Chapter 16
History of Cosmic Magnetic Fields

Richard Wielebinski

1 Magnetic Fields in Antiquity and Modern Times

The earliest records of magnetic items in antiquity go back some 2500 years. Lodestones are found in many places on Earth. Thales of Miletus discussed the action of lodestones found in the province Magnesia. Also records exist that the Chinese used 'Magnetic Spoons' that were the basis of the development of the compass. The compass was later used by mariners for navigation, for the discoveries around the Earth.

The first serious publication about magnets is attributed to William Gilbert (1540–1603) who carried out systematic experiments. Gilbert discovered that the Earth was also magnetic. Early investigation of the Earth's magnetism was carried out by Carl Friedrich Gauss (1777–1855); in fact Gauss is a unit of magnetic force, still in use. Charles Coulomb (1736–1806) discovered the inverse square law for magnetic attraction. Some prominence of the action of cosmic magnetic fields can be attributed to Johannes Kepler (1571–1630) who thought that magnetic fields may be responsible for the motion of the Earth around the Sun. Isaac Newton (1643–1727) demolished this proposal of Kepler, by showing that only gravitation is responsible for the motion of planets. Curiously it must be noted that also in gravitation the inverse square law is observed just as in the action of magnetic fields and electricity.

The next era of the investigations of magnetic fields came with Hans Christian Oersted (1777–1851) who showed that an electric current produces a magnetic field. New experiments carried out by Andre Marie Ampere (1775–1836) and Michael Faraday (1791–1869) advanced the understanding of the role of magnetic

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fields. The major contribution came from James Clerk Maxwell (1831–1879) who developed the basic theory of electricity and magnetism.

2 The Measurement of Magnetic Fields

The flux density of magnetic fields was traditionally measured in the unit of Gauss, still used widely in astronomy. The international standard of Tesla was introduced; 1 Tesla = 10,000 Gauss. Also, the unit of Oersted and amperes/meter are used to measure magnetic field strength. Various magnetometers have been developed for the measurements of magnetic fields. Magnetometers have been flown on various space probes giving us information about the magnetic fields in planets. In addition, optical observations of polarization were made, but the explanation for this phenomenon was controversial. Some optical astronomers claimed that this was a scattering effect. The Davis–Greenstein mechanism (see Fig. 16.1), described in 1951, showed that optical polarization can be caused by the alignment of dust grains by magnetic fields.

The remote sensing of magnetic fields was started by experiments of Pieter Zeeman (1865–1943). He showed that a spectral line is split by a strong magnetic field (see Fig. 16.2a). This was used immediately by Hale (1868–1938) to prove that sunspots were magnetic effects. This confirmed the suggestions that were often made in previous years of the existence of magnetic fields in the Sun. Photographs that showed organized loops in the solar corona suggested the action of magnetic

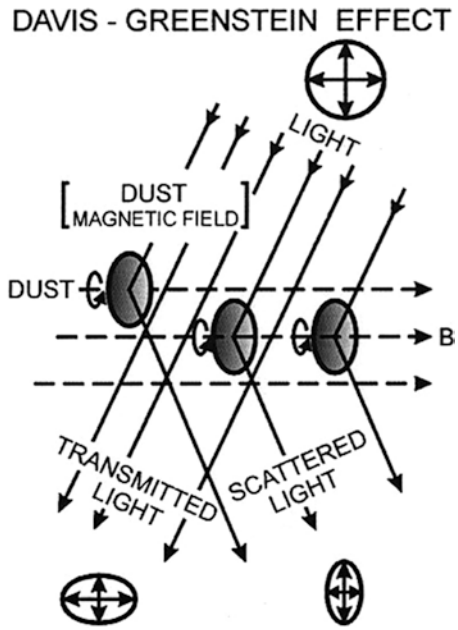

Fig. 16.1 The action of magnetic fields in optical light that can be interpreted by the Davis and Greenstein (1951) effect (Courtesy: MPIFR).

