OBSERVATIONS OF MAGNETIC FIELDS IN GALAXIES

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ABSTRACT. Magnetic fields are present in every corner of the Universe. The Earth, the Sun and most of the planets are known to possess dipolar magnetic fields. In the Galaxy many individual objects like stars, pulsars, bipolar nebulae and supernova remnants are found to have associated magnetic fields. It seems that the rotation plays a significant role in the ability of a cosmic object to develop a magnetic field. The magnetic field of the Galaxy is observed to be oriented along the galactic plane as evidenced by both optical and radio polarization observations. Radio maps of the Galactic centre reveal poloidal magnetic fields as 'wisps' or 'strings' around Sagittarius A. Observations of nearby galaxies give us remarkable information about the large-scale magnetic fields in these building blocks of the Universe. Magnetic fields play an important role in the formation of jets of radio galaxies. Further out, in clusters of galaxies, definitive evidence has been given for the existence of intergalactic magnetic fields.

1. THE EARLY EVIDENCE FOR MAGNETIC FIELDS

As often happens in astronomy, observations preceded theoretical arguments. Optical polarization observations of Galactic nebulae were made as early as 1920. Optical polarization was detected in the Andromeda nebula (M31) by Öhman already in 1942, but no theory suggested a magnetic field. Theoretical arguments supporting the existence of magnetic fields were given by Alfvén et al. (1949) and by Fermi (1949) who argued that the cosmic-ray isotropy required containment by a Galactic magnetic field in the halo. At this time new observing techniques allowed the study of optical polarization in the Galaxy. The scattering off the dust grains (Rayleigh effect) was known to produce polarized light. An additional interpretation of optical polarization was given by Davis & Greenstein (1951) who argued that oblate grains aligned by magnetic fields could also produce appreciable optical polarization. This effect has now been shown to work in galaxies where complementary optical and radio observations have been made for a number of objects.

The fact that radio observations could play an important role in tracing of magnetic fields in galaxies was recognized quite early. There are five important methods of measurement which are applicable to different cosmic objects.

1. The measurement of the synchrotron emission intensity (at low radio frequencies) gives magnetic field intensity in conjuction with equipartition arguments.

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2. The mapping of polarized radio emission at several frequencies allows to correct for Faraday effects and in the end gives $B_\perp$.
3. Study of the rotation measure (RM) of distant radio sources gives us information about $B_\parallel$.
4. The combination of pulsar RM and dispersion measure (DM) allows us to determine the Galactic magnetic field strength $B_\parallel$.
5. The Zeeman effect can be measured in HI, OH, H_2O, and CCS clouds giving us information about the magnetic fields in these objects.

All these five techniques have been used extensively to advance our knowledge about the magnetic fields in the Universe.

2. STUDIES OF MAGNETIC FIELDS IN GALAXIES

The history of discovery of magnetic fields in galaxies has been given in numerous books and review articles. Here I would like to recall some important steps, all of them being related to the implementation of some new measuring technique. The existence of a magnetic field in the Galaxy was first established by optical polarization observations of Hiltner (1949) and Hall (1949) and confirmed by radio continuum observations (Westerhout et al. 1962; Wielebinski et al. 1962). Magnetic fields in M31 could be inferred already from the optical polarization studies of Öhman (1942). Several other observers continued the difficult task of observing the optical polarization of galaxies. In the radio domain the early Westerbork observations of M51 (Mathewson et al. 1972) showed polarized emission and hence implied the existence of an ordered magnetic field. The gross of the new information about magnetic fields in galaxies came from the consequent use of the 100-m radio telescope of the Max-Planck-Institute for Radioastronomy at higher radio frequencies, where the effects of Faraday rotation become negligible. Also the Very Large Array of the NRAO turns out to be an excellent polarization measuring instrument, but with the limitation that a satisfactory field of view is available only at the lower radio frequencies (where the Faraday effects are greatest).

In recent years several books and review articles have appeared giving details of the observations of magnetic fields (e.g. Beck 1986; Sofue et al. 1986; Beck & Gräve 1987; Wielebinski 1990; Beck, Kronberg & Wielebinski 1990; Krause 1990; Beck 1991a). In the following the most recent results of observations of magnetic fields in galaxies will be described.

