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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.

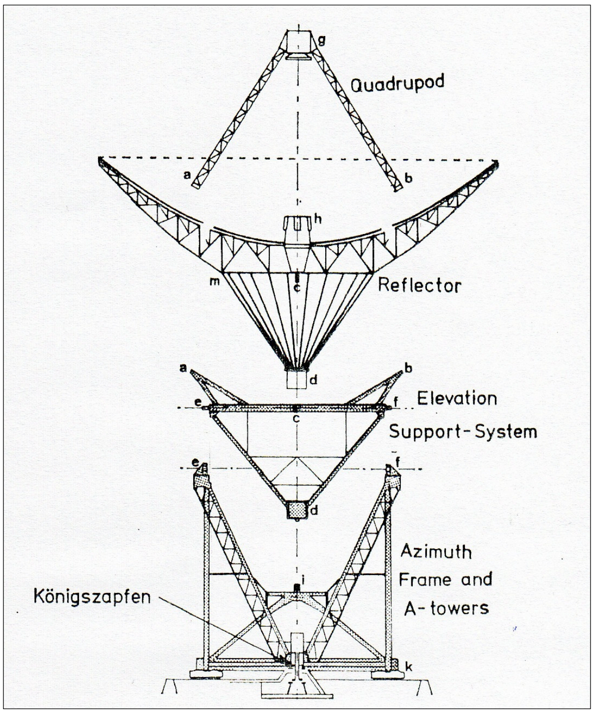

Figure 1: The basic construction design of the 100-m dish. Note the elevation bearing points (e, f) and the octahedron construction points (a, b). The ballast is at point d. There is a cross structure between points (e, f). The flexible joint lies at the apex point c.

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.

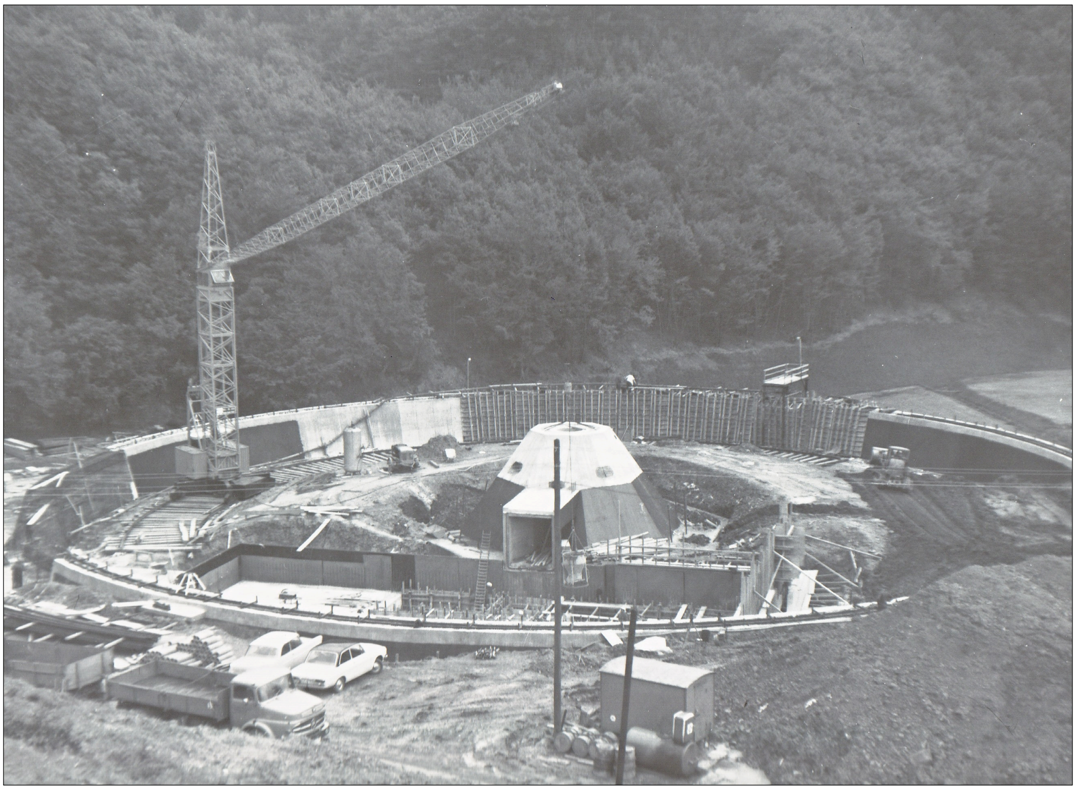

Figure 2: The foundations for the 100-m radio telescope in the construction phase (1968).

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.

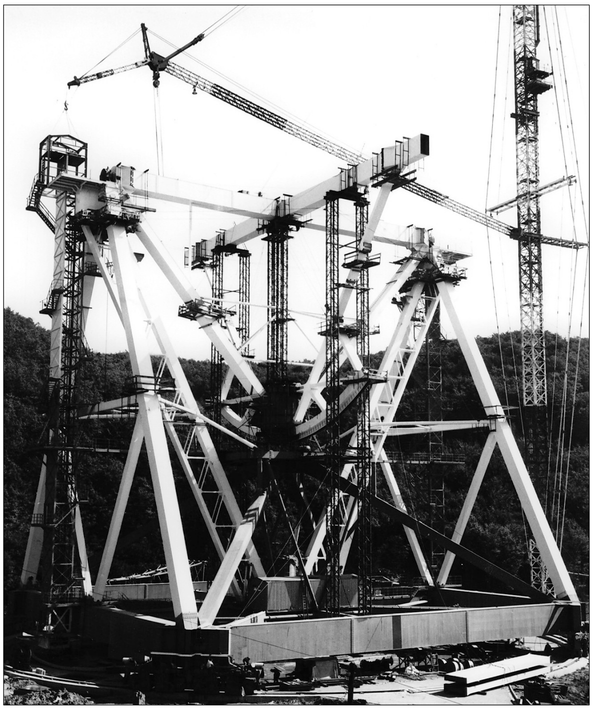

Figure 3: The A-frame support structure and the tipping section being assembled (1969). Note the cross structure in the centre where a flexible joint connects to the reflector structure.