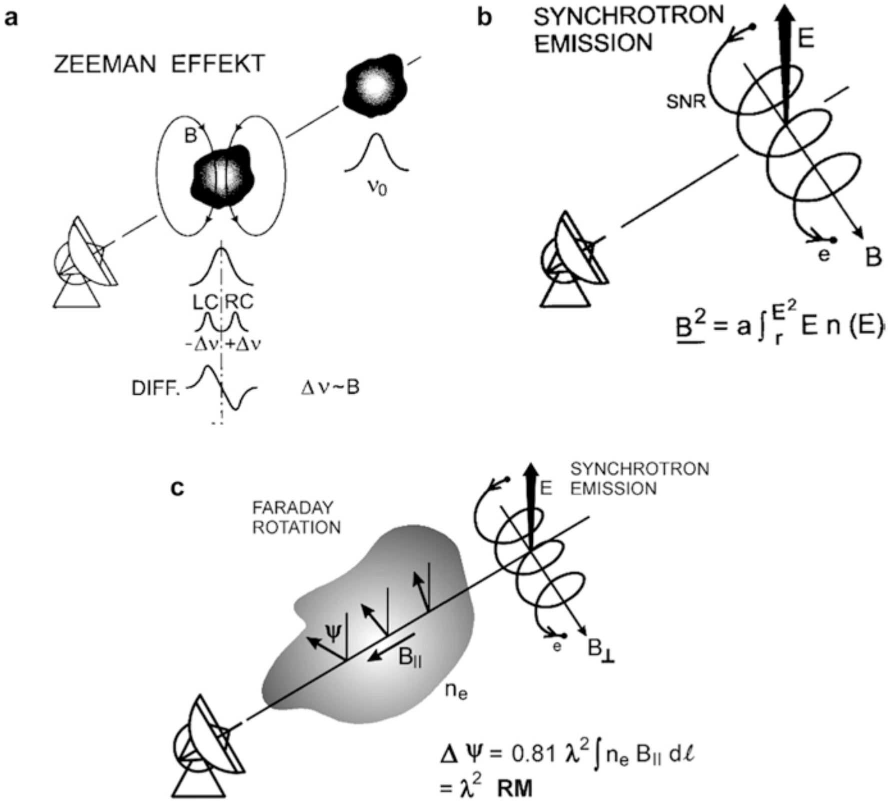

Fig. 16.2 (**a**) The Zeeman Effect is the most direct method of measuring of magnetic fields. (**b**) Synchrotron emission allows the association of linear polarization with the magnetic fields. (**c**) Faraday rotation is caused by magnetic fields in a thermal medium (Courtesy: MPIFR).

fields. The Zeeman Effect observations were possible only when strong magnetic fields were present in the cosmic objects.

A new method of studying magnetic fields came as a result of radio astronomy. The original detections of radio waves by Karl Jansky (1905–1950) and Grote Reber (1911–2002) were finally interpreted to be due to synchrotron emission – hence polarized (see Fig. 16.2b). The study of these polarized radio waves led to an extraordinary development in the understanding of the role of cosmic magnetic fields in our Universe. The Zeeman Effect (Fig. 16.2a) observations have also advanced with modern receiving systems, but still they cover only a small field in comparison with the huge advances in the study of synchrotron emissions from cosmic objects: from the Sun, the Milky Way, supernova remnants, radio galaxies and even the magnetic fields surrounding a black hole.

An additional observational method of studying magnetic fields has been developed with the use of Faraday rotation (see Fig. 16.2c) of the magnetic field in the line-of-sight. The measurement of the linear polarization (*E*-vector) gives information about the magnetic fields normal to the magnetic field direction. This observation of the Faraday rotation allows the study of magnetic fields in three dimensions.

3 Origin of Cosmic Magnetic Fields

The origin of the cosmic magnetic fields is still unclear. The generation of the 'seed fields' needs the separation of electric charges. Suggestions have been made (Durrer & Neronov, 2013) that a primordial magnetic field with $B < 10^{-12}$ G did exist in the early Universe. Observations with HESS and FERMI high energy systems give a lower limit of $B > 10^{-16}$ G. The analysis of CMB spectra set a limit of 5×10^{-9} G. Observations of the IGM at a redshift of about 7 suggest an upper limit of $(2–3) \times 10^{-9}$ G. In galaxies we see magnetic fields with $B \sim (1–10) \times 10^{-6}$ G. The amplification of the cosmic magnetic fields can be envisaged by various methods. The dynamo mechanism (Parker, 1979; Krause & Rädler, 1980) was developed first to explain the Earth's magnetic fields but was also successfully applied to magnetic fields in other cosmic objects (e.g. Wielebinski & Krause, 1993). This dynamo theory was very helpful in understanding the magnetic fields in galaxies.

4 Magnetic Fields in the Milky Way

The earliest optical polarization observations by Hiltner (1949) and Hall (1949), made in sections of the Milky Way, were at first discussed in ambivalent ways. It took a long time to convince the optical community that these were indeed the signatures of magnetic fields. Large catalogues of the polarization of stars were made (e.g. Behr, 1959), first for the northern sky. Mathewson and Ford (1970) continued this work in the southern skies. Possibly the largest atlas of starlight polarization was gathered by Fosalba et al. (2002). The general result was that the magnetic fields are parallel to the Galactic plane, with some local deviations. Also, the optical polarization of the Crab Nebula was detected by Dombrowsky (1954).

4.1 Synchrotron Emission

The radio continuum emission of the Milky Way at low radio frequencies originates in the synchrotron emission process. In fact, the first large survey of radio emission, made by Grote Reber (1944) at 160 MHz, showed that the radio emission was concentrated along the Galactic plane and that the correct centre of our Milky Way was some 30° away from what was derived from earlier optical observations (see Fig. 16.3).

