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A HISTORY OF RADIO ASTRONOMY POLARISATION MEASUREMENTS

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Abstract: While intensity of electromagnetic radiation (radio, infrared, light, or X-ray) gives us primary information about the distribution of the baryonic matter in the Universe, polarisation is a parameter that enables us to investigate many additional details. Polarisation at radio frequencies gives us details of emission processes since the non-thermal synchrotron process dominates at low radio frequencies in emission regions. In addition, polarised radio sources can be used as probes of the intervening interstellar medium through which the radio waves are propagated. Faraday rotation effects are observed and in conjunction with known thermal emission can be used to determine magnetic fields. The Zeeman effect, a direct method of determining magnetic fields, depends on the observation of the circular polarisation components of a spectral line. In this paper I describe the early polarisation observations of radio sources, but in addition I follow the developments through to the present day.

Keywords: radio astronomy, polarisation

1 INTRODUCTION

The beginnings of radio polarisation studies date back to the publications of James Clerk Maxwell (1831–1879) who in his famous equations had to account for the polarisation of electromagnetic waves. Subsequent work by Heinrich Hertz (1857–1894) showed that polarisation is a basic consideration in the transmission of electromagnetic waves from a transmitter to a receiver. The 'Hertzian Dipole' is still a basic radiating antenna element used in antenna theory. Hertz showed that dipoles had to be aligned to receive transmitted radio waves while 90° misalignment led to no detectable signal. Later, radio engineers were at the forefront in defining polarisation: the Institute of Radio Engineers in 1942, followed by the Institute of Electrical and Electronic Engineers in 1969. Only in 1973 did the International Astronomical Union publish its definitions.

The early observations of radio emission by Jansky (1905–1950) and Reber (1911–2002) at first eluded interpretation. Whipple and Greenstein (1937: 181) discussed the "… interstellar radio disturbances …" and concluded that there was "… failure of black-body radiation to account for Jansky's observations quantitatively." Henyey and Keenan (1940) gave an account of the intensities expected from (radio) free-free emission of hydrogen and argued that they did agree with the quoted intensity values of the Reber (1940) observations, possibly within a factor of two. Here it must be noted that the methods of intensity calculations were problematical at that time, with engineers discussing with physicists and astronomers how intensity was to be defined. Reber (1944) followed up his earlier publication with the first radio map of our Galaxy. Writing also in 1944, Unsöld (1946) argued that Reber's intensity values could be explained by thermal emission if the interstellar gas had a temperature of 100,000K.

Radio observations of the Sun made as early as 1939 but published only after 1945 (e.g. Hey, 1946; Reber, 1946; Schott, 1947), usually at metre wavelengths, implied effective temperatures of around millions of degrees. The intensities were lower at higher frequencies, which again suggested the failure of the thermal interpretation. The solar community was the first to search for an alternative interpretation. Kiepenheuer (1946) discussed the emission of electrons in a magnetic field as a source of solar radio waves. This discussion was continued by Unsöld (1947) who agreed that in addition to thermal radio waves from the Sun 'Ultra-strahlung' must be present during eruptions. A review of the possible interpretation of cosmic radio waves was given by Reber and Greenstein (1947), who hinted at a non-thermal spectrum for solar emission. In a much-forgotten paper Moxon (1946) actually presented results of observations of our Galaxy at three frequencies, clearly deriving a non-thermal spectrum. Elder et al. (1948) and Schwinger (1949) studied the emission in synchrotron generators, and they coined the term 'synchrotron radiation', which was produced by energetic electrons in magnetic fields. This radiation, as observed when the accelerated electrons entered the Earth's magnetic field, was polarised.

The earliest reports about the polarisation of radio emission came from observers studying the Sun (e.g. Martyn, 1946; Little and Payne-Scott, 1951; Payne-Scott and Little, 1951), negating the thermal free-free process. The next step in interpretation was taken by Alfvén and Herlofson (1950), who suggested that electrons in magnetic fields generated the radio emission exhibited by the newly-discovered 'radio stars'. Kiepenheuer (1950) extended this interpretation, pointing out that this emission process may also apply to the radio emission from our Galaxy. Finally Shklovsky (1953: 983) proposed "… that emission of the Crab Nebula at radio and optical bands is synchrotron radiation of relativistic electrons in the magnetic field." In the USSR, Dombrovskii (1954) made optical observations of the Crab Nebula and showed that the light was linearly polarised, concluding that it was synchrotron emission, as suggested by Shklovsky. This great idea changed the whole thinking about the origin of cosmic radio waves.

Linear polarisation of synchrotron emission in a uniform magnetic field (e.g. Westfold, 1959; see Figure 1) is seen normal to the magnetic field orienttation and can be as much as 75% of the total intensity. In addition, a small (relative to the linear polarisation) circular polarisation component is expected (e.g. Legg and Westfold, 1968). An extensive review of the synchrotron emission process was published by Ginzburg and Syrovatsky in 1965.

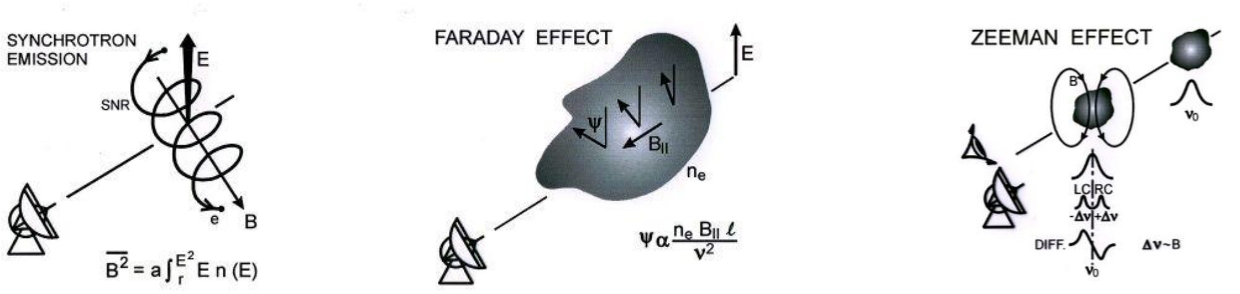

Figure 1: The basic effects of importance in radio astronomy polarisation studies. Left: Synchrotron emission; centre: Faraday rotation; and right: the Zeeman effect (after Wielebinski and Klein, 2010).

The search for radio polarisation concentrated on the Crab Nebula (also known as Taurus-A). The detection was preceded by numerous negative reports, albeit at long wavelengths, until success was finally achieved at short radio wavelengths. The depolarisation of the radio waves was expected to be strongest at low radio frequencies due to the Faraday effect in thermal regions. The detection of radio polarisation of the Crab Nebula was made at 3.15cm (Mayer et al., 1957), confirming depolarisation at longer wavelength. In a way, the Crab Nebula can be considered the 'Rosetta Stone' of radio astronomy as it allowed progress in our understanding of cosmic radio emission.

The detection of polarised radio waves from Jupiter followed (see Radhakrishnan and Roberts, 1960). In 1962 detections of diffuse radio polarisation in our Galaxy were made (Wielebinski et al., 1962; Westerhout et al., 1962), and ionospheric Faraday rotation of the detected linear polarisation was observed by Wielebinski and Shakeshaft (1962). Also, the radio galaxies Cygnus-A (Mayer et al., 1962a) and Centaurus-A (Bracewell et al., 1962) were observed to be polarised, confirming the synchrotron emission interpretation. These detections laid a foundation for the study of cosmic magnetic fields in radio sources. Linearly-polarised radio emission gives us information about the magnetic fields normal to the line of sight. Faraday rotation (see Figure 1) that is detectable, for example, in Centaurus-A (Cooper and Price, 1962) and in our Galaxy (Muller et al., 1963) occurs along the line of sight in thermal interstellar regions, adding another parameter to the study of magnetic fields. With these two pieces of information we can delineate the morphology of magnetic fields in three dimensions.

The Zeeman effect (see Figure 1) requires the observation of the difference between left and right circular polarisations that are produced in a magnetic field. The Zeeman effect at radio frequencies was predicted by Bolton and Wild (1957) to be observable in the HI line. The first reliable detection of the radio Zeeman effect was achieved by Verschuur (1968). Pulsars were discovered by Hewish et al. (1968) and immediately reports of their polarisation were made (see Lyne and Smith, 1968). In fact, the polarisation of pulsar signals was an important step in their interpretation in terms of rotating neutron stars. Meanwhile, the detection of Faraday rotation in clusters of galaxies implied the presence of magnetic fields in intergalactic space.

The study of polarisation is highly instrumentally dependent. Hence progress takes place in steps, in response to new technical possibilities. The development of new technologies, like digital polarimeters, and new analysis software, like rotation measure synthesis, led to new conclusions.

Synchrotron emission, which is polarised, is generated by relativistic electrons in magnetic fields. The *E*-vector is seen normal to the magnetic field orienttation. Maximal linear polarisation in a homogeneous magnetic field is 75%, but in practice only a much lower polarisation percentage is usually observed.

The Faraday effect rotates the *E*-vector in a thermal medium in a parallel magnetic field. The Rotation Measure (*RM*) is a parameter derived from multi-frequency polarisation observations:

$$RM = \psi\,\lambda^{-2} \quad \text{radians metre}^{-2} \qquad (1)$$

where ψ is the angle of Faraday rotation and λ is the wavelength.

The Zeeman effect is the splitting of a line by a magnetic field into two circularly-polarised components. The difference between left and right circular polarisation gives the magnitude of the magnetic field for a particular spectral line.

