

# Magnetic Fields in Galaxies

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**Abstract.** Most of the visible matter in the Universe is ionized, so that cosmic magnetic fields are quite easy to generate and due to the lack of magnetic monopoles hard to destroy. Magnetic fields have been measured in or around practically all celestial objects, either by in-situ measurements of spacecrafts or by the electromagnetic radiation of embedded cosmic rays, gas or dust. The Earth, the Sun, solar planets, stars, pulsars, the Milky Way, nearby galaxies, more distant (radio) galaxies, quasars and even intergalactic space in clusters of galaxies have significant magnetic fields, and even larger volumes of the Universe may be permeated by “dark” magnetic fields. Information on cosmic magnetic fields has increased enormously as the result of the rapid development of observational methods, especially in radio astronomy. In the Milky Way, a wealth of magnetic phenomena was discovered, which are only partly related to objects visible in other spectral ranges. The large-scale structure of the Milky Way’s magnetic field is still under debate. The available data for external galaxies can well be explained by field amplification and ordering via the dynamo mechanism. The measured field strengths and the similarity of field patterns and flow patterns of the diffuse ionized gas give strong indication that galactic magnetic fields are dynamically important. They may affect the formation of spiral arms, outflows, and the general evolution of galaxies. In spite of our increasing knowledge on magnetic fields, many important questions on the origin and evolution of magnetic fields, their first occurrence in young galaxies, or the existence of large-scale intergalactic fields remained unanswered. The present upgrades of existing instruments and several radio astronomy projects have defined cosmic magnetism as one of their key science projects.

## KEYWORDS:

Cosmic rays – dynamo action – Faraday rotation – Galactic Center – galaxies: radio emission – halos – interstellar medium – jets – magnetic fields: origin, evolution, strength, structure – Milky Way: radio emission – polarization – pulsars – radio telescopes – spiral arms – synchrotron emission – Zeeman effect

## 1. Introduction

The first report of a cosmic magnetic field outside the Earth was the result of a direct measurement of the Zeeman effect in the magnetic fields in sunspots in 1908. In 1950 it was suggested that the observed cosmic rays would require magnetic fields for their creation and their containment within the Galaxy. Optical polarization observations were first successful in 1949. Polarization of optical and infrared emission can also be caused by elongated dust grains which are aligned in magnetic fields due to the Davis-Greenstein mechanism first described in 1951. This interpretation was not accepted for a long time in the optical astronomy community. With the advent of radio astronomy this controversy was resolved and an active study of magnetic fields could begin.

Radio astronomy began in 1932 with the detection of continuum radio emission from the Milky Way. It became quickly clear that the observed radio waves were of a non-thermal nature and an interpretation of this phenomenon was actively sought. This was given in 1950 – the radio emission is due to relativistic cosmic-ray electrons gyrating in magnetic fields, emitting radio waves by the synchrotron process – when the theory of synchrotron emission theory was developed. In particular, it was soon pointed out that synchrotron emission should be highly polarized. In fact, in homogenous magnetic fields, up to 75% linear polarization of the continuum emission can be expected. This

suggestion was taken up by observers of optical radiation who found in 1954 that the Crab Nebula was highly polarized and hence emitting light through the synchrotron process. The radio confirmation of the polarization of the Crab Nebula followed in 1957. The first definite detection of the linear polarization of the Galactic radio waves was published by in 1962. At the same time the polarization of the bright radio galaxy Cygnus A and the Faraday rotation of the polarization angles of the linearly polarized radio emission in Centaurus A were detected. Observations at two frequencies of a section of the Milky Way showed that the interstellar medium of the Milky Way can also cause Faraday effect. During this exciting time of definite detections of interstellar and extragalactic magnetic fields by observations of linear polarization, the Zeeman effect of radio spectral lines proved to be more elusive. Several groups attempted to measure magnetic fields by this direct method. It was in 1968 that finally the Zeeman effect at radio wavelengths was successfully observed in the absorption profile of the H I line in the direction of Cassiopeia A. From this time onward considerable data were collected on the distribution of magnetic fields in the Milky Way.

In the optical range, the polarization is produced by the different extinction along the minor and major axis of dust grains, while at far-infrared and submillimeter wavelengths the elongated dust grains themselves emit polarized emission, which was first detected in the 1980s. Progress has been slow, until recently an increase in reliable data became possible with the advent of submillimeter telescopes on excellent sites and sensitive polarimeters.

The first suggestions about the presence of magnetic fields in nearby galaxies were made in 1958, based on observations of the polarization of stars in the Andromeda galaxy, M31. In 1967 observations of the linear polarization of diffuse starlight started in bright nearby galaxies. In 1970 the polarization of stars in the Magellanic Clouds implied the presence of magnetic fields in these neighboring galaxies. Low-frequency radio observations of galaxies showed non-thermal spectra and hence indicated the presence of magnetic fields. The first detection of the linear polarization of the radio emission from nearby galaxies in 1972 led the way to massive improvement on our knowledge of the morphology of magnetic fields in galaxies. These early radio observations were in good agreement with the early optical polarization studies of galaxies.

In this review, the status of our knowledge about the magnetic fields in our Milky Way and in nearby star-forming galaxies is summarized. Magnetic fields are a major agent in the interstellar and intra-cluster medium and affect the physical processes in various ways. They contribute significantly to the total pressure which balances the gas disk of a galaxy against gravitation. Magnetic reconnection is a possible heating source for the interstellar medium (ISM) and halo gas. They affect the dynamics of the turbulent ISM and the gas flows in spiral arms. The shock strength in spiral density waves is decreased and structure formation is reduced in the presence of a strong field. The interstellar fields are closely connected to gas clouds. Magnetic fields stabilize gas clouds and reduce the star-formation efficiency to the observed low values. On the other hand, magnetic fields are essential for the onset of star formation as they enable the removal of angular momentum from protostellar clouds via ambipolar diffusion. MHD turbulence distributes energy from supernova explosions within the ISM and drives field amplification and ordering via the dynamo mechanism. In galaxies with low star-formation activity or in the outer disks, the magneto-rotational instability can generate turbulence and heat the gas. Magnetic fields control the density and distribution of cosmic rays in the ISM. Cosmic rays accelerated in supernova remnants can provide the pressure to drive a galactic outflow and generate buoyant loops of magnetic fields (through the Parker instability). Understanding the interaction between the gas and the magnetic field is a key to understand the physics of galaxy disks and halos and the evolution of galaxies.

The magnetic field of the Milky Way is of particular importance for experiments to detect *ultra-high-energy cosmic rays* (UHECRs). Results from the first years of AUGER indicate that the arrival directions of detected UHECRs with energies of more than  $10^{19}$  eV show a statistically significant coincidence with the positions of known nearby active galaxies. This interpretation only holds if the deflections in the magnetic fields of the intergalactic medium and the Milky Way halo are not larger than a few degrees. However, little is known about the structure and strength of the magnetic field in the halo of our Milky Way and beyond.

There is one class of galaxies where magnetic fields play a crucial role: “active” galaxies which are governed by a central Black Hole. The formation of jets and radio lobes can only be understood with the presence of magnetic fields. The physics of these phenomena is quite different from that in “normal” star-forming galaxies and will not be discussed in this review.

Magnetic fields have also been detected in the intergalactic medium surrounding the galaxies in a cluster through observations of non-thermal diffuse radio halos and the Faraday effect of background radio sources seen through the cluster. These intracluster magnetic fields are probably generated by turbulent gas motions as the result of massive interactions between galaxies and the intracluster gas. Magnetic fields affect thermal conduction in galaxy clusters and hence their evolution. Outflows from galaxies may have magnetized the intergalactic medium, so that the general intergalactic space may be pervaded with magnetic fields. Unfortunately, cosmic rays and dust grains are missing outside of galaxies and galaxy cluster, and magnetic fields remain invisible. Intracluster magnetic fields are also beyond the scope of this review.

Cosmological models of structure formation indicate that the intergalactic space is probably permeated by magnetic filaments. Galactic winds, jets from active galaxies and interactions between galaxies can magnetize the intergalactic medium. The detection of magnetic fields in intergalactic filaments and observations of the interaction between galaxies and the intergalactic space is one of the important tasks for future radio telescopes. Until now the arguments for the presence of magnetic fields in the distant Universe is based on observations of the non-thermal radio emission and Faraday rotation in galaxies at high redshift. Magnetic fields existed already in QSOs at epochs with redshifts of at least  $z \approx 5$  and in starburst galaxies at redshifts of at least  $z \approx 4$ , but the earliest magnetic fields are yet to be discovered (section 5).

## 2. Observational methods

As the methods of measuring of magnetic fields have been discussed widely in the literature, a short summary of the methods clarifies the present limitations.

### 2.1 Optical and far-infrared polarization

Elongated, rotating dust grains can be aligned with their major axis perpendicular to the field lines by paramagnetic alignment (Davis and Greenstein 1951) or, more efficiently, by radiative torque alignment (Hoang and Lazarian 2008). When the particles are observed with their major axis perpendicular to the line of sight (and the field is oriented in the same plane), the different extinction along the major and the minor axis leads to polarization, with the E-vectors pointing parallel to the field. This is the basis to measure magnetic fields with optical and near-infrared polarization, by observing individual stars or of diffuse starlight. Extinction is most efficient for grains of sizes similar to the wavelength. These small particles are aligned only in the medium between molecular clouds, not in the dense clouds themselves (Cho & Lazarian 2005).

The detailed physics of the alignment is complicated and depends on the magnetic properties of the particles. The degree of polarization  $p$  (in optical magnitudes) due to a volume element along the line of sight  $\delta L$  is given by Ellis & Axon (1978):

$$p = \frac{K B_{\perp}^2 \zeta \delta L}{N_H T_g T^{1/2}}$$

where  $T$  is the gas temperature  
 $T_g$  is the grain temperature  
 $N_H$  is the gas density  
 $\zeta$  is the space density of grains  
 $B_{\perp}$  is the magnetic field strength perpendicular to the line of sight

Light can also be polarized by scattering, a process unrelated to magnetic fields. This contamination is small when observing stars but needs to be subtracted from diffuse light, requiring multi-color measurements.

In the far-infrared (FIR) and submillimeter wavelength ranges, the emission of elongated dust grains is intrinsically polarized and scattered light is negligible. If the grains are again aligned perpendicular to

the magnetic field lines, the E-vectors point perpendicular to the field. FIR polarimetry probes dust particles in the warm parts of molecular clouds, while sub-mm polarimetry probes grains with large sizes which are aligned also in the densest regions. The field strength can be crudely estimated from the velocity dispersion of the molecular gas along the line of sight and the dispersion of the polarization angles in the sky plane, the *Chandrasekhar-Fermi method* (Chandrasekhar & Fermi 1953), further developed for the case of a mixture of large-scale and turbulent fields by Hildebrand et al. (2009) and Houde et al. (2009).

## 2.2 Synchrotron emission

Charged particles (mostly electrons) moving at relativistic speeds (cosmic rays) around magnetic fields lines on spiral trajectories generate electromagnetic waves. Cosmic rays in interstellar magnetic fields are the origin of the diffuse radio emission from the Milky Way (Fermi 1949; Kiepenheuer 1950). A single cosmic-ray electron of energy  $E$  (in GeV) in a magnetic field with a component perpendicular to the line of sight of strength  $B_{\perp}$  (in  $\mu\text{G}$ ) emits a smooth spectrum with a maximum at the frequency:

$$\nu_{\text{max}} \approx 4 \text{ MHz } E^2 B_{\perp}$$

where  $B_{\perp}$  is the strength of the magnetic field component perpendicular to the line of sight. For particles with a continuous power spectrum of energies, the maximum contribution at a given frequency comes from electrons with about twice lower energy, so that  $\nu_{\text{max}}$  becomes about 4x larger.

The half-power lifetime of synchrotron-emitting cosmic-ray electrons is:

$$\begin{aligned} t_{\text{syn}} &= 8.35 \cdot 10^9 \text{ yr } B_{\perp}^{-2} E^{-1} \\ t_{\text{syn}} &= 1.06 \cdot 10^9 \text{ yr } B_{\perp}^{-1.5} \nu^{-0.5} \end{aligned}$$

where  $B_{\perp}$  is measured in  $\mu\text{G}$ ,  $E$  in GeV and  $\nu$  in GHz.

The emissivity  $\varepsilon$  from cosmic-ray electrons with a power-law energy spectrum in a volume with a magnetic field strength  $B_{\perp}$  is given by:

$$\varepsilon \sim N_0 \nu^{(\gamma+1)/2} B_{\perp}^{(1-\gamma)/2}$$

where  $\nu$  is the frequency  
 $N_0$  is the density of cosmic-ray electrons per energy interval  
 $\gamma$  is the spectral index of the power-law energy spectrum of the cosmic-ray electrons ( $\gamma \approx -2.8$  for typical spectra in the interstellar medium of galaxies).

A source of size  $L$  along the pathlength has the intensity:

$$I_{\nu} \sim N_0 B_{\perp}^{(1-\gamma)/2} L$$

A power-law energy spectrum of the cosmic-ray electrons with the spectral index  $\gamma$  leads to a power-law synchrotron spectrum  $I \sim \nu^{\alpha}$  with the spectral index  $\alpha = (\gamma + 1)/2$ . The initial spectrum of young particles injected by supernova remnants with  $\gamma_0 \approx -2.2$  leads to an initial synchrotron spectrum with  $\alpha_0 \approx -0.6$ . These particles are released into the interstellar medium. A stationary energy spectrum with continuous injection and dominating synchrotron loss has  $\gamma \approx -3.2$  and  $\alpha \approx -1.1$ . If the cosmic-ray electrons escape from the galaxy faster than within the synchrotron loss time, the stationary spectrum has  $\gamma \approx (\gamma_0 - \delta) \approx -2.8$  and  $\alpha \approx (\alpha_0 - \delta/2) \approx -0.9$ , where  $\delta$  is the exponent of the energy dependence of the electron diffusion coefficient ( $D = D_0 (E/E_0)^{\delta}$ , typically  $\delta \approx 0.6$ ).

The energy densities of cosmic rays (mostly relativistic protons + electrons), of magnetic fields and of turbulent gas motions, averaged over a large volume of the interstellar medium and averaged over time, are comparable (*energy equipartition*):

$$W_{\text{cr}} \sim \frac{B^2}{8\pi} \sim \frac{\rho v^2}{2}$$

where  $W_{\text{cr}}$  is the energy density of cosmic rays  
 $B^2 / 8\pi$  is the energy density of the total magnetic field  
 $\rho v^2 / 2$  is the energy density of turbulent gas motions with density  $\rho$  and velocity dispersion  $v$ .

On spatial scales smaller than the diffusion length of cosmic-ray electrons (typically a few 100 pc) and on time scales smaller than the acceleration time of cosmic rays (typically a few million years), energy equipartition is not valid.

Energy equipartition between cosmic rays and magnetic fields allows us to estimate the total magnetic field strength:

$$B_{\text{eq}} \sim ((k+1) I_v / L)^{2/(5-\gamma)}$$

This revised formula by Beck & Krause (2005) (see also Arbutina et al. 2012) is based on integrating the energy spectrum of the cosmic-ray protons and assuming a ratio  $k$  between the number densities of protons and electrons in the relevant energy range. The revised formula may lead to significantly different field strengths than the classical textbook formula which is based on integration over the radio frequency spectrum. Note that the exponent of  $2/7$  given in the minimum-energy formula in many textbooks is valid only for  $\gamma = -2$ . The widely used *minimum-energy* estimate of the field strength is smaller than  $B_{\text{eq}}$  by the factor  $((1 - \gamma) / 4)^{2/(5-\gamma)}$ , hence similar to  $B_{\text{eq}}$  for  $\gamma \approx -3$ .

The above formula is valid for steep spectra with  $\gamma < -2$ . For flatter spectra, the integration over the energy spectrum of the cosmic rays diverges and the calculation of  $W_{\text{cr}}$  has to be restricted to a limited energy interval.

For electromagnetic particle acceleration mechanisms, the proton/electron density ratio  $k$  for GeV particles is  $\approx 40$ –100, which directly follows from their different masses. (For an electron-positron plasma,  $k = 0$ .) If energy losses of the electrons are significant, e.g. in strong magnetic fields or far away from their places of origin,  $k$  can be much larger, and the equipartition value is a lower limit of the true field strength. (Due to the small exponent in the formula, the dependence on the input parameters is weak, so that even large uncertainties do not affect the result much.) On the other hand, the nonlinear relation between  $I_v$  and  $B_{\perp}$  may lead to an overestimate of the true field strength when using the equipartition estimate if strong fluctuations in  $B_{\perp}$  occur within the observed volume. Another uncertainty occurs if only a small volume of the galaxies is filled with magnetic fields. Nevertheless, the equipartition assumption provides a reasonable first-order estimate. Independent measurements of the field strength by the Faraday effect in “magnetic arms” leads to similar values (section 4.2). Furthermore, estimates of the synchrotron loss time based on the equipartition assumption can well explain the extent of radio halos around galaxies seen edge-on (see section 4.6). Finally, the magnetic energy density based on the equipartition estimate is similar to that of the turbulent gas motions (Fig. 20), as expected from turbulent field amplification. Note that the equipartition estimate still holds in starburst galaxies where secondary electrons can contribute significantly (Lacki & Beck 2013).

In our Galaxy the accuracy of the equipartition assumption can be tested directly, because there is independent information about the energy density and spectrum of local cosmic rays from in-situ measurements and from  $\gamma$ -ray data, which are emitted by the electrons via bremsstrahlung. Combination with the radio synchrotron data yields a local strength of the total field of  $\approx 6 \mu\text{G}$  and  $\approx 10 \mu\text{G}$  in the inner Galaxy. These values are similar to those derived from energy equipartition. Combination of radio and  $\gamma$ -ray data also yields field strengths similar to equipartition in the Large Magellanic Cloud (Mao et al. 2012) and in the starburst region of M82 (Yoast-Hull et al. 2013).

*Linear polarization* is a distinct signature of synchrotron emission. The emission from a single electron gyrating in magnetic fields is elliptically polarized. An ensemble of electrons shows only very low circular polarization, but strong linear polarization with the plane of the E vector normal to the magnetic field direction. The intrinsic degree of linear polarization  $p$  is given by:

$$p_0 = \frac{1 - \gamma}{7/3 - \gamma}$$

Considering galactic radio emission with  $\gamma \approx -2.8$  a maximum of  $p_0 = 74\%$  linear polarization is expected. In normal observing situations the percentage polarization is reduced due to fluctuations of

the magnetic field orientation within the volume traced by the telescope beam (section 2.3) or by Faraday depolarization (section 2.4). The observed degree of polarization is also smaller due to the contribution of unpolarized thermal emission which may dominate in star-forming regions.

### 2.3 Magnetic field components

Table 1: Magnetic field components and their observational signatures. Note that anisotropic turbulent fields and regular fields cannot be distinguished by polarization observations; Faraday rotation helps.

Field component	Notation	Property	Observational signature
Total field	$B^2 = B_{\text{turb}}^2 + B_{\text{reg}}^2$	3D	Total synchrotron intensity, corrected for inclination
Total field perpendicular to the line of sight	$B_{\perp}^2 = B_{\text{turb},\perp}^2 + B_{\text{reg},\perp}^2$	2D	Total synchrotron intensity
Turbulent field	$B_{\text{turb}}^2 = B_{\text{iso}}^2 + B_{\text{aniso}}^2$	3D	Total synchrotron emission, partly polarized, corrected for inclination
Isotropic turbulent field perpendicular to the line of sight	$B_{\text{iso},\perp}$	2D	Unpolarized synchrotron intensity, beam depolarization, Faraday depolarization
Isotropic turbulent field along line of sight	$B_{\text{iso},\parallel}$	1D	Faraday depolarization
Ordered field perpendicular to the line of sight	$B_{\text{ord},\perp}^2 = B_{\text{aniso},\perp}^2 + B_{\text{reg},\perp}^2$	2D	Intensity and vectors of radio, optical, IR or submm polarization
Anisotropic turbulent field perpendicular to the line of sight	$B_{\text{aniso},\perp}$	2D	Intensity and vectors of radio, optical, IR or submm polarization, Faraday depolarization
Regular field perpendicular to the line of sight	$B_{\text{reg},\perp}$	2D	Intensity and vectors of radio, optical, IR or submm polarization
Regular field along line of sight	$B_{\text{reg},\parallel}$	1D	Faraday rotation and depolarization, Zeeman effect

The intensity of synchrotron emission is a measure of the number density of cosmic-ray electrons in the relevant energy range and of the strength of the *total magnetic field* component in the sky plane. Polarized emission emerges from *ordered fields*. As polarization "vectors" are ambiguous by 180°, they cannot distinguish *regular* (or *coherent*) *fields* with a constant direction within the telescope beam from *anisotropic turbulent* (or *striated*) *fields*, generated from isotropic turbulent magnetic fields by compression or shear of gas flows, which have a preferred orientation, but frequently reverse their direction on small scales. Unpolarized synchrotron emission indicates *isotropic turbulent fields* with random directions which have been amplified and tangled by turbulent gas flows.

Magnetic fields in galaxies preserve their direction only over the coherence scale, which can be determined by field tangling or by turbulence. If  $N$  is the number of cells with the size of the turbulence scale within the volume observed by the telescope beam and if the coherence length is constant, wavelength-independent depolarization occurs (Burn 1966):

$$DP = p/p_0 = N^{-1/2}$$

If the medium is pervaded by an isotropic turbulent field  $B_{\text{turb}}$  (unresolved field with randomly changing direction) plus an ordered field  $B_{\text{ord}}$  (regular and/or anisotropic) which has a constant orientation in the volume observed by the telescope beam, it follows for constant density of cosmic-ray electrons:

$$DP = 1 / (1 + q^2)$$

and for the equipartition case (Sokoloff et al. 1998):

$$DP = (1 + 3.5 q^2) / (1 + 4.5 q^2 + 2.5 q^4)$$

where  $q = B_{\text{iso},\perp} / B_{\text{ord},\perp}$  (components in the sky plane). This gives larger DP values (i.e. less depolarization) than for the former case.

## 2.4 Faraday rotation and Faraday depolarization

The linearly polarized radio wave is rotated by the Faraday effect in the passage through a magneto-ionic medium (Fig. 1). This effect gives us another method of studying magnetic fields – their regular component along the line of sight. The rotation angle  $\Phi$  induced in a polarized radio wave is given by:

$$\Phi = k \lambda^2 \int n_e B_{\parallel} dl$$

with  $\lambda$  wavelength of observation  
 $n_e$  thermal electron density  
 $B_{\parallel}$  mean strength of the magnetic field component along the line of sight  
 $dl$  pathlength along the magnetic field

and  $k$  is a constant (see below). In practice, the parameter Faraday Depth (FD) is used (Burn 1966):

$$\Phi = FD \lambda^2$$

where  $FD = 0.81 \langle n_e B_{\parallel} \rangle L$  (rad m<sup>-2</sup>)

with  $n_e$  thermal electron density in cm<sup>-3</sup>  
 $B_{\parallel}$  mean strength of the magnetic field component along the line of sight in  $\mu$ Gauss  
 $L$  pathlength in parsec.

The observable quantity Rotation Measure ( $RM = \Delta\Phi / \Delta\lambda^2$ ) is identical to the physical quantity FD only in the rare cases when  $\Phi$  is a linear function of  $\lambda^2$ . If the rotating region is located in front of the emitting region (“Faraday screen”),  $RM = FD$ . In case of a single emitting and rotating region with a symmetric magnetic field profile,  $RM \approx FD / 2$  if Faraday depolarization (see below) is small.