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-

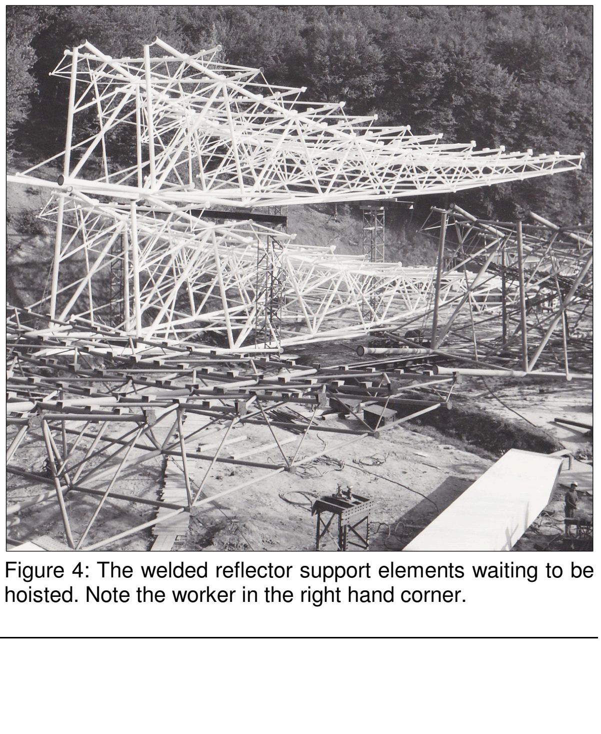

Figure 4: The welded reflector support elements waiting to be hoisted. Note the worker in the right hand corner.

