fully-steerable dish on the Stockert Mountain (elevation 435m, near Bonn), to be operated by Bonn University. At the same time, a 36-m transit dish in Berlin-Adlershof (East Germany), intended for HHI Galactic research, was also funded. In 1962 an important report 'Denkschrift zur Lage der Astronomie' ('Memorandum on the State of Astronomy') was published by the Deutsche Forschungsgemeinschaft (DFG)[1] suggesting developments in astronomy for the next decades in West Germany. One of these proposed developments was to build a major radio telescope. The construction of the Berlin Wall in 1961 led to the move of Professor Dr Otto Hachenberg, the Director of the HHI in Berlin-Adlershof, who lived in West Berlin but worked in the East, to the University in Bonn. This strengthened the Astronomical Institute of Bonn University, leading to the founding of a new independent Radio Astronomy Institute.

After his move to Bonn, Professor Hachenberg immediately began planning an 80-m radio telescope. Building on experience with the construction of the 36-m transit dish in Berlin-Adlershof, the achievement of good surface accuracy became the main goal. Initial funding for the design phase of the new Bonn radio telescope came from the Government of the state of Nordrhein-Westfalen in Düsseldorf. German steel companies were contacted and asked to submit designs for this large new instrument. Bonn University's 25-m Stockert dish built in 1956 was in a way merely an enlargement of the German World War II 7.5-m Würzburg Riese radar antenna, but it could only operate down to a wavelength of 11 cm.[2] One of the important design specifications for the new large telescope was that it should operate at high frequencies, even at 23 GHz (1.3-cm wavelength). This stipulation was a result of the rapidly-expanding field of radio spectroscopy at short cm wavelengths. The symmetrical structure of the 36-m dish in Berlin-Adlershof was a firm guide for Professor Hachenberg during the design discussions. The supporting structure of the 36-m radio telescope was placed on concrete supports and load tests were carried out before mounting. It became clear that symmetrical structures could have predictable deflections under gravity.

The firms Krupp and MAN became involved in the design and each was asked to prepare two different design proposals. Ing. [= Engineer] Ben Hooghoudt was asked to act as consulting engineer for the project. The antenna division of the Krupp Company, led by Dipl.-Ing. E. Geldmacher, submitted a design prepared by Dipl.-Ing. Helmut Altmann that met (in fact exceeded) the desired specifications. In the design phase the decision was made to abandon a very stiff steel construction in favour of a flexible one, but with the parabolic shape remaining through elevation movement due to elasticity. Depending on the funding, an extension of the diameter of the dish to 90 m became a realistic consideration. As a result of this excellent design, in 1964 the Bonn University astronomers, Professors Friedrich Becker, Wolfgang Priester and Otto Hachenberg, submitted a detailed application to the Volkswagenstiftung[3] for funds to build this large new radio telescope.[4] To ensure sufficient operating funds, subsequent negotiations led to the founding of the Max-Planck-Institut für Radioastronomie (henceforth MPIfR) in Bonn.

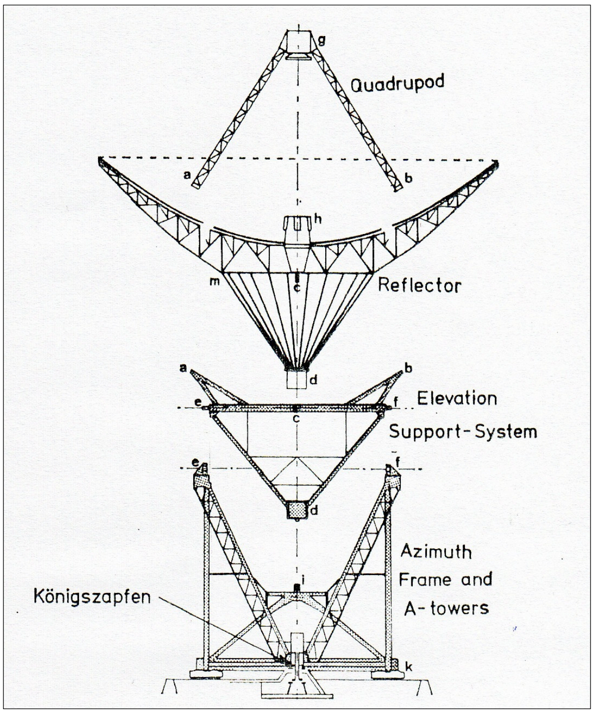

Figure 1: The basic construction design of the 100-m dish. Note the elevation bearing points (e, f) and the octahedron construction points (a, b). The ballast is at point d. There is a cross structure between points (e, f). The flexible joint lies at the apex point c.

Originally the Volkswagenstiftung also approved a second German radio astronomy project, the construction of a 160-m low frequency dish proposed by Dr Sebastian von Hoerner from the University of Tübingen. However, this project was not pursued, and hence more funds became available for the Bonn radio telescope. Since the design computations suggested that a very exact surface accuracy could be achieved even for a reflector of 100-m diameter it was decided to construct a 100-m radio telescope.

2 THE CONSTRUCTION OF THE 100-m RADIO TELESCOPE

In the early design stages it was decided to adopt a completely new approach and abandon the 'classical' design with stiff steel structures, such as used with the largest parabolas in existence at that time, namely the Jodrell Bank Mark I and the Parkes Radio Telescopes. The 100-m dish was to have a surface accuracy of better than 1 mm r.m.s. The Krupp Company's Small Antenna Division, led by E. Geldmacher, studied symmetrical structures with radial symmetry, held—like an umbrella—at one point. The tipping structure (including the prime focus cabin) was to be separate from the reflecting dish, and suspended at two points. This allowed for an easier computation of deformations caused by gravity during the changing elevation of the reflector. In this process the 'soft spots' of the complex grid of tubes could be identified and the dimensions of the tubes changed to optimize the overall surface deformation. A more theoretical approach to the problem of the construction of large reflecting telescopes was made by von Hoerner (1967) and called 'homology'. In the end, the trial and error procedures used in the design of the 100-m radio telescope came close to the more theoretical 'homology' method. A patent application was submitted by Altmann (1965) for his novel construction. The final step in the design was the use of new IBM software (FRAN) to check the final deflection performance of the 100-m dish. At that time, these calculations could be made only for sections of the reflector due to limited computing power, but later calculations, with full computing power, confirmed the original results.

Figure 2: The foundations for the 100-m radio telescope in the construction phase (1968).

The design of the 100-m radio telescope (see Figure 1) included several novel features. The tipping structure was an octahedron held at two points. The elevation bearings and encoders were mounted in the A-frame support structure at these points. A cross-beam structure within the octahedron ensured a stable tipping structure. It must be pointed out that in this design the octahedronal structure supporting the prime focus cabin and the tipping section (holding the ballast load) were independent of the reflector. The elevation drive was by means of a large ring tooth and floating wheel drive in one of the octahedron arms. Originally four elevation drive units were planned, but oscillations forced a reduction to two drive units. This change had no effect on the accuracy of the positioning or tracking of the radio telescope. The azimuth drive was by means of 16 motors and 32 wheels with ~100 tons load through each wheel on the rail track. The reflector, an umbrella-like structure, was held at the ballast point and contacted the tipping structure in a flexible joint in the cross at the apex point only, an idea of Helmut Altmann.

The search for a suitable site for the radio telescope had already started in 1966. It was clear that the site should be in a secluded valley and not be on a mountain like the 25-m Stockert dish—which was exposed to man-made interference. Several sites were investigated, and the final choice fell on an almost north-south valley close to the village of Bad Münstereifel-Effelsberg. This site had the additional advantage that it was just on the right side of the border of the State of Nordrhein-Westfalen. As a result of this choice the State Government in Düsseldorf offered the site to the MPIfR.

Considerable time was needed to sort out the land ownership titles and to purchase the site, and the construction of such a complex structure required many different subcontractors. An association of companies, the ARGE STAR, was formed involving as major partners Krupp (steel elements) and MAN (on-site assembly). The first step involved the construction of the foundations (see Figure 2). A small creek (Effelsberger Bach) which marked the boundary between the States of Nordrhein-Westfalen and Rheinland-Pfalz had to be moved. The whole site was 15.4 hectares in extent, and extended across both States, but the radio telescope itself was in the State of Nordrhein-Westfalen.

The foundation of the radio telescope was a concrete ring supported on concrete piles. The ring was to take the 64-m diameter azimuth drive track. In the centre of the ring foundation a pyramid-like 'Königszapfen' (king pin) was constructed. This central section was to position the radio telescope on the 64-m track in the azimuthal direction. In addition, underground rooms for the electrical supply and workshops were constructed within the foundation area. The azimuth encoders were placed in the centre of the Königszapfen and the cable twist was installed to allow for the azimuth movement. A tunnel to accommodate all of the cables was constructed from the Königszapfen to the control building. These cables were separated from the power supply, with the digital and the coaxial radio frequency cables in soft iron ducts, in order to reduce all mutual interference. The elevation cable twists were constructed in the elevation bearings area.

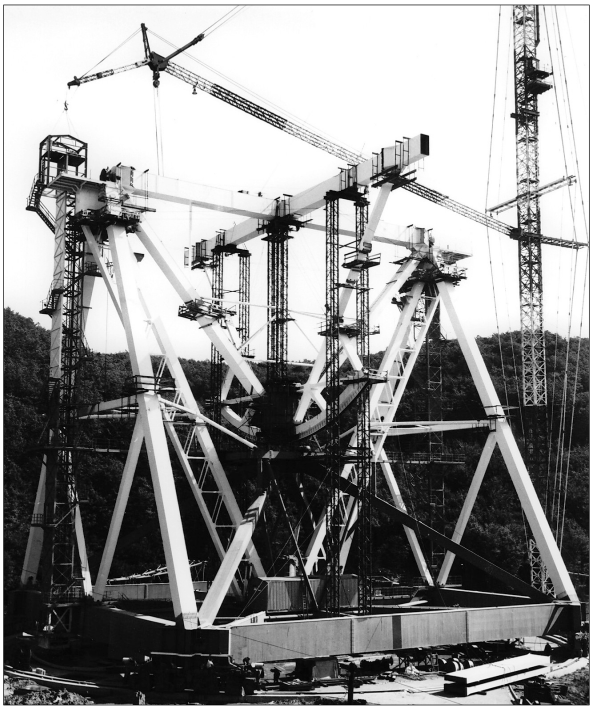

Figure 3: The A-frame support structure and the tipping section being assembled (1969). Note the cross structure in the centre where a flexible joint connects to the reflector structure.

The beginning of the on-site telescope construction required the erection of a 130-m high crane. This part of the telescope assembly was the responsibility of the MAN Company. A level area was made available for the welding of the individual ('orange slice') reflector sections. A hut was built where a cutting machine could produce the complex tube parts for the reflector. The supporting A-frame structure, a more massive steel construction, was made at Krupp's workshops and brought by road to the site. By 1969 the A-frame support structure was being assembled (see Figure 3). Note that the A-frame structure is a box-line construction made of large welded steel sheets, not of many pipe elements. At the same time the welding of the reflector support structure was proceeding on the ground (Figure 4). Great care was taken in the weld-

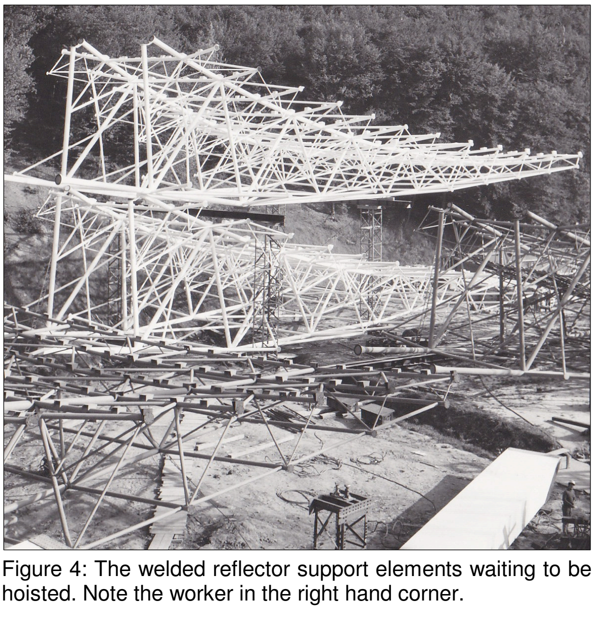

Figure 4: The welded reflector support elements waiting to be hoisted. Note the worker in the right hand corner.

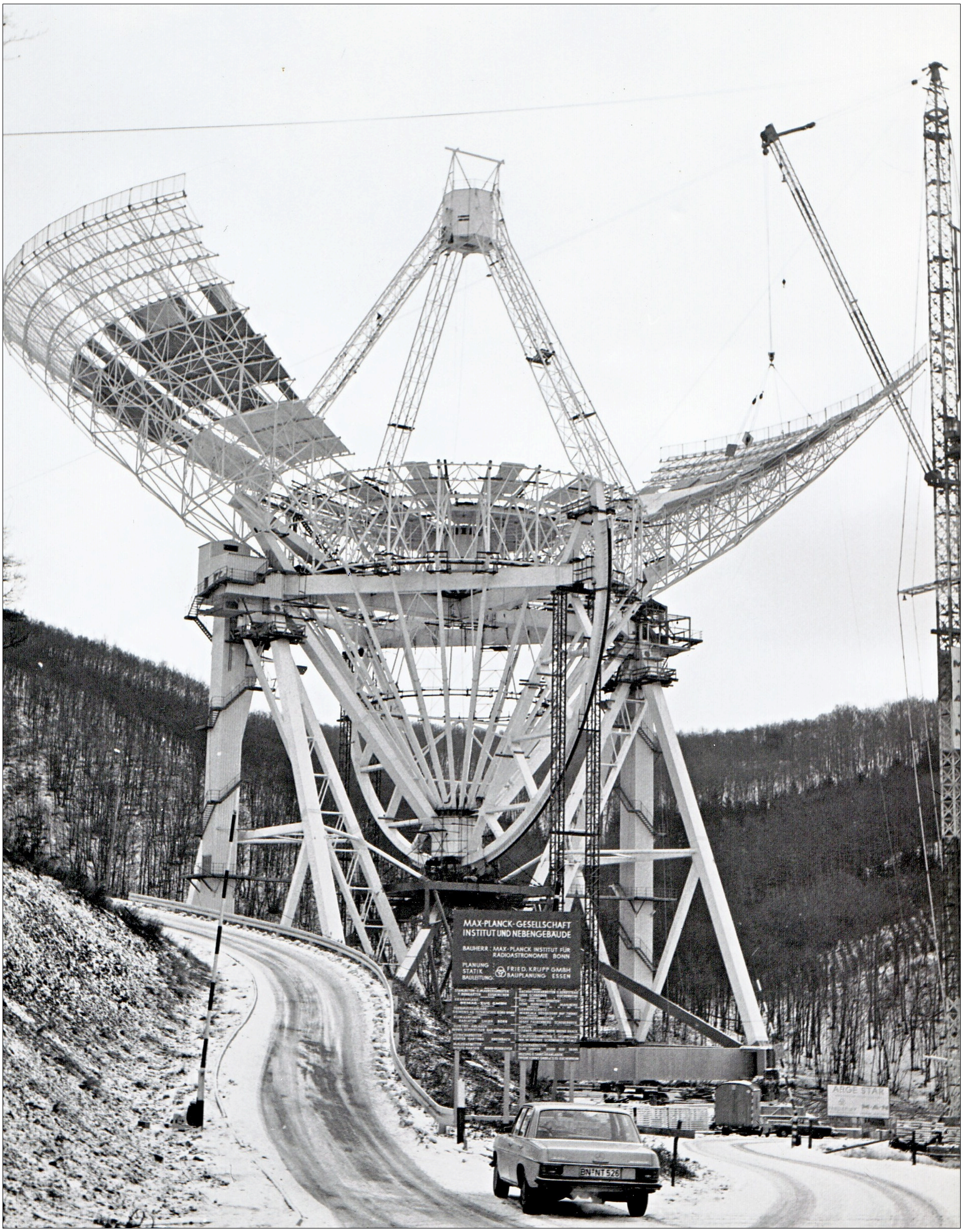

Figure 5: The early assembly stage of the reflector with two ‘orange slice’ sections in place. The assembly of the reflector required drive in azimuth from the very beginning.

ing of the tubes since it was clear that high accuracy was needed to produce a successful structure. The angles at which the individual tube elements were joined in a weld were critical. The whole site was cluttered with telescope sections in various stages of assembly. The mounting of the reflecting panels was partly done on the ground before lifting. The ‘orange slice’ sections were placed alternatively on opposite sides of the dish (see Figures 5 and 6). For this purpose the azimuth drive had to be installed in the earliest stage of the construction. The final section of the reflector was hoisted in 1970, having less than a 0.5-cm gap in the final assembly. This was a remarkable achievement in steel construction accuracy. Final surface adjustment could only be made after all of the panels were in place. A view of the almost-completed antenna is shown in Figure 7.

Several additional major components of the radio telescope require special mention. The antenna, which was of altazimuth design, rotated on a steel track. The 64-m diameter ring track embedded on the ring foundation (rail cross-section 29 cm × 14 cm) was delivered in sections that were welded on site by the thermite process. The adjustment of the track required high accuracy, and the 0.1-mm level was finally reached. The axes of the radio telescope were leveled to an accuracy of 0.2 mm.

The reflecting panels were another crucial component of the construction. There were 17 rings of panels of different types. The inner rings 1 to 9 (up to 60-m diameter) had honeycomb panels (glued aluminium) delivered by the Dornier Company. The next section of the reflector from 60-m to 80-m diameter (rings 10 to 14) had aluminium frame panels that were delivered by the MAN Company. The final 3 rings of panels (rings 15 to 17) out to 100-m diameter were wire mesh reflecting surface on steel frames made by Aviolanda in Holland. The surface accuracy of the honeycomb panels was better than 0.2 mm. The aluminium frame panels came with ~0.3 mm accuracy. Each panel was supported on special bolts at four corners. The supporting bolts allowed adjustment from inside the dish surface. The panels were painted with a special white paint selected for maximum reflection of infrared radiation. A 1.8-m high vertical ‘collar’ was added on the periphery of the 100-m reflector, a series of reflecting mesh sections, that were intended to reduce the sidelobes and hence man-made interference.

Figure 6: Assembly of the panels on the partly-constructed reflector.

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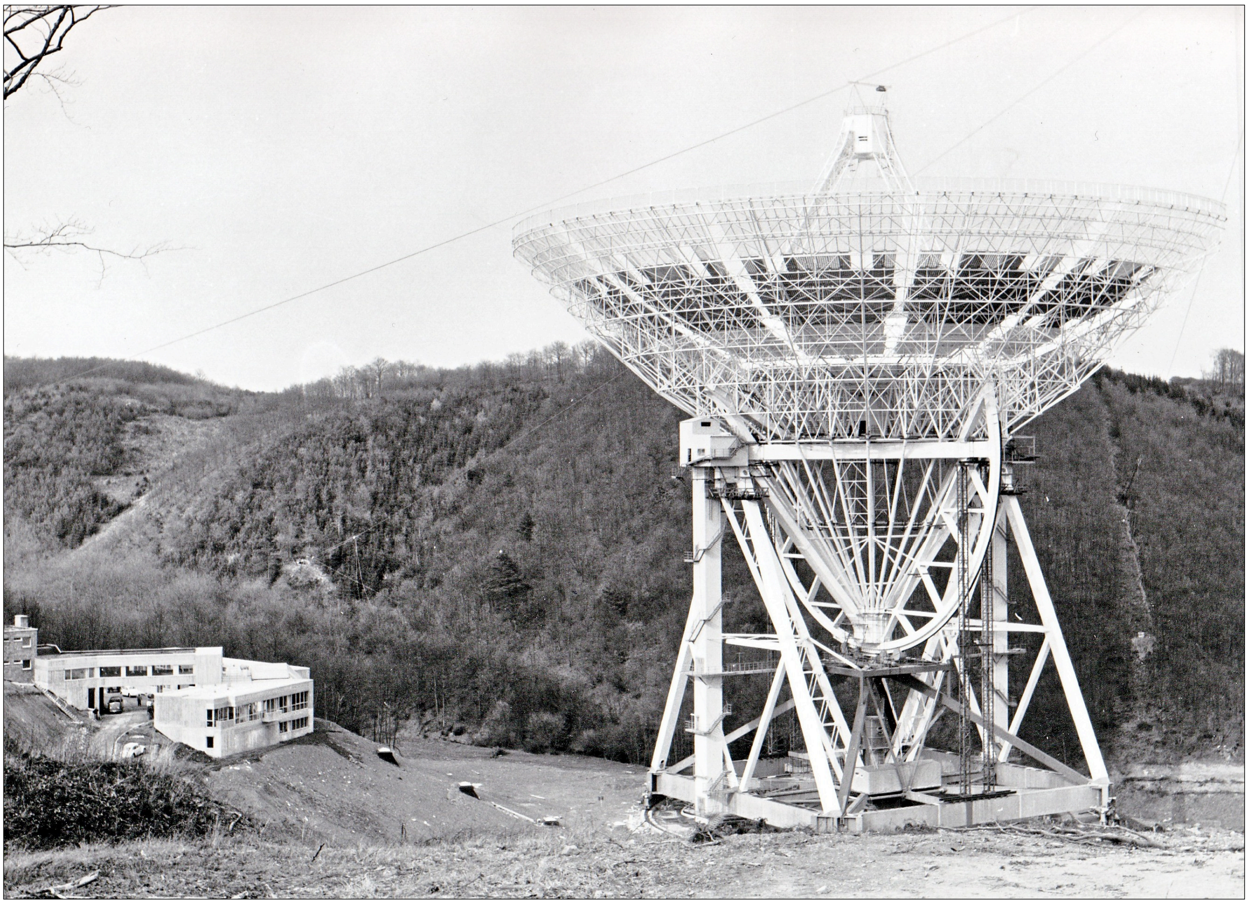

Figure 7: The view of the almost-completed radio telescope in early 1971. The control building is seen on the left. A tunnel joins the central ‘Königszapfen’ to the control building and contains several ducts for cables.

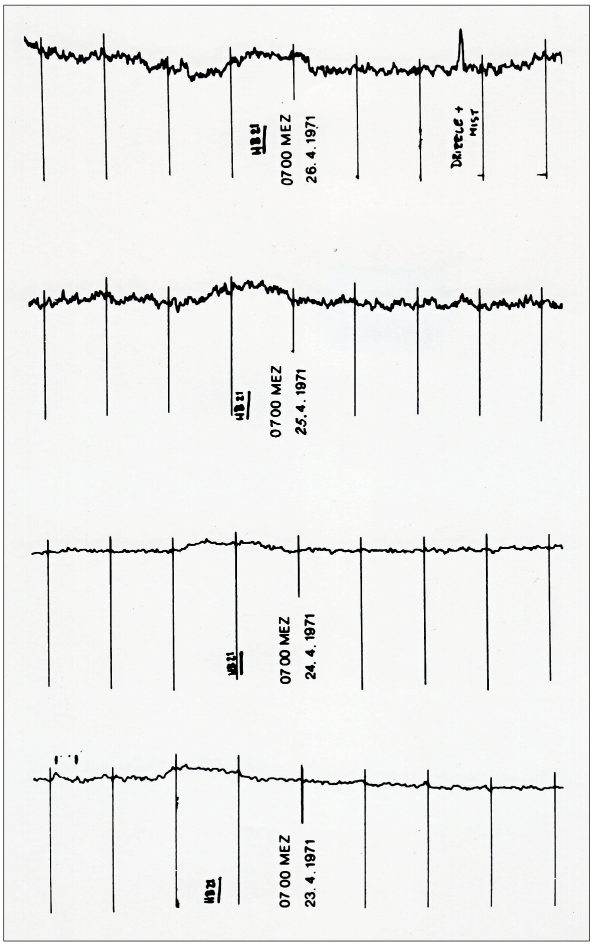

Figure 8: First light obtained with an uncooled 11-cm receiver in the primary focus. Drift scans through the radio source HB 21.

The geometry of the 100-m dish was a Gregorian system with the possibility to insert a receiver at the prime focus. A central hole of 1.0 m incorporated a large bearing which allowing for prime focus receiver rotation. The Gregorian sub-reflector was 6.5 m in diameter. Considerable effort was needed in the design of both the prime focus and secondary focus cabins. This was an in-house effort. For some descriptions of the Effelsberg Radio Telescope see Hachenberg (1968; 1970); Hachenberg, Grahl and Wielebinski (1973) and Wielebinski (1970).

From the very beginning, the plan was for the telescope drive to be computer controlled. The electric drive system was a concept of the AEG-Telefunken company. The incremental encoders for the antenna axes came from the Heidenhain Company, and were capable of 2 arc sec readout. For control of the drive system, a Ferranti ARGUS 500 computer was chosen. The astronomical drive system was an in-house effort of the Computer Division of the MPIfR (see Stumpff et al., 1972). The electronic receivers were constructed in the Electronics Division of the MPIfR (Keen and Zimmermann, 1973). First light was received at 2.7 GHz (11-cm wavelength) on 23 April 1971 when a simple dipole was inserted in the prime focus (Figure 8). The telescope was first driven, while taking observing data for the 408 MHz (73 cm) radio continuum survey during the official opening on 12 May 1971.

Many measurements had to be made of crucial sections to optimize telescope performance. In the early stage of the telescope operations, drive oscillations were experienced in the elevation motors. This was resolved by removing two of the four planned drives and reinforcing the brakes. This problem was solved through consultation with Ben Hooghoudt. The surface of the dish was measured by tape and theodolite showing that the design specification of 1 mm r.m.s. was met. The predicted focus changes of some 90 mm in the elevation direction and 20 mm in the vertical direction during a full elevation tipping were confirmed by astronomical observations. Furthermore the change of the reflector from one parabolic shape to another with elevation change was confirmed. The pointing of the telescope was found to be some 10″ absolute, with ± 2″ in the tracking mode. In fact, the overall telescope performance exceeded the original specifications. In addition to the first light at 2.7 GHz, a 408 MHz receiver was installed at the prime focus. The 408 MHz observations that were made during the construction phase of the telescope led ultimately to a very famous all-sky radio continuum survey (Haslam et al., 1982), in some ways the logo of the MPIfR (see Figure 9).

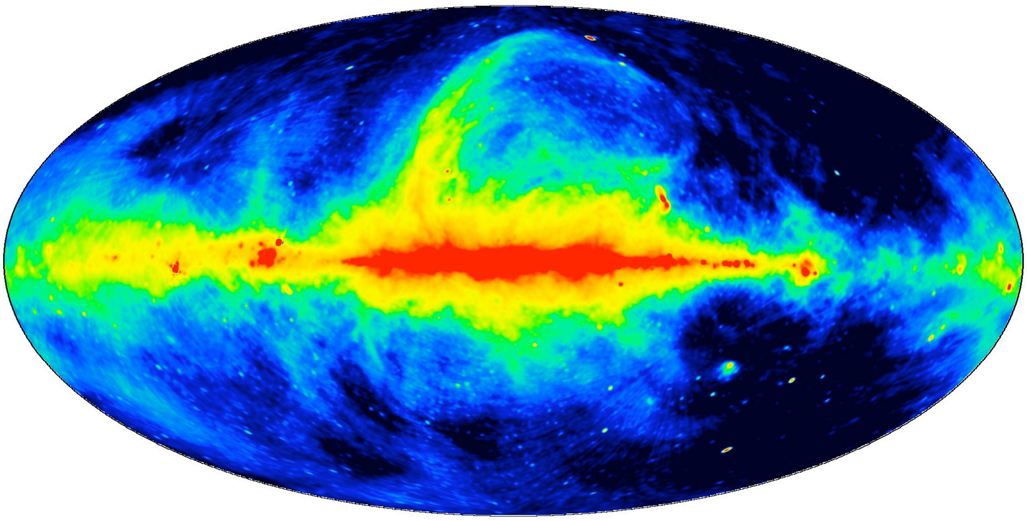

Figure 9: The 408 MHz all-sky radio continuum survey, a combination of observations with radio telescopes at Jodrell Bank, Effelsberg and Parkes (after Haslam et al., 1982).

3 THE MAX-PLANCK-INSTITUT FÜR RADIOASTRONOMIE

The decision to finance such a major instrument as the 100-m radio telescope was coupled with finding a research organisation that would ensure reliable operations. The Max-Planck-Gesellschaft, the major German research organisation devoted to fundamental research, decided to take on this role and founded the Max-Planck-Institut für Radioastronomie (MPIfR). The plan was to have strong technical and astronomical divisions. The founding Director, appointed in 1966, was Professor Otto Hachenberg who was also a full Professor at Bonn University. Hachenberg's astronomical interests were solar research and HI studies of the Galaxy.

As usual at that time, the Institute was to be managed by a 'Direktorenkollegium', with two additional Directors. The MPG takes great care in the selection of Directors based on the 'Harnack Principle'. This Principle aims at appointing Directors, and giving them sufficient staff and funds to implement a certain field of research. The additional Directors appointed in 1969 were Professor Peter G. Mezger from the National Radio Astronomy Observatory (NRAO) in the USA (whose interest was mainly spectroscopy) and Professor Richard Wielebinski from the University of Syd-ney (with interests in radio continuum and pulsars). At this early time the Directors were responsible for different technical Divisions: Hachenberg for the Telescope Division, Mezger for the Computer Division, and Wielebinski for the Electronics Division that constructed the receivers for the new radio telescope. The three Directors were given sufficient new positions to implement both viable technical Divisions and their own astronomical research groups. Although independent, the Institute was closely linked with Bonn University; in fact, the two new Directors became Honorary Professors of Bonn University in 1971, which gave them the right to give lectures and to supervise Ph.D. students.

The arrival of the two new Directors early in 1970 led to a dynamic phase in building up the Institute. Professor Hachenberg enlarged his research group, mainly by adding staff previously appointed to the Bonn University Institute of Radio Astronomy, although some new staff members with interest in Galactic HI research came from The Netherlands. Professor Mezger came back from the NRAO with several German expatriates, but he also recruited staff in the USA who were interested in spectroscopy. Professor Wielebinski brought some Australian researchers with him, as well as some selected people from The Netherlands and from the Jodrell Bank Radio Observatory. In fact, several software specialists involved in large-scale surveys came from Jodrell Bank and transferred their methods to Effelsberg (see, e.g., Haslam, 1974).

The technical Divisions were recruited mainly from local engineers, technicians and software specialists. In the final phase of the Institute build-up the staff totalled some 180 positions. At first the Institute was scattered through several buildings in Bonn as well as at sites on Stockert mountain and in Effelsberg. In 1973 a new building in Bonn-Endenich was ready and a move of all of the groups could be implemented. However, a basic decision was made to keep a strong staff (some 35 positions) at the 100-m radio telescope site. This decision was a guarantee of good support for future observations. In addition to the staff positions, graduate students were accepted as the MPG offered generous scholarships for Ph.D. students. Another scheme of the MPG, but also of the Alexander von Humboldt Foundation, allowed visitors from outside Germany to come to the Institute for varying periods. In general some 250 people were working at the MPIfR. This international mixture of staff, students and visitors made an important contribution to the development of the MPIfR.

4 EARLY OBSERVATIONAL RESULTS

In July 1972 test observations were carried out with an 11-cm receiver at the prime focus of the radio telescope. One of the first tests was to confirm the movement of the focus with changes in elevation. The observed movements proved very close to the predicted ones and these corrections were built in to the drive programme. Regular radio continuum observations at 11 cm started in August 1972. In October 1972 a 2.8-cm receiver became available and was immediately used for astronomical observations. In fact the two first publications made with the 100-m telescope were at 2.8 cm: the first observations of pulsars at this short wavelength (Wielebinski et al., 1972; see Figure 10) and sensitive measurements of a radio star (Altenhoff et al., 1973).

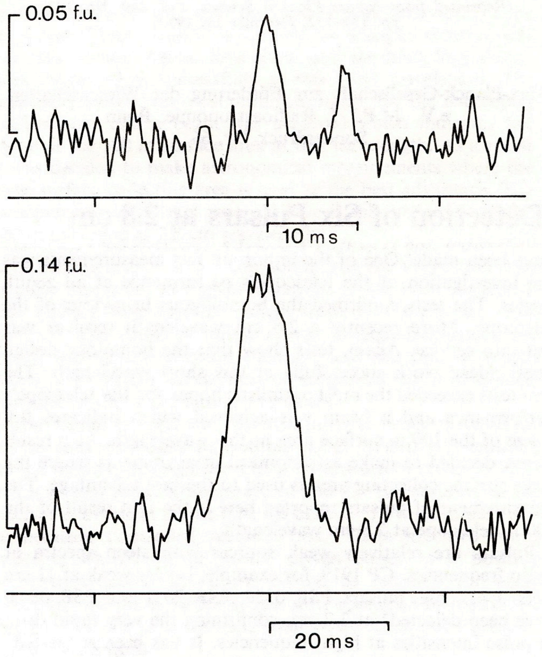

Figure 10: The first observations of pulsars at 2.8 cm. Top: BP 2020, bottom: JP 2021 (after Wielebinski et al., 1972).

The excellent stability of the 11-cm receiver showed that it would be possible to make very sensitive radio continuum observations by the addition of individual scans. At first only scans were added (e.g. Berkhuijsen and Wielebinski, 1973), but later a spectacular result of extending this method was the production of a complete map of the Andromeda Nebula (M31) showing its spiral structure (Berkhuijsen and Wielebinski, 1974; see Figure 11). This result revealed that a single dish radio telescope could compete effectively

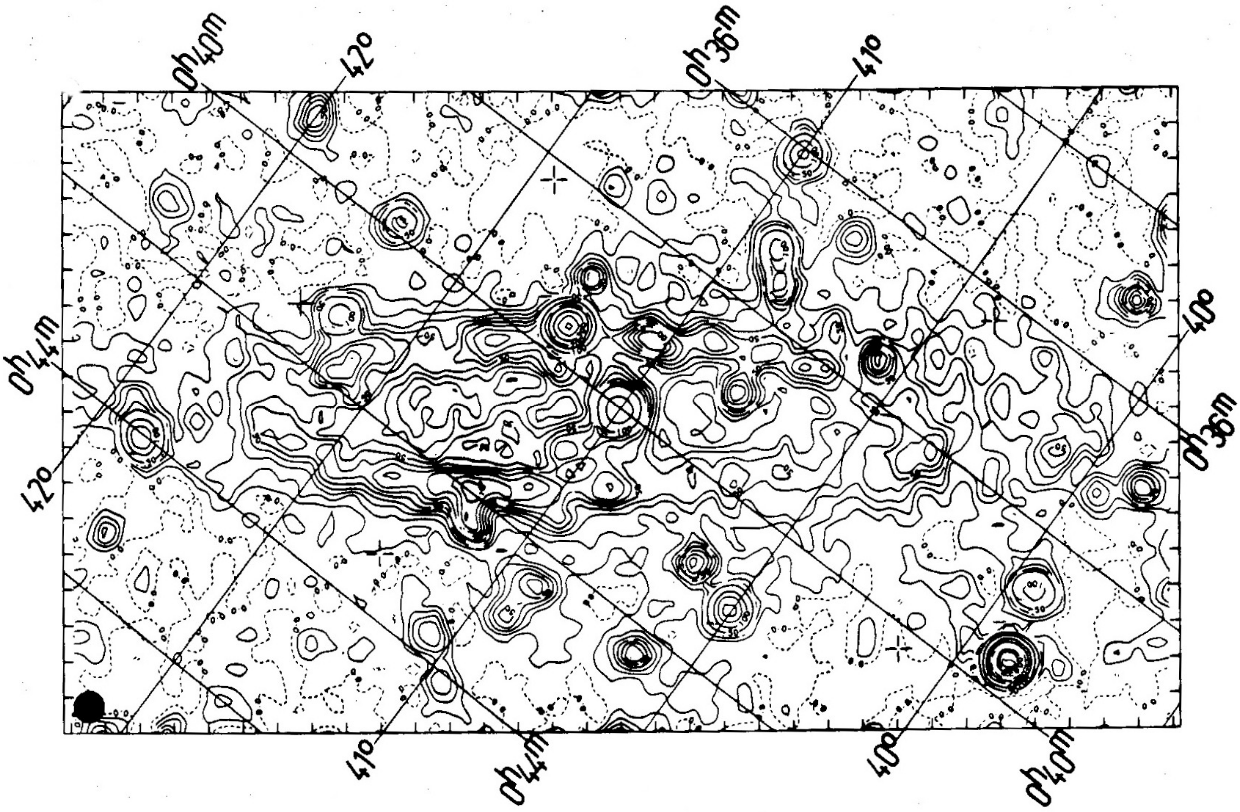

Figure 11: The radio continuum map of the Andromeda Nebula (M31) at 11 cm (after Berkhuijsen and Wielebinski, 1974).

with aperture synthesis arrays, in particular since the radio continuum maps from a single dish contained all spatial components. The aperture synthesis telescopes usually lost the large-scale structures and hence the data were of little use for the determination of the spectrum.

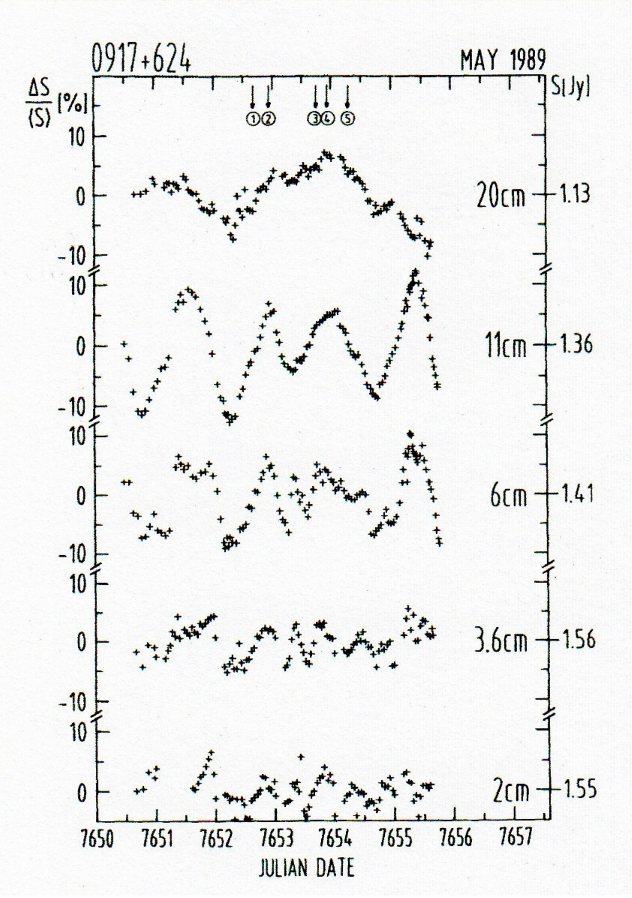

Figure 12: Simultaneous observations of intra-day variability in Effelsberg and at the VLA (after Qian et al., 1992).

The year 1973 saw numerous developments that extended the observational capability of the Effelsberg Radio Telescope. During this year cooled receiver systems for 21 cm and 6 cm were installed. The first spectroscopy tests were also carried out, which revealed the need to improve the baselines, especially for broad-band observations. The first very long baseline interferometry (VLBI) observations were conducted with transatlantic baselines (see Preuss et al., 1974). The first polarization observations were made (Baker et al., 1973) using single channel receiver systems with rotation of the receiver in the prime focus. The Max Planck Society was asked by the German Federal Ministry of Research to make telemetry observations of the German-US HELIOS satellite which orbited the Sun and required high sensitivity observations, and these were initiated in 1974. These daytime observations required constant receiver changes and hence reduced the time available for astronomical observations. The HELIOS project came to a conclusion in 1976.

Several important large scale surveys were started soon after scheduled observations became possible. The 408 MHz all sky survey (Haslam et al., 1982) was started during the early construction phase at Effelsberg. The survey, which was an important contribution to our knowledge about the distribution of radio intensities, was continued at Parkes and then completed at Jodrell Bank. A sensitive radio continuum survey of the Galactic Plane at 6 cm was carried out (Altenhoff et al., 1979) giving a basis for further spectroscopic studies. A catalogue of extragalactic sources with flux densities >1 Jy at 5 GHz was compiled (Kühr et al., 1981). Another important calibrator paper (Baars et al., 1977) used data from Effelsberg as well as other radio telescopes. Pulsar observations concentrated on the determination of the spectra of pulsars, given the great sensitivity of the Effelsberg Radio Telescope at short wavelengths.

Receiver development continued with an average of two new receiving systems being added each year. At first uncooled systems were tested out at 15 GHz and 23 GHz, which showed the good operational capabilities of the radio telescope. Dual channel receivers were added to the long list of receiver systems, allowing sensitive polarization studies. The advent of a tunable maser receiver system for the 23 GHz band in 1974 enabled new sensitive spectroscopic observations. The first extragalactic H_2O observations were made (Churchwell et al., 1977). Also, extragalactic NH_3 was detected (Martin and Ho, 1979). The 8.6 GHz system allowed the detection of interstellar $^3He^+$ (Rood et al., 1979), an important cosmological parameter. Pulsar detections made at 23 GHz by Bartel et al. (1977) extended the spectral studies of these objects.

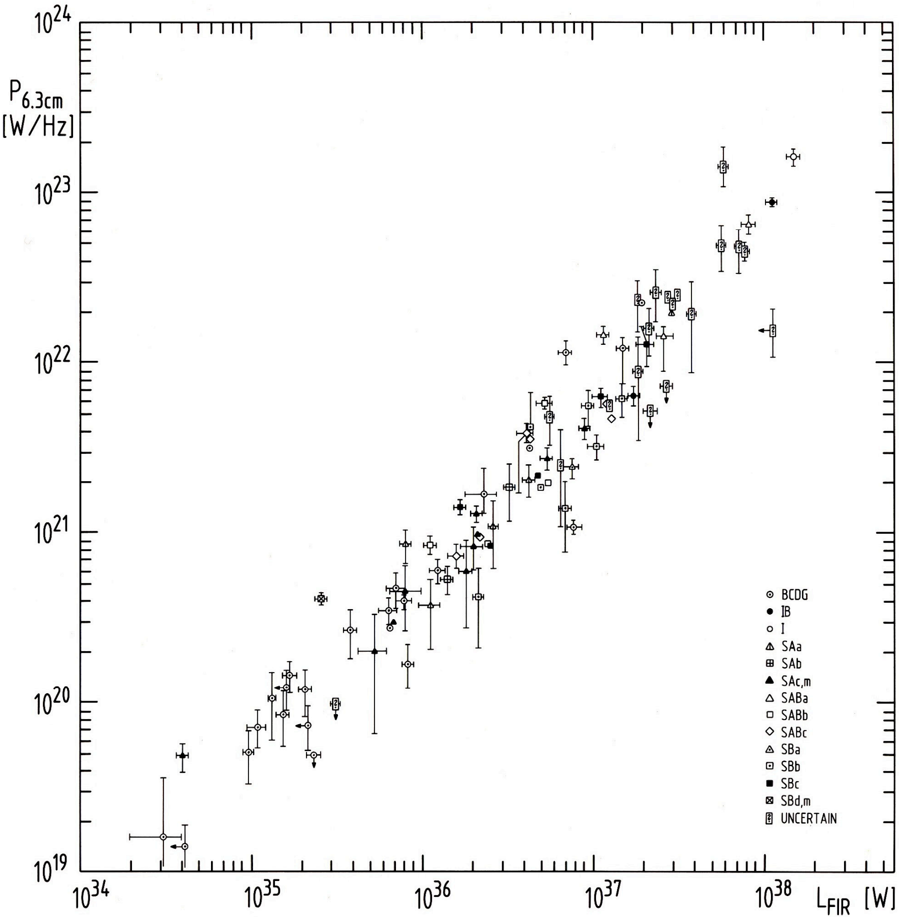

Figure 13: The FIR-radio continuum correlation (after Wunderlich et al., 1987).