As Faraday rotation angle is sensitive to the sign of the field direction, only regular fields give rise to Faraday rotation, while turbulent fields do not. For typical plasma densities and regular field strengths in the interstellar medium of galaxies, Faraday rotation becomes significant at wavelengths larger than a few centimeters. Only in the central regions of galaxies, Faraday rotation is strong already at 1-3 cm wavelengths. Measurements of the Faraday rotation angle from multi-wavelength observations allow determination the strength and direction of the regular field component along the line of sight. Its combination with the total intensity and the polarization pseudo-vectors yields in principle the three-dimensional picture of galactic magnetic fields and the three field components regular, anisotropic and turbulent.

By definition the regular magnetic fields point towards the observer when  $RM > 0$ . The quantity  $\langle n_e B_{\parallel} \rangle$  is the average of the product ( $n_e B_{\parallel}$ ) along the line of sight which generally is not equal to the product of the averages  $\langle n_e \rangle \langle B_{\parallel} \rangle$  if fluctuations in  $n_e$  and  $B_{\parallel}$  are correlated or anticorrelated. As a consequence, the field strength  $\langle B_{\parallel} \rangle$  cannot be easily determined from RM even if additional information about  $\langle n_e \rangle$  is available, e.g. from pulsar dispersion measures (section 3.3).

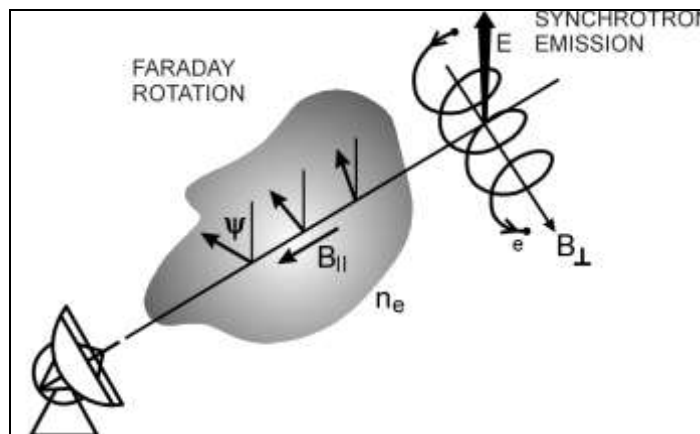


Fig. 1: Synchrotron emission and Faraday rotation

Measurement of RM needs polarization observations in at least three frequency channels with a large frequency separation in a frequency range where Faraday depolarization is still small. In case of strong Faraday depolarization (see below), the polarization angle  $\Phi$  is no longer a linear function of  $\lambda^2$ . Large deviations from the  $\lambda^2$  law can also occur if several emitting and Faraday-rotating sources are located within the volume traced by the telescope beam. In such cases, the RM measured over a small wavelength range strongly fluctuates with wavelength, and polarization data with many frequency channels (spectro-polarimetry) are needed to allow application of *RM Synthesis* (Brentjens & de Bruyn 2005).

RM Synthesis Fourier-transforms the complex polarization data from a limited part of the  $\lambda^2$  space into a data cube that provides at each point of the map a *Faraday spectrum* with FD as the third coordinate. The total span and the distribution of the frequency channels and the channel width define the resolution in the Faraday spectrum given by the width of the *Rotation Measure Spread Function (RMSF)*, allowing the cleaning of the FD data cube, similar to cleaning of synthesis data from interferometric telescopes (Heald 2009). If the RMSF is sufficiently narrow, magnetic field reversals and turbulent fields can be identified in the Faraday spectrum (Frick et al. 2011; Bell et al. 2011; Beck et al. 2012). RM Synthesis is also able to separate FD components from distinct foreground and background regions and hence, in principle, to measure the 3D structure of the magnetized medium.

In a region containing cosmic-ray electrons, thermal electrons and purely regular magnetic fields, wavelength-dependent Faraday depolarization occurs because the polarization planes of waves from the far side of the emitting layer are more rotated than those from the near side. This effect is called *differential Faraday rotation* and is described (for one single layer with a symmetric distribution of thermal electron density and field strength along the line of sight) by (Burn 1966):

$$DP = | \sin (2 RM \lambda^2) / (2 RM \lambda^2) |$$

where RM is the observed rotation measure, which is half of the total rotation measure through the whole layer. DP varies periodically with wavelength. With  $|RM| = 100 \text{ rad m}^{-2}$ , typical for normal galaxies, DP has zero points at wavelengths of  $(12.5 \sqrt{n}) \text{ cm}$ , where  $n = 1, 2, \dots$  (Fig. 2). At each zero point the polarization angle jumps by  $90^\circ$ . Observing at a fixed wavelength hits zero points at certain values of the intrinsic RM, giving rise to *depolarization canals* along the level lines of RM. At wavelengths just below that of the first zero point in DP, only the central layer of the emitting region is observed, because the emission from the far side and that from the near side cancel (their rotation angles differ by  $90^\circ$ ). Beyond the first zero point, only a small layer on the near side of the disk remains visible. Applying RM Synthesis to multichannel observations can recover the region as a broad component in the Faraday spectrum.

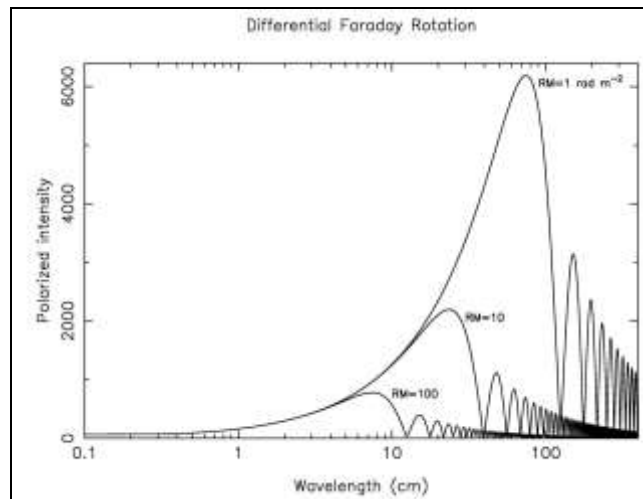


Fig. 2: Wavelength of maximum polarized emission for a synchrotron spectrum with spectral index  $\alpha = -0.9$  and depolarization by differential Faraday rotation (Arshakian & Beck 2011)

Turbulent fields also cause wavelength-dependent depolarization, called *Faraday dispersion* (Sokoloff et al. 1998). For an emitting and Faraday-rotating region (*internal dispersion*):



$$DP = (1 - \exp(-S)) / S$$

where  $S = 2 \sigma_{RM}^2 \lambda^4$ .

$\sigma_{RM}^2$  is the dispersion in rotation measure and depends on the turbulent field strength along the line of sight, the turbulence scale, the thermal electron density, and the pathlength through the medium. The main effect of Faraday dispersion is that the interstellar medium becomes “optically thick” for polarized radio emission beyond a wavelength, depending on  $\sigma_{RM}$  (Fig. 3), and only a front layer remains visible in polarized intensity. Galaxy halos and intracluster media have typical values of  $\sigma_{RM} = 1\text{--}10 \text{ rad m}^{-2}$ , while for galaxy disks typical values are  $\sigma_{RM} = 10\text{--}100 \text{ rad m}^{-2}$ . Centers of galaxies can have even higher dispersions. Fig. 3 shows the optimum wavelength ranges to detect polarized emission for these regions.

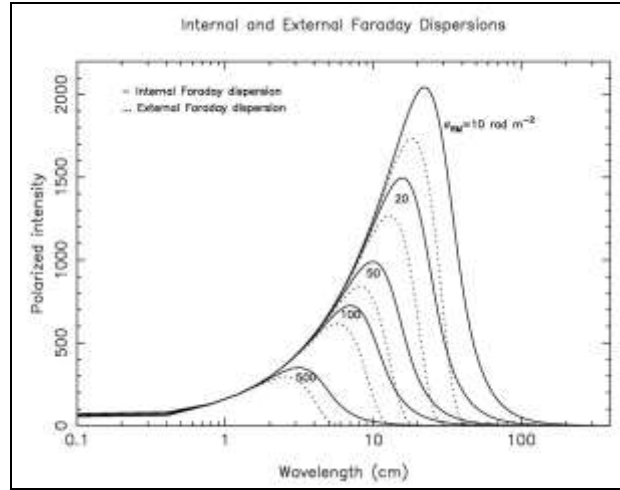


Fig. 3: Wavelength of maximum polarized emission for a synchrotron spectrum with spectral index  $\alpha = -0.9$  and depolarized by Faraday dispersion parameterized by  $\sigma_{RM}$ . Solid curve: internal Faraday dispersion within an emitting source, dotted curve: external Faraday dispersion in a foreground object (Arshakian & Beck 2011)

Regular fields in a non-emitting foreground *Faraday screen* do not depolarize, while turbulent fields do (*external Faraday dispersion*). For sources larger than the telescope beam:

$$DP = \exp(-S)$$

At long wavelengths  $S = \sigma_{RM}^2 \lambda^4$  (Tribble 1991). Unresolved *RM gradients* within the beam also lead to depolarization, similar to Faraday dispersion.

Faraday depolarization can also be classified as *depth depolarization* (differential Faraday rotation, Faraday dispersion along the line of sight) and *beam depolarization* (RM gradients, Faraday dispersion in the sky plane). Both types occur in emitting regions, while in non-emitting Faraday screens only beam depolarization occurs.

## 2.5 Zeeman effect

The Zeeman effect is the most direct method of remote sensing of magnetic fields. It has been used in optical astronomy since the first detection of magnetic fields in sunspots of the Sun. The radio detection was first made in the H I line. In the presence of a magnetic field  $B_{\parallel}$  along the line of sight, the line at the frequency  $\nu_0$  is split into two components (*longitudinal Zeeman effect*, Fig. 4):

$$\nu_0 \pm \frac{e B_{\parallel}}{4 \pi m c}$$

where  $e$ ,  $m$  and  $c$  are the usual physical constants. The two components are circularly polarized of the opposite sign. The frequency shift is minute, e.g. 2.8 MHz/Gauss for the HI line. More recent observation of the OH or H<sub>2</sub>O lines used the higher frequency shifts of these molecular line species (e.g. Heiles & Crutcher 2005). In magnetic fields perpendicular to the line of sight, two shifted lines together with the main unshifted line, all linearly polarized. This *transversal Zeeman effect* is much more difficult to observe and has not yet been detected in the interstellar medium.

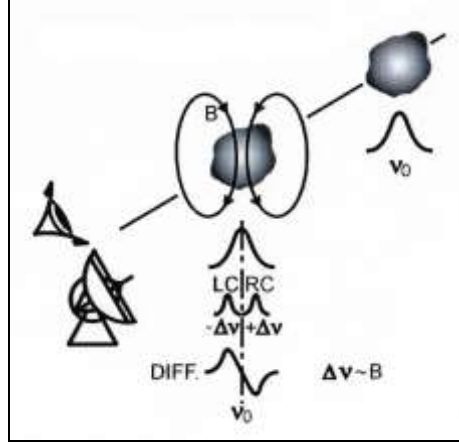


Fig. 4: The longitudinal Zeeman effect, splitting of a line into two components with opposite circular polarization

## 2.6 Field origin and amplification

The origin of the first magnetic fields in the Universe is still a mystery. The generation of the very first “seed” fields needs a continuous separation of electric charges, e.g. by the *Biermann battery*, the *Weibel instability* (Lazar et al. 2009) or fluctuations in the intergalactic thermal plasma after the onset of reionization (Schlickeiser 2012). These may generate a seed field of  $\leq 10^{-12}$  G in the first galaxies or stars. A large-scale intergalactic field of  $\leq 10^{-12}$  G may be generated in the early Universe (Widrow 2002) and could also serve as a seed field in protogalaxies. This is consistent with the average strength of intergalactic fields of  $\geq 10^{-16}$  G, derived from high-energy  $\gamma$ -ray observations with HESS and FERMI, assuming that the secondary particles are deflected by the intergalactic fields (Neronov & Vovk 2010). However, such a large-scale primordial field is hard to maintain because the galaxy rotates differentially, so that field lines get strongly wound up, in contrast to the observations (Shukurov 2005). Moreover, a coherent large-scale field as observed e.g. in M31 cannot be explained by the primordial field model. The same is true for kinematical models of field generation by induction in shearing and compressing gas flows, which generate fields with a coherence length of a few kiloparsecs and frequent reversals.

Magnetization of protogalaxies to  $\geq 10^{-9}$  G could be achieved by field ejection from the first stars or the first black holes (Fig. 5), followed by dynamo action. The dynamo transfers mechanical into magnetic energy. It amplifies and/or orders a seed field. The *small-scale* or *fluctuation dynamo* does not need general rotation, only turbulent gas motions (Brandenburg & Subramanian 2005). The source of turbulence can be thermal virialization in protogalactic halos or supernovae in the disk or the *magneto-rotational instability (MRI)* (Rüdiger & Hollerbach 2004). Within less than  $10^8$  yr weak seed fields are amplified to the energy density level of turbulence and reach strengths of a few  $\mu$ G (Schleicher et al. 2010).

The “*mean-field*”  $\alpha$ - $\Omega$  dynamo is driven by turbulent gas motions from supernova explosions or cosmic-ray driven Parker loops ( $\alpha$ ) and by differential rotation ( $\Omega$ ), plus magnetic diffusivity ( $\eta$ ) (e.g. Parker 1979; Ruzmaikin et al. 1988; Beck et al. 1996). It generates a large-scale (“mean”) regular field from the turbulent field in a typical spiral galaxy within a few  $10^9$  yr. If the small-scale dynamo already amplified turbulent fields of a few  $\mu$ G in the protogalaxy, the large-scale dynamo is needed only for the organization of the field (“order out of chaos”). The field pattern is described by modes of different azimuthal symmetry in the plane and vertical symmetry or antisymmetry perpendicular to the plane. Several modes can be excited in the same object. In almost spherical, rotating bodies like stars, planets or galaxy halos, the strongest mode consists of a toroidal field component with a sign reversal across the equatorial plane (vertically antisymmetric or “odd” parity mode A0 with azimuthal

axisymmetry in the plane) and a poloidal field component of odd symmetry with field lines crossing the equatorial plane (Fig. 6). The halo mode can also be oscillatory and reverse its parity with time (e.g. causing the cycle of solar activity). The oscillation timescales (if any) are very long for galaxies and cannot be determined by observations.

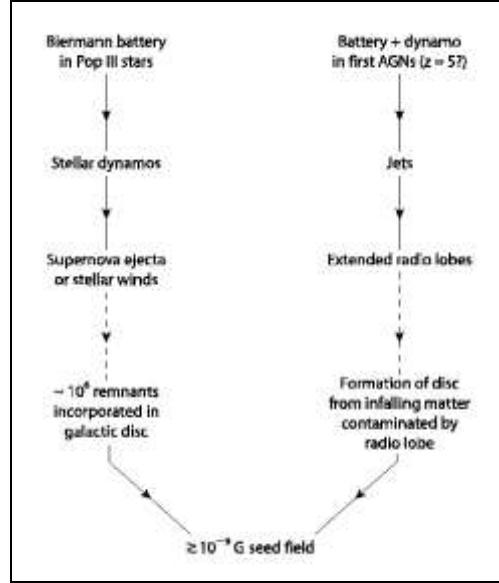


Fig. 5: Origin of seed fields in protogalaxies (Rees 2005). The last stage can be replaced by the small-scale dynamo.

In flat, rotating objects like galaxy disks, the strongest mode of the  $\alpha$ - $\Omega$  dynamo consists of a toroidal field component, which is symmetric with respect to the equatorial plane and has the azimuthal symmetry of an axisymmetric spiral in the disk without a sign reversal across the plane (vertically symmetric or “even” parity mode S0), and a weaker poloidal field component of even symmetry with a reversal of the vertical field component across the equatorial plane (Fig. 6). The next higher azimuthal mode is of bisymmetric spiral shape (even mode S1) with two sign reversals in the plane, followed by more complicated modes. The pitch angle of the spiral field depends mainly on the rotation curve of the galaxy, the turbulent velocity and the scale height of the warm diffuse gas (Shukurov 2005). The field in fast rotating galaxies has a small pitch angle of about  $10^\circ$ , while slow differential rotation or strong turbulence leads to larger pitch angles of  $20^\circ$ – $30^\circ$ .

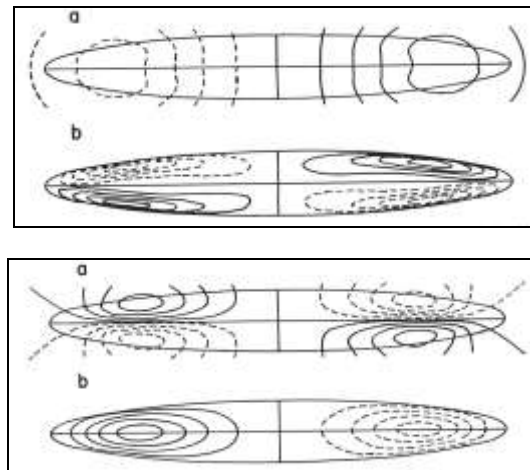


Fig. 6: Poloidal field lines (a) and contours of constant toroidal field strength (b) for the simplest version of an odd-symmetry dipolar (top) and an even-symmetry quadrupolar (bottom) dynamo field (Stix 1975). More realistic dynamo fields can have many “poles”.

Enhanced supply of turbulent magnetic fields by the small-scale dynamo in spiral arms may result in a concentration of large-scale regular magnetic fields between the material arms (Moss et al. 2013), as observed in many galaxies (section 4.4). A similar result can be obtained by the inclusion of a fast outflow from spiral arms (Sur et al. 2007) or by introducing a relaxation time in the dynamo equation (Chamandy et al. 2013).

In principle, the halo and the disk of a galaxy may drive different dynamos and host different field modes. However, there is a tendency of “mode slaving”, especially in case of outflows from the disk into the halo. The more dynamo-active region determines the global symmetry, so that the halo and disk field should have the same parity (Moss et al. 2010). This is confirmed in external galaxies (section 4.7), while our Milky Way seems to be different (section 3.5).

The ordering time scale of the  $\alpha$ - $\Omega$  dynamo depends on the size of the galaxy (Arshakian et al. 2009). Very large galaxies did not yet have sufficient time to build up a fully coherent regular field and may still host complicated field patterns, as often observed. The field ordering may also be interrupted by tidal interactions or merging with another galaxy, which may destroy the regular field and significantly delays the development of coherent fields (section 5). Strong star formation as the result of a merger event or mass inflow amplifies the turbulent field and can suppress the  $\alpha$ - $\Omega$  dynamo in a galaxy if the total star-formation rate is larger than about 20 solar masses per year. Continuous injection of small-scale magnetic fields by the small-scale dynamo in turbulent flows in star-forming regions may also decelerate the  $\alpha$ - $\Omega$  dynamo and allow initial field reversals to persist (Moss et al. 2012).

The  $\alpha$ - $\Omega$  dynamo generates large-scale helicity with a non-zero mean in each hemisphere. As total helicity is a conserved quantity, small-scale fields with opposite helicity are generated which suppress dynamo action, unless these are removed from the system (e.g. Vishniac et al. 2003). Hence, outflow with a moderate velocity or diffusion is essential for an effective  $\alpha$ - $\Omega$  dynamo (Sur et al. 2007). This effect may relate the efficiency of dynamo action to the star-formation rate in the galaxy disk (section 4.6).  $\alpha$ - $\Omega$  dynamo models including outflows with moderate velocities can also generate X-shaped fields (Moss et al. 2010). For fast outflows the advection time for the field becomes smaller than the dynamo amplification time, so that the dynamo action is no longer efficient.

There are several more unsolved problems with dynamo theory (Vishniac et al. 2003). The “mean-field” model is simplified because it assumes a dynamical separation between the small and the large scales. The large-scale field is assumed to be smoothed by turbulent diffusion, which requires fast and efficient field reconnection. One of the main future tasks is to compute the “mean” quantities  $\alpha$  and  $\eta$  from the small-scale properties of the interstellar medium, which is only possible with numerical modeling. MHD simulations of a dynamo driven by the buoyancy of cosmic rays (Hanasz et al. 2009) and of a dynamo driven by supernovae (Gressel et al. 2008; Gent et al. 2013) confirm the overall description of the  $\alpha$ - $\Omega$  model. Improved models with a spatial resolution of smaller than the turbulence scale, hence  $\approx 10$  pc, should include the whole rotating galaxy disk and the halo and consider all relevant physical effects. The multiphase interstellar medium has also to be taken into account (de Avillez & Breitschwerdt 2005). Rapid progress in modeling galactic magnetic fields can be expected in near future.

While the predictions of the  $\alpha$ - $\Omega$  dynamo model have been generally confirmed by present-day observations (sections 4.3 and 4.6), the primordial model of field amplification is less developed than the dynamo model and is not supported by the data. A wound-up large-scale seed field can generate only the even bisymmetric mode (S1) or the odd dipolar mode (A0), both of which were not observed so far. On the other hand, the number of galaxies with a well-determined field structure is still limited (Appendix). Future radio telescopes will be able to decide whether the dynamo or the primordial model is valid, or whether a new model has to be developed.

### 3. Magnetic fields in the Milky Way

#### 3.1 Optical, far-infrared and sub-mm polarization

The earliest optical polarization observations in 1949 were interpreted to be due to dust alignment in magnetic fields and hence a tracer of magnetic fields in galaxies. It took some time to convince the optical community that the polarization was due to dust grains aligned in magnetic fields. The radio polarization observations (section 3.2) confirmed the magnetic explanation. A large catalogue of the polarization of stars was made by Behr (1961). This work continued in the southern skies, as well as other observers, culminating in an all-sky catalogue of Mathewson & Ford (1970a) with 1800 entries and Axon & Ellis (1976) with 5070 entries. The general conclusion of this work, that there is a magnetic field aligned along the Galactic plane, still holds today. A very homogeneous region of alignment, with high polarization values, was seen towards the anticenter (Galactic longitude  $l \approx 140^\circ$ ). Well aligned magnetic field vectors are also seen along the North Polar Spur that extends in to the northern halo from  $l \approx 30^\circ$ . These early observations were possible for nearby stars, a few at a maximal distance of 4 kpc. A more recent compilation of 9286 stars, collected by Heiles (2000) and discussed by Fosalba et al. (2002) (Fig. 7), included some stars out to  $\approx 8$  kpc. In view of these distance limitations it is not possible on the basis of optical polarization alone to model the magnetic field of the Milky Way.