The Zeeman effect allows the determination of magnetic field intensity directly since each line species (HI; OH; H_2O) has its own typical difference between left and right circular polarisations (e.g. see Heiles and Crutcher, 2005). On the other hand, determination of the magnetic field intensity from radio continuum data is indirect. One important method is to assume equipartition between magnetic fields and cosmic rays (e.g. Beck and Krause, 2005). The observed Faraday rotation also can be used when the path length and electron density are known. With pulsar observations this technique is of particular importance since both the Rotation Measure and Dispersion Measure are determined—this is again a direct method of determining the magnetic field strength (e.g. see Lyne and Smith, 1969).

2 TECHNIQUES OF RADIO POLARISATION OBSERVATIONS

Radio polarisation observations were a driver for instrumental developments. For solar observations at metre wavelengths crossed dipole antennas were usually used (e.g. Little and Payne-Scott, 1951; Payne-Scott and Little, 1951). The next simplest observation mode is to place a linearly-polarised feed at the focus of a single parabolic dish radio telescope. The feed can be rotated or else the feed may remain fixed in the telescope and the Earth's rotation can be used. These methods were pioneered for example by Mayer et al. (1957) who used the 50-foot Naval Research Laboratory (NRL) dish. Instrumental effects were dominant and many improvements were necessary to make reliable radio polarisation measurements. A simple dipole-reflector feed in a parabolic reflector has an elliptical beam pattern (different beams in the *E* and *H* planes) and hence instrumental signals can look like real linear polarisation. In particular, the effects of ground radiation must be carefully calibrated.

The next step in the evolution of the polarimeter was to place two orthogonal dipoles as feeds of a parabolic radio telescope. By switching between the orthogonal dipoles and rotating the whole system more reliable polarisation values could be obtained. At higher frequencies waveguide feeds are used, but crossed dipoles are invariably needed to couple out the orthogonal polarisations. In such circular waveguide feeds an additional metal collar-like structure can be added to adjust the antenna feed (amplitude and phase distributions) for minimum instrumental polarisation. The collar-like structure was developed in Cambridge by Wielebinski (1963) resulting in successful polarisation detection. Considerable progress to obtain polarisation purity was attained by using corrugated multi-mode wave-guide structures (e.g. Minnett and Thomas, 1968). Such structures allow the superposition of several waveguide modes and hence give a designed phase-amplitude distribution that could be optimised for the best polarisation performance. Antennas pick up ground radiation that appears as if it was a polarised source. By tipping the antenna a correction for ground radiation is possible. Ferrite rotators have also been used instead of feed rotation at microwave wavelengths.

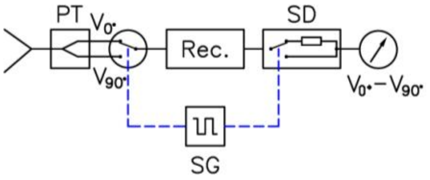

Figure 2 (upper): Block diagram of an analogue switching polarimeter. PT = polarisation transducer; Rec = receiver; SG = square wave generator; SD = synchronous detector.

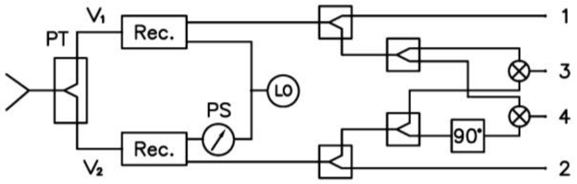

Figure 2 (lower): Block diagram of an analogue correlating polarimeter. PT = polarisation transducer; Rec = receiver; LO = local oscillator; PS = phase switch; 90° phase shift; outputs 1 and 2 = total power; outputs 3 and 4 = linear polarisation of circular outputs at transducer (after Wielebinski and Klein, 2010).

Some indirect methods of polarisation measurement were also developed: for example taking the difference between a narrow bandwidth and a broad one, as the result of the Faraday effect, polarisation could be indicated (see Razin, 1956; 1958). However, this method cannot give exact information about the polarisation intensity or the polarisation angle. In the early days of radio astronomy, when low noise amplifiers were scarce, switching between the orthogonal dipoles was employed (e.g. Wielebinski, 1963; see Figure 2 upper diagram) with the receiving system being rotated in 45° steps. The use of two amplifier chains and a correlating polarimeter (e.g. Westerhout et al., 1962; see Figure 2 lower diagram) was the ultimate practice in later years.

Polarisation can be described in terms of the Stokes parameters (I, Q, U, V), where I is the total intensity, Q and U are the linear polarisation parameters and V is the circular polarisation parameter (see e.g. Tinbergen, 2005), and

$$I^2 \geq Q^2 + U^2 + V^2 \tag{2}$$

The correlating polarimeter would analyse the incoming two channels and give the Stokes parameters (I, Q, U) if the inputs were from a circularly-polarised feed. If the two inputs were linearly polarised (which was simpler to manufacture) the outputs were (I, Q, V).

Analogue polarimeters have been constructed with bandwidths of up to 2 GHz, limited by the 90° phase-shifter characteristics (see Wielebinski et al., 2002). Also multi-channel analogue polarimeters are in use. The design of the feeds, polarisation transducer (following the feed) and the 90° phase shift in the receiver chain are crucial for successful polarisation observations.

Interferometers were used for polarisation observations from the early years of radio astronomy. Descriptions of the method of polarisation observations with interferometers can be found in Little and Payne-Scott (1951), Hanbury Brown et al. (1955), Morris et al. (1964a) and Conway and Kronberg (1969). A source would be observed with a sequence of feed dipoles in parallel and with the dipoles crossed. Rotation in steps of 45° would also be employed. There are some advantages to be had in reduction of the instrumental polarisation effects with an interferometer, but it requires good calibration. However, it must be noted that with interferometers source structure plays an important role: some spatial frequencies are lost due to the discrete antenna spacing, and they are more difficult to retrieve in polarisation than in total intensity. On the other hand, when observing compact sources the loss of the general background polarisation can be of advantage.

Aperture synthesis arrays have been adapted to map polarised radiation in extended sources (e.g. see Ryle et al., 1965; Weiler and Seielstad, 1971; Kronberg, 1972; Hargrave and Ryle, 1974) and in very long baseline interferometry (e.g. Cotton et al., 1984). Most recently, the advent of fast digital chips, in particular the FPGA chips, have allowed the construction of wide-band digital polarimeters.

A more detailed discussion of the techniques of polarisation measurement can be found in Tinbergen (2005) and in Wielebinski and Klein (2010).

3 EARLY RADIO POLARISATION OBSERVATIONS

Solar radio waves were detected as early as 1939 but publication came only later (e.g. Hey, 1946; Reber, 1944; Schott, 1947; Southworth, 1945) and indicated that in addition to the thermal quiet Sun a non-thermal component was present during solar eruptions. Radio polarisation of this solar emission was detected (e.g. Martyn, 1946; Little and Payne-Scott, 1951; Payne-Scott and Little, 1951) leading to the development of radio polarimeters (e.g. Hatanaka et al., 1955) for observations first at metre wavelengths and later at microwave frequencies (Akabane, 1958). In fact interferometers were used to study solar polarisation from the very beginning (see Cohen, 1958, and references therein). In this paper I will not describe the history of the polarisation observations of the Sun, as there are many details of the studies of the Sun that can be found in the literature (e.g. see Krüger, 1979; Kundu, 1982).

3.1 Radio Sources

In the early observations of 'radio stars' by Ryle and Smith (1948) it was noted that the emission had some similarities to solar radio radiation, and hence polarisation should be expected. Negative results of polarisation observations were first reported by Hanbury Brown et al. (1955) at metre wavelengths using a two-antenna interferometer at Jodrell Bank. At Cambridge, the long parabolic cylindrical reflectors and corner reflectors that were developed for the successful detection of radio sources were unsuitable for polarisation observations. Observations at 21cm by Westerhout (1956) using the 7.5-m 'Würzburg' dish failed to detect polarisation from selected radio sources. The next directed attempts to detect radio polarisation concentrated on the Crab Nebula. The break-through was made by Mayer et al. (1957), who used the 50-foot NRL dish at 3.15 cm to detect polarisation in the Crab Nebula, a supernova remnant (SNR). There was a steady evolution of the polarisation receivers for this historical single dish that became a leader in this field of research. Almost at the same time Kuz'min and Udal'tsov (1957) confirmed the Crab Nebula polarisation observations at 10cm. In this case a ferrite rotator was employed with a 31-m 'hole in the ground' dish. Both of these observations indicated that Faraday rotation was indeed depolarising the longer wavelength observations.

Radio emission from Jupiter was first detected by Burke and Franklin (1955) at 22.2 MHz. The emission was time variable and showed considerable circular polarisation (Franklin and Burke, 1956). This radio emission has since been interpreted to be a result of the cyclotron emission process. Later Sloanaker (1959) detected radio emission from Jupiter at 10cm. This emission was found to be linearly polarised by Radhakrishnan and Roberts (1960) at 960 MHz (λ31cm), suggesting that it was due to a non-thermal process. The polarised emission of Jupiter originated in outer regions of the planet's atmosphere, similar to the Earth's van Allen Belt, where rather strong magnetic fields are present. Two 90-foot antennas connected as an interferometer at the Owens Valley Radio Observatory (OVRO) of the California Institute of Technology were used for these observations. John Bolton, who was involved in the construction of the OVRO dishes, insisted on providing polarisation capabilities from the very beginning (see Roberts, 1994). This interferometer, with receiver instrumentation at various frequencies, specialised in polarisation observations of radio sources in the following years.