5 RADIO CONTINUUM RESEARCH WITH THE 100-m RADIO TELESCOPE

Following the early success of radio continuum observations, of both compact sources and of extended emission, numerous observational projects were carried out. Some of the receivers were operated in the dual beam mode to reduce the noise due to weather effects. For compact sources the discovery of intra-day variability (Witzel et al., 1986) deserves a special mention (see Figure 12). This discovery resulted in the development of a new research field (e.g. Heeschen et al., 1987; Wagner et al., 1996; Quirrenbach et al., 1991; Wagner and Witzel, 1995). This became a way to study compact regions in Active Galactic Nuclei (AGNs).

The launch of the IRAS satellite in 1983 led to several supporting projects with the 100-m radio telescope. The most important result achieved in this context was the discovery of the far infrared-continuum correlation for galaxies (de Jong et al., 1985; Wunderlich et al., 1987). This surprising result (see Figure 13) has also been found to hold for distributed FIR-radio continuum intensities in nearby galaxies (see, e.g., Beck and Golla, 1988).

The mapping of extended objects at high radio frequencies required the development of new software methods. To reduce the scanning noise a 'basket weaving' technique was developed by Emerson and Gräve (1988). Weather effects become a serious problem at high radio frequencies. This led to the development of a multi-beam method of mapping extended sources (Emerson et al., 1979). Deep surveys of the Galactic Plane were made (e.g. Kallas et al., 1980, 21 cm; Reich et al., 1984, 11 cm) leading to the detection of a large number of new supernova remnants (e.g. Reich et al., 1988). The more recent Galactic Plane surveys have been made with full polarization (e.g. Junkes et al., 1987; Duncan et al., 1999; Reich, 2006). The mapping of polarization allows the determination of the magnetic field. A medium latitude Galactic Plane survey at 1.4 GHz, with full polarization information, mapping b = ± 20° of the northern Galactic Plane, is currently nearing completion, and the first section has been published by Uyaniker et al. (1999). The various surveys made with the 100-m radio telescope can be found in the 'Survey Sampler' at the home page of the MPIfR (see, e.g., Figure 14). More recently, the Effelsberg maps were combined with data from interferometers to give good angular resolution and exact calibration of the zero levels. An example of this is a paper by Landecker et al. (2010) where Effelsberg polarization data are combined with the Canadian Galactic Plane Survey.

The Galactic Centre has been the subject of many studies in the radio continuum as well as spectroscopy (see, e.g., Figure 15). Originally it was believed that there was an intense HII region at the Galactic Centre. However, carefully-calibrated data at several frequen-

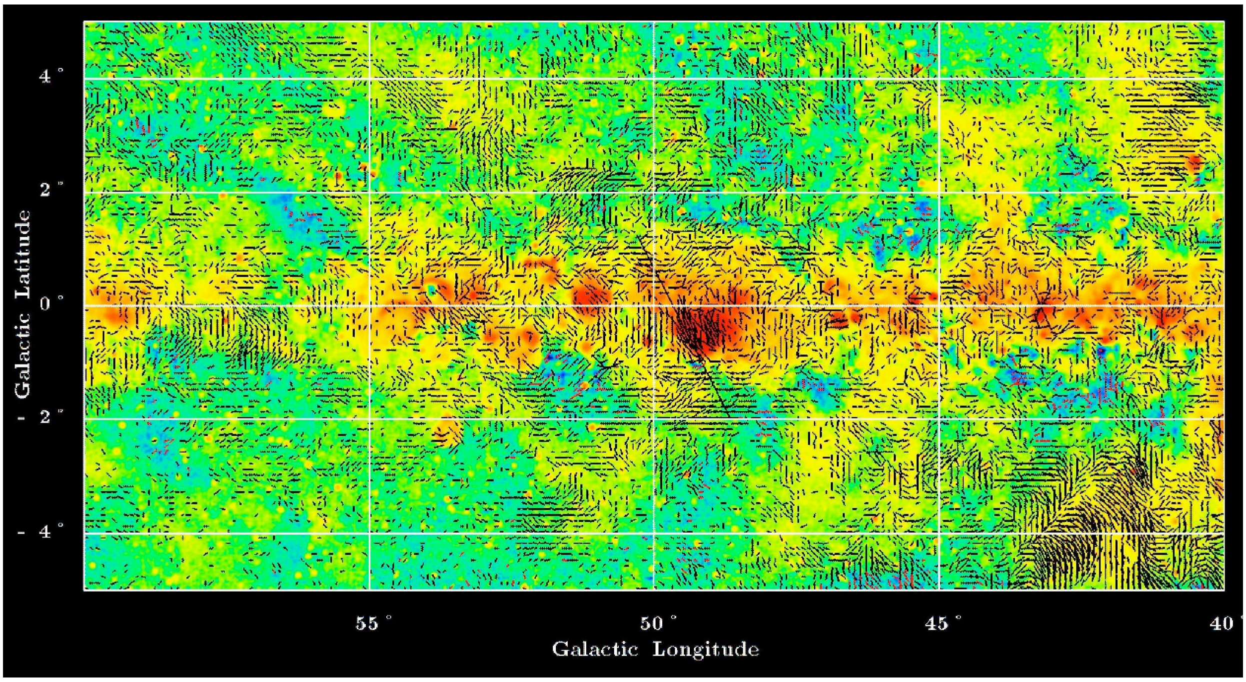

Figure 14: A section of the Galactic Plane with polarization observed at 11 cm in Effelsberg (courtesy Professor Dr E. Fürst, MPIfR).

cies indicated an unusual inverted spectrum (see Reich et al., 1988). In addition polarization mapping of the Galactic Centre showed that this region is highly polarized (Seiradakis et al., 1989). Maps of this region at 32 GHz (Reich et al., 1989) indicated very high rotation measures in the filaments seen in the Galactic Centre. The interpretation of these observations was given by Lesch and Reich (1992) in terms of monoenergetic electrons.

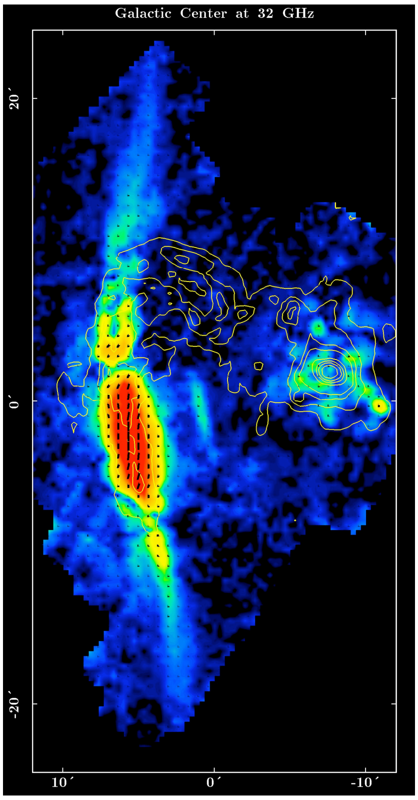

Figure 15: The Galactic centre at 9 mm in the radio continuum (courtesy: W. Reich, MPIfR).

The 100-m Effelsberg Radio Telescope showed its great ability in the studies of nearby galaxies, in particular of the magnetic fields in these basic building-blocks of the Universe. Following the early map of the Andromeda Nebula, observations were carried out of all larger nearby galaxies at higher frequencies where the resolution was better. The use of the 6-cm receiver with full bandwidth of 500 MHz allowed the detection of halos around edge-on galaxies, and multi-beam observations allowed studies of many galaxies at 2.8 cm. The advent of polarization observations led to the development of a whole research field—'magnetic fields in galaxies'. The first polarization map was made of M31 at 11 cm (Beck et al., 1980). These observations showed an unexpected, remarkably homogeneous magnetic field, a ring-like structure. Observations at 6 cm and at 2.8 cm were made, as well as at 9 mm (Klein et al., 1982; Beck et al., 1979; Klein et al., 1988). The Faraday effect was observed in multi-frequency observations and used to probe the magnetic fields in the line of sight. An *Atlas of Magnetic Fields* can be inspected on the home page of the MPIfR. Just as in the case of the Galactic Plane, a combination of 100-m dish observations with an interferometer data set (in this case usually with VLA data from the NRAO) leads to maps with good angular resolution and great diffuse emission sensitivity (e.g. Fletcher et al., 2010)—see Figure 16.

The observation of the radio continuum of clusters of galaxies led to the discovery of halos (e.g. Wielebinski et al., 1977; Wielebinski, 1978) around these objects. The 100-m radio telescope, with its great sensitivity to diffuse radio emission, could study the halo of Coma A at several frequencies (Deiss et al., 1997; Thierbach et al., 2003). This discovery implied that there are substantial intergalactic magnetic fields in clusters of galaxies.

Another interesting direction of research in studying magnetic fields was observation of the Zeeman effect with the Effelsberg Radio Telescope. The H_2O line

Zeeman effect was detected by Fiebig and Güsten (1989), indicating strong magnetic fields of B ~ 50 μGauss in molecular clouds.

The subject of magnetic fields has been a major topic of research that originated in the Effelsberg observations, and numerous reviews and books have been published as a result of this initiative (e.g. Sofue at al., 1986; Wielebinski and Krause, 1993; Beck et al., 1996; Beck, 2001; Uyaniker et al., 2004; Wielebinski and Beck, 2005; Beck and Wielebinski, 2011).

6 SPECTROSCOPY WITH THE EFFELSBERG RADIO TELESCOPE

Spectroscopy is one of the major observational directions at the Effelsberg Radio Telescope. This particular research focus was actively pursued by Professor Mezger until his retirement in 1996. In some years (especially in 1974) up to 70% of the observing time was devoted to spectroscopic investigations (Schwartz, 1979). In the last ten years that fraction of the observing time has been somewhat lower, but still between 30% and 40%. In the following account, we outline some of the spectroscopic projects pursued with the Effelsberg Radio Telescope over the years.

In 1974, almost immediately after the commissioning the radio telescope, 21-cm hydrogen line observations were carried out in a search for line emission and absorption towards extragalactic sources (Mebold et al., 1978; 1982). A survey of galactic HI emission in a selected part of the sky, a 20° × 10° field in the Cassiopeia-Perseus region, was published by Braunsfurth and Reif (1984). Investigations of neutral hydrogen emission from specific sources included an HI survey of polar ring galaxies (Huchtmeier 1997) and HI observations of compact high-velocity clouds (Westmeier et al., 2005). In the winter of 2008/2009, an HI survey covering the whole sky north of –5° declination (the so-called Effelsberg-Bonn HI survey, or EBHIS) was started with the 100-m radio telescope (Winkel et al., 2010).

The early years at Effelsberg were also intensively used to investigate cosmic radio recombination lines, mainly hydrogen lines. These result from very highly-excited states of the atom (quantum numbers of ≥100), close to ionization, which can only exist in almost empty space. The radio recombination line of hydrogen at 2.7 cm (H134 α) was found in the direction of a supernova remnant (Downes and Wilson, 1974b). Later a survey of the recombination line H110α at 4.8 GHz towards 262 galactic radio sources was published, together with a search for absorption in the formaldehyde molecule (H_2CO) towards these sources (Downes et al., 1980). The determination of oxygen abundance, derived from radio recombination lines, and its variation in the Galaxy was studied by Mezger et al. (1979) and also by Wink et al. (1983).

Identifications of new molecules in space are of particular interest to spectroscopy researchers. The discovery of different molecules and investigation of their properties in both line emission and absorption has been an important field of research with the Effelsberg Radio Telescope over the last four decades. First detections include formic acid (HCOOH), which was found in Sgr B2 (Winnewisser and Churchwell, 1975), and interstellar methyldiacetylene (CH_3C_4H) was traced in the dark dust cloud TMC1 (Walmsley et al., 1984). The first detection of cyanoallene ($H_2CCCHCN$) was also made at Effelsberg (Chin et al., 2006). The different molecules provide insights into the density, temperature and many additional properties of the cosmic environment (Mauersberger, 1996). Ammonia was detected in the neighbourhood of the Galactic Centre (Güsten et al., 1981). Further observations of the Galactic Centre showed a neutral ring of ammonia (Serabyn and Güsten, 1986).

Maser emission of formaldehyde (H_2CO) in the direction of the star-forming region NGC 7538 was detected with the 100-m radio telescope (Downes and Wilson, 1974a). Formaldehyde absorption in the direction of the centre of the starburst galaxy M82 (Graham et al., 1978) was also traced. Inversion lines of ammonia (NH_3) provide a number of maser transitions (Ungerechts et al., 1982; Mauersberger et al., 1987; Wilson et al., 2006).

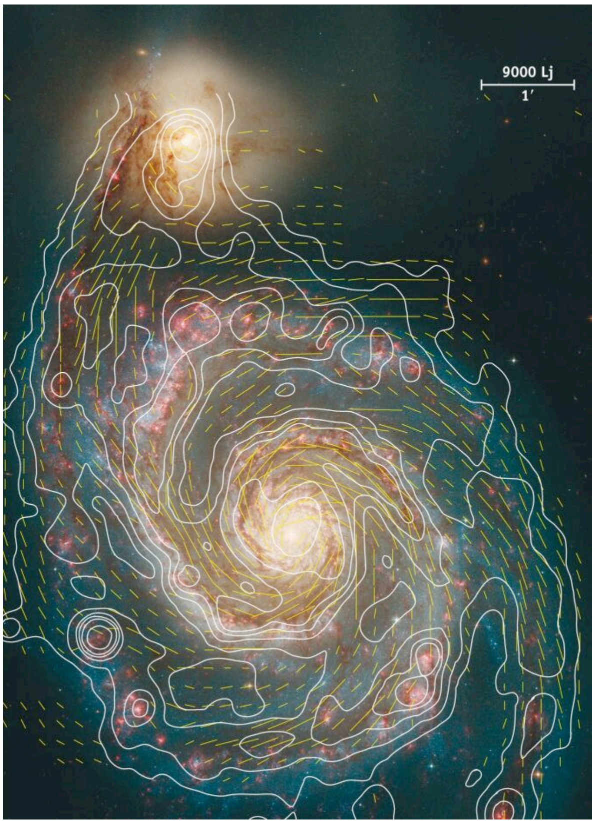

Figure 16: The magnetic field of M51 based on Effelsberg and VLA observations (Fletcher et al., 2010).

Other molecular line investigations at Effelsberg included the first observations at 7 mm of new sources with SiO maser line emission (Spencer et al., 1981), and an extended survey of infrared (IRAS) point sources in the 1612 MHz transition of hydroxyl (OH) led to the identification of almost 600 new OH/IR stars (Te Lintel Hekkert et al., 1991). Observations for this latter project were performed with the Dwingeloo, Effelsberg and Parkes Radio Telescopes.

Unlike optical, UV, X-ray or infrared observations, radio data from molecules allow astronomers to discriminate between different isotopes, in particular between isotopes of H, He, C, N, O, Si and S. The first galactic isotope ratio gradient, that of $^{12}C/^{13}C$, was established on the basis of Effelsberg and 42-m Green Bank data (Henkel et al., 1982; see also Wilson and Rood, 1994).

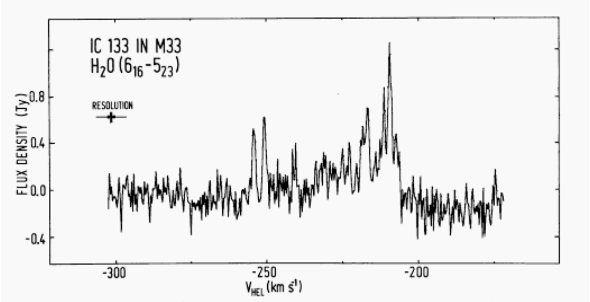

Figure 17: Detection of H_2O maser emission in the galaxy M33 (after Churchwell et al., 1977).

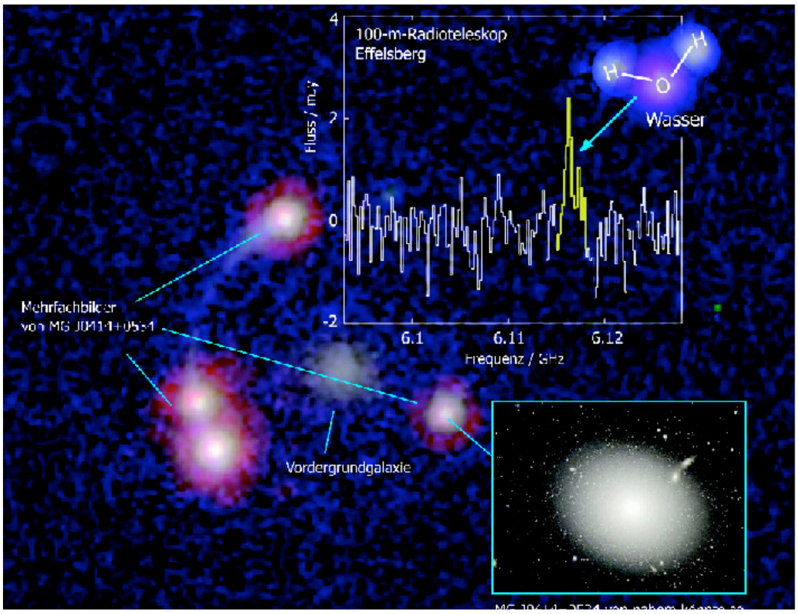

Figure 18: Water maser emission in quasar MG J0414+534 (after Impellizzeri et al., 2008).

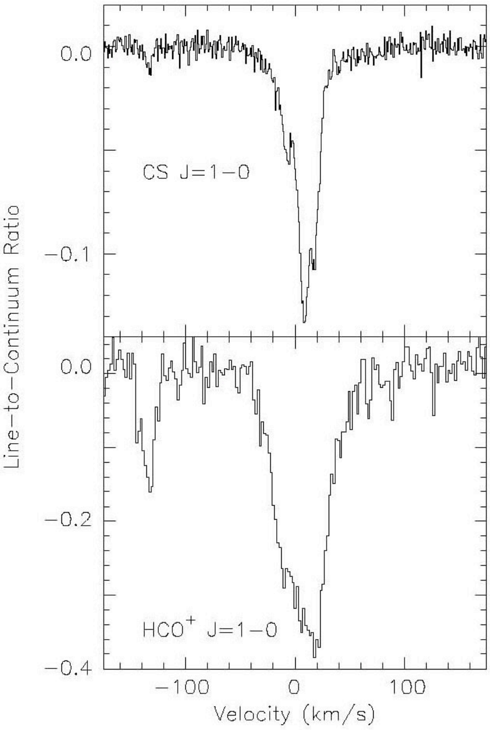

Figure 19: The radio galaxy PKS 1830-211 showing molecular absorption by CS and HCO^+ (after Henkel et al., 2009).

The 100-m radio telescope, with its large surface area and high sensitivity, is a very useful instrument for tracing the weak emission from molecules at large distances, i.e. outside the Milky Way (Henkel, 1996), and two molecules, ammonia (NH_3) and water (H_2O), were first identified in extragalactic sources using the Effelsberg Radio Telescope. Martin and Ho (1979) detected ammonia in the galaxy IC342, and Churchwell et al. (1977) were able to trace the water molecule in IC 133, a bright star-forming region in the nearby galaxy M33 (see Figure 17).

Not only were the very distant sources of interest, but also the very close ones. The same two molecules were found when Altenhoff et al. (1983) used the Effelsberg Radio Telescope to observe Comet 1983d, while Bird et al. (1997) detected ammonia in yet another comet, the famous Hale-Bopp.

Different maser lines of interstellar methanol (CH_3OH) in our Galaxy were investigated with the Effelsberg Radio Telescope, and a new transition was identified (Wilson et al., 1985; Menten et al., 1986). The investigation of maser emission of the water molecule in external galaxies is a stronghold of the 100-m radio telescope. Soon after its first detection, water masers were also traced in the peculiar galaxy NGC 3079 (Henkel et al., 1984), and subsequently in the direction of 3C 403, an active galaxy at a distance of almost 750 million light years (Tarchi et al., 2003). Water maser emission has recently been traced in MG J0414+0534, a galaxy with a red-shift of z = 2.64, corresponding to a light travel time of more than 11 billion years. Two effects, the enhancement of the signal by means of maser amplification as well as a galaxy in the foreground acting as a gravitational lens, had to work together in order to make the signal detectable from such a large distance (Impellizzeri et al., 2008; see Figure 18). The Effelsberg Radio Telescope is an integral part of the Megamaser Cosmology Project, which aims to measure the Hubble Constant to 3% accuracy and constrain the flatness of the Universe and the equation of state of dark energy (e.g. Reid et al., 2009).

The investigation of molecules can also help to prove the validity of nature's laws across the Universe. Murphy et al. (2008) used observations of ammonia made at Effelsberg and Parkes in order to confirm that the mass ratio of the proton and the electron in distant galaxies has much the same value as on Earth (see also Henkel et al., 2009; Figure 19). The CO J=(1-0) line was detected in two quasars at redshifts of 4.1 and 4.7 with the Effelsberg Radio Telescope (Riechers et al., 2006).

There have been a large number of excellent results from spectroscopic observations made with the 100-m radio telescope. The appointment of Professor K. Menten to the position of Director at the MPIfR in 1996 ensured continuity in this field of research. New receivers, continued telescope improvements for short cm wavelengths and digital FFT spectrometers will help to ensure the future success of the Effelsberg Radio Telescope.

7 PULSAR RESEARCH AT EFFELSBERG

Studies of pulsars at high radio frequencies characterized the early direction of pulsar research with the 100-m radio telescope. Pulsar observations were made between 1.4 GHz and 45 GHz in many frequency bands. Observations of HI absorption in the direction of pulsars (Graham et al., 1988) helped to determine the distances of several objects. The evolution of the pulse shape with frequency was studied implying a radius-to-frequency mapping. The first mm-wavelength detection of pulsars was made with the 100-m radio telescope (Wielebinski et al., 1993). From these multifrequency studies precise spectra of pulsars could be determined (e.g. Malofeev et al., 1994). Additional observations dealt with studies of microstructure, single pulse polarization and pulse-to-pulse variations—all topics closely related to the search for an understanding of the pulsar emission mechanism. Studies of pulsar rotation measures (e.g. Mitra et al., 2003) gave important information about the interstellar medium. The detection of millisecond pulsars at Effelsberg (Figure 20) added a new line of pulsar research.[5] This led to surveys of the pulse shapes, spectra and polarization of millisecond pulsars (e.g. Kramer et al., 1998; 1999; Xilouris et al., 1998).

Pulsar searches with the Effelsberg Radio Telescope were confined to pilot projects (e.g. Lorimer et al., 2000). More recently, using data from the Fermi satellite, millisecond pulsars have been discovered at Effelsberg. The evolution of the pulse shape of PSR 1913+16 allowed the geometry of the system to be determined (Kramer, 1998; Figure 21). Pulsar timing became a very important direction of pulsar research. Timing evolution, adding long-term data points, became a regular feature of the Effelsberg pulsar observations (e.g. Wolszczan et al., 2000). The MPIfR pulsar group was the organizer of the Pan-European Pulsar Network leading to an extensive *Pulsar Data Archive* on the home page of the MPIfR. Also the group participated in the Descartes Prize award of the European Union. Pulsar research received a great impetus with the recent appointment of Professor Michael Kramer to the Direktorenkollegium of the MPIfR.

8 VERY LONG BASELINE INTERFEROMETRY

The first VLBI experiments involving Effelsberg were carried out in 1973. At first these were tests of the transatlantic baselines, which showed that the addition of the 100-m radio telescope improved greatly the sensitivity of the network. Initially these were *ad-hoc* experiments organized between various partners (Preuss et al., 1974). The first experiments were conducted with the NRAO Mark II recording system and a rubidium clock. The bandwidth was limited and hence also the sensitivity. Nevertheless, studies of superluminal radio sources became possible (e.g. Cohen et al., 1977; Figure 22). This direction of research became very important in the succeeding years.

The MPIfR decided to implement a 3-station Mark II correlator so that data reduction could also be carried out in Bonn, and this was completed in 1977. The retirement of Professor Hachenberg led to the appointment of Dr Ken Kellermann (NRAO) as one of

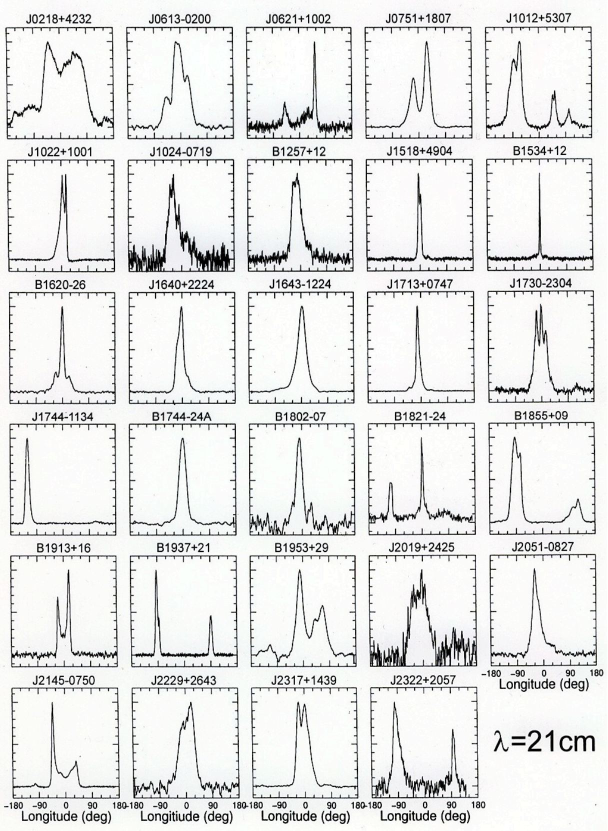

Figure 20: The Effelsberg millisecond pulsar survey (after Kramer et al., 1998).

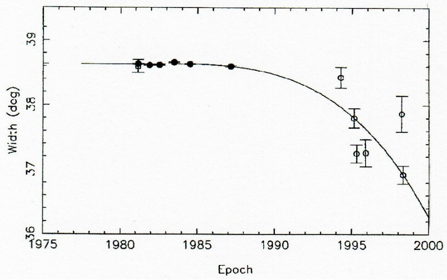

Figure 21: Component separation of pulsar B1913+16. Early data are from Arecibo. Note that the 1995 to 2000 observations, that confirmed the precession, came from Effelsberg (after Kramer, 1998).

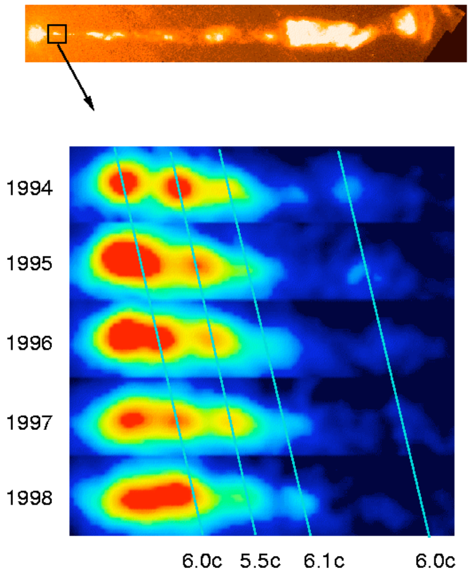

Figure 22: Superluminal motion in the jet of M87 (courtesy: Dr T.P. Krichbaum, MPIfR).

the Directors of the MPIfR, and this strengthened the VLBI research. The study of superluminal motions continued (e.g. Eckart et al., 1986; Porcas, 1981) with interesting results. A more sensitive Mark III recording system (with a wider bandwidth), developed at the Haystack Observatory, was implemented in the late 1970s. This led to improved sensitivity and hence new observational possibilities. A 3-station Mark III correlator was completed in Bonn in 1982, in collaboration with the Geodesy Institute of Bonn University. Some of the data reduction was now carried out with this correlator. Also a hydrogen maser clock became available, leading to the possibility of longer integration times and hence increased sensitivity. Following the discovery of gravitational lensing at Jodrell Bank, this subject became an important direction of research at Effelsberg (e.g. Porcas et al., 1979; 1981; Figure 23).

In 1979 Effelsberg became an associate member of the US VLBI Network. Then in 1980 discussions took place between directors of European radio astronomy institutes that led to the foundation of the European VLBI Network (EVN). The MPIfR was one of the founding members of the EVN and later it became involved in the development of JIVE (Joint Institute for VLBI) in Dwingeloo. The Networks changed the VLBI observations from *ad-hoc* experiments to regularly-scheduled VLBI periods at all of the participating radio telescopes. Transatlantic experiments continued with either the NRAO (the VLBA system), Caltech or Haystack as partners. The EVN had its own European schedule but also participated in global experiments. Up to 30% of the observing time at Effelsberg was occasionally devoted to VLBI. The increase in the Bonn correlator capacity, first to 5 (Mark III) in 1990 and in 2000 to 10 stations (Mark IV), was completed. Many interesting discoveries can be attributed to the participation of Effelsberg in VLBI: observations with an angular resolution of 100 microarcseconds (Bartel et al., 1988) revealed helical jet motions (Qian et al., 1992; Steffen et al., 1995); jet and counter-jet in Cygnus A (Krichbaum et al., 1998); ejections of super-luminal components after gamma-ray flares (Otterbein et al., 1998) and sub-milliarcsecond imaging of quasars (Zensus et al., 2002). The launch of the HALCA VLBI satellite by the Japanese Space Institute (ISAS) in 1997 led to the participation of the 100-m telescope in various interesting experiments. Intra-day variability could be studied with space VLBI (Bach et al., 2006). Also mm-VLBI became a reality with first a 43-GHz system (Krichbaum et al., 1988) and later an 86-GHz receiver system on the 100-m radio telescope (Lobanov et al., 2000). Effelsberg also participated in the 3 mm observations of Sgr A (Krichbaum et al., 1998).

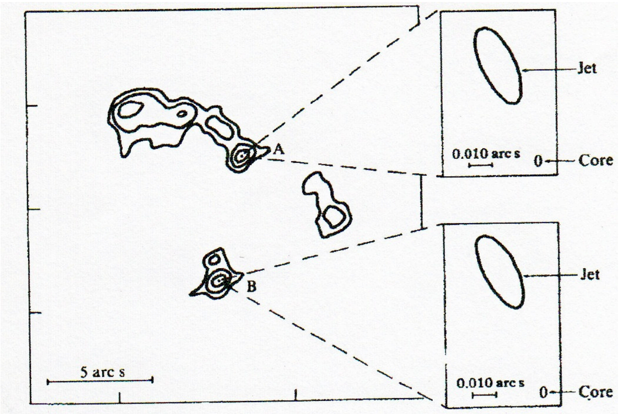

Figure 23: Gravitational lensing of the double quasar 0957+561 (after Porcas et al., 1981).

Employing the high-sensitivity VLBI array which includes Effelsberg, one of the brightest radio supernovae ever seen, SN 2008iz, was recently detected and monitored (Brunthaler et al., 2010). Then by observing H_2O and methanol masers, parallaxes of massive star-forming regions can be observed out to distances of 5-8 kpc. As a consequence, the precise locations of spiral arms can finally be traced in a substantial part of our Galaxy (Rygl et al., 2010). VLBI studies, including Effelsberg, are presently being carried out to determine the proper motions of M81 and M82. The proper motion of M33 has already been determined (Brunthaler et al., 2005).

VLBI continues to be an important part of the Effelsberg observations, now with the Mark V system. Since 1997 Professor J.A. Zensus has promoted this research direction as a Director at the MPIfR.

9 THE MAINTENANCE AND UPGRADES AT THE 100-m RADIO TELESCOPE

Any mechanical instrument requires maintenance and offers possibilities for improvements. Both have been consequently carried out at Effelsberg, thus ensuring that a state-of-the-art 100-m radio telescope is always available to astronomers. The painting of the antenna is a never-ending task, and summer work always includes painting of sections of the dish to prevent corrosion. Early spectroscopy observations at 6 cm showed the need for structural additions to reduce the baseline problems in broad band observations. This was solved in 1974 by the construction of a pyramid-type reflector to cover the secondary cabin.

The first major maintenance work was needed as a result of problems with the glue of the honeycomb panels. Failure of the glue seam would lead to entry of water and consequent damage during frosty periods, so all of the 816 honeycomb panels (rings 1 to 9) were replaced by aluminium cassette panels during 1980-1982. As a result of the panel change, surface measurements were repeated and for the first time holography was employed on the 100-m radio telescope, allowing a considerable improvement in the surface accuracy.

The use of the secondary focus cabin led to several major refurbishing projects. The performance of the sub-reflector *in situ* was found to differ from what was expected on the basis of ground measurements, implying a change in the geometry. Hence a new sub-reflector, with improved surface accuracy and adjustable panels, was purchased in 1985. The use of the radio telescope in the secondary focus for sensitive continuum observations also required a redesign of the structure of the cabin. The original construction with three lengthy openings was followed by a very large opening below the pyramid roof. This solution proved unpractical since the large dielectric cover experienced vibrations, which caused instabilities at higher frequencies. The final construction that was implemented was to reduce the height of the secondary focus cabin to allow each secondary focus horn to have the best individual dielectric cover. Also blowers were added to keep the dielectric covers dry. In addition a motor opening of the pyramid was implemented. This solution is still in use at the present time. The secondary focus became the site of several multibeam systems.

In 1987 the first break of the azimuth track after a period of very low temperatures was discovered. This required opening up the supporting concrete foundation. The rail track gave repeated trouble, and breaks occurred in 1989 and in 1996 that led to the decision to replace the whole rail. This was a major undertaking with numerous unexpected difficulties. The rails, whose acquisition led to many problems, came in sections and had to be welded. The whole radio telescope was lifted ~1 m by hydraulic jacks. The thermite welding process was again used, but with considerable difficulties, as the original information about welding tracks with such large cross-sections had been lost. In 1996 a new track, with a design that prevented moisture seeping in, was finally completed.

More recently, all of the outer three wire mesh rings of panels (rings 14-16) were replaced by perforated aluminium surface panels on aluminium frames. Again a surface measurement and adjustment followed, with consequent improvements. Telescope pointing and tracking could also be improved. In 2006 the 6.5-m sub-reflector was replaced by a new unit that has an active surface with 96 motor-adjustable panels. The panels of the sub-reflector can be dynamically controlled, leading to a considerable improvement in radio telescope efficiency. The new panels and the new sub-reflector have nearly doubled the telescope's efficiency, especially at 7 mm. In addition, the insertion of primary focus receivers was automated. New primary focus receiver boxes of 1.25-m diameter have multi-frequency capability using a hexapod suspension for movement of individual systems into the phase centre.

During the 40 years of operation numerous routine maintenance projects had to be carried out. Changes in the drive system, regrinding of the wheels, and maintenance of the motors are just a few of the projects that must be mentioned. There was also a continuous upgrading of the computer system. The original Ferranti computer was replaced first by Modcomp and later by VAX computers. Recently the complete drive programme and observer interface were migrated to a VME system and Linux PCs. The receivers were continuously upgraded to match the state-of-the-art developments and the observational demands of the astronomers. The implementation of several multi-beam systems in the secondary focus added to the sensitivity of radio continuum observations. The various observational methods and targets, namely radio continuum, spectroscopy, pulsars and VLBI, required state-of-the-art analysis and recording equipment. This was continually implemented, often with partners in European and US radio observatories.

The 100-m Effelsberg Radio Telescope is in excellent technical condition, and currently is capable of matching the performance of any other dish in the world. Since 2007, it has been complemented by the Effelsberg station of the European LOFAR radio telescope network for observations at metre wavelengths.

10 NOTES

1. The Deutsche Forschungsgemeinschaft (DFG) is Germany's leading research funding organization (see: www.dfg.de).
2. After the War these antennas found their way to radio astronomy observatories throughout Europe (e.g. see Dagkesamanskii, 2007; Edge and Mulcay, 1976; Orchiston et al., 2007; Radhakrishnan, 2006; Smith, 2007; Sullivan, 2009; van Woerden and Strom, 2006) and even in the USA (Burke, 2007; Sullivan, 2009).
3. The Volkswagenstiftung is an independent, non-profit organization, and has been funding research projects in all disciplines since 1962 (see: www. volkswagenstiftung.de).
4. Although Krupp's design was chosen, a joint company (ARGESTAR) of Krupp and MAN was then formed in order to construct the radio telescope.
5. Note that the first millisecond pulsar was discovered in the U.S.A. back in the early 1980s (see Backer et al., 1982).

11 ACKNOWLEDGEMENTS

Details of the construction of the Effelsberg Radio Telescope were published in *Nuncius Hamburgensis* Band 12 (© Hamburg University) in 2011, and we wish to thank Professor Gudrun Wolfschmidt for permission to reproduce this material—in a slightly revised form—in this journal. The construction photographs are © MPIfR, and the photographer was K. Schewe. Figure 18 is from a MPG press release. We also wish to thank the following colleagues who helped us to collate important results of observations: C. Henkel, M. Kramer, A. Kraus, T.P. Krichbaum, K.M. Menten, R. Porcas, W. Reich and T. Wilson. Finally, our thanks go to the editors of *JAH*^{2} for their help in finalizing this paper.

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ASTRONOMY AND CONSTELLATIONS IN THE *ILIAD* AND *ODYSSEY*

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Abstract: The *Iliad* and the *Odyssey*, in addition to their supreme status as cornerstones of world literature, are a rich source of information about the scientific and technological knowledge of ancient Greeks in both pre-Homeric and Homeric times. The two Homeric epic poems, which we date to the 8th century BC, include, *inter alia*, a wealth of astronomical elements, informing about the Earth, the sky, the stars, constellations and asterisms such as the Pleiades and the Hyades. They also offer a more erudite image of Homer, which reflects the cosmological views of his period. The model of the Universe that is presented is continuous and has three levels: the lower level corresponds to the underworld, the middle one to the Earth and the upper one to the sky. But the key point of this paper is to illuminate the fact that the ancient Greek appellations for many of the stars and constellations have remained the same even after three millennia.

Keywords: *Iliad*, *Odyssey*, Homeric cosmological model

1 INTRODUCTION

The *Iliad* and the *Odyssey* are not only of supreme literary importance, but are, as well, a rich source of historical, scientific, technological and astronomical knowledge of the ancient Greeks in pre-Homeric and Homeric times. These two epic poems, which we date to the 8th century BC, include a wealth of information about the Earth, the sky, the stars (e.g. Sirius), constellations such as Ursa Major, Boötes and Orion, and star clusters like the Pleiades and the Hyades. They therefore offer us the possibility of seeing the more general cosmological views of that time.

A large number of authors have considered different astronomical aspects, facts and allusions in the *Iliad* and the *Odyssey* (e.g. see Walker, 1872; Schoch, 1926a; 1926b; 1926c; Neugebauer, 1929; Lorimer, 1951; Dicks, 1970; Trypanis, 1975; Gendler, 1984; Lovi, 1989; Genuth, 1992; Kirk, Raven and Schofield, 1995; Konstantopoulos, 1998; Wood and Wood, 1999; Flanders, 2007; Baikouzis and Magnasco, 2008; Minkel, 2008; and Varvoglis, 2009). This illustrates the continuing interest in this attractive subject. It is our aim here to analyze the astronomical data and allusions in the Homeric epics in order to better understand the cosmological model of the Universe that would prevail for a millennium after the Trojan War.

D.R. Dicks (1970: 10) has stated that: "We can't form a clear idea about the shape and the position of the Earth with respect to heavens and the underworld from the Homeric epics." Strictly speaking, this may be true. However, we wish to explore the prospect that it is in fact possible to ascertain a cosmological model from the passages and astronomical information contained in the *Iliad* and the *Odyssey*. We will investigate which constellations and celestial phenomena were known to Greeks of that era, and how these were woven into a complex model of the Universe. We will also consider the names of the stars and constellations, several of which are exactly the same today as in Homeric times.

2 THE POSITION OF THE OCEAN, THE EARTH AND THE SKY IN THE HOMERIC UNIVERSE

2.1 The Ocean and the Earth

The ancient teachings of Orpheus (dating as far back as the 13th Century BC) are considered to be the basis of the first mystic Greek religion, with poems and hymns of great beauty. Nearly all of the ancient Greek sages and writers drew inspiration from themes found in the Orphic Hymns, and were thus influenced in formulating their individual theories and teachings.

Besides the Orphic Hymns (Petrides, 2002), the Homeric epics are a rich source of historical and technological facts. Indeed, an astronomer who studies in detail the descriptions in the *Iliad* and the *Odyssey* will discover a treasure-trove of astronomical information. It is generally believed that Homer lived in the Iron Age (a period roughly spanning 1200 to 550 BC), but told stories that occurred in the Late Bronze Age (ca. 12th century BC).

As Emile Mireaux (1959: 9) writes:

> The Iliad and the Odyssey contain elements from the old Mycenean civilization; basically, however, although they refer to events of the 12th century BC, the lives of their heroes (social, political economical and family), their laws and customs … all reflect the way of life witnessed by the poet who composed the epic.

The two epic poems took their definite form in the Ionic cities of Anatolia in the 9th or 8th century BC;

first came the *Iliad* and later the *Odyssey* (Trypanis, 1975). The poems describe the culture, religious beliefs, general knowledge and habits of Greek populations during this period. They also describe the cosmological model that would prevail for the next millennium, i.e. up to the time of Ptolemy and his *Almagest.*

The Earth of the Homeric Universe was a circular flat disk surrounded by a huge circular river, the Ocean, a model first appearing in the Orphic Hymn "X. To Pan, The Fumigation from Various Odors", verse 15: "Old Ocean [Okeanos] too reveres thy high command, whose liquid arms begirt the solid land."

This mythical 'river' is different from the seas: it is something that defines the boundaries of the terrestrial world. Above all, Ocean is the primal and original creative element, the starting point of all things: "I can put the currents to sleep and, if you wish, of the river Ocean, which was the beginning of everything." (*Iliad*: XIV, 245-246).[1] Ocean is the male ancestor of the gods, who had Tethys as his spouse during the Creation: "I shall go to the ends of the Earth to find the father of all gods, the Ocean and Tethys the mother." (*Iliad*: XIV, 200).