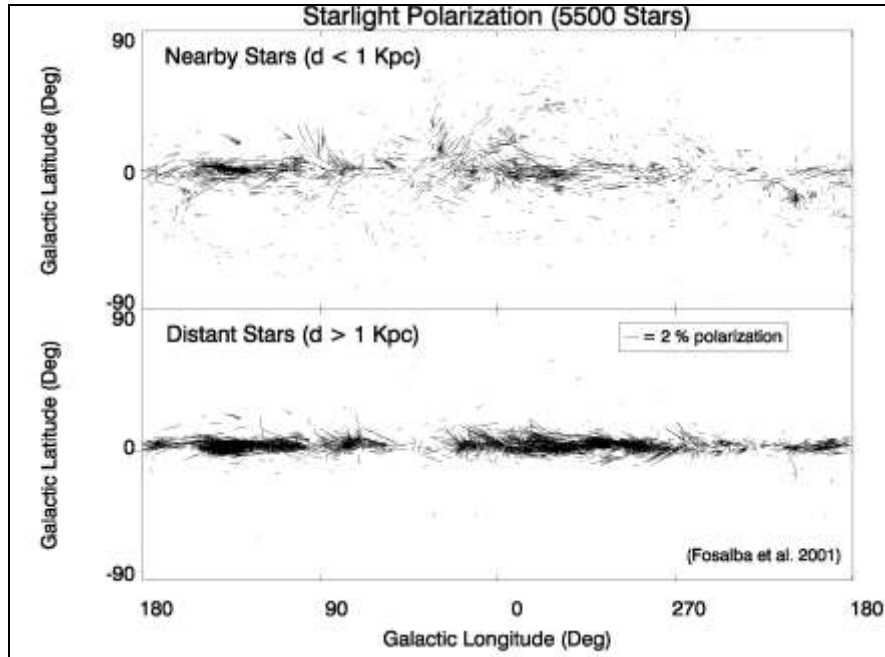


Fig. 7: Optical starlight polarization in the Galactic plane for two distance intervals (Fosalba et al. 2002)

Polarization observations of the diffuse far-infrared or sub-mm emission in the Milky Way are restricted to dense molecular/dust clouds. The Chandrasekhar-Fermi method (section 2.1) gives field strengths of a few mG, similar to Zeeman measurements of OH maser lines in other dense clouds (section 3.4). Interferometric observations in the sub-mm range with sub-parsec resolution reveals hourglass morphologies in the envelopes of the dust cores of ultra-compact HII regions (Tang et al. 2009). The supercritical cores seem to collapse in a subcritical envelope supported by strong magnetic fields, suggesting that ambipolar diffusion plays a key role in the evolution of the cloud. The correlation of the field orientation in the intercloud medium on a scale of several 100 pc, derived from optical polarization, with that in the cloud core on a scale of less than 1 pc, derived from sub-mm polarimetry, further indicates that the fields are strong and preserve their orientation during cloud formation (Li et al. 2009).

### 3.2 Radio continuum

#### 3.2.1 All-sky surveys in total intensity

The radio continuum emission of the Milky Way and star-forming galaxies at frequencies below 10 GHz mostly originates from the synchrotron process and hence traces the distribution of magnetic fields and cosmic rays. The contribution of thermal radio emission is generally small, except in bright star-forming regions. Only at frequencies higher than 10 GHz the thermal emission may dominate locally. At frequencies below about 300 MHz absorption of synchrotron emission by thermal gas can become strong. Hence the observation of total radio continuum intensity in the frequency range of about 300 MHz - 10 GHz is a perfect method to investigate magnetic fields. Since the observed intensity is the integral from many emission areas along the line of sight, its interpretation is not always simple. Furthermore, the angular resolution of all-sky surveys (Fig. 10) is limited and hence cannot show the details of extended sources.

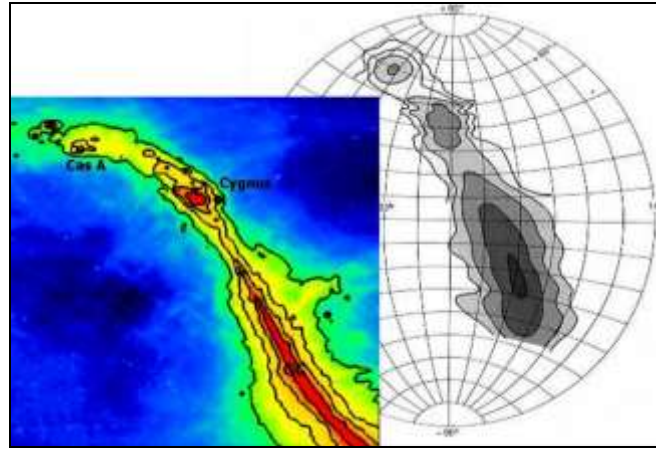


Fig. 8: The early sky map at 160 MHz of Reber (1944) (black-white) and a recent map at 1.4 GHz (color) (courtesy Wolfgang Reich)

Numerous radio continuum surveys were made in the early days of radio astronomy (Appendix, Table 2). The early all-sky surveys showed the Galactic emission with a maximum towards the Galactic center, the band of emission along the Galactic plane, maxima in the tangential directions of the local spiral arm: Cygnus ( $l \approx 80^\circ$ ) in the northern and Vela ( $l \approx 265^\circ$ ) in the southern skies and some “spurs” of emission. In addition a few strong extragalactic sources were seen superposed on the Galactic emission.

The analysis of total synchrotron emission gives an equipartition strength of the total field of  $6 \pm 2 \mu\text{G}$  in the local neighborhood and  $10 \pm 3 \mu\text{G}$  at 3 kpc radius (Berkhuijsen, in Beck 2001). The radial exponential scale length of the total field is about 12 kpc. These values are similar to those in external galaxies (section 4.2).

The angular resolution has improved so that at present all-sky surveys with resolution of under  $1^\circ$  are available. At 1.4 GHz the surveys delineated many extended Galactic sources (HII regions, SNRs) seen along the Galactic plane. Some extragalactic sources like Centaurus A, Virgo A, Cygnus A and the Magellanic Clouds are also clearly seen in the all-sky survey. Surveys at 45 MHz covered most of the sky with medium angular resolution. At these low frequencies, absorption of the synchrotron emission by ionized gas takes place near the Galactic plane.

The WMAP satellite surveys at frequencies from 23 GHz to 94 GHz (Bennett et al. 2003; Hinshaw et al. 2009) gave us a new view of the radio continuum sky at high radio frequencies. At the highest WMAP frequencies mainly thermal emission originating in interstellar dust is observed. An additional component due to spinning dust has been postulated (Draine & Lazarian 1998), to be seen in the 10–100 GHz frequency range. This spinning dust component has been confirmed (Dobler et al. 2009) in the WMAP data set.

There is a large gap between the lower frequency all-sky surveys and the high-frequency data. A 5 GHz all-sky survey with compatible angular resolution but also good sensitivity is badly needed. Table 2 in the Appendix lists the all-sky surveys with the best angular resolution at a given frequency.

### 3.2.2 All-sky surveys in linear polarization

Linear polarization of the continuum emission is a more direct indicator of magnetic fields, because there is no confusing thermal component. However, linear polarization is subject to Faraday effects (section 3.3). After the first detections of polarized Galactic radio waves in 1962 (Fig. 9) several all-sky polarization surveys were made (Appendix, Table 3). The early polarization surveys did not have sufficient angular resolution to elucidate many details. These surveys were made at the low radio frequency of 408 MHz where Faraday effects are considerable. A multi-frequency collection of polarization data for the northern sky was published by Brouw & Spoelstra (1976), albeit not fully sampled.

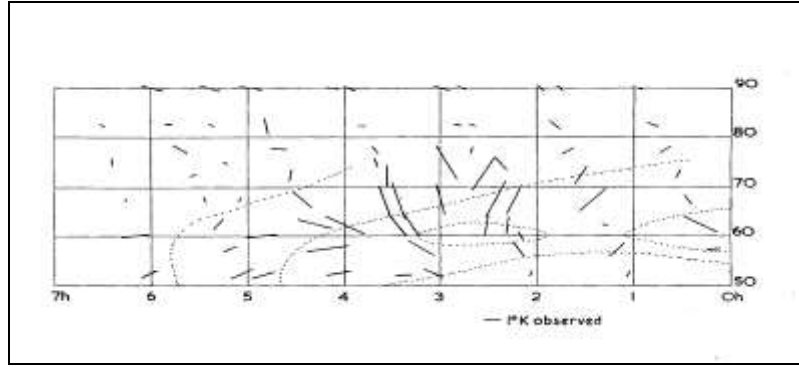


Fig. 9: First detection of polarized synchrotron emission (E-vectors) in the Milky Way at 408 MHz (Wielebinski et al. 1962)

Major progress was achieved by Wolleben et al. (2006) and Testori et al. (2008) who mapped the whole sky in linear polarization at 1.4 GHz with an angular resolution of 36 arcminutes (Fig. 10). Several polarization maxima are seen, e.g. towards the “Fan region” at  $l \approx 140^\circ$ ,  $b \approx 10^\circ$ , where the line of sight is oriented perpendicular to the local spiral arm. The “North Polar Spur” (NPS) emerges from the Galactic plane at  $l \approx 30^\circ$  as well as additional spur-like features are the results of magnetic fields compressed by expanding supernova remnants. In particular, the NPS can be followed, in polarization, to the southern sky. Towards the inner Galaxy (Galactic longitude  $90^\circ < l < 270^\circ$ , Galactic latitude  $|b| < 30^\circ$ ) strong turbulence in the polarized intensity is seen, due to Faraday effects on small scales (section 2.4). The NRAO VLA sky survey (NVSS) has also recently been analyzed in polarization (Rudnick & Brown 2009). All-sky polarization data at 23 GHz was published by the WMAP team (Kogut et al. 2007; Hinshaw et al. 2009). There is good agreement between the 23 GHz and the 1.4 GHz polarization maps in the polarization features away from the Galactic plane, but the high-frequency map shows less Faraday depolarization towards the inner Galaxy and near the plane. The PLANCK satellite will soon provide new polarization surveys in six frequency bands (30–350 GHz) with high sensitivity and resolution.

Another major survey has been started which will cover the whole sky at frequencies between 300 MHz and 1.8 GHz and will allow the measurement the RM of the diffuse emission over the whole sky (Wolleben et al. 2009). A summary of all-sky polarization surveys is given in Reich (2006) and in Table 3 of the Appendix.

*Galactic plane* surveys have been made from the earliest days of radio astronomy to delineate the extended Galactic sources like supernova remnants and HII regions, usually with no linear polarization data (Appendix, Table 4). Many of the published Galactic plane surveys between 22 MHz and 10 GHz cover only a narrow strip along the Galactic plane in the inner Galaxy. Total intensity surveys at several frequencies were used to separate the thermal HII regions (with a flat radio spectrum) from the steep-spectrum non-thermal sources (supernova remnants). From the total intensity surveys numerous previously unknown supernova remnants could be identified.



Since non-thermal sources are polarized it was obviously necessary to map the Galactic plane also in linear polarization. The first step in the evolution of our knowledge about the polarization of the Galactic plane was the 2.7 GHz survey by Junkes et al. (1987), followed by the surveys of the southern Galactic plane at 2.3 GHz (Duncan et al. 1995) and the northern counterpart at 2.7 GHz (Duncan et al. 1999), which covered a relatively wide strip ( $|b| < 5^\circ$ ) around the plane. Early high-resolution observations by Wieringa et al. (1993) showed that a lot of small-scale polarization is present in the Galactic emission which is unrelated to any structures in total intensity. The next major development is the Effelsberg Medium Latitude Survey (EMLS) at 1.4 GHz that will ultimately cover  $\pm 20^\circ$  distance from the Galactic plane (Uyaniker et al. 1999; Reich et al. 2004). A section of the southern Galactic plane has been mapped at 1.4 GHz with arcminute resolution (Gaensler et al. 2001; Haverkorn et al. 2006), complemented on the northern sky by the DRAO survey (Taylor et al. 2003; Landecker et al. 2010) (Fig. 11). A survey of a  $5^\circ \times 90^\circ$  strip along the Galactic meridian  $l = 254^\circ$  with the Parkes telescope at 2.3 GHz is underway (Carretti et al. 2010).

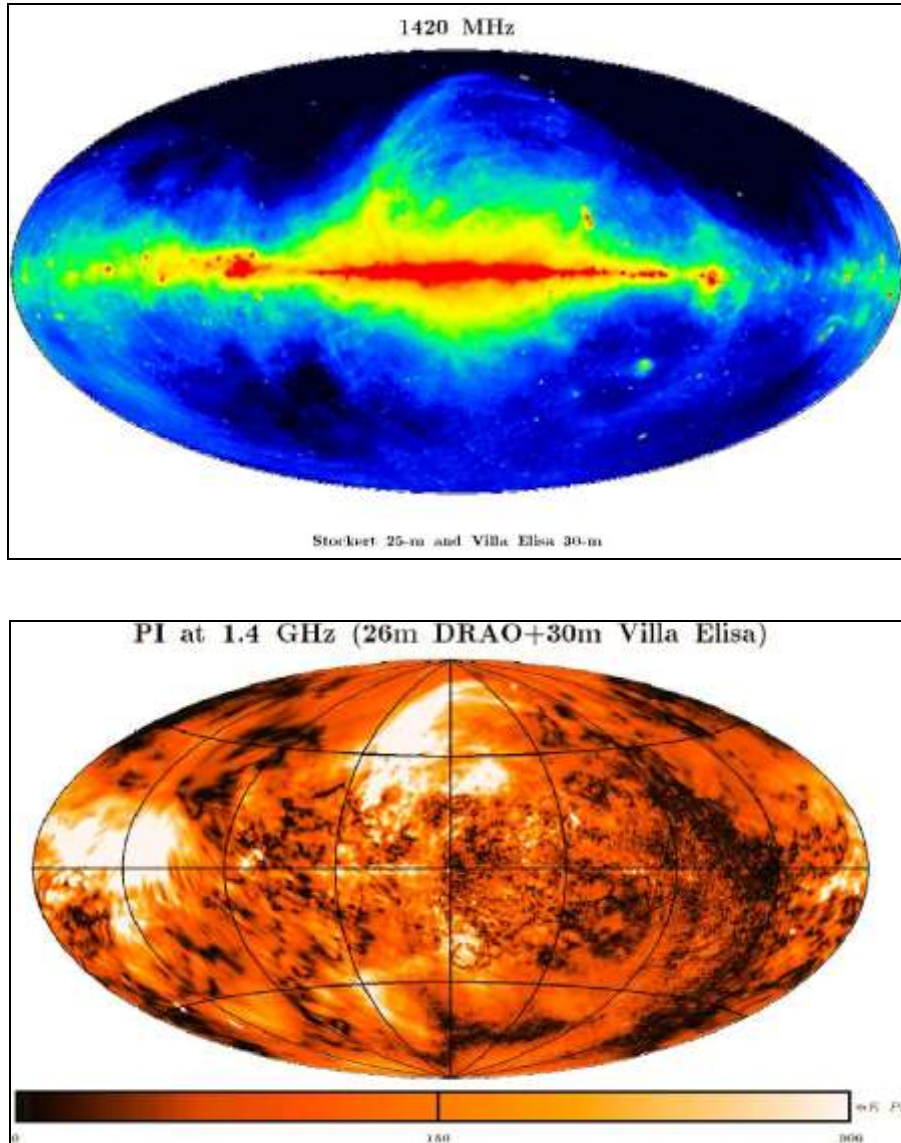


Fig. 10: All-sky surveys in total intensity (top) and polarized intensity (bottom) at 1.4 GHz (Reich 1982; Wolleben et al. 2006; Testori et al. 2008)

In all the above mentioned surveys *Faraday effects* (section 2.4) play an important role. At frequencies of 1.4 GHz and below, Faraday rotation generates small-scale structures in polarization which are not related to physical structures. Even at 5 GHz Faraday rotation plays an important role near the Galactic plane ( $|b| < 5^\circ$ ). With high enough angular resolution, Faraday rotation leads to complete depolarization at certain values of Faraday rotation measure (RM) (Fig. 2), showing up as “canals” in



the maps of polarized intensity (e.g. Haverkorn et al. 2003; 2004; Schnitzeler et al. 2009; Fig. 11). However, a careful determination of the extended polarized background is necessary for a reliable determination of polarized intensity, polarization angles and RM. When this “absolute calibration” is done, most of the “canals” disappear. As a second new phenomenon, “Faraday Screens” were discovered (e.g. Gray et al. 1998; Uyaniker et al. 1999; Wolleben & Reich 2004; Schnitzeler et al. 2009). These are foreground clouds of diffuse thermal gas and magnetic fields which Faraday-rotate or depolarize the extended polarized emission from the background. In addition to the well-known polarized SNRs and unpolarized HII regions, molecular clouds, pulsar-wind nebulae, and planetary nebulae were identified as Faraday Screens. Depending on the rotation angle and the polarization angle of the background emission, such screens may appear bright or dark. The strength and structure of regular fields can be estimated via the RM. Such observations can trace magnetic structures to sub-parsec scales.

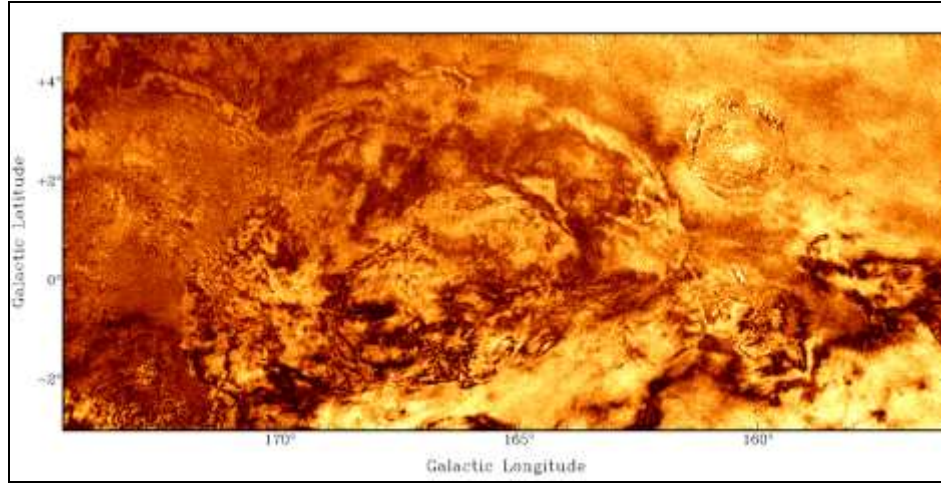


Fig. 11: A section of the Galactic plane at 1.4 GHz (Landecker et al. 2010)

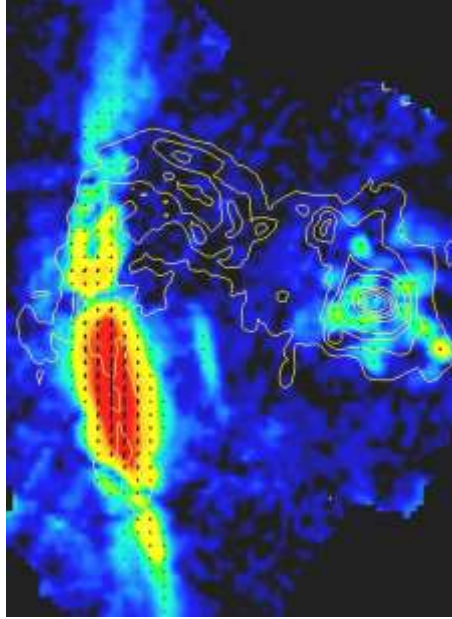
The present data set on the intensity distribution and polarization of the Galactic plane (listed in Table 4 of the Appendix) is impressive. Sensitive surveys at higher radio frequencies are needed to allow a systematic study of the Faraday Screen phenomenon. This is being achieved e.g. by a Sino-German survey of the Galactic plane at 5 GHz with the Urumqi telescope (Sun et al. 2007; 2011; Gao et al. 2010; Xiao et al. 2011).

### 3.2.3 The Galactic Center

The Galactic Center is unique source with unusual radio continuum features. Mapping of the Galactic Center region by Yusef-Zadeh et al. (1984) showed several features vertical to the plane. The radio continuum emission is most intense and has a flat spectral index (Reich et al. 1988), for many years accounted to thermal emission. However, this intense emission is highly polarized (e.g. Seiradakis et al. 1985) and has been interpreted to be due to mono-energetic electrons (Lesch et al. 1988). Also the polarization “strings” imply vertical magnetic structures, much different from the azimuthal directions of the magnetic fields seen along the Galactic plane. Mapping of the Galactic Center at 32 GHz (Reich 2003) showed that RMs in excess of  $\pm 1600 \text{ rad m}^{-2}$  are present in the vertical filaments. The discussion about the intensity of the magnetic fields have yielded very high values (mG range) based on Zeeman splitting observations (e.g. Yusef-Zadeh et al. 1996), while other authors (e.g. Crocker et al. 2010), based on the radio synchrotron spectrum, suggest much lower values in the 50-100  $\mu\text{G}$  range.

Detailed high-resolution studies also brought controversial results. High resolution radio maps of the Galactic Center (e.g. Nord et al. 2004) showed a spiral structure at the position of Sgr A\* and thin vertical radio continuum “strings”. Polarimetric observations at sub-mm wavelengths suggest a stretched magnetic field (Novak et al. 2000), as expected in sheared clouds, while the large-scale ordered field is mostly toroidal (Novak et al. 2003). Near-IR polarimetry suggests a transition from toroidal to poloidal field configuration in the Galactic Center (Nishiyama et al. 2010).

A recent interpretation of the magnetic field phenomena in the Galactic Center was given by Ferrière (2009). If our Galaxy does not differ much from nearby galaxies, the vertical field detected close to the center is a local phenomenon.



*Fig. 12: Galactic Center region. Total intensity (contours), polarized intensity (colors), and B-vectors at 32 GHz, observed with the Effelsberg telescope. The map size is about 23' x 31' along Galactic longitude and latitude. The Galactic Center is located at the peak of total emission (from Wolfgang Reich, MPIfR).*

### 3.3 Faraday Rotation of extra-galactic radio sources and pulsars

Faraday rotation (FR) is a powerful tool for studying magnetic fields. First, ionospheric rotation, later Faraday effects due to the Galactic ISM were detected soon after the discovery of linear polarization of the Galactic radio waves. At first the FR of diffuse emission was studied. Later with increasing samples of EGRS modeling of the magnetic field was attempted. Finally pulsars, most of which are concentrated to the Galactic plane were used to model the Galactic magnetic fields.

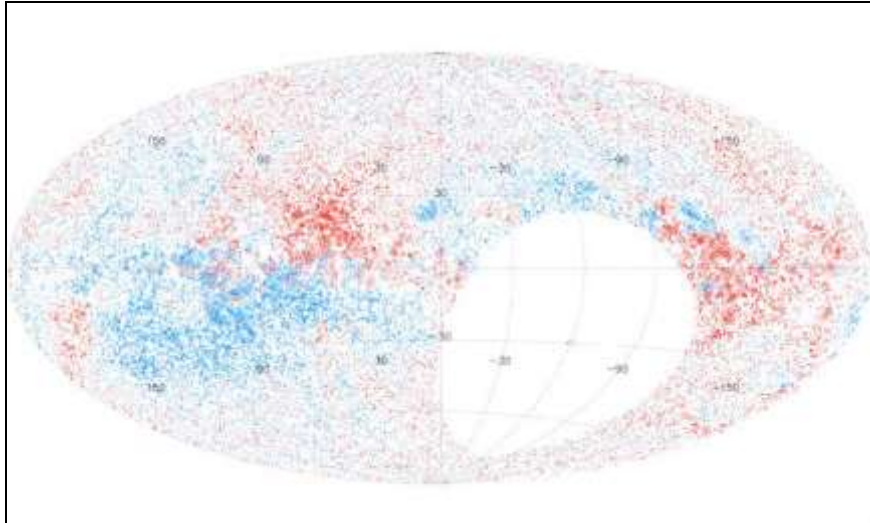
#### 3.3.1 Extra-galactic radio sources (EGRS)

Faraday rotation measures (RMs) towards EGRS originate in the source itself and in the magneto-ionic media in the foreground (intergalactic space, intervening galaxies, Milky Way, interplanetary space and ionosphere of the Earth). The contributions from intergalactic space, intervening galaxies and interplanetary space are generally small. The contribution from the ionosphere of the Earth is subtracted with help of calibration sources with known polarization angle, leaving RM from the Milky Way and intrinsic RM. Interestingly, the intrinsic RM dispersion of extragalactic sources is smaller than the RM dispersion in the Galactic foreground for sightlines that are separated by at least  $1^\circ$ , so that the contribution by the Galactic foreground becomes very important at low and intermediate Galactic latitudes (Schnitzeler 2010).