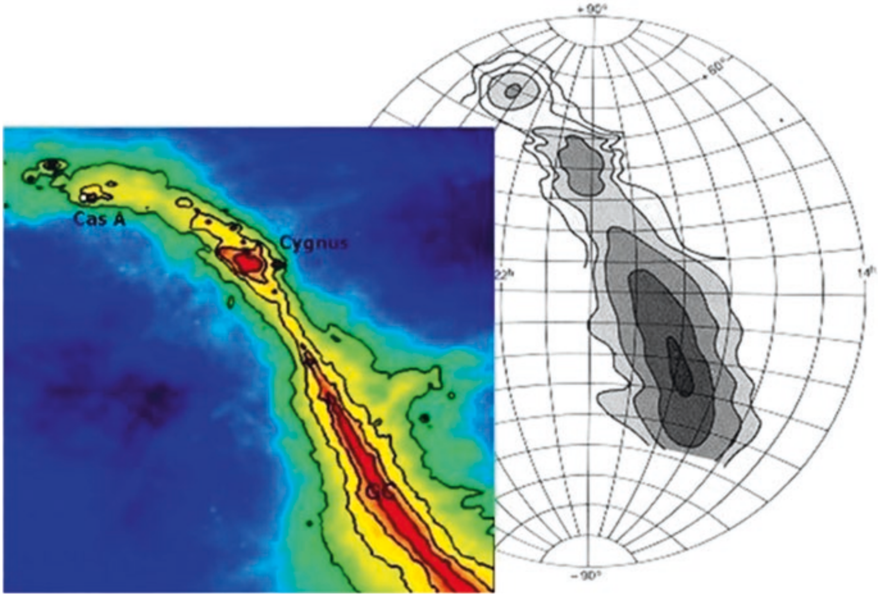

Fig. 16.3 The first survey of the radio sky (right) by Reber (1944) and a recent map of the same area (left). (Courtesy: W. Reich, MPIfR)

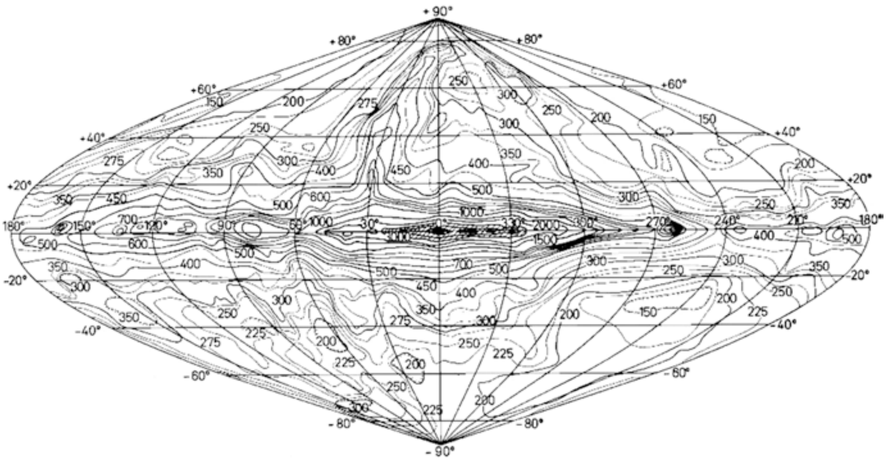

Fig. 16.4 The all-sky survey at 150 MHz (Landecker & Wielebinski, 1970)

One of the long-term efforts in observational radio astronomy, made by many observers, was to produce all-sky surveys at various frequencies. The author was involved in the 150 MHz all-sky survey (see Fig. 16.4) by Landecker and Wielebinski (1970). At the Max-PIanck-Institut für Radioastronomie (MPIfR) several important all-sky surveys were made at higher frequencies (e.g. Haslam et al., 1982; Reich &

Reich, 1986; Reich et al., 2001). Later the mapping of linear polarization was added (e.g. Junkes et al., 1987; Reich et al., 2001). Southern sky mapping of the radio polarization was made by Duncan et al. (1995). Mapping of magnetic fields in the Galactic plane was recently conducted by Sun et al. (2011) using the Urumqi radio telescope. The completion of an all-sky polarization map at 1400 MHz was achieved by Wolleben (see Fig. 16.5).

Since synchrotron emission is polarized, considerable effort was made to detect radio polarization in the Milky Way. These efforts were at first not successful, due to instrumental difficulties. The year 1962 was the 'Annus Mirabilis' for radio polarization; the linear polarization of the Milky Way was detected (Wielebinski et al., 1962; Westerhout et al., 1962). The first detection of Galactic polarization is shown in Fig. 16.6. In the 1962 observations the effect of the ionosphere, causing Faraday rotation of the *E*-vectors, was detected (Wielebinski & Shakeshaft, 1962). The polarization in supernova remnants and radio galaxies was also detected (Mayer et al., 1962; Cooper & Price, 1962). The magnetic field strength in the Galaxy has been estimated to be several 10^{-6} G. In supernova remnants and in radio galaxies, magnetic fields of ~10^{-3} G were derived.