3. RESULTS ON SPIRAL FACE-ON GALAXIES

At the lowest radio frequencies (like 327 MHz) the nonthermal emission intensity gives us information about the total magnetic field strength (in conjunction with equipartition arguments). Some recent results which were obtained with a good dynamic range give considerable insight into the magnetic field morphology of galaxies. A classical example, shown in Figure 1, is a Westerbork map of the Andromeda nebula, M31. The magnetic fields are obviously confined to a 'ring' which is known also in other spectral domains. Several other galaxies have been mapped at low radio frequencies.

All the nearby northern galaxies have been mapped by now in polarization at a number of frequencies with different angular resolutions. In particular at the highest frequency, at 10.7 GHz, the polarization maps from Effelsberg show the magnetic fields unaffected by Faraday rotation. The result of the Effelsberg radio mapping of M51 (Fig. 2) clearly shows

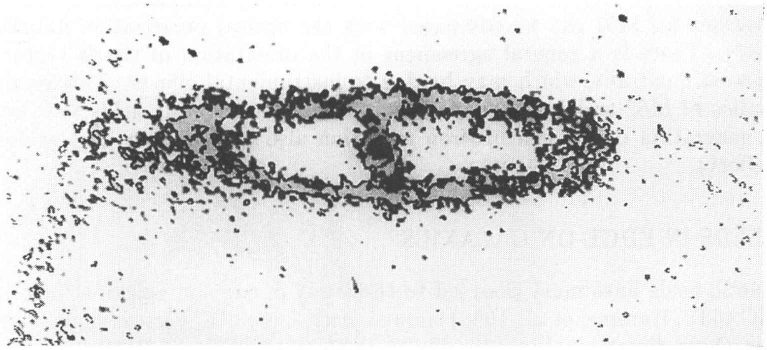

Fig. 1: The radio continuum emission from Andromeda nebula, M31, at 327 MHz. Westerbork observations courtesy of G. Golla, MPIfR.

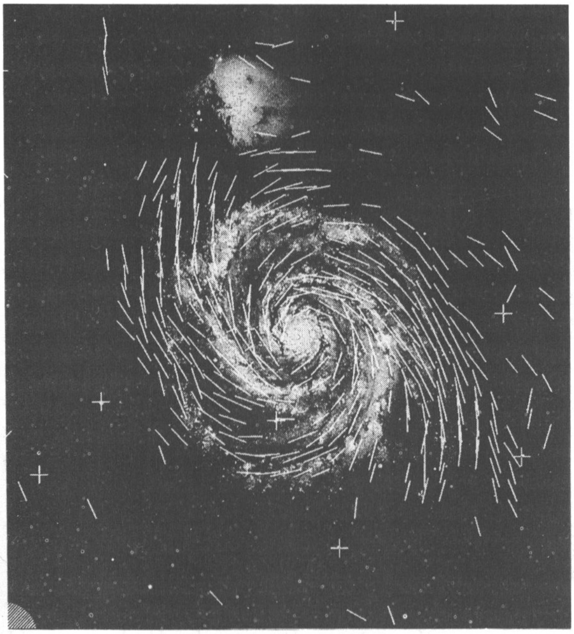

Fig. 2: The magnetic field orientation in M51 derived from Effelsberg 2.8 cm observations (courtesy of N. Neininger, MPIfR).

that the magnetic field follows in general the spiral arms. A slight displacement towards the inside of the arm (the dust lane) is also seen. Small-scale perturbations, like bridges between spiral arms, seem to coincide with aligned magnetic fields.

At lower radio frequencies (1.4–1.6 GHz VLA data) the magnetic field is often not seen in some sections of a spiral arm. An example of this effect is found in the galaxy NGC 6946 (Beck 1991b). This is due to Faraday depolarization which implies that considerable magnetic field (and thermal electrons) are present away from the disk of the galaxy. The

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classical method of analysis of the morphology (e.g. Tosa & Fujimoto 1978) assumed that the magnetic fields were confined to the disk and therefore needs to be reassessed.

The radio observations for M51 can be compared with the optical polarization data of Scarrott et al. (1987). There is a general agreement in the orientation of the B vectors except in the south-west quadrant, which may be due to instrumental effects. This result and also similar studies of M82 and M104 suggest that the same magnetic fields that are responsible for the generation of the synchrotron radiation also are aligning dust grains (Davis-Greenstein effect).