Here a word of caution must be given. The intrinsic polarization and RM of any EGRS may originate in the nucleus of a radio galaxy or in the extended lobes. Hence, when making observations at various frequencies to obtain the correct RM, care must be taken that the same source structure is measured. In particular there are problems in combining data from single dish observations with those of an interferometer at other frequencies. More recent observations use many adjacent frequency channels to accurately determine the RM, if a sufficiently wide band is used (*RM Synthesis*, section 2.4). This also helps to separate the intrinsic RM from that in the foreground. If RM Synthesis is not available, averaging over a large number of RMs is used reduce the intrinsic contributions.

The earliest catalogues of RM towards EGRS were collected by Simard-Normandin & Kronberg (1980) showing the all-sky distribution of RMs. In this compendium of sources there were only a few sources with measured RM along the Galactic plane, where the Galactic magnetic fields are concentrated, as was seen in the all-sky continuum surveys. Hence the interpretation of this data gave us an indication of a local magnetic field only. In recent years additional data on the RM of sources in the Galactic plane were obtained (Brown et al. 2007; Van Eck et al. 2011). However, all these surveys cover only partially the Galactic plane, so that interpretation is difficult. The highest observed values were  $|RM| \approx 1000 \text{ rad m}^{-2}$  towards the Galactic Center. Similarly high  $|RM|$  values were determined by Roy et al. (2008), who surveyed an area directly at the center of our Galaxy. There is neither a uniform coverage of the Galactic plane nor of the whole sky as yet. A statistical method to visualize the RM distribution over the sky was developed by Johnston-Hollitt et al. (2003) who used 800 sources. This work showed several areas of consistent RM values (of the same sign) as well as structures above and below the plane.

An important addition to the data set was undertaken by Taylor et al. (2009), who reanalyzed the NRAO VLA Sky Survey (NVSS) (Fig. 13). This study involved 37,543 sources and added a huge number of new RMs, but is limited by the rather close frequency separation of the two frequency bands which leads to large RM errors. The averaged RM towards extragalactic sources reveal no large-scale reversal across the plane around Galactic longitudes  $120^\circ$  and also  $-120^\circ$  (according other observations showing a reversed sign in the southern region, not shown in Fig. 13): The local disk field is part of a large-scale symmetric field structure. However, towards the inner Galaxy the RM signs are opposite above and below the plane. This reversal may be due to local features (Wolleben et al. 2010b) or to an antisymmetric toroidal field in the Milky Way's halo (section 3.5).



*Fig. 13: Rotation measures determined from the NVSS catalog (Taylor et al. 2009). Red symbols: positive RM, blue symbols: negative RM. The size of a circle scales linearly with RM magnitude.*

Another project to increase the number of RMs over the whole sky was undertaken at the Effelsberg radio telescope, combining polarization data in 8 channels in two bands around 1.4 and 1.6 GHz. This instrumental combination allows for accurate determination of the RM of sources. Some 1600 new RMs were added and a preliminary result is given in Wielebinski et al. (2008). The preliminary data for 2469 sources were used to model the Galactic magnetic field (Sun et al. 2008; section 3.5).

A survey of compact sources in the southern hemisphere that is being carried out with the Australia Telescope Compact Array will provide reliable Faraday depth spectra for over 3000 sightlines (Schnitzeler et al., in prep.). These sightlines will fill the gap below declination  $-40$  degrees that is not covered by the RM catalogue from Taylor et al. (2009), and for the first time we will have a complete and well-sampled view of the entire Milky Way and its halo.

### 3.3.2 Pulsars

Pulsars are the ideal sources to probe the magnetic fields through the Faraday effect. Since pulsars have no measurable angular structure and they are highly polarized they are the ideal probes. Pulsars are Galactic objects and hence their distribution is close to the Galactic plane towards the inner Galaxy. In fact very few pulsars are known towards the anti-center of the Galaxy. Hence a combination of pulsars and EGRS is optimal for studies of the Galactic magnetic field. Pulsars also allow measurement of the Dispersion Measure (DM) which follows from the signal delay occurring in the foreground medium. Together with the RM the value of the average regular magnetic field in the line of sight can be deduced:

$$\langle B_{\parallel} \rangle = 1.232 \frac{\text{RM}}{\text{DM}} \mu\text{G}$$

Application gives an average strength of the regular field in the local spiral arm of  $1.4 \pm 0.2 \mu\text{G}$ . In the inner Norma arm, the average strength of the regular field is  $4.4 \pm 0.9 \mu\text{G}$ . However, this estimate is only valid if variations in the regular strength and in electron density are *not correlated*. If they are correlated, the above formula gives an overestimate of  $\langle B_{\parallel} \rangle$ , and an underestimate for anti-correlated variations (Beck et al. 2003). The dispersion of pulsar RMs yields an estimate for the turbulent field strength of about  $5 \mu\text{G}$  and for the turbulence length of about  $50 \text{ pc}$  (Rand & Kulkarni 1989).

The major compilation of pulsar rotation measures, also using already published data, are given in Han et al. (2006; 2009). Additional results are found in Mitra (2003), Noutsos et al. (2008) and Van Eck et al. (2011). The distribution of rotation measures, as given by Han (2007), shows a huge variation of signs and magnitudes. This may indicate a large-scale regular magnetic field with multiple reversals (section 3.5) or the effect of localized regions, e.g. HII regions (Mitra et al. 2003; Nota & Katgert 2010).

The RM values increase for distant objects, but very few pulsars were found beyond the Galactic Center (Fig. 14). The limit of  $|\text{RM}| \approx 1000 \text{ rad m}^{-2}$  for EGRS holds also for pulsars. This seems to indicate that the RM towards EGRS is partly averaged out in passage through the Galaxy. The large-scale regular field of the outer Milky Way is either weak or frequently reversing its direction.

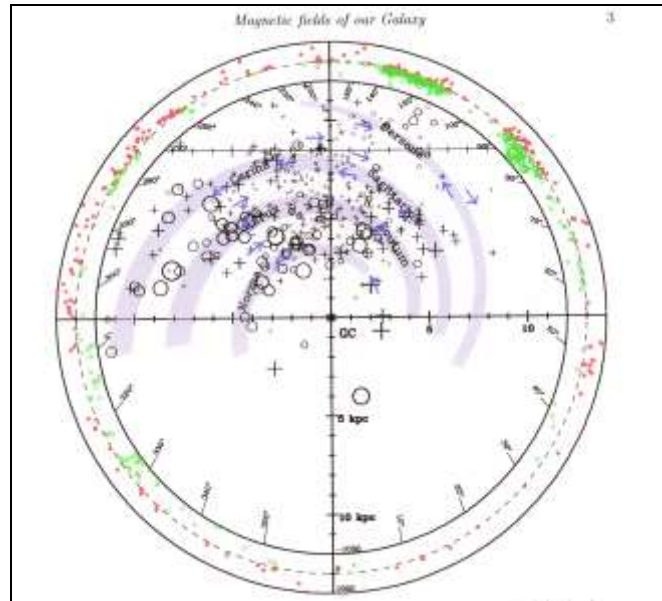


Fig. 14: Faraday rotation measures (RM) of pulsars in the Milky Way (within inside circle) and of extragalactic radio sources (between inside and outside circles). Plus signs indicate positive RM towards pulsars, small circles negative RM. Red symbols indicate positive RM towards extragalactic sources, green symbols negative RM. The blue arrows suggest large-scale magnetic fields along a model of spiral arms in the Milky Way. Our sun is located at the upper crossing of coordinate lines (Han 2008).



### 3.4 Zeeman effect

The Zeeman effect is the most direct method of measuring magnetic fields. It has been used in the optical range for detecting magnetic fields in The Sun and in stars. At radio wavelength the use of the Zeeman effect proved to be more difficult. For one, the frequency shifts caused by the weak magnetic fields are minute and require sophisticated instrumentation. The HI line gave the first definitive detections, usually in absorption towards strong Galactic sources (Verschuur 1968). The technique was refined so that at present magnetic fields as weak as  $\approx 5 \mu\text{G}$  can be detected with the Arecibo telescopes (Heiles & Crutcher 2005). The observation of the Zeeman effect in the OH molecule (e.g. Crutcher et al. 1987) advanced the field further. It became clear that many of the positive detections were in molecular clouds with maser sources. Strong magnetic fields ( $\approx 80 \text{ mG}$ ) were detected in interstellar  $\text{H}_2\text{O}$  maser clouds (Fiebig & Güsten 1989). Millimeter-wavelength astronomy gave us additional results for high recombination lines (Thum & Morris 1999) or in such molecules as CN (Crutcher et al. 1999) or CCS (Levin et al. 2000). A compilation of present-day Zeeman measurements of the magnetic field in gas clouds (Fig. 15) gives a mean total field in the cold neutral interstellar gas of  $6 \pm 2 \mu\text{G}$ , so that the magnetic field dominates thermal motion but is in equipartition with turbulence, as also found on much larger scales in external galaxies (section 4.2). Beyond cloud densities of  $\approx 1000 \text{ cm}^{-3}$  the field strength scales with  $n^{0.65 \pm 0.05}$  (Crutcher et al. 2010).

The importance of magnetic fields in the star-formation process is obvious. Diffuse clouds are subcritical with respect to collapse and probably balanced by magnetic fields, while dense molecular are supercritical and collapse. The transition from subcritical to supercritical state may be the result of ambipolar diffusion or turbulence. Zeeman observations in the HI and OH lines can measure the ratio of mass to magnetic flux in the cloud envelope and the core. A smaller ratio in the core may indicate that supersonic turbulence plays a similarly important role as ambipolar diffusion (Crutcher et al. 2009), but effects of the field geometry also have to be taken into account (Mouschovias & Tassis 2009). More and higher-quality data are needed.

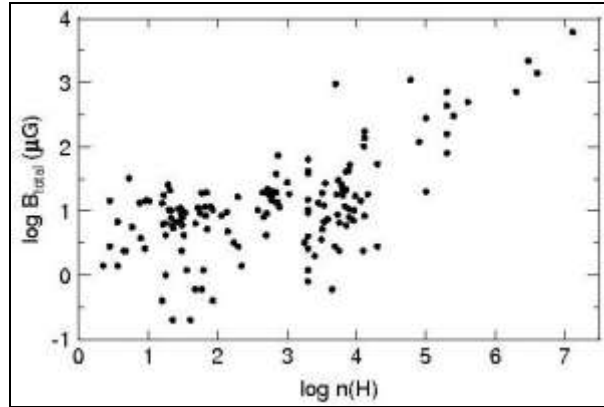


Fig. 15: Zeeman measurements of the total magnetic field in gas clouds plotted against the hydrogen volume density  $n_{\text{H}}$  (in  $\text{cm}^{-3}$ ). To derive the total field  $B_{\text{total}}$ , each measured line-of-sight component was multiplied by a factor of 2 which is the average correction factor for a large sample (Crutcher et al. 2010).

The use of the Zeeman data for the investigation of a large-scale regular magnetic field of the Galaxy was attempted by several authors (e.g. Fish et al. 2003). The number of detected sources was rather small and the interpretation in terms of Galactic magnetic fields rather inconclusive. Han & Zhang (2007) collected a large data set of Zeeman results and studied the question if the magnetic fields in molecular clouds preserve information of the direction of the large-scale magnetic fields in the spiral arms. In spite of a larger data set all that the conclusion offered was that clouds “may still remember the directions of regular magnetic fields in the Galactic ISM to some extent”.

### 3.5 Modeling the magnetic field of the Milky Way

Based on all the data described in previous sections models of the magnetic fields of the Milky Way have been repeatedly made. At first the low frequency all-sky data was used to describe the Galactic non-thermal emission (e.g. Yates 1968) produced in magnetic fields. The all-sky survey of Haslam et al. (1982) has been interpreted by Phillips et al. (1981) and Beuermann et al. (1985). Using the data on the HII regions (e.g. Georgelin & Georgelin 1976) of the Galaxy it could be shown that the spiral structure is also seen in the diffuse radio continuum emission.

The RM data first for pulsars and later for extragalactic radio sources (EGRS) also led to modeling of the magnetic fields of the Milky Way. The RMs towards pulsars are due to the ISM in the direction of the inner Galaxy. There are few pulsars known outside the inner quadrants. The data on EGRS gave information about the Faraday effects over much of the sky but not for the Galactic plane. Until recently there were very few EGRS observed through the inner Galactic plane.

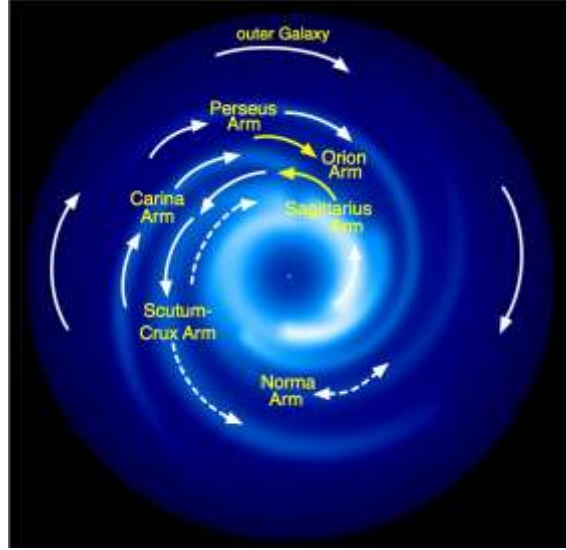
The collection of 543 rotation measures of EGRS distributed across the sky by Simard-Normandin & Kronberg (1980) showed that there were areas with similar RM directions, suggesting organized magnetic fields over larger Galactic scales. Pulsar observers were the first to point out that in addition to large areas of similar magnetic field directions there were some regions where the field *reverses* along Galactic radius. These results were analyzed with wavelets (e.g. Stepanov et al. 2002) and confirmed the existence of at least one large-scale reversal. Since most of the EGRS investigated were away from the Galactic plane they did not trace the Galactic magnetic field in the disk, more likely were indications of some local magnetic features. The number of RMs has been steadily increasing (e.g. Taylor et al. 2009) which increased the sampling of the Galaxy considerably. The same general conclusions were reached as in the earlier work – organized magnetic structures in sections of the Galaxy and highly disorganized magnetic fields towards the central region. One of the disadvantages of the available data is the fact that the southern sky data is very spare and needs additional observations. Progress has been made in observations of EGRS in the Galactic plane (Brown et al. 2007; Van Eck et al. 2011), but the sampling is still not uniform and not dense enough along the plane. The RMs of EGRS in the very center of the Galaxy were studied by Roy et al. (2008) who detected mainly positive RM values, suggesting a magnetic field aligned with a central bar.

The analysis of data from radio continuum all-sky surveys at 1.4 and 23 GHz, from RMs towards EGRS, the best available thermal electron model and an assumed cosmic ray distribution (Sun et al. 2008, Sun & Reich 2010) constrained the average field strength of the Galaxy to  $\approx 2 \mu\text{G}$  for the regular field and  $\approx 3 \mu\text{G}$  for the random field in the solar neighborhood, similar to the results from pulsar RMs (section 3.3.2). An axisymmetric spiral (ASS) magnetic field configuration (section 2.6) fits the observed data best, but one large-scale reversal is required about 1–2 kpc inside the solar radius. The local field is oriented parallel to the plane and its direction is symmetric (even parity) with respect to the Galactic plane, while the toroidal component of the halo field has different directions above and below the Galactic plane (odd parity, see section 2.6), to account for the different signs of the observed RM data. If this antisymmetry is globally valid for the Milky Way, its halo field has a dipolar pattern, in contrast to that found in external galaxies (section 4.7). However, some of the asymmetry can be explained by distorted field lines around a local HI bubble (Wolleben et al. 2010b). Observations with better sampling of the sky are needed (section 5).

Pulsars are ideal objects to deduce the Galactic magnetic field because their RMs provide field directions at many distances from the Sun. Since most pulsars are concentrated along the Galactic plane, they sample the field in the disk. Analysis of the pulsar and EGRS data led to several attempts to model the Galactic magnetic field (Brown et al. 2007; Van Eck et al. 2011; Jansson & Farrar 2012). The local magnetic field in the Perseus arm is clockwise. A large-scale magnetic field reversal is present between the Scutum-Crux-Sagittarius arm and the Carina-Orion arm (Fig. 16;). This reversal was often used as an argument for a bisymmetric spiral (BSS) field structure, although such a reversal can be local or be part of a more complicated field structure. Detailed analysis (e.g. Vallée 1996; Noutsos et al. 2008) has shown that this concept of a single large-scale field mode is not compatible with the data. The analysis of the previous interpretations by Men et al. (2008) also showed that presently there is no proof of either a BSS or a ASS configuration and that the field structure is probably more complicated.

Studies of the effects of large HII regions on the RM changes of pulsars beyond these Faraday screens showed that some earlier interpretations that some of the claimed field reversals are only

local (Mitra et al. 2003). Furthermore, the comparison of the RM of pulsar and EGRS towards the Galactic Center (Brown et al. 2007) revealed similar values of RM, as if there were no other half of the Galaxy. This result suggests that the RMs are dominated by local ISM features and that the large-scale field is weak and cannot be delineated from the available data. Only RM data free from the effects of HII regions should be used, as demonstrated by Nota & Katgert (2010).



*Fig. 16: Model of the large-scale magnetic field in the Milky Way's disk, derived from Faraday rotation measures of pulsars and extragalactic sources. Yellow arrows indicate confirmed results, while white and dashed arrows still need confirmation (from Jo-Anne Brown, Calgary).*

The magnetic field structure of the Milky Way is probably quite complex and shows details which cannot be resolved yet in external spiral galaxies. The existence of one large-scale field reversal in the Milky Way is puzzling. Very few large-scale reversals have been detected so far in external spiral galaxies, and none along the radial direction (section 4.4). The different observational methods may be responsible for this discrepancy between Galactic and extragalactic results. RMs in external galaxies are averages over the line of sight through the whole disk and halo and over a large volume traced by the telescope beam, and they may miss field reversals, e.g. if these are restricted to a thin region near to the galaxy plane. The results in the Milky Way are based on RMs of pulsars, which trace the magneto-ionic medium near the plane. Alternatively, the Milky Way may be “magnetically young” and may still not have generated a coherent large-scale field over the whole disk. The timescale for fully coherent fields can be longer than the galaxy age, e.g. if frequent interactions with other galaxies occur (section 2.6). Another model to explain reversals is the continuous generation of small-scale fields; these may disturb the action of the large-scale dynamo and allow reversals of the initial field to persist (Moss et al. 2012).

Little is known about the large-scale field in the Milky Way's halo. In the Galactic Center vertical magnetic fields apparently extend into the halo (section 3.2.3). From a survey of RMs of EGRS towards the Galactic poles, Mao et al. (2010) derived a local large-scale field perpendicular to the plane of  $+0.31 \pm 0.03 \mu\text{G}$  towards the south Galactic pole, but no significant field towards the north Galactic pole. This is neither consistent with an odd-symmetry halo field as suggested from the antisymmetry of the toroidal field nor with an even-symmetry halo field as found in several external galaxies (section 4.7). On the other hand, Jansson & Farrar (2012), modeling the diffuse polarized emission and RMs, found evidence for X-shaped vertical field components, similar to those in external galaxies. Again, the halo field may be more complicated than predicted by large-scale dynamo models, and regions with different field directions exist.

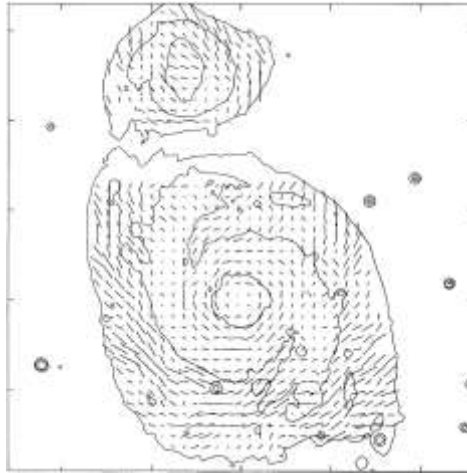
While observations in the Milky Way can trace magnetic structures to much smaller scales than in external galaxies, the large-scale field is much more difficult to measure in the Milky Way. This information gap will be closed with future radio telescopes which will find many new pulsars in the Milky Way (and in nearby galaxies) and which allow us to observe the detailed magnetic field structure also in external galaxies (section 5).

## 4. Galaxies

Magnetic fields in external galaxies can be observed with the same methods as in the Milky Way, except for extragalactic pulsars which have been found so far only in the Magellanic clouds. Naturally the spatial resolution of the telescopes is much worse in galaxies, and the detailed structure of extragalactic fields on scales below about 100 pc is still invisible. On the other hand, the large-scale field properties, like the overall pattern and the total extent, can be best measured in external galaxies. Observations in the Milky Way and in external galaxies are complementary.

### 4.1 Optical polarization, infrared polarization, and Zeeman effect

Weak linear polarization (generally below 1%) is the result of extinction by elongated dust grains in the line of sight which are aligned in the interstellar magnetic field (the Davis-Greenstein effect, see section 2.1). Optical polarization surveys yielded the large-scale structure of the field in the local spiral arm of our Milky Way (section 3.1). The first extragalactic results by Hiltner (1958) were based on starlight polarization of globular clusters in M31 and showed that the magnetic field is aligned along the galaxy's major axis. Polarization of starlight in the LMC also gave evidence for ordered fields near 30 Dor (Mathewson & Ford 1970b) and possibly along the Magellanic stream (Schmidt 1976).



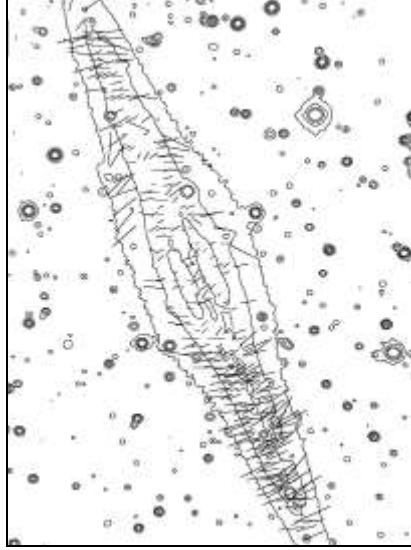
*Fig. 17: Spiral galaxy M51. E-vectors of the optical polarization of diffuse light which trace the spiral magnetic field orientation (Scarrott et al. 1987). Compare with the radio polarization map in Fig. 23.*

Polarization from diffuse optical light was used to search for large-scale magnetic fields, though some unknown fraction of the polarized light is due to scattering on dust particles. A survey of 70 nearby galaxies revealed degrees of polarization of  $\leq 1\%$  (Jones et al. 2012). Indications for ordered fields along the spiral arms were found in M82 (Elvius 1962), M51 and M81 (Appenzeller 1967; Scarrott et al. 1987), in NGC1068 (Scarrott et al. 1991) and in NGC6946 (Fendt et al. 1998). The pattern in M51 (Fig. 17) agrees well with the radio polarization results (see Fig. 23) in the inner spiral arms but large differences are seen in the outer arms and in the companion galaxy, which is unpolarized in the radio image. In the Sa-type edge-on Sombrero galaxy M104 and the Sb-type edge-on NGC4545, optical polarization indicates a field along the prominent dust lane and vertical fields above the plane (Scarrott et al. 1990), in agreement with the results from radio polarization (section 4.7). The polarization of the Sc-type edge-on galaxies NGC891 (Fig. 18), NGC5907 and NGC7331 shows fields near the galaxy plane which are predominantly oriented perpendicular to the plane (Fendt et al. 1996), possibly aligned along the vertical dust filaments observed in these galaxies. Radio continuum polarization, on the other hand, traces the magnetic fields in the diffuse medium which are mostly oriented parallel to the plane and have significant vertical components only beyond some height above the plane (section 4.7).