This mythical 'river' has no sources, nor estuary; it is "apsorroos", i.e. cyclically moving or backward-flowing. Its current goes back to where it started in a ceaseless and eternal motion. From this Ocean, mentioned 19 times in the *Iliad* and 14 in the *Odyssey*, all other waters on Earth were created: seas, rivers and lakes. This is mentioned in the *Iliad*: "The all-powerful Ocean, the deep-current one, from whom all sea, river, source and fountain springs, and every deep well." (*Iliad*: XXI, 195-197).

In the *Odyssey*, the Ocean is described as terrible and fearful: "…'cause he has deep currents and large rivers in his midst, which no one without a fast ship can pass across." (*Odyssey*: XI, 160). However, we are not given a definite description of the exact shape or size of the Ocean; we just learn about its watery structure.

Although Dicks is correct that we cannot get a clear idea about the position of the Earth in the cosmos, it can certainly be said that in the Homeric cosmological model, the Earth is between the sky and the underworld. Its precise structure and shape are not known, we just suppose it is a circular disk since it is surrounded by the circular watery Ocean. In the *Iliad*: (VIII, 13-16), a contrary view about Tartarus (a 'deep place' below sky, Earth and the sea) is given when Zeus threatens the gods that he will send them there:

> … or I shall throw him down with my own hands, in the darkness of Tartarus, long away to the depths of the world, that has iron gates and copper threshold, under the Hades as far as the heavens are from the Earth. (*Iliad*: VIII, 13-16).

In parallel, Homer imagines Hades in the depths of the Earth:

> … and if you go to the ends of the Earth and the sea, where Japetus and Cronus reside, and winds do not blow on them, nor the sunlight shines on them and deep Tartarus surrounds them from everywhere. (*Iliad*: VIII, 480).

One can conclude Homer believes that a) Hades is below the Earth and surrounded by Tartarus; b) the Earth is the center of the Universe and of life; and c) the starry sky is supported by the Earth (*Odyssey*: ix, 534). This is depicted in Figure 1.

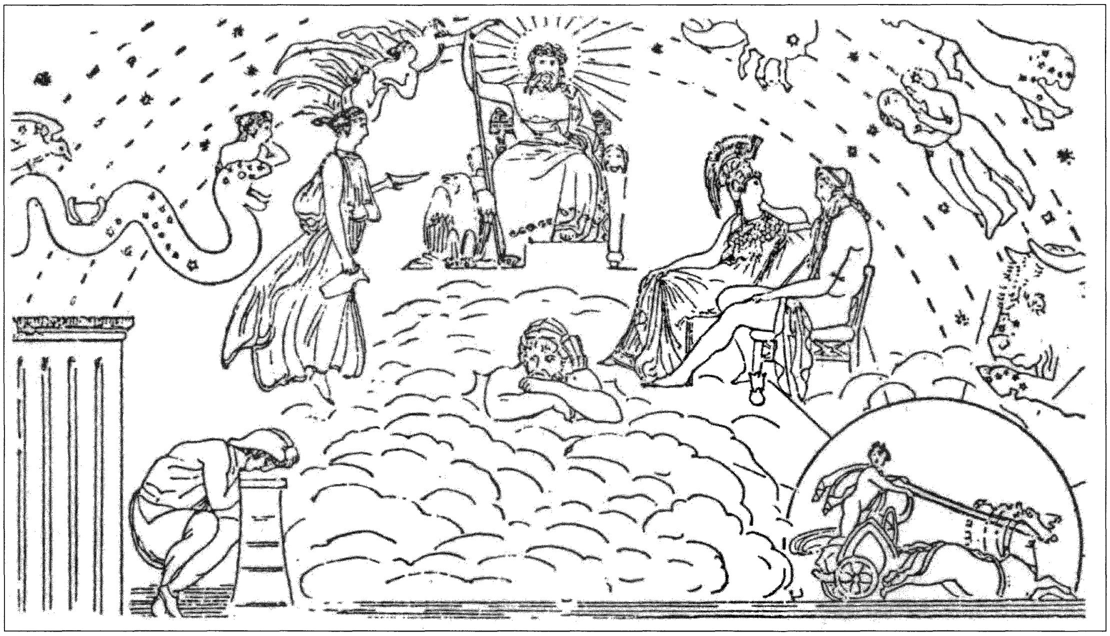

Figure 1: The Homeric Universe. In the Universe of Homer's times, the mountains can be seen to rise over the surface of the great disk of the Earth, the Ocean spreading around them, while the center is dominated by Mount Olympus which rises up to heaven. In its highest peak, the all-seeing Zeus is seated, supervising both immortal gods and mortal men, sometimes rewarding and sometimes punishing them. Beyond Olympus spreads Heaven, supported by the pillars of Atlas. In heaven we can locate the Moon, the stars and the constellations. In particular, in this figure we can distinguish the Pleiades open cluster and the constellations of Hydra, Corvus, Crater, Cancer, Leo, Gemini, Taurus as well – these constellations are not specifically referred to by Homer (after Cotsakis, 1976: 18).

2.2 The Sky

Heaven, with its luminous stars, is depicted as a hemispherical dome exactly covering the flat Earth (*Odyssey*: xi, 17). That is, the cosmos of this time was envisioned as a celestial dome over a disk-like Earth floating on water. The view of this age as recorded in the *Odyssey* is that the sky rests upon the Earth with the columns that keep the whole world in equilibrium held up by the mythical Atlas: "The daughter of the Atlas, of the one who knows the depth of every sea and he alone lifts the tall columns that divide Heaven and Earth in two." (*Odyssey*: i, 53-54).

For the ancient Greeks, the sky was a dome made of solid matter, iron or copper, held up there by tall columns or, according to another view, by some giant. Homer combines these two views by having Atlas supporting the columns. Hesiod in *Theogony* (1988: 517) writes that Zeus was the one who had assigned this duty to Atlas.

For Homer the sky was, more specifically, made of copper, as described in the *Iliad*: "… the Achaeans, white in dust to the top, for the horses were lifting it up to the copper sky with their feet." (V, 504). Or, in another passage: "They were fighting there and the iron noise was thundering up to the copper sky through the air." (XVII, 424-425). In another "polychalcus", that is "… of much copper." (*Iliad*: V, 504, *Odyssey*: iii, 2; *Iliad*: II, 458; XVI, 364; XIX, 351). There are also references to an iron sky in the *Odyssey*: (xv, 329 and xvii, 565), but it is not known whether this was meant metaphorically or in some other context.

We thus conclude that the sky was perceived by the ancient Greeks as something solid though unreachable. Its unimaginable distance was often used in similes to confer vastness. For example, the glory of Nestor's golden shield reached the skies: "… and then we shall take the shield of Nestor, whose glory has reached the stars." (*Iliad*: VIII, 192-193). Similarly, the glory of Penelope, which also was reaching the wide skies (*Odyssey*: xix, 108).

The space between sky and Earth was filled firstly by the dense air: "… up to the air its vast branches extended." (*Iliad*: XIV, 288), and over this layer and towards the direction of the sky there was the clean and transparent 'aether', lighter than the air. Aether is essentially the 'higher air', through which the heavens can be seen:

> … and up to the stars, which twinkle in windless aether, charming around the luminous moon – every peak, every edge, every side is visible, as a vast aether opened by the sky, which made visible all the stars to the joy of the shepherds. (*Iliad*: VIII, 554-559).

Above the aether, on the peaks of Olympus that reach the sky, the gods dwell: "… and he offered a lot of sacrifices to the gods that dwell in heavens." (*Odyssey*: i, 68-69), and "Without the opinion of the gods, who dwell in heavens … but now he is like the gods who enjoy the heavens." (*Odyssey*: vi, 242-245). The gods are described either as "Olympians" or "heavenly gods", because the tallest peaks of Olympus seemed to touch the heavens: "Our father, son of Cronus, first of the heavenly ones …" (*Odyssey*: i, 46). Finally, it is mentioned that above the aether there was the "polychalcus" sky (*Iliad*: II, 458; XVI, 364; XIX, 351).

Of course, one should not assume that the Homeric sky was a barren metallic dome; it was, as Homer sings, full of life, the life of the stars and the constellations. Thus, the ancient Greeks were calling the sky "… full of stars." ("asteroeis") (*Iliad*: VI, 108; XV, 371), and star-decorated (*Odyssey*: ix, 535), as was natural for a people living in a country with few cloudy nights.

On this celestial dome, Helios, the god of the Sun, travels on its path, so he is described with the adjective 'ouranodromos' (sky-running): "For they were perished due to their own fault, the impious, who ate the oxen of the sky-running Helios and he deprived them of the day of their homecoming." (*Odyssey*: i, 7-9). This is only one out of 119 references to the Sun in the Homeric epics: there are 42 references in the *Iliad* and 77 in the *Odyssey*. As a god, Helios appears 34 times (8 in the *Iliad* and 26 in the *Odyssey*). In stark contrast, for the Moon (Selene) there are only three references in the *Iliad*: (VIII, 554; XVII, 367; XVIII, 484) and only two in the *Odyssey*: (iii, 46 and ix, 144). Besides, the Moon appears under its archaic name, "Mene" one more time in the *Iliad*: (XIX, 374). A possible explanation for the scarcity of lunar references is that the main events in the *Iliad*—that is, the battles—took place only during the daylight, whereas in the *Odyssey* the Moon was usually hidden behind the clouds: "For it was thick darkness around and the moon, hidden in clouds, didn't shine in the skies." (*Odyssey*: ix, 144).

Before moving on to examine the stars and constellations in the epics, it is interesting to present some meteorological and climatologic elements as they appear in the *Iliad* and the *Odyssey*. The air between the sky and the Earth is traversed by the winds and the clouds, through which the omnipotent Zeus covers the sky, sends the rains onto the Earth and throws his lightning and thunders (*Iliad*: XVI, 364-365; XII, 25-26; *Odyssey*: v, 303; xxiii, 330).

As is mentioned in Rhapsody V in the *Iliad*, the gates of both Heaven and Olympus are formed by dense clouds. Their guards are the Orae (Hours), goddesses of the seasons who regulate the weather conditions:

> … and Hera moves the horses violently with the whip; the gate of Heaven thunders open in front of them, which the guardians of the vast Sky and Olympus, the Hours, block with the cloud or remove it. (*Iliad*: V, 749-751).

3 THE STARS AND THE CONSTELLATIONS IN THE *ILIAD* AND THE *ODYSSEY*

Let us now examine closely all the Homeric references to the constellations, the stars and the planet Venus, as they appear in the two epics.

Homer mentions in the *Iliad* the "autumnal" star:

> Then Athena gave power and courage to Diomedes, so that excellently amidst the Greek multitudes he would be glorified and take shining fame everywhere. From his helmet and shield a flame was visible, which pours light without sleeping, as the autumn star, bathed in the Ocean, shines with its full light. (*Iliad*: V, 1-5).

The "autumn star" is actually Sirius, the brightest fixed star of the night sky. Sirius appears every year, for the geographical latitude of Greece, in the night sky in late July or early August. This is mentioned also by Richard H. Allen, who writes (1963: 120):

> Homer alluded to Sirius in the Iliad as Οπωρινός, the star of Autumn; but the season intended was the last days of July, all August, and part of September – the latter part of summer. The Greeks had no word exactly to our 'autumn' until the 5th century before Christ, when it appeared in writings ascribed to Hippocrates. Lord Derby translated this celebrated passage: A fiery light. There flash'd, like autumn's star, that brightest shines. When newly risen from his ocean bath.

Although it cannot be supported with certainty, the Homeric man, perceiving the Earth as a flat circular disk surrounded by the Ocean, considered that the Sun, the Moon and most stars rose from the Ocean and set back in it. The idea of a spherical Earth appeared much later, with the Pythagorean philosophers in the 5th century BC.

In the *Iliad*: (XVIII, 478-488) it is mentioned that on the shield of Achilles, which was constructed by the god Hephaestos (Vulcan) after an order by Thetis (Achilles' mother), were depicted all of the constellations (Figure 2):

> And he made first a powerful and large shield, all with art and triple circle around. With five bendings this shield was made and upon it various images he designed with his wise knowledge: The earth, the sky, the sea he drew, the untiring sun, the full moon, the stars that crown from everywhere the sky, Orion's power, the Hyades, the Pleiades, the Bear, also called the Wagon, which rotates always at the same place, watching Orion, the only one that doesn't experience the bathing in the Ocean.

Wood and Wood (1999) have speculated on how the sky during Homeric times may have appeared. Although interesting in its approach, their work is considered unproven and controversial.

The Hyades and the Pleiades, which are actually two open clusters, were called 'constellations' by the ancient Greeks—today they are both included in the constellation Taurus. Taurus is not mentioned by Homer, although he mentions the adjacent constellation Orion, and with the stressing phrase "Orion's power". This is exactly the way Orion is mentioned by Hesiod (West, 1988: 598, 615, 619). Both authors refer to the constellation's "power", alluding to its apparent brightness.

Homer ends his stellar reference with the circumpolar constellation Ursa Major, which does indeed 'watch' Orion. Ursa Major does not "... experience the bathing in the Ocean ...", i.e. it never 'contacts' the sea, because its position near the North Celestial Pole keeps it away from the horizon as the Earth rotates.

The Hyades and the Pleiades are mentioned together with the other star asterisms as 'constellations' in their own right, in both the *Iliad* and the *Odyssey* (v, 272-277). The Pleiades are mentioned just once in the first poem, together with the Hyades (in the passage above, XVIII, 485), and once in the *Odyssey*: (v, 272). Indeed, in the *Odyssey* there are references to all of the above-mentioned star clusters and constellations:

> Then he set sail, a joyful Odysseus (Ulysses), and, sitting at the helm, was steering artfully; and no sleep closed his eyes as he was staring at the Pleiades, and the Shepherd, who is late to set, and the Bear, also called the Wagon by many, which rotates always at the same place, watching the Hunter, the only one that doesn't bathe in the Ocean's wave. For Calypso had told him to keep that star on his left hand while sailing. (*Odyssey*: v, 270-277).

As R.H. Allen (1963: 96) writes: "Homer characterized the constellation of Boötes as 'οψέ δύων', meaning late in setting, a thought and expression [that has] now become hackneyed by frequent repetition."

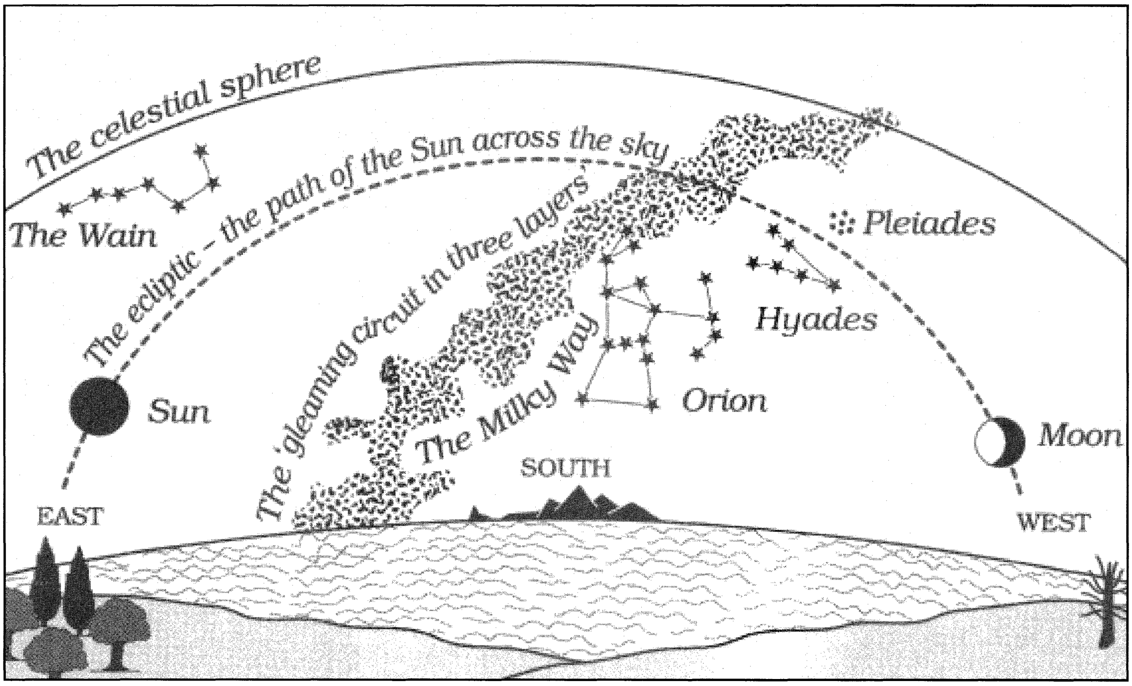

Figure 2: The Homeric Universe as it was depicted on the shield of Achilles (after Wood and Wood, 1999: 199).

Homer states that the constellation Boötes is late/ slow in setting, and Aratos that it "… lingers more than half the night …" (since it is very long and narrow with its long side oriented north-south on the celestial sphere). So Boötes rises 'on his side', all at once, and sets nearly vertically (starting from its right lower corner for the sky of Athens, and becoming more and more vertical), feet setting first, then his waist, and his upper body setting last, therefore taking only a short time to rise but a very long time to set.

It must also be noted in the cited verses that, for the first and only time in the epics, there is a reference to the use of constellations for orientation in the sea. Calypso advises Ulysses that, in order to keep the right course, he must keep always on his left the Bear (Ursa Major). Of course, this means that, having on his left a northern constellation, he would travel eastwards. So Homer was placing Ogygia, the island of Calypso, somewhere to the west of all Greece, since Ithaca, where he was bound, was in the western part of Greece itself.

As Homer believed that the Earth was a flat circular disk surrounded by the Ocean, he was certain that the Sun, the Moon and the stars rise from the Ocean and set in it; only Ursa Major did not set for ancient people living on the northern shores of the Mediterranean Sea. In Greek mythology, Zeus lusted after a nymph named Callisto. Hera, Zeus' wife, out of jealousy turned Callisto into a bear. Zeus later swept her, and her son Arcas, into the sky forming the constellation of Ursa Major. Aristotle mentions that the bear is the only animal that, because of its thick fur can dauntlessly roam the icy northern polar regions. The circumpolar character of Ursa Major is in our age only partial, but in protohistoric times, when Alpha Draconis (Thuban) was the 'Pole Star', all seven of the brightest stars in Ursa Major never set. Today, due to the precession of the Earth's axis, Alkaid (Eta Ursae Majoris, the last star in the tail) remains under the northern horizon of Athens, Ithaca and central Greece in general, for approximately three hours. Only in northern Greece and in places with a geographical latitude higher than $\varphi = 40.1°$ are all of Ursa Major's brightest stars circumpolar. Allen (1963: 419) states: "Sir George Cornewall Lewiss writes – for Homer's line Arctos, sole star that never bathes in th' ocean wave (by reason of precession it then was much nearer to the pole than it now is)." The difference in the declination of Alkaid (η UMa) between Homeric times and today is $>15°$, so in antiquity all of Ursa Major was circumpolar even from the southernmost tip of Greece.

Homer, however, does not mention explicitly the Great Bear, so a modern commentator could argue that Ursa Minor (the Lesser Bear), is meant, or even a combination of both. Most probably, though, he meant the Great Bear, as it has much brighter stars, it is a much larger and more impressive constellation, and, most important, Ursa Minor was (according to the tradition) introduced to the Greeks by Thales of Miletus in the 6th century BC—that is, two centuries after Homer. Ursa Minor is still a totally circumpolar constellation as seen from Europe.

The last constellation mentioned in the *Odyssey* is Orion the Hunter. Its appearance in the night sky each year coincided with the start of the rainiest and stormiest part of the year; therefore Orion is called "stormy" and destructive. Both Hesiod and Aristotle mention that the rising of Orion was a certain warning for sailors that storms are coming (Hesiod, *Works and Days*: 598, 615, 619; Aristotle, *Meteorology*: 2.5.4).

In *Iliad's* Rhapsody XXII, both Orion and Sirius are mentioned. The brightest fixed star, Sirius, is referred to as Orion's dog. Today, Sirius is known as Alpha Canis Majoris, the brightest star in the constellation of Canis Major (the Great Dog). Homer presents Sirius as an ominous sign in the sky, as every summer it is connected with the so-called "dog burnings" (*The Iliad*, 1950: Chapter 22, verses 25-31):

> … like the star that comes to us in autumn, outshining all its fellows in the evening sky – they call it Orion's dog, and though it is the brightest of all stars it bodes no good bringing much fever, as it does, to us poor mortals.

3.1 'Dog burnings' and 'Dog days'

In antiquity the heliacal rise of Sirius was connected with a period of the year of extremely hot weather, "*κυνικά καύματα*"("kynica kavmata", canine burnings). This period corresponded to late July, August and early September in the Mediterranean region. Romans also knew these days as "dies caniculariae", the hottest days of the whole year, associated with the constellation of the Great Dog, the hunter's (Orion's) dog Sirius. Ancient Greeks theorized the extra heat was due to the addition of the radiation of bright Sirius to the Sun's radiation.

In ancient Greek folklore, people called the summer days after the heliacal rise of Sirius "dog burnings" without correlating them with the Dog star or the constellation, but with dogs in general, thinking that only dogs were so crazy as to go outside when it was so hot. This belief has persisted through the centuries and can be found in modern Greek folklore in the belief that during the hot days of July and August, and especially between July 24 and August 6 dog bites are infectious (Theodossiou and Danezis, 1991: 115).

According to an ancient myth, the inhabitants of the island Kea were dying from a famine caused by the drought brought on by the dog burnings around 1600 BC. Then, the god Apollo gave an oracle to call Aristaeus, the god's son, from the region of Phthia, in order to help them. Upon arriving on Kea, Aristaeus performed rituals, cleansings and sacrifices to Zeus Ikmaeus, the lord of the rains and the skies, and to Kyon Apollo, that means to Apollo the Dog. Both gods listened to his pleas and they sent Etesian Winds, the northern winds blowing over the Aegean Sea every mid-summer for forty days, so that people could survive the unbearable heat. After that, the people of Kea, incited by Aristaeus, made sacrifices to the constellation of Canis Major and to Sirius. In order to remember his beneficence, they honored Aristaeus as "Aristaeus Apollo" and pictured his head on one side of their coins, while on the other side they depicted Sirius crowned with rays.

The late Professor and Academician of the National Technical University of Athens, Pericles S. Theochares (1995: 183) wrote:

> This myth alludes to the relation of Sirius with the Earth. The sacrifices were made to Zeus Meilichius, a god of the weather, of the sun and rain, and to Sirius, who causes the dog burnings on Earth; they believed

> that not only the Sun is responsible for the great heat of the summer, but also Sirius when standing next to the Sun. This was probably the belief of the builders of the Argolis pyramids, orienting their entrance corridors towards the azimuth of Sirius.

In ancient poetry Sirius is mentioned as a star with especially negative influence, something obvious in the Homeric verse "… it bodes no good … to us poor mortals." (*Iliad*: XXII, 25-31). Because the Greeks of that era had noticed that people tended to become sluggish during the dog days, they had consolidated the belief that Sirius was exerting a halting influence on human activities. For this reason, even Hippocrates refers to the bad influence of this star on humans. Hippocrates made much, in his *Epidemics* and *Aphorisms*, of this star's power over the weather, and the consequent physical effect upon mankind (Allen, 1963: 126).

3.2 The Planet Venus

Venus is mentioned in both the *Iliad* and the *Odyssey*. In *Iliad*'s Rhapsody XXII (verse 317) Homer mentions Hesperus, the Evening Star, and in XXIII (verse 226) Eosphorus (Lucifer in Latin), the Morning Star that brings the light of dawn. In both cases Venus is the object really mentioned, although Homer considers them most probably as two different stars:

> And as amidst the stars the evening star proceeds bright, that most beautiful among the stars of the sky, likewise the lance was shining, which was thrown by his right hand with malevolent purpose towards divine Hector, watching to find an uncovered part of his soft body. (*Iliad*: XXII, 317-321).

Similarly in the second passage: "When Lucifer heralds the light and golden Eos (the Dawn) emerges from the sea's depths, the fire was fading and flames stopped." (*Iliad*: XXIII, 226-228).

In Homer's *Odyssey* the passage brings us once again to the sea: "As the all-bright star emerged that comes first to herald the light of the night-born Dawn, then the foam-happy ship was nearing the island." (*Odyssey*: xiii, 98-100). It means that Ulysses reaches Ithaca before dawn, the time Venus appears, as the brightest star 'coming' before dawn.

3.3 Solstices

Also in the *Odyssey*, there is a clear reference to the solstices as "turnings of the Sun": "Syria they call an island – if you ever heard of it – higher than Ortygia, to the turning of the Sun." (*Odyssey*: xv, 403-404).

3.4 Other Ancient Authors about the Stars, Constellations and Sirius

Homer's epics assuredly influenced other ancient Greek poets and authors who mentioned the stars and the constellations of the sky. The most references are to the brightest star, Sirius.

Due to its bright apparent magnitude (–1.46), Sirius had a special place in the mythology, legends and traditions of most peoples of the Earth. Its very name means in Greek "sparking", "fiery" or "burning'", or "flamboyant"; this name is most ancient, as it occurs in the Orphic *Argonautics*: "… just when for three consecutive days lost its light the flamboyant sun." (*Argonautics*: 121-122; Petrides, 2005), as well as in Homer (*Iliad*: XXII, 25-32 and *Odyssey*: v, 4).

In about the same period as Homer, or slightly later, Hesiod in his famous book, *Works and Days*, mentions several constellations that the farmer needs to watch for his daily work as well as three references to the solstices. For example, Hesiod suggests that the harvest should start when the Pleiades rise (heliacal rise), while seeding should start when they are about to set. Hesiod spoke of all the stars and constellations mentioned by Homer, with a special reference to Sirius. Indeed, he mentions Sirius in three different passages. In the first one he gives some advices to his brother Perses about grape-gathering: "And when Orion and Sirius reach the middle of the sky and the rose-fingered Dawn watches Arcturus, then, Perses, gather all grapes and bring them to the house." (Hesiod, 1988: 609-610), while in the other two he speaks about the dog burnings: "Then Sirius, the star proceeds a little more over the head of the mortal men each day and takes a larger part of the night." (ibid.: 417) and "For Sirius dries the head and the knees and the body is dry from the heat." (ibid.: 587).

Another work by Hesiod, *Aspis Irakleous* (*Shield of Hercules*), is to a certain extent an imitation of "Aspis Achilleos" (the Shield of Achilles) as it is described in the *Iliad*: (XVIII, 468-817). In this work, too, Hesiod mentions the bright star Sirius twice (Hesiod, 1988: 391):

> 'Their souls descend into Hades to be dressed with earth, while their bones, when the skin around them is melted by fiery Sirius, get rotten in the black earth.' (Shield of Hercules, 151). And: 'When the noisy, blue-winged cicada, sitting on a green branch in summer, starts singing to people, and his food and drink is the soft dew, and all day long, starting from the dawn, pours its voice in the most terrible heat, when Sirius burns the body, then primes start appearing on the millets that are sowed in summer'.

The poet Aeschylus (525-456 BC) in his tragedy *Agamemnon* also mentions Sirius the dog (verse 967).

Apollonius of Rhodes (3rd century BC) wrote his *Argonautics*, a major epic poem remolding in a poetic form the mythical expedition of the Argonauts from Thessaly to Colchis of the Black Sea. Apollonius also mentions Sirius in connection with the unbearable heat of the summer (Apollonius, 1988: Song III, v. 517):

> When Minoan islands were heated from the sky by Sirius and for a long time their dwellers didn't find any treatment to this … [And later on] 'He appeared again like Sirius, which rises to the heights from Ocean's edge.' (ibid.: Song III, v. 956).

Theognis (570–480 BC), a significant elegy poet from Megara, wrote several symposium poems, distinguished for their dignity and their respect of the gods. He even gives a rule for wine drinking, adding some information for the period around the rise of Sirius: "Witless are those men, and foolish, who don't drink wine even when the Dog Star is beginning …" (Wender, 1984: 1039-1040).

Eratosthenes (276-194 BC) uses the word "sirios" as an adjective, writing for example: "Such stars are called sirios by astronomers, due to the quivering motions of their light." (Eratosthenes, 1997: 34).

Nonnus, a Greek epic poet of the 5th century AD from the Egyptian city of Panopolis, writes in his *Dionysiaka* about the dog burnings of Sirius: "He sent an opposite puff of winds to cut off the hot fever of Sirius." (Nonnus, *Dionysiaka*: V 275).

In the Byzantine period, Princess Anna Comnene [Komnene, or latinized Comnena, according to Wikipedia] writes in her *Alexias*: "… even though it was summer and the sun had passed through Cancer and was about to enter Leo – a season in which, as they say, the star of the Dog rises." (Comnene, 2005: Book 3, XII.4).

4 DESCRIPTION OF A TOTAL SOLAR ECLIPSE IN THE *ODYSSEY*

In Rhapsody XX of the *Odyssey* there is the following passage: "The entrance and all the yard is full from shadows of the dead, who run in the dark. The Sun disappeared from the sky, and a thick dimness fell everywhere." (XX, 356-357).

This passage probably describes an astronomical phenomenon, possibly the most ancient Western record of a total solar eclipse. As totality is a relatively rare astronomical event for a given place, occurring on the average once every 360 years, if the area of totality is restricted then a very probable date could be determined for that eclipse (Varvoglis, 2009).

Although no solar or lunar eclipses are directly mentioned in a Homeric text, the previous verses motivated two astronomers, Constantinos Baïkouzis from the Laboratory of Mathematical Physics at The Rockefeller University in New York and Marcelo Magnasco from the Proyecto Observatorio, Secretaría de Extensión, Observatorio Astronómico de La Plata, to attempt a precise determination of the date Ulysses returned to Ithaca. They hypothesized (2008) that in the *Odyssey*: XX, 356-357 Homer refers to a total eclipse of the Sun that occurred on the day Penelope's suitors were exterminated.

A prediction of an event like this is included in the literature, as the oracle Theoclymenus had warned the suitors that "The Sun will be obliterated from the sky, and an unlucky darkness will invade the world when the householder comes back and blood will be found in their dishes." (*Odyssey*: XX, 350-355).

This quotation was correlated by Baikouzis and Magnasco with other references to ancient solar eclipses in ancient texts, and certain similarities were found. Moreover, in the Homeric text there are another four astronomical 'markers' concerning the return of Ulysses to Ithaca.

The first one is the phase of the Moon: Homer notes more than once that it was the time of New Moon, so the prime prerequisite for a solar eclipse is satisfied, according to Baikouzis and Magnasco (2008).

The second has to do with Venus, which six days before the slaughter of the suitors was visible high in the sky: "As the all-bright star emerged that comes first to herald the light of the night-born Dawn, then the foam-happy ship was nearing the island." (*Odyssey*: xiii, 98-100).

The third 'marker' is about the stars and constellations Ulysses was seeing when he left the island of Calypso: 29 days before the day in question, the Pleiades were visible after sunset, as well as the constellation Boötes.

The fourth is the reference to the god Hermes (Mercury) who "… flies westwards …" of the Ogygia island 33 days before the eclipse. According to Baikouzis and Magnasco (2008) this is a reference to the planet Mercury appearing low in the sky before sunrise. The planet undergoes retrograde motion once every 116 days, around the eastern edge of its apparent orbit.

Haris Varvoglis (2009), Professor of Astronomy at the University of Thessaloniki, notes that if we suppose that this last passage refers to the planet Mercury, then its western elongation (to the west of the Sun) and its turn to the east, along with the position of the Pleiades over the western horizon after sunset, and the simultaneous visibility of Boötes and with the apparition of Venus as 'Morning Star', all coincide once every 2000 years. Since it is known from the archaeological excavations of Troy that its destruction occurred around 1190 BC, it is clear that, if in the decades before or after that year such an astronomical coincidence happened, this can not be anything other than an independent confirmation of the year of Troy's destruction (Varvoglis, 2009: 3).

Knowing the probable year of Troy's destruction, combining all the previous astronomical information in Homer, and considered 1684 New Moons between 1250 and 1125 BC, Baikouzis and Magnasco used planetarium software to research the astronomical past of the Ionian Sea region. They discovered that a total solar eclipse occurred in 1178 BC and was visible as such from Ithaca. After a more precise calculation, they verified the exact date on the Julian calendar: 16 April in 1178 BC. They set this date as the day the suitors were exterminated. If this is true and the wanderings of Ulysses indeed covered ten years, as Homer states, then the capture and destruction of Troy should have happened in 1188 BC.

Baikouzis and Magnasco say that their research may not prove beyond a doubt the timing of the return of Ulysses to Ithaca, but it at least proves that Homer knew of certain astronomical phenomena that occurred centuries before his own age. If they are right and Homer 'tied' that date to astronomical events that can be verified, then this fact can help historians to date the fall of Troy with far greater precision.

A possible counter-argument to that position is that Homer, who is presumed to have lived in the 8th century BC, would have found it difficult to describe astronomical events that occurred more than four centuries earlier. Also, although the words of Theoclymenus seem to describe a solar eclipse, the poet may have merely wanted to give a general image in fitting with the dark fate of Penelope's suitors. Science journalist J.R. Minkel (2008) reports in *Scientific American*:

> Researchers say that references to planets and constellations in the Odyssey describe a solar eclipse that occurred in 1178 B.C., nearly three centuries before Homer is believed to have written the story. If correct, the finding would suggest that the ancient poet had a surprisingly detailed knowledge of astronomy … Greek scholars Plutarch and Heraclitus advanced the idea that Theoclymenus's speech was a poetic description of an eclipse. They cited references in the story that the day of the prophecy was a new moon, which would be true of an eclipse. In the 1920s researchers speculated that Homer might have had a real eclipse in mind, after

> calculating that a total solar eclipse (in which the moon blocks out the sun) would have been visible on April 16, 1178 BC over the Ionian Islands, where Homer's poem was set. The idea languished, however, because the first writings on Greek astronomy did not come until centuries later.

Minkel's reference to "... some researchers in the 1920s ..." includes a link to an article by C. Schoch (1926a), who first determined 16 April 1178 B.C. as the date of the total solar eclipse connected with the words of Theoclymenus (but see, also, Schoch, 1926b; 1926c; and Neugebauer, 1929).

5 CONCLUSIONS

The cosmological model of Homer, which records the views of his age, and perhaps older views as well, survived in Ionia for centuries after his death.

Writing most probably in the 8th century BC, Homer presents the Earth as a disk surrounded by the watery Ocean on all sides. The starry sky is a solid vault that must be supported in order not to fall, while Hades, an underworld, exists below Earth, being as far from the Earth as the sky.

Not all of the planets known in antiquity were mentioned in the Homeric poems, but there is persuasive evidence that their characteristics and the correlation of the state of the sky with the passage of time on Earth were widely known after a great number of empirical observations had been carried out.

In conclusion, it can be said that the Homeric references show that certain constellations and certain celestial phenomena were known to the Greeks of that age. A number of stars had been named, and they were so familiar that they were used in similes regarding gods and humans. Another interesting point is that Homer mentions some stars and several constellations under exactly the same names as used today.

Beginning with the *Iliad*, the first reference to a star occurs in the 5th Rhapsody (V, 5), where Sirius is presented as an autumnal star; it seems natural that the first star mentioned is the brightest one of the night sky. A richer astronomical reference is in the description of the shield of Achilles (XVIII, 478-488). Homer states that upon it were depicted Orion, the Hyades, the Pleiades and the Bear or Wagon, "... which rotates always at the same place, watching Orion ..." and without ever touching the Ocean. This seems to be a clear implication that this constellation is circumpolar and always visible from the northern latitudes where the epic's story is taking place. This fact makes the Bear suitable as an easily-seen navigator's aid, so its inclusion in a popular poem would be of practical use for the society. Towards the end of the *Iliad* Homer again mentions Sirius, calling it Orion's dog (XXII, 29).

In the *Odyssey* there is again a reference to circumpolar stars and to the usual constellations (v, 279-287), but this time Boötes is added.

So, in total, Homer mentions three constellations (the circumpolar Ursa Major, Orion and Boötes); two open clusters, which were then known as constellations (the Pleiades and the Hyades); the bright star Sirius indirectly (as the autumn's star and the 'bad star' bringing the dog's burnings to people); and the planet Venus as a star with its ancient Greek names for the Evening Star and the Morning Star.

There is a 'star' mentioned without a name in the *Odyssey* (V, 286): "For she told him to keep that star on his left hand when sailing in the sea." The mathematician Konstantinos Mavrommatis (2000) suggests that this is probably the Pole Star of that age. Also, the astronomer Chariton Tomboulidis (2008) mentions that in the *Iliad* goddess Athena is likened to a 'spark' star: "From the peaks of Olympus she dashed as the star that Cronides threw as a sign to humans ... a bright star and infinite the sparks that are thrown." (IV, 75-78). Probably Homer alludes here to a shooting star or meteor, as such 'stars' would be more often observed back then in the very dark skies of ancient Greece.

In the *Odyssey* there is also a very clear reference to solstices (xv, 403-404) and a probable one to the phenomenon of stellar scintillation (xii, 318).

Finally, although solar or lunar eclipses are not explicitly mentioned in the Homeric epics, it has been suggested (Schoch, 1926a; Baikouzis and Magnasco, 2008) that in the *Odyssey* (XX, 356-357) Homer alludes to a total solar eclipse from which even a specific date for the arrival of Ulysses in Ithaca can be extracted. However, caution should be taken in this instance not to confuse poetic metaphors with real astronomical events, as Homer lived approximately four centuries after the mooted eclipse of 16 April 1178 BC.

It is a fact that there is only one case of using stars or constellation(s) for orientation purposes in Homeric texts (*Odyssey*: v, 271-277). The task of teaching practical applications of astronomy was undertaken by Hesiod half a century later, with his opus *Works and Days*, which offered to Greek people the first calendar for agricultural works, a guide of seasonal activities based on the heliacal rising or setting of various stars, constellations or of the Pleiades open cluster.

The Homeric astronomical literary tradition was followed by several ancient Greek authors, such as Hesiod with his books *Works and Days* and *Shield of Hercules*, the tragic poet Aeschylus in his tragedy *Agamemnon*, Apollonius of Rhodes with his *Argonautics*, Eratosthenes of Cyrene with his *Catasterismoi*, Nonnus with his *Dionysiaca* and even the Byzantine Princess Anna Comnene with her *Alexias*.

All these references indicate that at least since Greek antiquity, starting with the Orphic Hymns (2006) and subsequently Homer's epic poems, and up to this day, certain stars and the surviving constellations retain exactly the same names.

6 NOTES

1. All the English translations from the *Illiad* and the *Odyssey* in this paper are from the Loeb editions, unless otherwise noted.

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COMETS IN AUSTRALIAN ABORIGINAL ASTRONOMY

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Abstract: We present 25 accounts of comets from 40 Australian Aboriginal communities, citing both supernatural perceptions of comets and historical accounts of historically bright comets. Historical and ethnographic descriptions include the Great Comets of 1843, 1861, 1901, 1910, and 1927. We describe the perceptions of comets in Aboriginal societies and show that they are typically associated with fear, death, omens, malevolent spirits, and evil magic, consistent with many cultures around the world. We also provide a list of words for comets in 16 different Aboriginal languages.

Keywords: Comets, Aboriginal Australians, Ethnoastronomy, History of Astronomy.

1 INTRODUCTION

Cometography is the study of comets from both from a scientific and historic perspective (Kronk, 2003a). Recorded sightings of comets date back to the second century BCE, with the possibly earliest written recording of a comet by the Chinese in 1059 BCE (Yeomans and Kiang, 1981; Xu et al,, 2000: 107-125). While historic accounts of comets and their role in mythology have been widely described in the literature (e.g. Baillie and McCafferty, 2005; Burnham, 2000; Donnelly, 2005; Kronk, 2003a; 2003b; Levy, 1994; Schechner, 1999), little research has been conducted regarding Aboriginal Australian accounts of comets. Ethnographic literature on Aboriginal communities reveals several perceptions of comets and accounts of historic comets. In some cases the comet is described but the author does not specify to which comet the account is referring (e.g. Morrill, 1864: 61; Roth, 1984: 8), although the description and dates provided allow us to identify the most probable comet to which the account is referring. In other cases, perceptions of a comet are described, but do not correspond to any particular one. The description of the object, combined with the dates of the event, allow us to identify the particular comet discussed, providing a more complete historical account. Evidence shows that Aboriginal Australians were astute astronomers (see Norris and Hamacher, 2009), having a complex social and religious economy associated with the night sky. Similar studies relating to meteors and cosmic impacts in Aboriginal Astronomy are presented in Hamacher and Norris (2010, and 2009), respectively.

This paper presents various Aboriginal perceptions of comets as well as descriptions of historic bright comets, including C/1843 D1, C/1844 Y1, C/1861 J1, C/1901 G1, 1P/1909 R1, C/1910 A1, and C/1927 X1. We begin by introducing the reader to basic information about Aboriginal Australians, the concept of 'The Dreaming' and a description of comets as a celestial phenomenon. We then present our data collection methods and describe the various perceptions of comets, then dividing up identifiable comets by the date of the recorded account.

1.1 Aboriginal Cultures

The cosmic and terrestrial landscapes were an inseparable and integral component of daily life to the hundreds of Aboriginal communities in Australia and played a vital role in the structure and evolution of oral traditions and ceremonies. Celestial objects and phenomena were believed to be intricately tied to events on the Earth. Because of this, rare cosmic events, such as a bright meteor, comet, or eclipse had great significance and meaning to those people who witnessed them. These events were often recorded in oral tradition and art, and were integral to the preservation and dissemination of both general and sacred knowledge within the community.

When researchers and scholars began visiting and studying Aboriginal communities and recording oral traditions in the early nineteenth century, very little was known about the diverse Aboriginal hunter/ gatherer societies that not only survived, but thrived in some of the world's harshest climates for more than 40,000 years. After the British colonised Australia in the late eighteenth century, Aboriginal communities were devastated by disease, limited access to resources, and outright genocide. As a result, the total Aboriginal population reduced from over 300,000 in 1788 (Jupp, 2001: 93) to just 93,000 by 1900 (Australian Bureau of Statistics, 2002). In many places, especially near British colonies, entire cultures, including the language, customs, and oral traditions, were virtually destroyed.

Despite the damage to many Aboriginal cultures, several Aboriginal communities still thrive and retain their collective knowledge and traditions, while a substantial amount of information about other Aboriginal communities has been recorded in the literature. Although this information represents a tiny fraction of the knowledge originally possessed by Aboriginal communities, it can help non-Aboriginal people understand Aboriginal beliefs and perceptions of natural phenomena at the time they were recorded.