4. MAGNETIC FIELDS IN EDGE-ON GALAXIES

The fact that magnetic fields lines must close led to the study of edge-on galaxies. Indeed the first map of NGC 4631 (Hummel et al. 1988) showed well-aligned 'E' vectors suggesting a field orientation in the z-direction (Fig. 3). Multi-frequency studies of NGC 4631 and NGC 891 (Hummel et al. 1991) confirmed this early hypothesis, namely that there are mainly vertical magnetic fields near the nucleus. Also the galaxy M82 shows eye-catching vertical filaments near the nucleus in radio continuum (Reuter et al. 1991). These dark (minima) filaments of continuum emission have their origin in the positions where no compact sources are seen in high resolution radio maps (Kronberg et al. 1985). In radio polarization an azimuthal field in the disk and a poloidal field component in the nucleus of M82 are seen (Reuter 1991). In optical polarization, after subtraction of the component due to scattering (Neininger et al. 1990), a poloidal magnetic field is also discernable in the nuclear area.

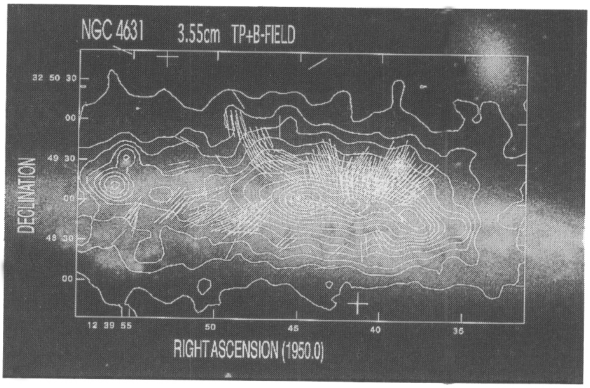

Fig. 3:
The magnetic field structure near the nucleus of NGC 4631. Poloidal filaments are seen (courtesy of G. Golla, MPIfR).

5. BARRED SPIRAL GALAXIES

The best studied barred spiral galaxy is M83. Earlier lower frequency VLA observations showed a ring-like magnetic field structure in the outer reaches of the galaxy (Sukumar & Allen 1989). Recent 2.8 cm Effelsberg observations of this galaxy (Neininger et al. 1991; Fig. 4) show a much more complex morphology. There is a magnetic field oriented along the bar. At the bar extremity the polarization disappears, possibly as a result of turbulence in that region. The magnetic fields re-emerge nearly at right angles to the bar field and follow the spiral arms. These observations surely need a more sophisticated interpretation than just in the frame of the dynamo theory, for example by lines frozen-in in streaming gas.

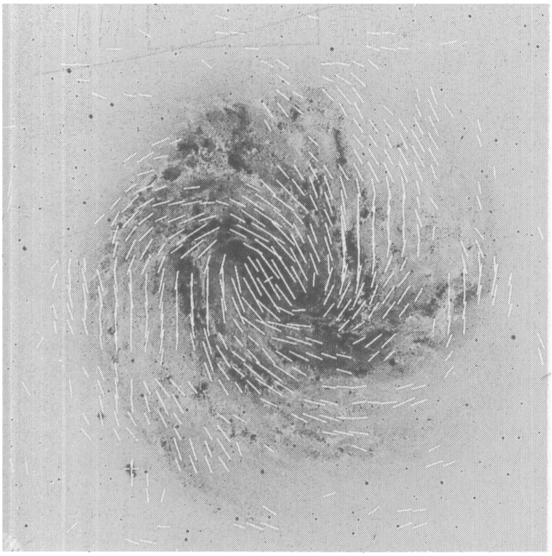

Fig. 4: The magnetic field orientation in M83 (Neininger et al. 1991)

6. DWARF/IRREGULAR GALAXIES

Although only a few results are available for these types of galaxies, nevertheless magnetic fields have been detected. In the Large Magellanic Cloud surprisingly regular magnetic field stucture is seen (Haynes et al. 1991). There is, however, one problem with the LMC: the magnetic field structure has a spiral-like morphology with the origin in the 30 Doradus nebula (which is not the rotation centre of the LMC). Also in NGC 55 and NGC 4449 magnetic fields have been detected.