3.1.1 Extragalactic Radio Sources

Observations of polarisation from extragalactic radio sources (EGRS), at first called 'radio stars', proved to be more difficult. Earliest observations, admittedly at metre wavelengths, showed no polarisation. Observations by Hanbury Brown et al. (1955) made at 1.9m did not detect polarisation in Cygnus-A. These results can be understood today from the fact that Cygnus-A has a small-scale structure of polarisation vectors in the radio lobes and thus one needs good angular resolution to overcome the Faraday depolarisation effects. Finally, the 50-foot reflector at the NRL succeeded in detecting low linear polarisation in Cygnus-A at 3.15cm (Mayer et al., 1962a), but only the average polarisation from the whole source. The next major step in the measurement of radio galaxies came from the then newly-completed 64-m Parkes Radio Telescope: the first observations of Centaurus-A by Bracewell et al. (1962) at 11cm immediately detected polarisation. An advantage of the Parkes dish was the good angular resolution (at that time), coupled with the fact that Centaurus-A is a very large source (see Bracewell, 2002). Almost simultaneously, Mayer et al. (1962b) and Radhakrishnan et al. (1962) reported the detection of polarisation in Centaurus-A. The Parkes dish was subsequently used by Gardner and Whiteoak (1962) at 20cm to observe polarised emission in a number of extragalactic radio sources. It is debatable who was first to make a detection, but one thing is clear: John Bolton, who was back at Parkes from Caltech, pushed polarimetry to be an integral part of the capability of what was then the best single-dish radio telescope in the world. This work paved the way for a whole new field of research.

Faraday rotation (see Figure 1) was found in Centaurus-A by Cooper and Price (1962), by observing at several frequencies between 970 MHz and 3 GHz, thus adding another parameter for the study of magnetic fields. Since Centaurus-A is a source many degrees across, its *RM* could be determined for several regions. Faraday rotation takes place in a thermal medium with a magnetic field along the line of sight. This direction of investigation was followed up by Gardner and Whiteoak (1963) for a number of EGRS seen in different directions in the Galaxy. Sources near the Galactic Plane showed much higher values of *RM* (see Davies and Gardner, 1966) suggesting that polarised EGRS could be used as probes of the magnetic fields in our Galaxy. More recently, the origin of Faraday rotation has been discussed (see Farnsworth et al., 2011; Pshirkov et al., 2011), and although there are some questions of detail the general opinion remains that *RM* can be used to derive the structure of galactic magnetic fields.

The Caltech group continued to make polarisation observations using the OVRO Two-element Interferometer at different wavelengths: 21.2cm (Seielstad and Wilson, 1963), 10.6cm (Seielstad et al., 1963)

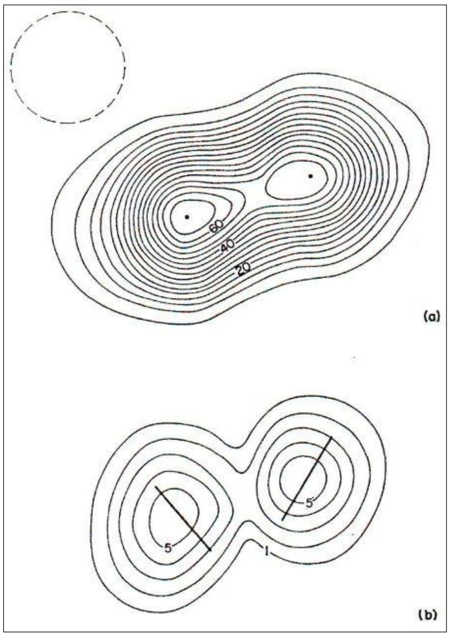

Figure 3: Early polarisation map of Cygnus-A at 1.55cm. Above: total intensity 1 unit = 0.18 K; below: polarised intensity 1 unit = 0.36 K, with the average polarisation *E*-vector (after Mayer and Hollinger, 1968).

and at 18cm (Morris et al., 1964c). With different interferometer spacings, Morris et al. (1964b) began to study the distribution of linear polarisation over the usually double sources. The realisation that the orientation of the linear polarisation vectors may be different in the two lobes was the major finding of this paper. It became clear that there is considerable structure in the EGRS with different orientations of polarisation vectors leading to depolarisation in single dish observations. A concise report on the methods used at Caltech is found in Morris et al. (1964a) and in references therein. It must be noted that the use of an interferometer (at Caltech) gave more accurate values of source polarisation since the overall diffuse polarisation was rejected, especially at the lowest frequencies. Observing at Parkes, Gardner and Davies (1966) produced a catalogue of polarisation of sources at wavelengths between 11.3 and 74cm. This catalogue was used by Davies and Gardner (1966) to confirm the earlier suggestion that the observed Faraday rotation did in fact originate in the magnetic fields and thermal regions of our Galaxy. Observations of linear polarisation were extended to 3.12cm by Berge and Seielstad (1969) using the OVRO Interferometer.

Another group that advanced the study of the polarisation of EGRS was at the Jodrell Bank Observatory (Kronberg and Conway, 1967), where a combination of the Mark I (250-foot) and Mark II (125-foot × 83-foot) radio telescopes made it the most powerful interferometer for studies of weak sources. This instrument was subsequently used by Conway and Kronberg (1969) to measure the distribution of polarisation in radio sources. A catalogue of the polarisation of EGRS at 610 MHz (Kronberg and Conway, 1970) followed. Further multi-frequency source polarisation observations were presented in Conway et al. (1972).

The National Radio Astronomy Observatory (henceforth NRAO) in Green Bank became involved in polarisation observations upon the completion of the 140-ft Radio Telescope. Discrete EGRS were observed by Sastry et al. (1967) at 6cm. Using the 140-ft dish at 1.55cm Mayer and Hollinger (1968; see Figure 3) finally solved the mystery of the low polarisation of Cygnus-A: the two lobes showed different polarisation orientations, and hence beam depolarisation gave the previously-observed low values. In addition, there were considerable *RM* gradients (Dreher et al., 1987) that led to depolarisation at lower radio frequencies. At first the 140-ft dish was in the forefront of polarisation observations. Then the successful implementation of aperture synthesis by Ryle and Neville (1962) in Cambridge led to its application in mapping polarisation in extended radio sources. Ryle et al. (1965) then published an early map of Cygnus-A. The two-dimensional distribution of polarisation in two EGRS was presented by Kronberg (1972) using Jodrell Bank Interferometer data.

The presence of circular polarisation in EGRS was under discussion from the theoretical point of view (e.g. Legg and Westfold, 1968). As a result, numerous observational attempts were made, albeit unsuccessfully. It was clear that any circularly-polarised component was very low. The first claims of successful detections came from the Nançay Radio Telescope by Biraud and Veron (1968) and Biraud (1969), with surprisingly high values. These claims were questioned (e.g. see Seielstad, 1969) or much lower limits were set (Gilbert and Conway, 1970).

Ryle et al. (1975; 1976) put a lower limit on the circular polarisation of several radio sources. Successful very low levels of circular polarisation were finally re-

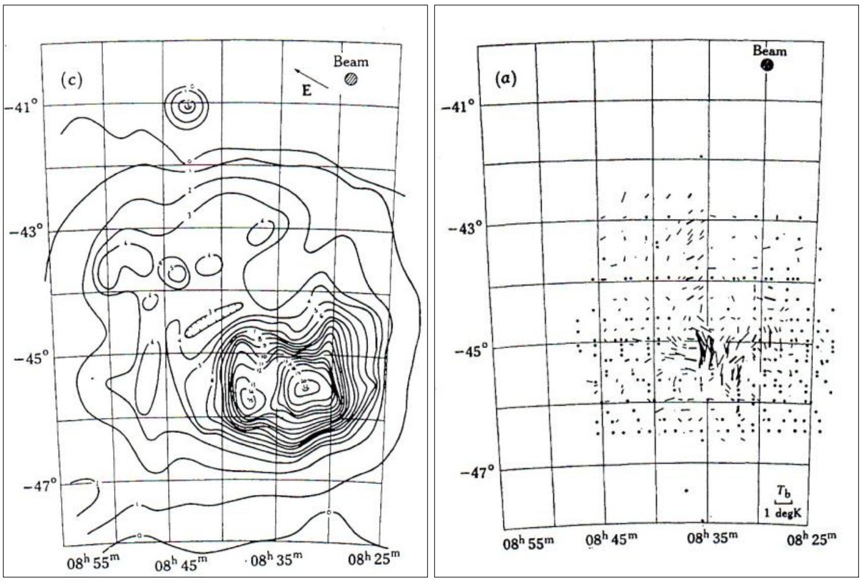

Figure 4: Early maps of the SNR Vela-X at 1410 MHz. Far left: total intensity; left: polarisation *E*-vectors (after Milne, 1968).

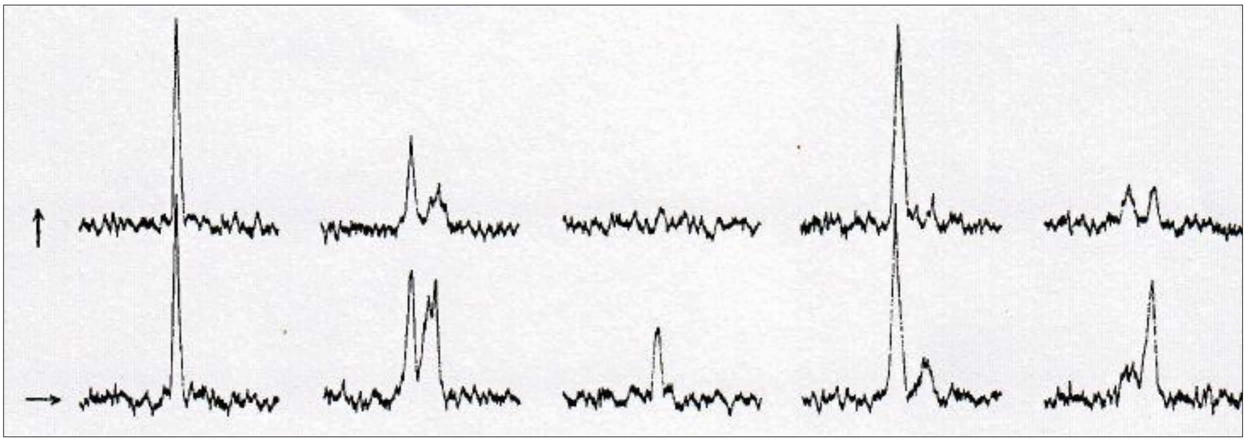

Figure 5: Polarisation of single pulses of PSR 0950+08 observed at 151 MHz with orthogonal dipoles as shown on the left (after Lyne and Smith, 1968).

ported by Conway et al. (1971), Roberts et al. (1975) and Weiler and Wilson (1977).