1.2 The Dreaming

Common among most Aboriginal cultures is the concept of 'The Dreaming', an English term coined by Francis Gillen in 1896 and adopted by Spencer and Gillen (1899) to refer to the period in the religious oral traditions of the Northern Arrernte people of Central Australia (Dean, 1996). The Dreaming is not a universal, homogeneous concept spanning all Aboriginal groups, but instead possesses substantial variations in the way it is viewed and understood by various Aboriginal groups across Australia. The Dreaming is viewed by some Aboriginal groups (e.g. the Tiwi and Wiradjuri) as the period during the creation of the world when totemic ancestors came into being, representing a past reality. For other groups, it represents a past, current and future reality, either concurrently parallel to our own reality (e.g. the Ooldea and Warrabri), or within our own reality (e.g. the Murinbata and Mardudjara). It should also be emphasized that the Dreaming does not necessarily represent a linear progression of time. In some cases, such as during ritual ceremonies, the past can become the present, so the term 'Dreamtime' used in an all-encompassing sense is not accurate, as it denotes a linear timeline, separating past, present, and future. The Dreaming is part of a diverse and complex social structure and system of laws and traditions that have been an integral aspect of Aboriginal cultures for thousands of years (see Bates, 1996; Rose, 1996; 2000; Stanner, 1965; 1976; 1979).

2 METHODOLOGY

The available literature, including books, journals, magazines, audio and video sources were reviewed for references to comets[1] or descriptions that may refer to comets but do not explicitly identify them as such. Most of the data are taken from ethnographies collected in the nineteenth and early twentieth centuries. Forty-one accounts were collected, including sixteen Aboriginal words for comets (see Table 1), representing forty Aboriginal groups from all Australian states except Tasmania (eight from Victoria, Queensland and the Northern Territory, seven from Western Australia, six from South Australia, and four from New South Wales). Historically, visible comets are identified by the date and or description of the account. In some cases, the identification is clear, while in other cases, the identification is inferred and should not be considered definitive.

We must stress that Indigenous views and accounts of comets are not homogeneous or unchanging over time. It is common for a particular celestial object or phenomena to have different views among members of the community, and these views are dynamic and evolving. It is therefore essential to understand that the accounts provided in this paper simply reference the community from which they came, and do not imply that everyone within that community or language group had the same view, reaction, or association with comets. Statements such as "The [Aboriginal group] saw comets as ______" are used only to denote the Aboriginal group or geographic area from which the account was taken. We must also emphasise that these records come largely from Western researchers and scholars, including some colonists that were not trained in linguistics, ethnology or anthropology. Therefore, these accounts are inherently biased. Fredrick (2008) analyses the academic backgrounds of the major contributors to Australian Aboriginal Astronomy, which gives an insight into the reliability and accuracy of the information provided by these researchers.

3 RESULTS

3.1 Aboriginal Perceptions of Comets

When Westerners began studying Aboriginal communities in the early 1800s, they noted that the Aboriginal people viewed extraordinary or unusual natural events with great dread (e.g. Eyre, 1845: 358-359; Palmer, 1884: 294). The unexpected arrival of a bright comet often triggered fear and was associated with death, spirits, or omens—a view held by various cultures around the world (e.g. Andrews, 2004; Bobrowsky and Rickman, 2007; McCafferty and Baillie, 2005). Such views include those of the Tanganekald of South Australia who perceived comets as omens of sickness and death (Tindale, n.d.), the Mycoolon of Queensland who greeted comets with fear (Palmer, 1884: 294), the Kaurna of Adelaide who believed that the Sun father, called *Teendo Yerle*, had a pair of evil celestial sisters who were 'long' and probably represented comets (Clarke, 1997: 129; Schurmann, 1839) and the Euahlayi of New South Wales saw comets as evil spirits that drank the rain-clouds causing drought,[2] with the cometary tail representing a large thirsty family that drew the river into the clouds (Parker, 1905: 99). The Moporr clan of Victoria described a comet as *Puurt Kuurnuuk*—a great spirit (Dawson, 1881: 101), while the Gundidjmara of Victoria saw a comet as an omen that lots of people will die (Howitt and Stähle, 1881). Aboriginal people in the Talbot District of Victoria likened comets (called '*Koonk cutrine too*') to smoke, where '*too*' means '*to smoke*' (Smyth, 1878: 200). This is similar to a report from Cape York Peninsula, where an Aboriginal community saw a comet as the smoke of a campfire (Roth, 1984: 8). Similarly, the Aboriginal people of Bentinck Island in the Gulf of Carpentaria called a comet *burwaduwuru*, which means "… testicle with smoke." (Evans, 1992: 196).

Table 1: Glossary of Aboriginal terms for comets.

Group	State	Term	Reference
Bindal	Queensland	Nilgoolerburda	Morrill (1864: 61, 62)
Boiwoorarng	Victoria	Jajowerong	Smyth (1878: 177)
Gumbaybggirr	New South Wales	Gumugan	Morelli (2008: 160)
Gunditjmarra (Moporr)	Victoria	Puurt Kuurnuuk	Dawson (1881: 101)
Kayardild	Queensland	Burwaduwuru	Evans (1992: 196)
Kwini	Western Australia	Kallowa Anggnal Kude	Mowaljarlai and Malnic (1993: 194)
Ngiyampaa	New South Wales	Yangki (Comet Halley)	Thieberger & McGregor (1983: 2.8)
Parnkalla	South Australia	Yandarri	Schurmann (1844: 79)
Pitjantjatjara	Northern Territory	Wuuluru	Goddard (1992: 202)
Djadjawurung*	Victoria	Koonk cutrine too	Smyth (1878: 200)
Wiradjuri	New South Wales	Muma	Rudder (2005: 403)
Wunambal	Western Australia	Kallowa Anggnal Kude	Mowaljarlai and Malnic (1993: 194)
Yarra Yarra	Victoria	Bullarto tutbyrum	Smyth (1878: 136)
Yolngu	Western Australia	Ngarrpiya	Lowe (2004: 116)
Unspecified	Western Australia	Binnar (also meteor)	Moore (1842: 126)
Unspecified	Victoria	Boiwoorarng	Smyth (1878: 163).

* From the Talbot District, Victoria (language group name not specified in text). Language group taken from the AIATSIS map of Aboriginal languages.

A common view among Aboriginal communities of the Central Desert links comets to spears (e.g. Spencer, 1928: 409). A Pitjantjatjara man named Peter Kunari (Anon, 1986: 20) described comets as the manifestation of a being named *Wurluru* who lived in the sky and carried spears that he occasionally threw across the heavens (a possible reference to meteors?). A similar association is shared by the Kaitish, which is discussed further in Section 3.3. The Rainbow Serpent, a much-feared evil spirit found in The Dreamings of many Aboriginal groups, was sometimes associated with comets (e.g. Healy, 1978: 194).[3] Trezise (1993: 107) speculated that the origins of the Rainbow Serpent lay in transits of Halley's Comet, which was seen every 76 years, reinforcing stories handed down by Kuku-Yalanji law-carriers and custodians of the Bloomfield River, Queensland.

Spencer and Gillen (1899: 550; 1904: 627-628; 1927: 415–417) describe a form of evil magic called *Arungquilta*, which involved meteors and produced comets and was used to punish unfaithful wives in Arunta communities. If a woman ran away from her husband, he would summon men from his group and a medicine man to perform a ceremony intended to punish her. In the ceremony, a pictogram of the woman was drawn in the dirt in a secluded area while the men chanted a particular song. A piece of bark, representing the woman's spirit, was impaled with a series of small spears endowed with *Arungquilta* and flung into the direction of where they believed the woman to be, which would appear in the sky as a comet (bundle of spears). The *Arungquilta* would find the woman and deprive her of her fat. After the emaciated woman died, her spirit appeared in the sky as a meteor. Strehlow (1907: 30) cites a nearly identical ceremony. However, in Strehlow's account, the man felt pity for his wife and decided to revive her by rubbing fat into her body. As she healed, the comet faded from view. In some Arrernte and Luritja communities, comets are spears thrown by an ancestral hero to make his wife obedient to him (Strehlow, 1907: 30). To some Arrernte clans, a comet was also a sign that a person in a neighbouring community had died, usually because of infidelity, and pointed to the direction of the deceased (Spencer and Gillen, 1899: 549). A similar description is given by Piddington (1932: 394) about the Karadjeri of coastal Western Australia, but is instead attributed to meteors. Given the two accounts by Spencer and Gillen of the same ceremony, it is possible they are confusing comets with meteors.

A direct association between comets and death is highlighted by a story from the Kimberleys of a great flood that was brought on by a "… star with trails …" called *Kallowa Anggnal Kude* (Mowaljarlai and Malnic, 1993: 194). Bryant (2001; see, also Bryant et al., 2007: 210-211) contends that this account is a description of a comet impact in the Indian Ocean off the northwest coast of Western Australia, which he speculates caused a massive tsunami that devastated the region. Bryant speculates that the "… star with trails …" is depicted in a rock painting at a place called 'Comet Rock' near Kalumburu, Western Australia (home the Wunambal and Kwini), which lies on a plain 5 km from the sea that is covered in a layer of beach sand.

3.2 Historic Visible Comets

In the two hundred years between 1800 and 2000, about forty naked eye comets were visible (Table 2) from Australia, or on average one every five years. So we could say that naked eye comets were not particularly rare, and this is reflected in the fact that some of the literature and ethnographic accounts relating to Aboriginal astronomy do not simply describe perceptions of comets but refer to particular historic comets, including the 'Great Comets' of 1843, 1861, 1901, 1910, 1927, and Comet Halley. In some cases, the comet is not identified by name, but is inferred from the description and date. Details of each comet observation or description are presented below.

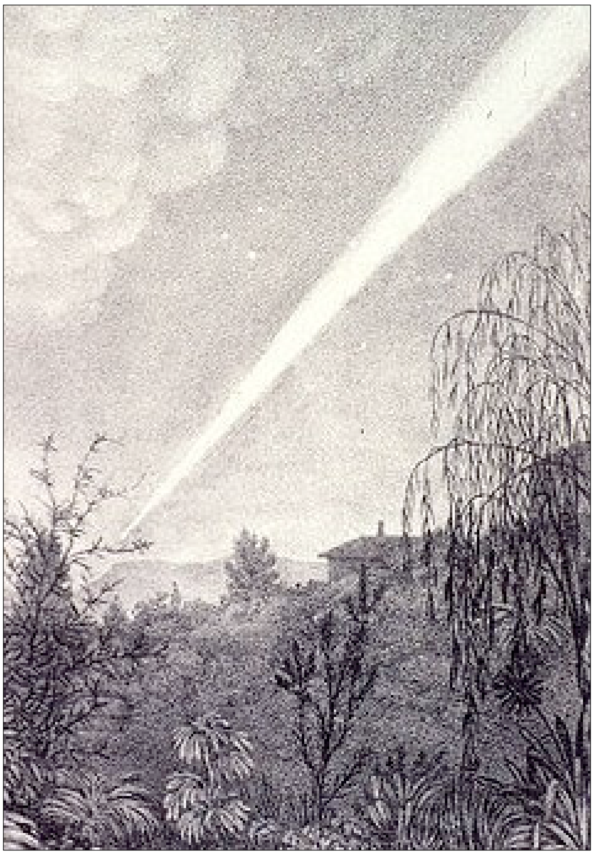

Figure 1: The Great Comet of 1843 (C/1843 D1) as seen from Tasmania (Van Diemen's Land). Painting by Mary Morton Allport (1806–1895). Reproduced from Wikimedia Commons under Creative Commons License.

3.2.1 C/1843 D1 (Great March Comet of 1843)

The Great Comet of 1843 (C/1843 D1) was a bright, sun-grazing comet visible in the Southern skies from late-February to mid-April. It was visible near the Sun (within 1°) and became brightest on 7 March (see Kronk, 2003a: 129; Sekanina and Chodas, 2008). The comet, so frightening in its brilliance (see Figure 1), prompted Aboriginal people near Port Lincoln (South Australia) to run and hide in caves (Schurmann, 1846: 242). The Ngarrindjeri of South Australia saw the comet as a harbinger of calamity, specifically to the white colonists. They believed the comet would destroy Adelaide then travel up the Murray causing havoc in its path, as described by Eyre (1845: 358-359):[4]

> In March 1843, I had a little boy living with me [in Moorunde, SA] by his father's permission, whilst the old man went up the river with the other natives to hunt and

> fish. On the evening of the 2nd of March a large comet was visible to the westward, and became brighter and more distinct every succeeding night. On the 5th I had a visit from the father of the little boy who was living with me, to demand his son; he had come down the river post haste for that purpose, as soon as he saw the comet, which he assured me was the harbinger of all kinds of calamities, and more especially to the white people. It was to overthrow Adelaide, destroy all Europeans and their houses, and then taking a course up the Murray, and past the Rufus [the site of an Aboriginal massacre], do irreparable damage to whatever or whoever came in its way. It was sent, he said, by the northern natives, who were powerful sorcerers, and to revenge the confinement of one of the principal men of their tribe, who was then in Adelaide gaol, charged with assaulting a shepherd; and he urged me by all means to hurry off to town as quickly as I could, to procure the man's release, so that if possible the evil might be averted. No explanation gave him the least satisfaction, he was in such a state of apprehension and excitement, and he finally marched off with the little boy, saying, that although by no means safe even with him, yet he would be in less danger than if left with me.

Le Souëf (in Smyth, 1878: 296) recounted events that took place when the Great Comet of 1843 was seen in Victoria (specific location not identified). When it was first seen, it caused "… dreadful commotion and consternation …" among the communities. "Spokesmen [presumably Elders or medicine men] gesticulated and speechified far into the night …" in an attempt to rid the comet, but with no success. When their actions seemed in vain, they packed up camp in the middle of the night and moved to the other side of the river and remained huddled together until morning. They believed that the comet had been sent to them by the Aboriginal people near Ovens River in northern Victoria to cause harm. They left the area and did not return until the comet faded away. Aboriginal people near Kilmore (Victoria) told Curr (1886: 50) that the tail of this 'grand comet' consisted of spears thrown by Aboriginal people near Goulburn to one another.[5]

3.2.2 C/1844 Y1 (Great Comet)

There were no Aboriginal accounts of this comet in the reviewed literature. However, the explorer Ludwig Leichhardt saw a comet in the sky on 29 December 1844 while walking along the banks of a creek in central Queensland (Lang, 1847:315), prompting him to name the site Comet Creek. The town of Comet in Queensland (originally Cometville) takes its name

Table 2: Naked eye comets that attained brightness greater than magnitude +2 recorded between 1800 and 2000, taken from Seargent (2009). Information regarding the Great Comet of 1844-1845 was taken from Bond (1850). When Comet Halley passed in 1986, it reached a maximum brightness of only +2.6 in early March and therefore is not included.

Year	Common Name	Designation	Duration Visible
1807	Great Comet of 1807*	C/1807 R1	Early September to Late December
1811	Great Comet of 1811	C/1811 F1	Late March to January
1819	Great Comet of 1819	C/1819 N1	Month of July
1825	Comet Pons	C/1825 N1	Late August to Late-December
1830	Great Comet of 1830	C/1830 F1	Mid March to Mid May
1831	Great Comet of 1831	C/1831 A1	Month of January
1835	Comet Halley	1P/1835 P1	Late September to Mid February
1843	Great March Comet of 1843	C/1843 D1	Early February to Mid April
1844	Great Comet	C/1844 Y1	Mid December to Late January
1847	Comet Hind	C/1847 C1	Late February to Late-March
1853	Comet Klinkerfues	C/1853 L1	Early August to Early October
1854	Great Comet of 1854	C/1854 F1	Late March to Mid April
1858	Comet Donati	C/1858 L1	Mid August to Late November
1860	Great Comet of 1860	C/1860 M1	Mid June to Late July
1861	Great Comet (Tebbutt)	C/1861 J1	Mid May to Mid-August
1874	Comet Coggia	C/1874 H1	Early June to Late August
1880	Great Southern Comet of 1880	C/1880 C1	Early to Mid February
1881	Great Comet (Tebbutt)	C/1881 K1	Late May to Late July
1882	Comet Wells	C/1882 F1	Late May to Early July
1882	Great September Comet of 1882	C/1882 R1	Early September to Early February
1887	Great Southern Comet of 1887	C/1887 B1	Mid to Late January
1901	Great Comet (Viscara)*	C/1901 G1	Mid April to Late May
1910	Great Daylight Comet of 1910	C/1910 A1	Mid January to Mid February
1910	Comet Halley	1P/1909 R1	Late April to Mid July
1911	Comet Belajawsky	C/1911 S3	Late September to Late October
1911	Comet Brooks	C/1911 O1	Late August to Late November
1927	Comet Skjellerup-Maristany	C/1927 X1	Late November to Early January
1941	Comet de Kock-Paraskevopoulos	C/1941 B2	Mid January to Late February
1947	Southern Comet of 1947	C/1947 X1	Early to Late December
1948	Eclipse Comet of 1948	C/1948 V1	Early November to Late December
1956	Comet Arend-Roland	C/1956 R1	Mid March to Mid May
1957	Comet Mrkos*	C/1957 P1	Late July to Late September
1961	Comet Wilson-Hubbard	C/1961 O1	Late July to Early August
1962	Comet Seki-Lines	C/1962 C1	Late February to Late April
1965	Comet Ikeya-Seki	C/1965 S1	Early October to Mid November
1969	Comet Bennett	C/1969 Y1	Mid February to Mid May
1970	Comet White-Ortiz-Bolelli	C/1970 K1	Mid May to Early June
1973	Comet Kohoutek	C/1973 E1	Late November to Late January
1976	Comet West*	C/1975 V1	Late February to Mid-April
1996	Comet Hyakutake	C/1996 B2	Early March to Early June
1997	Comet Hale-Bopp	C/1995 O1	July 1996 to October 1997

* These comets possessed two or more distinctive tails visible to the naked eye.

from this creek (now called Comet River). For further details see Edwards (1994).

3.2.3 C/1861 J1 (Tebbutt): The Great Comet of 1861

After surviving the shipwreck of the *Peruvian* in the Great Barrier Reef in 1846, four members of the crew reached Cleveland Bay on the coast of Queensland near present-day Townsville. One of the survivors, James Morrill, lived among the local Aboriginal people for 17 years, publishing his journals in 1864 (Morrill, 1864). He notes how the Aboriginal people used the same word for comets and stars (*nilgoolerburda*) and explains that comets were believed to be the spirits of men killed far away returning home, making their way from the clouds to the horizon. He described seeing a comet during the previous dry season (June to November) and noted that the Aboriginal people thought it was "… one of the tribe who had been killed in war …" (ibid.: 61). Morrill does not give a date for this sighting, but does go on to say that he witnessed a nearly total solar eclipse about six years earlier. From 1846 to 1864, only two nearly total solar eclipses (where the Moon covered >80% of the Sun) were visible from this region: on 5 April 1856 (t_e = 17:05:31) and 18 September 1857 (t_e = 17:28:04, where t_e is the time of mid-eclipse), despite Morrill claiming that he only saw one eclipse during the time that he was living among the Aboriginal people. This gives a period of approximately five years between the eclipse and the comet sighting, revealing the best candidate is the Great Comet of 1861 (C/1861 J1 Tebbutt), which is depicted in Figure 2 as the Earth was about to pass through its tail. This comet was discovered by the Windsor-based Australian amateur astronomer, John Tebbutt, and from Australia was visible as a conspicuous naked eye object from mid-May through to near the end of June, during the dry season (see Kronk, 2003a: 293; Orchiston, 1998a; 1998b), which implies that Morrill's account was recorded in 1862. This comet had a distinctive tail that at its best extended 42°, and the comet appeared brightly in the northern sky throughout June as the Earth approached its tail (see Ellery, 1861; Raynard, 1872; Scott, 1861). The Aboriginal people told Morrill the comet was a spirit coming down from the clouds onto the horizon (Morrill, 1864: 61).

3.2.4 C/1901 G1 (Comet Viscara)

While engaging in ethnographic fieldwork in Queensland from 1901 to 1908, anthropologist and Northern Protector of Aboriginals, Walter E. Roth (1984: 8), noted that the Tjungundji people near Mapoon (Marpuna) on the western coast of Cape York Peninsula saw a comet as a fire lit by two old women. This was probably a reference to the recent Great Comet of 1901, which was visible exclusively in the Southern skies from mid-April to late-May and displayed distinctive, bright twin tails (Gill, 1901; Tebbutt, 1901; see Figure 3). In early May, when it reached peak brightness, the comet transversed the boundary between Taurus and Eridanus. The head of the comet, of magnitude 0 on 3 May and +2 on 6 May, would have appeared in the western evening skies near the horizon with the twin tails, comprising a 30° straight tail and a 10° curved tail, pointing upwards towards the star Sirius. By 12 May, the longer tail extended to the star δ Leporis (Kronk 2007: 10-14; The Great Comet …, 1901). At this time, the comet would have looked very much like two smoke columns diverging from a single point on the horizon. The comet remained visible until 23 May with the tails increasing in length to 45° and 15°, respectively (Bortle, 1998).

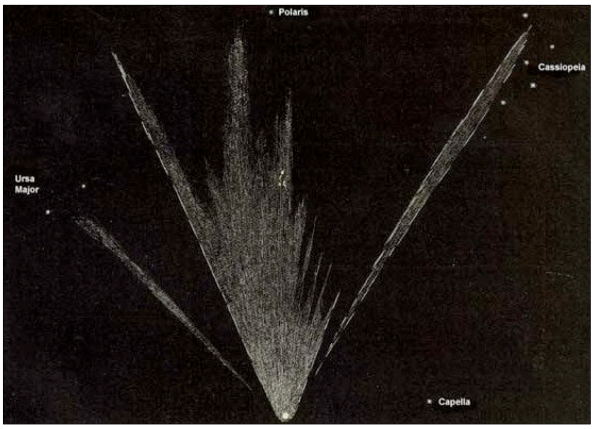

Figure 2: Williams' drawing of C/1861 (Tebbutt) made on 30 June 1861, just after the Earth passed through its tail. By this time it was a very conspicuous object but was only visible to Northern Hemisphere observers (after Chambers, 1889: 465).

The Kaitish of the Northern Territory believed a comet was a bundle of spears belonging to a star endowed with a very strong magic. The people feared these spears would be thrown to Earth, killing many. Spencer and Gillen (1904: 629; 1912: 327) describe a bright comet visible during their stay in 1901, which is probably a reference to C/1901 G1. To avert the evil of the comet, a young, celebrated medicine man named Ilpailurkna was visiting the area from the neighboring Unmatjera clan. Each night he would project his magic stones towards the comet. As the comet faded away, its evil was overcome and the people were very grate-

Figure 3: Photograph of the Great Comet of 1901 with bright twin tails, taken at the Royal Observatory, Cape of Good Hope, South Africa (after Mitton, 2009:120).

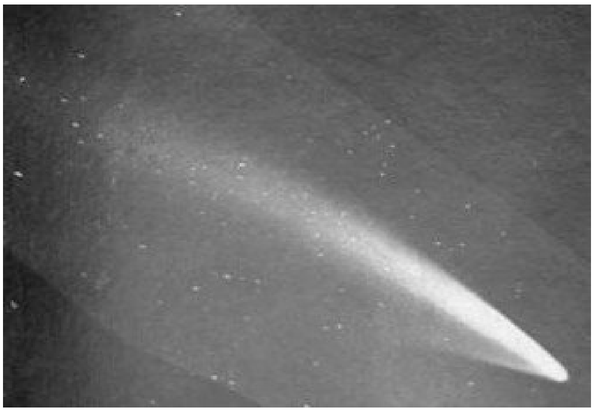

Figure 4: The Great Daylight Comet of 1910 appeared just four months before Comet Halley but was brighter than Venus at its peak (image rotated clockwise by 90). Photograph from Lowell Observatory, reproduced from Wikimedia Commons under Creative Commons License.

ful that Ilpailurkna had saved them.[6]. In the eyes of the community, had Ilpailurkna not driven the comet away, it would have fallen to Earth as a bundle of spears and everyone would have been killed (ibid.: 630).

3.2.5 C/1910 A1 (Great Daylight Comet of 1910) and 1P/Halley in 1910

In 1910, the world awaited the return of the famous Comet 1P/Halley in May. However, the unexpected arrival of a bright comet in mid-January created much fear and awe (e.g. *New York Times*, 1910; Burnham, 2000: 184). Deemed the Great Daylight Comet of 1910 (see Figure 4), it was bright enough to be seen during the day and at its peak, was brighter than Venus. It began to fade away in early February, followed a few months later by the arrival of the fainter, but still significant, Comet Halley (Kronk 2007: 170-179). When Comet Halley returned in 1986, many of the older people around the world who recalled seeing it in 1910 had clearly described the Great Daylight Comet of 1910 and not Halley (ibid.).[7]

Figure 5: Drawing of Comet Skjellerup-Maristany by R.A. McIntosh on 5 December 1927 (Orchiston Collection).

In 1985 Jack Butler, a Jiwarli man from the Henry River in Western Australia, told of a "… star with a tail in the east …" he saw early in the year 1910 as a child (Butler and Austin, 1986: 85-88). The comet caused fear among the elder men who "… questioned what it was." When the comet faded away the men were confused and wondered where it had gone. According to Butler, the object he saw in 1910 was Comet Halley. However, the Great Daylight Comet of 1910 was prominent in the morning twilight, consistent with the "… star with a tail in the east …" visible early in the year. Therefore, it is probable that Butler was describing the Great Daylight Comet of 1910 rather than Comet Halley.[8]

3.2.6 C/1927 X1 (Comet Skjellerup-Maristany)

Paddy Roe, a Nyigina elder, told of the appearance of a comet in the early twentieth century by an Aboriginal community on the Roebuck Plains west of Broome, Western Australia (Duwell and Dixon, 1994: 80). The comet, which he described as "... a star with a tail ...", was seen as a bad omen. However, after nothing bad happened the community held a celebratory corroboree. Roe states that the comet was first seen during the "... new moon when the moon was a crescent ..." (this refers to the time after a new Moon when the Moon appears as a thin crescent). These accounts date to the period "... between the Wars ...", presumably referring to World Wars I and II (between 1918 and 1939). The best candidate is the Great Comet of 1927 (see Figure 5), discovered on 4 December 1927 by the Australian amateur astronomer John Francis Skjellerup when it was a third magnitude object with a 1° tail (although others claimed to have discovered it on 28 November 1927; see Orchiston, 1999). The comet, first detected in the Southern Hemisphere, was visible primarily during the day and early evening. By the time it was visible at night, it faded rapidly. Since the comet was near the solar disc but could still be seen during the day, the sighting of Comet Skjellerup-Maristany is consistent with being seen at the time of a new Moon (the day it was claimed to have first been discovered, 28 November 1927, was just after new Moon, see Makemson, 1928; Seargent, 2009: 147-148), although this identification is uncertain.

4 DISCUSSION AND CONCLUSION

The relatively sudden and effectively unpredictable nature of comets (that is, unpredictable without making detailed observations over long periods of time) are the likely driving force behind their generally negative views not only among Aboriginal Australians, but among most cultures of the world (see Ridpath, 1985). Of the 25 accounts given in this paper, all but two were attributed to negative concepts, namely fear, bad omens, death, malevolent spirits or evil magic. This is consistent with global views of comets (e.g. Ridpath, 1985; Yeomans, 1991). The only non-negative views of comets likened them to smoke (Bobrowsky and Rickman, 2007; Evans, 1992: 196; Roth, 1984: 8; Smyth, 1878: 200), a view shared by some Maori tribes of New Zealand, who called some comets *Auahi-roa* or *Auahi-turoa*, from the words *auahi* meaning 'smoke' and *roa* meaning 'long' (see Best, 1922; Orchiston, 2000) and by the Aztecs of Mesoamerica who called comets *citlalinpopoca*, meaning 'star that smokes'. (Aveni, 1980: 27).

It is unclear whether comets had always been viewed with fear or whether this fear was triggered by a coincidental catastrophic event. Clearly, some accounts establish a perceived link between the appearance of a comet and unrelated malign events, such as drought (e.g. Parker, 1905: 99), death or disease (e.g. Howitt and Stähle, 1881; Spencer and Gillen, 1899: 549; Tindale, n.d.), the presence of a hostile enemy (e.g. Morrill, 1864: 61), or a natural disaster (e.g. Mowaljarlai and Malnic, 1993: 194)—views shared by many cultures of the world (e.g. Andrews, 2004: 111-121; Köhler, 1989: 292).[9] While scientists now know that comets are responsible for a percentage of destructive exploding meteors (see Napier and Asher, 2009) [10] and cosmic impacts (see Bobrowsky and Rickman, 2007), there is no evidence to link comets with disease outbreaks.

Most recorded views of comets indicate that the people who saw them were surprised. Although comets are not seen as frequently as other transient celestial phenomenon (such as meteors), they do make an appearance every few years. Total solar eclipses occur less frequently than comets, but appear as a reoccuring phenomenon in the oral traditions of many Aboriginal communities (e.g. Bates, 1944; Johnson, 1998; Norris and Hamacher, 2009; Warner, 1937). However, there are few accounts of comets in oral traditions (at least to the extent that they can be easily identified as such) and we are curious as to why this is the case.

Are there accounts of comets that we have failed to recognise? Some of these accounts may be found in the form of rock art, such as motifs found in rock engravings of the Sydney region, including the Bulgandry figure near Woy Woy, New South Wales (see Figure 6). If the objects held by Bulgandry represent the Sun and crescent Moon (e.g. Norris, 2008), then we may speculate that his 'hair' actually represents a comet. The hair or headdress of some culture heroes, such as Daramulan (McCarthy, 1989), has a similar appearance to comets and have been described by Elkin (1949: 131) as representing spears, suggesting a possible parallel with the communities from the Northern Territory that associate comets with spears. Numerous other examples of similar motifs are found in rock art of the Sydney region. We are currently looking into the possibility that these engravings represent comets, but any connection at present is simply speculation.

Although nearly all of the descriptions in this paper are second-hand Western accounts of Aboriginal perceptions of comets, these accounts provide an important historical record of Great Comets from an Aboriginal perspective. We conclude that comets are frequently associated with spears due to the comet's appearance resembling a bundle of spears, and that perceptions of comets amongst Aboriginal societies were usually associated with fear, death, omens, malevolent spirits, and evil magic, due to their awe-inspiring and relatively unexpected nature, consistent with many cultures around the world. We attribute their generally negative views to their unpredictable and significant appearance in an otherwise well-ordered cosmos. However, we remain puzzled by the fact that nearly all accounts are from colonial times, with few accounts in the recorded oral tradition and no apparent trace of comets in pre-colonial Aboriginal art.

5 NOTES

1. Comets and meteors are sometimes conflated. Tindale (1983: 376) categorizes comets and fireballs (bright meteors) together, despite them being different phenomena, though he only discusses the former. Some languages use the same word for both phenomena. For example, although the Spanish words for comet and meteor are *cometa* and

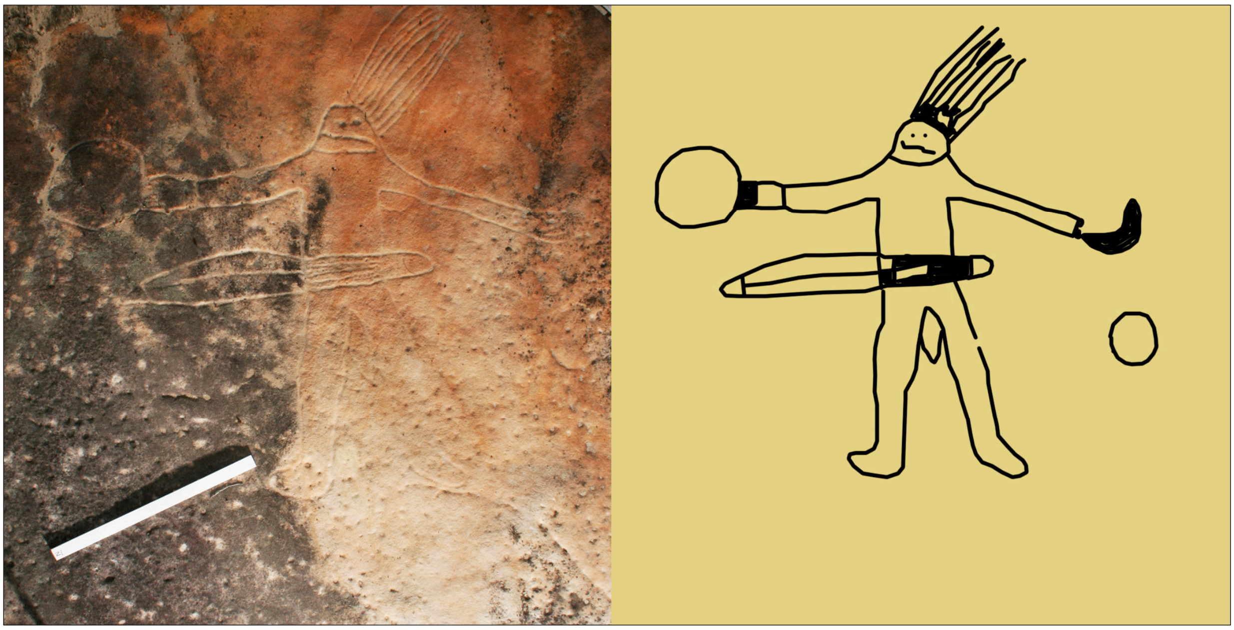

Figure 6: The Bulgandry petroglyph near Woy-Woy, NSW. Left - Image © Ray Norris (2007). Right - Drawing by W.D. Campbell (1893).

and *meteoro*, respectively, the word *cometa* is preferred by rural Mexicans to describe both phenomena (Köhler, 1989: 289). In some Australian Aboriginal languages, the word for comet and meteor are reported to be the same, such as *nilgoolerburda*, in the Bindel language of northern Queensland (Morrill, 1864: 61) and *binnar* in a Western Australian language (Moore, 1842: 126,145). In some cases, the description of one seems to indicate the other.

2. It is unclear if this view was due to the coincidental arrival of a comet before or during a major drought. One candidate is the Great Comet of 1825 (C/1825 N1), which was visible from late August until the end of December 1825. From 1826-1829, a severe drought hit New South Wales, causing Lake George and the Darling River to completely dry up (Shaw, 1984). Another possible candidate (of many) was the Great Southern Comet of 1880 (C/1880 C1), visible in the evening skies in February (Kirkwood, 1880; Morris, 1880), which preceded a significant drought in New South Wales.
3. Additional information regarding the evil of comets can be found in Barker (n.d.) at the Australian Institute for Aboriginal and Torres Strait Islander Studies in Canberra. This item is under restricted access and cannot be copied or quoted (Fredrick, 2008: 105).
4. Johnson (1998:49) mistakenly attributes this account to the Great Comet of 1811 (personal communication).
5. Curr stated that he recalled the event in 1842, although the only bright comet over the years prior to and following 1842 was in 1843.
6. A similar description of medicine men throwing magical stones at a comet to drive it away is given by Hambly (1936: 23).

7 There are no reported Aboriginal accounts of the 1986 return of Comet Halley found in the literature. However, the comet was adopted as the logo for the Arnhem Land Progress Aboriginal Corporation (2009). Comet Halley's return is also featured in Aboriginal artwork and literature, including Brogus Nelson Tjakamurra's painting 'Halley's Comet' (1986) and Sam Watson's novel 'The Kadaitcha Sung' (1990).

8. During the joint University of California-Los Angeles/University of Adelaide Expedition to northwestern Australia (1953-1955), Tindale (2005: 377) explained how researchers used Comet Halley as an indicator of age for more mature Aboriginal informants. While using either Comet Halley or the Great Comet of 1910 would have been sufficient for their study, it is probable that the informant's descriptions were of the January comet.
9. Throughout history, people have tried to make a connection between passing comets and destructive events (e.g. Gadbury, 1665), including disease outbreaks (e.g. Bobrowsky and Rickman, 2007: Chapter 5) and natural disasters (Bryant, 2001). Comet impacts may have caused environmental change in the past, creating poor environmental conditions where starvation and the spread of disease were more rampant. Others (e.g. Wickramasinghe et al., 2004) have speculated that cometary debris contains microbial bacteria, referred to as 'cometary panspermia', which seeded life on Earth and may be responsible for disease epidemics, such as SARS and the Bubonic Plague. This idea has met substantial criticism (see Vaidya, 2009) and is not generally accepted by the scientific community. Scientists, however, more generally accept the hypothesis that amino acids and water were brought to Earth via comets, and later evolved into life.
10. Although the composition of the 1908 Tunguska (Napier and Asher, 2009), 1930 Curuçá (Bailey et al., 1995), and 1935 Guyana (Steel, 1996) bolides has not been well established, they all occurred when the Earth passed through major meteoroid streams, which are produced by the dust tails of passing comets.

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COSTA LOBO AND THE STUDY OF THE SUN IN COIMBRA IN THE FIRST HALF OF THE TWENTIETH CENTURY

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Abstract: In 1925 the first scientific unit devoted to astrophysics was created in Portugal as a section of the Astronomical Observatory of the University of Coimbra. A spectroheliograph, the state-of-the-art instrument for solar physics was installed at the Observatory. This achievement was due to the efforts of Francisco Costa Lobo, Professor of Mathematics in the Faculty of Sciences and astronomer at the Observatory. As President of the Institute of Coimbra (IC), an academy associated with the University which had been founded in 1852, he managed to get Government support and to establish some international scientific contacts which were essential to his goals. Several articles published in *O Instituto*, the journal of the Institute, reveal the chain of events leading up to the beginning of solar studies in Coimbra and the outcome of the first investigations at the new section of the Observatory. Coimbra benefited from the cooperation of the French astronomers Henri Deslandres and Lucien d'Azambuja, both of whom were at the Meudon Observatory in Paris. D'Azambuja visited Coimbra to help install the spectroheliograph. Costa Lobo's son, Gumersindo Costa Lobo, also played a pivotal role in this endeavor. Together they gave birth to the cooperation between Meudon and Coimbra, which persists today and is one of the oldest scientific exchanges between the two countries.

Keywords: astrophysics, solar phenomena, Francisco Costa Lobo, Gumersindo Costa Lobo, Astronomical Observatory of the University of Coimbra, Institute of Coimbra

1 INTRODUCTION

On 25 July 1914, Francisco Costa Lobo (Figure 1), the first astronomer at the Astronomical Observatory of the University of Coimbra (henceforth UC) in Portugal, arrived in Paris accompanied by Captain Carlos Nogueira Ferrão (1871–1938) and the Captain's son, Álvaro Ferrão, carrying the optical components of all instruments they would need to observe the total solar eclipse of 21 August. Following an invitation from Nikolay Donitch (1874–1956), an astronomer at the Imperial Academy of St. Petersburg, Russia, they wanted to travel to Theodosia in the Crimean Peninsula, which was the most suitable place to observe this particular eclipse. The remaining instruments had already been shipped on 10 July and, in the short time they spent in Paris, Costa Lobo met Henri Deslandres, Director of the Meudon Observatory who warned him of the serious difficulties he would face in getting to Russia given the prevailing political situation. On 31 July Costa Lobo reached Berlin, and found a city which was preparing for war. That same night Germany issued an ultimatum to Russia, which ignited the First World War. At 6 a.m. the following day, Costa Lobo met Sidónio Pais, the Portuguese Ambassador in Berlin and his former colleague in the Faculty of Mathematics at the UC, in order to try to obtain transportation to Theodosia, but this was to prove impossible. He was eventually persuaded to give up, and he and his entourage took the last train to Basel, Switzerland. Over the next five days Costa Lobo kept hoping that he would find some sort of transportation which would allow him to fulfil his long-prepared mission. His aim was finding answers to two questions that had occurred to him while observing the solar eclipse of 17 April 1912. One question concerned the Moon's polar flattening and the other the refracting effect in the Moon's valleys. Unfortunately he was obliged to return to Portugal, and the only alternative left was to observe the partial solar eclipse that would be visible from Coimbra, using instruments at the Observatory. Meanwhile, the instruments that had been sent to Theodosia were only returned to Portugal after the war had ended (Costa Lobo, 1914).

Figure 1: Francisco Miranda da Costa Lobo, 1865–1945 (after Amorim, 1955: frontispiece)

This episode reveals Costa Lobo's determination when pursuing scientific knowledge. He had graduated from the UC in mathematics and philosophy in 1884, obtaining a high grade, and was immediately invited by both faculties to become a teacher. He chose the Faculty of Mathematics, where he completed his Ph.D. on 27 July of that same year with a thesis on the "Resolution of Undetermined Equations". On 7 January 1885 the by-then 21 year old Costa Lobo became a substitute Professor of Integral and Differential Calculus and in 1892-1893 he was appointed a full Professor of Astronomy.

Francisco Costa Lobo participated actively in Portuguese political life. In 1889 he was appointed substitute Governor of the Coimbra District. As a member of the Progressist Party he was elected Deputy to the National Parliament on 11 March 1905 by the same District, and was re-elected on 13 September 1906. Costa Lobo returned to the Parliament in 1908, after the dictatorial Government of João Franco ended with the regicide of King Carlos. With the proclamation of the Republic on 5 October 1910, politics lost its initial appeal and although he became a member of the new Monarchic Party his political involvement was considerably reduced, and was largely replaced by his increased academic activity.

As a researcher, Costa Lobo specialized in the study of the Sun. On 18 November 1904 he became First Astronomer at the Coimbra Astronomical Observatory (Reis, 1955: 31). His interest in solar physics began in 1907 when he went on a scientific excursion to some of Europe's important astronomical observatories, and meet Henri Deslandres (1853–1948), Director of the Meudon Observatory. Deslandres convinced him that the Coimbra Observatory needed to acquire a spectroheliograph, that recently-invented instrument which was revolutionizing the study of the Sun.

On 17 April 1912 Costa Lobo arranged with his students and with a Captain Ferrão who was an excellent photographer, to observe a solar eclipse from Ovar, which was close to Porto. They succeeded in registering the most important phases of this eclipse with a small cinematographic apparatus (see Bonifácio et al, 2010),[1] and a report that he sent to the Academy of Sciences in Paris was published on 28 May in the *Comptes Rendus* (Costa Lobo, F., 1912). Gumersindo Sarmento da Costa Lobo (1896–1952), the son of Francisco Costa Lobo, also worked in the field of solar physics, and participated in some of the investigations carried out by his father in Coimbra.

The history of Coimbra's Astronomical Observatory dates back to 1772 when the Marquis of Pombal reformed the old University. The new statutes demanded that an observatory be installed so that the University could offer practical lessons of astronomy and longitude determination. At first an ambitious building located over the ruins of Coimbra's medieval castle was projected, but work was suspended in September 1775 due to problems with the location and a shortage of funding. In 1799 a new and less ambitious building (Figure 2), located in the courtyard of the University and quite close to the beautiful Baroque University Library, was inaugurated (Bandeira, 1942; Pinto, 1893).