Correction of the diffuse optical polarization for scattering effects is difficult and has never been attempted so far. Instead, polarization techniques were developed in the infrared where scattering is negligible. Near-IR polarization in a dust lane of the edge-on galaxy NGC4565 indicates a plane-



parallel field (Jones 1989), similar to that seen at radio wavelengths. In the far-IR and sub-mm ranges, the emission of aligned dust grains is intrinsically polarized and the degrees of polarization can reach several %. The galaxy M82 was observed at 850  $\mu\text{m}$  (Greaves et al. 2000), but the derived bubble-type field pattern is in contrast to the radio data indicating a field that is oriented radially outwards (Reuter et al. 1992), while near-IR polarimetry shows a vertical field (Jones 2000). Potential differences between IR, sub-mm and radio polarization data should be investigated with the polarimeters at the JCMT, APEX, ALMA and SOFIA telescopes.



*Fig. 18: Edge-on spiral galaxy NGC891. E-vectors of optical polarization of the diffuse light, indicating vertical magnetic fields (Fendt et al. 1996). Compare with the radio polarization map in Fig. 41.*

Zeeman measurements in external galaxies are still very rare. Robishaw et al. (2008) detected the effect in the OH megamaser line at 18 cm in 5 distant starburst galaxies and derived field strengths in these dense gas clouds between 0.5 mG and 18 mG. Measurements in nearby galaxies will become possible with the Square Kilometre Array (section 5).

## 4.2 Magnetic field strengths

The dynamical importance of the total magnetic field  $B$  may be estimated by its energy density which is proportional to  $B^2$ . Due to its vector nature, the dynamical effect of the magnetic field also depends on its structure and degree of ordering (section 4.4). The average strength of the component  $B_{\perp}$  of the total field and  $B_{\text{ord},\perp}$  of the resolved ordered field in the plane of the sky can be derived from the total and polarized radio synchrotron intensity, respectively, if energy-density equipartition between total cosmic rays and total magnetic field  $B$  is valid (section 2.2). The field strengths  $B_{\perp}$  are given by the mean surface brightness (intensities) of synchrotron emission, hence do not depend on the distance to the galaxy.

The observed radio emission from galaxies has a contribution of thermal emission from ionized gas (and at frequencies beyond about 50 GHz also from dust) which needs to be subtracted to obtain the pure synchrotron part. The mean thermal fraction is about 10% at 21 cm and about 30% at 3 cm, but may increase to  $\geq 50\%$  in star-forming regions. A proper subtraction of the radio thermal intensity needs an independent thermal template, e.g. the H $\alpha$  intensity corrected for extinction with help of a dust model based on far-infrared data (Tabatabaei et al. 2007). For a crude separation of thermal and synchrotron intensity components, comparison of the observed radio spectral index with an assumed synchrotron spectral index is sufficient.

The average equipartition strength of the total field (corrected for inclination) for a sample of 74 spiral galaxies is  $B = 9 \pm 2 \mu\text{G}$  (Niklas 1995). The average strength of 21 bright galaxies observed since 2000 is  $B = 17 \pm 3 \mu\text{G}$  (Fletcher 2010). Dwarf galaxies host fields of similar strength as spirals if their star-formation rate per volume is similarly high. Blue compact dwarf galaxies are radio bright with

equipartition field strengths of 10–20  $\mu\text{G}$  (Klein et al. 1991). Spirals with moderate star-forming activity and moderate radio surface brightness like M31 (Fig. 26) and M33 (Fig. 36), our Milky Way’s neighbors, have  $B \approx 6 \mu\text{G}$ . In “grand-design” galaxies with massive star formation like M51 (Fig. 23), M83 (Fig. 24) and NGC6946 (Fig. 25),  $B \approx 15 \mu\text{G}$  is a typical average strength of the total field.

In the density-wave spiral arms of M51 the total field strength  $B$  is 25–30  $\mu\text{G}$  (Fig. 19). Field compression by external forces like interaction with other galaxies may amplify the fields (section 4.8). The strongest fields in spiral galaxies (50–300  $\mu\text{G}$ ) are found in starburst galaxies like M82 (Adebahr et al. 2013; Lacki & Beck 2013), the “Antennae” NGC4038/9 (Fig. 44), in nuclear starburst regions, like in the nuclear ring of NGC1097 (Fig. 35) and of other barred galaxies, and in nuclear jets (Fig. 49).

If energy losses of cosmic-ray electrons are significant in starburst regions or massive spiral arms, the equipartition values are lower limits (section 2.2). The average equipartition field strength in normal spirals is proportional to the average gas surface density, but this relation is no longer valid for starburst galaxies (Thompson et al. 2006). Due to strong energy losses of the cosmic-ray electrons and even protons, the equipartition field strength is probably underestimated by a factor of a few. Field strengths of 0.5–18 mG were detected in starburst galaxies by the Zeeman effect in the OH megamaser emission line at 18 cm (Robishaw et al. 2008). However, these values refer to highly compressed gas clouds and are not typical for the interstellar medium.

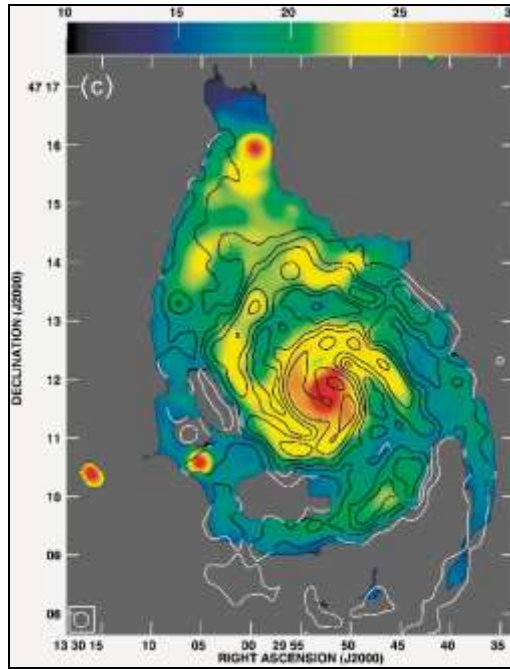


Fig. 19: Spiral galaxy M51. Total equipartition magnetic field strengths (in  $\mu\text{G}$ ), corrected for the inclination of the galaxy (Fletcher et al. 2011)

The relative importance of various competing forces in the interstellar medium can be estimated by comparing the corresponding energy densities. In the local Milky Way, the energy densities of the stellar radiation field, turbulent gas motions, cosmic rays, and total magnetic fields are similar (Boulares & Cox 1990). The mean energy densities of the total magnetic field and of the cosmic rays in NGC6946 and M33 are  $\approx 10^{-11} \text{ erg cm}^{-3}$  and  $\approx 10^{-12} \text{ erg cm}^{-3}$ , respectively (Beck 2007; Tabatabaei et al. 2008), similar to that of the turbulent motions of the cold, neutral gas with density  $\rho$  across the star-forming disk (Fig. 20). The turbulent energy may be underestimated if  $v_{\text{turb}}$  is larger than 7 km/s or if the warm gas also contributes. The energy density of the warm ionized gas  $E_{\text{th}}$  with electron density  $n_e$  is one order of magnitude smaller than that of the total magnetic field  $E_B$ , which means that the ISM in spiral galaxies is a *low- $\beta$  plasma* ( $\beta = E_{\text{th}}/E_B$ ), similar to that of the Milky Way (Boulares & Cox 1990). Hot gas also contributes to  $E_{\text{th}}$ , but its contribution is small. The overall dominance of turbulent energy is surprising because the supersonic turbulence should heat the gas, but is also derived from numerical ISM simulations (de Avillez & Breitschwerdt 2005). Further investigations with higher resolution are needed.

The radial distribution of synchrotron intensity in many spiral galaxies is well described by an exponential decrease with a scalelength  $l_{\text{syn}}$  of about 4 kpc. In case of equipartition between the energy densities of magnetic fields and cosmic rays, the scalelength of the total field is  $(3 - \alpha) l_{\text{syn}} \approx 16$  kpc (where  $\alpha \approx -1$  is the synchrotron spectral index). The scalelength of the ordered field is even larger (Fig. 20). These are still lower limits because energy losses of cosmic-ray electrons increase with increasing distance from their origin in the galaxy's star-forming regions, and a lower density of cosmic-ray electrons needs a stronger field to explain the observed synchrotron intensity. Fields in the outer disk of galaxies can be amplified by the  $\alpha$ - $\Omega$  dynamo even without star-formation activity because turbulence can be generated by the magneto-rotational instability (MRI, section 2.6). The typical scalelengths of the density of neutral and ionized gas are only about 3 kpc, so that the magnetic field energy dominates over the turbulent energy in the outer region of galaxies if a constant turbulent velocity is assumed (Fig. 20). The speculation that magnetic fields may affect the global gas rotation (Battaner & Florido 2000; Ruiz-Granados et al. 2010) needs testing by future radio observations with higher sensitivity and at low frequencies where energy loss of electrons is smaller.

In spiral arms of galaxies the typical degree of radio polarization is only a few %. The total field  $B_{\perp}$  in the spiral arms must be mostly *isotropic turbulent* with random orientations within the telescope beam, which typically corresponds to a few 100 pc at the distance of nearby galaxies. The typical ratios of isotropic turbulent fields to resolved ordered fields are  $\geq 5$  in spiral arms and circumnuclear starburst regions, 0.5–2 in interarm regions and 1–3 in radio halos. Turbulent fields in spiral arms are probably generated by turbulent gas motions due to supernovae (de Avillez & Breitschwerdt 2005) or by spiral shocks (Dobbs & Price 2008), driving a small-scale dynamo (section 2.6).

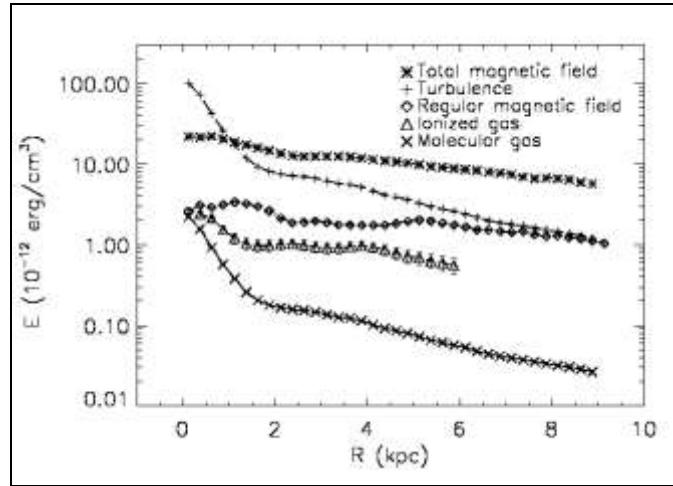


Fig. 20: Spiral galaxy NGC6946. Radial variation of the energy densities of the total magnetic field  $E_B$  ( $B^2/8\pi$ ), the ordered (mostly regular) magnetic field ( $B_{\text{reg}}^2/8\pi$ ), the turbulent motion of the neutral gas  $E_{\text{turb}}$  ( $0.5 \rho_n v_{\text{turb}}^2$ , where  $v_{\text{turb}} \approx 7$  km/s), the thermal energy of the ionized gas  $E_{\text{th}}$  ( $0.5 n_e k T_e$ ) and the thermal energy of the molecular gas  $E_n$  ( $0.5 \rho_n k T_n$ ), determined from observations of synchrotron and thermal radio continuum, and the CO and HI line emissions (Beck 2007).

Magnetic turbulence occurs over a large spectrum of scales. The maximum scale of the turbulence spectrum in the Milky Way derived from the dispersion of rotation measures of pulsars is  $d \approx 50$  pc (Rand & Kulkarni 1989). This scale can also be derived from the depolarization by the superposition of emission from turbulent fields at centimeter wavelengths (section 2.3). For a typical degree of polarization of 1% in spiral arms, 500 pc resolution in nearby galaxies and 1 kpc pathlength through the turbulent medium,  $d \approx 40 \text{ pc } f^{1/3}$  where  $f$  is the filling factor of the ionized medium. At decimeter radio wavelengths the same turbulent field causes Faraday dispersion (section 2.4). Typical depolarization of 50% at 20 cm, an average electron density of the thermal gas of  $0.03 \text{ cm}^{-3}$  and an average strength of the turbulent field of  $10 \mu\text{G}$  yields  $d \approx 10 \text{ pc } / f$ . The two estimates agree for  $d \approx 30$  pc and  $f \approx 0.3$ , consistent with the results derived with other methods.

Faraday dispersion can also be used to measure the strength of isotropic turbulent magnetic fields. However, the achievable accuracy is limited because the ionized gas density has to be determined from independent measurements. The increase of the mean degree of polarization at 1.4 GHz with

increasing distance from the plane of edge-on galaxies can constrain the parameters and, for NGC891 and NGC4631, yields strengths of the isotropic turbulent magnetic fields in the plane of 11  $\mu\text{G}$  and 7  $\mu\text{G}$  and scale heights of 0.9 kpc and 1.3 kpc, respectively (Hummel et al. 1991).

The strength of the *resolved ordered* (regular and/or anisotropic turbulent) fields  $B_{\text{ord}}$  in spiral galaxies is determined from the total equipartition field strength and the degree of polarization of the synchrotron emission. Present-day observations with typical spatial resolutions of a few 100 pc give average values of 1–5  $\mu\text{G}$ . The ordered field is generally strongest in the regions between the optical spiral arms with peaks of about 12  $\mu\text{G}$  e.g. in NGC6946, is oriented parallel to the adjacent optical spiral arms, and is stronger than the tangled field. In several galaxies like in NGC6946 the field forms coherent *magnetic arms* between the optical arms (Fig. 25). These are seen at all wavelengths and hence cannot be the effect of weak Faraday depolarization in the interarm regions. Magnetic arms are probably signatures of higher modes generated by the  $\alpha$ - $\Omega$  dynamo (section 4.4). In galaxies with strong density waves some of the ordered field is concentrated at the inner edge of the spiral arms, e.g. in M51 (Fig. 23), but the arm-interarm contrast of the ordered field is small, much less than that of the isotropic turbulent field. The ordered field in M51 is smoothly distributed.

The *regular* (coherent) component of the ordered field can in principle be determined from Faraday rotation measures (section 2.4), if the mean electron density is known. In the Milky Way, the pulsar dispersion measure is a good measure of the total electron content along the pathlength to the pulsar. Only 19 extragalactic radio pulsars have been found so far, all in the LMC and SMC. In all other galaxies, the only source of information on electron densities of the warm ionized medium comes from thermal emission, e.g. in the H $\alpha$  line. However, thermal emission is dominated by the HII regions which have a small volume filling factor, while Faraday rotation is dominated by the diffuse ionized emission with a much larger filling factor. If the average electron density of the diffuse ionized medium in the Milky Way of 0.03–0.05  $\text{cm}^{-3}$  is assumed also for other galaxies, Faraday rotation measures yield regular field strengths of a few  $\mu\text{G}$ . The strongest regular field of 8  $\mu\text{G}$  was found in NGC6946 (Beck 2007), similar to the strength of the ordered field, hence most of the ordered field is regular in this galaxy. The similarity between the average regular (RM-based) and the ordered (equipartition-based) field strengths in NGC6946 and several other galaxies demonstrates that both methods are reliable and hence no major deviations from equipartition occur in this galaxy on scales of a few kpc (but deviations may occur locally).

The situation is different in radio-bright galaxies like M51, where the average regular field strength is several times smaller than the ordered field (section 4.4). The total field is strong, so that the energy loss of cosmic-ray electrons is high and the equipartition field is probably underestimated (section 2.2). This even increases the discrepancy between the two methods because the RM is not affected. The high-resolution observations of M51 indicate that anisotropic turbulent fields related to the strong density waves contribute mostly to the ordered field.

### 4.3 The radio – infrared correlation

The highest total radio intensity (tracing the total, mostly turbulent field) generally coincides with the strongest emission from dust and gas in the spiral arms. The total radio and far-infrared (FIR) or mid-IR (MIR) intensities are highly correlated within galaxies. The exponent of the correlation is different in the spiral arms and the interarm regions (Dumas et al. 2011; Basu et al. 2012). The magnetic field and its structure play an important role to understand the correlation (Tabatabaei et al. 2013a). The scale-dependent correlations (using wavelets) between the radio synchrotron and IR emissions are strong at large spatial scales, but break down below a scale of a few 100 pc, which can be regarded as a measure of the electron diffusion length that seems to depend on the degree of field ordering (Tabatabaei et al. 2013b). Differences in typical electron ages between galaxies may also play a role (Murphy et al. 2008).

Synchrotron intensity depends on the density of cosmic-ray electrons, which are accelerated in supernova remnants and diffuse into the interstellar medium, and on about the square of the strength of the total magnetic field  $B_{\perp}$  (section 2.2). Infrared intensity between wavelengths of about 20  $\mu\text{m}$  and 70  $\mu\text{m}$  (emitted from warm dust particles in thermal equilibrium, heated mainly by UV photons) is a measure of the star-formation rate. (Below about 20  $\mu\text{m}$  wavelength, large PAH particles and stars contribute; emission beyond about 70  $\mu\text{m}$  comes from cold dust which is heated by the general radiation field.) Hence, the radio-infrared correlation can be interpreted as a correlation between the

strength of the isotropic turbulent field and the star-formation rate (Fig. 21). In NGC6946 this correlation has a smaller exponent of  $0.16 \pm 0.01$  (Tabatabaei et al. 2013a). In contrast, the ordered field in NGC4254 is uncorrelated with the star-formation rate and weakly anticorrelated in NGC6946 where the ordered field is strongest in interarm regions with low star-formation rates (Tabatabaei et al. 2013a, see also section 4.4).

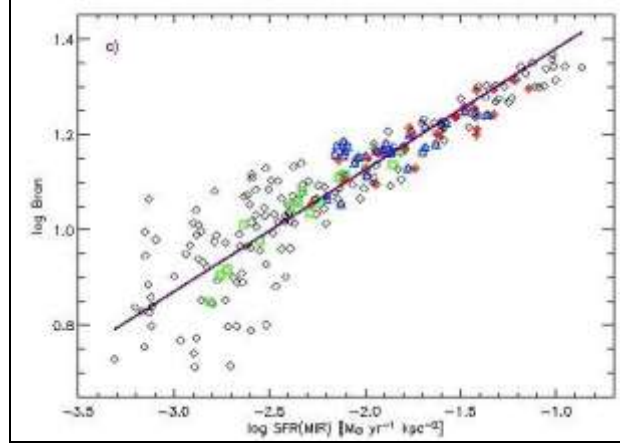


Fig. 21: Spiral galaxy NGC4254. Correlation between the strength of the isotropic turbulent equipartition field and the star-formation rate per area (determined from the  $24\ \mu\text{m}$  infrared intensities) within the galaxy, plotted on logarithmic scales. The slope of the fitted line gives an exponent of  $0.26 \pm 0.01$  (Chyży 2008).

The radio-IR correlation requires that magnetic fields and star-formation processes are connected. In the “calorimeter” model, valid for starburst galaxies with strong fields where energy losses of the cosmic-ray electrons are strong,  $B^2$  is assumed to increase with the infrared luminosity to obtain a linear radio-FIR correlation (Lisenfeld et al. 1996). In galaxies with low or medium star-formation rate (SFR), the cosmic-ray electrons can leave the galaxy and a combination of several processes with self-regulation is needed to explain the correlation within galaxies. If the dust is warm and optically thick to UV radiation, the IR intensity is proportional to the local SFR. Then, a possible scenario is the coupling of magnetic fields to the gas clouds ( $B \sim \rho^a$ , where  $\rho$  is the neutral gas density), the Schmidt-Kennicutt law of star formation ( $\text{SFR} \sim \rho^b$ ) (Niklas & Beck 1997). Depending on the values of the exponents  $a$  and  $b$  and whether or not equipartition between the energy densities of magnetic fields and cosmic rays is valid, a linear or nonlinear radio-IR correlation is obtained (Dumas et al. 2011; Basu et al. 2012).

The radio-IR correlation also holds between the integrated luminosities of galaxies, which is one of the tightest correlations known in astronomy. Its explanation involves many physical parameters. The tightness needs multiple feedback mechanisms which are not yet understood (Lacki et al. 2010). The correlation holds for starburst galaxies up to redshifts of at least 4, and the average radio/IR ratio increases towards high redshifts (Murphy 2009). The detection of strong radio emission in distant galaxies (which is at least partly of synchrotron origin) demonstrates that magnetic fields existed already in the early Universe. A breakdown of the correlation is expected when the Inverse Compton loss of the cosmic-ray electrons dominates the synchrotron loss; the redshift of the breakdown gives information about the field evolution in young galaxies (Schleicher & Beck 2013).

Future radio telescopes like the SKA will allow the investigation of magnetic fields in young galaxies and search for their first fields (section 5). Faraday rotation of polarized QSO emission in intervening galaxies also reveals magnetic fields in distant galaxies if they are regular on the spatial scale corresponding to the angular size of the background source. With this method, significant regular fields of several  $\mu\text{G}$  strengths on scales of about 10 kpc were discovered in galaxies up to redshifts of about 2 (Bernet et al. 2008; Kronberg et al. 2008). Detection of regular fields in young galaxies is a critical test of  $\alpha$ - $\Omega$  dynamo models (section 5).

## 4.4 Magnetic field structures in spiral galaxies

### 4.4.1 Ordered fields

At wavelengths  $\leq 6$  cm, Faraday rotation of the polarized synchrotron emission is generally small (except in central regions), so that the B-vectors directly trace the orientations of the ordered field (which can be regular or anisotropic turbulent, see section 2.3). Spiral patterns were found in almost every galaxy, even in those lacking optical spiral structure like the ringed galaxy NGC4736 (Fig. 22) and flocculent galaxies, while irregular galaxies show at most some patches of spiral structure (sections 4.6 and A.2). Spiral fields are also observed in the nuclear starburst regions of barred galaxies (section 4.5). Galaxies of type Sa and S0 and elliptical galaxies without an active nucleus have little star formation and hence produce only few cosmic rays that could emit synchrotron emission. The only deep observation of a Sa galaxy, M104 with a prominent dust ring, revealed weak, ordered magnetic fields (Krause et al. 2006).

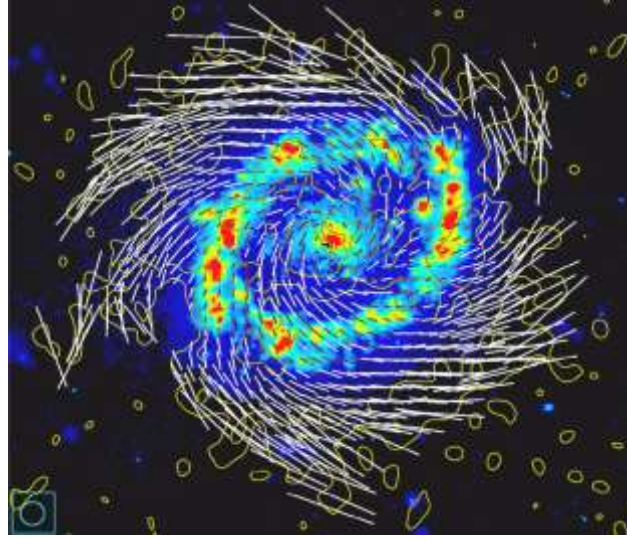


Fig. 22: Ring galaxy NGC4736. B-vectors of polarized radio intensity at 8.46 GHz (3.5 cm), observed with the VLA (Chyży & Buta 2008). The background  $H\alpha$  image is from Johan Hendrik Knapen (Inst. Astr. de Canarias).