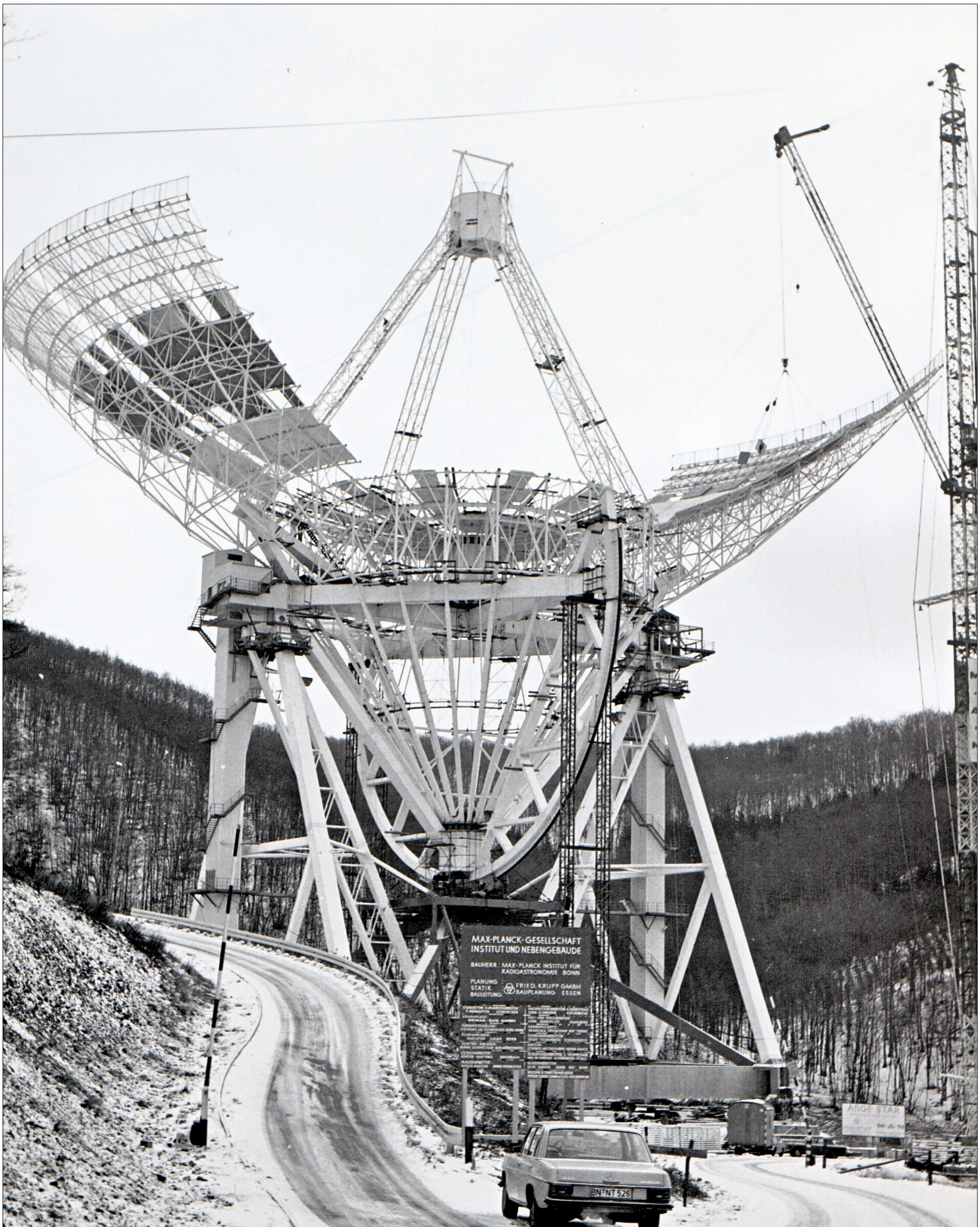

Figure 5: The early assembly stage of the reflector with two 'orange slice' sections in place. The assembly of the reflector required drive in azimuth from the very beginning.

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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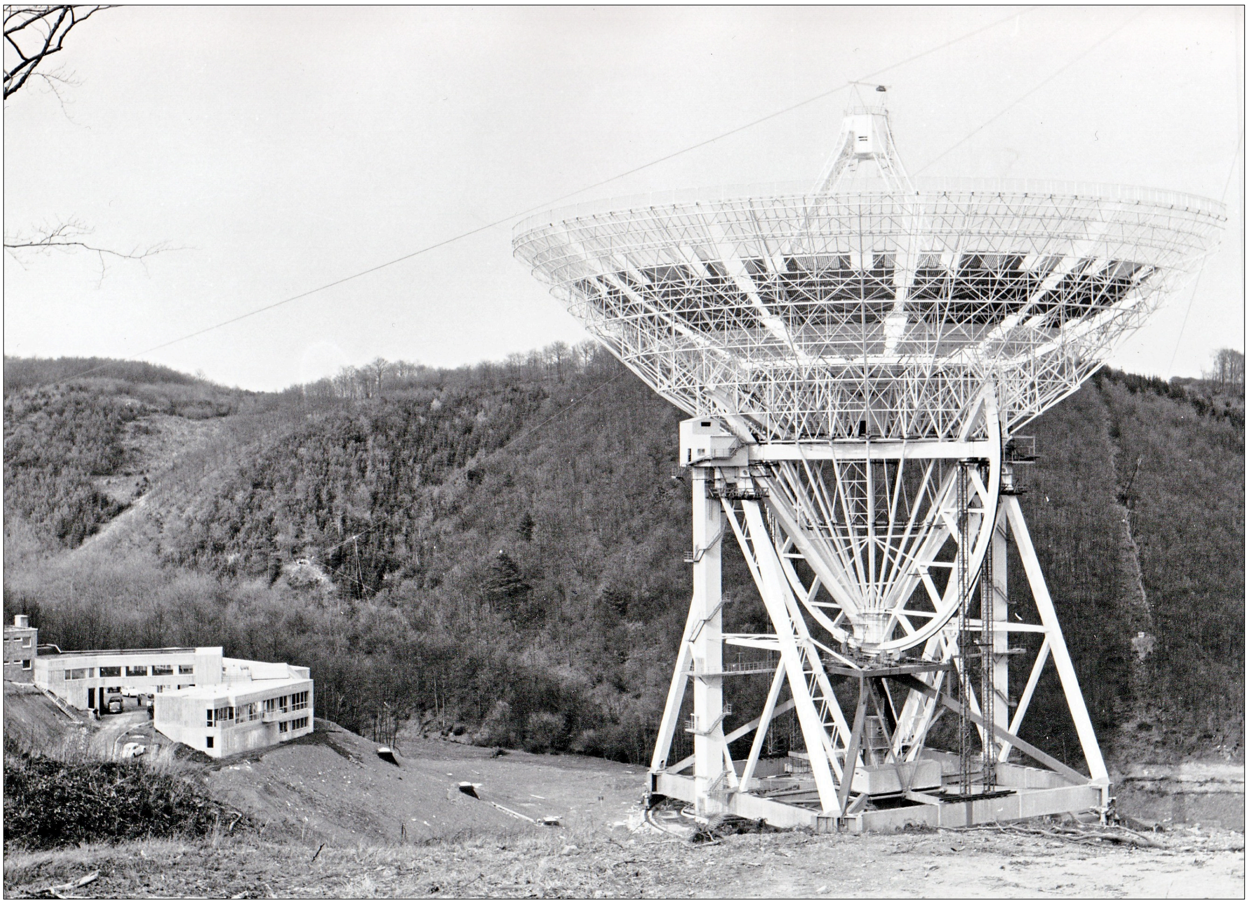

Figure 7: The view of the almost-completed radio telescope in early 1971. The control building is seen on the left. A tunnel joins the central 'Königszapfen' to the control building and contains several ducts for cables.