In this paper we report, on the basis of several articles published in *O Instituto* (*The Institute*), how the first spectroheliograph was installed in Portugal and how it allowed not only the beginning of solar physics in this country but also cooperation with France—which continues to this day. We also analyse the scientific research carried out in Coimbra, based on several articles published in the same journal, and the involvement of the academic society Instituto de Coimbra, its publisher, in the creation of the solar physics section in Coimbra. This was mainly due to

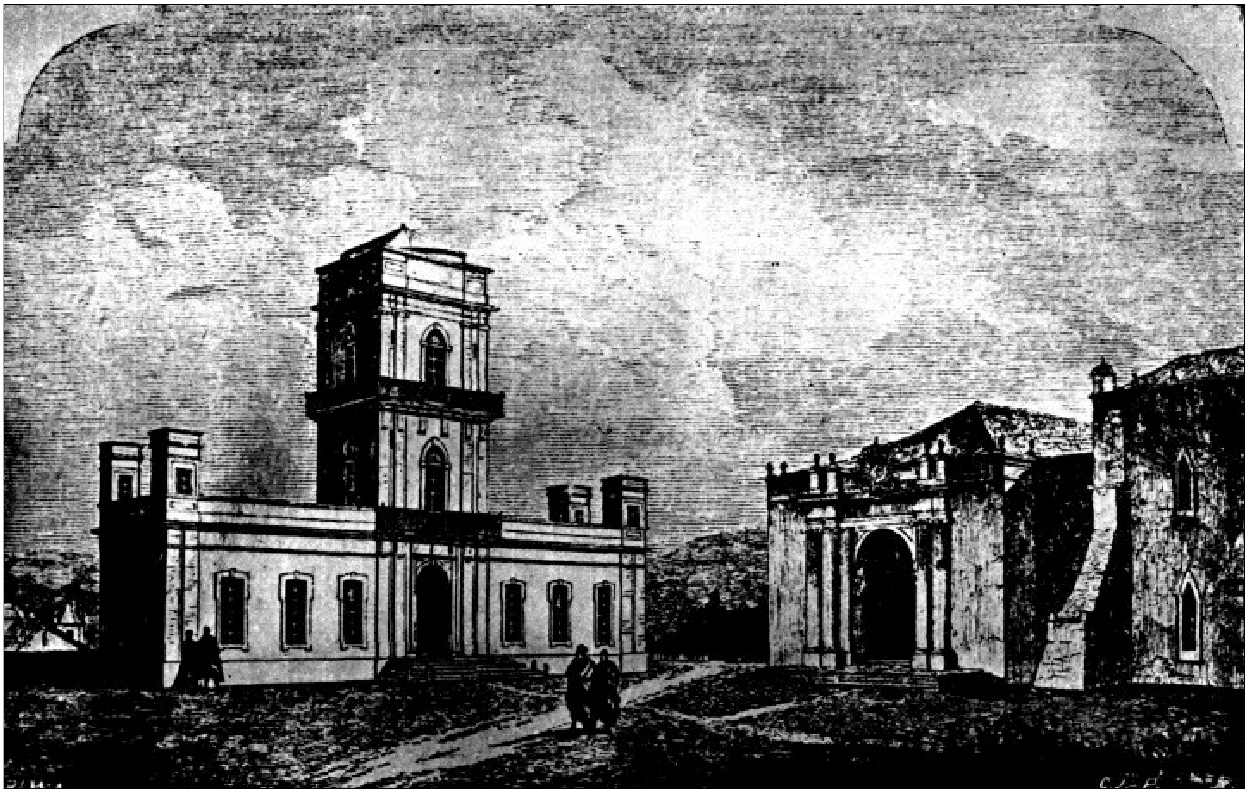


Figure 2: The main building of the Astronomical Observatory of the University of Coimbra. The house in the courtyard of the University was demolished in 1951 during the city renewal ordered by the Salazar regime (after Bandeira, 1942: 541).

its President, Costa Lobo. Among the people involved in the project, we devote special attention to Costa Lobo's son and to Lucien D'Azambuja. Their articles and conferences on solar physics were an outcome, at least in part, of the observations performed in Coimbra and the cooperation between the observatories at Coimbra and Meudon, following the general recommendation on international cooperation made by George Ellery Hale (1868–1938).

2 COSTA LOBO AND THE INSTITUTE OF COIMBRA

The Institute of Coimbra (IC) was an academic society founded in 1852 to promote sciences, literature and arts, and to develop Portuguese culture (Leonardo et al, 2009a). It was divided into three classes: the moral and social sciences, the physical and mathematical sciences, and literature and fine arts. Besides participating in the general assemblies, the IC fellows were supposed to produce works in their fields of expertise and to attend conferences organized by their class. Initiated by a group of professors, this academy had its most visible part in the journal *O Instituto*, which was published for almost one and a half centuries. When it closed, after 141 volumes, it was the scientific and literary journal with the greatest longevity in Portugal. Of its articles, 18% were devoted to science, and, within them, almost 10% were on astronomy and astrophysics (Leonardo et al, 2009b).[2] Reading these articles, mostly authored by members of the IC, one can learn a lot about science in Portugal in the second half of the nineteenth century and the beginning of the twentieth. The IC, which had a library and a reading room on its premises, regularly organized congresses and conferences. Its influence may be measured by the list of its associates, including some of the most renowned Portuguese scholars in various fields, and by the list of distinguished foreign correspondents.

Costa Lobo was elected President of the IC in 1913, and held this position until his death in 1945. This period was also one of the most productive in the history of the Institute: the congresses and conferences organized or attended by the IC members were numerous. We only mention the Congresses of the Spanish and Portuguese Associations for the Development of Science (Porto, 1921; Coimbra, 1925, and Lisbon, 1932), the Congresses of the International Astronomical Union (Cambridge, England, 1925, Leiden, 1928, and Cambridge, United States, 1932) and the General Assemblies of the Geodesic and Geophysics International Union (Stockholm, 1928, and Lisbon, 1933). The organization of the 5th General Assembly of the Geodesics and Geophysics International Union, held in Lisbon from 17 to 25 September 1933, benefited from the personal engagement of Costa Lobo.

He also managed to include many international astronomers as corresponding members of the Institute, including the following British colleagues: Frank Dyson (Director of the Royal Observatory Greenwich and Astronomer Royal), Harold Spencer Jones (Chief Assistant at the Royal Observatory and later Astronomer Royal), John Henry Reynolds (President of the Royal Astronomical Society), Arthur Stanley Eddington (a distinguished Professor at Cambridge) and Frederick J.M. Stratton (Director of the Solar Physics Observatory at Cambridge) who wrote Costa Lobo's obituary in the *Monthly Notices of the Royal Astronomical Society of London* (Stratton, 1946). French corresponding members were Henri Deslandres, Lucien D'Azambuja and Armand Lambert, from Paris and Meudon Observatories. Reviewing the minutes of the General Assemblies of the IC from 1924 to 1939 we find at least 16 European astronomers and directors of observatories who became corresponding and/or honorary members of the IC. Beside those already mentioned above, the list includes scientists from the French observatories of Lyon (J. Mascart), Marseille (I. Bosler) and Strasbourg (Ernest Esclangon);, the Canadian Observatory in Ottawa (F. Henroteau);, the Italian Observatory at Arcetri (Antonio Abetti), the Greek Observatory of Athens (M. D. Enginitis), the Spanish Observatory in Madrid (Enrique Gastardi); and the Polish Observatory at the University of Warsaw (J. Kanawsi). Many articles on astronomy were published in *O Instituto* by Costa Lobo himself and by some of the corresponding members (e.g. see Dyson, 1932; Stratton, 1940). As a whole they portray the evolution of this discipline in Portugal, and in particular the work done at the UC Astronomical Observatory with the creation and initial activity of the solar physics unit and the study of the Sun during the early twentieth century.

The IC and the Astronomical Observatory of the UC always had a connection, as shown by the succession of articles in *O Instituto* emanating from the Observatory. Of the almost 70 articles about astronomy that were published in *O Instituto*, many reported the results of observations made at the Observatory. Examples include the observations of eclipses and comets by the astronomer Rodrigo Ribeiro de Sousa Pinto from 1858 to 1862 and determinations of the longitude and latitude of the Observatory. Costa Lobo became Director of the Observatory on 23 September 1922 while continuing to serve as IC President.

3. THE STUDY OF THE SUN IN THE NINETEENTH CENTURY

The historical development in the eighteenth and nineteenth centuries of so-called 'solar-terrestrial physics' was strongly influenced by numerous European scientists (Schröder, 1997). The systematic observation of solar eclipses and planetary transits gave rise to the discovery of new structures on the solar surface. One example was the solar corona, that whitish halo that encircles the Sun during a total solar eclipse. On 8 July 1842, a total eclipse was visible in southern and central Europe, and many observers reported seeing rose-colored prominences extending from the solar limb (e.g. see the photo in Becker, 2010: 115). In 1852, observations confirmed that these prominences emerged from a reddish layer with the aspect of a sierra, which was named the chromosphere. The Portuguese astronomer Professor Matias de Carvalho de Vasconcelos (1832–1910), assisted Belgian's Adolphe Quetelet (1796–1874) in observing the solar eclipse of 15 March 1858 at the Observatory of Brussels. Carvalho was on a scientific trip to several European observatories and universities, and he delayed his departure from Brussels after being invited by Quetelet to participate in the eclipse observation. He took responsibility for the magnetic measurements, which he described in a report to the Faculty of Philosophy at

UC which was published in *O Instituto* in that same year (see Vasconcelos, 1858).

An important new approach to solar studies was spectral analysis, a technique developed in Heidelberg in 1859 by two Germans, the physicist Gustav Kirchhoff (1824–1887) and the chemist Robert Bunsen (1811–1899). In 1863, an article titled "The Sun, under the recent discoveries of Kirchhoff and Bunsen" (our English translation) by the French historian and engineer Auguste Laugel (1830–1914) was published in *O Instituto*. The discovery of Fraunhofer lines in the solar spectrum provided an excellent means to investigate the chemical composition of the Sun (and stars) (see Hearnshaw, 2010). Spectroscopic analysis laid the foundations of solar physics, and the explanation of the Fraunhofer lines confirmed the existence of a solar atmosphere enveloping the photosphere.

The impact of sunspots and other solar events on the Earth generated a strong interest in the study of the Sun, especially since they could cause magnetic disturbances to telegraphic transmissions, that new technology that was flourishing worldwide in the second half of the nineteenth century (see Leonardo et al., 2009c). One of these events, on 29 August 1859, became famous for its effects on international telegraphic communications and for the simultaneous observation of a white light solar flare by Richard Carrington (1826–1875) (Clark, 2007a; 2007b). This confirmed the importance of acquiring tools to predict their occurrence or, at least, to explain their origin.

In the second half of the nineteenth century many scientists became interested in solar eclipses as a consequence of the availability of new techniques and instruments. Whenever a solar eclipse was predicted, many groups vied for the best spots in the world to perform their observations. Portuguese astronomers also had this interest. Even though it was only partial in Portugal, the eclipse observed in Belgium by Matias de Carvalho in 1858 was monitored in the two national observatories, and the First Astronomer at the Observatory of Coimbra (who would become Director in 1866), Rodrigo Ribeiro de Sousa Pinto (1811–1891), published his measurements in *O Instituto* (see Pinto, 1858).

Although the determination of exact longitudes was an important by-product of these eclipse observations, the interest of the new solar gazers was the possibility of photographing the chromosphere and the solar corona, which were only visible on those rare occasions. The French physicists Louis Fizeau (1819–1896) and Léon Foucault (1819–1868) took the first successful photograph of the Sun in 1845. At the Königsberg Observatory in Prussia, in 1851, Berkowski obtained the first useful Daguerreotype of a solar eclipse (De Vaucouleurs, 1961). Then the British astronomer and chemist Warren De la Rue (1815–1889) introduced the wet collodion process and devised a method to avoid the sensitive collodion plates being overexposed by the Sun's glare. This technique showed a record number of visible sunspots and was used to photograph a solar eclipse at Rivabellosa, Basque Country (Spain) on 18 July 1860 (see Hufbauer, 1991; Costa Lobo, 1933b). Using a photoheliograph from the Observatory at Kew, De la Rue managed to register the successive appearance and disappearance of the prominences, on both sides of the lunar disc, an achievement that proved conclusively that they belonged to the Sun (Hingley, 2001).

An official Portuguese expedition comprising Sousa Pinto and Jacinto António de Sousa (1818–1880) from Coimbra, João de Brito Capello (1830–1901) from the Infante D. Luiz Meteorological Observatory in Lisbon, and a technician, was sent to Spain to observe this same July 1860 eclipse (Pinto, 1861; cf. Bonifácio et al. 2007a). The outcome of the mission was restricted to further calculations of longitude differences, due to the inefficiency of the observing instruments hastily gathered from the Observatories of Coimbra and Lisbon, which proved incapable of performing their required photographic or spectroscopic functions. In August and September 1860, following this eclipse mission, de Sousa[3] was commissioned to visit the most important European scientific institutions, especially those having meteorological and magnetic observatories (Malaquias, et al., 2005). He visited the Observatory at Kew on 26 August 1860, and in his report he referred to the Dallmeyer Photoheliograph, presumably the one used by De la Rue, but because of its high cost and the prospect of further improvements occurring in this field, he did not recommend that Portugal should purchase one. He added:

> The observation of sunspots, in relation to the discussed question [determining a relationship between their position, magnitude and number and variations in the elements of the Earth's magnetic field], can meanwhile be performed by an ordinary telescope … (Sousa, 1861: 149; our translation).

In 1871 the Coimbra Observatory bought a photoheliograph made in Germany by Repsold & Söhne and Steinheil (Bandeira, 1942: 557), and in this same year a daily solar photography research program started at the Infante D. Luiz Observatory in Lisbon in which Capello was actively engaged. In the process, he developed important contacts with De la Rue at Kew, the Angelo Secchi (1818–1878), in Rome and Pierre Jules Janssen (1824–1907) at Meudon Observatory. This programme ended in 1880, after several years with no significant progress (Bonifácio, et al., 2007b).

By then it was imperative to find a way to study the solar atmosphere on a regular basis, outside the brief periods allowed by total solar eclipses, but the intensity of the light emitted by the Sun's photosphere made this difficult. Janssen solved this problem during his observation of the 18 August 1868 solar eclipse in India. Using spectroscopic methods, he observed that the vapours of the prominences emitted a characteristic spectrum with bright emission lines. These lines included those of hydrogen and a line from a new element, which was named helium and assumed at the time to exist only on the Sun. When, after the eclipse, he directed his spectroscope to the same prominence on the Sun's limb, the bright lines were still visible. Isolating one of them, by means of a second slit, and slowly moving the first slit to the point where the light fell upon it, he managed to draw the outline of the prominence (see Launay, 2008). By a strange coincidence, the very same idea occurred at the same time to the Englishman Joseph Norman Lockyer (1836–1920) (see Lockyer, 1873-79).

Janssen laid the foundations of the first astrophysical observatory in the world, at Meudon, on the outskirts of Paris, and initially research there was mainly devoted to the study of the Sun (Launay, 2008). Based on the ideas of Janssen and Lockyer, Henri Deslandres, Janssen's successor at Meudon, and George Ellery Hale in the U.S.A., independently developed a new instrument, the spectroheliograph, which is still used today for studying the solar atmosphere. Hale was the first person to build a usable instrument, in 1890-1891, based on an idea that occurred to him in 1889 and was the theme of his senior thesis at the Massachusetts Institute of Technology, entitled "The Photography of Solar Prominences" (Glass, 2006: 161-163). His goal was to obtain a monochromatic photograph of the Sun's chromosphere. The first challenge was to get a device capable of projecting a steady image of the Sun, obtained by a coelostat[4] comprising two flat mirrors (Figure 3). One of the mirrors could track the Sun and direct a fixed image on the second mirror, which was then refracted by an objective. The light was then projected through a first slit into a spectroscope, with a second slit used as a monochromator to isolate a single wavelength. In order to record a complete monochromatic image of the Sun on a photographic plate the synchronous motion of several parts of the apparatus was necessary. The alternatives were to maintain a fixed monochromator and move the solar image in the first slit at the same rate as the photographic plate or move only the monochromator and fix all the constituents, reproducing the equivalent motions by optical or mechanical devices (Kuiper, 1953: 617).

4 SOLAR PHYSICS AT THE BEGINNING OFTHE TWENTIETH CENTURY

In August 1869, the Americans Charles Young (1834–1908) and William Harkness (1837–1933), working at the U.S. Naval Observatory, detected a green emission line in the coronal spectrum at 5303 Å, very close to a known line of iron (Hufbauer, 1991: 62). The origin of this line was a complete mystery, and several scientists proposed that it belonged to a new element, which they called 'coronium'. When news of this new line reached Portugal in July 1870 António dos Santos Viegas (1835–1914), a Professor in the Faculty of Philosophy of the UC, went to Rome in order to study the spectral analysis of the Sun with two of Italy's leading specialists: Secchi and Lorenzo Respighi (1824–1889). Viegas' plan was to invite the international community to observe the total solar eclipse which would be visible from Portugal—weather permitting—on 22 December 1870 (Bonifácio et al., 2007a).

However, Young preferred to observe from Jerez de la Frontera in Spain, and was clever enough to make a another discovery. Besides the dark lines of the ordinary solar spectrum, he also noted the appearance of bright lines, as the slit of the spectroscope moved along the Sun's limb (Frost, 1910). This was called the 'flash spectrum' since it only lasted a few seconds. These lines, which originated from a lower layer of the chromosphere, were identical to those from the prominences. The absorption lines were dark, in the midst of the solar spectra, in spite of being bright in the flash spectra.

Hydrogen, helium and calcium were identified in the spectrum of the chromosphere, and by isolating the light from one of these lines an image of the solar chromosphere could be taken. The monochromatic images of the Sun, obtained with the spectroheliograph, differed from the selected line, a phenomenon that suggested that they were being emitted at different altitudes in the chromosphere. For the calcium spectrum, the H and K lines were used, while for hydrogen the Hα (red) line was used. The H and K lines provided more information, since getting three photos, one using the central region of the streak (K_3), another the intermediate region (K_2) and the last one using the edge portion (K_1), provided three distinct images, each relating to a specific height.

As the photographic data on the Sun's chromosphere were accumulating, new findings were made. The most important was that some spectral lines coming from sunspots were split, as occurs in a magnetic field. Hale (1908) confirmed this Zeeman Splitting was due to magnetic fields by showing that many doublets were polarised in opposite directions. The polarisation of the sunspots was related to the direction of their vortices (Hufbauer, 1991).

The first decade of the twentieth century, when a new breed of scientists made a deep commitment to understanding the Sun, was a turning point in solar science. Knowledge of the Sun surpassed the positional estimates and measurements of distance, size, mass, rotation rate and direction of motion and moved on to their physical and chemical constitution. It was established that the Sun was composed of terrestrial elements, that the temperature of the photosphere was about 6000 K, and that sunspots followed an eleven-year cycle and were associated with strong magnetic fields (ibid.).

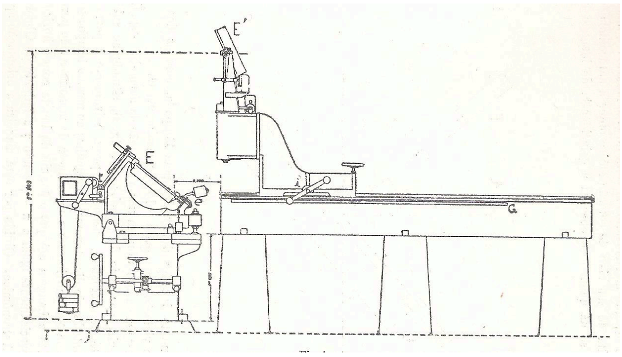


Figure 3: Schematic representation of the Coimbra coelostat (after Costa Lobo, 1933b: 453).

The *O Instituto* published a lecture given at the Valladolid Congress of 1915 by Victoriano Fernández Ascarza, an astronomer of the Madrid Observatory. In the first half of the lecture, which was devoted to solar problems, Ascarza (1916) reported on recent major advances in solar physics and problems that were still pending. Reference was made to the spectroheliograph, since Spain already had two of these instruments, the first having been installed at the Ebro Observatory in Tortosa, Catalonia, in 1908, and the second at the Madrid Observatory, in 1911.[5]

By the second decade of the twentieth century, solar physics was an internationally well-established field, being studied by well-respected investigators such as Deslandres and Hale. Many were the solar phenomena that needed further investigation, like the sunspots, the faculae, the prominences and the filaments. In his article, Ascarza (1916: 31) renewed Hale's appeal for an international cooperative effort to investigate the sunspots. This cooperation should be based on the uniformity of the observational methods and its world-wide articulation to guarantee the continuity of the information gathered long-term. Costa Lobo who was at Ascarza's lecture, eagerly answered this appeal and started procedures that would culminate in the creation of a centre devoted to solar physics at the UC.

5 POLITICAL AND SCIENTIFIC CONDITIONS FOR THE CREATION OF SOLAR PHYSICS IN PORTUGAL

Costa Lobo's accomplishment was rare in Portugal, due to the precarious social and economic conditions of the country at that time. The establishment in 1910 of the Republic, which inherited not only a poor continental country but also a decadent empire, gave way to political instabilities that hindered the needed reforms and generated social turbulence in an illiterate society hoping for the implementation of the promises of the Republican revolution. The First World War aggravated the situation, since the participation of a Portuguese expeditionary corps in combat in France and Belgium led to an immense number of casualties. This situation hindered any investments that might not generate an immediate financial return.

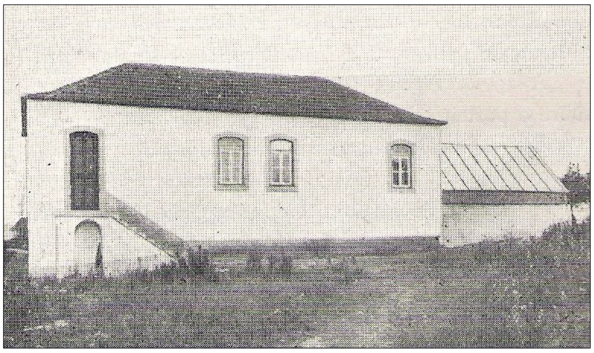


Figure 4: The pavilion where the spectroheliograph was installed (after Bandeira, 1942: 548).

In spite of this bleak scenario, Costa Lobo relied on his good political connections. Despite his political affiliation with the Monarchist Party, he only re-entered active politics when his friend and former Faculty colleague, Sidónio Pais (1872–1918), became President of the Republic in 1918, after leading the revolution on 5 December 1917 that deposed the Government of Afonso Costa (1831–1937) and removed from the Presidency Bernardino Machado (1851–1944), another Coimbra professor.[6] Costa Lobo was again elected Deputy to the Assembly of the Republic and became Chairman of a Commission for Education Reform (Amorim, 1955). The assassination of Sidónio Pais on 14 December 1918, less than one year after his inauguration, was certainly a major blow for Costa Lobo, who called it a "… great loss for the nation …" when he addressed the IC General Assembly of 26 September 1918 (*O Instituto,* 66: 1). At least, it was enough to make him return to Coimbra.

Interest in this new field of solar physics already existed in Coimbra, as a study of Coimbra's climate between 1866 and 1916, published in 1922, shows. Its author was Anselmo Ferraz de Carvalho (1878–1955), who was then Director of the Magnetic and Meteorological Observatory of the UC and who succeeded Costa Lobo in 1945. The study provided a statistical treatment of all observations of temperature, humidity, rainfall, etc. made at the Magnetic and Meteorological Observatory during the previous fifty years. One chapter was devoted to a comparison of air temperature and other weather phenomena with the number of sunspots and solar irradiance. Based on sunspot numbers collected by Alfred Wolfer and published in the *Monthly Weather Review* before 1914, Carvalho was not able to confirm the idea that an increase in the number of sunspots should correlate with a decrease in temperature. Indeed there was no clear correlation between temperature variations and the number of sunspots. There was also no clear relation between sunspots and rainfall, although low rainfall was generally associated with a maximum of spots (Carvalho, 1922: 41-46).

On the scientific side, after attending the Congress of Valladolid in 1915, representing the IC, and having also been present at the Congress of Granada in 1911 (which was promoted by the Spanish Association for the Advancement of Science), Costa Lobo laid the foundation for the establishment of the Portuguese Association for the Progress of Science, and he served as its President for a number of years. The creation and intensification of scientific relations between Portugal and Spain was one of his goals.[7] As mentioned, Ascarza's paper in *O Instituto* motivated Portuguese scientists to follow the Spanish example. It was no coincidence that the chosen area was the study of the Sun, since Spain had already responded to Hale's appeal by installing two spectroheliographs, and since the two Iberian countries are the European countries with the largest solar exposure. In 1925, simultaneously with the installation of a spectroheliograph in Coimbra, the second Joint Congress of the Portuguese and Spanish Associations for the Advancement of Sciences[8] took place in that city with the collaboration of the IC. The inauguration speech by Costa Lobo, titled "Astronomy in Portugal in the Present Time" (our English translation), was published in *O Instituto* (Costa Lobo, 1925a) and was certainly a response to Ascarza's earlier lecture.

Costa Lobo also represented Portugal in the First and Second Congresses of the International Mathematical Union, which took place in Strasbourg (France) in 1920 and in Toronto (Canada) in 1924. Costa Lobo was a well-known personality in the international scientific community, his contacts being numerous and notable. That was a clear advantage not only for his astronomical projects but also for the IC and the UC.

6 INSTALLATION OF THE SPECTROHELIOGRAPH IN COIMBRA

In 1912 Costa Lobo started to implement his plan to install a spectroheliograph in his Observatory. The instrument, similar to that in place at Meudon Observatory, was constructed following Deslandres' specifications. Due to the lack of a suitable place for this apparatus in the Observatory building, another site was selected, at Cumeada (Figure 4), next to the old Meteorological and Magnetic Observatory which had been founded in 1864.

As Costa Lobo's good friend, Deslandres had offered his support and assistance in 1907 and turned out to be a key figure in the whole process (he even provided some pieces of the instrument). There were many problems associated with this enterprise, the most notorious being the budget, in view of the cost of the imported equipment and the technical expertise necessary. In the words of Gumersindo Costa Lobo (1940: 10-11; our translation):

> The accomplishment of this enterprise was full of difficulties, if not impossible … the necessary equipment is extremely expensive, its assembly is considered very delicate by those who are authorities in this area, and the problem had never before been approached in Portugal. In short, the problem of erecting what we might consider a major physics laboratory for the new study of the Sun had to be solved in such a way that investigations could be performed at the same level of perfection as those achieved abroad and efficiently managed at the beginning of this area of research in Portugal, while allowing for our effective international collaboration in this work. (Costa Lobo, G., 1940: 10-11).

The various components of the spectroheliograph were ordered from instrument-makers in several countries. With the outbreak of the First World War these actions had to be suspended, but as soon as peace was established Francisco Costa Lobo re-activated the previous settlements and also resolved some problems associated with price increases.

Francisco's son, Gumersindo Costa Lobo, played an essential role in the installation of the spectroheliograph. Being aware of the novelty of this new technology and the reluctance of Portuguese technicians to handle it, he decided to specialise in the subject himself, so in 1923, at the age of 27, he went to Meudon where he was trained under Deslandres and his assistant, Lucien d'Azambuja (1884–1970). On his return to Portugal, later that year, "… all the services of the installation and scientific investigation of the [new] section of Astrophysics at the Astronomical Observatory were entrusted to him." (Amorim, 1955: 26).

The construction of the spectroheliograph pavilion started immediately after Gumersindo Costa Lobo's return from Paris. Deslandres sent d'Azambuja (Figure 5) to Coimbra on an official mission at the expense of the French government to provide the instruments with the required precision. D'Azambuja had Portuguese ancestry in that he was the grandson of Diego, a Portuguese immigrant from Azambuja, a small city close to Lisbon (Mouradian and Garcia, 2007: 7). He went on to become one of the most eminent astronomers in France, succeeding Deslandres as Director of the Meudon Observatory. His career at this Observatory started when he was only 15 years old, but he received a doctorate in 1930. Throughout his career his wife, Marguerite Roumens d'Azambuja (1898–1985), who shared his interest in the Sun, was his scientific assistant (Martres, 1998).

In "Les Nouveaux Instruments Spectrographiques de L'Observatoire Astronomique de l'Université de Coimbra", published in *O Instituto* in 1926, which followed his communication titled "Astronomy in Portugal in the Present Time" (1925b; our English translation), Costa Lobo senior described the new instrument. It was identical to that at Meudon, but contained new improvements that, in Costa Lobo's words, made it "… the most remarkable instrument for the study of the solar atmosphere installed in Europe …" (Costa Lobo, F., 1926: 129; our translation).

The spectroheliograph had a coelostat, made in France by the engineer Georges Prin, which was composed of two flat mirrors, each with a diameter of 40-cm, and placed in an external pavilion with a removable ceiling (Figure 6). The lower mirror facing the Sun rotated by means of a precise clock-drive which completed a full rotation in 48 hours. This generated a fixed image of the Sun that was projected through a small window to an objective, with an aperture of 25-cm and a focal length of 4-m. Constructed by the optician Marie Amédée Jobin and specially adapted for producing images using the K_3 calcium line, it was located in a isolated room. The objective rested on top of a movable platform connected to a speed transformer propelled by a Baudot motor.

Figure 5: Lucien d'Azambuja (left) and Henri Deslandres (right) in 1903 (after Mouradian and Garcia, 2007: 7).

The light beam was then projected through a first slit and a collimator lens, mounted in a linear support, and ended up in the dispersive system composed of three flint prisms with an angle of 60º and 15-cm on the edge. The dispersed light was then projected into a second slit, which selected the spectral line, just before a photographic plate. These components rested in a movable platform similar to that of the objective and connected to a second Baudot motor. The motions of both motors, made in Jules Carpentier's workshop, were synchronised (Figure 7).[9] Some of these pieces were manufactured locally (Costa Lobo, 1926: 129-134).

On 12 April 1925 the first spectroheliogram of the Sun in the K_3 line was obtained. The spectroheliograph has been operational ever since.

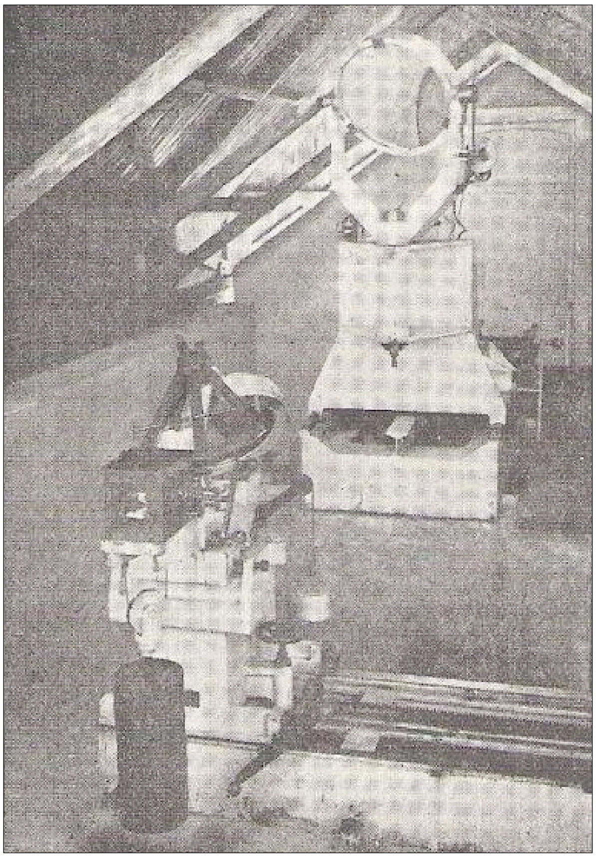


Figure 6: The ceolostat of Coimbra's spectroheliograph (after Costa Lobo, 1933b: 145).

7 SUBSEQUENT SCIENTIFIC ACTIVITY

As a part of an international scientific effort, the requisites were very demanding. One of the first resolutions by Costa Lobo was to publish all the results in a new publication titled *Anais do Observatório Astronómico da Universidade de Coimbra – Fenómenos Solares* (in English: *Annals of the Astronomical Observatory of the University of Coimbra – Solar Phenomena*). His expressed goal of this new publication, as outlined in his Introduction in the first volume, was to "Record the investigations performed and the results obtained in several branches of astronomical science at the Astronomical Observatory of the University of Coimbra." (Costa Lobo, 1929: 5). Notwithstanding its stated purpose, the *Anais* focused solely on solar physics.

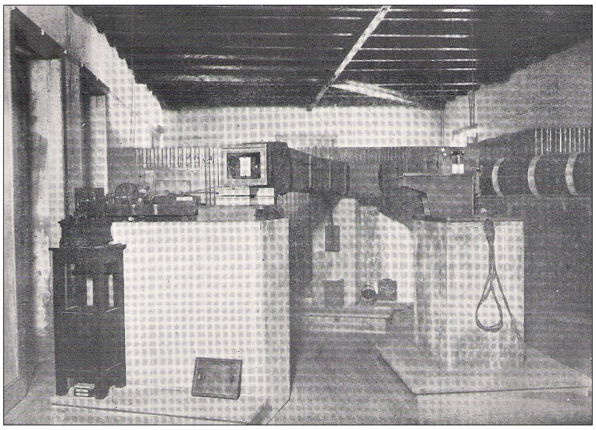


Figure 7: The spectroheliograph room (after Costa Lobo, 1933b: 146).

Each volume of the *Anais*, which was divided by the months of the year, contained charts of the major chromospheric phenomena, like facular regions, sunspots, prominences and filaments, and reported on their daily numbers and relative areas. The local spectroheliograms were also included. In the last pages, the annual data were depicted graphically.

In the first phase of the observational program, when meteorological conditions allowed, spectroheliograms were obtained using the calcium II K_3 line, but, in 1926, at least two images were being taken daily, one with the K_3 line and the other with the K_1 line. In this way it was possible to compare the aspect of two different altitudes of the solar chromosphere. To use the Hα line of hydrogen some adjustments and further equipment were necessary, like a diffraction grating, which was ordered from Adams Hilger & Company and arrived in 1932 (Costa Lobo, 1940). These images were sent to Meudon, which worked as an international hub, compiling all information that arrived from cooperating observatories worldwide. Since March 1919, d'Azambuja had been responsible for preparing continuous maps of solar phenomena (filaments, faculae and spots) that he reported in "Cartes synoptiques de la chromosphère et catalogue des filaments de la couche supérieur" (Coffey and Hanchett, 1998), whose publication in the *Annales de l'Observatoire de Paris*, *Section de Meudon* started in 1928 (Martres, 1998). He used images from other observatories (e.g. Mount Wilson in the USA, Kodaikanal in India, and Coimbra in Portugal) to fill in the missing days (Kiepenheuer, 1953: 402). Since the Meudon and Coimbra instruments were identical, the spectroheliograms sent from Coimbra did not need any adjustments.

The publication of the *Anais* … was announced at the Third General Assembly of the International Astronomical Union, held in 1928 in Leiden (Netherlands), where Costa Lobo (1928) presented a paper on "Several results obtained from spectroheliograph observations made in the years 1926 and 1927" (our English translation of the original French title). In his paper Costa Lobo used a graphical representation that he had invented to depict the image of the solar chromosphere (see Figures 8 and 9). By dividing the initial photographic image into 36 equal-angle sectors and displaying them in a radial manner he could strongly reduce the image distortion. Deslandres also mentioned the first volume of the *Anais* … in a communication to the Academy of Sciences of Paris, which was subsequently reproduced in an article that was published in the *Comptes Rendus*:

> This first volume assembles the observations from the year 1929. It reproduces the photographic samples of the solar upper layer and adds a very original depiction that, by a new projection method, presents all the details of the Sun, keeping the surfaces. Finally, the coordinates of all the interesting points are given in specific tables. This publication brings great credit to the Coimbra Observatory and to its director. (Deslandres, 1932: 2265; our translation).

Through the examination of the daily spectroheliograms, the number, position and dimension of the principal solar structures—sunspots, faculae, filaments and prominences—were measured. All parameters of solar activity were classified, and its evolution was carefully documented.

Costa Lobo pointed out that the photospheric facular regions, bright areas in the solar surface with a wider extension than the sunspots, were more important than the sunspots. By 1929, quite a variety of explanations of the sunspots had been proposed, so Costa Lobo summarized them in his Introduction to Volume I of the *Anais* …. Some authors considered them the result of a local and irregular cooling of the solar surface or of falling vapours producing cavities in the photosphere, while others explained them with convection currents, regions of high pressure, condensations of the photosphere, irregularities of gaseous matter, or special solar atmospheric movements. None of these theories related the formation of sunspots to faculae, so Costa Lobo proposed that sunspots were a consequence of faculae and had the same nature, in spite of their different dispositions. The formation of all sunspots within a facular regions, their disappearance before the faculae, and the fact that they were more numerous in areas of maximal facular activity, supported this theory. This had consequences in the influence of solar activity on terrestrial phenomena, since the effect of faculae was contrary to that of sunspots. The contradictory results between the frequency of the sunspots and the values of temperature and magnetic variations on Earth could therefore be explained. These influences were monitored in the *Anais* …, which also included data received from the Coimbra Meteorological and Geophysics Institute, such as maximal and minimal temperatures, solar irradiance and magnetic variations.

Costa Lobo classified the prominences as eruptive—those which appeared everywhere in the solar surface except in the facular regions, and as explosive—those which were supposedly produced by the impulsion of facular matter. Filaments were related to the eruptive prominences, being classified as thin, large, curved or discontinuous.

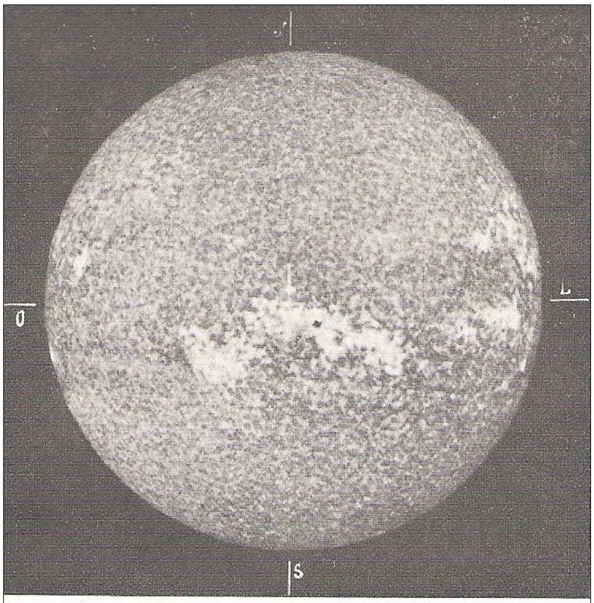
Gumersindo Costa Lobo's participation in these investigations was highlighted, with his father writing that:

> The cooperation of the assistant Dr. Gumersindo Sarmento da Costa Lobo has been of remarkable competence and of unsurpassable care, after showing special knowledge of the work in solar physics conducted at the Meudon Observatory. (Costa Lobo, F., 1929: 19; our translation).

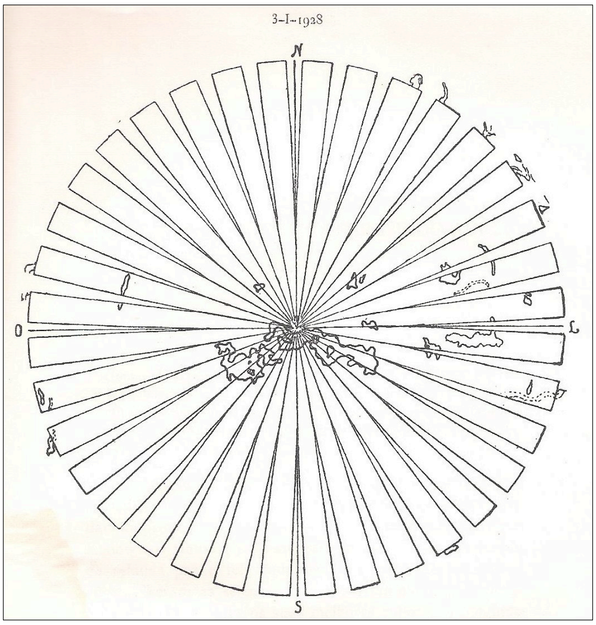
The importance of the new research centre in solar physics prompted a visit to Coimbra by British Astronomer Royal Frank Dyson on 26 November 1931. Dyson attended the celebrations organized by the Faculty of Sciences at the UC and the IC in honour of Isaac Newton (Costa Lobo, F., 1934).[10]

As a representative of the Portuguese Government, Costa Lobo (1933b) attended the General Assembly of the International Astronomical Union in Cambridge, Massachusetts (USA), from 2 to 9 September 1932. At this meeting, the Commission of Solar Physics approved with applause a resolution that acknowledged the great importance of the work done at the Observatory of Coimbra and expressed the wish that these observations should continue to be sent to Meudon and also to Zurich (Switzerland) in order to be included in the *Bulletin for Character Figures of Solar Phenomena*, a publication of the IAU directed by the Swiss astronomer William O. Brunner, which was initiated in 1928 to report solar data from observatories around the globe.[11]

Despite all the enthusiasm and commitment of Francisco and Gumersindo Costa Lobo, the exiguity of the Observatory's staff was an obstacle, especially in view of the exceedingly large amount of data collected that had to be carefully logged and analysed.



K$_3$, 10^h 7^m — 14^m



Figures 8 (upper) and 9 (lower): Spectroheliogram taken on 3 January 1928 with the calcium II K$_3$ line and the corresponding graphical representation by F.M. Costa Lobo (after Costa Lobo, 1928: following page 356).

In 1933 the second volume of the *Anais* … appeared, again supervised by Francisco Costa Lobo, and focusing on the 1930 observations. In the Introduction a second invention of Costa Lobo is presented—a special sphere for facilitating the visualisation of the position of solar structures (see Figure 10). He characterized his sphere as "… an instrument with which it was possible that a single person can acquire the transformations that demand at least five persons using ordinary processes." (Costa Lobo, F., 1933a: 9;

Figure 10: Costa Lobo's solar sphere (courtesy: Museum of Science of the University of Coimbra).

our translation). Also in 1933, the Congress of the Geographic and Geophysics International Union took place in Lisbon, and was organized by Costa Lobo. His son also participated, giving a lecture on "Means and Methods of Observation of Solar Activity".

In an article published in *O Instituto* in 1931 the Polish astronomer, Ladislas Gorczynsky, wrote:

> Portugal is one of few countries that possess valuable and modern scientific appliances for solar investigations. Due to Prof. Dr. Costa Lobo, President of the IC and Director of the Astronomical Observatory, the creation in Portugal of an important centre of solar studies imposes on the country the broadening of these investigations to the numerous and wide possessions that this great country holds, located in advantageous positions, even if we only consider those bathed by the Atlantic waters. (Gorczynsky, 1931: 110; our translation).

Figure 11: Gumersindo Sarmento da Costa Lobo, 1896–1952 (after Amorim, 1955: following page 24).

8 GUMERSINDO COSTA LOBO AND CONTINUATION OF THE SOLAR STUDIES

When he became 70, on 18 February 1934, Costa Lobo was made emeritus, and had to leave his job as Director of the Observatory and the Chair he had held at the UC for 50 years. He was replaced by Manuel dos Reis (1900–1993), a Professor of Mathematics who supervised the following volumes of the *Anais* …, which maintained the structure established by Costa Lobo. No major scientific analysis was tried by Reis, the merit of the publication being that of the photographs, the numerical charts and the annual graphics, although at the end of each month there were some notes that referred to particular events. The exchange of spectroheliograms with Meudon was maintained, except during the years of the Second World War (Reis, 1946: 8). Meanwhile, Gumersindo Costa Lobo (Figure 11) continued the solar investigations initiated by his father.