The gas flow in “smooth” galaxies (no bar, no tidal interaction, no strong density wave) is almost circular, while the field lines are spiral and do *not* follow the gas flow. If large-scale magnetic fields were frozen into the gas, differential rotation would wind them up to very small pitch angles. The observed smooth spiral patterns with significant pitch angles ( $10^\circ$ – $40^\circ$ , see Fletcher 2010) indicate a general *decoupling* between magnetic fields and the gas flow due to magnetic diffusivity, which is a strong indication for  $\alpha$ - $\Omega$  dynamo action (section 2.6). There is no other model to explain the magnetic spiral patterns in many types of galaxies.

However, the spiral pattern of magnetic fields cannot be solely the result of  $\alpha$ - $\Omega$  dynamo action. In gas-rich galaxies with strong density waves, the magnetic spiral pattern generally follows the spiral pattern of the gas arms. In the prototypical density-wave galaxy M51, for example, the pitch angle of the magnetic lines is mostly similar to that of the cold gas in the inner galaxy, but deviations occur in the outer parts of the galaxy, where the tidal effects of the companion galaxy are strong (Patrikeev et al. 2006). In dynamo theory, the pitch angle of the magnetic lines depends on global parameters (section 2.6) and is difficult to adjust to the pitch angle of the spiral structure of the gas. In the outer galaxy, ordered fields coincide with the outer southern and south-western spiral arms; these are possibly tidal arms with strong shear. The north-eastern field deviates from the gas arm and points towards the companion, signature of the interaction.

If the beautiful spiral pattern of M51 seen in radio polarization (Fig. 23) is due to a regular field, it should be accompanied by a large-scale pattern in Faraday rotation, which is not observed. This means that most of the ordered field is *anisotropic turbulent* and probably generated by compression and shear of the non-axisymmetric gas flow in the density-wave potential. From an analysis of



dispersions of the radio polarization angles at 6.2cm in M51, Houde et al. (2013) measured a ratio of the correlation lengths parallel and perpendicular to the local ordered magnetic field of  $1.83 \pm 0.13$ . The anisotropic field is strongest at the positions of the prominent dust lanes on the inner edge of the inner gas spiral arms, due to compression of isotropic turbulent fields in the density-wave shock. Anisotropic fields also fill the interarm space, without signs of compression, probably generated by shearing flows. Regular fields also exist in M51 but are much weaker (see below).



Fig. 23: Spiral galaxy M51. Total radio intensity (contours) and B-vectors at 4.86 GHz (6.2 cm), combined from observations with the VLA and Effelsberg 100-m telescopes (Fletcher et al. 2011). The background optical image is from the HST (Hubble Heritage Team). Graphics: Sterne und Weltraum

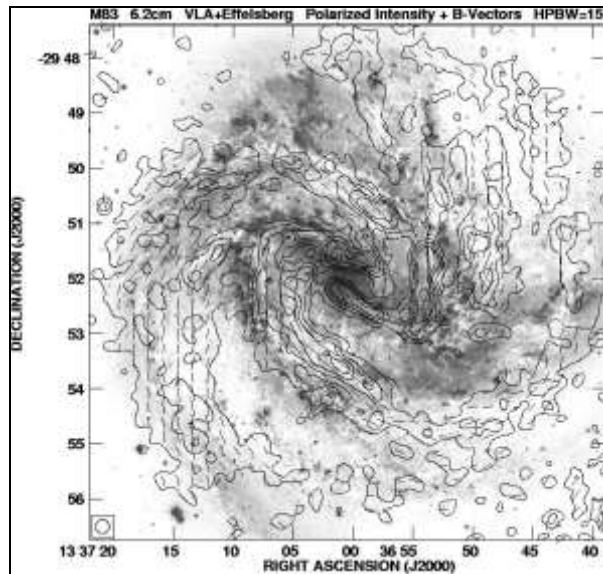


Fig. 24: Barred galaxy M83. Polarized radio intensity (contours) and B-vectors at 4.86 GHz (6.2 cm), combined from observations with the VLA and Effelsberg telescopes (Beck et al., unpublished). The background optical image is from Dave Malin (Anglo Australian Observatory).

M83 (Fig. 24) and NGC2997 (Han et al. 1999) are cases similar to M51, with enhanced ordered (anisotropic) fields at the inner edges of the inner optical arms, ordered fields in interarm regions and ordered fields coinciding with the outer optical arms. Density-wave galaxies with less star-formation activity, like M81 (Krause et al. 1989b) and NGC1566 (Ehle et al. 1996), show little signs of field compression and the ordered fields occur mainly in the interarm regions.

Observations of another gas-rich spiral galaxy, NGC6946, revealed a surprisingly regular distribution of polarized emission with two symmetric *magnetic arms* located in interarm regions, with orientations parallel to the adjacent optical spiral arms and no signs of compression at the inner edge of the gas arms (Fig. 25). Their degree of polarization is exceptionally high (up to 50%); the field is almost totally ordered and mostly regular, as indicated by Faraday rotation measures. With the higher sensitivity at 20 cm wavelength, more magnetic arms appear in the northern half of NGC6946, extending far beyond the optical arms, but located between outer HI arms. Magnetic arms have also been found in M83 (Fig. 24), NGC2997 and several other gas-rich spiral galaxies. Magnetic arms can be explained in the framework of dynamo models (section 2.6).

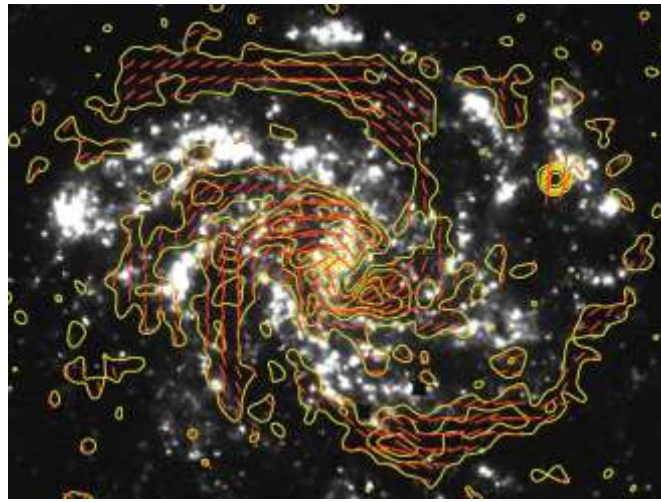


Fig. 25: Spiral galaxy NGC6946. Polarized radio intensity (contours) and B-vectors at 4.86 GHz (6.2 cm), combined from observations with the VLA and Effelsberg 100-m telescopes (Beck 2007). The background H $\alpha$  image is from Anne Ferguson. Graphics: Sterne und Weltraum

Ordered magnetic fields may also form spiral features that are disconnected from the optical spiral pattern. Long, highly polarized filaments were discovered in the outer regions of IC342 where only faint arms of HI line emission exist (Krause et al. 1989a). More recent observations at 20 cm revealed a system of such features extending to large distances from the center (Fig. 27).

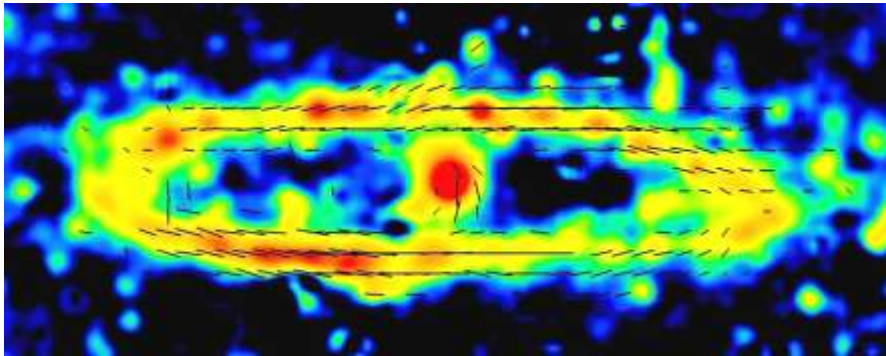


Fig. 26: Spiral galaxy M31. Total radio intensity (colors) and B-vectors (corrected for Faraday rotation) at 4.75 GHz (6.3 cm), observed with the Effelsberg telescope (Berkhuijsen et al. 2003)



In the highly inclined Andromeda galaxy, M31 (Fig. 26), the spiral arms are hard to distinguish due to the insufficient angular resolution. Star formation activity is concentrated to a limited radial range at around 10 kpc distance from the center (the “ring”). The ordered fields are strongest in the massive dust lanes where the degree of polarization is about 40%. The field follows the “ring” with a coherent direction (Fig. 29).

At wavelengths of around 20 cm, a striking asymmetry of the polarized emission occurs along the major axis of all 12 spiral galaxies observed so far with sufficiently high sensitivity that have inclinations of less than about  $60^\circ$ . The emission is almost completely depolarized by Faraday dispersion, e.g. in IC342 (Fig. 27) on one side of the major axis, which is always the kinematically *receding* one (positive radial velocities). In strongly inclined galaxies, both sides of the major axis become Faraday-depolarized at around 20 cm, as a result of the long pathlength. The asymmetry is still visible at 11 cm, but disappears at smaller wavelengths. This tells us that, in addition to spiral fields in the disk, fields in the halo are needed, as predicted by  $\alpha$ - $\Omega$  dynamo models (Urbanik et al. 1997; Braun et al. 2010; see section 4.7). The effect of such halo fields becomes prominent at 20 cm because most of the polarized emission from the disk is Faraday-depolarized (section 2.4). Testing by observations at longer wavelengths will soon become possible with LOFAR (section 5).

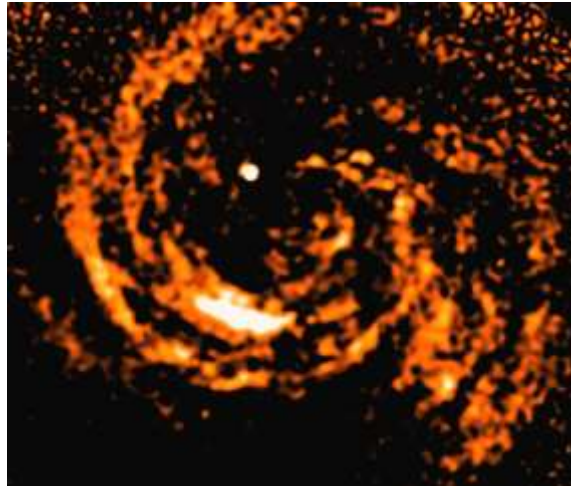


Fig. 27: Spiral galaxy IC342. Polarized radio intensity at 1.46 GHz (20.5 cm), combined from VLA C- and D-array observations. The field size is about  $30' \times 28'$ . The inner and north-western parts are depolarized at this wavelength (Beck, unpublished).

#### 4.4.2 Regular fields

Ordered magnetic fields as observed by polarized emission can be anisotropic (see above) or regular (with a coherent direction). *Faraday rotation measures* (RM) are signatures of such regular fields. RM is determined from multi-wavelength radio polarization observations (section 2.4). Spiral dynamo modes (section 2.6) can be identified from the periodicity of the azimuthal variation of RM in inclined galaxy disks (Fig. 28), where the RM can be determined from diffuse polarized emission (Krause 1990) or from RM data of polarized background sources (Stepanov et al. 2008). If several dynamo modes are superimposed, Fourier analysis of the RM variation is needed. The resolution of present-day observations is sufficient to identify not more than 2–3 modes.

The disks of a few spiral galaxies indeed reveal large-scale RM patterns giving strong evidence for modes generated by the  $\alpha$ - $\Omega$  dynamo. M31 is the prototype of a dynamo-generated magnetic field (Fig. 29). The discovery became possible thanks to the large angular extent and the high inclination of M31. The polarized intensity at 6 cm is largest near the minor axis where the field component  $B_\perp$  is largest (Fig. 30a), while the maxima in  $|RM|$  are observed near the major axis where the line-of-sight field component  $B_\parallel$  is strongest (Fig. 30b). This single-periodic RM variation is a clear signature of a dominating axisymmetric spiral (ASS) disk field (dynamo mode  $m = 0$ ) (Fletcher et al. 2004), which extends to at least 25 kpc distance from the center when observed with an *RM grid* (see below) (Han et al. 1998).

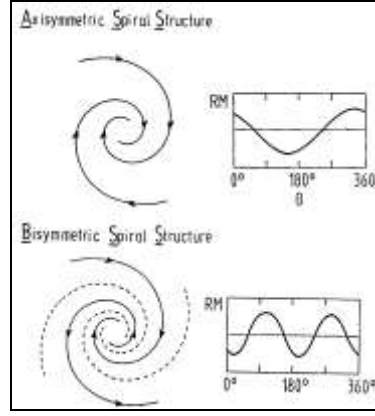


Fig. 28: Azimuthal RM variations (measured from the major axis) for axisymmetric spiral (ASS) and bisymmetric spiral (BSS) fields in inclined galaxies (Krause 1990)

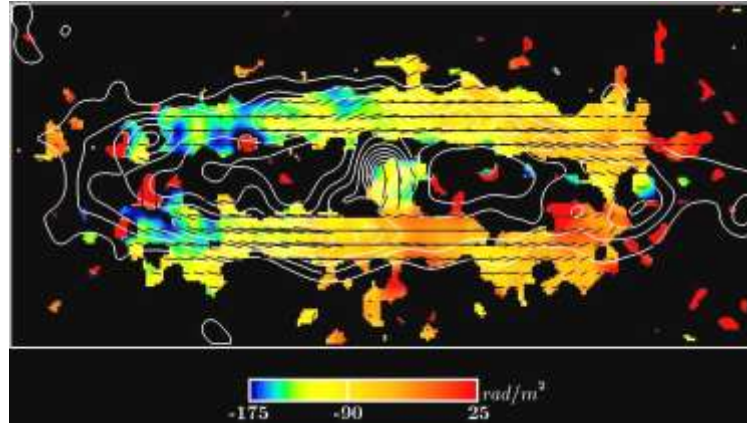


Fig. 29: Spiral galaxy M31. Total radio intensity at 4.75 GHz (6.3 cm) (contours), B-vectors and Faraday rotation measures between 4.75 GHz (6.3 cm) and 2.7 GHz (11.1 cm) (colors), derived from observations with the Effelsberg telescope (Berkhuijsen et al. 2003). The average rotation measure of about  $-90 \text{ rad/m}^2$  is caused by the foreground medium in the Milky Way.

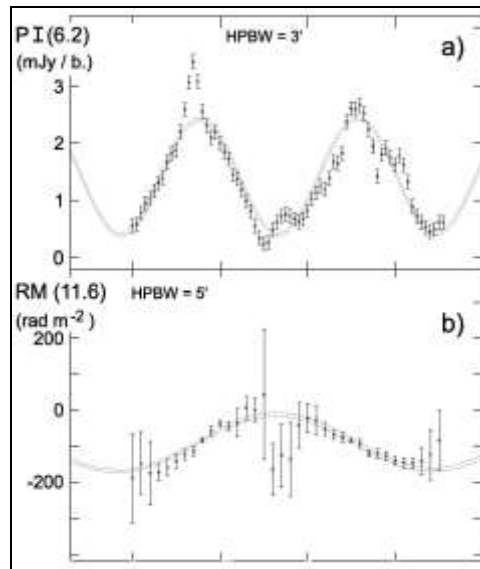


Fig. 30: Spiral galaxy M31. (a) Polarized intensity and (b) Faraday rotation measures between 4.75 GHz (6.3 cm) and 2.7 GHz (11.1 cm) along the azimuthal angle in the plane of the galaxy, counted counterclockwise from the northern major axis (left side in Fig. 29) (Berkhuijsen et al. 2003)

Other galaxies with a dominating ASS disk field are the nearby spiral IC342, the Virgo galaxy NGC4254, the almost edge-on galaxies NGC253, NGC891 and NGC5775, the irregular Large Magellanic Cloud (LMC) and a few further candidates (see Appendix).

By measuring the signs of the RM distribution and the velocity field on both sides of a galaxy's major axis, the *inward* and *outward* directions of the radial component of the ASS field can be easily distinguished (Fig. 31). Dynamo models predict that both signs have the same probability, which is confirmed by observations. The ASS fields of M31, IC342, NGC253 and the ASS field component in NGC6946 point inwards, while those of NGC4254, NGC5775 and the ASS component of the disk field in M51 point outwards.

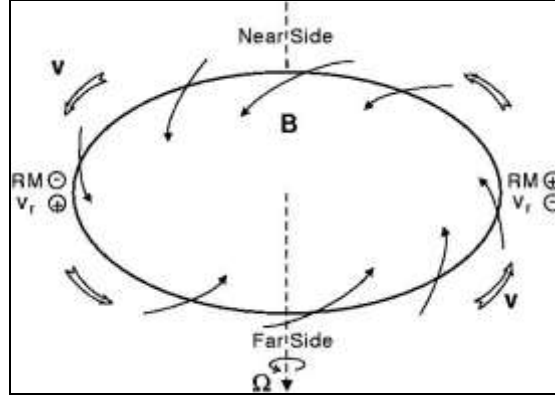


Fig. 31: The sign of the Faraday rotation measure  $RM$  and the sign of the rotation velocity component  $v_r$  along the line of sight, measured near the major axis of a galaxy, are opposite in the case of the inward direction of the radial component of an ASS-type field, while the signs are the same for the outward field direction. Trailing spirals are assumed (Krause & Beck 1998).

M81, M83 and an intervening galaxy at a redshift of 0.4 in front of the quasar PKS1229-021 (Kronberg et al. 1992) are the only candidates so far for a bisymmetric spiral (BSS) field ( $m = 1$ ), characterized by a double-periodic RM variation, but the data quality is limited in all these cases. Dominating BSS fields are rare, as predicted by dynamo models. It was proposed that tidal interaction can excite the BSS mode, but no preference for BSS was found even in the most heavily interacting galaxies in the Virgo cluster (section 4.8). The idea that galactic fields are wound-up primordial intergalactic fields that are of BSS type (section 2.6) can also be excluded from the existing observations.

Faraday rotation in NGC6946 (Fig. 32) and in other similar galaxies with magnetic arms can be described by a superposition of two azimuthal dynamo modes ( $m = 0$  and  $m = 2$ ) with about equal amplitudes, where the quadrisymmetric spiral (QSS)  $m = 2$  mode is phase shifted with respect to the density wave (Beck 2007). This model is based on the RM pattern of NGC6946 that shows different field directions in the northern and southern magnetic arm (Fig. 32). A weaker QSS mode superimposed onto the dominating ASS mode is indicated in the disk of M51 and in the inner part of M31. A superposition of ASS and BSS modes can describe the fields of M33 and NGC4254, while three modes (ASS+BSS+QSS) are needed for several other galaxies (Fletcher 2010; Appendix, Table 5).

In most galaxies observed so far, a spiral polarization pattern was found, but no large-scale RM pattern as a signature of regular fields. In many cases the available polarization data is insufficient to derive reliable RMs. In other cases the data quality is high but no large-scale RM patterns are visible. In density-wave galaxies, strong compression and shearing flows generate *anisotropic* fields (with frequent reversals) of spiral shape which are much stronger than the underlying regular field, like in M51 (see above). In galaxies without density waves, several dynamo modes may be superimposed but cannot be distinguished with the limited sensitivity and resolution of present-day telescopes. Another explanation is that the timescale for the generation of large-scale modes is longer than the galaxy's lifetime, so that the regular field is not fully organized and still restricted to small regions.

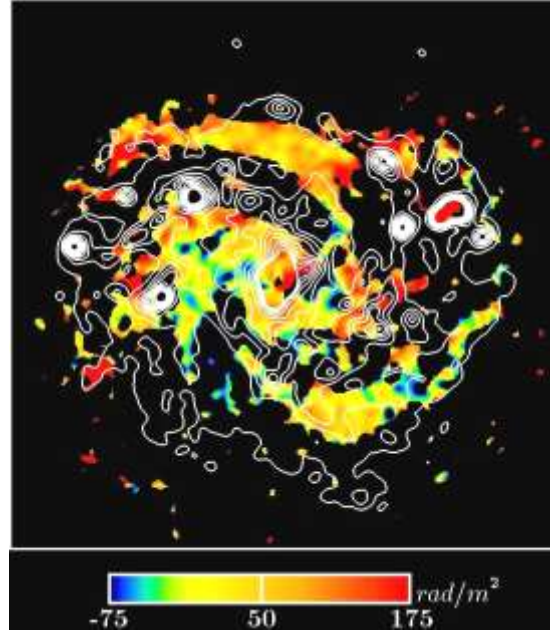


Fig. 32: Spiral galaxy NGC6946. Total radio intensity at 4.86 GHz (6.2 cm) (contours) and Faraday rotation measures between 8.46 GHz (3.5 cm) and 4.86 GHz (6.2 cm) (colors), derived from combined observations with the VLA and Effelsberg telescopes (Beck 2007). The average rotation measure of about  $+50 \text{ rad/m}^2$  is caused by the foreground medium in the Milky Way.

Large-scale *field reversals* were discovered from pulsar RMs in the Milky Way (section 3.5), but nothing similar has yet been detected in spiral galaxies, although high-resolution RM maps of Faraday rotation are available for many spiral galaxies. In M81 the dominating BSS field implies two large-scale reversals (Krause et al. 1989b). The disk fields of several galaxies can be described by a mixture of modes where reversals may emerge in a limited radial and azimuthal range of the disk, like in NGC4414 (Soida et al. 2002). However, no multiple reversals along the radial direction, like those in the Milky Way, were found so far in the disk of any external galaxy. A satisfying explanation is still lacking (section 3.5). Reversals on smaller scales are probably frequent but difficult to observe in external galaxies with the resolution of present-day telescopes. Only in the barred galaxy NGC7479, where a jet serves as a bright polarized background (Fig. 50), several reversals on 1–2 kpc scale were detected in the foreground disk of the galaxy (Laine & Beck 2008).

While the azimuthal symmetry of the dynamo modes is known for many galaxies, the vertical symmetry (*even* or *odd*) is much harder to determine. The RM patterns of even and odd modes are similar in mildly inclined galaxies. The toroidal field of odd modes reverses its sign above and below the galactic plane. Thus, in a mildly inclined odd field, half of the RM is observed compared to that in an even field, which cannot be distinguished in view of the large RM variations caused by ionized gas density and field strength. The symmetry type becomes only visible in strongly inclined galaxies, as a RM sign reversal above and below the plane. Only even-symmetry fields were found so far (in M31, NGC253, NGC891 and NGC5775), in agreement with the prediction of dynamo models (section 4.7).

If polarized emission is too weak to be detected, the method of *RM grids* towards polarized background QSOs can still be applied. This allows the determination of a large-scale field pattern in an intervening galaxy on the line of sight (Kronberg et al. 1992). Here, the distance limit is given by the polarized flux of the background QSO which can be much larger than that of the intervening galaxy, so that this method can be applied to much larger distances than the analysis of RM of the polarized emission from the foreground galaxy itself. At least 10 randomly distributed background sources behind the galaxy disk are needed to recognize simple patterns and several 1000 sources for a full reconstruction (Stepanov et al. 2008). Present-day observations are not sensitive enough, and one has to wait for the SKA and its precursor telescopes.

