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INVITED REVIEWS

Milestones in the Observations of Cosmic Magnetic Fields

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Abstract Magnetic fields are observed everywhere in the universe. In this review, we concentrate on the observational aspects of the magnetic fields of Galactic and extragalactic objects. Readers can follow the milestones in the observations of cosmic magnetic fields obtained from the most important tracers of magnetic fields, namely, the star-light polarization, the Zeeman effect, the rotation measures (RMs, hereafter) of extragalactic radio sources, the pulsar RMs, radio polarization observations, as well as the newly implemented sub-mm and mm polarization capabilities.

The magnetic field of the Galaxy was first discovered in 1949 by optical polarization observations. The local magnetic fields within one or two kpc have been well delineated by starlight polarization data. The polarization observations of diffuse Galactic radio background emission in 1962 confirmed unequivocally the existence of a Galactic magnetic field. The bulk of the present information about the magnetic fields in the Galaxy comes from analysis of rotation measures of extragalactic radio sources and pulsars, which can be used to construct the 3-D magnetic field structure in the Galactic halo and Galactic disk. Radio synchrotron spurs in the Galactic center show a poloidal field, and the polarization mapping of dust emission and Zeeman observation in the central molecular zone reveal a toroidal magnetic field parallel to the Galactic plane. For nearby galaxies, both optical polarization and multifrequency radio polarization data clearly show the large-scale magnetic field following the spiral arms or dust lanes. For more distant objects, radio polarization is the only approach available to show the magnetic fields in the jets or lobes of radio galaxies or quasars. Clusters of galaxies also contain widely distributed magnetic fields, which are reflected by radio halos or the RM distribution of background objects. The intergalactic space could have been magnetized by outflows or galactic superwinds even in the early universe. The Zeeman effect and polarization of sub-mm and mm emission can be used for the study of magnetic fields in some Galactic molecular clouds but it is observed only at high intensity. Both approaches together can clearly show the role that magnetic fields play in star formation and cloud structure, which in principle would be analogous to galaxy formation from protogalactic clouds. The origin of the cosmic magnetic fields is an active field of research. A primordial magnetic field has not been as yet directly detected, but its

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existence must be considered to give the seed field necessary for many amplification processes that have been developed. Possibly, the magnetic fields were generated in protogalactic plasma clouds by the dynamo process, and maintained again by the dynamo after galaxies were formed.

Key words: magnetic fields — polarization — ISM: magnetic fields — galaxies: magnetic fields — pulsars

1 AT THE BEGINNING

Magnetic fields have been observed everywhere in the universe. Historically, the existence of the magnetic field of the Earth has been known in China for over 4000 years. Chinese emperors of the Han Dynasty used 'magnetic carts' to point the way on the tours of their empire. The Roman chronicler Plinius recorded that in ancient Greece, in the province called 'Magnesia', iron ore with magnetic properties had been mined possibly for thousands of years. The use of the compass for navigation was practised by Chinese, Arab, Portuguese, Spanish and English seafarers. In England William Gilbert performed experiments with magnets around 1600. A series of important discoveries of magnetic effects were made by Coulomb, Faraday, Oersted, and Gauss.

The basic experiment of Zeeman, the observation of the splitting of spectral lines by passage through a magnetic field, opened the way to remote sensing of magnetic fields. A few years after Zeeman's result was published, in 1908, G. E. Hale observed magnetic fields in the Sun. The detection of magnetic fields in Ap stars was made by Babcock (1947).

The first discussion about the need of an interstellar magnetic field to explain the isotropy of the cosmic radiation was given by Alfvén (1937), but Fermi (1949) stressed that the fields filled the vast expanses of interstellar space. The first observations of the polarization of starlight, made by Hiltner (1949) and Hall (1949), were at first interpreted to be due to the scattering by dust in the Galactic plane. An alternative explanation by Davis & Greenstein (1951) was that magnetic fields may align the dust grains.

A spectacular result was the study of the polarization of the Crab Nebula by Dombrovsky (1954) who followed up the suggestion by Shklovskij (1953) that the light of the Crab nebula is due to synchrotron emission and is therefore polarized. Oort & Walraven (1956) and Woltjer (1957) followed up these observations with two dimensional vector plots of the polarization of the Crab nebula, proving that it was indeed optical synchrotron radiation. New optical polarization observations and historical observations of this object can be found in Hickson & van den Bergh (1990).

The advent of radio astronomy, starting in the 1950's, allowed the measurement of magnetic fields in a variety of cosmic objects. Data have been gathered on the magnetic fields in the Milky Way, nearby galaxies, clusters of galaxies and distant radio galaxies. In this review, we will not be dealing with the magnetic fields of the Earth, the Sun and the planets. Instead, we will concentrate on the many aspects of the Galactic and extra-galactic magnetic fields.

The detection of radio polarization in the Galaxy (Westerhout et al. 1962; Wielebinski et al. 1962) gave the final proof that magnetic fields exist in the Milky Way. These early observations showed that the radio polarization was subject to ionospheric Faraday rotation at lower radio frequencies. Polarization of the radio continuum emission of discrete radio sources was observed by Mayer et al. (1962). In the succeeding years, both the Galactic polarized emission and the discrete radio sources were shown to be subject to Faraday rotation by the

Galactic magnetic fields along the line of sight. This discovery gives the second radio method of measuring magnetic fields.

The Zeeman effect was used at optical wavelengths to measure the magnetic field of the Sun and of the magnetic stars. The radio Zeeman effect was predicted for the HI line by Bolton and Wild (1957) but it took some time to be detected. The radio Zeeman effect was finally found by Verschuur (1968) in HI clouds in the Galaxy. Zeeman effect studies of other molecular species that probe magnetic field strengths in different molecular clouds were also successful. The observations, however, are difficult and data gathering during the past years has been slow.

Soon after the discovery of the first pulsar it was realized that these objects could be ideally used to measure the magnetic fields of the Galaxy. This was pointed out first by Lyne & Smith (1968). In some ways pulsar studies combined with Galactic polarization observations are the best method to investigate the Galactic magnetic field.

The earliest maps of radio galaxies showed that considerable polarization is present and that magnetic fields are involved in the emission process (e.g., Cooper & Price 1964; Morris et al. 1964; Högbom & Carlsson 1974). The advent of large synthesis radio telescopes in Westerbork, Holland and the Very Large Array in Soccoro, New Mexico contributed significantly to this subject.

The search for radio polarization in normal galaxies led to the first detection of the regular magnetic fields in M51 by Mathewson et al. (1972), the mapping of M31 by Beck et al. (1978) followed. This field of research, which requires observations at several high frequencies, and has been dominated by the observations with Effelsberg radio telescope. More recently, the combination of Effelsberg single dish maps with the VLA data greatly advanced our knowledge of galactic magnetic fields.

Diffuse radio continuum emission was found to be present in clusters of galaxies (e.g., Ryle & Windram 1968; Willson 1970; Wielebinski 1978). In particular, the investigation of the Coma A cluster led to the conclusion that magnetic fields of B $\sim 2\,\mu$G are present in the intracluster medium between the galaxies. This result came both from an equipartition argument for the continuum data (e.g. Deiss et al. 1997) and Faraday rotation studies by Kim et al. (1990). Certainly clusters of galaxies represent the largest magnets in the Universe.

The existence of magnetic fields in the more distant Universe has been the subject of many papers. We refer to the excellent review by Kronberg (1994) who showed that Lyman-α systems with $z = 2.0 \sim 3.0$ possess magnetic fields. Additional reviews on magnetic fields in galaxies have been made by Zeldovich et al. (1983), Rees (1987), Wielebinski & Krause (1993), Beck et al. (1996), Zweibel & Heiles (1997) and Beck (2001).

Note that Zeeman splitting and Faraday rotation can detect the magnetic field component along the line of sight, i.e., $B_{||}$, and are sensitive to its sign, whereas synchrotron radiation and polarimetry (of starlight or dust) mostly reflect on the field component perpendicular to the line of sight, $B_{\perp}$.

2 OPTICAL POLARIZATION

In retrospect, the earliest method of tracing the magnetic fields of the Galaxy was actually successful. The first reports (Hiltner 1949; Hall 1949) of the polarization of starlight came simultaneously with the suggestion that magnetic fields may align the dust grains, and theoretical work by Davis & Greenstein (1951) implied that polarization was caused by dust grains so lined-up. However, the problem of separating simple scattering effects from polarization due to dust grains aligned in magnetic fields makes the interpretation ambiguous. This led to a controversy that continued for many years. Many optical astronomers were convinced that only scattering was responsible for all observed polarization, while one can say that much of the polarization is in fact due to magnetic alignment. In fact, other possibilities exist as to the cause of polarization of thermal dust emission, such as dust grains in an anisotropic radiation field (e.g., Onaka 2000) or different populations of grains at different temperatures, see Goodman (1996) for a review on both the observational and theoretical aspects.

2.1 Polarization of Stars

Polarization of starlight can be used to detect magnetic fields out to 1 or 2 kpc from the Sun. In the late 1950s, a substantial catalog of the polarization of stars in the northern hemisphere was compiled by Behr (1959). This work was continued in the southern hemisphere by Mathewson and Ford (1970a) who eventually presented an all-sky distribution of starlight polarization. Their catalog includes polarization measurements by Hiltner (1956), Hall (1958), Behr (1959), Loden (1961), Appenzeller (1968), and Visvanathan (1967). The general conclusion of this work is still valid today that the magnetic field of the Galaxy is in general aligned along the Galactic plane. Some additional effects were also noted that indicated irregularities of the local field.