Unfortunately, Gumersindo had long lived in the shadow of his father, which probably prevented him from receiving the recognition that he deserved. He concluded his graduation in mathematical sciences in 1919 with a higher grade than his father achieved (i.e. 19/20 vs. 18/20), and was then appointed Second Assistant in the Mathematical Section. Always committed to astronomy, he became deeply involved in the installation of the solar physics section. As already mentioned, in 1923 he was sent on a scientific mission to Meudon Observatory, and other trips would follow in 1930, 1935, 1938 and 1950, all made on his own. This made him the most capable investigator in the field in Portugal. He took his doctoral examination in 1926, defending a thesis on fluid resistance. He was promoted to First Assistant in 1930 and lectured on rational mechanics and celestial mechanics as well as giving practical courses of rational mechanics, probability calculus and astronomy, and astronomical progress. An active member of the IC, he was elected its Secretary on 6 March 1935. Besides his academic tasks, Gumersindo was a painter and a musician, and he was also an accomplished pianist.

His scientific activities, which led to many published and conference papers, were largely devoted to his special area of expertise—solar physics, and in particular the study and classification of chromospheric events. Based on an analysis of around 4000 photos of the Sun, taken from 1925 onwards, Gumersindo Costa Lobo (1933a) presented his first conclusions in a paper titled "The classification of some chromospheric phenomena and their comparison with terrestrial phenomena" (our translation) which appeared in the journal *A Terra – Revista de Sismologia e Geofísica*. He concluded that some events should be regarded as components of others, which were more general, like filaments and prominences. In 1933, he presented an extensive article in the *Revista da Faculdade de Ciências,* with the title "Spectroheliographic instruments and their application to the study of the solar atmosphere" (1933b; our translation), where he described the working of the equipment in Coimbra and reported the major investigations and results of the last few years. In this memoir, he introduced new spectroscopic methods to determine the velocity, based on the Doppler-Fizeau effect, and he referred to the most important findings associated with the variation in the

Sun's rotation with latitude. The Astronomical Observatory was also equipped to determine velocities of solar chromospheric structures, and he was able to acquire pictures of the Sun, by successive sections, using a wider slit. In this way, instead of getting a monochromatic image, he could obtain an approximately circular picture, with each section containing a small portion of the spectrum (Figure 12). By analysing the displacement of each spectrum, it was possible to determine the speed of that portion of the solar chromosphere.

The calculations described and performed by Gumersindo Costa Lobo included the correction due to the relativistic effect proposed by Einstein in his theory of relativity. This correction was particularly interesting because Gumersindo's father was strongly opposed to Einstein's Special and General Theories of Relativity, supporting an alternative theory (till the end of his life) that retained the concepts of absolute time and absolute space (see Costa Lobo, F, 1917; 1936; 1937).

Following in his father footsteps, Gumersindo Costa Lobo attended the General Assembly of the International Astronomical Union which took place in Paris in 1935, where he was elected a member of Commission 10 (Sunspots and Characteristic Solar Figures). He was already there in Paris on one of his scientific visits to the Meudon Observatory, one of the places where the sessions took place, another being the Paris Observatory. Gumersindo described the General Assembly and, in particular, the discussions of the two solar Commissions (10 and 11) in which he participated in a report published in *O Instituto* (Costa Lobo, 1938). The 90th volume of *O Instituto* included another paper written by Gumersindo Costa Lobo (1936) on "The observation of solar phenomena and some contributions for its interpretation" where he explained some interpretations of the solar structures observed in the Coimbra spectrographic data. He also pointed to the close connection between filaments—those dark streaks observed in the solar surface—and the prominences, seen beyond the solar limb. He concluded that filaments and prominences were different aspects of the same thing.

In Volume 100 of *O Instituto*, Gumersindo Costa Lobo published a synoptic report of his activities at the 1938 General Assembly of the IAU as a representative of Portugal. He was elected a member of Commission 11, which was devoted to Chromospheric Phenomena and the Solar Corona (Costa Lobo, G., 1942: 646). There he expressed the necessity of a scale for the eruptive phenomena and a choice of symbols based on a more detailed study of these phenomena. Taking part in the Congress of Portuguese Scientific Activity, in 1940, he presented a communication on "The Creation of Astrophysics Studies in Portugal (Costa Lobo, 1940) where he mentioned Hale's (1924) invention of the spectrohelioscope. This instrument was a modified form of the spectroheliograph that allowed direct viewing of the Sun in one wavelength through the replacement of the photographic plate by an optical device. Gumersindo proposed in 1935 to use Coimbra's spectroheliograph as a spectrohelioscope, but the relevance of the spectroheliograms that were obtained by the first instrument and the small dispersion of the first spectroscopes delayed this operation (Costa Lobo, 1940).

The elder Costa Lobo published his three final papers in Volumes 102 and 103 of *O Instituto*. One of these papers related to the origin of sunspots, and Costa Lobo gave his final interpretation of these phenomena. He reaffirmed his belief—now shared worldwide—of the relationship between sunspots and faculae, and that the sunspots always appeared inside faculae, the former disappearing before the latter, which meant that sunspots were a process resulting from faculae and both had a common cause. According to Costa Lobo, convection currents that sometimes caused eruptive prominences also produced sunspots in facular regions. Faculae had an origin external to the Sun. In regard to the solar cycle and its periodicity, Costa Lobo cited a reference in the *Transactions of the 6th IAU General Assembly in Stockholm* of 1938 which stated that the sidereal orbit period of Jupiter (11.8 years) around the Sun agreed perfectly with the main sunspot period during the interval 1880-1925 (Costa Lobo, 1943: 461). Based on this fact, Costa Lobo suggested that some rogue masses of external origin were captured or deflected by Jupiter and directed towards the solar surface. It was their collision with the photosphere that induced the formation of faculae. This scenario could also explain why faculae only occurred in the 'royal zone', between 2° and 40° latitude; in 1630 Christoph Scheiner (1573–1650) used this expression in reference to the narrow belt on both sides of the Sun's equator where the sunspots appeared (Brody, 2002).

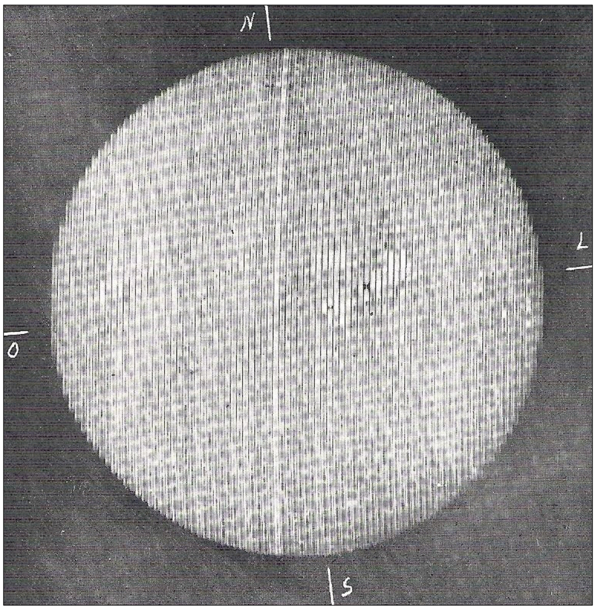


Figure 12: Picture of the Sun taken 2 July 1932 by the method of a wider second slit (after Costa Lobo, G, 1933b: Plate IV).

Francisco Costa Lobo continued working until the end of his life and in the process collected a long list of honours including the Jansen Gold Medal of the *Académie des Sciences de Paris*. He remained President and an Honorary Member of the IC until his death, which occurred on 29 April 1945.

In the session on 2 May 1949, the IC received Lucien and Marguerite d'Azambuja, who were corresponding members of the IC and were invited to present their work in Coimbra. After addressing the audience with a few words in Portuguese, Marguerite d'Azambuja read her communication, "Some present problems relative to sunspots and solar faculae" (D'Azambuja, M., 1949; our translation). In her lecture she commented on the rotational velocity of the Sun and its variation with latitude, with a maximum value at the solar equator, and the variation in the number of sunspots during the solar cycle. There was a mean duration of 11 years between two sunspot minima, and the first sunspots were generated at symmetrical higher latitudes between 30º and 40º N and S, increased in number towards the equator during the cycle and disappeared before quite reaching it. Within the faculae, sunspots were places with very high magnetic fields, which were opposite in the two hemispheres, and reversed each cycle.[12] Proposed explanations for the sunspot cycle were of two kinds: some people considered an external cause linked to tides caused by the planets, while others deemed the cause was internal to the Sun.

Lucien d'Azambuja later presented a report (1949) on "Progress of research on the solar atmosphere during the last fifty years." (our translation). He drew his conclusions from the observations collected in Meudon, including those sent from Coimbra. Lucien d'Azambuja assumed the existence of *activity centres* with similar evolution, a concept that incorporated several solar events. In a region of the solar disk a very bright and circular zone was formed and in this facular speck little sunspots would almost immediately appear. In the following days two principal spots surpassed the others in the enlarged facular region, one on the West (the leading sunspot) and the other on the East (the following spot) with the axis that joined them slightly slanted in relation to the solar equator. These spots would grow and, after a stability period, the following spot would fragment and disappear and, sooner or later, the same would happen with the leading spot. Gradually, the facular region attenuated and, in most cases, all traces would fade away after two months. An activity centre was also a stage for such other luminous phenomena as *chromospheric eruptions*. D'Azambuja also discussed the influence of solar activity on the Earth, especially the effects following chromospheric eruptions.

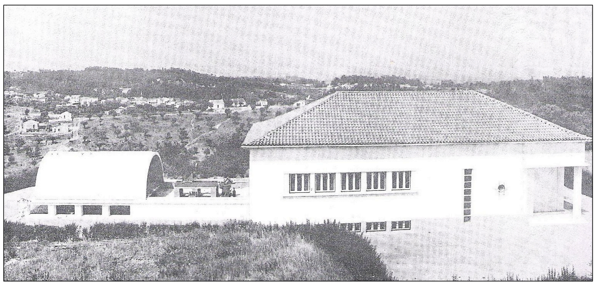


Figure 13: The present spectroheliograph building in Santa Clara, Coimbra. (after da Silva, 1969: after page. 235)

In the same year the lectures were delivered by the d'Azambujas, an article appeared in *O Instituto* authored by the Swedish astronomer Yngve Öhman (1903–1988), a corresponding member of the IC, who explained the new methods of "Astronomical investigation based on the polarization of light" (Öhman, 1949; our translation) and their application to the study of the Sun.

In 1951, answering a new request for cooperation made by the Meudon Observatory, the Director of Coimbra's Observatory, Manuel dos Reis, issued a request to the Dean of the University who promptly dispatched it to the Ministry of Education. Reis requested that Portugal send Gumersindo Costa Lobo on another scientific mission to Meudon to gather information on the construction of a new device that would allow the cinematographic registration of solar events. This instrument was to be installed in Coimbra and it would allow Portugal's participation in an international effort to obtain a continuous daily photographic record of solar activity. Reis thought that Gumersindo Costa Lobo was ideal for this assignment, given his vast expertise. The request was granted, but it would prove to be the last time that Gumersindo went to Meudon and the first trip that he did not have to pay for from his own pocket.

9 CONCLUDING REMARKS

The cooperation between the Coimbra and Meudon Observatories was one of the oldest scientific programmes that involved two nations (Mouradian and Garcia, 2007). From 1925 to the present day, the two Observatories have been exchanging observations, which were collected using similar instruments. In 1966, Coimbra's spectroheliograph was transferred to its new location in Santa Clara, Coimbra (Figure 13), where it is still working—although the observations are now automated (Silva, 1969). The renovations were undertaken from 1980 onwards, but without changing the optical layout, although they included new optical components, new dispersion gratings and high quality slits. The computer control, storage and data processing were enabled by the installation of a CCD camera (see Mouradian and Garcia, 2007).

Today 240 to 260 observations are made per year, using the old spectroheliograph, but the UC Astronomical Observatory now has an archive with about 30,000 solar spectra collected since 1926. This database is available online, and visitors may observe approximately 20,000 images of the Sun by accessing the web site http://www.astro.mat.uc.pt/novo/observatorio/site/index.html and obtain complementary information on any particular day.

Solar activity is an astronomical problem that has prompted considerable attention due to the effect that major solar events have on the Earth. As Francisco Costa Lobo mentioned back in 1925, the key question is: "What might occur if profound alterations [here on Earth] should extend beyond the limits where human life can subsist?" (Costa Lobo, F., 1925a: 566; our translation), and with an average of 250 clear sunny days each year, Portugal is in a privileged position for solar observations. Coimbra's spectroheliograph was among the first ten to be built in Europe (Kuiper, 1953), and was one of the most advanced apparatus of this type at that time. In a report to the National Board of Education on his training in the Observatories of Paris and Greenwich in 1932, the geographical engineer José António Madeira (who later became Chief-observer in the astrophysics section of the Coimbra Observatory) compared the methods for studying solar phenomena in Greenwich with those performed at Coimbra and concluded that "… this observatory does not possess, like the one of Coimbra, modern spectroheliographic installations that permit the permanent study of the Sun by spectral means." (Madeira, 1933:

373; our translation), and this fact justified Frank Dyson's decision to visit Coimbra. According to Gumersindo Costa Lobo, in 1940 there were only three heliophysical installations in the world that could match that of Coimbra (Costa Lobo, G., 1940: 25-26). While Gumersindo did not mention their locations, we can assume that two of them were at Meudon and Mount Wilson.

The *Anais do Observatório Astronómico de Coimbra* collected a massive amount of solar data in the 16 volumes that cover the period 1929-1944, and the spectroheliograms sent to Meudon and Zurich were, undoubtedly, indispensable to the world effort in solar physics, not only for their quality but also for their uniqueness on some days. However, international historians of science have largely ignored Coimbra's solar investigations.[13] Several authors assign the whole merit to Lucien d'Azambuja and the Meudon Observatory, and they disregard the contribution made by the Coimbra Observatory since 1931 to the *Bulletin for Character Figures of Solar Phenomena*. This situation could be due to the delayed publication of the results, especially after Volume XI (for example the last volume of the *Anais do Observatório Astronómico de Coimbra*, Number 16, containing the observations of 1944, was only published in 1975). Nevertheless, the spectroheliograms collected at Coimbra were sent regularly to Meudon, where they were preferred to any other (Costa Lobo, G., 1940: 20). Unfortunately, the Coimbra Observatory and, in particular its solar physics section, always faced a lack of skilled personnel to process the over-abundance of observations.

The presence of the D'Azambujas in a conference in Coimbra in 1949 confirms their gratitude for the cooperation they received from Coimbra. In their presentations, we may see the confirmations of some of the hypotheses on the chromospheric activity raised by the Costa Lobos. Francisco Costa Lobo, besides his invention of the planar transformation to depict solar events (also called 'Costa Lobo's system') and his solar sphere, was one of the first astronomers who recognized the connection between faculae and sunspots and provided a new explanation for their appearance. He was also a pioneer in classifying a new species of explosive prominences. Although Francisco Costa Lobo is relatively well-known in Portuguese academic circles, his son is largely unknown. Although Costa Lobo senior had the means and the contacts to create the solar physics section, it was Gumersindo Costa Lobo who provided the necessary technical know-how. Gumersindo made continuous and impressive progress in classifying solar structures, and established the common nature of filaments and prominences when some authors still considered them different and independent events. In the words of Coimbra's Professor of Mathematics Diogo Pacheco de Amorim, speaking in memory of Gumersindo at the IC, destiny wanted that it would be in this house and at its service that he fell victim to the disease that took his life (Amorim, 1955: 28). Gumersindo Costa Lobo died prematurely in 1952 while still in his mid-50s.

10 NOTES

1. This film showed the variation in the luminous intensity of Baily's beads, the beads of sunlight observed near the beginning and the end of a solar eclipse, due to irregularities in the Moon's surface.
2. Although having an encyclopaedic attribute, this periodical was also the most important scientific publication in Coimbra until the creation of the *Revista da Faculdade de Ciências da Universidade de Coimbra* in 1931. This latter journal was also the initiative of Francisco Costa Lobo, who was by then the Director of the Faculty of Sciences at the UC. All volumes of *O Instituto* are available online at the following web site: http://www.uc.pt/bguc/BibliotecaGeral/InstitutoCoimbra/EdDigital.
3. Jacinto de Sousa was a Professor in the Philosophy Faculty at the UC who became an expert in meteorology. He was secretary of the IC from 1855 to 1860. The goal of his journey abroad was to gather information and to select instruments for a new Meteorological and Magnetic Observatory in Coimbra. This was eventually built in 1862 under Sousa's supervision and he was its first Director. The first meteorological and magnetic observations were made in 1864.
4. The heliostat and the siderostat, devices with applications similar to those of the coelostat, used a single mirror, but produced rotating images of the Sun. A long paper about these instruments was published in *O Instituto* in 1934 (see Pinto, 1934).
5. The Jesuits had founded the Ebro Observatory in 1904, and its principal instruments had been in use since 1905. It was the observation site of the solar eclipse on 30 August 1905, when astronomers from France, England, the United States, Germany, Belgium, Spain and Portugal came together (see Selga, 1915: 22).
6. Pais, Afonso Costa and Machado were all active members of the IC. Afonso Costa was a member of many Governments and Prime Minister on three occasions, and he even participated in a course of popular lectures organized by the IC to educate those in Coimbra belonging to the lower social classes. Bernardino Machado was elected President of the Republic in 1915 and in 1925, and was President of the IC between 1896 and 1908.
7. Costa Lobo also attended two other congresses of the Spanish Association for the Advancement of Science, which took place in Bilbao in 1919 and in Salamanca in 1923.
8. The first congress of the two associations was held in Porto in 1921, but Costa Lobo did not integrate the IC delegation. A third joint congress of the two associations would occur in May 1932 in Lisbon, also organized by Costa Lobo.
9. In the same article, Costa Lobo (1926) also described the stellar spectrograph, which had been acquired at the same time and complemented the astrophysics section of the Observatory.
10. Frank Dyson's successor as Astronomer Royal and Director of the Royal Observatory at Greenwich was Harold Spencer Jones, who came to Coimbra on 17 April 1942 as a guest of the IC to give a lecture on the determination of the Earth-Sun distance (Boletim do Instituto, 1943. *O Instituto*, 103, 377-378).
11. In 1939 it would be renamed the *Quarterly Bulletin on Solar Activity* (Hufbauer, 1991).
12. This discovery was made by Hale in 1923, confirming his hypothesis of 1915 when the beginning

of a new solar cycle demonstrated that the newly-formed sunspots, in higher latitudes, had opposite magnetic polarity to those of the previous cycle, near the solar equator. This situation gave way to a redefinition of the solar cycle period as a 22-year magnetic cycle (Hale and Nicholson, 1925; Hufbauer, 1991).

13. As an example, see Martres (1998) or Hufbauer (1991), where the participation of the Astronomical Observatory of the UC is completely ignored.

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HIGHLIGHTING THE HISTORY OF FRENCH RADIO ASTRONOMY. 6: THE MULTI-ELEMENT GRATING ARRAYS AT NANÇAY

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Abstract: After constructing a number of simple antennas for solar work at Nançay field station, during the second half of the 1950s and through into the 1960s radio astronomers from the Paris Observatory (Meudon) erected five different innovative multi-element arrays. Three of these operated at 169 MHz, a fourth at 408 MHz and the fifth array at 9,300 MHz. While all of these radio telescopes were used for solar research, one of the 169 MHz arrays was used mainly for galactic and extra-galactic research. In this paper we discuss these arrays and summarise the science that was achieved with them during this important period in the development of French radio astronomy.

Keywords: French radio astronomy, solar radio emission, Nançay, multi-element arrays, A. Boischot, É.-J. Blum, J.-F. Denisse, M. Pick, J.-L. Steinberg.

1 INTRODUCTION

French involvement in radio astronomy has a long history, dating back to Nordmann's unsuccessful attempt to detect solar radio emission at 0.3-3 MHz from Grands-Mulets in the Alps in 1901. However, the earliest positive developments only took place in the years immediately following WW II when a fledgling radio astronomy group at the École Normale Supérieure led by Jean-François Denisse and Jean-Louis Steinberg carried out research from the roof of the Physics Building in Paris and from a field station located at Marcoussis, 20 km south of Paris.

In 1952 Marius Laffineur (Institute of Astrophysics, Paris) and Jean-Louis Steinberg attended the URSI Congress in Sydney, Australia, where they saw the innovative radio telescopes developed by scientists from the CSIRO's Division of Radiophysics at the Dapto, Hornsby Valley and Potts Hill field stations.[1] Steinberg was particularly impressed by the E-W solar grating array that Chris Christiansen had developed at Potts Hill. This instrument was the first one to produce high resolution observations of the distribution of 1420 MHz radio emission across the solar disk. The array consisted of 32 aerials arranged in an E-W straight line at uniform spacings; the combined response of the array produced a series of fan-shaped beams. The design of this instrument and the main observational results were recently reviewed in this journal by Wendt et al. (2008).

Steinberg returned to Paris convinced that French radio astronomy needed a radio-quiet field station and similar arrays. This was the genesis of the Nançay field station, 190 km south of Paris.[2]

After the transfer of the Radio Astronomy group from the École Normale Supérieure to Paris Observatory (Meudon), solar and non-solar research began at Nançay with two recycled 7.5m ex-German WWII Würzburg antennas (Orchiston et al., 2007)[3] and a number of smaller dishes, some of which were configured as interferometers. Kundu's two element interferometer was the first one to use Earth rotation synthesis to produce a one-dimensional distribution of solar radio emission (see Orchiston et al., 2009).

The next major development in French radio astronomy occurred in the second half of the 1950s when three different multi-element arrays designed principally for solar research were constructed at Nançay.

This paper reviews the technical specifications of these three instruments and other multi-element grating arrays that were developed at that site a little later, and the associated scientific research.[4] In addition to the personal involvement of three of the authors of this paper (MP, J-LS and AB), we discuss the work of the following colleagues: Yvette Avignon, Constantin Caroubalos, Bernard Clavelier, Jean-François Denisse, Anne-Marie Malinge-Le Squeren, Michel Moutot, Gérard Trottet, Émile-Jacques Blum, Michel Ginat, Mohan Joshi, Pierre Lantos, Yolande Leblanc, Paul Simon and Marc Vinokur. Regrettably, the last seven colleagues are no longer with us, but Émile-Jacques Blum was looking forward to participating in this project and had he survived he would certainly have been a co-author of this paper. He died on 22 September 2009, and we would like to dedicate this paper to his memory.

The instruments discussed in this paper were constructed and operated with the participation of the following technical staff: Claude Chantelat (deceased), Michel and Yvette Chapuis, Christian Couteret, Alain Gerbault, Jean-François Mangin, Marcele Parise (deceased) and Roland Tocqueville.

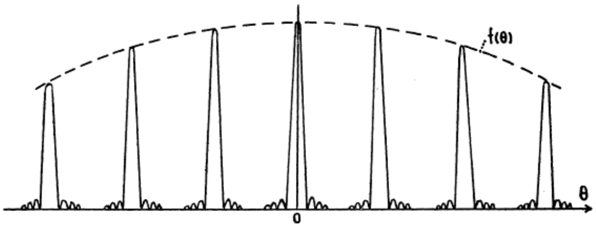


Figure 1: Radiation pattern of an E-W grating array.

2 THE CONSTRUCTION OF THE ARRAYS AT NANÇAY

2.1 Introduction

Major developments of French solar radio astronomy started with the founding of the Nançay field station in 1953. This site offered for the first time in France the possibility of developing arrays with long baselines, and E-W grating arrays operating at 169 MHz, 408 MHz and 9300 MHz were built. They were meridian instruments and their principle was similar to that of the 1,420 MHz Potts Hill array built by Christiansen and Warburton (1953) in Australia. Identical antennas were distributed at equal spacings along an E-W axis and their signals were added using transmission lines with equal electrical lengths. In hour angle this produced a series of 'fringes' (fan beams), which were equally spaced near the meridian plane (see Figure 1). A periodic one-dimensional image was obtained through the motion of the source across the fringes due to the rotation of the Earth.

Another meridian array was also constructed, but it had 8 antennas that were spaced along a N-S baseline (Maligne et al., 1959). This array operated at 169 MHz, but in contrast to the E-W arrays the motion of the source at noon was parallel to the fringes and images could only be obtained by using a multi-beam system.

2.1.1 The Principle

If $f(\alpha, \beta)$ is the reception pattern in amplitude of each individual antenna, that of a multi-element interferometer, $D(\alpha, \beta)$, is given by

$$D(\alpha, \beta) = f(\alpha, \beta)\,\frac{\sin n\frac{\Phi}{2}}{n \sin\frac{\Phi}{2}} \qquad (1)$$

where

$$\Phi = (2\pi d/\lambda)\sin\alpha \qquad (2)$$

and d is the distance between two neighboring antennas, n the number of antennas, λ the observing wavelength, α the angle between the line of sight and the meridian plane, and β the angle between the line of sight and the horizontal plane.

Near the meridian plane, the radiation pattern consists of a series of fan beams (see Figure 1) separated by an angle

$$\Delta\alpha = \lambda/d \qquad (3)$$

2.1.2 The 169 MHz and 408 MHz E-W Grating Arrays: A Brief History

The first array began operating in June 1956 and consisted of 8 parabolic antennas (Blum et al., 1956). These had a diameter of 5-m, meridian mountings, and were spaced at 50-m intervals. From November 1956 the array consisted of 16 antennas, and on 14 April 1957 it began observations in its final configuration (see Figure 2), with 32 antennas (Blum et al., 1957; Boischot, 1958). The operating frequency was 169 MHz (λ = 1.775 m).

In 1963, it was decided to use 16 antennas (that is, every second antenna) to build a new array working at 408 MHz, and to operate at 169 MHz with the remaining 16 antennas, keeping the same resolving power with a field of view reduced to 1° at 169 MHz, but wide enough for the radio Sun. The 408 MHz array began operating in October 1965 (see Clavelier, 1968b).

In 1968, the 16 parabolas of the E-W array working at 169 MHz were replaced by new, flat low-bandwidth antennas (diameter 3-m) with equatorial mountings, and the 408 MHz array was then operated with 32 antennas, raising the field of view to 50′. This upgraded version at 408 MHz was in operation by the end of 1972. On 2 September 1971 a fire destroyed

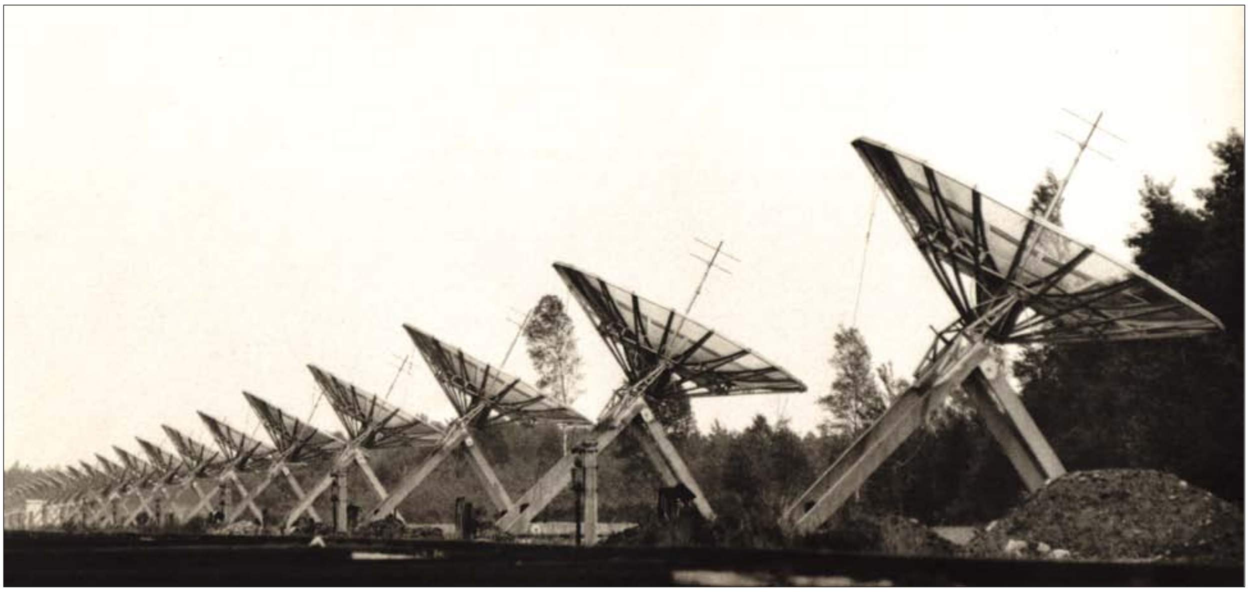


Figure 2: The 32 parabolic antennas of the E-W array.

the receiver of the 169 MHz array. The decision was then taken to develop a radioheliograph able to give a two-dimensional image of the Sun. The E-W branch of this new instrument started operating at 169 MHz in 1975.

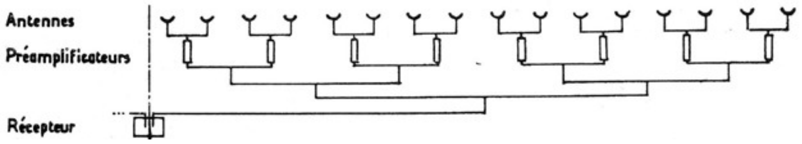


Figure 3: Schematic diagram showing the western half of the Nançay 169 MHz E-W array.

2.2 The Initial 169 MHz E-W Array with 32 Antennas

2.2.1 The Antennas

This was a 1550-m meridian instrument with antennas spaced at equal intervals along an E-W line. Signals from the antennas were added through equal electrical lengths and produced a series of E-W fringes after quadratic detection. The resolving power was 3.8′ (in theory 3′) and the angular distance between neighbouring grating lobes was 2° 02′. The E-W orientation was accurate to ~1′. For practical reasons (ground reflections, ionospheric effects), the observations were limited to declinations of ≥ –33°. Point sources could be located in the E-W direction with an accuracy of better than 1′.

Each antenna was a 5-m diameter parabola fed from its focus by a dipole (and its reflector). The surface was made of mesh tightened between 20 parabolic ribs that were distributed regularly around the focal axis. The surface accuracy was about ±1 cm at the centre and ±1.5 cm on the edges. A single dipole illuminated the parabola over an angle of 120°. The effective area of an antenna was ~15m^2 and the gain was 17.8 dB. The half power beam width of each antenna was ~20°.

2.2.2 The Receiver

The whole receiver used vacuum tube technology. The configuration of the interferometer is schematized in Figure 3. The signal from each dipole was fed to a coaxial cable through a transformer. The signals from consecutive neighbouring antennas were first added before being fed to a preamplifier with a gain of 50 dB (adjustable within ± 3 dB) and a band pass of 11 MHz. There were sixteen identical preamplifiers. This was the first array in radio astronomy to use a series of preamplifiers distributed along the antennas.

The signal was fed by coaxial cables of equal length to a receiver located in the central building. The receiver contained a post-amplifier to enhance the high frequency signal, a mixer with its local oscillator and an intermediate frequency amplifier at 11 MHz with a pass band of 2.5 MHz.

Radio sources were observed to determine the characteristics of the interferometer. A difficulty was to identify the crossing of the central (zero order) fan beam by the radio source. For this purpose, two other amplifiers were tuned at 11 + 0.9 MHz and 11 – 0.9 MHz respectively with a pass band of 0.7 MHz, so that the overall receiver was tuned to 169 + 0.9 MHz and 169 – 0.9 MHz. Thus, the antenna polar diagram was made of two sets of grating fan beams, but only the central fan beams coincided, giving an easy method to identify them.

Figure 4 shows observations of the discrete sources Virgo A, Hydra A and Cygnus A. As these sources are at different right ascensions, their transit times are different as well as the distances between successive beams (Blum et al., 1957). Radio source observations were used to determine the deviations in shape and position of the grating fan beams from the theoretical ones, and also to check the level of first side lobes (in principle 4.5%, but measured to be ~12%). The uncertainties in the determination of the right ascension were 15″ and 25″ for the most intense and the weakest sources respectively.

The finite width of the pass band, 2.5 MHz, produced a loss of coherency with hour angle and a progressive smearing of successive fan beams with their distance from the central one. This effect limited the observing time for the Sun to about ± 40 minutes around noon.

2.3 The 408 MHz E-W Array

The frequency 408 MHz was chosen for three reasons: (1) the increase in resolution compared to the E-W array at 169 MHz; (2) this frequency range had not yet been explored; and (3) the 406-410 MHz frequency range had been allocated to radio astronomy and thus was protected to some extent.

The resolution was 1′.7 and the accuracy in the localization of the sources in the E-W direction was 20″. The field of view (distance between consecutive grating fan beams) was 25′, which is smaller than the width of the Sun and led to an overlap of its eastern and western edges.

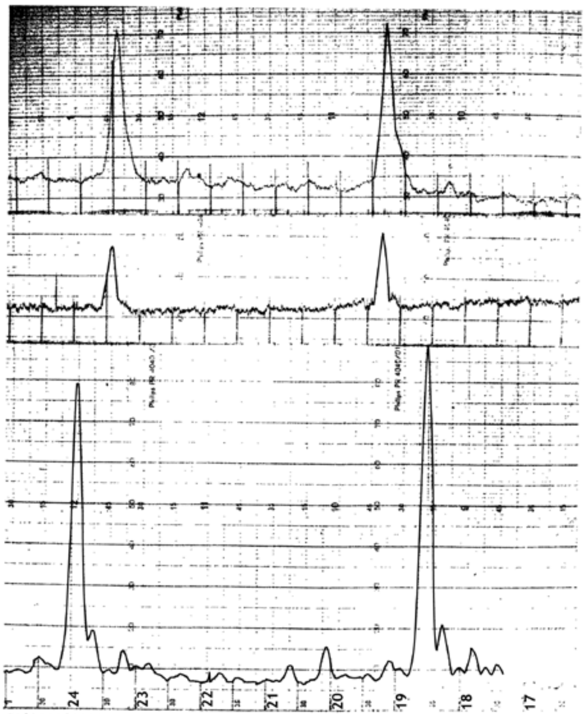


Figure 4: Records of radio sources. From top to bottom: Virgo A, Hydra A and Cygnus A. (after Blum et al., 1957).

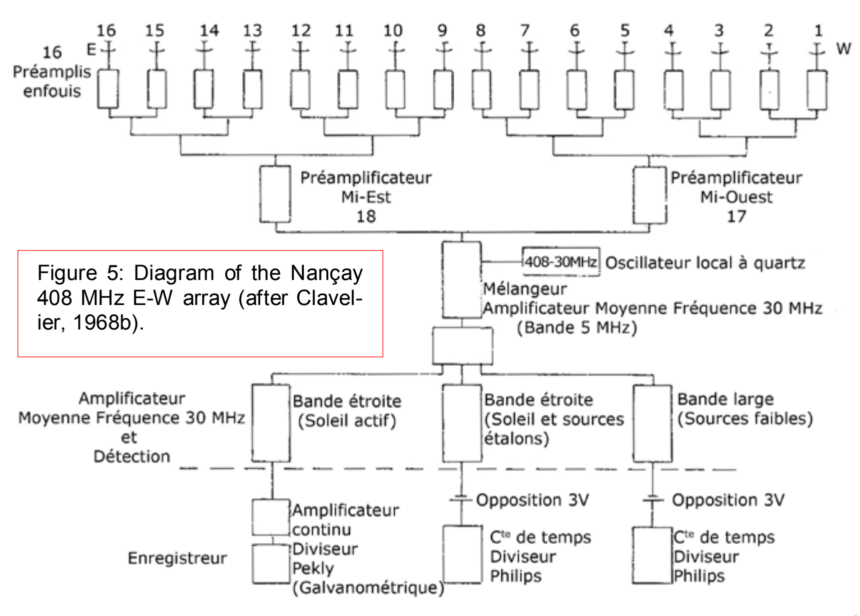


Figure 5: Diagram of the Nançay 408 MHz E-W array (after Clavelier, 1968b).

At 408 MHz the individual antenna pattern is narrower than at 169 MHz and the observing time around noon would have been too short with fixed antennas. In order to allow observations during 1 hour around the meridian transit, a new antenna feed was developed, such that the illumination of the parabolas was only partial in the E-W (horizontal) direction; it was made of an array of two dipoles (each associated with its own linear reflector) giving an illumination of 40° and 70° at 10 dB respectively in the planes parallel and perpendicular to the dipoles. The widths of the resulting antenna patterns were 28° at 6 dB (22° at 3 dB) in the horizontal plane and 11.5° (8.5°) in the vertical plane.

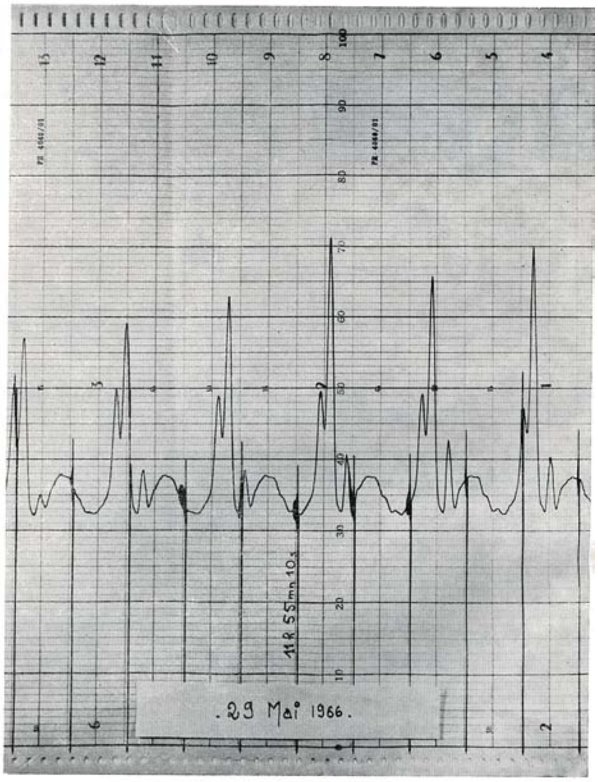


Figure 6: Record at 408 MHz of a solar radio source exhibiting two components (after Clavelier, 1967).

2.3.1 The Receiver

Figure 5 shows the design of the interferometer. The main differences between it and the 169 MHz array were: (1) a preamplifier buried at a depth of 1-m close to each antenna; and (2) 'mid-east' and 'mid-west' amplifiers to compensate for the signal loss in the coaxial cables. In the central building, after a change of frequency to 30 MHz the signal was divided into three parts and sent to three amplifiers, one with a band pass of 4 MHz (used exclusively for weak calibrators) and the other two with narrower band passes of 0.4 MHz (normal observing mode) and 0.5 MHz (for bursts of short duration or high intensity).

Note that for the first time in radio astronomy the preamplifiers were transistorized. In Figure 6, solar observations at 408 MHz show the presence of two active centres.

2.4 The 9300 MHz E-W Array

The 9300 MHz ($\lambda = 3.2$ cm) array was operating with eight antennas from February 1958 and with 16 antennas (Figure 7) from July 1959 (Pick and Steinberg, 1959; 1961). This radio telescope is still in operation. The sixteen antennas with filled aperture are attached to a 23-m metallic girder taken from US military radars, and are positioned at a regular spacing of 1.46-m. This girder, which is supported by four concrete piles, can be rotated around its E-W horizontal axis in order to point at various declinations. The signal is fed through waveguides to the receiver which is also supported by the girder. This avoids the use of rotating junctions, which could introduce phase variations depending on inclination (phasing must be accurate to ~10%, i.e. 3 mm).

The resolution is 4.5′ and the distance between two grating lobes is 1° 15′, much greater than the width of the Sun at this wavelength. But by using deconvolution techniques, it is possible to measure radio source diameters down to 2′.

2.4.1 The Antennas

Each antenna, which is a parabolic mirror with a diameter of 1.10-m and a focal length of 0.55-m, is illuminated by a horn. In order to increase the observing time (as for the 408 MHz array), horns have a width larger than their height and illuminate only the central part of the mirror in the E-W direction. This results in an E-W beam width of 7°, which allows an observing time of about 45 minutes. The waveguide is curved from the horn, and then crosses the reflector. The junctions by pairs have a Y shape. To avoid energy losses and phase variations due to moisture, waveguides were filled with nitrogen under pressure. Glass windows were inserted between the horns and the wave guides.

The impedances were matched by means of screws inserted in the wave guides. The standing wave ratio is ≤1.1 in a band pass of 100 MHz. Observations of the Sun were used to achieve the phasing of the array. When using only two neighboring antennas (putting absorbing masks in front of all of the other ones), the Sun can be considered as a point source and produces a sine wave. The shift between its meridian transit time and the time of maximum of the central fringe provides the phase correction to be applied to the antenna pair. This correction is made by inserting pieces of dielectric material in the waveguides. The side lobes level is ≤10%.

2.4.2 The Receiver

The original receiver was a super-heterodyne with an intermediate frequency of 34 MHz and a 10 MHz band pass. Its noise factor was 8 dB and its noise temperature 1500°. The same metal box contained the mixer, the local oscillator and the IF preamplifier. This box was mounted on the girder. The main amplifier and the power supply were located in the cabin.

2.5 Construction of the Multibeam Arrays at Nançay

2.5.1 The Multibeam N-S Array at 169 MHz

A new multi-beam N-S array was built in 1960 (Joshi, 1962) (see Figure 8). It was designed mainly to measure the declinations of more than one hundred radio sources during their transit in the central beam of the E-W grating array. This instrument also observed the Sun until 1964.

Figure 7: The Nançay 9300 MHz E-W array.

Figure 8: The 8 parabolic antennas of the N-S array.

The N-S array contained eight 10-m parabolic dishes at 110-m spacings. The distance between grating lobes was 55.2′, and the half-power beam width was 7′. The signal from each antenna was amplified and then transmitted to the central laboratory by buried coaxial cables (see Figure 9).