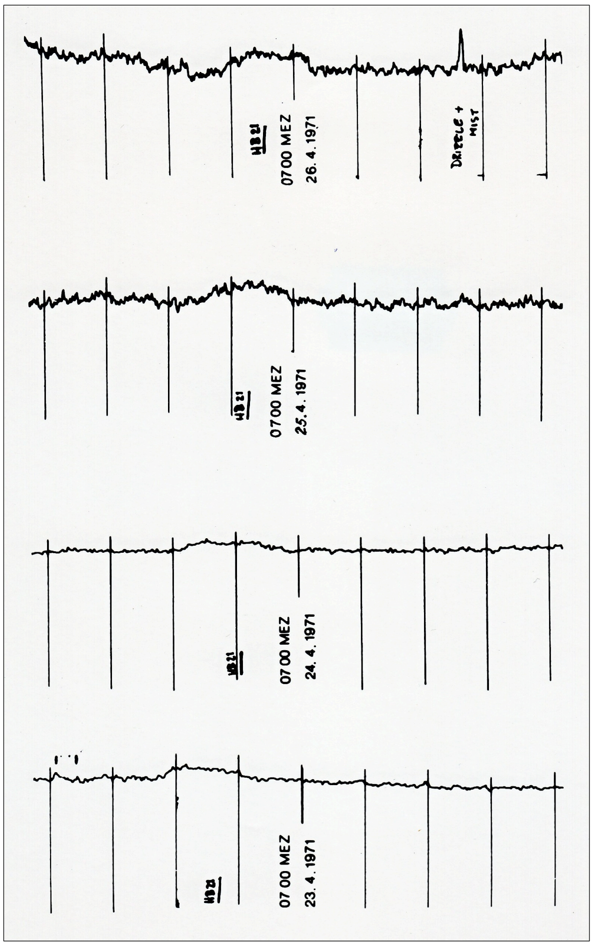

Figure 8: First light obtained with an uncooled 11-cm receiver in the primary focus. Drift scans through the radio source HB 21.

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).

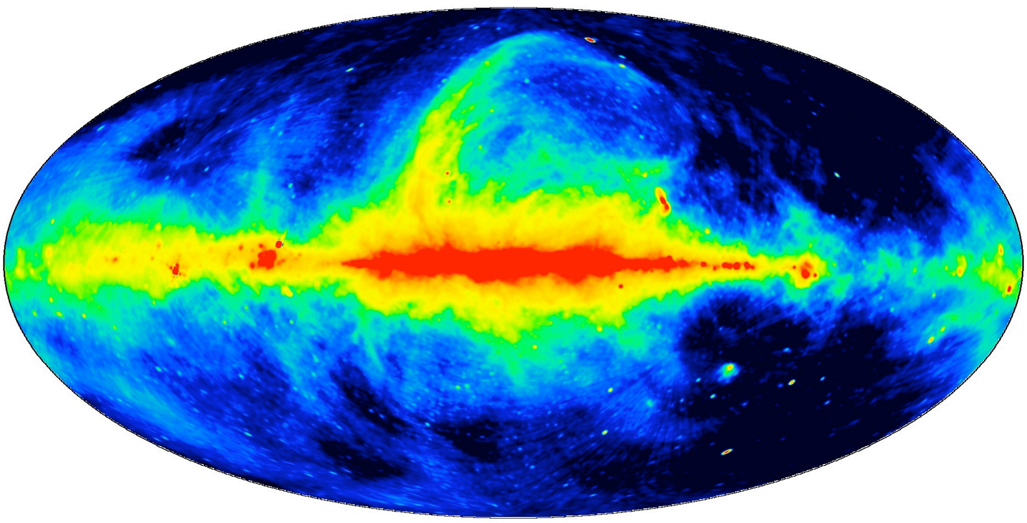

Figure 9: The 408 MHz all-sky radio continuum survey, a combination of observations with radio telescopes at Jodrell Bank, Effelsberg and Parkes (after Haslam et al., 1982).

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

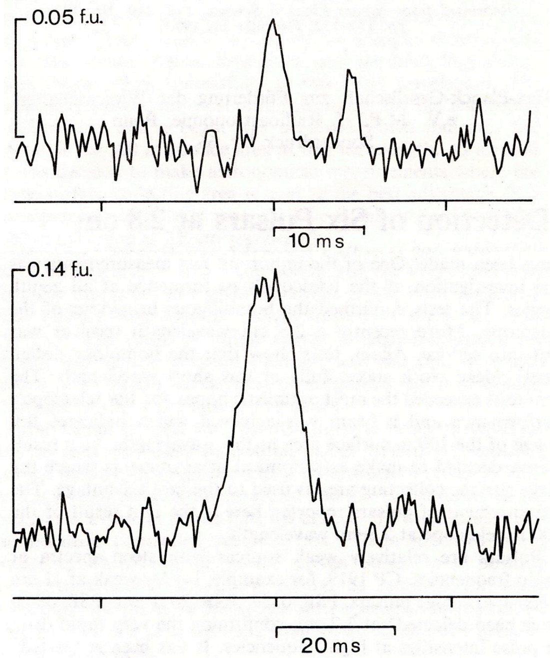

Figure 10: The first observations of pulsars at 2.8 cm. Top: BP 2020, bottom: JP 2021 (after Wielebinski et al., 1972).

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).