3.1.2 Supernova Remnants

As already discussed, the Crab Nebula, the prototype supernova remnant, was the first radio source to be detected in polarisation. It was clear from theoretical considerations that polarisation identified a SNR. However, since SNRs are less intensive than radio galaxies and the polarisation is usually a smaller fraction of the total intensity, their polarisation studies needed considerable instrumental development. In fact, at first a radio source was considered to be a SNR if found in the Galactic Plane and if it had a steep non-thermal spectrum. Using this method Milne (1970) identified 97 supernova remnants. Later flat-spectrum plerionic centre-filled sources were identified as supernova remnants, and here the presence of polarisation played a major role in their interpretation. The second SNR to be mapped in polarisation was Cassiopeia-A (Mayer and Hollinger, 1968). Cassiopeia-A (a young SNR) has a very well-developed shell structure but with a radial magnetic field. Older SNRs are invariably observed with a tangential magnetic field (e.g. Dickel and Milne, 1976). The Parkes Radio Telescope was used by Milne (1968; see Figure 4) to map the Vela-X SNR in polarisation at three frequencies. The first aperture synthesis observations of Cassiopeia-A were made by Ryle et al. (1965). Later Seielstad and Weiler (1968) published one-dimensional strip scans over four SNRs. The next development was the publication of synthesis maps by Weiler and Seielstad (1971) of two supernova remnants.

3.1.3 Pulsars

Pulsars were first discovered by Hewish et al. (1968), and have a high degree of polarisation, especially at low radio frequencies (e.g. Lyne and Smith, 1968; see Figure 5). At first linear polarisation was observed but later circular polarisation of pulsars was detected as well. Observations of polarisation by Radhakrishan and Cooke (1969) were crucial in establishing the rotating neutron star model for pulsars. Pulsars have in some ways an opposite evolution of polarisation when compared to radio sources: in radio sources polarisation usually increases at higher frequencies because of a reduced depolarisation by the Faraday effect. In pulsars there is a fall off in polarisation at higher radio frequencies (e.g. Manchester, 1971; Seiradakis and Wielebinski, 2004). This unusual feature of pulsars, attributed to the emission mechanism, is not yet well understood. The polarisation of pulsars is so stable that it can be used to calibrate the polarisation characteristics of a radio telescope (see Xilouris, 1991).

3.2 Polarisation of the Galactic Background (Foreground)

Radio astronomers began quite early to search for the radio polarisation of galactic emission. The first published report was by Razin (1956; 1958), who observed at 207 MHz (1.45m) and 91 MHz (3.3m) with low resolution antennas and claimed that he detected linear polarisation at these low radio frequencies. The observations were made by taking the difference between a narrow and broadband signal, and expecting the Faraday effect to depolarise the signal in the broadband channel. In view of later observations this detection claim must be questioned as other observers, working at similar radio frequencies, did not confirm this result. In Cambridge Thomson (1957), using a 160 MHz receiver, switched between orthogonal feed dipoles on a 7.5-m Würzburg dish. In Australia Pawsey and Harting (1960) also failed to detect any polarised signal at 215 MHz. Moving to higher frequencies (408 MHz), Pauliny-Toth et al. (1961) searched in the direction of the Galactic Spur at *l* = 30° but again failed to detect polarisation. The breakthrough came in 1961 with Wielebinski et al. (1962; Figure 6) working in Cambridge and Westerhout et al. (1962) in Dwingeloo

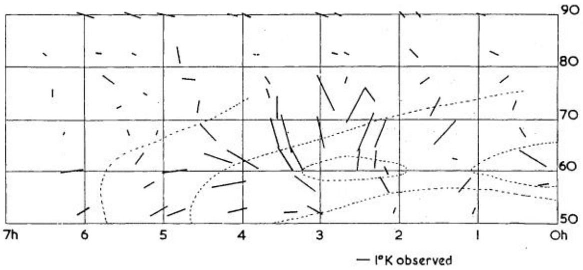

Figure 6: 408 MHz polarisation observations (*E*-vectors) of the Milky Way in the direction of the Galactic Anti-Centre with 7.5° angular resolution. Dashed lines are intensity contours of the Galactic Plane at the same frequency (after Wielebinski et al., 1962).

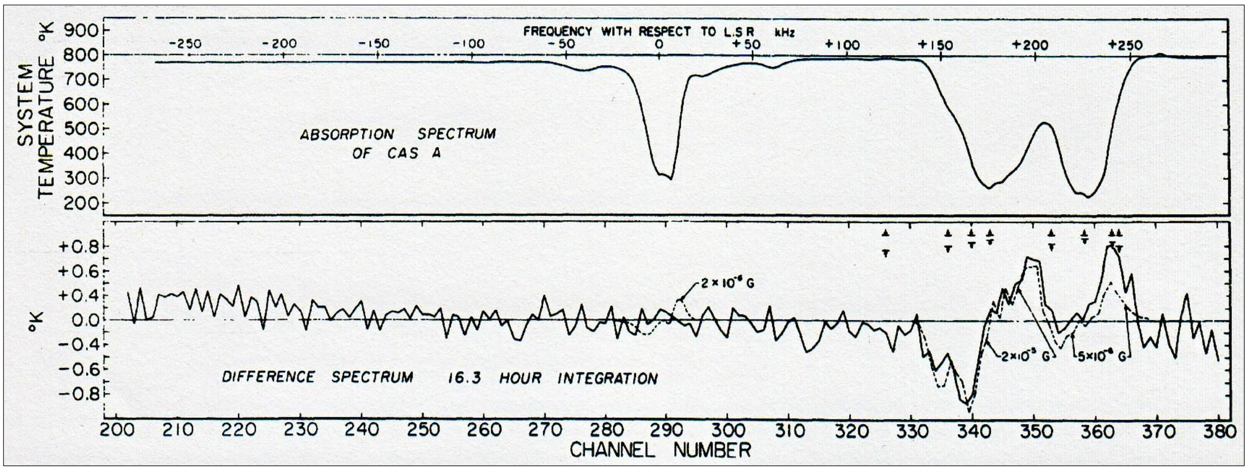

Figure 7: The first detection of the Zeeman effect by Verschuur (1968). The top trace shows the HI absorption spectrum in the direction of Cassiopeia A; the bottom trace shows the difference in left and right circular polarisations giving the typical S-like signature of a Zeeman effect detection.

making real detections at 408 MHz. Polarisation was found in many areas but in particular in the 'fan region' at *l* = 140°, *b* = 10°. The orientation of the observed polarisation vectors implied alignment of the magnetic field along the Galactic Plane. This result was in good agreement with the optical polarisation observations in this region. In addition, at *l* = 30° vertical vectors were observed suggesting that the North Polar Spur was a magnetic phenomenon. Both of these research groups were successful only after a considerable upgrade of the observing systems, with particular care given to reducing the instrumental polarisation. In Cambridge I made a new 'top hat' feed, put the receiving system on the rotating tube (which resulted in no more cable twists), and in the end I added a circulator to reduce the reflections between the Adler tube parametric amplifier and the antenna feed. In fact I was sure that I detected polarisation in 1961 but Martin Ryle insisted on additional proof of the reality of these observations. This was made by Wielebinski and Shakeshaft (1962) with ionospheric Faraday rotation studies that confirmed the reality of the galactic polarisation. Galactic Faraday rotation was detected by Muller et al. (1963) by observing the 'fan region' at 610 MHz.

A northern sky survey at 408 MHz by Wielebinski and Shakeshaft (1964) showed widespread linear polarisation. Southern sky polarisation observations were made with the Parkes Radio Telescope by Mathewson and Milne (1965) at 408 MHz and by Mathewson et al. (1967) at 620 and 408 MHz thus completing a data set for all-sky. After these initial detections the measurement of galactic polarisation became routine, especially at higher radio frequencies around 1420 MHz (e.g. Bingham, 1966). This development paved the way for the study of galactic magnetic fields.

A review of the state of our knowledge about the early polarisation results of observations of cosmic radio waves was given by Gardner and Whiteoak (1966).

3.3 The Zeeman Effect

The method par excellence for measuring magnetic fields is the Zeeman effect that depends on polarisation. A line is split by a magnetic field into two circularly-polarised components, in addition to the basic line frequency (see Figure 1c). The measurement of the frequency difference gives the magnetic field strength (e.g. Verschuur, 1968). The first detection of magnetic fields in sunspots used the Zeeman effect at optical wavelength (Hale, 1908).

In 1957 Bolton and Wild suggested that interstellar magnetic fields could be traced by observing the HI line and noting the existence of the Zeeman effect. In practice it was difficult to get a positive detection as the radio telescope had to provide a very clean circular polarisation in order to detect the Zeeman effect. After several unsuccessful attempts to measure the radio Zeeman effect (e.g. see Davies et al., 1963), the first detection was finally achieved by Verschuur (1968; Figure 7) using the NRAO 140-ft dish at Green Bank. At first all efforts were concentrated on the HI line. These observations showed that the magnetic field intensities in HI clouds were ~100 μGauss. These values were far greater than in the diffuse magnetic field in the spiral arms of our Galaxy where magnetic fields of only 3 to 10 μGauss had been deduced from radio continuum polarisation observations. Later Zeeman effect measurements in OH or H_2O molecular clouds showed even higher magnetic field strengths than in HI clouds. There are many problems in achieving the necessary polarisation purity for making successful Zeeman effect observations with radio telescopes. The differences in the opposite circular polarisations are minute and most feeds have a 'beam squint', a deadly effect for observers.