These signals were then mixed with that of a local oscillator. The outputs of the mixers were 2 MHz-wide frequency bands centred at 11.55 MHz. These eight bands were sent to eight delay lines made of coaxial cables, which allowed choosing the direction of the central grating lobe. Each band was fed to an amplifier with 15 outputs. Finally, there were 15 sets of 8 intermediate frequency bands. Each set was sent to a delay line system, and the 8 outputs were added. These 15 systems produced 15 grating lobes which were shifted by 1/16 of the grating lobe spacing: the spacing between the grating lobes was filled with the 15 shifted lobes (Figure 9). The 169 MHz output of the E-W array was mixed with the same local oscillator, and the intermed-

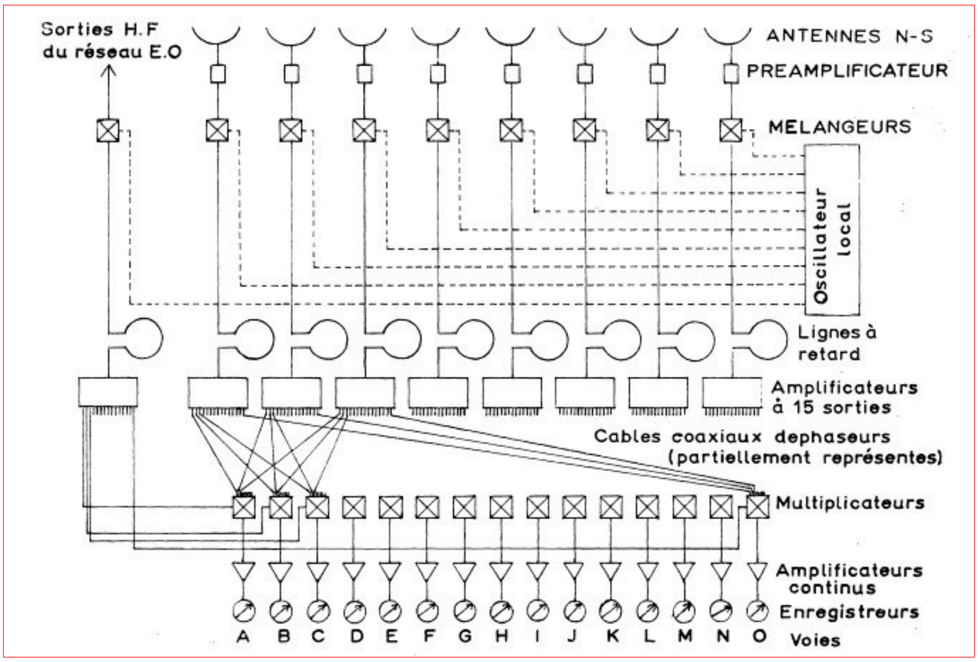


Figure 9: Diagram of the Nançay 169 MHz N-S multi-beam array and multi-channel receiver (after Joshi, 1962).

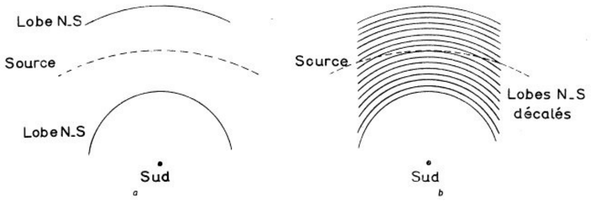


Figure 10: Two main lobes of the multi-beam N-S array. Left: A source crossing the meridian between two successive beams will be not recorded. Right: A series of beams shifted from the position of the main beam. The sources crossing the meridian will be recorded (after Joshi, 1962).

iate frequency voltage was multiplied by the fif-teen outputs of the N-S array. The 15 resulting signals were plotted on three 5-channels recorders. The lobes of the instrument on the celestial sphere are represented in Figure 10. Note that a radio source was recorded only when it appeared both in an E-W and a N-S lobe (see Figure 11).

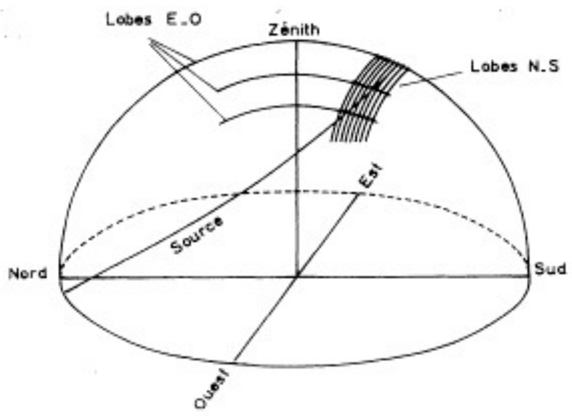


Figure 11: The lobes of the E-W and N-S arrays on the celestial sphere and the transit of the radio source in the lobes (after Joshi, 1962).

Figure 12 shows the transit of the radio source Hydra A: the source appeared in channels I and J, and its coordinates could be determined. For each trace, intensity is shown as a function of time. The positional accuracy of the system was estimated as 1 second in hour angle and 1′ in declination, which were rather good values at that time.

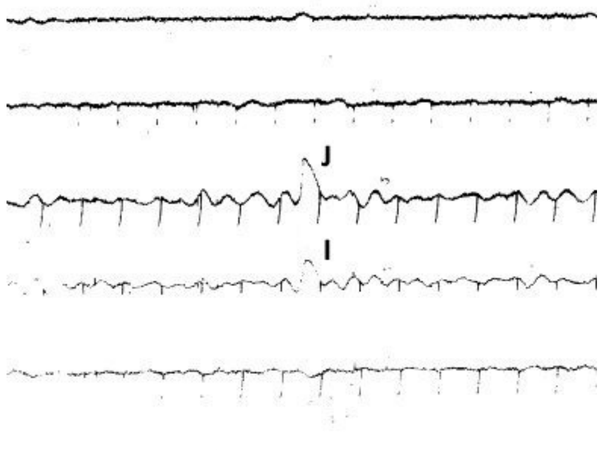


Figure 12: Transit of the radio source Hydra A in a few successive beams of the N-S multichannel array: the source is culminating between lobes I and J (after Joshi, 1962).

2.5.2: The Multibeam E-W Array at 169 MHz

With the remaining 16 antennas of the 169 MHz array, an E-W multi-beam array was constructed and has been in operation since July 1967 (Vinokur, 1968). The principle of this instrument was comparable to that of the N-S array (see the previous Section). Its main achievement was the high rate and the short exposure times of the resulting picture on film which could be as fast as 1/160 second (ibid.). Figure 13 shows an example of storm burst activity, where one can see variations of bursts faster than 1/20 second. On 2 September 1971 a fire destroyed the cabin and all of the receivers.

3 SOLAR RESEARCH AT NANÇAY WITH THE THREE ARRAYS AT 9300, 408 AND 169 MHz

3.1 Introduction

Observations at different frequencies sample different heights and physical conditions in the solar atmosphere, with lower frequencies coming from higher levels above the photosphere. Therefore, by operating at different frequencies the Nançay arrays provided a powerful way of studying the quiet Sun and the disturbed Sun and investigating the association between radio bursts and energetic solar particles in order to understand solar-terrestrial relations. The multi-frequency approach chosen by Blum, Denisse and Steinberg turned out to be fully justified, as illustrated below.

It is worth mentioning that the main goal of the large Nançay E-W array was to study noise storms, which were recognized as a type of activity that was more stable and more permanent than other types of solar radio burst emission (see Blum et al., 1957). The 150-200 MHz frequency range appeared as the most favorable for this study (Benoit, 1956). Blum et al. (1957; our translation) emphasized

> … the importance of identifying, for the study of solar-terrestrial relations, the positions of the active centres, and particularly those which were associated with radio emission.

Monthly maps from the Nançay array were published in the *Solar Geophysical Data on Solar Activity* from 1957 until October 1990, and these showed the position and intensity of the 169 MHz noise storm centres.

At 9300 MHz, the magnitude of the flux density of the 'radio condensations' associated with sunspot groups was very early on recognized as an efficient indicator of up-coming flare activity (see Section 3.2.1) and, until recently, daily messages reporting these flux density values were sent from Nançay to the Centre de Prévision de l'Activité Solaire et Géomagnétique de l'Observatoire de Paris-Meudon, which was the regional centre of the International URSIgram and World Data Service.

Historically, solar radio emission has been divided into three categories: (1) emission from the quiet Sun; (2) the slowly varying component (SVC) which is thermal in origin and is associated with the transit of various optical features across the solar disk; and (3) sporadic activity, including a large variety of bursts.

3.2 The Quiet Sun

The level of emission from the quiet Sun at a given frequency is usually masked by the SVC-emitting sources. However, it is possible to determine the base level of emission by subtracting the SVC emissions. This was first demonstrated by Christiansen and Warburton (1953). The method adopted was to superimpose a number of daily one-dimensional profiles and to draw their lower envelopes. The same technique was applied to the Nançay observations.

3.2.1 9300 MHz Emission

The quiet Sun emission at 9300 MHz was first measured for a two month period during August-September 1959 (Pick and Steinberg, 1961). Figure 14 shows that the width of the quiet Sun at 9300 MHz is more or less the same as that of the optical disk, which is represented by the solid line, AB. Therefore the emission originates from a region close to the chromosphere. The brightness temperature of the quiet Sun was estimated to be ~20,000 K.

3.2.2 169 MHz and 408 MHz: The Quiet Sun Emission and its Variation with the Solar Cycle

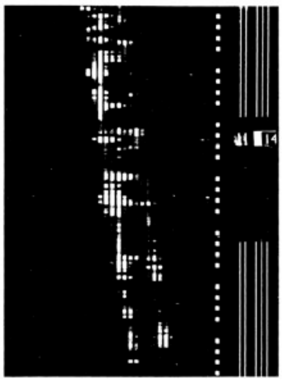
Boischot (1958) determined the level of quiet Sun emission at 169 MHz as the lower envelope of daily observations (see Figure 15, right panel), during quiet periods (1956-1957) in the early part of the sunspot cycle. But even so, the number of days without noise storms or burst activity was limited (Boischot and Simon, 1959). At this frequency, the daily shape of the Sun can change considerably. This is illustrated in Figure 15 where individual strip scans of the Sun taken in April and July 1957 are shown respectively in the upper and the lower part of the left-hand panel. This figure also shows that relative to April, there is a significant decrease of almost 20% in the general level of emission in July.

Boischot (1958) also underlined the difficulty in determining the contribution from the different localized sources distributed over the total surface of the Sun and concluded that the error involved in defining the lowest level of the emission at 169 MHz from a limited observing period was far from negligible.

The next studies were thus performed with a larger sample of observations. Moutot and Boischot (1961) estimated the quiet Sun temperature for the 1958-1960 period assuming that the emission of the 'minimum envelope' originated in a uniformly-bright disk with a diameter measured at half power by the E-W interferometer; they found a brightness temperature of 800,000 K ± 15%.

Once the E-W and N-S arrays were both operating successfully, Avignon and Le Squeren-Malinge (1961) and Leblanc and Le Squeren (1969) investigated the shape and size of the corona at 169 MHz, and its change in the course of a solar cycle. The latter authors considered the variation of the 'quiet Sun' by taking the lowest envelope of the different curves recorded over periods of one month. Figure 16 displays the variations in the equatorial dimension of the 'quiet Sun'; the diameter was 47′ ± 2′ at the time of maximum solar activity, then it decreased between January 1960 and December 1961 to reach a minimum value of 38′ ± 1′ and thereafter remained more or less

Figure 13 (right): Storm burst activity observed with the multi-beam E-W array at 169 MHz. The vertical axis shows time, and each bright spot is illuminated for one second at intervals of two seconds. The horizontal axis shows the angle between the line of sight and the meridian plane of the array (after Vinokur, 1968).



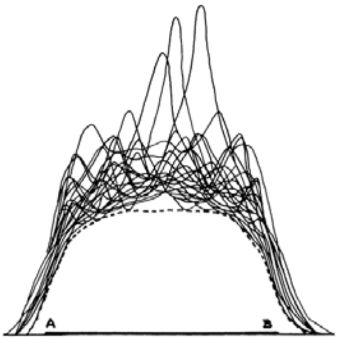


Figure 14: Superimposed individual scans of 9300 MHz emission obtained during August-September 1959, showing peaks due to 'radio plages'. Upon subtracting these, the level of quiet Sun emission (dashed line) is derived. The solid line, A-B, indicates the diameter of the optical Sun (after Pick and Steinberg, 1961: 49).

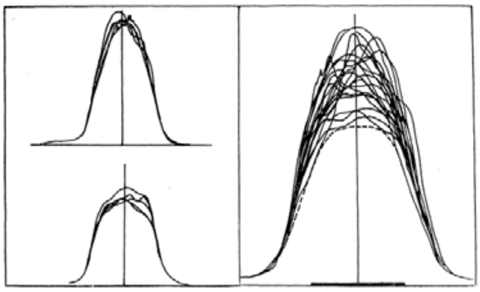


Figure 15 (left): Slow variations observed with the E-W Interferometer at 169 MHz; records obtained between 16 and 26 April 1957 (top) and 8 and 12 July 1957 (bottom). Figure 16 (right): the dotted line represents the estimated emission from the quiet Sun in 1956-1957 (after Boischot, 1958).

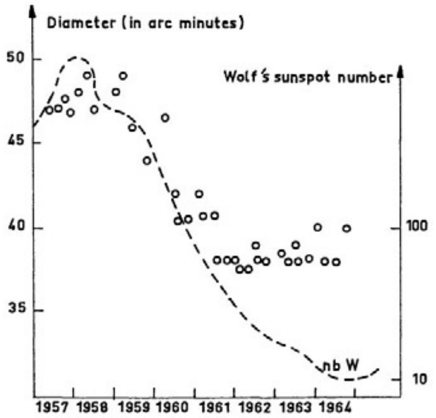


Figure 16: Apparent variations in the equatorial width of the 'Minimum Sun' (circles) during a solar cycle and variation in the Wolf sunspot number (dashed line) (after Leblanc and Le Squeren, 1969).

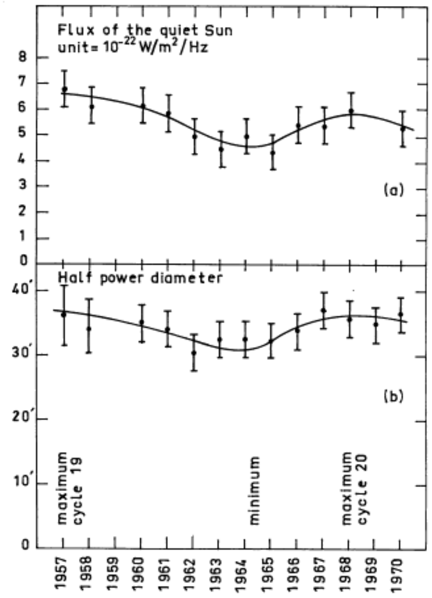


Figure 17: Flux (a) and E-W diameter at half power (b) of the radio quiet Sun at 169 MHz between 1957 and 1970 (after Lantos and Avignon, 1975).

Table 1: Values of T_b (10^5 K)

f (MHz)	T_b		Reference
	Holes	Arches	
160-169	11.5	6.3	Trottet and Lantos (1978)
160-169	6.6	8.5	Chiuderi-Drago et al. (1977)
160-169	..5.7		Dulk et al. (1977)
408	4.1	6.0	Trottet and Lantos (1978)
408	4.3	6.3	Chiuderi-Drago et al. (1977)

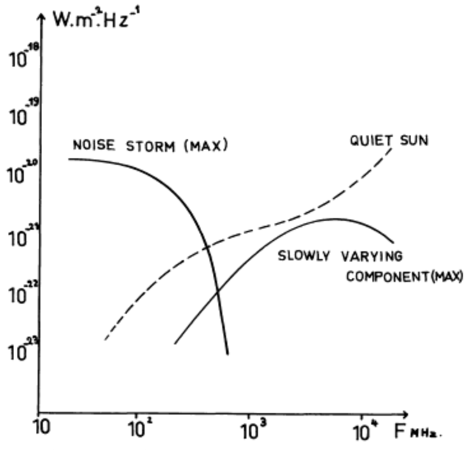


Figure 18: Spectra of noise storms and slowly varying components (after Clavelier, 1967).

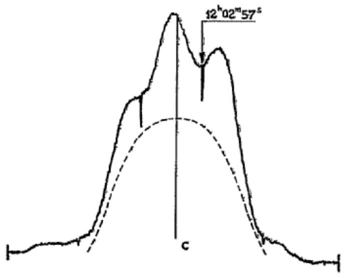


Figure 19: Scan of the Sun obtained on 7 March 1958, showing the presence of two intense radio plages (after Pick-Gutmann and Steinberg, 1959).

constant. In the same figure, the quarterly variation in Wolf sunspot numbers is plotted. It can be seen that the decrease in the E-W diameter started slightly after the beginning of the decay of the photospheric activity; the latter continued until 1964, although the diameter reached its minimum value in 1961. This suggests that the shape and size of the 'lower envelope' could still be affected until 1961 by the presence of localized sources. The N-S diameter measured from June 1960 to December 1963 was 32′ ± 3′, and no variation was found during this period. The authors, however, noticed that the limited resolving power prevented the observation of any change <6′ in this direction. The ratio of the N-S and E-W lowest dimensions of the corona gave an ellipticity of 0.84, identical to that obtained by Conway and O'Brien (1956) in 1953-1954 at 214 MHz.

Leblanc and Le Squeren found that the flux density at 169 MHz varied from $12.5 \times 10^{-22}\,\mathrm{W m^{-2} Hz^{-1}}$ at the maximum to $6.0 \times 10^{-22}\,\mathrm{W m^{-2} Hz^{-1}}$ at the time of minimum activity. The latter value corresponded to a brightness temperature of 1.1×10^6 K. The authors concluded that this temperature may be considered equal to the electron temperature in the corona, which was assumed to be optically thick at this frequency.

Finally, Lantos and Avignon (1975; cf. Avignon and Lantos, 1971) determined the dimensions, temperature and density of the solar corona for the period 1957-1970, which extends from the maximum of cycle 19 to the maximum of cycle 20. The lower envelope was defined over a year, which was the main difference with the analysis performed by Leblanc and Le Squeren (1969*)*. Another criterion used by Lantos and Avignon (1975) was to select periods when accurate measurements of point sources were available for calibration. Figure 17 shows that the flux density and the E-W diameter have only small and simultaneous variations. It was concluded that the quiet Sun brightness temperature remains constant (T_b = 750,000 K), in agreement with measurements made by Conway and O'Brien (1956) at 214 MHz during a minimum of solar activity (T_b = 820,000 K) and with the value (800,000 K) obtained by Liu Xu Zhao and He Xiang Tao (1974) at 146 MHz.

The most interesting comparison was with the coronal holes detected at 160 MHz with the Culgoora Radioheliograph and also with the OSO 7 satellite in the 284 Å [FeXV] line by Dulk and Sheridan (1974); the brightness temperature over the radio coronal holes was 700,000K ± 20%. It was then proposed that the coronal holes seen in the far ultra-violet corresponded to the radio quiet corona as defined by the lower envelope method. It is interesting to note that this brightness temperature was comparable to the value found by Moutot and Boischot (1961) for the period 1958-1960. Avignon et al. (1975) also derived the flux density and the brightness temperature (460,000 K) of the quiet Sun at 408 MHz with the E-W Nançay array and the E-W arm of the Medicina North Cross in Italy. Again, they interpreted the lower envelop as resulting from the transit of extended coronal holes across the disk.

In 1978, Trottet and Lantos (1978) conducted a new data analysis in which they considered that the 'minimum radio quiet Sun' brightness was the result of two distinct components, coronal holes and regions of closed magnetic arches, mixed in variable proportions. The brightness temperatures of both components were obtained from one-dimensional observations with the E-W Nançay Interferometers at 408 and 169 MHz, using FeXV images in order to estimate their relative areas. Trottet and Lantos (ibid.) concluded that there was marginal consistency between the radio and UV observations. Table 1 summarizes the brightness temperatures obtained at 160-169 MHz and 408 MHz by them and, for comparison, the values found by other studies conducted at approximately the same time.

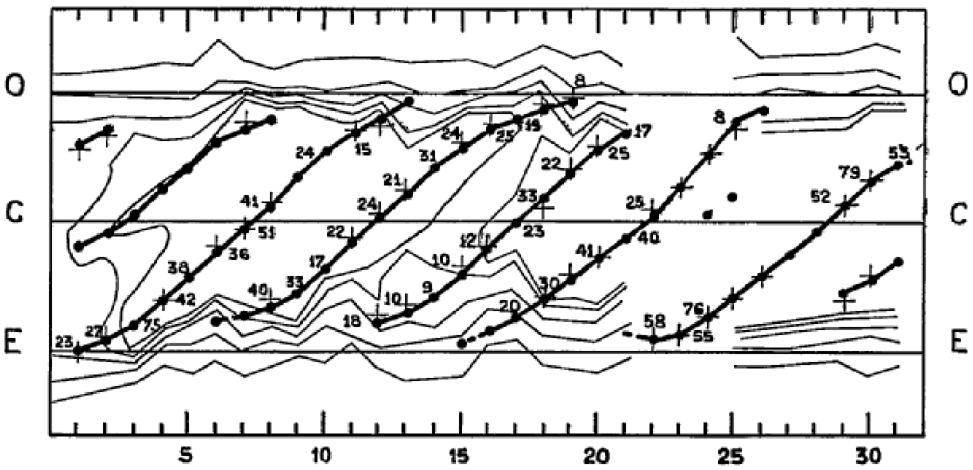


Figure 20: Map showing the evolutionary histories of individual radio plages present at 9300 MHz during March 1958. The numbers listed for the individual radio plages (black dots) are their intensities, in arbitrary units. The crosses indicate the associated optical centres. The O, C and E lines indicate the optical western limb, central meridian and eastern limb of the Sun, respectively. The series of thin lines correspond to lower level brightness contours (after Pick-Gutmann and Steinberg, 1959).

3.3 The Slowly-Varying Component

At metre wavelengths, the solar radio flux contains a slowly varying component of thermal origin which is easily recognizable during periods without noise storms as radio flux increases (RFI's) superimposed on the quiet Sun emission (see Section 3.2). Figure 18 displays spectra of the quiet Sun, the slowly varying component (SVC) and noise storms, and shows that the SVC flux density gradually diminishes as the frequency decreases below 3 GHz (Clavelier, 1967). In the absence of noise storms, it was early realized that the sources at 169 MHz and 9300 MHz had different characteristics

3.3.1 The Slowly Varying Component at 9300 MHz

Christiansen and Mathewson (1959) showed that the SVC measured at 1420 MHz was thermal emission from active regions. This finding was confirmed at 9300 MHz by Pick and Steinberg (1961) who analyzed the Nançay observations. They found a good concordance between the respective daily positions of the radio plages (also called 'radio condensations') and the associated active centres. They showed that the altitudes of the microwave sources varied between 20,000 and 30,000 km above the photosphere (see also Gutmann and Steinberg, 1959).

From the data obtained during March 1958, it was possible to estimate the duration, the brightness and the variations with heliographic longitude of the radio plages. Often two or even three of them were present on the Sun at any one time (see Figure 19). The motion of individual radio plages across the solar disk, and the way in which they varied in intensity during their passage is illustrated in Figure 20. Their durations were typically one solar rotation.

In a study of all the optical active centres associated with radio emission observed at 9300 MHz from July 1959 to December 1963, Avignon et al. (1966) showed that the importance of this emission depended upon the magnetic structure of the centres. Figures 21 and 22 show how the parameter *d/D*, previously introduced by Caroubalos and Martres (1964), was chosen to define the magnetic structure of the optical centre, where *D* is proportional to the square root of the total area of the sunspots and *2d* is the smallest distance between two sunspots of opposite polarity. When only one spot is visible, if there is a filament close to it, such as in configuration B (bottom of Figure 21, and also Section 3.5.2), *d* is chosen as the distance between the spot and the filament which marks the magnetic polarity inversion line, otherwise *d* is undefined. The relationship between the flux density at 9300 MHz and the total area of the spots is displayed in Figure 22. This figure shows clearly the existence of two families, the first one with a strong longitudinal magnetic field gradient (*d/D* <0.2, Categories 1 and 5) for which the flux density depends sharply on the spotted area, and the other one (*d/D* >0.2, Categories 2, 3, 4) for which this dependence is weak. For the first of these families the frequency of appearance of flares (importance >1) goes up very quickly with the area of

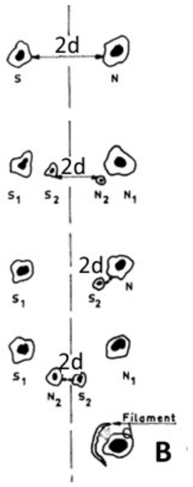


Figure 21: Measurement of parameter *2d* (see text) (after Caroubalos and Martres, 1964).

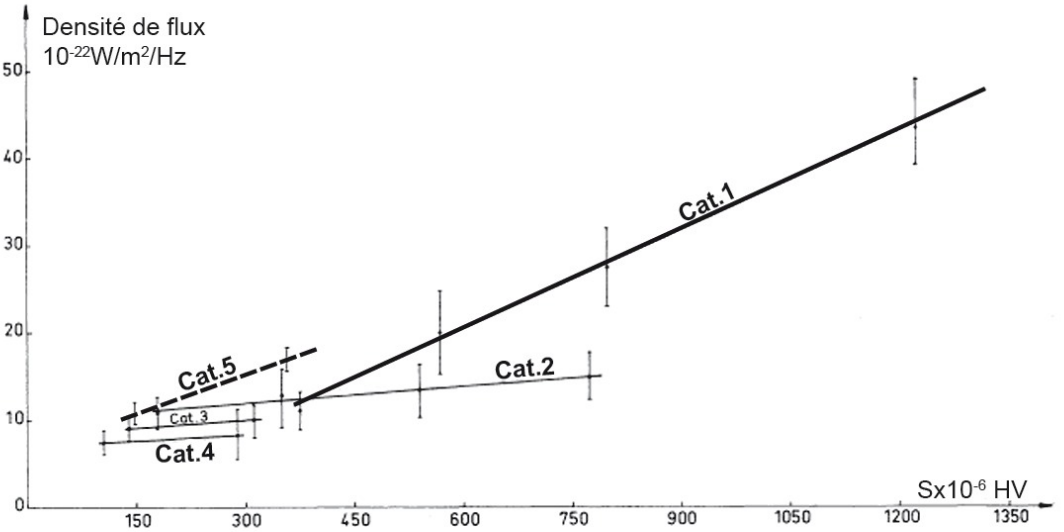


Figure 22: Variation of the flux density at 9300 MHz versus the sunspot area. Category 1: *d*/*D* ≤ 0.2; Category 2: 0.2 < *d*/*D* ≤ 1; Category 3: *d*/*D* > 1; Category 4: Unipolar centres; Category 5: Centres of B configuration≤ 0.2 see text) (after Avignon et al., 1966).

the spots. This is consistent with results found elsewhere, concerning the magnetic structure of active centres associated with cosmic rays or proton events (Ellison et al, 1962) or with Type IV bursts (see Section 3.5.2). This is also consistent with the results obtained by Moutot and Boischot (1961), who showed that active centres with an emission >15 × 10^{-22} W $m^{-2}Hz^{-1}$ at 9300 MHz were always associated with a noise storm at metre wavelengths. It was proposed that at 9300 MHz, the sources belonging to the first family were generated by the thermal gyromagnetic emission mechanism introduced by Kakinuma and Swarup in 1962.

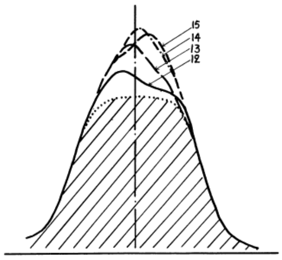


Figure 23: Sources of emission of the slowly varying component seen for four successive days in May 1958. The authors' estimate of the level of quiet Sun emission is also indicated (dotted line) (after Moutot and Boischot, 1961).

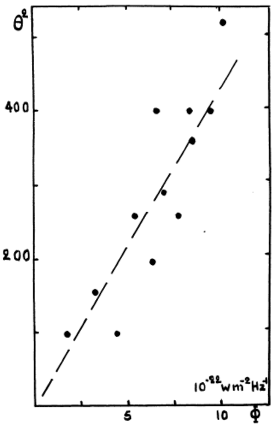


Figure 24: Plot of flux density (ϕ) versus the square of the apparent diameter ($θ^2$) for active centres at 169 MHz (after Moutot and Boischot, 1961).

Similar studies performed at 7.5 cm, 9.1 cm and 21 cm showed that, at decimetre wavelengths, these two families can no longer be distinguished. Furthermore, Kakinuma and Swarup (1962) showed that in general the flux density of strong radio sources is higher at the longer wavelengths than at 3 cm. Thus, Avignon et al. (1966) suggested that for the radio-emitting sources belonging to the first family, the spectrum between 3 cm and 6 cm could be flatter than for those belonging to the second family. They anticipated that this property could be of interest for forecasting solar flare activity.

3.3.2 The Slowly Varying Component at 169 MHz

3.2.2.1 *Observed Characteristics*

As already discussed in Section 3.2.2, Boischot (1958) showed that the shape of the Sun at 169 MHz varied from day to day. This is illustrated in Figure 23 for four successive days. Moutot and Boischot (1961) estimated that the apparent diameter of the radio sources superimposed on the quiet Sun ranged between 10′ and 20′. These sources could reach 15-20% of the flux of the quiet Sun. Moreover, they found a positive correlation between the square of the apparent diameters and the flux densities of these centres, as shown in Figure 24, and they concluded that the brightness temperature was approximately the same for all centres, and was ~1.2 × 10^6 ± 10% K.

In Figure 23, the maximum of emission attributed to the SVC follows the solar rotation and the authors assumed that the emission was associated with an active centre. However, in other cases, as shown in Figure 15 (left panel), the maximum did not rotate regularly, so the authors suggested that these cases corresponded to the presence of several active centres whose emissions were superimposed upon one another.

When they could distinguish the contribution of an emitting centre near the central meridian over a period of at least two days, they discussed the possibility of deducing the altitude of the emitting centre from its apparent velocity of rotation and its heliographic latitude. Assuming a mean latitude, *L*, of 20° for the

1958-1960 period, the mean altitude found during this interval was h = 140,000 km ± 30,000 km. A similar value of 125,000 km was found by Leblanc (1970), who extended this study to a larger number of observations during the period 1957-1968.

On four different occasions during 1959 the N-S Interferometer was used by Moutot and Boischot (1961) to determine the heliocentric latitude of active regions, and it was then possible to compute h for each of these with a much better accuracy. The values reported in Table 2 show some variation from one centre to another.

Table 2: Calculated heights of four different active regions (after Moutot and Boischot, 1961: 175).

Date	*h* (km)
5-6 March 1959	200,000 ± 20,000
8-9 July 1959	240,000 ± 20,000
10-11 July1959	80,000 ± 8,000
26-27 July 1959	190,000 ± 20,000

Moreover, Moutot and Boischot (ibid.) underlined that an important characteristic of these emissions was their directivity; no emissive region was observed at a distance >10′ from the central meridian of the Sun. This suggested that the directivity of the SVC at 169 MHz could be explained by assuming that the emissive regions were situated near the critical plasma level. In all cases, for sources located near the critical level refraction is important, so the emergent radiation is almost radial, whatever the initial direction. Consequently, the radiation emitted near the centre of the Sun will be received at the Earth, whereas for regions situated near the limb, the brightness temperature will be small.

3.3.2.2 *The Link with Optical Features: A Long History*

The SVC at metre wavelengths had been observed for decades, but its origin and its link with optical features was somewhat controversial. In Boischot (1958) and Moutot and Boischot (1961), the radio flux increases (RFI's) of the SVC were measured at 169 MHz with the E-W Interferometer, and were interpreted as the radio counterpart of the coronal enhancements which overlie calcium plages. As the radio sources often had large apparent diameters, of >8′, and could persist for several solar rotations, Leblanc (1970) proposed that RFI's would correspond to old and broadly-dispersed plages.

Subsequently, Axisa et al. (1971), using the same radio telescope, compared the radio sources at 169 MHz with the optical features, plages and filaments observed in Hα. They emphasized that

> When followed on photographs taken in Hα, the filaments are seen to suffer temporal changes in visibility, not apparent on the synoptic maps. (ibid.).

Thus they used for this comparison the synoptic maps from Meudon Observatory, where calcium plages and filaments were sketched (see Figure 25). On these maps, all the filaments were reported in Carrington co-ordinates at the dates of their heliographic central meridian passage, if they were visible for at least two days (whatever their heliographic longitude) during their transit of the solar disk. These synoptic charts allowed Axisa et al. (ibid.) to interpolate the position of the filaments on dates when they were not visible in the daily observations. They found that ~60% of the sources could be associated with one or several filaments and 5% with calcium plages; for 35% of them, the association either with calcium plages or with filaments was possible and thus inconclusive. For the RFI's correlated with filaments, the authors concluded that their emission originated in regions located at the base of streamers which overlay filaments. In addition, the correlation was extended to the direction of the filament: when a RFI was related to a filament (or a system of them) which extended over several tens of degrees perpendicular to the meridian, this RFI had the shape of a broad hump which remained at the meridian for several days; conversely, when the RFI corresponded to a short filament approximately parallel to the meridian, its rotation was more regular and the hump was narrower. As filaments traced the inversion line between two regions of opposite magnetic polarity, all of the RFI's correlated with filaments were representative of the same basic magnetic structure. This remark led to a coherent explanation of the radio sources whose shape would no longer be circular, but rather would have the form of elongated structures, called 'dense sheets', which would more or less follow the orientation of the underlying filaments, i.e. of the photospheric inversion line of magnetic polarity.

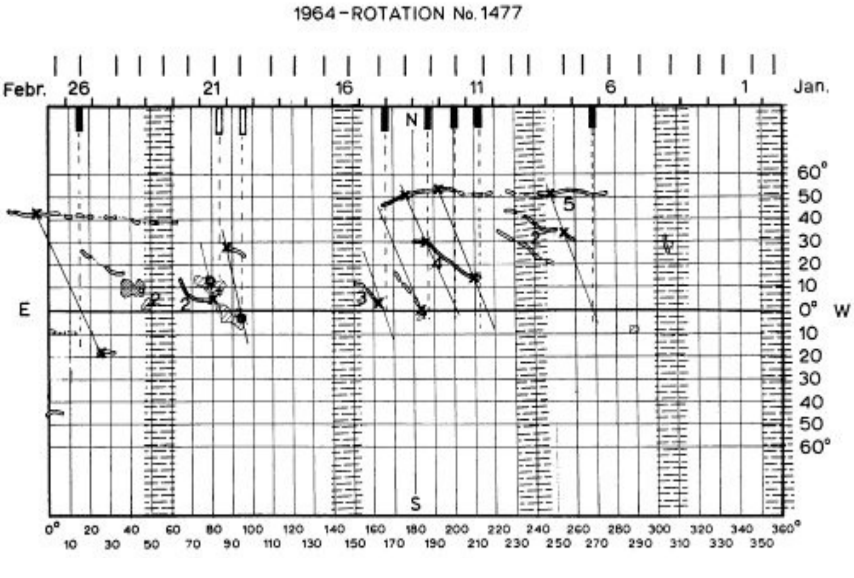


Figure 25: The association between RFI's (radio flux increases) and optical features. Black rectangles below the time scale of the synoptic map of Meudon Observatory indicate the meridian passage of a RFI related to filaments. Open rectangles correspond to the meridian passage of a RFI related to both filaments and calcium plages (undetermined cases). Dashed areas correspond to no available data. Crosses and heavy dots represent respectively the crossings of filaments and plages by the meridian trace (sketched by the light line) (after Axisa et al., 1971).

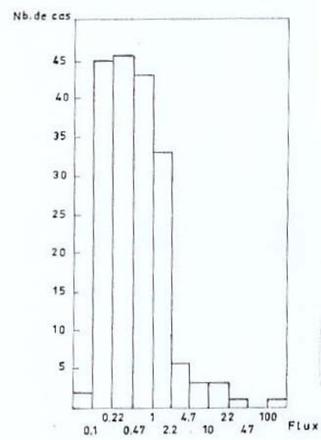


Figure 26: Histogram of flux densities (10^{-22} $Wm^{-2}Hz^{-1}$) of all centres (slowly varying component and storm centres) at 408 MHz (after Clavelier, 1967).

More than one decade later, when the Nançay Radioheliograph (NRH) observations became available, this radio telescope was employed as an aperture synthesis instrument using Earth rotation to obtain two-dimensional maps of the Sun at 169 MHz. The first observations showed no apparent association either with active regions or with filaments (Alissandrakis et al., 1985). Most of the sources appeared to be associated with inversion lines of photospheric magnetic polarity; they were located within the coronal plasma sheet, which delineates the inversion line between the north and south polarities of the large-scale magnetic field. Lantos and Alissandrakis (1996) proposed that the radio emission of the SVC came from arcades of moderately-dense loops spanning the neutral lines and located below the coronal streamer belt.

Quite recently, Mercier and Chambe obtained high-resolution maps of the SVC with the NRH at several frequencies. At 169 MHz, these maps show that many SVC sources appear as elongated bright ribbons oriented along the magnetic inversion lines of the photospheric field (to be published; private communication). These results are consistent with and indeed extend the early results from one-dimensional observations.

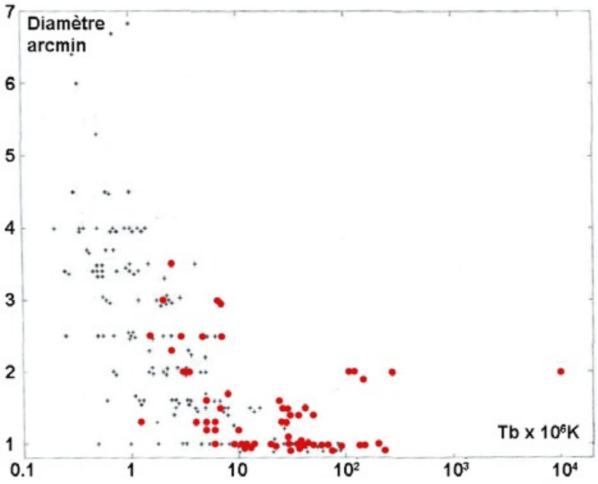


Figure 27: Plot of diameters versus brightness temperatures for all centres (slowly varying component and storm centres) observed at 408 MHz. The red circles indicate centres which were also observed at 169 MHz (after Clavelier, 1967).

3.3.3 408 MHz: Differentiation Between the SVC and Noise Storm Centres

Most of the results obtained at 408 MHz were published by Clavelier (1967; 1968a). The radio spectra displayed in Figure 18 show that the SVC and noise storm flux densities at 408 MHz in many cases are of the same order. The histogram of flux densities of all SVC and noise storm centres is shown in Figure 26. In about 90% of cases, the flux densities are $<2 \times 10^{-22}$ $Wm^{-2}Hz^{-1}$. Figure 27 shows the distribution of the centres as a function of their diameter and of their brightness temperature (T_b). Those centres which were observed simultaneously at 169 MHz are indicated by red circles, and it is seen that centres with a high brightness temperature have in general a small diameter (<2′) and are associated with noise storms at 169 MHz. Conversely, centres with diameters of >2.5′ and $T_b < 5 \times 10^6$ K are not associated with noise storms. They are the sources of the SVC and are associated with faculae devoid of sunspots (Clavelier, 1968a).

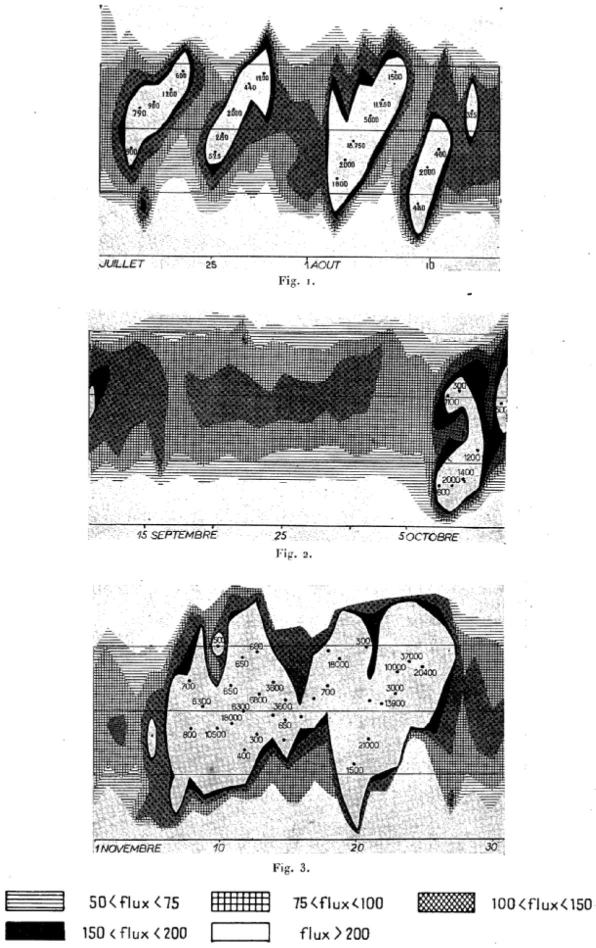


Figure 28: Three diagrams showing the distribution of solar radio emission at 169 MHz during the period July-November 1956. The horizontal lines represent the western limb, equator and eastern limb of the optical Sun. The active centres are indicated by dots, accompanied by their flux levels. The flux unit shown in the isophotes is 10^{-24} $Wm^{-2}Hz^{-1}$ (after Avignon et al, 1957).

3.4 Noise Storm Centres at 169 MHz and 408 MHz

At 169 and 408 MHz, noise storm emissions are the most frequent form of solar radio activity. They consist of a background continuum with superimposed bursts of short duration (a fraction of a second), named by Wild and McCready (1950) Type I bursts (cf. Denisse, 1959a). The first systematic study of the continuum was carried out at Nançay with the large E-W Array at 169 MHz and later at 408 MHz.

3.4.1 169 MHz Emission

From 29 May 1956, daily solar observations were made with the E-W Interferometer. The first results on the diameter, duration, altitude and formation circumstances of the active centres at 169 MHz were published by Avignon et al., (1957; 1959) and Boischot (1958).

The basis for illustrating some of these parameters was a diagram that the French radio astronomers developed to show the daily distribution and intensity of individual active regions. Three examples of these diagrams are shown in Figure 28. In the first and third panels the Sun was particularly active, but in the middle panel it was relatively quiet. When the Sun is particularly active, a number of different centres may be present at the same time.

From these diagrams, the authors concluded that the flux densities of storm centres can reach 50 or 100 times those of the quiet Sun level. Most storm centres have diameters ranging between 3′ and 9′ (see Figure 29), but several of them are unresolved by the instrument and therefore could be <1′.

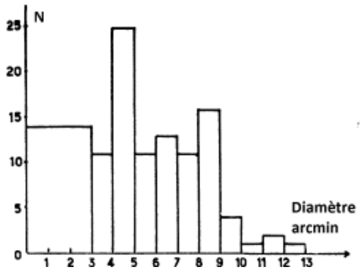


Figure 29: Histogram of the diameters of active centres, in minutes of arc (after Boischot, 1958).

The duration of these storm centres was very variable, from hours to days, but was always <6 days. Boischot (1958) noted that surely it was not limited by a beaming effect as one can observe these centres as far as 10′ beyond the optical limb of the Sun. When active centres could be associated with specific sunspots, it was possible to estimate the altitude of the centres above the photosphere using two methods: (1) by measuring their apparent speed of rotation and (2) by determining the points of appearance and disappearance of centres at the limb of the Sun. The results from both methods showed that the altitudes lay between 0.15 $R_\odot$ and 1 $R_\odot$, in general much higher than the critical altitude calculated for the normal corona at the observing frequency. Boischot (ibid.) and Blum and Malinge (1960) found that noise storm centres were not always located vertically above their associated sunspots, and that they sometimes did not follow the rotation of the optical Sun.