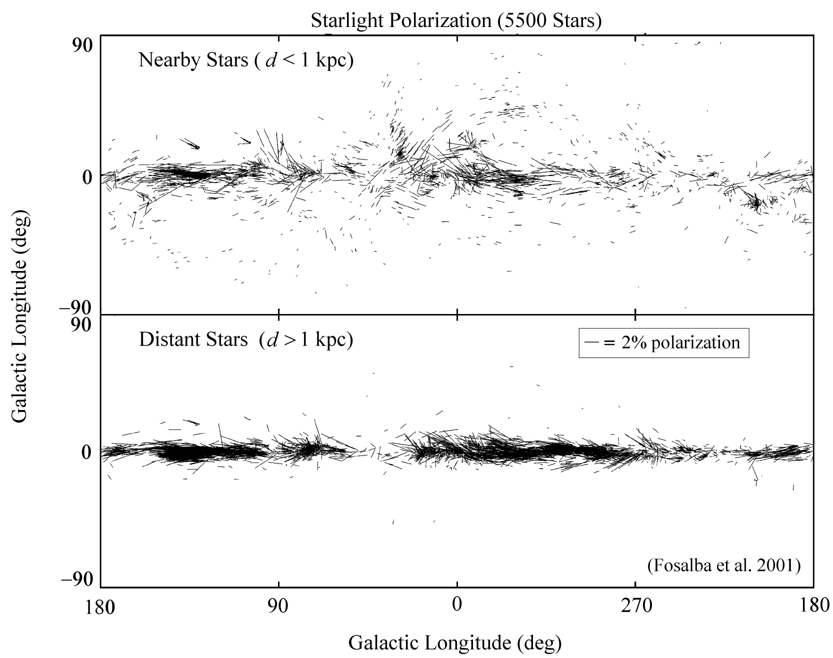

Fig. 1 Distribution of starlight polarization. Nearby stars show the local perturbations, and distant stars show the larger-scale field parallel to the galactic plane (courtesy P. Fosalba).

Using the data available at the time, Axon & Ellis (1976) compiled a catalog of 5070 stars with reliable distances. Recently, Heiles (2000) has compiled a new catalog of starlight polarizations of 9286 stars, using all previously available data including 1800 stars from Mathewson &

Ford (1970a), 126 stars from Appenzeller (1974), 495 stars from Schroeder (1976), 1660 southern OB stars from Klare & Neckel (1977), 313 nearby stars from Krutter (1980), 358+118 stars from Korhonen & Reiz (1986), 1000 nearby stars from Leroy (1993), 133 stars from Bel et al. (1993), 51 stars at high Galactic latitudes from Berdyugin et al. (1995), 361 stars from Reiz & Franco (1998), and 126 stars from Goodman (unpublished data). After the Heiles' catalog was compiled, some new data from Berdyugin's group (Berdyugin & Teerikorpi 1997, 2001; Berdyugin et al. 2001) and others (e.g., Serkowski & Shawl 2001) have been published.

The starlight data show that the percentage polarization increases with increasing extinction and/or distance (Behr 1959; Appenzeller 1968; Fosalba et al. 2002), showing the Davis and Greenstein effect from interstellar dust grains. Many analyses have reached the conclusion that *the local regular magnetic fields of our Galaxy point to the direction* $l \sim 82°$*, and seem to follow the spiral pattern very closely* (e.g., Heiles 1996; Andreasyan & Makarov 1989), although the local distortions can be clearly seen in the nearby stars (see Fig. 1). The polarization "vectors" in the southern Galactic pole (eg. Berdyugin & Teerikorpi 2001) seem unperturbed by any other features and hence the direction of local fields can be seen clearly. Most recent analysis of the polarization data (e.g., Fosalba et al. 2002) shows that the regular magnetic field is about 39% to 62% of the total magnetic energy.

Starlight polarization was mainly used to study the local magnetic fields (within 1 or 2 kpc), as stated above. However, it is worth noting some other applications of the data. For a long time, the data were used to probe the intervening clouds (e.g., Markkanen 1979; Gomez de Castro et al. 1997). The excess polarization of Vega-like stars was used to statistically study the circumstellar material (Bhatt & Manoj 2000). Angular power spectrum analysis of the data may be used to model the Galactic polarized continuum emission at other wavelengths (Fosalba et al. 2002).

2.2 Nearby Galaxies

Optical polarization observations of nearby galaxies can reveal the magnetic fields in the galactic disk or dust lanes.

The observations of M31 by Hiltner (1958) were shown to require a magnetic field aligned along the major axis. A discussion of the polarization produced by interstellar dust in external galaxies was given earlier by Elvius (1951, 1956). Polarimetric observations of several galaxies by Appenzeller (1967) showed optical polarization vectors but were interpreted to be due to reflection as well as interstellar absorption with a magnetic field directed along the spiral arms. First polarization of stars, later photoelectric surface photometry in Magellanic Clouds (e.g., Mathewson & Ford 1970b, 1970c; Schmidt 1970) gave us some real insight of the magnetic fields in these nearby galaxies.

The next important development in this field is creditted to S.M. Scarrott who for many years delivered numerous results on magnetic fields using his electronographic camera methods. Up to 30% optical polarization in the halo region of M82 (Bingham et al. 1976) and strong polarization along the dust lanes of M104 (Scarrott et al. 1977) were published. The optical polarization in most cases indicated the presence of large-scale magnetic fields in galaxies (Elvius 1978). The advent of the CCD has added more sensitivity to various polarimeter systems. Scarrott et al. (1987) showed the perpendicularity between the radio and optical polarization vectors, exactly as expected if magnetic dichroism and the synchrotron process are responsible for the polarization at the shorter and longer wavelengths respectively. The polarization map of NGC 1068 (Scarrott et al. 1991, see Fig. 2) is so impressive that apart from the immediate nuclear zone, the orientation of the polarization vectors form a spiral pattern in both the arm and interarm regions, rather than a circular one expected from the scattering of bright nuclei. The pattern can be explained in terms of a magnetic field with a spiral configuration and by polarization produced by dichroic extinction (see discussion by Wood 1997). Therefore, in galaxies with low inclinations, the polarization vectors are coherent on kpc scale-lengths and follow spiral configurations. In galaxies with high inclinations, such as M104 and NGC 5128 (Scarrott et al. 1996), the polarization in the central regions is oriented parallel to the dust lane. In NGC 1808 (Scarrott et al. 1993), the polarization orientations follow the spiral arms on kpc scales, indicative of a magnetic field coherent on a galactic scale (Scarrott 1996).

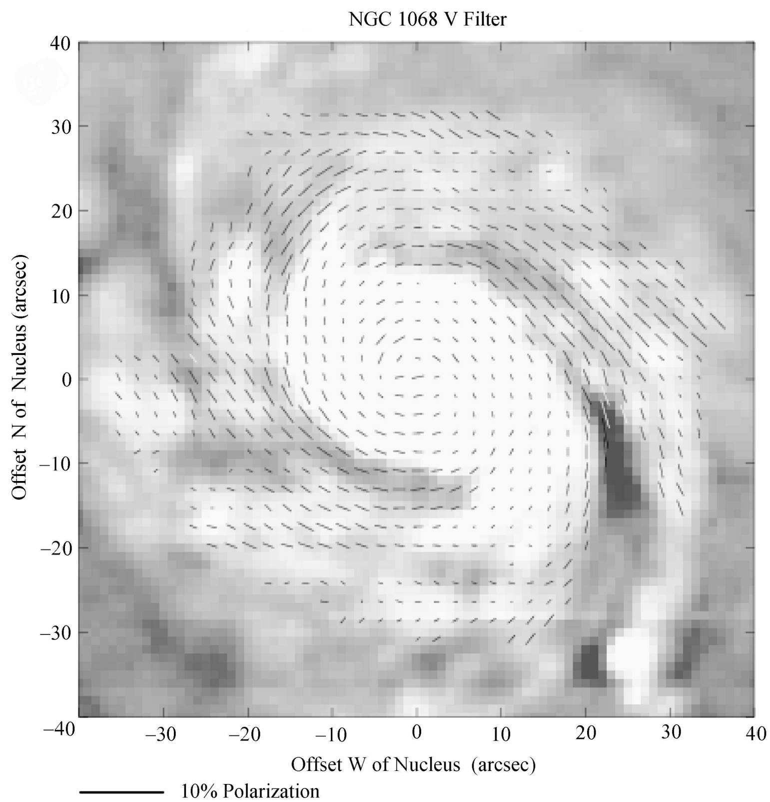

Fig. 2 Optical polarization vectors for NGC 1068 (courtesy Peter W. Draper after Scarrott et al. 1991).

Meanwhile, other groups also contributed to the optical polarization of galaxies. King (1986) found that the scattering of light from the bright nucleus of NGC 7331 is predominant along the major axis of the galaxy, elsewhere the polarization is consistent with being produced by the transmission of light through elongated grains partially aligned by the galactic magnetic field and the Davis-Greenstein mechanism. Fendt et al. (1996) observed three edge-on galaxies (NGC 891, 5907 and 7331). Except the dominant orientation given by the anisotropic scattering, NGC 891 has polarization orientations indicating magnetic fields perpendicular to the major axis, and NGC 7331 has polarization indicating a toroidal field. These polarization maps are understandable after the two effects are considered and modelled (Wood & Jones 1997). The polarization map of NGC 6946 (Fendt et al. 1998) is affected by foreground galactic scattering in one quadrant due to its low Galactic latitude ($b \sim 11.7°$).

Optical polarization observations of more distant galaxies (e.g., Tadhunter et al. 1992; Scarrott et al. 1990) or active galaxies (Draper et al. 1993; Cimatti et al. 1993) have been used to investigate some interesting issues, such as the "unified" scheme of AGNs, emission mechanisms (Breeveld & Puchnarewicz 1998) and hot spots (Lähteenmäki & Valtaoja 1999). One may have noticed that the Hubble Space Telescope is equipped with polarizers, which provide high resolution polarization maps even at the ultraviolet band (e.g., Kishimoto et al. 2002), that can be used to study hidden galactic nuclei and the scattering grains.