Ordered fields of nearby galaxies seen edge-on near the disk plane are preferably oriented parallel to the plane (section 4.7). As a result, polarized emission can be detected from distant, *unresolved* galaxies if they are symmetric (not distorted by interaction) and their inclination is larger than about  $20^\circ$  (Stil et al. 2009). This opens another method to search for ordered fields in distant galaxies. As the

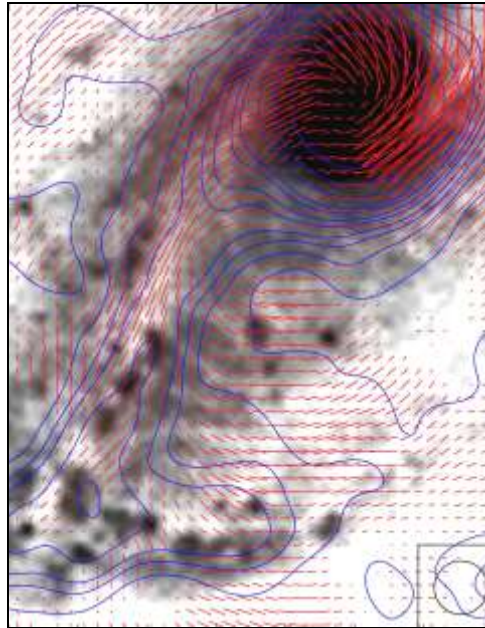
plane of polarization is almost independent of wavelength, distant spiral galaxies with known orientation of their major axis can also serve as background polarized sources to search for Faraday rotation by intergalactic fields in the foreground.

In summary, magnetic field structures in spiral galaxies are complex. The observations can best be explained as a superposition of dynamo-generated modes of regular fields coupled to the diffuse warm gas, plus anisotropic turbulent fields by shearing and compressing flows, plus isotropic turbulent fields coupled to the cold gas. The magnetic fields in barred galaxies behave similarly (section 4.5). For a more detailed model of the physics of the field-gas interaction, high-resolution data with future telescopes are required (section 5).

#### 4.5 Magnetic fields in barred galaxies

Gas and stars in the gravitational potential of strongly barred galaxies move in highly noncircular orbits. Numerical models show that gas streamlines are deflected in the bar region along shock fronts, behind which the cold gas is compressed in a fast shearing flow (Athanassoula 1992). The compression regions traced by massive dust lanes develop along the edge of the bar that is leading with respect to the galaxy's rotation because the gas rotates faster than the bar pattern. The warm, diffuse gas has a higher sound speed and is not compressed. According to simulations, the shearing flows around a bar should amplify magnetic fields and generate complicated field patterns changing with time (Otmianowska-Mazur et al. 2002). The asymmetric gas flow may also enhance dynamo action and excite the QSS ( $m = 2$ ) mode (Moss et al. 2001).

20 galaxies with large bars were observed with the Very Large Array (VLA) and with the Australia Telescope Compact Array (ATCA) (Beck et al. 2002; 2005a). The total radio luminosity (a measure of the total magnetic field strength) is strongest in galaxies with high far-infrared luminosity (indicating high star-formation activity), a result similar to that in non-barred galaxies. The average radio intensity, radio luminosity and star-formation activity all correlate with the relative bar length. Polarized emission was detected in 17 of the 20 barred galaxies. The pattern of the ordered field in the galaxies with long bars (NGC1097, 1365, 1559, 1672, 2442 and 7552) is significantly different from that in non-barred galaxies: Field enhancements occur outside of the bar (upstream), and the field lines are oriented at large angles with respect to the bar.



*Fig. 33: Southern half of the barred galaxy NCC1097. Total radio intensity (contours) and B-vectors at 8.46 GHz (3.5 cm), observed with the VLA (Beck et al. 2005a). The background optical image is from Halton Arp (Cerro Tololo Observatory).*



NGC1097 (Fig. 33) is one of the nearest barred galaxies and hosts a huge bar of about 16 kpc length. The total radio intensity (not shown in the figure) and the polarized intensity are strongest in the downstream region of the dust lanes (southeast of the center). This can be explained by a compression of isotropic turbulent fields in the bar's shock, leading to strong and anisotropic turbulent fields in the downstream region. The surprising result is that the polarized intensity is also strong in the upstream region (south of the center in Fig. 33) where RM data indicate that the field is regular. The pattern of field lines in NGC1097 is similar to that of the gas streamlines as obtained in numerical simulations (Athanasoulas 1992). This suggests that the ordered (partly regular) magnetic field is aligned with the flow and amplified by strong shear. Remarkably, the optical image of NGC1097 shows dust filaments in the upstream region which are almost perpendicular to the bar and thus aligned with the ordered field. Between the region upstream of the southern bar and the downstream region the field lines smoothly change their orientation by almost  $90^\circ$ . The ordered field is probably coupled to the diffuse gas and thus avoids being shocked in the bar. The magnetic energy density in the upstream region is sufficiently high to affect the flow of the diffuse gas.

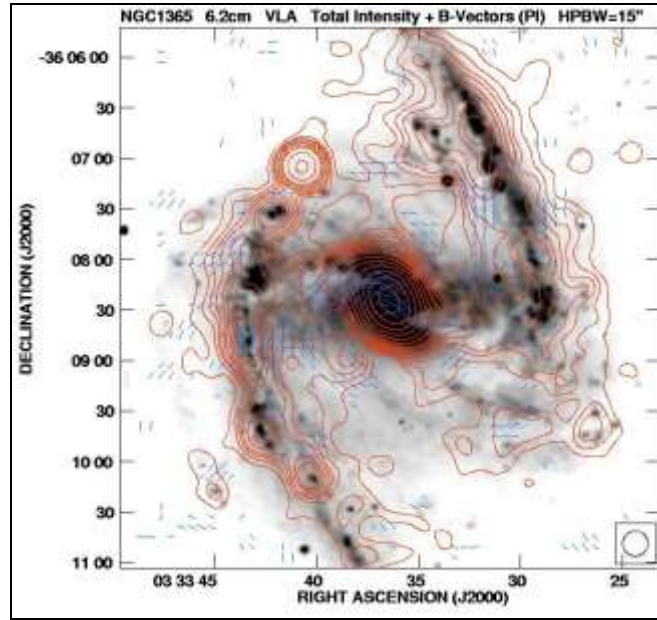


Fig. 34: Barred galaxy NGC1365. Total radio intensity (contours) and B-vector at 4.86 GHz (6.2 cm), observed with the VLA (Beck et al. 2005a). The background optical image is from Per Olof Lindblad (ESO).

NGC1365 (Fig. 34) is similar to NGC1097 in its overall properties, but the polarization data indicate that the shear is weaker. The ordered field bends more smoothly from the upstream region into the bar, again with no indication of a shock. M83 is the nearest barred galaxy but with a short bar; it shows compressed ordered fields at the leading edges of the bar on both sides of the nucleus and some polarization in the upstream regions (Fig. 24). In all other galaxies observed so far (section A.2) the resolution is insufficient to separate the bar and upstream regions.

The central regions of barred galaxies are often sites of ongoing intense star formation and strong magnetic fields that can affect the gas flow. Radio emission from ring-like regions has been found in NGC1097, NGC1672, and NGC7552 (Beck et al. 2005b). NGC1097 hosts a bright ring with about 1.5 kpc diameter and an active nucleus in its center (Fig. 35). The ordered field in the ring has a spiral pattern and extends towards the nucleus. The orientation of the innermost spiral field agrees with that of the spiral dust filaments visible on optical images. Magnetic stress in the circumnuclear ring can drive mass inflow at a rate of  $dM/dt = -h/\Omega (<b_r b_\phi> + B_r B_\phi)$ , where  $h$  is the scale height of the gas,  $\Omega$  its angular rotation velocity,  $b$  the strength of the turbulent field and  $B$  that of the ordered field, and  $r$  and  $\phi$  denote the radial and azimuthal field components (Balbus & Hawley 1998). For NGC1097,  $h \approx 100$  pc,  $v \approx 450$  km/s at 1 kpc radius,  $b_r \approx b_\phi \approx 50$   $\mu$ G gives an inflow rate of several  $M_\odot/\text{yr}$ , which is sufficient to fuel the activity of the nucleus (Beck et al. 2005a).

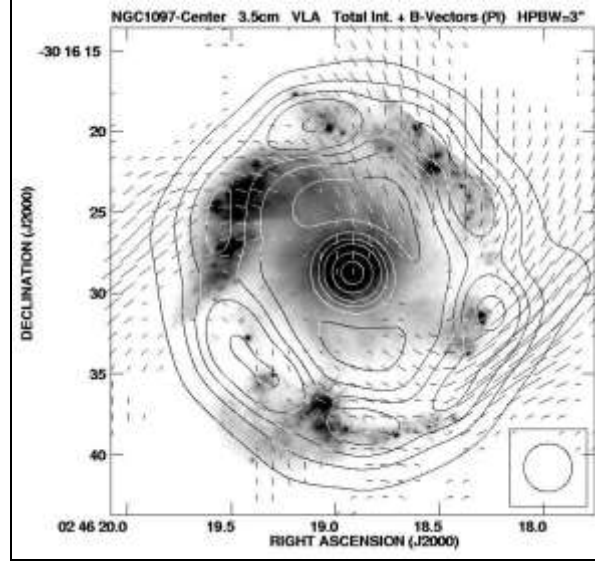


Fig. 35: Central star-forming ring of the barred galaxy NGC1097. Total radio intensity (contours) and B-vectors at 8.46 GHz (3.5 cm), observed with the VLA (Beck et al. 2005a). The background optical image is from the Hubble Space Telescope.

In summary, the isotropic turbulent field in galaxies with massive bars is coupled to the cold gas and compressed in the bar's shock. The ordered field outside the bar region follows the general flow of the cold and warm gas, possibly due to shear, but decouples from the cold gas in front of the shock and goes with the diffuse warm gas. The polarization pattern in barred galaxies can be used a tracer of the flow of diffuse gas in the sky plane and hence complements spectroscopic measurements of radial velocities. Detailed comparisons between polarimetric and spectroscopic data are required, as well as MHD models including the back-reaction of the magnetic fields onto the gas flow.

Radio polarization data have revealed differences but also similarities between the behaviours of ordered magnetic fields in barred and non-barred galaxies. In galaxies without bars and without strong density waves the field lines have a spiral shape, they do not follow the gas flow and are probably amplified by dynamo action. In galaxies with massive bars or strong density waves the field lines mostly follow the flow of the diffuse warm gas. Near the shock fronts galaxies with strong bars and with strong density waves (section 4.4) reveal a similar behaviour: Isotropic turbulent fields are coupled to the cold gas, are shocked and become anisotropic turbulent, while regular fields are coupled to the warm diffuse gas and hence avoid the shock.

#### 4.6 Flocculent and irregular galaxies

*Flocculent* galaxies have disks but no prominent spiral arms. Nevertheless, spiral magnetic patterns are observed in all flocculent galaxies, indicative that the  $\alpha$ - $\Omega$  dynamo works independently of density waves. The multi-wavelength data of M33 and NGC4414 call for a mixture of dynamo modes or an even more complicated field structure (Appendix, Table 5). Ordered magnetic fields with strengths similar to those in grand-design spiral galaxies have been detected in the flocculent galaxies M33 (Fig. 36), NGC3521, NGC5055 and in NGC4414, and also the mean degree of polarization is similar between grand-design and flocculent galaxies (Knapik et al. 2000).

Radio continuum maps of *irregular*, slowly rotating galaxies may reveal strong total equipartition magnetic fields, e.g. in the Magellanic-type galaxy NGC4449 (Fig. 37) and in IC10 (Fig. 38). In NGC4449 some fraction of the field is ordered with about 7  $\mu$ G strength and a spiral pattern. Faraday rotation shows that this ordered field is partly regular and the  $\alpha$ - $\Omega$  dynamo is operating in this galaxy. The total field is of comparable strength (10-15  $\mu$ G) in starburst dwarfs like NGC1569 (Kepley et al. 2010) where star formation activity is sufficiently high for the operation of the small-scale dynamo (section 2.6). In these galaxies the energy density of the magnetic fields is only slightly smaller than that of the (chaotic) rotation of the gas and thus may affect the evolution of the whole system. The starburst dwarf galaxy NGC1569 shows polarized emission, but no large-scale regular field. In dwarf galaxies with very weak star-forming activity, no polarized emission is detected and the isotropic

turbulent field strength is several times smaller than in spiral galaxies (Chyży et al. 2011), sometimes less than  $5 \mu\text{G}$  (Chyży et al. 2003). The latter value may indicate a sensitivity limit of present-day observations or a threshold for small-scale dynamo action.

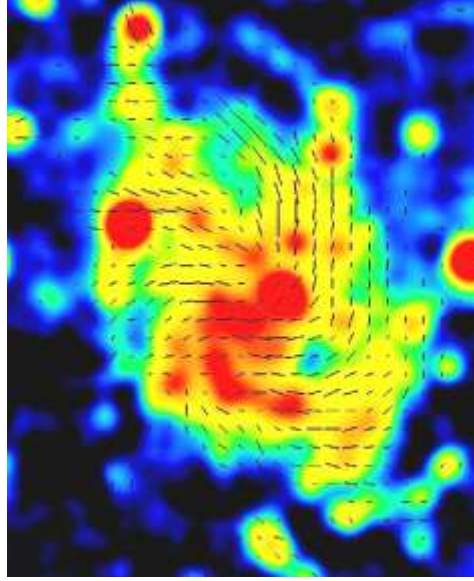


Fig. 36: Flocculent galaxy M33. Total radio intensity (colors) and B-vectors of the flocculent galaxy at 8.35 GHz (3.6 cm), observed with the Effelsberg telescope (Tabatabaei et al. 2008)

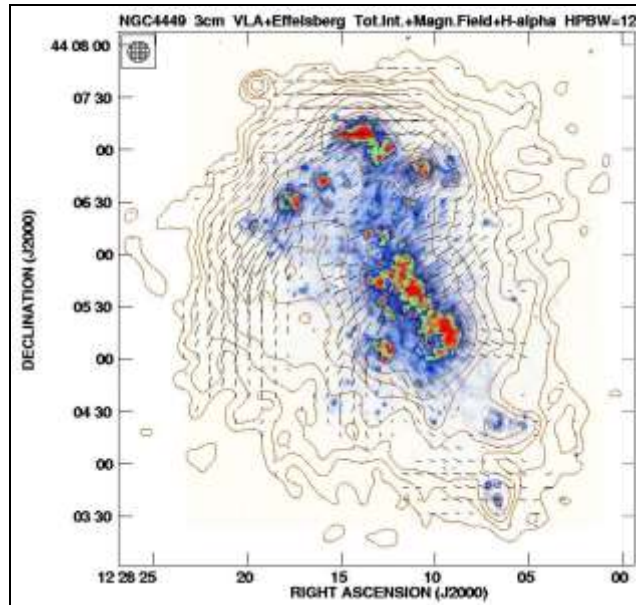


Fig. 37: Magellanic-type galaxy NGC4449. Total radio intensity (contours) and B-vectors at 8.46 GHz (3.5 cm), combined from VLA and Effelsberg observations (Chyży et al. 2000). The background image shows the H $\alpha$  emission.

The Magellanic Clouds are the closest irregular galaxies and deserve special attention. Polarization surveys with the Parkes single-dish telescope at several wavelengths had low angular resolution and revealed weak polarized emission. Two magnetic filaments were found in the LMC south of the 30 Dor star-formation complex (Klein et al. 1993). ATCA surveys of an RM grid towards background sources show that the LMC probably contains a large-scale magnetic field similar to large spirals (Gaensler et al. 2005) and that the field of the SMC is weak and uniformly directed away from us, possibly part of a pan-Magellanic field joining the two galaxies (Mao et al. 2008).



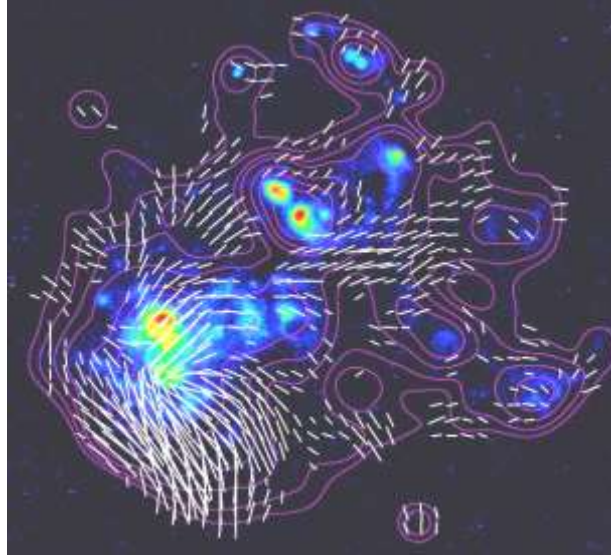


Fig. 38: Irregular galaxy IC10. Total radio intensity (contours) and B-vectors at 4.86 GHz (6.2 cm), observed with the VLA (from Chris Chyży, Kraków University). The background H $\alpha$  image is from Dominik Bomans (Bochum University).

#### 4.7 Radio halos

Radio halos are observed around the disks of most edge-on galaxies, but their radio intensity and extent varies significantly. The halo luminosity in the radio range correlates with those in H $\alpha$  and X-rays (Tüllmann et al. 2006), although the detailed halo shapes vary strongly between the different spectral ranges. These results suggest that star formation in the disk is the energy source for halo formation and the halo size is determined by the energy input from supernova explosions per surface area in the projected disk (Dahlem et al. 1995).

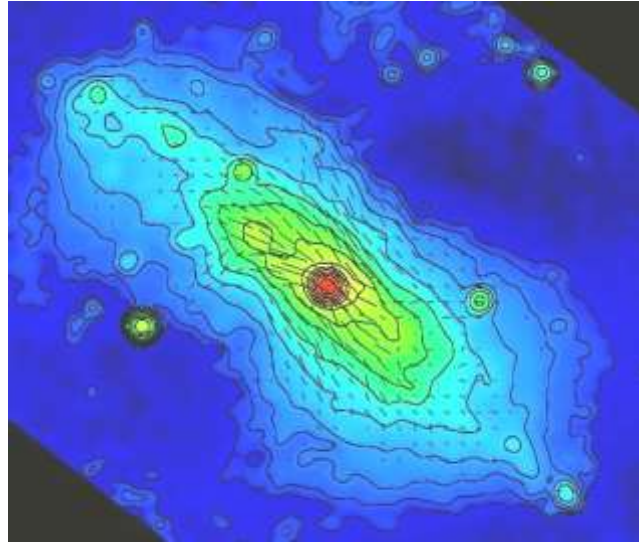


Fig. 39: Almost edge-on spiral galaxy NGC253. Total radio intensity (contours) and B-vectors at 4.86 GHz (6.2 cm), combined from observations with the VLA and the Effelsberg telescope (Heesen et al. 2009b)

In spite of the different intensities and extents of radio halos, their exponential scale heights at 5 GHz are about 1.8 kpc (Dumke & Krause 1998; Heesen 2009a), with a surprisingly small scatter in the sample, ranging from one of the weakest halos, NGC4565, to the brightest ones known, NGC253 (Fig. 39) and NGC891 (Fig. 41). In case of equipartition between the energy densities of magnetic field and

cosmic rays, the exponential scale height of the total field is at least  $(3 - \alpha)$  times larger than the synchrotron scale height (where  $\alpha \approx -1$  is the synchrotron spectral index),  $\geq 7$  kpc. The real value depends on the energy losses of the cosmic-ray electrons propagating into the halo (section 2.2). A prominent exception is NGC4631 with the largest radio halo observed so far (Fig. 42). With large scale heights, the magnetic energy density in halos is much higher than that of the thermal gas, while still lower than that of the dominating kinetic energy of the gas outflow.

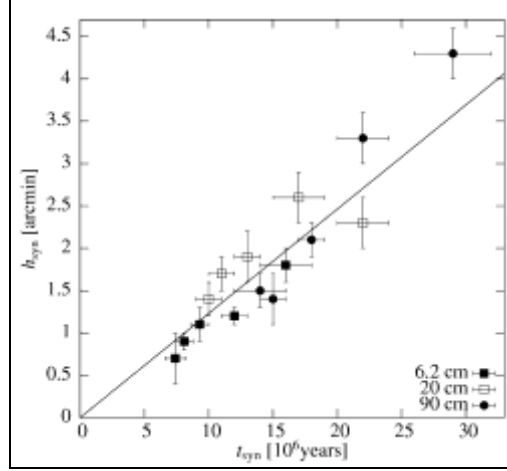


Fig. 40: Synchrotron scaleheights of the northern radio halo of NGC253 at different distances from the center and at different wavelengths, as a function of synchrotron lifetime of cosmic-ray electrons. The slope of the linear fit corresponds to a bulk outflow speed of about 300 km/s (Heesen et al. 2009a).

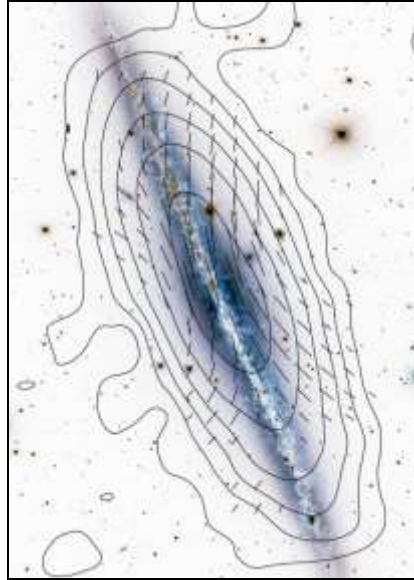


Fig. 41: Edge-on spiral galaxy NGC891. Total radio intensity (contours) and B-vectors at 8.35 GHz (3.6 cm), observed with the Effelsberg telescope (Krause 2009). The background optical image is from the CFHT.

Radio halos grow in size with decreasing observation frequency. The extent is limited by energy losses of the cosmic-ray electrons, i.e. synchrotron, inverse Compton and adiabatic losses (Heesen et al. 2009a). The stronger magnetic field in the central region causes stronger synchrotron loss, leading to the “dumbbell” shape of many radio halos, e.g. around NGC253 (Fig. 39). From the radio scale heights of NGC253 at three frequencies and the electron lifetimes (due to synchrotron, inverse Compton and adiabatic losses) an outflow bulk speed of about 300 km/s was measured (Fig. 40). The similarity of the scale height of the radio halos around most edge-on galaxies observed so far, in spite of the different field strengths and hence different electron lifetimes, indicates that the outflow speed

increases with the average strength of the total field and with the star-formation rate (Krause 2009). Outflows slower than the escape velocity are often called *fountain flows*, while escaping flows are *galactic winds*.

Radio polarization observations of nearby galaxies seen edge-on generally show a disk-parallel field near the disk plane (Dumke et al. 1995). High-sensitivity observations of several edge-on galaxies like NGC253 (Fig. 39), NGC891 (Fig. 41), NGC5775 (Tüllmann et al. 2000, Soida et al. 2011) and M104 (Krause et al. 2006) revealed vertical field components which increase with increasing height above and below the galactic plane and also with increasing radius, the so-called *X-shaped* halo fields. The X-pattern is even seen in NGC4565 with its low star-formation rate and a radio-faint halo, thus this pattern seems to be a general phenomenon.

The observation of X-shaped field patterns is of fundamental importance to understand the field origin in halos. The field is probably transported from the disk into the halo by an outflow emerging from the disk. The X-shaped halo field is consistent with the predictions from  $\alpha$ - $\Omega$  dynamo models if outflows with moderate velocities are included (section 2.6). Numerical models (neglecting magnetic fields) indicate that global gas outflows from the disks of young galaxies can also be X-shaped due to pressure gradients (Dalla Vecchia & Schaye 2008). MHD models are still lacking.