4.2 *The Galactic Centre*

The Galactic centre is a very special region of the Milky Way. Its exact position was determined by radio observations as the most intense emission region. It certainly stands out in the many all-sky surveys. The general opinion suggests that a black hole defines the Galactic centre. Detailed observation of the Galactic centre by Yusev-Zadeh and Morris (1984) showed non-thermal filaments that were poloidal

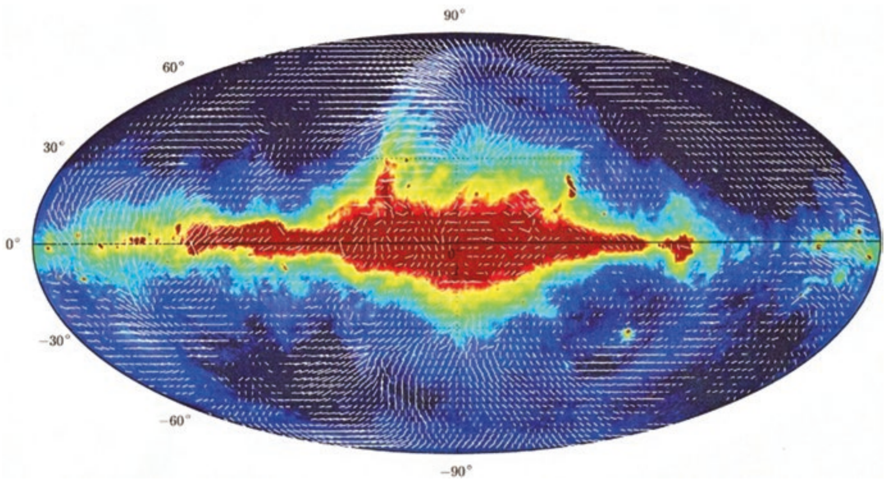

Fig. 16.5 A recent compilation of *E* vectors of the whole sky. (Courtesy: M. Wolleben)

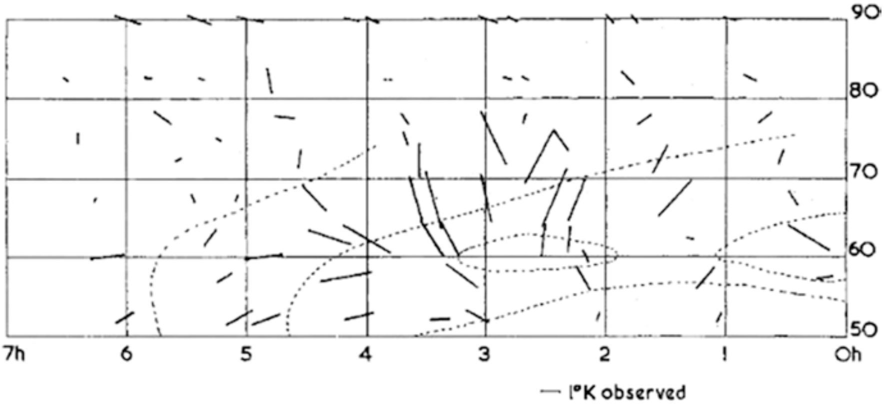

Fig. 16.6 The 408 MHz map of a section of the Galactic plane (Wielebinski et al., 1962). Note the *E* vectors are shown and the magnetic field is seen at 90° relative to the *E* field after correction for Faraday rotation

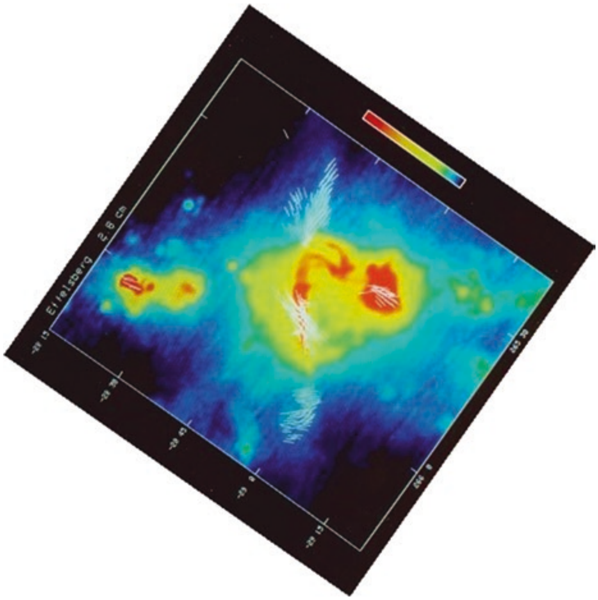

Fig. 16.7 The 2.8 cm map of the Galactic centre by Seiradakis et al. (1985) showing poloidal magnetic fields

relative to the Galactic plane. Observations of polarization by Seiradakis et al. (1985) near the Galactic centre (see Fig. 16.7) confirmed that, unlike in the overall Galactic plane where the magnetic fields are aligned with the plane, poloidal magnetic fields are observed. These observations have now been supported by the recent

Event Horizon Telescope observations of the black hole in M87 – the presence of magnetic fields has been confirmed (see Fig. 16.14).