2.3 Polarization Observations at Infrared, Far-infrared, Millimeter, Submillimeter Ranges

Recently a return to the dust polarization method of measuring magnetic fields has been made possible by the advent of polarization measurements in the infrared, far-infrared, sub-mm and mm (e.g., Cudlip et al. 1982; Dowell et al. 1998; Hildebrand et al. 2000). We expect no scattering at these wavelengths and hence the polarization originates in the emission of dust particles aligned by the magnetic field. Observations of linear polarization from the thermal emission of magnetically aligned dust grains provide a relatively easy means of exploring the magnetic field morphology (Heiles et al. 1993). Polarization observations of molecular clouds have been used to study the role of magnetic fields in the formation and evolution of the clouds and in the process of star formation.

With greatly improved sensitivity and increased number of measuring pixels, it is now possible to use polarimetry to trace magnetic fields not only in the prestellar cores of bright molecular clouds (e.g., Ward-Thompson et al. 2000), but also in thermal streamers, in the accretion disk around T Tauri stars (e.g., Tamura et al. 1999), in the envelopes of young stellar objects (Holland et al. 1996), and in other sources of dust emission (e.g., Vallée et al. 2000). Magnetic fields around protostars (Greaves & Holland 1998) are banded and there is probably a centrally contracted field, which collimates the bipolar outflowing gas (Greaves et al. 2001; Momose et al. 2001). The fields are most likely to be toroidal in the circumstellar disk (Tamura et al. 1999).

On the global scale, polarization maps at different wave bands reveal the emission from dust grains orientated by the same magnetic fields, giving roughly consistent results, e.g., the polarization maps of the Orion clouds at 1.3 mm and 3.3 mm by Rao et al. (1998) and $350\,\mu$m by Hildebrand et al. (2000). However, one should note that the emission at longer wavelengths comes from colder dust and that at shorter wavelengths, from warmer dust. As these clouds have a temperature gradient from the a hot core to a cold ambient envelope or even colder large-scale clumpy ridges, so one should be careful when interpreting the polarization observations in terms of predominant magnetic fields in given regions. Sometimes separation is possible (e.g., Schleuning et al. 2000). Near the hot cores or HII regions the fields tend to be distorted by star formation or expansions so that they have smaller length scales or vary rapidly in space. The inclination or 3D structure of the magnetic field in some cases can be obtained by comparison of the Zeeman splitting measurements (see Schleuning et al. 2000; Hildebrand et al. 2000).

Due to limited sensitivity and resolution, it is still too early to observe the dust polarization at these bands in nearby Galaxies, although Greaves et al. (2000) have reported results on M82 and Siebenmorgen et al. (2001) on NGC 1808. The integral FIR polarization observed for the first time from the core of the quasar 3C 279, is a completely different story, being related to synchrotron radiation (Klaas et al. 1999). However, in our Galaxy, there is a "central molecular zone" at the Galactic center, with a size as large as 400 $\times$ 75 pc (Pierce-Price et al. 2000). The thermal dust continuum emission traces the temperature-weighted column density of dust grains and wide-ranging network of dusty filaments, which can be observed at mm, sub-mm, far-infrared bands. Werner et al. (1988) first detected the polarization in the far-infrared band, and concluded that the field was predominantly azimuthal. Afterwards, more and better data were accumulated for the circumnuclear disk (or the so-called dust ring) in a few pc from Sgr A* (Hildebrand et al. 1990, 1993; Novak et al. 2000), the giant molecular cloud Sgr B2 at 100 pc from the center as well as some other clouds near the center (Novak et al. 1997, 2000), and for thermal filaments (Morris et al. 1992). All results are consistent with a large-scale azimuthal field with respect to the Galaxy. Evidently the gravitational force dominates the magnetic force within the neutral gas layer and then the differential rotation shears the field out into the azimuthal configuration (Morris 1998). Recent polarization observations at 450 μm in a large area revealed the toroidal magnetic fields probably permeating most of the molecular zones ($> 170\,\mathrm{pc} \times 30\,\mathrm{pc}$) and the fields are parallel to the Galactic plane (see Fig.6, Novak et al. 2002, 2000). This is complementary to the dipole field delineated by the non-thermal filaments (see next Section).

3 THE ZEEMAN EFFECT

Zeeman measurements are used mainly to detect the magnetic fields in molecular clouds and provide information about the direction of the field along the line of sight (see Crutcher 1999), which is a key step to understanding the process of star formation in cloud cores (e.g., Li 1998). Combination of results from both polarimetry of dust emission and Zeeman observations can provide a three-dimensional view of the magnetic fields in the clouds (Houde et al. 2002).

As mentioned in the Introduction, the optical Zeeman effect was used by G.E. Hale at the turn of the 20th century to measure the magnetic field of the Sun and by Babcock (1947) to measure the magnetic fields in peculiar magnetic stars. A very important use of the Zeeman splitting is the measurements of spectral lines at radio frequencies. The detection of the HI line in 1951 led to the suggestion by Bolton and Wild (1957) to search for the Zeeman effect at radio frequencies. This observation has turned out to be rather difficult, because the side-lobe effect and other instrumental corrections have to be considered. Finally Verschuur (1968) and Devies et al. (1968) gave a definite proof of the Zeeman effect in the Perseus spiral arm by observing HI in *absorption* against Cassiopea A. Meanwhile, observation of the Zeeman effect in HI *emission* profiles has been always very difficult: the inherently weak effect due to the weak magnetic fields (a few μG along the line of sight) is difficult to pick up against strong instrumental effects (e.g., Verschuur 1995a), and such observations rarely produced consistent results (e.g., Verschuur 1995b; Troland & Heiles 1982; Myers et al. 1995).

OH maser occurs in much denser clouds ($10^7\mathrm{cm}^{-3}$) than diffuse HI emission ridges ($10^3\mathrm{cm}^{-3}$), where the fields are also much stronger which helps the detection of Zeeman splitting. Early attempts to identify Zeeman pairs in OH maser spectra were generally not successful. Once interferometric maps became available, one usually finds that the proposed Zeeman components came from widely separated regions in a same maser source. Verification of OH maser sources came from VLBI observations (Reid et al. 1980; Zheng et al. 2000) which showed some pairs to come from the same position within the size of a maser spot. OH masers have now been detected in the prestellar cores of clouds, L1544 (Crutcher & Troland 2000). Up till now, the number of detections is not very large. All previous detections of the OH lines (and other lines or absorptions) with Zeeman effect have been summarized by Crutcher (1999) and new observations made by, for example, Bourke et al. (2001).

The first attempt to use the Zeeman data to derive the large-scale magnetic field of the Milky Way was made by Reid & Silverstein (1990), and later extended by Caswell & Vaile (1995). It was not possible to determine the large-scale magnetic field of the Galaxy in view of the small number of sources, so a survey of a large number of OH masers is needed (see Argon et al. 2000). However, one should note that the star-formation activity may have changed the initial geometry of the magnetic field preserved during the contraction from interstellar density ($1\,\mathrm{cm}^{-3}$), through the density of giant molecular clouds ($10^3\,\mathrm{cm}^{-3}$), to the density of OH masers near newly formed OB stars ($10^7\,\mathrm{cm}^{-3}$).

Magnetic fields of several tens of mG in interstellar H_2O maser clumps ($\sim 10^{10}\,\mathrm{cm}^{-3}$) were first detected by Fiebig and Güsten (1989). The VLA and VLBA have been used to study the Zeeman effect in water masers (Sarma et al. 2001). More recently attempts to detect the Zeeman effect in a variety of lines have been made: the H30α recombination line by Thum and Morris (1999), the CN line by Crutcher et al. (1999), and the CCS line by Levin et al. (2001). Note that OH and H_2O masers arise in very small regions in high-density clouds under special conditions. New detections of CN Zeeman effects offer a good chance to measure the magnetic fields in clouds with densities of 10^5 to $10^6\,\mathrm{cm}^{-3}$ (Crutcher et al. 1999).

Note that observation of HI absorption towards the nuclear region of other (preferably edge-on) galaxies can provide information of magnetic fields in the redshifted clouds or circumnuclear ring around the nuclear region (e.g., Sarma et al. 2002). This seems to be useful but is limited to just a few lines of sight.

4 THE RM of EXTRAGALACTIC SOURCES

Following the detection of the polarization of extra-galactic sources, the Faraday rotation effect was found by Cooper & Price (1962) from the wavelength dependant emission in the source Centaurus A. Soon afterwards, it was noticed that the rotation measures were dependant on both Galactic latitudes (Garder & Whiteoak 1963) and longitudes (Morris & Berge 1964). From the emission source to the observer, the Faraday rotation can be expressed as

$$\mathrm{RM} = 0.810 \int_{\mathrm{source}}^{\mathrm{Sun}} n_e \boldsymbol{B} \cdot d\boldsymbol{l}, \tag{1}$$

where the rotation measure, RM, is in rad m^{-2}, n_e is the electron density (in cm^{-3}), $\boldsymbol{B}$ is the vector magnetic field (in μG), and $d\boldsymbol{l}$ is the line element vector of the line of sight (in pc) pointing towards us. The dependence implies that most RMs originate from (the local arm of) our Galaxy (see Berge & Seielstad 1967).

Studies of the Faraday rotation across the Galaxy were first made by Gardner & Davies (1966) and later by Gardner et al. (1969). Many observers continued to gather data on the polarization of discrete sources (e.g., Kronberg and his students: Vallee & Kronberg 1975; Kronberg & Wardle 1977), however the process of collecting (reliable?) data in early days is slow (e.g., Tabara & Inoue 1980). The successful polarization observation of radio source led to RM catalogs across the sky (e.g., Ellis & Axon 1978; Simrad-Normandin et al. 1981; Broten et al. 1988). A fit of RMs to a model that included a longitudinal (azimuthal) magnetic field with a local anomaly was made by Vallee & Kronberg (1975). Many papers with a re-analysis of the existing data followed (e.g., Ruzmaikin & Sokoloff, 1977; Sofue et al. 1979; Inoue & Tabara 1981). Simard-Normandin & Kronberg (1980) took the average RM of a cone 15° radius to represent the Galactic RM sky and for the first time identified several large features related to loop II, loop I, etc. They showed that the RM at high latitudes is well correlated with, and influenced by the large scale prevailing magnetic fields. This eventually became a standard for discussing "the Galactic Rotation Measure".