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

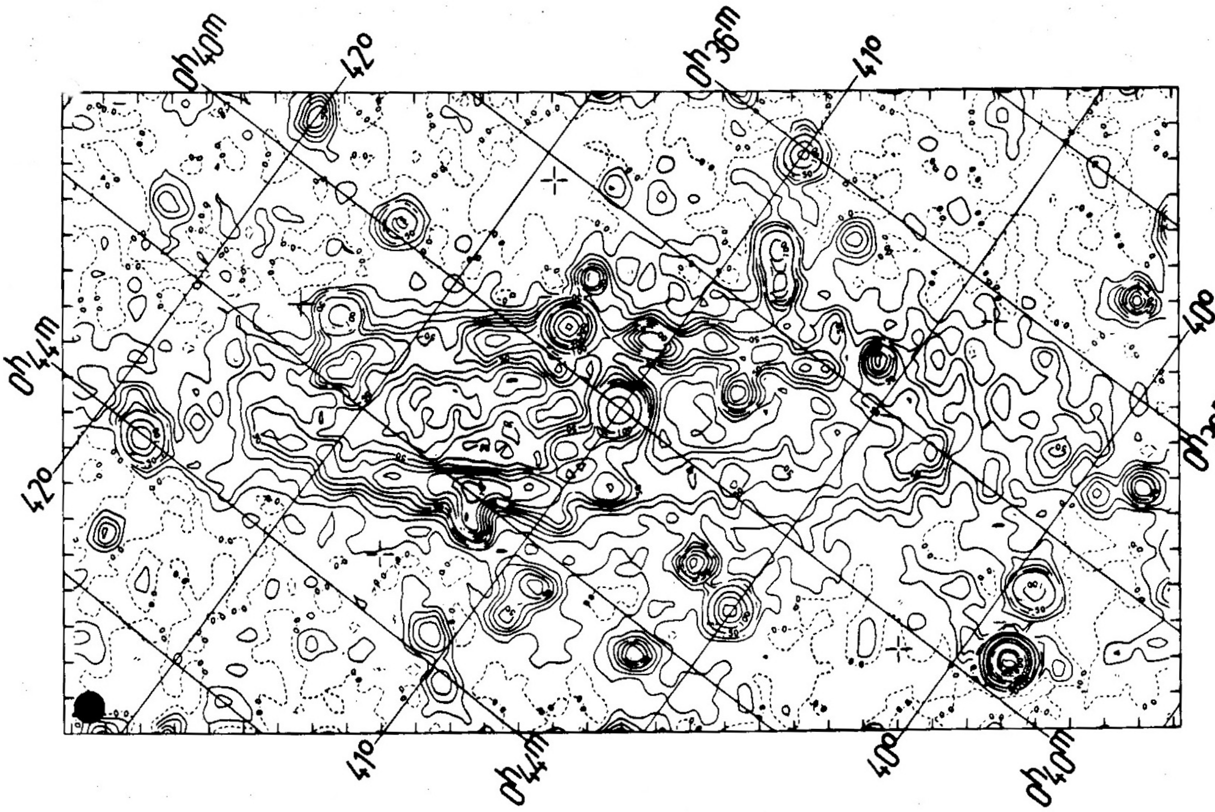

Figure 11: The radio continuum map of the Andromeda Nebula (M31) at 11 cm (after Berkhuijsen and Wielebinski, 1974).

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.

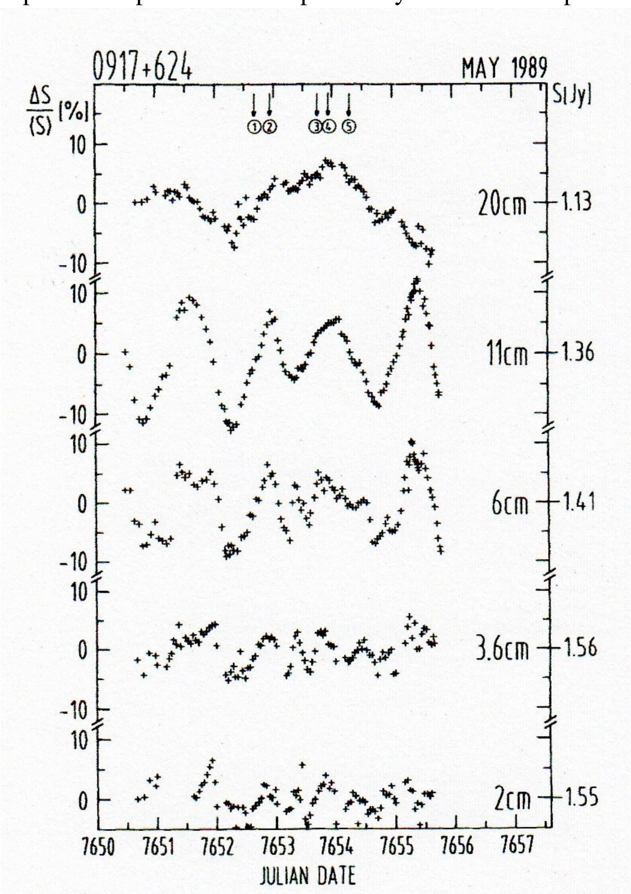

Figure 12: Simultaneous observations of intra-day variability in Effelsberg and at the VLA (after Qian et al., 1992).

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.

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.