4 THE ERA OF NEW RADIO TELESCOPES WITH POLARISATION CAPABILITIES

The advent of new large radio telescopes that became operational in the 1970s (the Cambridge Ryle 5-km Radio Telescope, the Westerbork Synthesis Radio Telescope and the Effelsberg 100-m dish) opened up new possibilities to make high-class polarisation observations. These instruments allowed observations to be made with good angular resolution in the cm-wavelength range. The 100-m single dish was of particular value in many of the new polarisation observations since it was very sensitive to weak diffuse emissions. The aperture synthesis arrays were capable of high angular resolution observations and

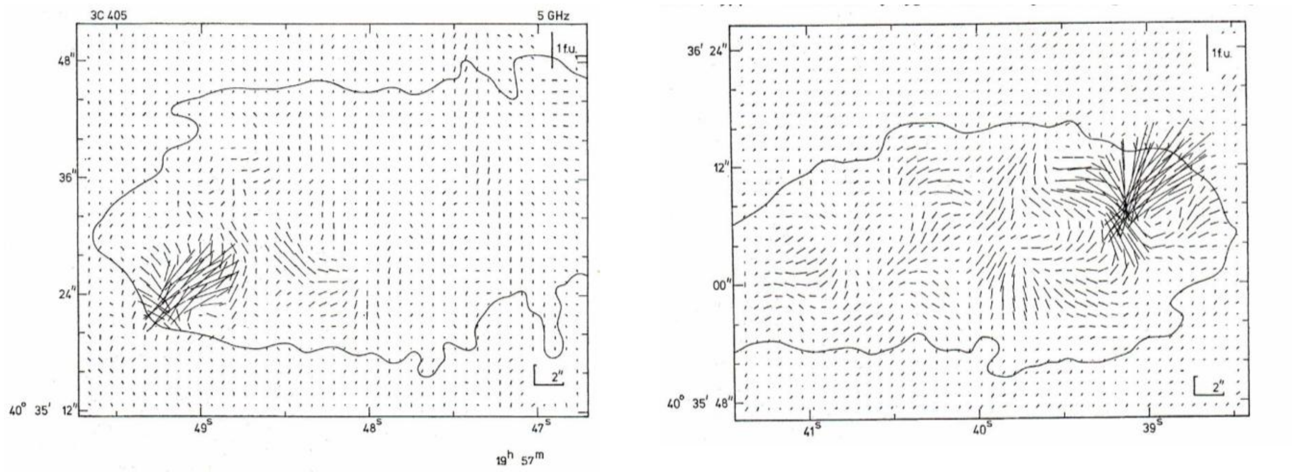

Figure 8: High resolution polarisation maps of the lobes of Cygnus-A observed at 5 GHz. The *E*-vectors are shown (after Hargrave and Ryle 1974; cf. Figure 3).

hence most suitable for compact source studies. Finally, a combination of both types of instruments gave the best data on extended objects.

The Very Large Array was inaugurated in 1980 and made a huge impact on our knowledge of the polarisation of radio sources. In particular the combination of VLA and large single dish data became of great importance in studying the polarisation of extended objects. The radio sources in the southern skies had to wait until the Australia Telescope Compact Array was completed in 1988 to see a similar dramatic development. These instruments dominate the research field up to the present day due to continued improvements, especially for polarisation measurements. In the following pages I will single out major contributions to a very rapidly-developing research field. It is not possible to make a detailed listing of all the polarisation observations made in the past 40 years. While in the 1960s the number of researchers involved in studies of radio polarisation numbered a dozen or so, a conference on magnetic fields or radio galaxies can now draw over 300 participants.

4.1 Radio Galaxies

The study of radio galaxies has made huge progress with the immense capabilities of aperture synthesis radio telescopes. A study of Cygnus-A by Hargrave and Ryle (1974, see Figure 8) using the 5-km Ryle Radio Telescope in Cambridge showed the details of the polarisation of the radio lobes of this source at 5 GHz. In a follow-up publication Hargrave and Ryle (1976) mapped Cygnus-A at 15 GHz but in total intensity only, as the steep spectrum of the emission precluded detection of polarisation. Using the Effelsberg 100-m Radio Telescope Baker et al. (1975) could map Cygnus-A in polarisation at 14 GHz but at low angular resolution. The NRAO interferometer at Green Bank also became an important source of polarisation data (e.g. Wardle and Kronberg, 1974; Kronberg and Wardle, 1977). Most of the results up to this time related to the linear polarisation.

The start of observations with the Westerbork Synthesis Radio Telescope led to a huge volume of new data on the polarisation of radio sources. For example, Miley (1973) studied the polarisation of head-tail galaxies. Westerbork studies of sources at 21cm and 6cm were used by Högbom and Carlson (1974) and Högbom (1979) to determine the spectra as well as polarisation across the sources. Multi-frequency studies have been published on many sources. The delineation of "… the largest sources in the Universe …" by Willis et al. (1974: 625) led to increased interest in polarisation studies in a bid to understand the jet-like phenomenon in radio galaxies. Multi-frequency observations were made of these large objects (e.g. see Willis and Strom, 1978; Strom and Willis, 1980). However, care has to be taken when comparing interferometer data at several frequencies: the spatial components must be compatible. Interferometers lose the large-spacing information, which can lead to misinterpretation of spectral and polarisation results.

In order to allow spectral investigations as well as robust polarisation determinations high frequency observations with the Effelsberg 100-m Radio Telescope were used (e.g. Baker et al., 1974; Stoffel and Wielebinski, 1978; Klein and Wielebinski, 1979).

The inauguration of the Very Large Array in 1980 opened up new and powerful instrumentation for mapping of polarisation. While it is difficult to single out individual papers, I would like to refer to the studies of Owen et al. (1980), Bridle et al. (1980), Perley et al. (1980), Fomalont et al. (1980) and Rudnick et al. (1985). One of the important early directions was the study of the magnetic fields in the jets of radio galaxies. With the four array configurations the aperture synthesis could be optimised for source size. One interesting development was the combination of the VLA and the 100-m Radio Telescope data for studies of radio galaxies (e.g. Kronberg et al., 1986). The general statement that can be made is: every radio galaxy shows synchrotron emission, and in cases where there is sufficient angular resolution and sensitivity polarised emission is observed. Hence all radio galaxies, out to the most distant ones at z ~ 6.0, have magnetic fields.

The development of Very Long Baseline Interferometry (VLBI) started with total intensity observations but later moved to polarisation mapping (e.g. Cotton et al., 1982; 1984). The combination of polarisation maps of jets made with the VLA and maps made with VLBI gave important information for the interpretation of emission processes in Active Galactic Nuclei (AGN).

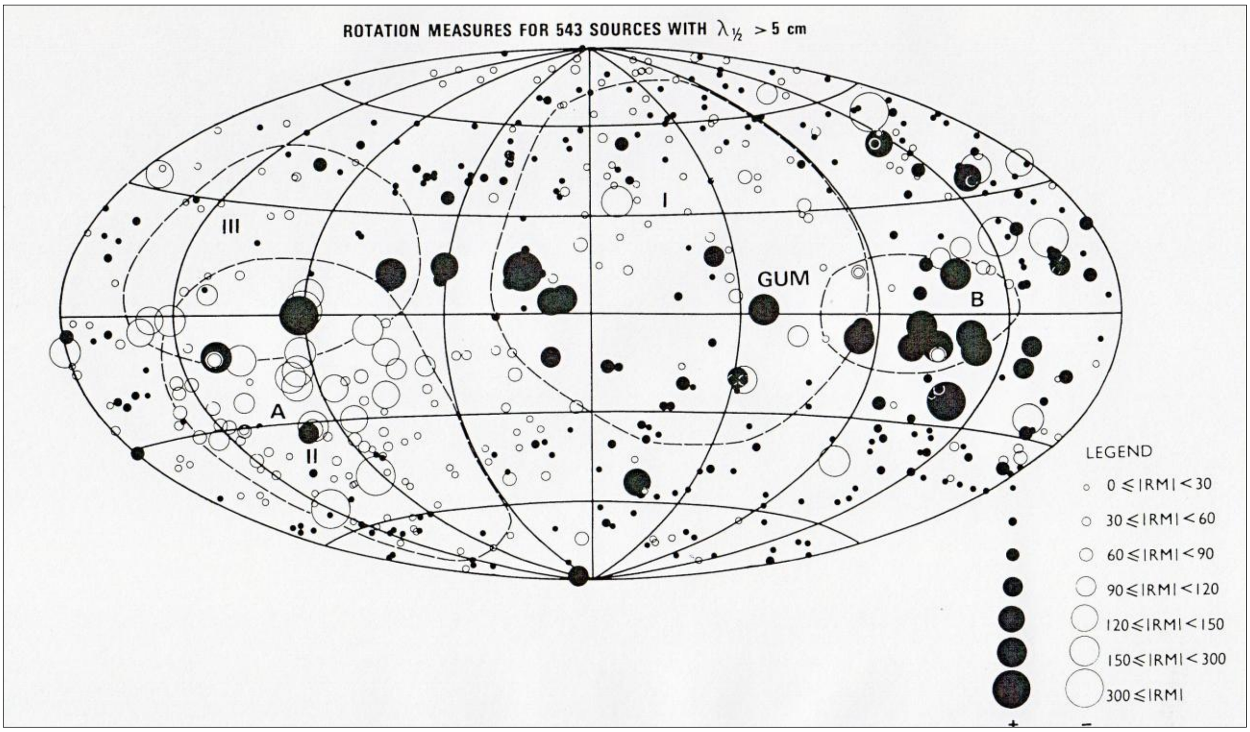

Figure 9: All-sky *RM* diagram (after Simard-Normandin and Kronberg, 1980).