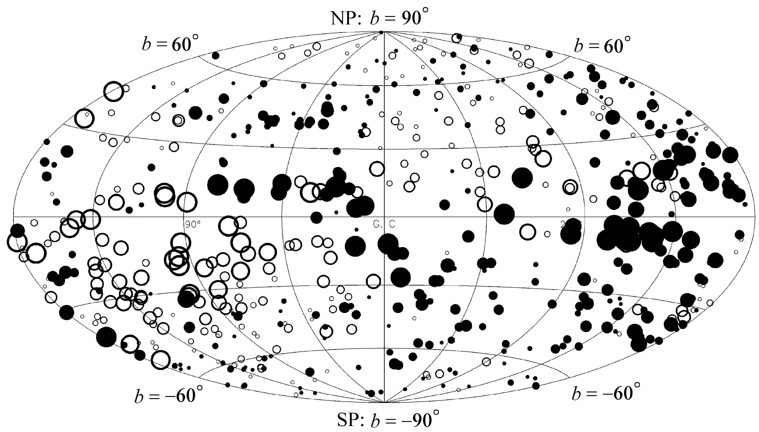

Fig. 3 Antisymmetric RM sky, shown by extragalactic radio sources. Filled symbols represent positive RMs, and open symbols, negative RMs (after Han et al. 1997).

The antisymmetric RM sky (see Fig. 3) was first noticed by Berge & Seielstad (1967) who even interpreted that as a result of magnetic fields directed toward $l = 260°$ for $b > 0°$ and toward $l = 80°$ for $b < 0°$. The antisymmetric feature was confirmed later by Vallee & Kronberg (1975) and Simard-Normandin & Kronberg (1980) with much more data, but was interpreted as the local perturbations of loop I. Andreasyan (1980) attributed the antisymmetry to the local disk field with reversed directions above and below the plane, as Berge & Seielstad (1967) suggested, while Han et al. (1997) argued that the antisymmetry is the result of the magnetic field in the thick disk or halo on the Galactic scale. Coincident with the vertical fields in the Galactic center, they suggested that A0 dynamo is responsible for the field structure.

Reliable RMs are now available for some 1000 sources in the literature. The sources are not well distributed on the sky. The main weakness is that very few sources with known RM are available within $|b| < 10°$ where the Galactic magnetic field is concentrated. Only a few observations at low latitudes (Clegg et al. 1992) produced good measurements. The situation will soon be improved significantly by the newly determined RMs of point sources from the Galactic Plane polarization surveys in the Southern and Northern skies (Gaensler et al. 2001; Brown & Taylor 2001). Nevertheless, Simard-Normandin & Kronberg (1980) and Sofue & Fujimoto (1983) compared the RM data at low latitudes with model predictions and found that the spiral fields with direction reversals are more suitable for our Galaxy. Concentrating on selected Galactic regions, Broten et al. (1988) have confirmed the existence of magnetic field reversals in the Milky Way. The most recent analysis by Frick et al. (2001) using wavelet method basically confirmed the previous conclusions on field reversals and the antisymmetry.

The RMs of extragalactic radio sources have also been used to investigate the small-scale (200 pc − 0.01 pc) structures of interstellar media and magnetic fields. This was mostly done by Cordes' group (Simonetti et al. 1984; Simonetti & Cordes 1986; Lazio et al. 1990; Clegg et al. 1992). They computed the structure function of RM spatial variations and found that the variation of (n_e, B) can be described by a power-law spectrum of turbulence, which is enhanced near the Galactic plane. Both the turbulent fluctuations of electron density (see Armstrong et al. 1995) and random magnetic fields are responsible for the variations (see Minter & Spangler 1996). For most directions the δRM is less than 10 rad m^{-2} in a few arcminutes for background sources, but the RM difference can be up to a few tens of rad m^{-2} near the Galactic plane, and small anomalous regions are possibly associated with some local Galactic features (e.g., Clegg et al. 1992).

Within the scope of the Canadian Galactic Plane Survey (Landecker et al. 2000), the RMs of some 380 sources were determined (Brown & Taylor 2001). All these sources are in the $b = \pm 4°$ range of the Galactic plane. This is in contrast to the data of Simard-Normandin & Kronberg (1980) where the sources are mostly away from the Galactic plane. In particular, the region of $l = 92.0°,\ b = 0.5°$, investigated in detail by Brown & Taylor (2001), shows that most of the extra-galactic sources have negative rotation measures.

5 MAGNETIC FIELDS FROM OBSERVATIONS OF PULSARS

The discovery of pulsars gave us a new method of measuring magnetic field. Since, for a pulsar, both the RM and the dispersion measure (DM) can be determined, the average magnetic field can be directly obtained, if the electron density and the magnetic field B are not correlated (Beck 2001). This was pointed out by Lyne & Smith (1968) and taken up by several investigators. A significant collection of observations of pulsar RMs was presented by Manchester (1972, 1974), who revealed the local uniform magnetic field of about 2.2±0.4 μG, and directed towards about $l \sim 90°$. Thomson & Nelson (1980) re-analyzed 48 pulsar RMs listed by Manchester & Taylor (1977) and found field reversal near the first inner spiral arm, i.e., the Carina-Sagittarius arm.

The acquisition of RMs and DMs has become an important "industry" in pulsar astronomy. A significant step here was made by Hamilton & Lyne (1987), who measured the Faraday rotation of 163 pulsars, so increasing the total number of pulsar RM measured to 185. Afterwards, Costa et al. (1991), Rand & Lyne (1994), Qiao et al. (1995), van Ommen et al. (1997) and Han et al. (1999) contributed a number of new RMs, providing RM data for some 320 objects. Note that pulsar observations are more concentrated in the Galactic plane than the observations of extragalactic sources, so pulsars are mostly used to probe the magnetic fields in the Galactic disk.

The interpretation of the pulsar RMs as a signature of galactic magnetic fields goes back to the papers of Simard-Normandin & Kronberg (1980) and Lyne & Graham Smith (1989). The latter authors confirmed the local field strength and direction found by Manchester (1974) and the reversal near the Carina-Sagittarius arm. They also suggested another field reversal outside the Perseus arm from a comparison of the pulsar RMs with the RMs of extragalactic radio sources.

Re-analyses of pulsar RM data mostly gave more detailed modeling of the structure of Galactic magnetic fields. Rand and Kulkarni (1989) noticed the significant effect of the North Polar Spur on pulsar RMs and suggested a concentric-ring model for the reversed fields. This was continued by Rand & Lyne (1994). Since the field reversals are expected in a bi-symmetric field structure on large scales, the model of bi-symmetric spiral field was fitted by Han & Qiao (1994) and Indrani & Deshpande (1998) after de-projecting all RMs onto the Galactic plane. This proved to be very successful for the local region (< 3 kpc). New RMs of distant pulsars by Rand and Lyne (1994) and Han et al. (1999, 2002) suggested the second and the third field reversals near the Crux-Sctum arm and the Norma arm. The most recent status in this field, described using much more new data was given by Han et al. (2002) who reported the detection of counterclockwise magnetic field near the Norma arm (see Fig. 4).

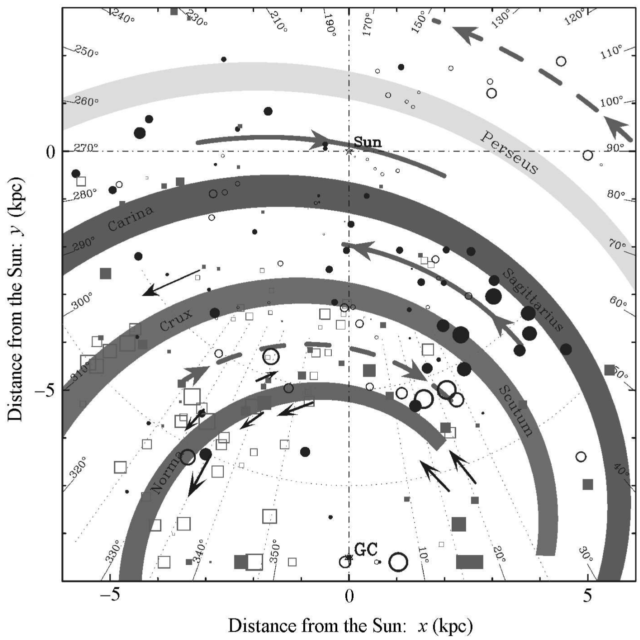

Fig. 4 RMs of pulsars in the Galactic disk reveal the large-scale magnetic fields and the field reversals from arm to arm (after Han et al. 2002).

The effects of HII regions on pulsar DM have been investigated by Walmsley & Grewing (1971). More recently, Mitra et al. (2002) have studied in detail several fields along the Galactic plane and showed that not only do the DMs increase but the RMs are also affected. In particular, some HII regions were shown to possess magnetic fields that are reversed in direction relative to the surrounding (regular) magnetic field.

6 RADIO POLARIZATION OF DIFFUSE EMISSION

The prediction of Shklovsky (1953) that synchrotron emission would be linearly polarized led to a number of attempts at its detection. The earliest attempts to observe linearly polarized radio emission were made by Thomson (1957), Razin (1958) and Pawsey & Harting (1960). All these early observers used small antennas at lower radio frequencies that, in retrospect, makes polarization detection hardly possible.