4.3 Zeeman Effect

The Zeeman Effect is a direct physical method to measure magnetic fields. A prediction of Bolton and Wild (1957) had to wait until Verschuur (1968) and Davies et al. (1968) published the first results for the HI line. It took a long time to achieve the necessary instrumental sensitivity. A new generation of Zeeman observations was made in various spectral lines: OH, H_2O, CN and others. These lines are found in maser sources that have high *B* fields. In view of strong magnetic fields in maser sources, the detection of magnetic fields is easier than with the HI line in the Galactic plane.

4.4 Pulsars

The detection of pulsars in 1968 raised immediately the question about magnetic fields in these neutron stars. Here we had the lucky fact; both the rotation measure and the dispersion measure can be observed, hence the average magnetic field can be determined. This was pointed out by Lyne and Smith (1968) showing that pulsars were cosmic objects with massive magnetic fields – magnetars (a special type of pulsar) have fields of 10^{15} G! The results of observations of magnetic fields of pulsars have been used to determine the magnetic field of the Galaxy. A notable paper on the derivation of Galactic magnetic fields using pulsars was published by Han et al. (1999).

5 Magnetic Fields in Nearby Galaxies

The earliest reports of magnetic fields in galaxies came from optical observers. Appenzeller (1967) and Scarrott et al. (1987) pioneered the mapping of magnetic fields in galaxies. The observations were very difficult and time consuming. The first detection of polarized radio emission in a galaxy (M51) was published by Mathewson et al. (1972) using the Westerbork Synthesis Array. Segalovitz et al. (1976) continued this project and mapped M51 and also M31. Observations by Beck et al. (1978) using the 100 m Effelsberg radio telescope (see Fig. 16.8) showed that the diffuse radio emission was lost in the synthesis array maps. This became particularly noticeable for multi-frequency observations; the synthesis arrays showed details but lost all the larger structures. The comparison of the magnetic

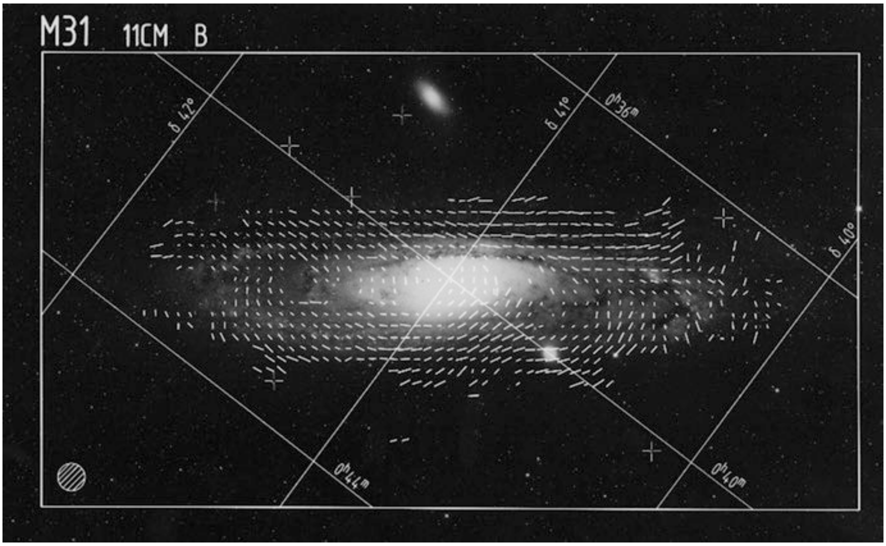

Fig. 16.8 The early map of magnetic fields in M31 made by Beck et al. (1980) with the Effelsberg 100 m radio telescope