4.2 Discrete Radio Sources as Probes of the Galactic Interstellar Medium

Following the early detections described in Section 2.1 a whole armada of researchers launched campaigns to catalogue EGRS polarisation at many wavelengths. The aim, in addition to understanding the emission mechanism, was to use the polarised sources as probes, since they emit electromagnetic waves that pass through the galactic (thermal) interstellar medium (ISM) and intergalactic space on the way to our radio telescopes. The discussion about the emission mechanism required studies at higher angular resolution of the sources themselves. The average *RM* of sources was attributed to the galactic ISM and has hence been used to derive a model of the galactic magnetic field. An example of a much-cited source catalogue, used for magnetic field studies, is the paper by Simard-Normandin and Kronberg (1980, see Figure 9). In this paper the *RM* of 543 sources distributed over the whole sky was compiled. Also, Tabara and Inoue (1980) compiled a catalogue of polarisation observations of over 1500 sources. However, the polarisation distribution in a source cannot be neglected. Using observations with different angular resolutions at different frequencies has led often to mistakes in the derived *RM* values. Using interferometry a clear source polarisation was obtained rejecting the polarised background but at a scale of the synthesised beam. A careful survey of 1600 selected sources in the northern sky with the Effelsberg Radio Telescope increased the data on point source polarisation to 2400 EGRS (Wielebinski et al., 2008).

A major step was recently achieved by Taylor et al. (2009) who re-analysed the 1.4 GHz NRAO VLA Sky Survey. The *RM* has been determined for 37,543 sources in the northern sky. The southern hemisphere was badly neglected and awaited a similar study, but this deficiency was rectified very recently by Carretti and Schnitzeler (2012).

The interpretation of these *RM*s suggests the presence of large areas with similar magnetic field orientations in the galactic halo, with some predominantly positive, and some negative, field directions. The earlier all-sky studies of *RM* did not include many sources along the Galactic Plane. This has been remedied recently with dedicated surveys by Brown et al. (2003; 2007) and van Eck et al. (2011). Along the Galactic Plane, where the spiral arms are causing the rotation, we see many sudden reversals. The values of *RM* increase towards the Galactic Centre. EGRS observations towards the Galactic Centre itself by Roy et al. (2008) suggest a field reversal around the Centre. These combined data (also with pulsar *RM* data) are a basis for modelling the magnetic fields in our Galaxy. From the data of van Eck et al. (2011) only one medium-scale reversal towards the Sagittarius spiral arm seems to be present.

Pulsars give complementary information to that obtained from studies of EGRS. For many years pulsars were more important as probes of galactic magnetic fields since they are clustered in the plane of our Galaxy, however the recent data on EGRS along the Plane (see above) has reduced this advantage. In addition, pulsars offer the possibility of investigating the distance of the object once the Rotation Measure and the Dispersion Measure have been determined. Lyne and Smith (1989) listed the *RM* of 185 pulsars, deriving the value of the local magnetic field as <B> ~ 3μGauss. Observations of pulsars also suggested that field reversals occur in our Galaxy. This study was followed up by Han and Qiao (1994) and Qiao et al. (1995), leading to models of the galactic magnetic field with a bi-symmetric field structure. Independent investigations by Vallée (1996) and Han, Manchester and Qiao (1999) continued the discussion about the nature of the galactic magnetic field. The effect of HII regions in front of pulsars was investigated by Mitra et al. (2003), who showed that this can lead to a field reversal. Also the previously-postulated field reversal beyond the Perseus spiral arm was disproved.

New observational *RM* data (Han et al., 2002; 2006; Noutsos et al., 2008) continued the discussion about the controversial nature of galactic magnetic fields. An investigation of the alternative interpretations, based on pulsar *RM*, by Men et al. (2008) could not give a clear answer about the nature of the galactic magnetic field. A combination of pulsar *RM*, the EGRS data and radio continuum polarisation is necessary to tackle this difficult question. As mentioned above, one medium-scale reversal has now been confirmed in our Galaxy. Many small-scale reversals are observed that may be caused by the local situation in the thermal clouds. It is of interest to note here that the *RM* values and field orientations derived using pulsars and EGRS towards the Galactic Centre are very similar. Since hardly any pulsars are observed beyond the Galactic Centre this would suggest that the *RM* of both types of sources occurs in foreground regions, with strong magnetic fields and high thermal electron density.

4.3 Diffuse (Galactic) Radio Emission

After the pioneering surveys made in the 1960s the mapping of the Galaxy in polarisation was virtually discontinued. It was only continued in Dwingeloo by Brouw and Spoelstra (1976) who mapped a large area of the northern sky at several frequencies between 408 MHz and 1400 MHz. Using the Dwingeloo data Spoelstra (1984) derived the *RM*, in particular for the ‘fan region’ at *l* = 140°, *b* = 10°. These values of *RM* were very low—a result of deriving the *RM* values with under-sampled low angular resolution data. A revival of polarisation mapping of the galactic emission came with the survey by Junkes et al. (1987) of the Galactic Plane at 11cm. In Effelsberg numerous surveys of a wide strip of the Galactic Plane were made at 21cm and 11cm. In Australia Duncan et al. (1997) mapped the southern Galactic Plane at 13cm with the Parkes Radio Telescope. These surveys turned out to be of great importance in discovering new supernova remnants. A review of recent galactic polarisation surveys is given in Reich (2006). The Galactic Centre was found to be highly polarised (e.g. Seiradakis et al., 1985; Reich, 2003) implying emission by mono-energetic electrons. A major step in polarisation studies of our Galaxy came from Wieringa et al. (1993; see Figure 10) who made a 325 MHz polarisation map with the Westerbork Radio Telescope, which showed that there is considerable structure in polarisation at low radio frequencies. This rapid variation of polarisation structure was found at high (4 arc minute) angular resolution.

The discovery of a large-scale interstellar Faraday rotation feature, a Faraday screen, by Gray et al. (1998) revived interest in the galactic radio continuum emission. This direction of work was taken up in Effelsberg with deep polarisation maps at 21cm with 9 arc minute resolution (e.g. Uyaniker et al., 1999), a part of a Medium Latitude Survey of the Galactic Plane. Numerous galactic Faraday screens were discovered. Also the Australia Telescope Compact Array was used by Gaensler et al. (2001) to map a section of the Galactic Plane at arc-minute resolution, deriving *RM* values for this area. The values derived were very much higher than was originally deduced by Spoelstra (1984), showing that the structure of the interstellar medium (ISM) is an important parameter. These maps also showed strong Faraday effects at higher angular resolution. On the other hand it became clear that there must be a reliable definition of the zero levels of the polarisation maps. The display of polarisation data changed with the advent of colour monitors and the data display showed black ‘canals’ of zero polarisation intensity (see Figure 11). The ‘canals’ are due to polarisation intensity going to zero as a result of small-scale Faraday rotation and may disappear or change once the correct zero level has been established. Details of the procedures used to establish the correct zero level can be found in Sun et al. (2007).

For the setting of the zero level, needed to understand the polarisation distribution, all-sky polarisation information was required. To achieve this goal the northern sky was mapped in 21cm polarisation by Wolleben et al. (2006) and the southern counterpart by Testori et al. (2008). As a result, an all-sky map of polarisation could be made (see Figure 12). This data set also gives information about directions where foreground polarisation is nearly zero, which is relevant to the Cosmic Microwave Background studies.

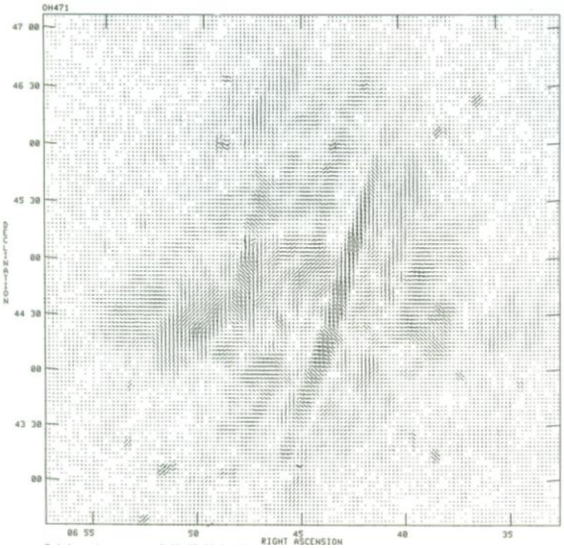

Figure 10: High resolution observations by Wieringa et al. (1993) showing polarisation (*E*-vectors) structure at 325 MHz with 4 arc minute resolution.