6.1 The Galactic Disk

Diffuse radio emission comes from the thin disk and thick disk of our Galaxy (Beuermann et al. 1985), with many spurs emerging from the disk (Haslam et al. 1982). The polarized emission at a few hundred MHz mainly comes from regions within a few hundred parsecs from the Sun (e.g., Spoelstra 1984) while the polarized emission at higher frequencies from more distant regions (Junkes et al. 1987; Gaensler et al. 2001).

The first definite detections of polarized Galactic emission in our Galaxy at 408 MHz reported by Westerhout et al. (1962) and Wielebinski et al. (1962). Both groups had to understand and correct the instrumental polarization of their radio telescopes which produced effects larger than the observed radio polarization signals and showed the "fan" structure of polarization angles around $l = 140°$, $b = 8°$. Soon after this pioneering work several groups took up the challenge to investigate the distribution of polarized emission in the Galaxy. The variation in the position angle of the observed polarization along with the ionospheric data (Wielebinski & Shakeshaft 1962) revealed that Faraday rotation was taking place in the Earth's ionosphere.

The observation of polarized emission at higher radio frequencies (Muller et al. 1963) showed additional Faraday rotation due to the magnetic fields in the interstellar medium of the Milky Way. Surveys of larger areas of linearly polarized radio emission were continued at several frequencies (e.g., Berkhuijsen & Brouw 1963; Wielebinski & Shakeshaft 1964; Mathewson & Milne 1965; Berkhuijsen et al. 1964; Mathewson et al. 1966; Baker & Smith 1971; Wilkinson 1973; Baker & Wilkinson 1974). Some observations were dedicated to the large radio features such as the North Polar Spur or other loops (Berkhuijsen 1971; Spoelstra 1971, 1972a, b, c). Early observations at 1400 MHz by Bingham (1966) showed that polarized emission was widely distributed in the Galaxy. A milestone in the observation of Galactic radio polarization is the map of the northern sky at five frequencies between 408 MHz and 1411 MHz, presented by Brouw & Spoelstra (1976). After this, mapping of Galactic polarization ceased and the attention of the observers turned to external galaxies (see the next Section) or large-scale continuum high-resolution surveys of the Galactic plane at 11 cm (Reich et al. 1984, 1990; Fürst et al. 1990a, b) and to 21 cm observations. However, recently, there is a renaissance in the polarization measurement (Reich et al. 1990, 1997, 2001; Dickey et al. 1999; McClure-Griffiths et al. 2001).

An early all-sky map at 150 MHz was published by Landecker & Wielebinski (1970). The all-sky map at 408 MHz (Haslam et al. 1982) has been available since 1982 after combining the survey data of both northern and southern hemispheres (Haslam et al. 1974, 1981). Radio maps of large areas of the sky at other frequencies are also available now (e.g., 22 MHz by Roger et al. 1999; 0.2 to 13.8 MHz by Manning & Dulk 2001; 45 MHz by Maeda et al. 1999; 2.3 GHz by Jonas et al. 1998).

The "Return to the Galaxy" was heralded by the analysis of the polarization data in the λ11 cm Galactic plane survey by Junkes et al. (1987). This higher frequency survey showed that, although most of the emission is local, some polarized radio waves must have come from some more distant features in the inner Galaxy. This agreed with the observations of the Galactic center by Seiradakis et al. (1985) at λ2.8 cm which showed a complex vertical magnetic field pattern and by Duncan et al. (1998) on the kpc polarized plume. A polarization survey of the *southern* Galaxy was made at 2.4 GHz by Duncan et al. (1995, 1997) using the Parkes radio telescope. The reduction of the $|b| < 5°$ strip of the 2.7 GHz *northern* survey was made by Duncan et al. (1999). All the evidence from both these surveys reveals a decreased polarized intensity in the inner plane due to Faraday depolarization.

The mapping of a wide strip of the Galactic plane at 1.4 GHz, called the "medium latitude survey", was started in Effelsberg by Uyaniker et al. (1998, 1999, see Fig. 5). As of date, large sections of the Galactic plane have been observed. The aim of this project is to map the whole Galactic plane visible from Effelsberg within $b = \pm 20°$. In fact, amazing structures are seen in polarized intensity in the anticenter regions, implying very turbulent and quite deep Faraday depolarization effects.

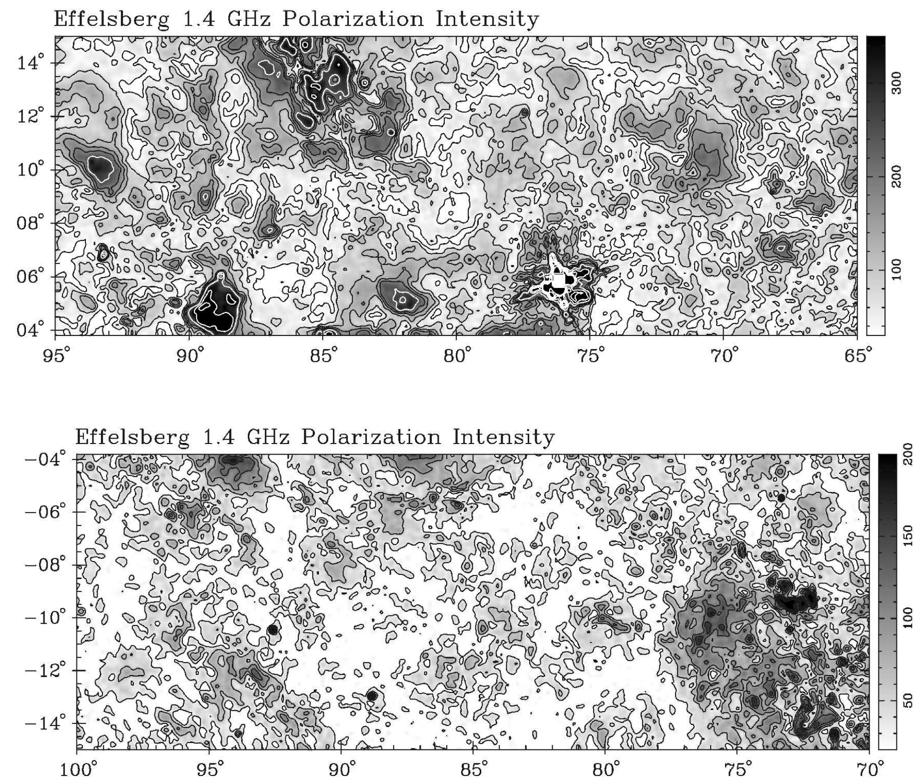

Fig. 5 Polarized intensity map of the outer Galaxy observed by Effelsberg telescope (courtesy W. Reich after Uyanıker et al. 2001).

The observed polarized emission is a modulation of an intrinsically highly polarized synchrotron background by Faraday rotation in the diffuse ionized gas in foreground material, such as H II regions in which the magnetic field is disordered on scales of 0.1–0.2 pc (Gaensler et al. 2001). In the Canadian Galactic plane survey, Gray et al. (1999) have identified several new remarkable phenomena around the W3/W4/W5/HB3 H II region/SNR complex in the Perseus Arm. The regular features detected in the polarization angle are superposed on the linearly polarized Galactic synchrotron background emission by Faraday rotation arising in foreground ionized gas having an emission measure as low as 1 cm^{-6} pc. The 'mottled' polarization arises from random fluctuations in a magneto-ionic screen of a medium in the vicinity of the H II regions themselves. At low frequencies, very complicated patterns are often observed in the polarized intensity and polarization angles on scales down to a few arcmin (Wieringa et al. 1993; Haverkorn et al. 2000). Obviously complete depolarization occurs in a very small depth of the local magnetoionic medium.

The comparison of high-frequency polarization maps of Galactic regions suggests that the RMs may be up to >200 rad m^{-2}. The polarization observations with arcminute resolution at 20 cm by Gaensler et al. (2001) in a large section of the southern sky show that the RMs vary between ± 150 rad m^{-2}. Some areas show considerable positive RMs while others have negative RMs on scales of up to a degree. Comparing the RM values with those of pulsars, some of the polarized features at 1.4 GHz probably originate in the spiral arm at a distance of a few kpc from the Sun (Dickey 1997). These latest results are of great significance because the rest of the Galaxy as well as the cosmological sky are observed through this foreground magnetic screen.

6.2 The Galactic Center

The Galactic center is the first radio source discovered by Carl Guthe Jansky in 1933. In the center there are the strong poloidal (dipole) fields (e.g., Reich 1994) and toroidal field (Novak et al. 2002, see Fig. 6). The best illustration of the poloidal fields is provided by the fine, highly polarized radio structures.

The first non-thermal filaments in the Galactic center were discovered by Yuzef-Zadeh et al. (1984) with VLA observations. This giant polarized radio arc is very striking, extending more than 1° on each side of the Galactic plane (Seiradakis et al. 1985; Tsuboi et al. 1986; Haynes et al. 1992). Later, radio observations using both single dish radio telescopes (Effelsberg 100 m, Nobeyama 45 m) and large synthesis telescopes (VLA, MOST, ATCA), have revealed many filaments, arcs or loops, threads (e.g., Anantharamaiah et al. 1991; LaRosa et al. 2000, 2001; Lang et al. 1999a, b), plumes (e.g., Duncan et al. 1998) and lobes (Sofue 1985). Most of these have been studied in great detail regarding the fine structure, polarization at several frequencies and hence the RMs and spectral indices examined. These strongly polarized nonthermal features are very narrow, with lengths of tens of pc but widths of less than 0.5 pc * (e.g., Inoue et al. 1984; Seiradakis et al. 1985; Tsuboi et al. 1986; Haynes et al. 1992). All but one are perpendicular to the Galactic plane (Lang et al. 1999b). The intrinsic magnetic field in the filaments or threads is predominantly aligned parallel to the filament (e.g., Lang et al. 1999a, b; Sofue et al. 1987). They are believed to be manifestations of strong vertical field lines (mG strength), i.e., they are illuminated flux tubes in large-scale pervasive fields (Yusef-Zadeh & Morris 1987a; Uchida et al. 1996). A consensus reached now is that these must be the consequence of a substantial poloidal magnetic field which pervades the central $\sim$100 pc of our Galaxy (Yusef-Zadeh & Morris 1987a; Morris & Yusef-Zadeh 1989). A primordial origin is suggested for the poloidal field. Equipartition magnetic field values in the magnetic tubes are at least 70 μG, perhaps about 0.4 mG (Bicknell & Li 2001) or even several mG (Yusef-Zadeh & Morris 1987b).