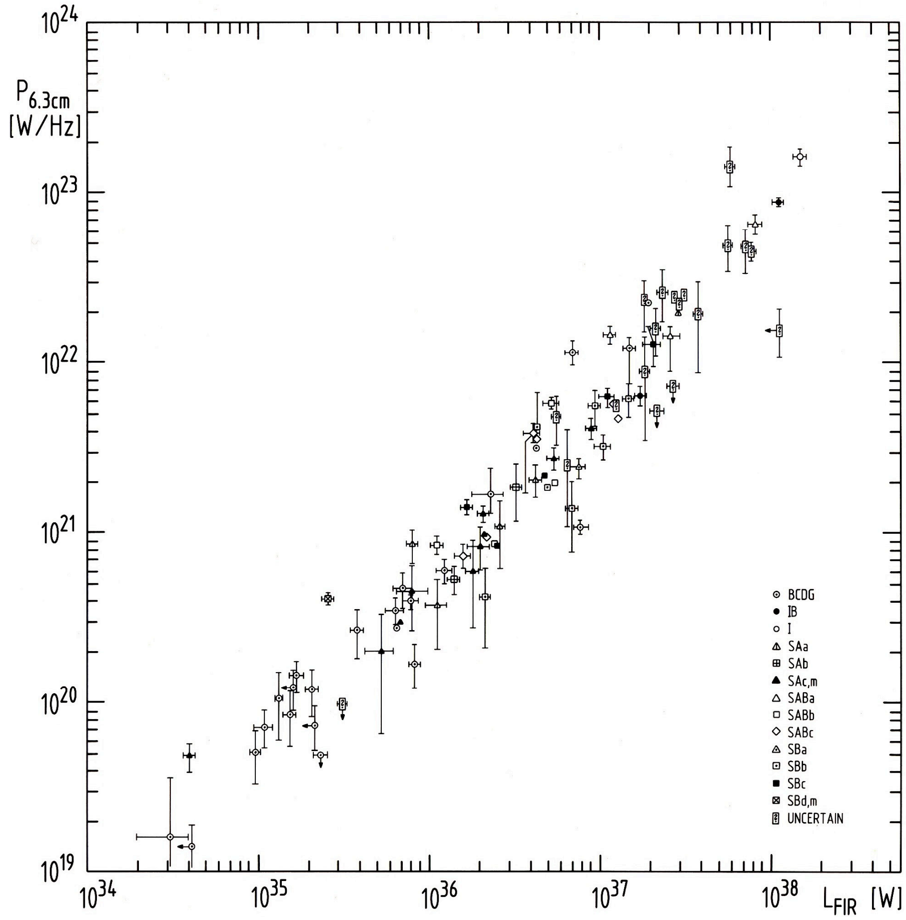

Figure 13: The FIR-radio continuum correlation (after Wunderlich et al., 1987).

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-

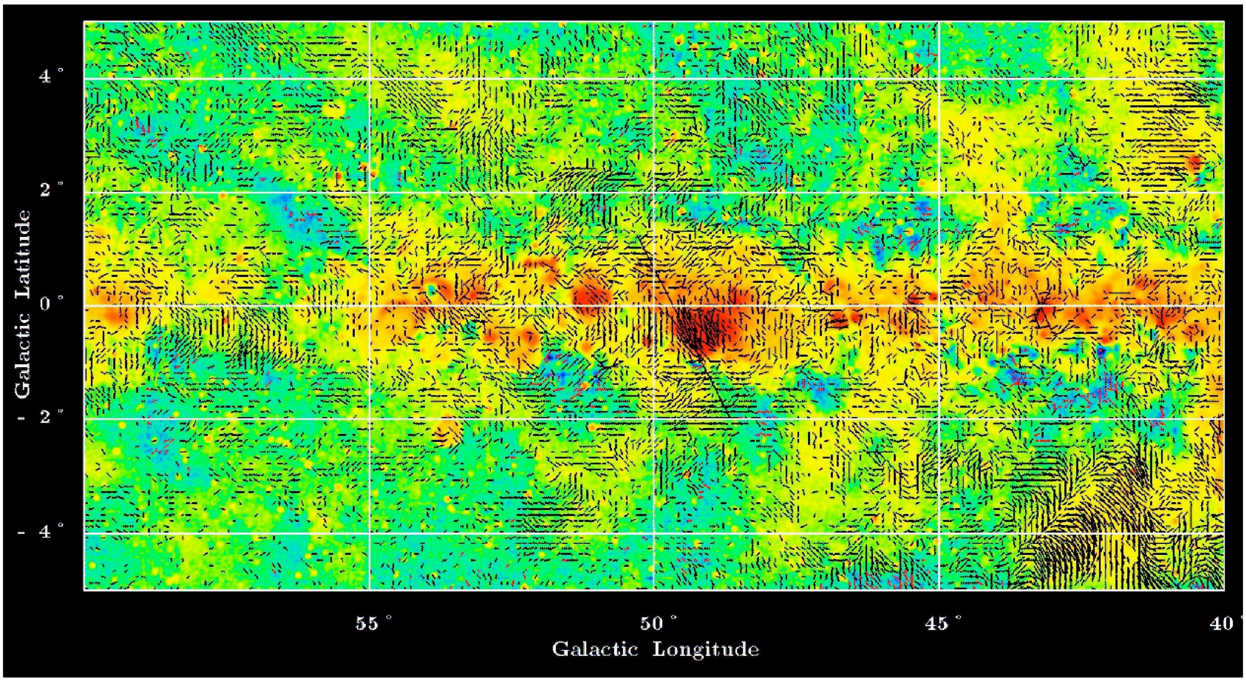

Figure 14: A section of the Galactic Plane with polarization observed at 11 cm in Effelsberg (courtesy Professor Dr E. Fürst, MPIfR).

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 mono-energetic electrons.