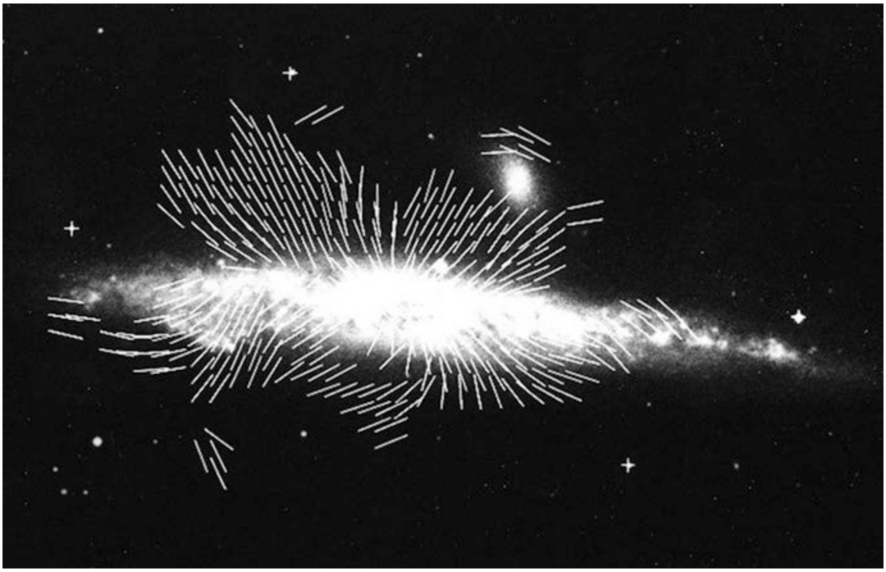

Fig. 16.9 An early map of the *B* field in the edge-on galaxy NGC4631. (Courtesy: MPIfR)

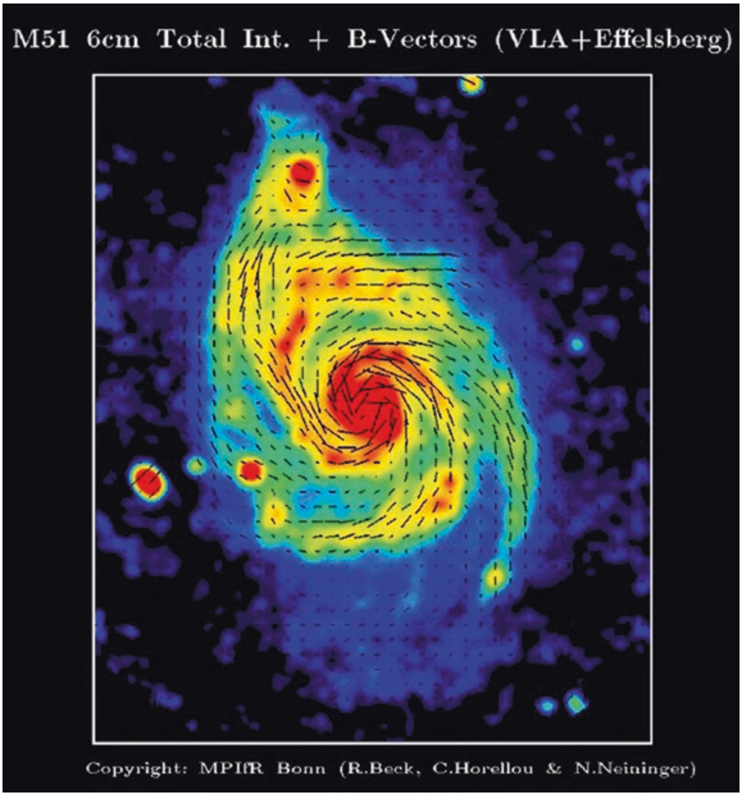

Fig. 16.10 Map of magnetic fields in M51 from a combination of VLA and Effelsberg data. (Courtesy: MPIfR)

fields from radio observations confirmed exactly the results from optical polarization observations.

The MPIfR magnetic fields group has made maps of magnetic fields in numerous nearby galaxies (e.g. see Figs. 16.9, 16.10, and 16.11 and the MPIfR home page). One of the important developments was the combination of a single dish map (with polarization) with a synthesis array map from Westerbork or from the VLA. Also the maps became coloured!

By now a huge number of nearby galaxies have been studied. The combination of single dish maps with aperture synthesis data give the best information. These computing methods developed at MPIfR are now used in many collaborating institutes.

The techniques for mapping galaxies that were developed at the MPIfR were also exported to the southern skies. Magnetic fields in the Magellanic Clouds (Haynes et al., 1986) and other southern galaxies were published.