Large RMs have been observed with irregular variations along the filaments (Inoue et al. 1984; Seiradakis et al. 1985; Sofue et al. 1987). The Faraday screen is very probably close to the Galactic center. Within a few arcminutes, the RM value can vary from 500 to -500 rad m^{-2} in "the Pelican" (Lang et al. 1999a), from 100 to 2300 rad m^{-2} in the Northern Threads (Lang et al. 1999b), from 2000 to 5500 rad m^{-2} along "the Snake" (Gray et al. 1995), or from -4200 to -370 rad m^{-2} in the filament G359.54+0.18 (Yusef-Zadeh et al. 1997). In the southern plume of the largest filament, the RM values are all negative with a maximum up to -2500 rad m^{-2}, but in the northern plume the RMs are mostly positive with some negative

* The fractional polarization can be artificially high (90%) in the VLA observations, due to the missing total flux at short spacelines by VLA measurements (see Lang et al. 1999).

holes, the positive values up to 1000 rad m^{-2} (Tsuboi et al. 1986). No coherent structure in the RMs can be found. However, Novak et al. (2001) noticed that the dominant RM values in the different (l, b) quadrants have an antisymmetric distribution, which probably indicates that in the whole Galactic halo from the Galactic center, the toroidal fields have different directions above and below the Galactic plane (see Han 2002).

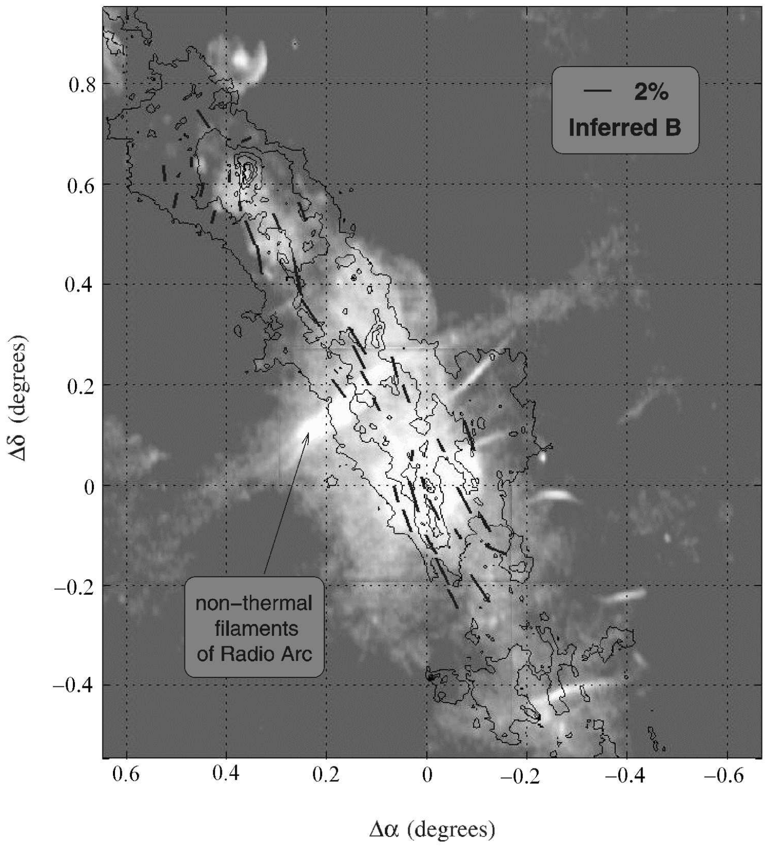

Fig. 6 Radio structure of the Galactic center at 90 cm and the toroidal magnetic fields in the central molecular zone revealed by the polarization at a submillimeter band (courtesy N.E. Kassim & D.T. Chuss. See Novak et al. (2002) for other information).

Though the connection of the filaments and the molecular clouds or HII regions can be identified in the observations (e.g., Uchida et al. 1996; Yusef-Zadeh et al. 1997; Reich et al. 2000), and magnetic fields can be anchored in the molecular clouds (Bicknell & Li 2001), the detailed process for particle acceleration is still a puzzle. It is not clear where the relativistic particles come from for the synchrotron emissions and why these particular field lines are picked out for illumination.

The observations of the Galactic center at mm, sub-mm and far-infrared bands have revealed the toroidal magnetic fields in the central molecular cloud-zones (Novak et al. 2000, 2002) parallel to the Galactic plane, as discussed earlier.

6.3 Nearby Galaxies

The first report of the presence of polarized radio emission (and hence magnetic fields) in an external galaxy came from Mathewson et al. (1972) using the then newly completed Westerbork Synthesis Radio Telescope. In this early work, the orientation of the $\boldsymbol{E}$ vectors could be shown to be in agreement with the optical observations of Appenzeller (1967) for M51. This work was followed up by Segalovitz et al. (1976) who mapped M51 at a second frequency as well as tried to observe M31.

Observations by Beck et al. (1978, 1980) of M31 using the 100 m Effelsberg dish at $\lambda =$ 11 cm allowed a definite detection of magnetic field, which showed a surprisingly homogenous distribution. From that time onwards practically all large nearby galaxies have been mapped, at ever higher frequencies, first in Effelsberg and later with the VLA (see reviews by: Wielebinski & Krause 1993; Beck et al. 1996; Beck 2000). An MPIfR polarimeter was taken to the Parkes radio telescope and led to the observations at several frequencies of the Magellanic Clouds (Haynes et al. 1986, 1991). The magnetic field in the Large Magellanic Cloud resembles a trailing spiral pattern around the kinematical center (Klein et al. 1993).

Multi-frequency maps, when made with identical angular resolution, allow a determination of the Faraday rotation in the spiral arms of the galaxy as well as the orientation of the original $\boldsymbol{E}$ vector and hence of the inherent magnetic field. The magnetic fields were found to be orientated with the spiral arms on a very large scale (kiloparsecs) and confined to the galactic plane in most nearby grand-designed spiral galaxies, such as M51 (Neininger & Horellou 1996), M81 (Krause et al. 1989b), M83 (Neininger et al. 1993) and NGC 2997 (Han et al. 1997).

A long discussion was begun, pushed by the theoretical considerations, on the origin of the cosmic magnetic fields (e.g., Tosa & Fujimoto 1978; Beck et al. 1996), with the aim of determining if the magnetic fields in galaxies are bi-symmetrical (BSS) or axi-symmetrical (ASS). The question of field configurations was repeatedly asked by the two diverging factions of theoreticians, the dynamo community wanting to see rings or ASS fields, while the primordial origin people wanting to see BSS fields. The variation of the RM as a function of the azimuthal angles has been used to distinguish between the BSS field and the ASS or ring field structure (see e.g., Krause 1989a, b). Detailed analysis of the RM distribution of several galaxies, though with large measuring uncertainties, showed that many galaxies have a strong ASS field as well as a BSS field. In some galaxies, the ASS field dominates (Krause & Beck 1999), while in others a BSS field seems to be dominant (M81, M51, see detailed situations in Table 1 of Beck 2000). Multi-mode fits to BSS and ASS patterns became necessary to interpret the detailed observational data. One should note, however, that the observed polarized emission mainly comes from a thinner disk, while the RMs are caused by the electrons and magnetic fields in the closer layer of a thicker disk or halo (plus the thinner disk). In some cases the halo contribution may be significant (e.g., Soida et al. 2001). Observations of irregular dwarf galaxies without systematic gas motions (Chyzy et al. 2000) and flocculent galaxies with only rudimentary spiral arms (Knapik et al. 2000) also revealed well-organized magnetic fields, indicating that some non-standard dynamo or other mechanisms are responsible for the regular magnetic fields.

Higher resolution observations of some galaxies (e.g., IC342: Krause 1993; M83: Beck 2000; NGC 2997: Han et al. 1999, see Fig. 7; NGC 1097: Beck et al. 1999; M51: Neininger & Horellou 1996) revealed that the polarized emission is strongest in the inner edge of the optical spiral arms or along the dust lanes, clearly associated with local compression effects by shock. This mostly happens in the inner disk ($< 2/3$ optical radius). However, an important result was the discovery of "magnetic arms" in the outer disk. These aligned magnetic fields exist between the optical spiral arms or extend independently from optical arms in some galaxies, e.g., NGC 6946 (Beck & Hoernes 1996), NGC 2997 (Han et al. 1999) and IC342 (Krause et al. 1989).

Recent developments coming from the polarization observations of barred galaxies, NGC 1097 (Beck et al. 1999), showed the magnetic fields following the gas streamlines and aligned with shearing flow. The observations also probed the magnetic field near the circumnuclear disk – a new area to explore in the future.