New surveys of polarisation along the Galactic Plane were made with China’s Urumqi Radio Telescope at 6cm wavelength (see Sun et al., 2011, and references therein). These surveys showed numerous Faraday screens as well as new sources (SNRs). These results, showing high values of *RM* (when compared with the Effelsberg 21cm data at the same angular resolution), support the recent observations that were made of compact sources in the Galactic Plane by Brown et al. (2007) and van Eck et al. (2011). The record of best angular resolution of diffuse polarisation (1 arc minute) is now held by Landecker et al. (2010), made with a combination of Dominion Radio Astrophysical Observatory and

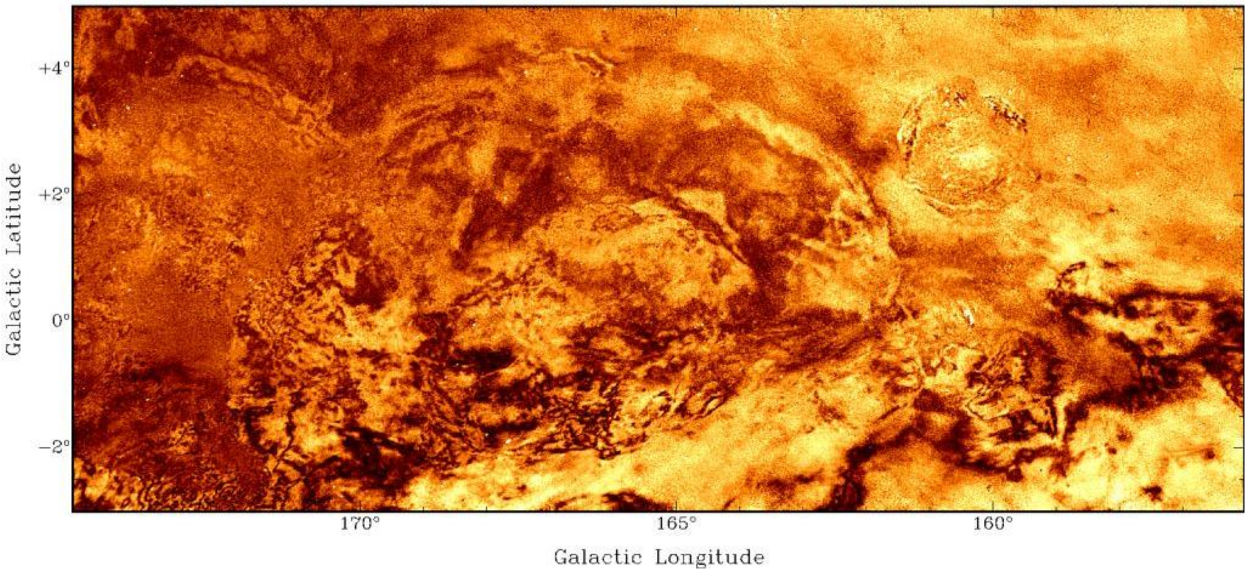

Figure 11: High angular resolution (1 arc minute) polarised intensity map of a section of our Galaxy (Landecker et al., 2010). This is a combination of Effelsberg and Canadian Galactic Plane Survey data. The display of polarisation is in colour, with high values bright, black being zero polarised intensity. The polarisation intensities were set to a correct zero level.

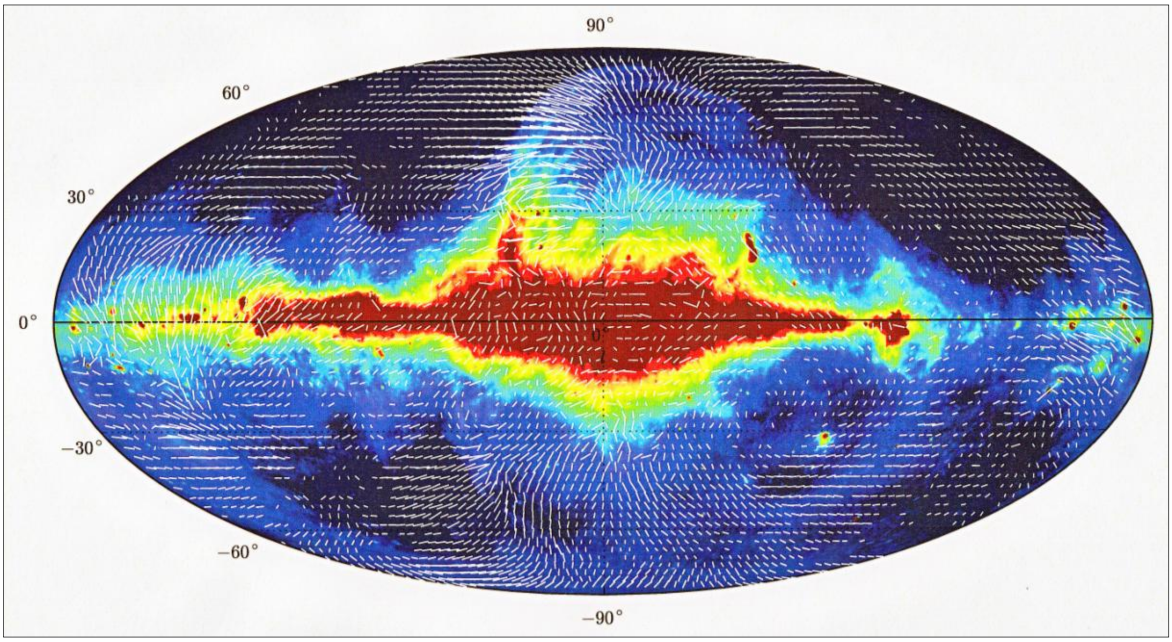

Figure 12: All sky polarisation (*E*-vectors) observed at 1400 MHz superposed on a total intensity colour map (courtesy: W. Reich). The plot was made by Maik Wolleben.

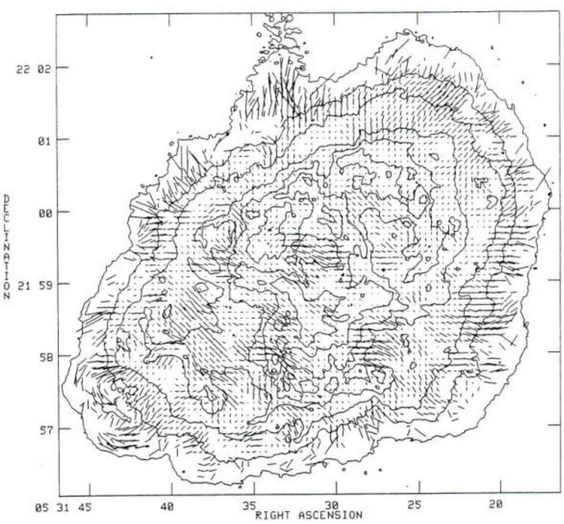

Figure 13 (left): The total intensity, percentage polarisation and projected magnetic field orientation in the Crab Nebula at 1410 MHz. Vector length of 30″ indicates 100% polarisation (after Bietenholz and Kronberg, 1990).

Effelsberg data at 21cm (see Figure 11). The *RM* synthesis (e.g. Brentjens and de Bruyn, 2005; Wolleben, Landeker et al., 2010) adds another new method in which polarisation is used to sample the ISM. Studies of the details of the *RM* in large galactic objects only became possible as a result of the application of *RM* synthesis (e.g. Wolleben, Fletcher et al., 2010).

Another interesting direction of study is that of the polarisation of the real background, the Cosmic Microwave Background (CMB). However the CMB is seen through the galactic foreground that must be carefully subtracted before any claim of cosmologi-

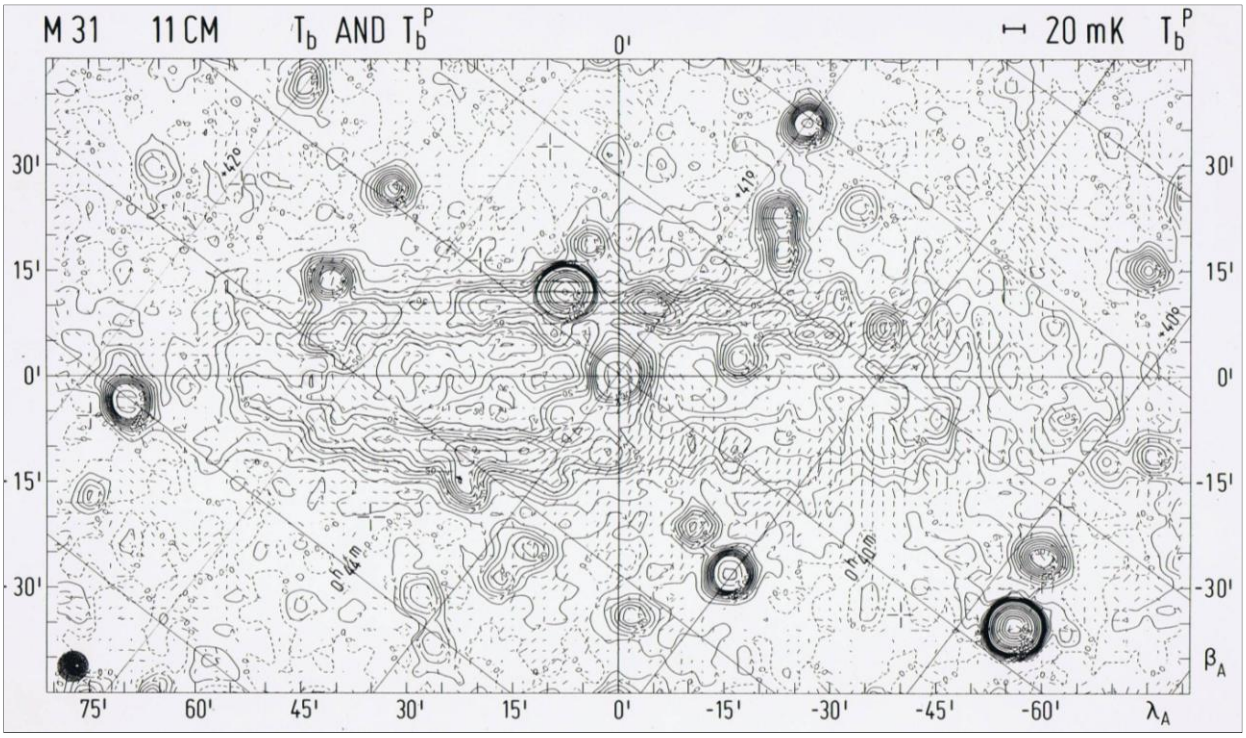

Figure 14: Polarisation of M31. *E*-vectors at 11cm wavelength are shown superposed on total intensity contours. In view of the low Faraday rotation a 90° vector rotation gives the 'B' field (after Beck, Berkhuijsen and Wielebinski, 1980).

cal polarisation can be made. Polarisation studies have been made with the WMAP satellite (Bennett et al., 2003; Kogut et al., 2007; Page et al., 2007; Hinshaw et al., 2009; Gold et al., 2009) and presented as all-sky maps. The observed data at 23, 33, 41, 61 and 94 GHz show the major polarisation features of the Galaxy at these high frequencies. There is good agreement with the 1.4 GHz maps of Wolleben et al. (2006) and Testori et al. (2008). The PLANCK satellite is also going to make an important contribution in this field of research at the highest radio frequencies. The gap in all-sky polarisation data between 1.4 GHz and 22 GHz is obvious and must be closed in the near future.