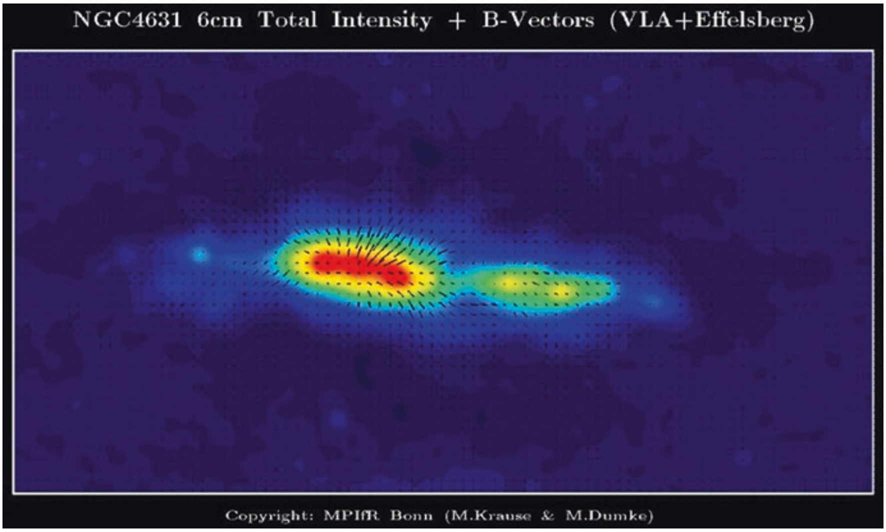

Fig. 16.11 A recent map of the edge-on galaxy NGC4631: vertical fields in the centre of the galaxy; fields along the plane elsewhere. (Courtesy: MPIFR)

6 Magnetic Fields in Radio Galaxies and Quasars

Radio galaxies and quasars are very intense celestial objects, highly polarized in view of the synchrotron emission process. One of the early observations was the detection of polarization in Centaurus A by Cooper and Price (1962). In the intervening years hundreds of polarization maps were published mostly by the large synthesis arrays (e.g. Högbom & Carlson, 1974; Klein et al., 1994). While in normal nearby galaxies the magnetic fields are oriented along their spiral arms, in radio galaxies many very complex direction changes are observed. A map of Centaurus A with polarization data is shown in Fig. 16.12. In view of their intensity many radio galaxies could be studied in great detail with the VLBI systems. A general structure of a nucleus and two lobes prevails. Also observations of circular polarization were successful giving additional information on the emission mechanisms.

7 Magnetic Fields in Clusters of Galaxies

Diffuse emission has been observed in clusters of galaxies. This is a hint that intergalactic magnetic fields are present in the clusters. In addition, through X-ray detection of clusters, estimates of magnetic fields can be made. The earliest detection of the Coma cluster halo was by Large et al. (1959). Following investigations with the Effelsberg radio telescope Wielebinski (1978) showed the extent of the Coma halo (see Fig. 16.13). Additional information could be gained by observing the Faraday rotation of point sources far behind the Coma halo.

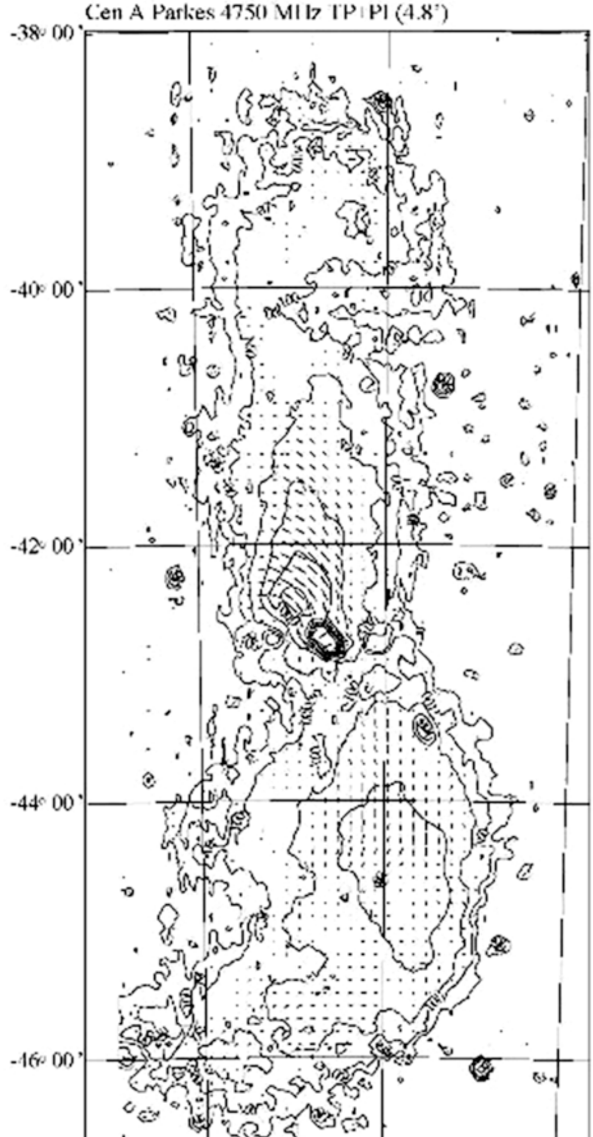

Fig. 16.12 A map of the radio galaxy Centaurus A where high polarization is observed in the lobes. (Courtesy: MPIfR)