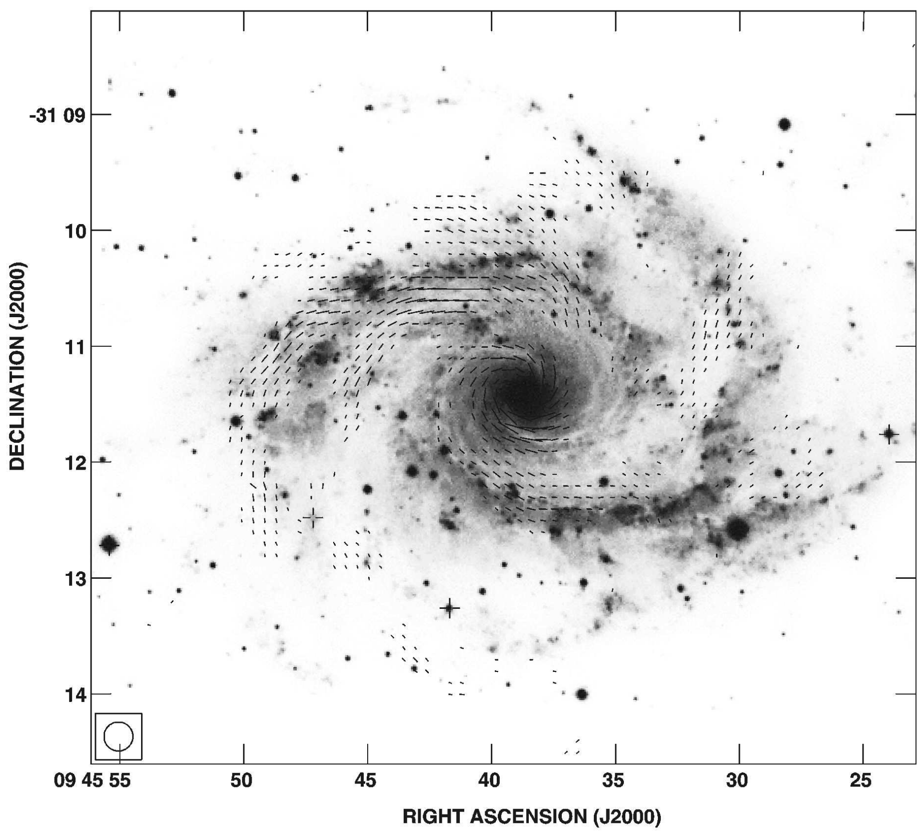

Fig. 7 Polarization observation of the grand-design spiral galaxy NGC 2997 at 6 cm by VLA (after Han et al. 1999). The polarization vectors E were rotated by 90° to show the B orientations.

Extended radio halos have been observed in several galaxies but only a few of them have ordered polarization reflecting ordered magnetic fields (e.g., Dumke et al. 1995). In some galaxies, like NGC 4631, M82 and the Milky Way, vertical or poloidal magnetic fields shown by polarized spurs are observed in the nuclear area (e.g Golla & Hummel 1994; Reuter et al. 1994). The magnetic fields in the halo probably result from outflows of gas from the disk into the halo and the cosmic rays for the radiation probably come from some central starburst. NGC 4666 may be another example of such starburst-driven superwinds (Dahlem et al. 1997).

6.4 Radio Galaxies and Quasars

Radio galaxies and quasars in the distant universe are most intensively illuminated by synchrotron emission of the relativistic particles in magnetic fields, both in the energetic jets of the central blackhole or in the outer lobes which are produced by the interaction of the jets with the intergalactic medium. The central core component is physically associated with galactic nuclei but can be resolved into finer structures when observed with VLBI.

Polarization studies of radio galaxies and quasars started with the detection of extended polarized components and their rotation measures in the nearest radio galaxy – Centaurus A (Cooper & Price 1962). Already at that time it was shown that the radio polarization observations of Centaurus A agreed well with the optical polarization studies by Elvius and Hall (1964). Radio polarization studies afterwards have demonstrated that the projected magnetic fields can appear uniform on scales exceeding a hundred kpc, or sometimes over several hundred kpc!

In the intervening years, hundreds of polarization maps of radio galaxies have been published, first at lower frequencies and now at higher frequencies and with better resolutions mostly by VLA and WSRT observations (e.g., Högbom & Carlsson 1974; Klein et al. 1994; Ishwara-Chandra et al. 1998). Many objects have multifrequency polarization data that have been analysed for magnetic fields (e.g., Johnson et al. 1995; Murgia et al. 2001). The fields are reflected by the polarized radio emission and their intrinsic direction (orientation). If corrected by foreground RMs, the fields are generally circumferential (see Fig. 8), either parallel with (for FR-II and one-side jets in FR-I sources) or perpendicular to (for two-sided jets of FR-I sources) the elongated jet or bridge component; in the lobes it wraps around the source edges or strong intensity gradients (see reviews by Miley 1980; Bridle & Perley 1984; Saikia & Salter 1988).

The magnetic field is irregular but sheared and compressed to a preferred direction so that the polarized radio emission is observed following the jets or the bands of jets. The deceleration or transverse shocks lead to compression and an orthogonal field. Due to the high intensity, radio mapping at arcsec resolution scale has been possible. A result of great significance is the "jump" of polarization vectors (and hence of magnetic field) by 90° from the center to the end of jets in some sources (see Bridle & Perley 1984). This seems to be a method of stabilizing the radio emission. It could be due to the action of a helical magnetic field in these cases.

Many objects (or even core components) have been studied using high resolution multifrequency VLBI/VLBA polarization data (e.g., Venturi & Taylor 1999). The most recent development is the parsec-scale RM project using the VLBA (Taylor 2000) to test the unified models for AGN by looking for orientation effects in the RM distribution of the quasar core. Probably the clouds entrained by jets and magnetic fields are responsible for the observed large variations of the RMs at pc or sub-pc scales (Zavala & Taylor 2002).

Detection of ordered magnetic fields at scale of hundreds to thousand pc in high redshift objects of $z > 2$ (Udomprasert et al. 1997; Athreya et al. 1998) poses a stiff challenge to the dynamo mechanism for generating magnetic fields, primarily due to the very short time available for amplification of the initial seed field.

Recently, the detection of *circular polarization* in AGN cores and nearby galaxy nuclei by the VLBA and ATCA (Homan et al. 2001; Rayner et al. 2000; Bower et al. 1999; Brunthaler et al. 2001) re-opened a window on the physical conditions and magnetic fields in the core regions. Typically, the mean degree of circular polarization is less than 1%. Its origin is not yet understood. However, a few possibilities exist such as synchrotron emission, cyclotron emission, coherent emission mechanisms, Faraday conversion in relativistic plasma and Scintillation-induced circular polarization (e.g., Macquart 2002). The radiation transfer processes seem to be the most promising.

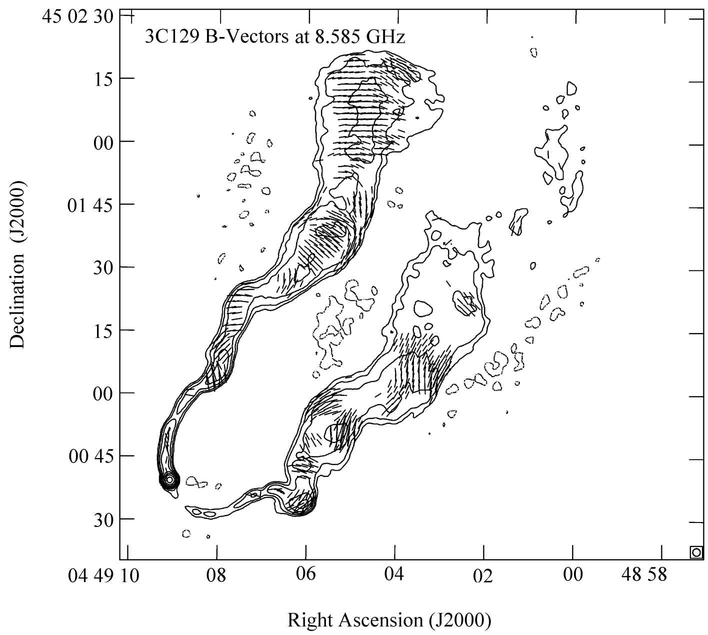

Fig. 8 Magnetic field vectors in the radio galaxies 3C 129 in the 3C 129 cluster (8.4 GHz observations, RM-corrected). (after Taylor et al. 2001).

6.5 Clusters of Galaxies

Diffuse radio emission in clusters of galaxies is due to intracluster magnetic fields. The estimation of the magnetic fields were mostly made through observations of radio halos and variable RMs of the sources in the clusters or the RMs of the background sources, though the lower limit of the field strength can be estimated from the hard X-ray detection. The most recent review on this topic by Carilli & Taylor (2002) has included a very good summary of recent progress in all respects.

A report of a halo in the Perseus cluster of galaxies was made by Ryle & Windram (1968), but the first clear detection was actually made by Large et al. (1959) in the Coma cluster. This was confirmed by the many studies that followed (e.g., Willson 1970; Wielebinski 1978). Further halos were found in the A754 (Wielebinski et al. 1977), A1367 (Gavazzi 1978) and other clusters A2255, A2256 and A2319 (e.g., Harris et al. 1980; Bridle et al. 1979; Harris & Miley 1978) though many candidates were reported (see the status presented by Hanisch 1982). Using recent radio survey data which cover most of the known clusters, a large sample of halo candidates has been found (e.g., Kempner & Sarazin 2001; Giovannini et al. 1999) and some of them have been confirmed already (e.g., Govoni et al. 2001a). Up to now, more than a dozen of halos are certainly detected and the number is increasing, maybe up to more than two dozen soon. Evidently, almost all halo clusters present clear features of recent mergers (e.g., Markevitch & Vikhlinin 2001; Feretti et al. 2001), indicating that the nonrelaxed state in the cluster is related to the radio emission. A strong correlation between the X-ray luminosity and halo radio power has been found (Liang et al. 2000; Govoni et al. 2001a).

The spectrum of the Coma halo emission has been a subject of numerous studies (e.g., Schlickeiser et al. 1987; Giovannini et al. 1993) which confirmed the non-thermal nature of the halo and hence its magnetic origin. The spectrum of the halos is very steep, often about -1.5 (Deiss et al. 1997; Liang et al. 2000), see the list in Henriksen (1998).