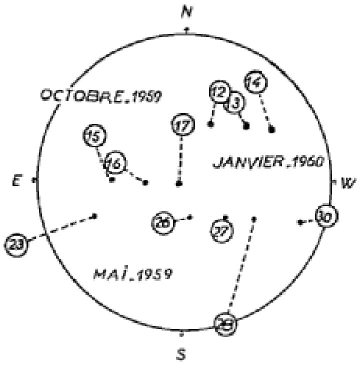


Figure 30: Solar map showing three different groups of positions of active centres (numbered circles) and their associated sunspots (black dots) on several successive days. The fact that the active centres do not always lie radially above their 'parent' sunspots is very apparent (after Blum and Malinge, 1960).

E-W and N-S positional determinations of storm centres by Blum and Malinge (1960) and Le Squeren (1963) resulted in quite precise identifications with optical centres, and the accuracy of the measurements was ~1′ in right ascension and 2-3′ in declination. But, in agreement with the one-dimensional (E-W) measurements, there still appeared to be no geometrical relationship between the radio and optical centres. When a storm centre was visible during several consecutive days, its position relative to the associated optical centre did not remain fixed. This is illustrated in Figure 30, which shows the positions of three groups of noise storm centres relative to their associated sunspots. Blum and Malinge (1960: 3120; our translation) suggested that:

> Perhaps these displacements indicate actual motions of the noise storm centres in the corona, changes in altitude for example, but one can also interpret them as apparent displacements due to the propagation of radio waves in a coronal environment with structural irregularity.

Le Squeren (1963) determined the average position of a large number of centres. Figure 31 shows that, except at higher longitudes, the average storm centre was not radially-situated with respect to the leading spot of the associated sunspot group. This figure also indicates a systematic pole-ward displacement of the storm centres with respect to the spot groups. Consequently, Le Squeren emphasized that the determination of the altitudes of the centres was impossible, except for those cases that were located at high longitudes.

Using the two dimensional Nançay measurements of positions of noise storm centres at 169 MHz and 200 MHz polarization measurements made at Nera Observatory (Netherlands), Maligne (1960) investigated the sense of polarization of the continuum as a function of the latitude of the associated optical centre. Figure 32 shows clearly that there was a prevailing sense of polarization for each hemisphere. About 10% of the cen-

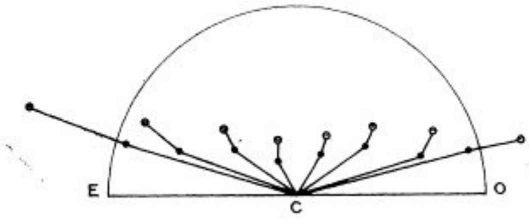


Figure 31: Mean positions of the noise storm centres (upper circles) and of their associated sunspots (lower circles) as the latter vary in heliocentric longitude. This figure shows a systematic displacement towards the central meridian of the Sun (after Le Squeren, 1963).

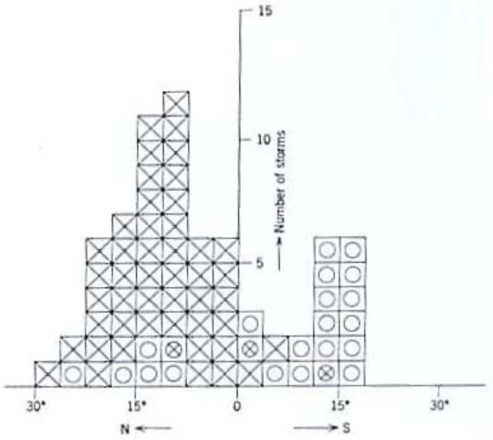


Figure 32: Latitude distribution of polarized storms. Key: circles = right-handed polarization; squares with crosses = left-handed polarization; circles with crosses = mixed polarization (after Le Squeren, 1963).

tres which were exceptions to the rule were associated with optical centres of rather complex structure, in which the magnetic field of the following spot was sometimes greater than that of the leading spot. Le Squeren (1963) proposed to associate the sense of polarization with the direction of the magnetic field in the leading spots, which was in agreement with the earlier results of Payne-Scott and Little (1951) and Komesaroff (1958). It was known that this direction was the same for all the optical centres in the same hemisphere. Thus it was concluded that the noise storm continua are usually polarized in the ordinary mode.

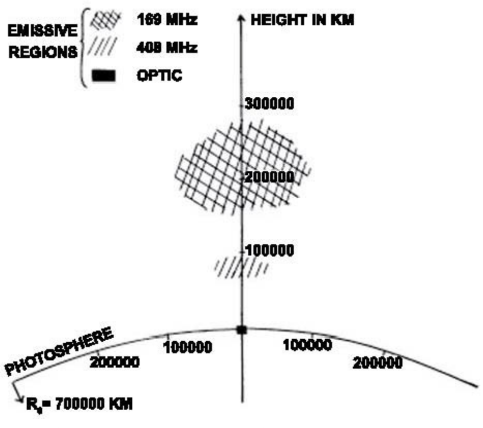


Figure 33: Schematic structure of a simple noise storm centre at 169 MHz and 408 MHz above an active region (after Clavelier, 1968).

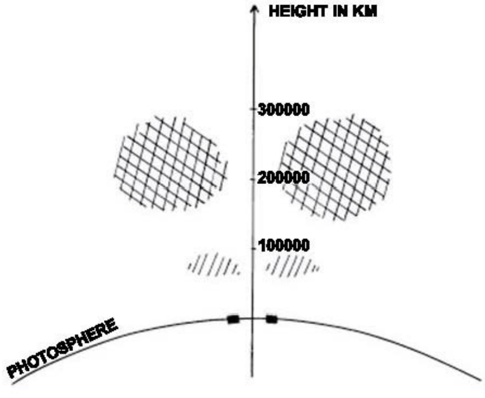


Figure 34: Schematic structure of a double noise storm centre at 169 MHz and 408 MHz (after Clavelier, 1968).

3.4.2 408 MHz Emission

Observations were obtained with a resolving power of 1.7′ which allowed the measurement of the E-W dimension of sources >1′ (Clavelier, 1967). The position of an emitting source was determined with an accuracy of 20″. The activity was compared with corresponding activities at 169 MHz and 9300 MHz, and it was concluded that the centres at 408 MHz were more stable that those at 169 MHz but less stable than centres at 9300 MHz. The respective characteristics of SVC and storm centres were summarized in Section 3.3.

Clavelier (1967) examined the association of noise storm centres with 'active regions' (AR's). Following the classification of the AR's by Martres et al. (1966), he showed that the quasi-totality of these centres was associated with magnetically-complex or anomalous eruptive AR's with anomalous inclination (i.e. an inversion line of polarities having a great inclination at the meridian).

Moreover, on certain days, Clavelier noted the existence of multiple (usually double) centres associated with the same active region (see Figure 6). The interesting result was that for all these double centres at 408 MHz, the corresponding AR appeared as two distinct eruptive zones with spots, each associated with a radio component (Clavelier, 1967; 1968a). The average height was accurately determined, and ranged between 70,000 and 80,000 km. Unfortunately, no polarization measurement was made at that time.

Results obtained at 169 and 408 MHz allowed Clavelier to draw a schematic picture of the structure of the active zones, as represented in Figures 33 and 34. The diameter was found to increase with altitude, but nothing could be said about the extension in latitude. Clavelier emphasized that the radio components of a double centre were probably independent. This was also confirmed by a study of the comparative evolution of head and tail fluxes in the same double centres: no correlation was found between the fluxes of these two components.

3.5 The Type IV Burst

3.5.1 The Discovery

In 1957 Boischot used the Nançay 32-element interferometer operating at 169 MHz to identify a new class of emission, the Type IV burst (Boischot 1957; 1958; 1959a). The observations revealed that a Type IV burst occurs after a solar flare, usually follows a Type II burst (whose emission is produced by large-scale shocks moving outwards through the corona) and lasts for tens of minutes. Type IV burst sources were generally of large diameter (typically 8′ to 12′) with no spatial structure (smooth appearance) and they moved outwards with speeds of several hundred km/s or more. An example is shown in Figure 35. Boischot and Denisse (1957) interpreted the Type IV emission as synchrotron radiation of relativistic electrons spiraling in the coronal magnetic field.

It was, however, rapidly recognized that Type IV bursts were much more complex events: they extended over a large range of frequencies in which several components with distinct physical origins could be distinguished. Intense centimetre-wave outbursts were found to be associated with metric Type IV emissions

(Avignon and Pick, 1959; Kundu, 1959). In 1961, two phases were distinguished by Pick-Gutmann (1961), as illustrated in Figure 36. The first phase (called ‘flare-continuum’ in 1970 by Wild) corresponded to a broad band emission, from centimetre to metre wavelengths, which started near the flash phase of the optical flare. The intensity variations were approximately similar at all frequencies and the radiation had little directivity. The second phase, called ‘continuum storm’ (or ‘stationary Type IV burst’ in 1963 by Wild et al.) was characterized by a smooth continuum detected from decimetre to decametre wavelengths which could last many hours and transformed progressively into an ordinary Type I storm. The emitting source was stationary, had a small angular diameter, was strongly polarized in the ordinary mode and was directed. Taking into consideration all of these properties, the continuum storm was interpreted as due to Cerenkov plasma radiation.

3.5.2 Association between Radio Emission and Energetic Particles Detected at the Sun or in the Vicinity of the Earth

3.5.2.1 *Association between Type IV Bursts and High Energy Proton Events*

The fact that Type IV emissions reveal the presence in the corona of MeV electrons stimulated many investigations on the association of these outstanding solar events with energetic particles detected in the environment of the Earth. Avignon and Pick-Gutmann (1959), and Pick-Gutmann (1961) investigated the association between Type IV bursts with relativistic protons detected by ground-level cosmic ray monitors, and proton events of lower maximum energy detected indirectly by their ionospheric effects: Polar Cap Absorptions (PCA’s) produced by 10-100 MeV protons were discovered during the International Geophysical Year (IGY, 1957-1959) (see Hakura and Goh, 1959; Thompson and Maxwell, 1960). Avignon and Pick-Gutmann (1959) found a quasi-systematic association between proton events and Type IV bursts radiating in the microwave domain with flux densities greater than 10^{-17} W m^{-2} Hz^{-1} and followed by storm continuum at metre wavelengths. These events were more favourably located in the western solar hemisphere. Avignon and Pick-Gutmann (ibid.) defined the radio importance of a flare as the energy radiated at 10 cm (i.e. the flux density at the maximum multiplied by the duration).

3.5.2.2 *Optical Characteristics of Type IV Bursts Associated with Flares*

Avignon, Martres and Pick (1964) examined the characteristics of chromospheric flares that gave rise to Type IV bursts associated with PCA’s. They found that for all the 16 selected events, except one, the active region and the flare were of a particular structure previously discovered by Ellison et al. (1962) in a study of flares connected with ground-level cosmic ray increases: two rows of centres with opposite polarities very close to each other, where the flare started between the two centres and evolved into two chains (so-called ‘ribbon flares’) that overlapped the spots (see Figure 37, Configuration A).

Building on an earlier study (see Martres and Pick, 1962), Avignon, Martres and Pick (1964) then considered the more general case of flares with long dur-

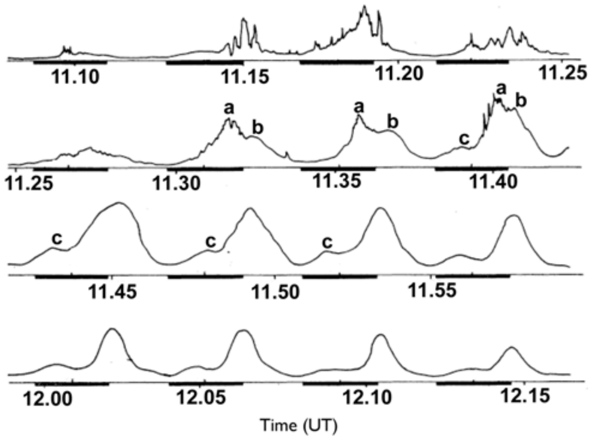


Figure 35: The Type IV burst of 7 November 1956 recorded at 169 MHz by the E-W Nançay interferometer array. This figure displays a succession of scans versus time. The variable source ‘a’ is probably the source of a Type II burst followed by the smooth source ‘b’ of the Type IV burst; the peaks ‘c’ are generated in the side lobes of the interferometer; the black bars indicate the position of the photospheric disk through the successive main lobes of the interferometer; the recording time of each main lobe is indicated below (after Boischot, 1958).

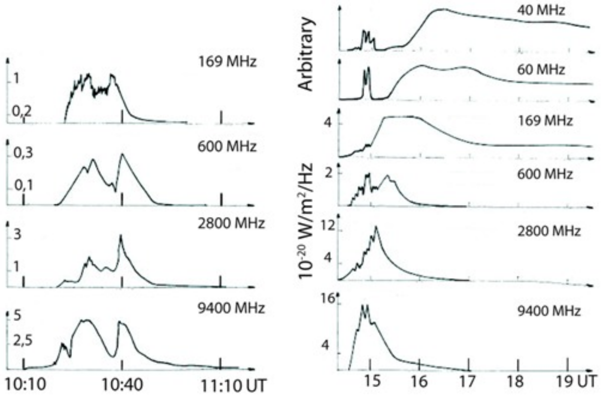
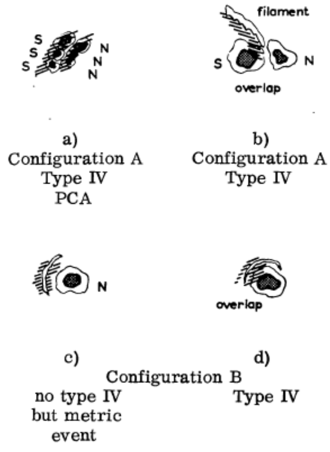


Figure 36 (left): First phase of the Type IV burst on 28 August 1958, showing the flux evolution measured at several frequencies; and (right): Flux evolution of another Type IV burst observed on 22 August 1958, when the first phase seen from high frequencies to 169 MHz at least is followed by a continuum storm of long duration that is well developed below 600 MHz (adapted from Pick-Gutmann, 1961).



a) Configuration A Type IV PCA

b) Configuration A' Type IV

c) d) Configuration B

c) no type IV but metric event

d) Type IV

Figure 37: Characteristics of flares at optical wavelengths associated with long-duration radio events at metre wavelengths that are either Type IV bursts or noise-storm enhancements (adapted from Avignon, Martres and Pick, 1964).

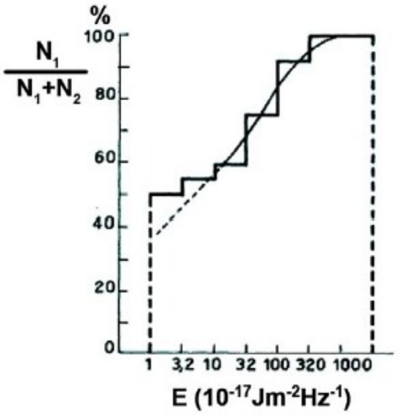


Figure 38: Probability of a flare to be associated with a SSC vs. their radio importance, i.e. the energy radiated at 2800 MHz. N1 and N2 correspond to the number of cases which are respectively geomagnetically-active or -inactive (after Caroubalos, 1964).

ation radio events at metre wavelengths which were either Type IV bursts or noise-storm enhancements. They were led to propose a new classification based on the radio importance and schematized in Figure 37.

For those events that were not associated with PCAs, the existence of a 'plage-filament', which occurred at the boundary between opposite polarities of the magnetic field, seemed to determine the location of the Hα flare and the occurrence of the metric event. When the configuration was A′ or B-c), and not B-d), the metre-wavelength Type IV event seemed to be associated with an Hα flare overlapping a sunspot. It was concluded that the occurrence of strong radio emission was enhanced by the presence of a strong gradient of the longitudinal magnetic field due to the proximity of spots of opposite polarities (see also Section 3.3 and Figure 21).

3.5.2.3 *Solar Radio Bursts and Geomagnetic Storms*

In 1964, Caroubalos investigated the association between Type IV bursts and sudden storm commencements (SSCs). Each Type IV burst was characterized by two parameters: its radio importance (the energy radiated at 10 cm) and its spectral character, defined as the ratio p of the duration of the metric emission measured at 169 MHz to the duration of the microwave emission measured at 10 cm (2800 MHz); the value of this parameter provides information on the existence of a second phase. The main results of this study are summarized as follows:

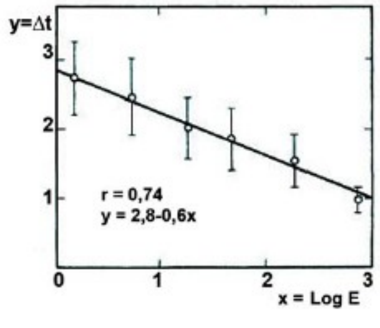


Figure 39: Time of disturbances followed by a SSC vs. the radio importance of the associated flare (after Caroubalos, 1964)

(1) The probability for Type IV bursts to be followed by SSCs is a function of their radio importance. Figure 38 shows that this probability increases rapidly for events with energies greater than 30×10^{-17} Jm^{-2} Hz^{-1} at 2800 MHz. The existence of a second phase of relatively long duration appears to be an essential condition for a Type IV burst to be followed by a SSC.

(2) There is a statistical relationship between the Sun-Earth transit time of the disturbances responsible for SSCs and the radio energy emitted by the associated Type IV bursts (see Figure 39).

In January 1960, a review paper on the properties of Type IV bursts and on their association with solar cosmic rays was presented at the First International Space Science Symposium in Nice (Denisse, et al., 1960).

4 THE CRAB NEBULA AND THE OUTER CORONA

With 3.8′ E-W pencil beams 2° apart, the 169 MHz E-W interferometer had the potential to also contribute in a significant way to the study of the outer corona through the observation of selected discrete radio sources while they were near the Sun.

The first such project took place in June 1957 when the Crab Nebula (Taurus A) was occulted by the Sun. Although observations were only possible on June 11 and 13, an increase in the diameter of the source was noted on both occasions. But more importantly, there was an

> … actual *increase* of total flux received from the Crab Nebula on the 13th; this result suggests that refractive processes in the corona might play an important role. (Blum and Boischot, 1957: 206).

In June of 1958 the Crab Nebula was again used to investigate the outer corona, and the Nançay observations confirmed both the increase in source diameter and in flux density as Taurus A approached the Sun. Figure 40, where data from 1957 and 1958 have been pooled, shows that both effects commenced when the Crab Nebula was at about $15R_{\odot}$. In a previous paper in this series we noted (Orchiston et al, 2007: 239) that it is interesting to compare these French results with Slee's 85.5 MHz observations of the same 1957 and 1958 events. He found that

> … the distribution of Crab nebula radiation is markedly affected by refraction and large-scale coronal irregularities. The secondary peak … was recorded in both 1957 and 1958, and suggests the existence of semi-permanent regions in the corona of higher than average electron density. (Slee, 1959: 151).

Slee also noted short-term changes in the transmission properties of the corona, which he associated with the ejection of disturbances from active regions on the solar disk.

5 NON-SOLAR RESEARCH WITH THE 169 MHz INTERFEROMETERS

5.1 The E-W Interferometer

As noted in a previous paper in this series (Orchiston et al., 2007: 239):

> One of the most challenging problems facing radio astronomers in the 1940s and 50s was to identify optical correlates for the many discrete sources found in the

course of the various sky surveys. Because of the comparative lack of resolution at radio wavelengths, it was difficult to determine the precise positions of most sources, but instruments like the Nançay 32-element E-W grating array (with its 3.8′ pencil beams) offered some hope. It is no surprise, therefore, to learn that this instrument was used by Boischot (1959[b]) to investigate source positions in the late 1950s. He subsequently published a table containing 25 different sources between Declination +60° and −20°, listing for each the Right Ascension, Declination, diameter or an upper limit to this parameter, the flux density and any correlation that could be made with sources detected by previous investigators.

5.2 The N-S Interferometer

By the end of 1961 the N-S interferometer was operational, and its 3.4 × 7′ pencil beam was used extensively by Mohan Joshi (1962) at 169 MHz for non-solar work. His principal project was to measure the precise positions and flux densities of 112 different radio sources. Most of these were identified with discrete sources recorded earlier at Fleurs in Australia (Mills, Slee and Hill, 1958) or during the Cambridge 3C survey (Edge et al., 1959).

An important outcome of Joshi's work (1962) was to resolve the controversy surrounding the optical identification of the radio source Hercules A. In the relevant area of the sky there were three different galaxies, but sources recorded at the Owens Valley Radio Observatory and Cambridge tallied with two of these. Joshi's Nançay observations showed conclusively that the 'Cambridge galaxy' was the correct identification (see Figure 41).

6 HERITAGE ISSUES

In 2003, the IAU established the Historic Radio Astronomy Working Group under the joint umbrellas of Commissions 40 (Radio Astronomy) and 41 (History of Astronomy) in order to encourage research into the early history of radio astronomy. One of the objectives of the WG is to establish how many of the pioneering radio telescopes used worldwide prior to 1961 have survived, and France has an important 'claim to fame' in this regard.

One of the Nançay radio telescopes discussed in this paper—the distinctive 9300 MHz 16-element interferometer designed by Steinberg and Pick—has survived in close to its original configuration, apart from the replacement of valves by transistors in the receiving system. Actually, to say that this radio telescope "… has survived …" is something of an understatement, for after more than fifty years operation it continues to contribute to science by providing daily strip scans of the one-dimensional distribution of solar radio emission

As the founder and inaugural Chair of the IAU Working Group, one of the authors of this paper (W.O.) believes that from a heritage perspective the 9300 MHz grating array at Nançay stands as a beacon of hope for world radio astronomy. Since almost all of the notable antennas from the pre-1961 era have long since disappeared, this radio telescope is an important part of our *international* radio astronomical heritage, and as such it should be preserved for the benefit of future generations. Furthermore, in terms of hardware, it is all that remains today from the pioneering era of French radio astronomy.

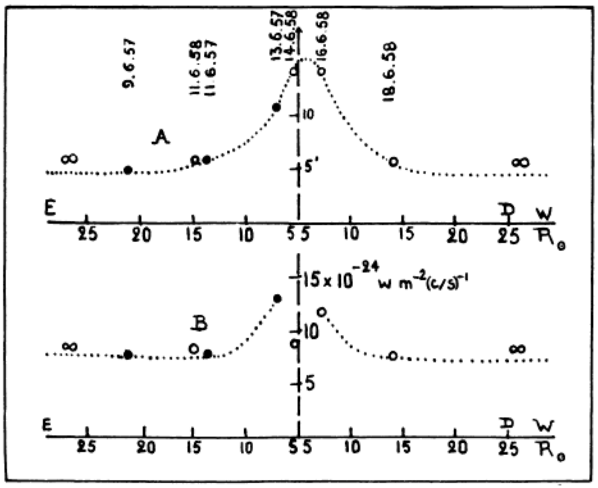


Figure 40: Variations in the apparent diameter (curve A) and flux density (curve B) of the Crab Nebula as it was occulted by the Sun in 1957 and 1958 (after Blum and Boischot, 1959: 283).

7 CONCLUDING REMARKS: NANÇAY AND THE FOUR LAST DECADES

The end of the 1960s was marked by the development in solar radio astronomy of a new generation of instruments giving access to spatially-resolved observations of the corona, with the construction of the first two radio-imaging instruments, the Culgoora Radioheliograph in Australia (Wild, 1967) and the Teepee T-Array at the Clark Lake Radio Observatory in the U.S.A. (Erickson and Fisher, 1971). In France, a new radio heliograph (NRH) was designed for Nançay which would provide images with a high temporal cadence of 100 images per second. This instrument was built in successive stages at the single frequency of 169 MHz. The first version, operational in 1976, was restricted to one dimension in the E-W direction (Bonmartin et al., 1977). Today, the NRH provides 2-D images in the frequency range 150-450 MHz. It allows quasi-simultaneous multi-frequency observations with a maximum number of 10 frequencies and a limit of 200 images per second (Kerdraon and Delouis, 1997).

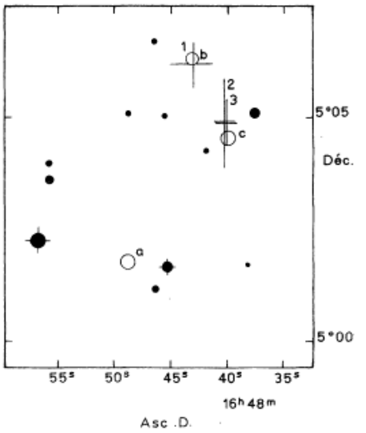


Figure 41: The region of the sky containing the discrete radio source Hercules A. Galaxies are marked by a, b and c and the crosses indicate source positions obtained by the Caltech (1), Cambridge (2) and Nançay (3) groups (after Joshi, 1962: 398).

In Nançay, there was also emphasis on high resolution spectroscopy at decametre wavelengths of solar and Jovian radio bursts, both in time and frequency (see Boischot, 1974). The Nançay Decameter Array operating in the 10-80 MHz frequency range was designed and built in the mid-1970s (Boischot et al., 1980; Lecacheux, 2000), and consists of two phased antenna arrays in opposite senses of circular polarization, each with an effective aperture of 4,000 m^2.

We do not intend to describe here the large number of results obtained in the last four decades with these instruments. We shall, however, emphasize the importance of coupling ground-based radio observations with space radio instruments for simultaneous or complementary observations in other parts of the electromagnetic spectrum (e.g. see Pick and Vilmer, 2008). The involvement of Nançay in space missions was first illustrated by the STEREO-1 (Caroubalos and Steinberg, 1974) and STEREO-5 (Poquerusse and Steinberg, 1978) experiments which were designed to detect and measure the directivity of solar burst radiation at 169 MHZ and at 60 and 30 MHz respectively. These experiments were based on simultaneous observations from the Earth (Nançay) and from a Soviet space probe (Mars-3 for STEREO-1 and Mars-7 for STEREO-5). Shortly afterwards, Nançay was officially associated with NASA's Voyager mission, a spare model of the flight radio astronomy instrument (PRA) being fed by the Nançay Decameter Array at the times of the Jupiter encounters (Boischot et al., 1981).

Since this period, the Nançay radio astronomers have offered regular significant contributions to many European, Russian and U.S. space experiments dedicated to the study of the solar corona, the Jovian magnetosphere and the heliosphere, including MARS 3 and 7, GRANAT, SMM, ULYSSES, Galileo, WIND, ACE, SOHO, STEREO and RHESSI.

8 NOTES

1. In 1952, these were merely three of the four radio astronomy field stations maintained by the Division of Radiophysics in and near Sydney. The fourth was located at Dover Heights. For a review of all of the field stations and remote sites established by the Division between 1946 and 1961 see Orchiston and Slee (2005). For a detailed account of the Dapto field station, which was devoted solely to solar research, see Stewart (2009) and Stewart et al. (2011). For details of the solar grating arrays at the Potts Hill field station see Wendt (2008), and Wendt et al. (2008; 2011).
2. For events leading up to the establishment of the Nançay field station see Orchiston et al. (2007: 225-226) and Steinberg (2004).
3. Radio astronomy is not just about science and instrumentation; it sometimes involves politics and public opinion. Steinberg (2001: 513) tells about an interesting episode concerning the railway line that was to be built at Nançay for the two Würzburg antennas:

   > When the inhabitants of Nançay village heard through rumours that a rail-line was to be built in the radioastronomy station, they immediately inferred that the line was going to be linked to the National Railways network through several of their pieces of land and they became very worried. In November 1953, we thus organized a meeting of all Nançay inhabitants. I told the villagers what our plans were and insisted on the fact that our gauge was to be 6 m as compared to 1.44 m for the regular lines. We succeeded in reassuring them.

4. This project was initiated under the auspices of the IAU Working Group on Historic Radio Astronomy in 2006, and five papers have been published to date. The first dealt with Nordmann's attempt to detect solar radio emission in 1901 (Débarbat et al., 2007); the second with early solar eclipse observations (Orchiston and Steinberg, 2007); the third with the Würzburg antennas that were at Marcoussis, Meudon and Nançay (Orchiston et al., 2007); the fourth with early solar work conducted at the École Normale Supérieure, Marcoussis and Nançay (Orchiston et al., 2009); and the fifth with the Nançay Large Radio Telescope (Lequeux et al., 2010). For an earlier overview see Denisse (1984).

9 ACKNOWLEDGEMENTS

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Dr Monique Pick (Gutmann) started her research in radio astronomy in 1957 at Paris-Meudon. Under the direction of J.L. Steinberg, she participated in the construction of the Nançay 3 cm array, and obtained her Ph.D. in 1961 under the direction of Jean-François Denisse. After the 1971 fire which destroyed the receiver of the 169 MHz array, she was the Project Scientist for the new Nançay Radio Heliograph until 1985. She then was the Head of the Nançay Radio Astronomy Station for eight years. Her main field of interest is the physics of the Sun and of the interplanetary medium. After a stay in 1967 at the Enrico Fermi Institute in Chicago she became involved in many space projects. Her present interest focuses on the study of coronal mass ejections and related phenomena.

Dr Jean-Louis Steinberg began working in radio astronomy with J.-F. Denisse and E.-J. Blum at the École Normale Supérieure after WW II. On his return from the 1952 URSI Congress in Sydney he began developing the Nançay radio astronomy field station, and from 1960 through to 1965 he and M. Parise led the design and construction at Nançay of 'Le Grand Radiotélescope'. In 1965, he began developing space research at Meudon Observatory. In 1960 Jean-Louis and J. Lequeux wrote a text book on radio astronomy, which was subsequently translated into English and Russian. In 1962 he was appointed Editor-in-Chief of *Annales d'Astrophysique*, which he and his wife ran until 1969. For the next five years he was one of the two Editors-in-Chief of *Astronomy and Astrophysics*. Jean-Louis has authored or co-authored about 80 scientific publications, and has received several scientific prizes and awards.

Dr Wayne Orchiston is an Associate Professor in Astronomy at James Cook University, Townsville, Australia. His main research interests relate to Cook voyage, Australian, English, French, Indian, New Zealand and U.S. astronomical history, with emphasis on the history of radio astronomy, comets, historically-significant telescopes, solar eclipses and transits of Venus. He has published extensively, and has edited the book *The New Astronomy. Opening the Electromagnetic Window and Expanding our View of Planet Earth* (Springer, 2005). He also has a book on early Australian radio astronomy, co-authored by Woody Sullivan, which will be published by Springer in 2011. Wayne is the founder and current Vice-Chairman of the IAU Working Group on Historic Radio Astronomy.

Dr André Boischot joined the French group of radio astronomers in 1954 at the beginning of the Nançay Observatory. He was first involved with Emile-Jacques Blum in the design and construction of the 32-element E-W 169 MHz solar array. He then worked with Le Grand Radiotélescope at Nançay on non-solar projects. Then, he initiated a new program to observe the Sun and Jupiter at decametric wavelengths and was co-investigator on the NASA 'Voyager' radio astronomy experiment where he studied the magnetospheres of the outer planets.

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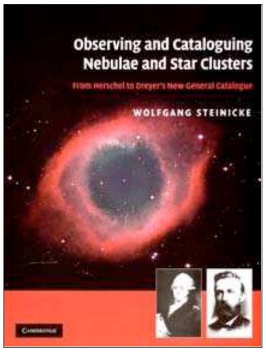
BOOK REVIEWS

Observing and Cataloguing Nebulae and Star Clusters. From Herschel to Dreyer's New General Catalogue, by Wolfgang Steinicke (Cambridge, Cambridge University Press, 2010), pp. 648, 359 illustrations. ISBN 978-0-521-19267-5 (hard cover), 248 x 192 mm, £90.00.

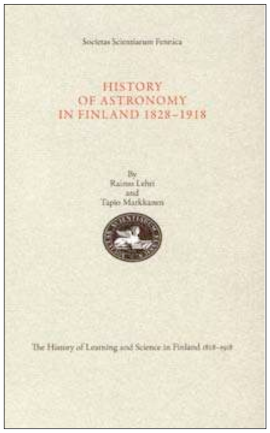


This is the slightly revised English edition of W. Steinicke's German thesis, reviewed in *JAH*^{2} 12(3), p. 255 (2009). With the text arranged in two columns, and the use of a slightly larger font size, this fundamental investigation of the prehistory, genesis and content of Dreyer's *New General Catalogue* makes a much more agreeable read than the German print-on-demand book. With 359 figures, among them many portraits of nowadays little-known astronomers and contemporary sketches of objects, 238 tables and 1628 references, this will remain the standard reference work in the field. An appendix gives a timeline of major events, from Messier's 1781 catalogue up to Dreyer's and Bigourdan's studies in the early twentieth century. This is followed by a long table with technical data on telescopes employed for nebular work, arranged by site. The final 28 pages contain indexes of names, sites, objects and subjects. The numerous citations, kept in their original language in the German edition, are now all translated into English, but scholars can always turn to the properly-referenced original sources.

With this labour of love, Steinicke has provided an invaluable service to historians of astronomy and deep sky observers.

Professor Hilmar W. Duerbeck

History of Astronomy in Finland 1828 - 1918, by Raimo Lehti and Tapio Markkanen (Sastamala, Societas Scientiarum Fennica, 2010), pp. 269, 40 b&w and 38 colour figures, ISBN 978-951-653-379-0 (soft cover), 150 x 235 mm, €28.



This book is part of the series *The History of Learning and Science in Finland 1828 - 1918*, and represents the first major account on this topic written in English.

The reader should not take the above time interval too seriously: the first 100 pages describe learning in the Middle Ages, Maupertuis' degree measurement in the eighteenth century, the rise of the Abo Academy, the installation of an observatory there and the appointment of Friedrich Argelander as its Director. The infamous Abo (Turku) town fire of 1827 put an end to these activities. The decision to build a new university in Helsinki, and the close collaboration of Argelander with its architect, Carl Ludwig Engel, led to the construction of a new observatory, finished in 1834, which would be a model for other ones like Pulkovo.

The next 100 pages trace the activities of the Helsinki Observatory Directors Argelander, Lundahl, Woldstedt, Lindelöf, and the more famous Adalbert Krueger and Anders Donner, who were responsible for the Finnish share of the Astronomische Gesellschaft and Carte du Ciel sky surveys. Special chapters are dedicated to Hugo Gyldén and Karl Frithiof Sundman, two specialists in celestial mechanics. The final two dozen pages trace the history of Finnish astronomy to the present. Memberships in the European Space Agency (1985) and the European Southern Observatory (2004), as well as the joint project of a Nordic Optical Telescope (NOT) on the Canary Islands are modern examples of the international collaboration that has always influenced the course of Finnish astronomy.

This book is highly recommended as a concise overview of the important astronomical contributions made by Finland.

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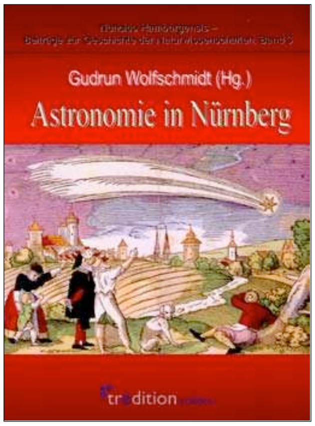
Astronomie in Nürnberg, edited by Gudrun Wolfschmidt (Tredition Science, Hamburg 2010), pp. 388, many color and b&w illustrations), ISBN 978-3-86850-609-9), 175 x 227 mm, €49.90.



This book includes 14 papers given at a conference held in Nuremberg in early 2005, commemorating the 500th anniversary of Bernhard Walther's death, and the 300th of that of Georg Christian Eimmart.

The first third of this book contains an overview paper by the editor, focussing on the instruments (including globes and atlases) used and built by Nuremberg artisans and astronomers from about AD 1450 to 1850. The next two papers deal with Johannes Regiomontanus and Bernhard Walther: Uta Lindgren investigates the impact of Regiomontanus' ephemerides on the discovery of America, and Richard Kremer elucidates the question of whether Walther was not only an excellent observer but also a theoretician who intended to use the observations for an improvement of planetary tables. Two shorter papers deal with Nuremberg calendar-makers and solar eclipses seen from the city. A paper by Hans Gaab focuses on the history of the first permanent observatory, installed by the mathematician, astronomer and engraver Georg Christoph Eimmart in 1678, up to its closure about 85 years later.

Eimmart, his observatory and his assistants and sucesssors are also the focus of the following papers: Doris Gerstl describes Eimmart's activities as an artist (copper engraver); Inge Keil gives a brief overview of Eimmart's estate of letters and papers kept at the St. Petersburg National Library; and Ronald Stoyan discusses the lunar maps of Eimmart, his daughter Maria Clara Eimmart and Tobias Mayer. Reinhard Schielicke discusses Erhard Weigel, his teachings, inventions and instruments, and Antal Adrás Deak describes the activities of Eimmart's student Johann Christoph Müller, an early Hungarian cartographer. Three more of Eimmart's assistants, Johann Philipp von Wurzelbau, Johann Leonhard Rost and Johann Gabriel Doppelmayr, are the topic of papers by Willi Deinzer, Hans Gaab and Olaf Simon, and Siegfried Kett.

All papers are in German. Due to the long digestion of the conference papers, some have been superseded in the meantime, while others are just short versions of previous publications. Eimmart's estate has been inspected in more detail in the meantime (see http://www.naa.net/ain/personen/eimmart_nachlass.asp), and more detailed biographies of Wurzelbau were given by Hans Gaab in the Beiträge zur Astronomiegeschichte series in recent years. Nevertheless, this is a good overview of the astronomical activities in this important German town.

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***Johann Bayer: Uranometria 1603*, edited by Ulrich Schaake and Winfried Berberich (Gerchsheim, Kunstschätzeverlag, 2010), 51 tables and text pages, unpaginated, ISBN 978-3-934223-35-6, 340 x 450 mm; *Die Himmelsvermessung des Johannes Bayer,* by Jürgen Hamel (Gerchsheim, Kunstschätzeverlag, 2010), pp. 176, ISBN 978-3-934223-36-3, 210 x 290 mm; the set: ISBN 978-3-934223-37-0, €178.00.**

This set contains a reprint of Bayer's famous star atlas *Uranometria*, first published in Augsburg in 1603—the atlas in which the stars were marked with Greek letters for the first time. In addition, there is an extensive explanatory book (in German) by astronomy historian Jürgen Hamel, in which he describes the development of star maps before and after Bayer, tries to elucidate the little we know about Johannes Bayer, and adds some explanatory information on the constellation maps—mainly taken from the 1720 German edition of the Bayer text. It also contains translations of the original introductory texts and dedicationary poems in Latin and Greek of Bayer's *Uranometria*.

Besides a small-size, medium-quality pocket edition of the Bayer atlas from the copy in the state and city library of Augsburg, which appeared in 1981 in West Germany, there exists the impressive large-size Archival Facsimiles Limited (England) reprinted in 1987. So, is there a need for a new edition? Most likely, although I would say that, at a time when thousands of old astronomical books are available as scanned copies in good quality (sometimes even in colour), such editions become more and more collectors' items.

The reproduction presented here is, contrary to the 1987 edition, a halftone print that better shows the delicate constellation figures, star symbols, and outlines of the Milky Way. In the 1603 edition, the plate descriptions were printed on the reverse of the plates, and in this way would faintly show up as mirror images on the plates. For this reason, the originals of the constellation plates were taken from the University of Heidelberg Library copy of the 1648 edition (where the backs of the pages are blank). However, the Heidelberg copy shows some slightly-disturbing marginal notes and lines by a previous owner. The text facsimiles were taken from the 1603 edition, kept at the Linda Hall Library in Kansas City, USA (see also http://www.lindahall.org/services/digital/ebooks/bayer/about.shtml).

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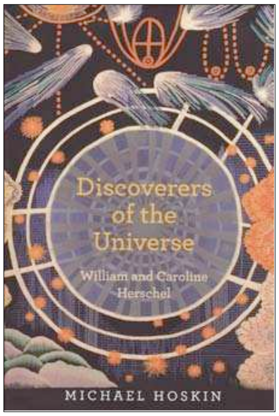
***Discoverers of the Universe. William and Caroline Herschel*, by Michael Hoskin (Princeton, Princeton University Press, 2011), pp. xviii+237, ISBN 978-0-691-14833-5, 160 x 240 mm; UA$29:95.**



Michael Hoskin is undoubtedly the maestro of the Herschels. Over the decades, he has entertained us with a succession of books and research papers that mainly relate to William and Caroline, so I have to admit that the thought of reading yet another tome on these famous discoverers of the Universe did not exactly fill me with joy.

However, I was in for a pleasant surprise, as this new book is not only very well written but it also reads like a novel, not an academic text—though in this instance fact is often stranger than fiction! Having been bombarded over the years with details of William's telescopes, his celestial observations and those of sister Caroline, and their collective invaluable contributions to astronomy, it is fascinating to read a book that sketches out the personalities and the human dramas behind these ‘key players’, as well as William’s son, John. In the process we also learn about William’s father; the gradual conversion of William from musician to astronomer (including “Hobnobbing with Royalty”); the valuable role that Alexander played in brother William’s early telescope-making exploits; how Caroline was craftily ‘kidnapped’ from her over-zealous mother in Germany so that she could ‘have a life’ in England; how she also gradually turned—but perhaps a little less willingly—from a life of music to one dominated by the stars; how William increasingly exploited her following his marriage to Mary; and last, but not least, how their son, John, “… sacrificed his chosen career in Cambridge …” in order to perform his “sacred duty” and complete his father’s lifetime work. This, of course, would lead him to South Africa.

Nonetheless, these comments should not lead you into thinking that Hoskin’s book is solely about the politics and sociology of astronomy, for it certainly is not. Among the 200 or so pages of text we also learn about William’s telescopes and the observing programs to which they were assigned by William and Caroline, William’s numerous academic publications, and John’s fields of research.

Also scattered throughout the book is a succession of figures. Some of these are taken from the original publications, others derive from the Herschel manuscripts—which Michael Hoskin surely knows better than anyone else—and others again present the appearance of houses associated with the Herschels. There are also numerous quotations, taken from published or manuscript sources. Part way through the book is a 16-page spread containing a selection of attractive coloured plates, some of which were new to me. At the end of the book there are 11 pages of notes and references relating to the individual chapters, then a brief “Bibliographical Essay” and finally, 3.5 pages of “Further Reading”. The only surprising omission is Ruskin’s 2004 book about John Herschel’s time at the Cape.

All in all I found this ‘a great read’, and Michael Hoskin is to be congratulated for producing a volume that gives us far more than a mere scientific or technical account of the Herschels. This fascinating book deserves to be on the bookshelf of anyone with an interest in the history of astronomy.

References

Ruskin, S., 2004. *John Herschel’s Cape Voyage. Private Science, Public Imagination and the Ambitions of Empire.* Aldershot, Ashgate.

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