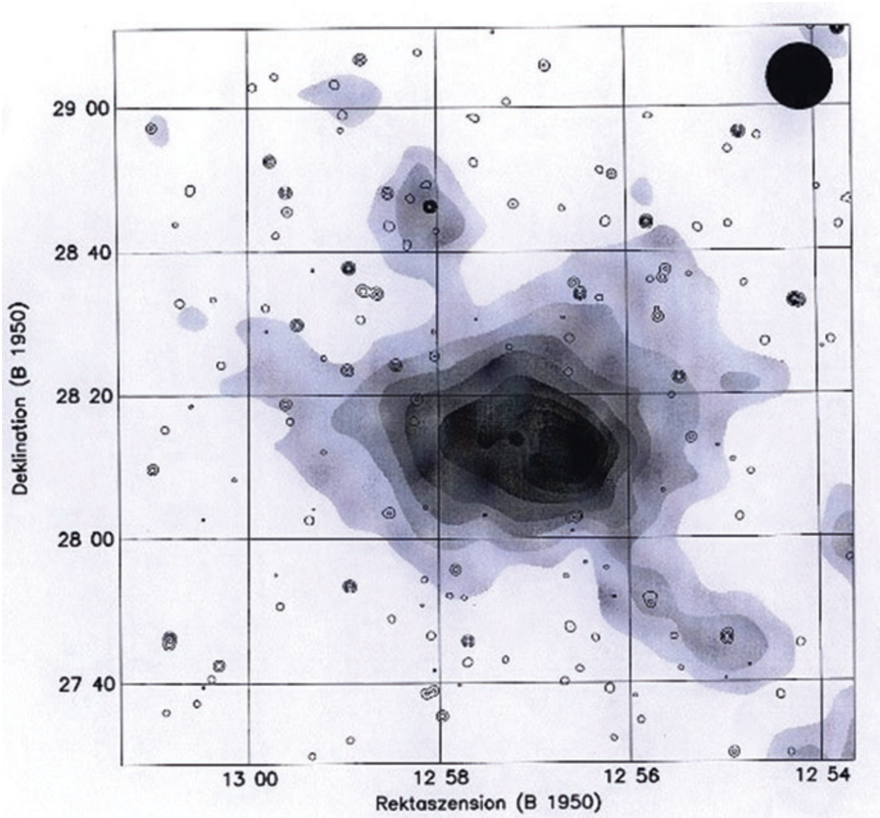

Fig. 16.13 A radio map of the Coma cluster by Wielebinski (1978), showing that intergalactic magnetic fields exist in clusters

8 New Developments in Observations of Magnetic Fields

Surveys of Faraday rotation of distant radio sources have been performed over many years (e.g. Simard-Normadin & Kronberg, 1980). These surveys relied on the collection of polarization observations made at several frequencies by different telescopes. These were often results of simple polarimeter observations. The recent development of low radio frequency arrays like the LOFAR system enable more detailed determination of the rotation measure of numerous sources. The LOFAR two-meter survey (van Eck et al., 2019) allowed studies of features in the Galactic plane at Faraday depths around 2 rad m^{-2}. An even more impressive publication by Betti et al. (2019) showed rotation measure structures through a high velocity cloud. The development of further low frequency arrays (Karoo and SKA) will provide us with spectacular new data on cosmic magnetic fields.

Possibly the most exciting recent publication dealt with the magnetic field in the surroundings of the M87 black hole. This observation, made with the Event Horizon

Fig. 16.14 A recent map of the black hole halo in M87 (Narayan et al., 2021). A magnetic structure is deduced from the observed polarization

Telescope, points to further important developments in our increasing knowledge of cosmic magnetic fields (see Narayan et al., 2021 and Fig. 16.14).

9 A Summary

Numerous books, reviews and papers have been published about cosmic magnetic fields in the past years (e.g. Berkhuijsen & Wielebinski, 1978; Beck et al., 1989; Wielebinski & Beck, 2005; Han, 2017). Possibly the most complete overview is found in Beck and Wielebinski (2021). The present contribution, a tribute to Wayne Orchiston on his 80th birthday, is not a complete review, it is a very personal view on the development of magnetic fields based on 60+ years of my participation in studying magnetic fields. Wayne Orchiston's involvement in the history of astronomy is a very important source of information for decades to come. Radio astronomy has only a short history in astronomical times. However, it has contributed a lot of knowledge about the Universe in this short time. Also, great astronomy projects are coming in the near future that will increase our knowledge: Earth-based in the radio domain with LOFAR and the Square Kilometre Array, also numerous space probes (like the James Webb Space Telescope) are coming. The next generation of students will have fantastic opportunities to increase our knowledge of the 'world', no, the Universe that we live in. In our complicated Universe cosmic magnetic fields play an important role.

I want to pay tribute to all my students and staff members. The Cosmic Magnetic Field group at the MPIfR has made a major contribution to our understanding of the Universe.

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