Not much radio polarization has been detected from the halo, except for some polarization associated with the halo-'G' in A2256 (Bridle et al. 1979), while multifrequency polarization observations revealed the polarization of many cluster objects (e.g., Feretti et al. 1995; Taylor et al. 2001; Govoni et al. 2001; Eilek & Owen 2002). Analyses of both the distribution and the variance of RMs of extended radio galaxies in the cluster (e.g., Dreher et al. 1987; Taylor et al. 2001; Govoni et al. 2001b; Eilek & Owen 2002) or the background sources (Vallee et al. 1987; Kim et al. 1991; Clarke et al. 2001) have almost reached the following consensus: the random magnetic field in the intracluster gas has a strength of $5\,\mu$G at a length scale of about 10 kpc, within a factor of 2 or 3 for different authors or different objects/regions. The magnetic field could be stronger towards the cluster center (e.g., Govoni et al. 2001b) and very high RMs (of radio galaxies) have been found near the center of the cooling flow clusters (e.g., Ge & Owen 1993). Recently, it has been found that X-ray emission is well correlated with the rms value of the cluster rotation measures (Dolag et al. 2001), implying that the the field strength decreases with the radius according to $B \sim N_e^{0.9}$ for A119. The central density-enhanced "cooling flow" regions can have magnetic fields up to $\sim 40\,\mu$G with coherence scales up to $\sim$50 kpc (Taylor & Perley 1993).

Radio relic sources have been detected in or between clusters of galaxies, for example, the bridge emission between Coma and A1367 (Kim et al. 1989), and the extended source adjacent to three Abell clusters of galaxies of Rood Group #27 (Harris et al. 1993). All relic sources have low surface brightness and obviously reflect the magnetic fields between the clusters. Some relic sources are significantly polarized.

7 THE ORIGIN OF MAGNETIC FIELDS

We have no direct observational evidence for the first cosmological magnetic fields. The fields, with observed intensities of $B \sim 2 - 10\,\mu$Gauss today must have started at a lower level and become amplified by some mechanism at some cosmological stage (cf. Kulsrud 1999). The "battery effect", proposed by Biermann (1952), generates magnetic fields of $B \sim 10^{-20}$ G at the most (e.g., Lesch & Chiba 1995). Several mechanisms to produce the seed fields at different epochs of the universe have been proposed, for example, Harrison (1973) aregued that turbublence in the radiation-dominated era produces the weak seed fields of presently 10^{-8} G; Hogan (1983) gave a basic argument for considering phase transition as a potential mechanism for the generation of primordial magnetic fields; Turner and Widrow (1988) proposed an inflation scenario for the creation of primordial magnetic fields; Quashnock et al. (1989) considered the thermoelectric effect in QCD phase transition to generate the magnetic field of 2×10^{-17} G in the early universe; Wiechan et al. (1998) showed that the plasma-neutral gas friction in a weakly ionized rotating protogalactic system creates the seed magnetic fields. The Biermann battery in ionization fronts can in principle produce reasonably strong magnetic fields (see Subramanian et al. 1994; Gnedin et al. 2000). Magnetic fields could originate deep in the early phases of the universe (see Grasso & Rubinstein 2001 for a review). The role of magnetic fields in the very early Universe, the symmetry braking during phase transitions or at the time of recombination (e.g., Sicitte 1997), structure formation (e.g., Totani 1999; De Araujo & Opher 1997; Battaner et al. 1997) even the big-bang nucleosynthesis, should be fully investigated (See Rees 1987).

Some progress has been made recently in the studies of the evolution of such primordial magnetic fields (e.g., Kulsrud et al. 1997; Howard & Kulsrud 1997). Some early papers (e.g., Piddington 1964, 1978) considered that if an intergalactic magnetic field exists with $B \sim 10^{-8}$ G, it could be compressed by galactic rotation to $B \sim 10^{-5}$ G, intensities that are actually observed in galaxies. This was supported by some papers (e.g., Sofue et al. 1979; Anchordoqui & Goldberg 2002) that claimed the detection of a lower limit of intergalactic magnetic field with B above $3{\times}10^{-9}$ G. However, these results contradict others (e.g., Blasi et al. 1999). Such a primordial magnetic field could in principle be detected by the Faraday rotation of microwave background polarization (Kosowsky & Loeb 1996) or by the correlation of the Faraday sky (Kolatt 1998).

If only a small seed magnetic field was generated in the early universe, then a rather large amplification, by a dynamo, for example, is needed to reach the observed values in cosmic objects (e.g., Parker 1979). However, magnetic fields in high redshift ($z \sim 2.0 - 3.0$) objects with Lyman-α damped systems have been found to be as strong as in nearby galaxies and in some clusters of galaxies (e.g., Kronberg et al. 1990, 1992; Athreya et al. 1998). This poses some challenge to galactic dynamo, since, at that time, galaxies should have rotated only a few times. The studies on the variance of residual RM (observed RM minus foreground Galactic RM) versus source redshift z (e.g., Oren & Wolfe 1995; Perry et al. 1993), mainly due to data quality, have produced controversial results on the cosmological evolution of the magnetic field (in the intervening clouds). At present, evidence has been accumulated for magnetic fields in the intergalactic space. In fact, magnetic fields can be easily-developed in the vicinity of an accreting disk of the black hole in the galaxy or quasar center (e.g., Contopoulos & Kazanas 1998), and then their outflows can magnetize a large fraction of the entire intergalactic medium (e.g., Daly & Loeb 1990; Furlanetto & Loeb 2001; Kronberg et al. 2001). Furthermore, the superwinds of primeval galaxies can also effectively seed magnetic fields into the intergalactic medium (Kronberg et al. 1999; Birk et al. 2000).

The explanation of the origin of Earth's magnetic field was the triumph of the mean field dynamo theory as developed by Parker (1955) and Steenbeck & Krause (1969a). This theory could be applied to planets (Steenbeck & Krause 1969b), to magnetic stars , and more recently to spiral galaxies (Ruzmaikin et al. 1988). Good reviews of the dynamo theory can be found in Parker (1979) and Krause & Rädler (1980). In the dynamo theory, Maxwell's equations are solved by introducing an α term that describes "looping" of the magnetic field in the z direction relative to the ω rotation. The solution for the "$\alpha - \omega$ dynamo" has been very successful in explaining many observational results. Stix (1975) applied the dynamo theory to an oblate spheroid, representing an edge-on galaxy. A series of papers by Ruzmaikin, Shukurov and Sokolov (see the 1988 book) have developed the mean dynamo theory to be applicable to magnetic fields in galaxies. In particular, the multi-mode solution (e.g., Baryshnikova et al. 1987) has shown that spiral magnetic fields seem to be possible within the frame of the dynamo theory. Most recently detailed discussion on kinematic dynamo and small-scale field were made by Schekochihin et al. (2002). The time evolution of a dynamo has been actively studied by, e.g., Brandenburg et al. (1989). In fact, a turbulent dynamo probably could produce strong magnetic rope-like structure but is difficult to generate large-scale magnetic fields (Subramanian 1998). A large-scale kinetic helicity is probably a necessary ingredient for a large-scale magnetic field (Blackman & Chou 1997) and helical turbulence may provide the key to the generation of large-scale magnetic fields (Blackman 2000; Brandenburg 2001). The density wave in spiral galaxies can provide a spiral shock wave and the subsequent α-effect which may alter the field configuration of the dynamo (Mestel & Subramanian 1991; Subramanian & Mestel 1993). Kulsrud (1999) looked into the many limitations of the dynamo theory. However, the current opinion is that most of the phenomena that are observed can be explained by a modified dynamo theory. A review of very recent developments in the magnetic dynamo theory, most impressively on the magnetic helicity and the evolution of kinetic and magnetic energy spectra, can be found in Blackman (2002). Many groups have added different physical considerations into the dynamo and used computer simulations to show possible consequences comparable to observational results, e.g., the bar-effect by Moss et al. (2001) and Otmianowska et al. (2002), the swing-excitation by Rohde et al. (1999), the very detailed considerations of supernova and superbubble-driven dynamo by Ferriére & Schmitt (2000) and the α-effect by magnetic buoyancy by Moss et al. (1999).

To explain the magnetic fields in young, high redshift galaxies, the evolution of protogalactic clouds and electrodynamic processes (Lesch & Chiba 1995) or the cross-helicity effect (Brandenburg & Urpin 1998) should be considered. It seems quite possible that large-scale magnetic fields in galaxies are the residue of dynamo processes in the plasma before the protogalactic plasma cloud collapsed and the galaxy formed. At that time all the conditions are very suitable for the dynamo operations and a seed field can be easily produced by the Biermann battery – the large-scale fields is then of primordial origin (Kulsrud et al. 1997, see also discussion in Schekochihin et al. 2002). Such a field, however, has to be maintained by the dynamo process in galaxies after the galaxy was formed.

8 CLOSING REMARKS

The subject of magnetic fields is in its infancy. While gravity (density wave theory) or star formation have received considerable attention, with large groups working in these areas, only a few workers have struggled to reveal the importance of magnetic fields in the cosmos. Very often the question is asked if magnetic fields are a basic parameter of our universe or only a consequence of rotation. An argument often used is that the energy density in magnetic fields is much less than in gravitational effects and is hence unimportant. However, magnetic fields have a unique directional effect on matter, if coupled. The coupling of magnetic fields to matter is poorly understood. The traditional description of "frozen-in magnetic fields" must give way to studies of the magnetic properties of interstellar matter at different temperatures. For instance recent sub-mm observations (Wielebinski et al. 1999) have shown that CO gas in galaxies can be seen with temperatures of 50 K or more. Now that we know that ionization in warm parts of molecular clouds is possible, we can imagine that magnetic fields could exert sufficient force to be of dynamic consequence. A quotation of Lou Woltjer that is often cited runs: "the poorer our knowledge the stronger the magnetic field". However, in view of the fact that magnetic fields are found everywhere in the universe, they deserve appropriate treatment and study.

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