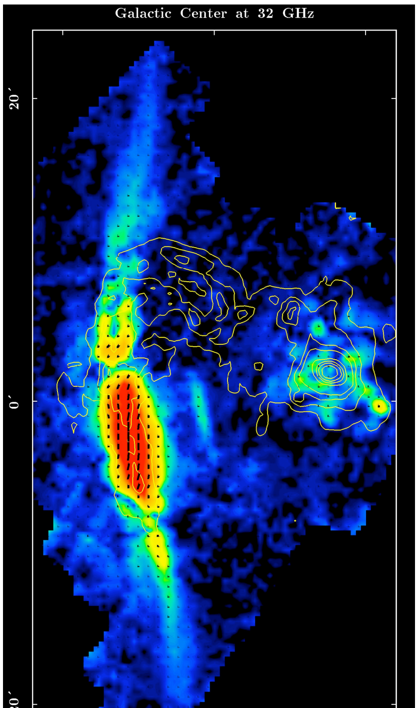

Figure 15: The Galactic centre at 9 mm in the radio continuum (courtesy: W. Reich, MPIfR).

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).

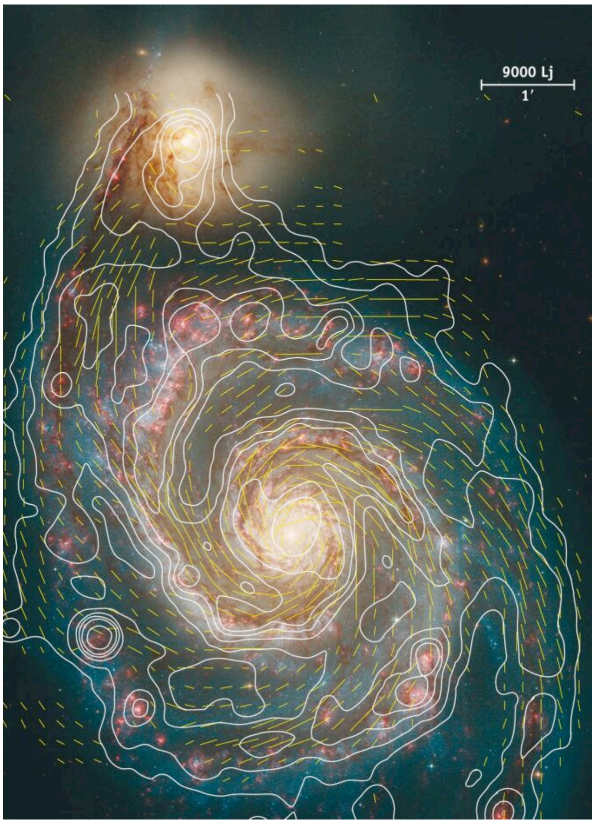

Figure 16: The magnetic field of M51 based on Effelsberg and VLA observations (Fletcher et al., 2010).

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).

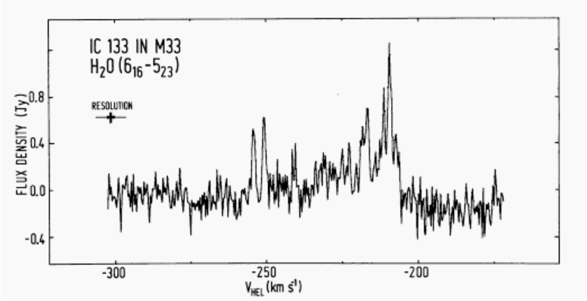

Figure 17: Detection of H_2O maser emission in the galaxy M33 (after Churchwell et al., 1977).

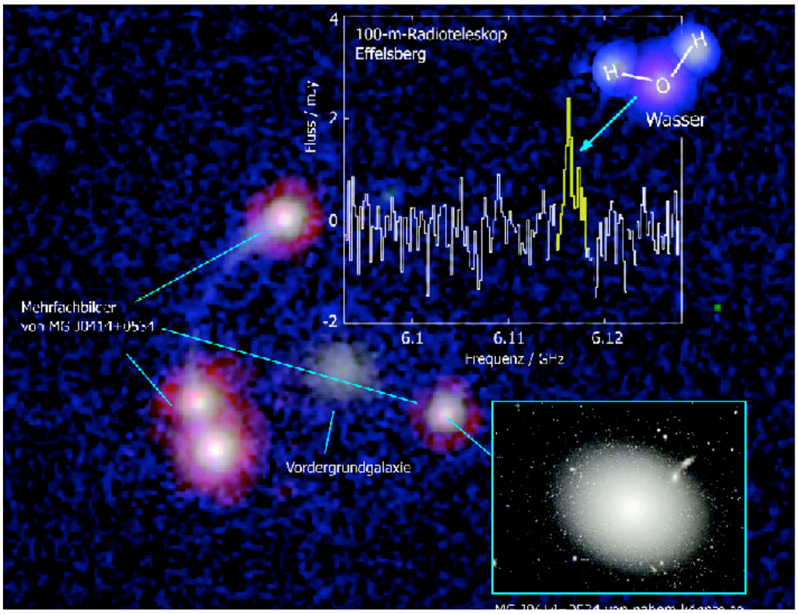

Figure 18: Water maser emission in quasar MG J0414+534 (after Impellizzeri et al., 2008).