4.4 Supernova Remnants

The advent of new sensitive radio telescopes allowed the discovery of new SNRs as well as detailed studies of known objects. In the discovery process not only polarisation data were used; the IRAS surveys gave excellent information about thermal regions. Hence the separation of diffuse (unpolarised) HII emission from non-thermal (polarised) SNR became an easy exercise. Reviews of the progress in the discovery of new SNRs are found in Milne (1990) and Reich (2002). Discoveries of SNRs are still in progress: whenever a sensitive survey of a wider region of the Galactic Plane is completed new supernovae are found. While most of the more extended SNRs were found with large single dishes (e.g. Parkes or Effelsberg) the more compact objects were discovered by synthesis instruments (e.g. Green and Gull, 1984). In the very recent survey at 6cm by Gao et al. (2011) two new SNRs were detected. Important sources of information about galactic SNRs are the catalogues of Green (1984; 2009).

The other direction of research on SNRs was to make detailed maps of selected objects. The Effelsberg 100-m Radio Telescope allowed the mapping of SNRs to higher radio frequencies (e.g. Baker et al., 1973). Also, synthesis arrays became involved in polarisation studies of SNRs. For this purpose considerable computing power was needed. As an example I cite the work of Bietenholz and Kronberg (1990) on the Crab Nebula. Using the VLA and the Ontario Centre for Large Scale Computations, images of 1.8″ resolution were obtained for the whole 7′ × 7′ field (see Figure 13). These data match the best optical polarisation observations that were ever made. Several other SNRs have also been studied in such detail.

4.5 Nearby Galaxies

Originally optical polarisation observations indicated the presence of magnetic fields in nearby galaxies. There were optical observations of the polarisation of individual stars in the Magellanic Clouds as well as of diffuse polarisation in some nearby galaxies. The start of observations with the Westerbork Synthesis Radio Telescope in 1972 led to the first report by Mathewson et al. (1972) of the detection of radio linear polarisation in M51 at 21cm. These early results indicated the presence of magnetic fields along the spiral arms of the galaxy. Follow-up Westerbork observations of M51 were made by Segalovitz et al. (1976), and their 21cm and 6cm maps revealed polarisation in different areas: the 21cm map showed polarised vectors in the outer galaxy while the 6cm observations gave detections near the nucleus, a problem inherent in fixed interferometer arrays. M31 also was observed at Westerbork, but the limitations of aperture synthesis maps of extended diffuse objects were shown—most of the diffuse polarised emission was not detectable.

The opposite is the situation with observations of a large single dish like the 100-m Effelsberg Radio

Figure 15: High resolution map showing magnetic *B*-field in M51, derived from multi-frequency observations with both the VLA and the Effelsberg 100-m Radio Telescope (after Fletcher et al., 2011).

Telescope—the diffuse emission was detected and the angular resolution was just acceptable. This was demonstrated with the 11cm polarisation observations of M31 (Beck et al., 1978; 1980; see Figure 14). A very regular, ring-like magnetic field was detected in M31. To improve the angular resolution of a single dish higher frequencies were needed: in the case of the 100-m Radio Telescope the transfer to

6cm, 2.8cm, 2cm and 1.2cm observations (e.g. Klein et al., 1982; 1983; Krause et al., 1984; Beck et al., 1985; 1987) gave the much-needed improvement in angular resolution, while the Faraday effects became minimal. Also, the polarisation of edge-on galaxies was mapped (e.g. Dumke et al., 1995), allowing searches for halo magnetic fields. Polarised emission was detected in the halo of M82 by Reuter et al. (1994). The 100-m Radio Telescope in Effelsberg became the major source of information about the polarisation of nearby galaxies in those early days. A review on this subject at that time was published by Sofue et al. (1986).

There has been a revolution in the studies of magnetic fields in nearby galaxies in recent years. In this field of research the Effelsberg Radio Telescope has played a major role. With its great sensitivity to diffuse emission, maps of all large galaxies could be made. An atlas of the magnetic fields in galaxies can be seen on the home page of the Max-Planck-Institute für Radioastronomie (see http://www3.mpifr-bonn.mpg.de/div/konti/mag-fields.html).

Virtually every nearby galaxy has been studied by now. A big step in the studies of nearby galaxies was the combination of Effelsberg and VLA data on polarisation (Beck et al., 1998), a combination of good angular resolution and diffuse emission sensitivity. The Andromeda Nebula has been explored in detail (Beck et al., 2003; Fletcher et al., 2004). Also the galaxy M33 was examined by Tabatebaei et al. (2008). Edge-on galaxies received special attention as the question of halo fields was investigated (e.g. Reuter et al., 1994, for M82; Krause et al., 2006, for M104; Soida et al., 2011, for NGC 5775). Barred galaxies were investigated (e.g. Beck et al., 2005, for NGC1097 and NGC1365), showing that magnetic fields follow the gas motions. Also, irregular galaxies were investigated and showed surprisingly regular magnetic fields (e.g. Chyży et al., 2000). The influence of a cluster environment on the magnetic fields was investigated in NGC 4254 by Chyży (2008). Recently, the SINGS Survey from Westerbork (Heald et al., 2009) presented a large volume of consistent data on the polarisation of galaxies. The Effelsberg polarisation mapping system also was transferred to the Parkes Radio Telescope and used to study the Magellanic Clouds at various frequencies (Haynes et al., 1991). The combination of VLA and 100-m Radio Telescope data led to spectacular images, for example of M51 made at 3.6cm with an angular resolution of 15 arc seconds but with complete diffuse emission (Fletcher et al., 2011; see Figure 15).

There is considerable literature attempting to interpret the origin of magnetic fields in galaxies. The original interpretation of the presence of large-scale magnetic fields in addition to small-scale (local) structure still holds. In some galaxies 'magnetic arms' (e.g. Beck, 2007, for NGC6946; Han et al., 1999, for NGC2997) were detected, which seem to be mostly in the inter-arm (optical) regions. The dynamo theory offers the most plausible interpretation of the presence of magnetic fields in galaxies—a seed field is amplified by galactic rotation. A long list of reviews on this subject exists. I point out here only the reviews of Wielebinski and Krause (1993), Beck et al. (1996), Han and Wielebinski (2002), Wielebinski and Beck (2010), and Beck and Wielebinski (2012).

4.6 The Zeeman Effect

There has been considerable progress in Zeeman effect observations. For one, the controversies (see Verschuur, 1995) that built up about HI observations have been resolved. In addition, measurements using different molecular species (e.g. OH: Güsten et al., 1994; H_2O: Fiebig and Güsten, 1989; or SO: Ushida et al., 2001) have been made. Some of the recent Zeeman effect measurements have been made at mm wavelengths and will certainly be a driver for the future. An extended review about more recent Zeeman effect results is given by Heiles and Crutcher (2005). A recent claim for extragalactic Zeeman effect detection (Wolfe et al., 2008) cannot be substantiated. A discussion about the 'beam squint' problem can be found in Fiebig et al. (1991).

4.7 Clusters of Galaxies

The large surveys of *RM* of EGRS were used in attempts to detect intergalactic magnetic fields (e.g. Sofue et al., 1979). These early claims did not stand further scrutiny. On the other hand there was progress in the observation of individual clusters. Haloes were observed in numerous clusters (e.g. Willson, 1970; Wielebinski, 1978), proving the existence of non-thermal emission. Also, polarised sources in some clusters (e.g. A2256; Bridle et al., 1979) confirmed the existence of magnetic fields in the intergalactic space within clusters of galaxies. Observations of compact radio sources beyond the Coma Cluster by Kim et al. (1990) showed an increase in *RM* of sources in the centre of the cluster caused by Faraday rotation in the inter-galaxy magnetic fields. Thus far, various attempts to determine the polarisation structure (and hence magnetic fields) in the haloes in clusters of galaxies have failed.

5 CONCLUDING REMARKS

The data presented here take account of more than 50 years of radio polarisation studies. Starting from small beginnings, great progress was made. The next generation of radio telescopes should take the field much further.

Each new radio telescope project (ALMA, Lofar, Askap, Meerkat and the SKA) includes polarisation facilities. Also, multi-beam polarimeters for mm- and sub-mm wavelengths have been constructed. However, it will need great vigilance by the polarisation community. Often in large projects the polarisation capability is dropped due to technical difficulties. It certainly costs more to have a polarisation capability but this is compensated for by the new and unique data that can be obtained.

I will certainly watch the progress in the next years with great interest, and I wish all the 'magnetic people' good luck in their research.

6 ACKNOWLEDGEMENTS

I would like to acknowledge the information that I received from many colleagues who pioneered radio polarisation observations: John Whiteoak, Ken Kellermann, Gart Westerhout, Wim Brouw, George Seielstad, Dave Morris, Phil Kronberg, Sir Francis Graham-Smith and (the late) V. Radhakrishnan. I am in particular indebted to Ken Kellermann for numerous additional suggestions. I am also grateful to Richard Strom, one of the referees, for carefully checking the manuscript and for his most valuable suggestions.

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