7. INTERPRETATION OF MAGNETIC FIELDS

There are a number of possible interpretations for the origin of magnetic fields in galaxies. The primodial origin has been favoured by several authors (e.g. Piddington 1964; 1972) Alternatively the dynamo theory (e.g. Krause & Rädler 1980; Ruzmaikin et al. 1988) does explain many of the observed features. Furthermore the interaction of magnetized plasma channelling in jets can create a magnetic field (e.g. Daly & Loeb 1990). At present the dynamo theory is favoured (Krause & Wielebinski 1991). One of the observational facts is that galaxies with high rotational velocities have the best organized magnetic fields. However, the dynamo theory has difficulties to explain detailed magnetic field structures, for example as observed in the barred galaxy M83 (Fig. 4). Possibly all of the phenomena

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mentioned above are contributing to generate the magnetic fields of a galaxy. It is important, however, that progress in observational discoveries should be adequately supported by theoretical considerations.

REFERENCES

Alfvén H., Richtmayer R.D., Teller F. (1949) *Phys. Rev.* **75**, 1169

Beck R. (1986) *IEEE Trans.* **PS-16**, 740

Beck R. (1991a) in *The Interstellar Disk-Halo Connection in Galaxies*, IAU Symp. No. 144, ed. H. Bloemen, Kluwer, Dordrecht, p. 267

Beck R. (1991b) *Astron. Astrophys.* (in press)

Beck R., Gräve R. (1987) *Interstellar Magnetic Fields*, eds. R. Beck and R. Gräve, Springer, Berlin

Beck R., Kronberg P.P., Wielebinski R. (1990) *Galactic and Intergalactic Magnetic Fields*, IAU Symp. No. 140, eds. R. Beck, P.P. Kronberg and R. Wielebinski, Kluwer, Dordrecht

Daly R.A., Loeb A. (1990) *Astrophys. J.* **364**, 451

Davis L., Greenstein J.L. (1951) *Astrophys. J.* **114**, 206

Fermi E. (1949) *Phys. Rev.* **75**, 1169

Hall J.S. (1949) *Science* **109**, 166

Haynes R.F. et al. (1991) *Astron. Astrophys.* (in press)

Hiltner W.A. (1949) *Science* **109**, 471

Hummel E., Lesch H., Wielebinski R., Schlickeiser R. (1988) *Astron. Astrophys.* **197**, 29

Hummel E., Beck R., Dahlem M. (1991) *Astron. Astrophys.* **248**, 23

Krause M. (1990) in *Galactic and Intergalactic Magnetic Fields*, IAU Symp. No. 140, eds. R. Beck, P.P. Kronberg and R. Wielebinski, Kluwer, Dordrecht, p. 187

Krause F., Rädler K.-H. (1980) *Mean Field Magnetohydrodynamics and Dynamo Theory*, Pergamon Press

Krause F., Wielebinski R. (1991), in *Reviews of Modern Astronomy*, Vol. 4, Springer Verlag, p. 260

Mathewson D.S., van der Kruit P.C., Brouw W.N. (1972) *Astron. Astrophys.* **17**, 468

Neininger N., Beck R., Backes F. (1990) in *Galactic and Intergalactic Magnetic Fields*, IAU Symp. No. 140, eds. R. Beck, P.P. Kronberg and R. Wielebinski, Kluwer, Dordrecht, p. 253

Neininger N., Klein U., Beck R., Wielebinski R. (1991) *Nature* **352**, 781

Piddington J.H. (1964) *Mon. Not. Roy. Astr. Soc.* **128**, 345

Piddington J.H. (1978) *Astrophys. Space Sci.* **59**, 237

Reuter H.-P. et al. (1991) *Astron. Astrophys.* (in press)

Reuter H.-P. (1991) Ph.D. Thesis, Bonn University

Ruzmaikin A., Sokoloff D., Shukurov A. (1988) *Nature* **336**, 341

Scarrott S.M., Ward-Thompson D., Warren-Smith R.F. (1987) *Mon. Not. Roy. Astr. Soc.* **224**, 299

Sofue Y., Fujimoto M., Wielebinski R. (1986) *Ann. Rev. Astron. Astrophys.* **24**, 459

Sukumar S., Allen R.J. (1988) *Nature* **340**, 337

Tosa M., Fujimoto M. (1978) *Publ. Astron. Soc. Japan* **30**, 315

Westerhout G., Seeger Ch.L., Brouw W.N., Tinbergen J. (1962) *Bull. Astron. Inst. Neth.* **16**, 187

Wielebinski R., Shakeshaft J.S., Pauliny-Toth I.I.K. (1962) *Observatory* **82**, 158

Wielebinski R. (1990) in *The Interstellar Medium in Galaxies* eds. H.A. Thronson, Jr. and J.M. Shull, Kluwer, Dordrecht, p. 349