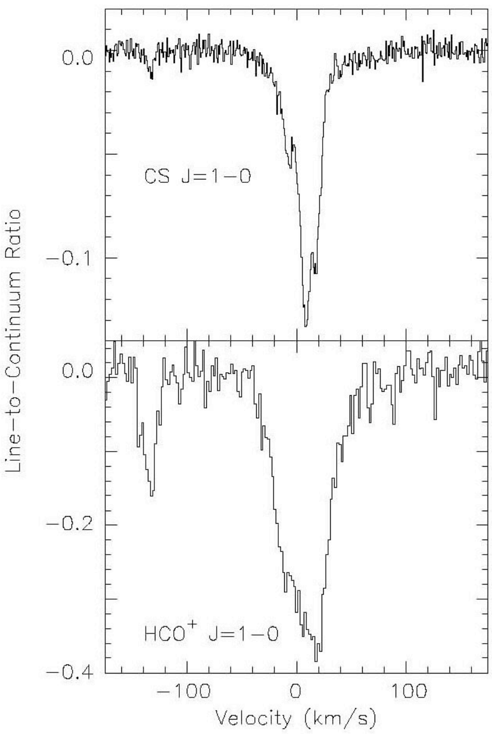

Figure 19: The radio galaxy PKS 1830-211 showing molecular absorption by CS and HCO^+ (after Henkel et al., 2009).

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

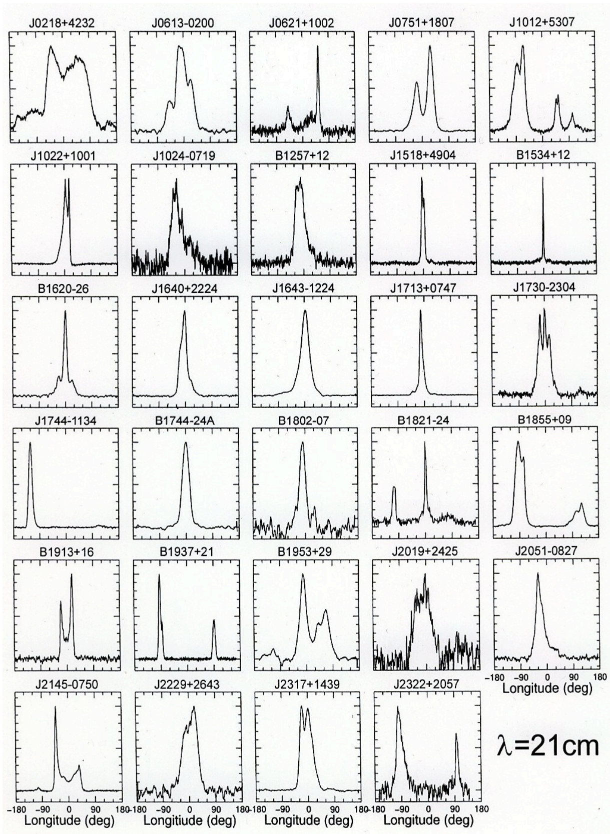

Figure 20: The Effelsberg millisecond pulsar survey (after Kramer et al., 1998).

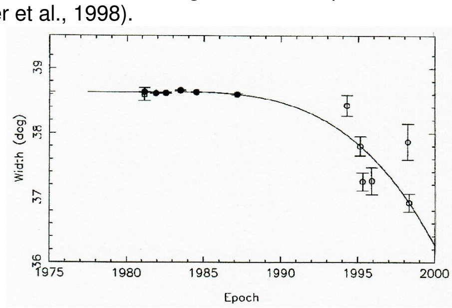

Figure 21: Component separation of pulsar B1913+16. Early data are from Arecibo. Note that the 1995 to 2000 observations, that confirmed the precession, came from Effelsberg (after Kramer, 1998).

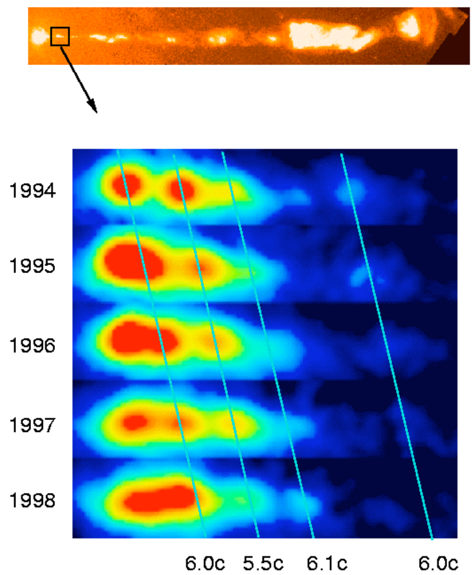

Figure 22: Superluminal motion in the jet of M87 (courtesy: Dr T.P. Krichbaum, MPIfR).

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

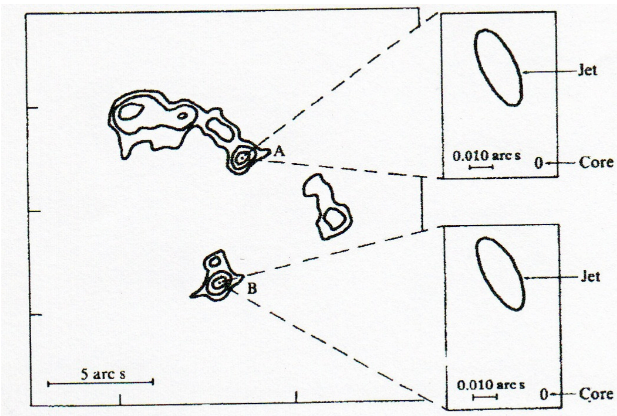

Figure 23: Gravitational lensing of the double quasar 0957+561 (after Porcas et al., 1981).

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-milliarc-second 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).

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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