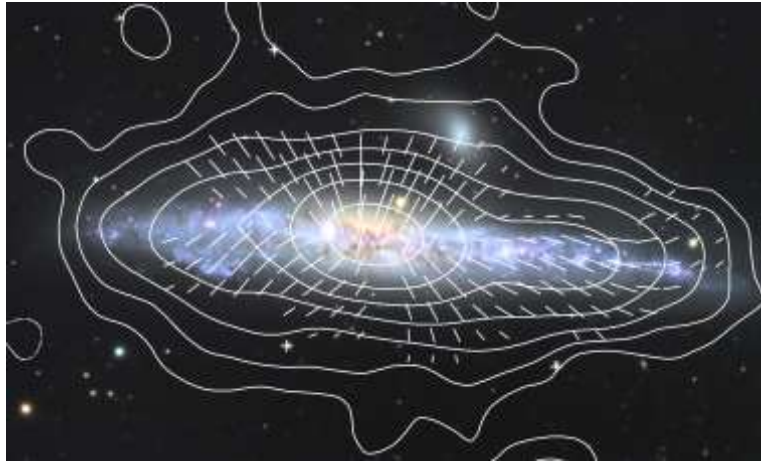
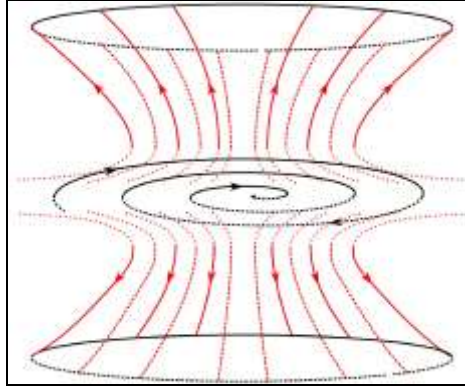


Fig. 42: Edge-on irregular galaxy NGC4631. Total radio intensity (contours) and B-vector at 8.35 GHz (3.6 cm), observed with the Effelsberg telescope (Krause 2009). The background optical image is from the Misti Mountain Observatory.

The exceptionally large radio halos around the irregular and interacting galaxies M82 (Reuter et al. 1992) and NGC4631 (Fig. 42) exhibit X-shaped halo fields with almost radial orientations in their inner regions. This indicates that the wind transport is more efficient here than in spiral galaxies. The small gravitational potential of irregular galaxies or external forces by neighboring galaxies may be responsible for high outflow velocities. The  $\alpha$ - $\Omega$  dynamo cannot operate under such conditions. The radio halos of M82 and NGC4631 were resolved into a few magnetic spurs, emerging from star-forming regions in the disk (Golla & Hummel 1994). These observations also support the idea of a fast galactic outflow which is driven by regions of star formation activity in the disk. The outflow cone of the starburst galaxy NGC253 hosts a helical magnetic field (Heesen et al. 2011).

Polarization "vectors" do not distinguish between halo fields which are sheared into elongated loops or regular dynamo-type fields. A large-scale regular field can be measured only by Faraday rotation measures (RM) (section 2.4). RM patterns are very hard to measure in halos, because the field components along the line of sight are small. The detailed analysis of the multi-frequency observations of the highly inclined galaxy NGC253 (Fig. 39) allowed to identify an axisymmetric disk field with even symmetry and an X-shaped halo field, also of even symmetry (Fig. 43). The combined analysis of RMs of the diffuse emission and extragalactic sources revealed an even-symmetry halo field in the LMC (Mao et al. 2012). The polarization asymmetry along the major axis observed around 20 cm in all spiral galaxies with less than 60° inclination observed so far gives further evidence that galaxies host even-parity fields (Urbanik et al. 1997; Braun et al. 2010; Vollmer et al. 2013).

Dynamo models for thin galaxy disks predict fields of even symmetry, in the simplest case a poloidal component of quadrupolar shape (section 2.6). The vertical component of such a quadrupolar field is largest near the rotation axis and decreases with distance from the rotation axis. Such an effect is possibly seen in NGC4631 (Fig. 42), while in several other edge-on galaxies the vertical field component *increases* with increasing distance from the rotation axis, giving rise to X-shapes. Furthermore, the field strength of a pure quadrupole-type field decreases rapidly with distance from the center (e.g. Prouza & Šmída 2003), while the observed radial profiles of polarized emission show a slow exponential decrease. The field structure cannot be a pure quadrupole. For example, dynamo models including winds can generate X-shaped fields (section 2.6).



*Fig. 43: Model of the symmetric (outwards-directed) halo field of NGC253. The spiral disk field is also symmetric with respect to the plane (from Heesen et al. 2009b).*

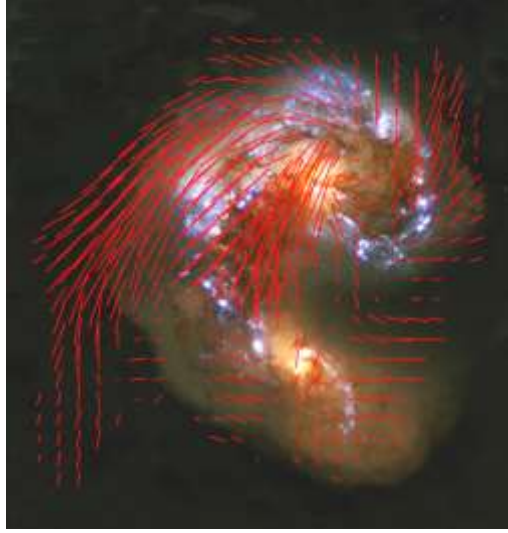
In summary, the detection of X-shaped fields in all galaxies observed so far can be explained by dynamo action and/or outflows. If outflows are a general phenomenon in galaxies, they can magnetize the intergalactic medium (IGM). Starburst dwarf galaxies in the early Universe were especially efficient in magnetizing the IGM. The extent of magnetic fields into the IGM is not yet visible. Energy losses of the cosmic-ray electrons prevent the emission of radio waves beyond some height while magnetic fields may still exist much further outwards. Low-energy electrons live longer, can propagate further into the IGM and emit synchrotron emission at low frequencies (section 2.2). Forthcoming observations with the Low Frequency Array (LOFAR) may reveal larger radio halos (section 5).

#### 4.8 Interacting galaxies

Gravitational interaction between galaxies leads to asymmetric gas flows, compression, shear, enhanced turbulence, and outflows. Compression and shear of gas flows can also modify the structure of galactic and intergalactic magnetic fields. In particular, fields can become aligned along the compression front or perpendicular to the velocity gradients. Such gas flows make turbulent fields highly anisotropic.

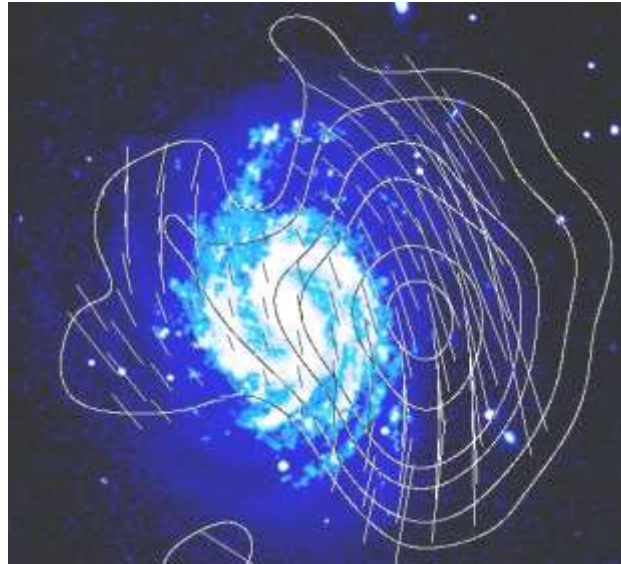
The classical interacting galaxy pair is NGC4038/39, the “Antennae” (Fig. 44). It shows bright, extended radio emission filling the volume of the whole system, with no dominant nuclear sources. In the interaction region between the galaxies, where star formation did not yet start, and at the northeastern edge of the system, the magnetic field is partly ordered, probably the result of compression and shearing motions along the tidal tail, respectively. Particularly strong, almost unpolarized emission comes from a region of violent star formation, hidden in dust, at the southern end of a dense cloud complex extending between the galaxies. In this region, highly turbulent magnetic fields reach strengths of  $\approx 30 \mu\text{G}$ . The mean total magnetic field is stronger than in normal spirals, but the mean degree of polarization is unusually low, implying that the ordered field, generated by compression, has become tangled in the region with violent star formation. After an interaction, the magnetic field strength in a galaxy decreases again to its normal value (Drzazga et al. 2011).





*Fig. 44: “Antennae” galaxy pair NGC4038/39. B-vectors of polarized radio intensity at 4.86 GHz (6.2 cm), observed with the VLA (Chyży & Beck 2004). The background optical image is from the Hubble Space Telescope.*

Interaction with a dense intergalactic medium also imprints unique signatures onto magnetic fields and thus the radio emission. The Virgo cluster is a location of especially strong interaction effects, and almost all cluster galaxies observed so far show asymmetries of their polarized emission (Appendix, Table 7). In NGC4254, NGC4522 and NGC4535 (Fig. 45), the polarized emission on one side of the galaxy is shifted towards the edge of the spiral arm, an indication for shear by tidal tails or ram pressure by the intracluster medium. The heavily disrupted galaxy NGC4438 (Vollmer et al. 2007) has almost its whole radio emission (total power and polarized) displaced towards the giant elliptical M86 to which it is also connected by a chain of H $\alpha$ -emitting filaments.



*Fig. 45: Spiral galaxy NGC4535 in the Virgo cluster. Polarized radio intensity (contours) and B-vectors at 4.75 GHz (6.3 cm), observed with the Effelsberg telescope (Weżgowiec et al. 2007). The background optical image is from the Digital Sky Survey.*

Interaction may also induce violent star-formation activity in the nuclear region or in the disk which may produce huge radio lobes due to outflowing gas and magnetic field. The lobes of the Virgo spiral NGC4569 reach out to at least 24 kpc from the disk and are highly polarized (Fig. 46). However, there is neither an active nucleus nor a recent starburst in the disk, so that the radio lobes are probably the result of nuclear activity in the past.

Tidal interaction is also the probable cause of the asymmetric appearance of NGC3627 within the Leo Triplet (Fig. 47). While the ordered field in the western half is strong and precisely follows the dust lanes, a bright magnetic arm in the eastern half crosses the optical arm and its massive dust lane at a large angle. No counterpart of this feature was detected in any other spectral range. Either the optical arm was recently deformed due to interaction or ram pressure, or the magnetic arm is an out-of-plane feature generated by interaction.

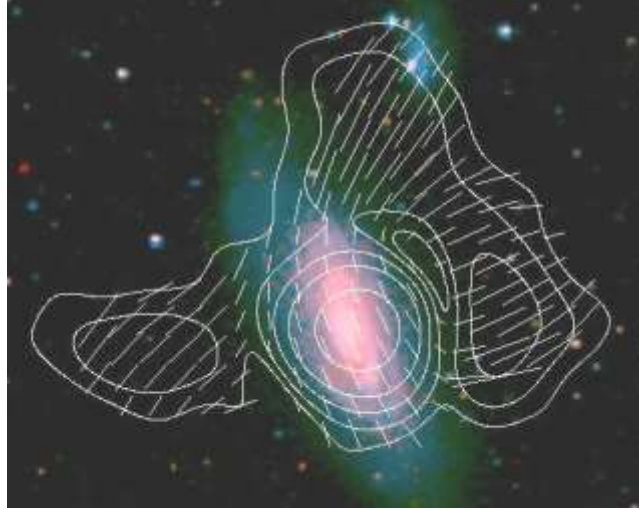


Fig. 46: Spiral galaxy NGC4569 in the Virgo cluster. Polarized radio intensity (contours) and B-vectors at 4.75 GHz (6.3 cm), observed with the Effelsberg telescope (Chyży et al. 2006). The background optical image is from the Digital Sky Survey.

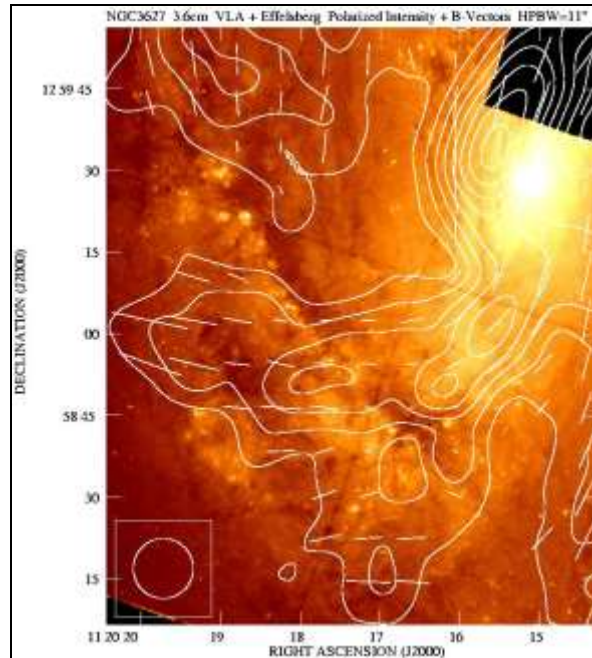


Fig. 47: Interacting spiral galaxy NGC3627. Polarized radio intensity (contours) and B-vectors at 8.46 GHz (3.5 cm), combined from observations with the VLA and Effelsberg telescopes (Soida et al. 2001). The background optical image is from the Hubble Space Telescope.

In a few cases a radio and gaseous bridge has been found between colliding galaxies. The radio emission is due to relativistic electrons pulled out from the disks together with gas and magnetic fields. This phenomenon (called “taffy galaxies”) seems to be rare because only 2 objects, UGC12914/5 and



UGC813/6, were found so far (Condon et al. 2002; Drzazga et al. 2011). This may be due to the steep spectrum of the bridges, making them invisible at centimeter wavelengths in weaker objects.

In compact galaxy groups tidal interactions may trigger rapid star formation in one or more member galaxies, causing supersonic outflows of hot gas. Some compact groups have long HI tails, indicating strong, tidally-driven outflows of the neutral gas from the system. If the expelled gas was magnetized it might provide the supply of magnetic fields into the intergalactic space. Starburst galaxies (either dwarf and massive) constitute the basic source responsible for the enrichment of the intra-group medium with relativistic particles and magnetic fields. There are grounds to expect that the compact galaxy groups show diffuse radio emission, with a spectrum rapidly steepening away from the cosmic-ray sources in galactic disks.

The best studied example of a compact group is Stephan's Quintet (at a distance of 85 Mpc), with its pool of hot gas extending between the galaxies (Nikiel-Wroczyński et al. 2013b). It shows a huge, long filament visible in radio continuum. Strong polarization of this intra-group emission (Fig. 48) indicates a substantial content of ordered (probably shock-compressed) magnetic fields.

In summary, polarized radio emission is an excellent tracer of tidal effects between galaxies and of ram pressure in the intracluster medium. As the decompression and diffusion timescales of the field are very long, it keeps memory of events in the past, up to the lifetime of the illuminating cosmic-ray electrons. Low-frequency radio observations will trace interactions that occurred many Gyr ago and are no longer visible in other spectral ranges. Tidal tails from interacting galaxies may also constitute a significant source of magnetic fields in the intracluster and intergalactic media.



*Fig. 48: Stephan's Quintet of interacting galaxies. Total radio intensity (contours) and B-vectors at 4.86 GHz (6.2 cm), observed with the VLA (from Marian Soida, Kraków University). The background optical image is from the Hubble Space Telescope.*

#### 4.9 Galaxies with jets

Nuclear jets are observed in several spiral galaxies. These jets are weak and small compared to those of radio galaxies and quasars. Detection is further hampered by the fact that they emerge at some angle with respect to the disk, so that little interaction with the ISM occurs. Only if the accretion disk is oriented almost perpendicular to the disk, the jet hits a significant amount of ISM matter, cosmic-ray electrons are accelerated in shocks, and the jet becomes radio-bright. This geometry was first proven for NGC4258 by observations of the water maser emission from the accretion disk (Greenhill et al. 1995). This is why NGC4258 is one of the rare cases where a large radio jet of at least 15 kpc length is observed (van Albada & van der Hulst 1982; Krause & Löhr 2004). The total intensity map of

NGC4258 (Fig. 49) reveals that the jets emerge from the Galactic center perpendicular to the accretion disk, which is oriented in east-west direction and is seen almost edge-on, and bend out to become the "anomalous radio arms", visible out to the boundaries of the spiral galaxy. The magnetic field orientation is mainly along the jet direction. The observed tilt with respect to the jet axis may indicate an additional toroidal field component or a helical field around the jet. The equipartition field strength is about  $300 \mu\text{G}$  (at the resolution of about  $100 \text{ pc}$ ), which is a lower limit due to energy losses of the cosmic-ray electrons and the limited resolution.

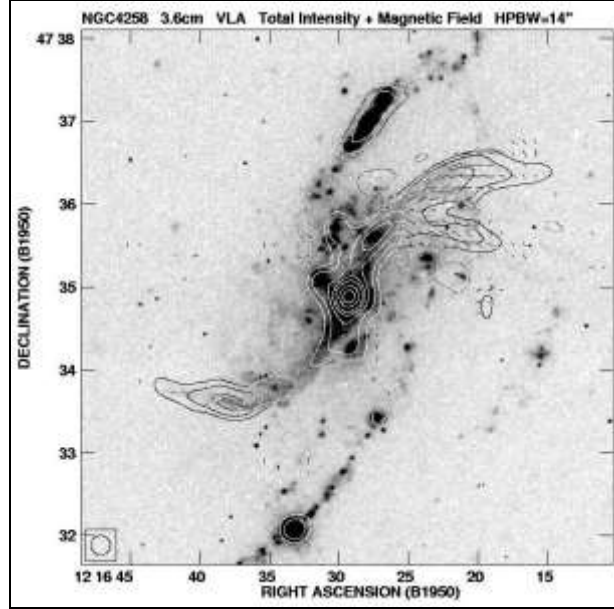


Fig. 49: Spiral galaxy NGC4258 with two jets. Total radio intensity (contours) and  $B$ -vectors at 8.46 GHz (3.5 cm), observed with the VLA (Krause & Löhrr 2004). The background  $H\alpha$  image is from the Hoher List Observatory of the University of Bonn.

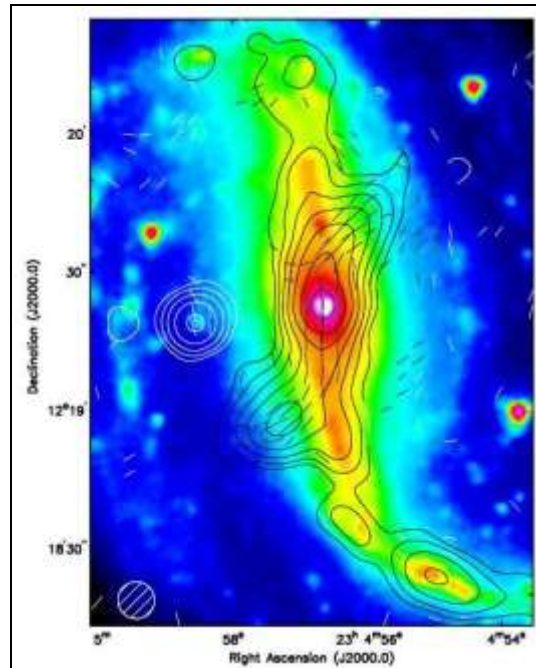


Fig. 50: Barred spiral NGC7479 with two jets. Total radio intensity (contours) and  $B$ -vectors at 8.46 GHz (3.5 cm), observed with the VLA (Laine & Beck 2008). The background shows a Spitzer/IRAC image at  $3.6 \mu\text{m}$  (NASA/JPL-Caltech/Seppo Laine)

The barred galaxy NGC7479 also shows remarkable jet-like radio continuum features: bright, narrow, 12 kpc long in projection, and containing an aligned magnetic field (Fig. 50). The lack of any optical or near-infrared emission associated with the jets suggests that at least the outer parts of the jets are extraplanar features, although close to the disk plane. The equipartition strength is 35–40  $\mu\text{G}$  for the total magnetic field and about 10  $\mu\text{G}$  for the ordered magnetic field in the jets. According to Faraday rotation measurements, the large-scale regular magnetic field along the bar points towards the nucleus on both sides. Multiple reversals on scales of 1–2 kpc are detected, probably occurring in the galaxy disk in front of the eastern jet by anisotropic fields in the shearing gas flow in the bar potential. Highly polarized radio emission from kpc-sized jets has also been detected e.g. in NGC3079 (Cecil et al. 2001), with the field orientations perpendicular to the jet's axis), and in the outflow lobes of the Circinus Galaxy (Elmouttie et al. 1995).

Jets in spiral galaxies may be more frequent than the available radio observations suggest. Future low-frequency observations may help, because they may show weak synchrotron emission from interface regions between the jets and the low-density halo gas.

#### 4.10 Elliptical and dwarf spheroidal galaxies

Elliptical galaxies with active nuclei are among the brightest known radio sources. Their jets and radio lobes are generated by magneto-hydrodynamic processes which are discussed elsewhere. Radio emission from quiet elliptical and S0 galaxies is also associated with their nuclei (Fabbiano et al. 1987). Apart from the nuclear activity, elliptical galaxies are radio-faint because star-formation activity is very low and cosmic-ray electrons are rare. A few ellipticals form stars in their inner regions, but synchrotron emission and hence magnetic fields were not yet detected.

The existence of magnetic fields in the halos of non-active ellipticals is a matter of speculation. Regular fields are not expected in ellipticals because the lack of ordered rotation prevents the action of the  $\alpha$ - $\Omega$  dynamo. Dwarf spheroidal galaxies have some ordered rotation, but lack turbulent gas. Turbulence in the hot gas of large ellipticals may drive a small-scale dynamo and generate turbulent fields with a few  $\mu\text{G}$  strength and turbulent scales of a few 100 pc (Moss & Shukurov 1996). However, there are no cosmic-ray electrons and hence no synchrotron emission. Detection of turbulent magnetic fields is only possible via the dispersion of Faraday rotation measures towards polarized background sources. Most large ellipticals are located in galaxy clusters where Faraday rotation will be dominated by the turbulent fields of the intracluster gas. For small ellipticals, the number of polarized background sources will only be sufficient with much more sensitive radio telescopes like the SKA. This leaves only isolated giant ellipticals for future studies.

Dwarf spheroidal galaxies are of interest to search for synchrotron emission from secondary electrons and positrons generated by the decay of dark-matter by WIMP annihilations, e.g. neutralinos (Colafrancesco et al. 2007). These galaxies do not generate thermal emission or primary electrons from star formation. Detection of radio emission would be of high importance, but all attempts failed so far. The main uncertainty is origin of magnetic fields in such systems (see above). If the field strength is a few  $\mu\text{G}$ , detection of synchrotron emission from dark-matter decay may be possible. Radio observations of several dwarf galaxies yielded only upper limits so far (Spekkens et al. 2013).

## 5. Outlook

Thanks to radio polarization observations, the global properties of interstellar magnetic fields in external galaxies and the field structures on pc and sub-pc sizes in the Milky Way are reasonably well known. However, the processes connecting the features at large and small scales are not understood because the *angular* resolution in external galaxies is too low with present-day radio telescopes. Most of the existing polarization data are observed in wide frequency bands and hence suffer from very low *spectral* resolution, which causes depolarization by gradients of Faraday rotation or by different Faraday rotation components within the beam or along the line of sight. Modern radio telescopes are (or will be) equipped with multichannel polarimeters, allowing application of *RM Synthesis* (section 2.4) and resolving Faraday components along the line of sight. This method is going to revolutionize radio polarization observations.

New and planned telescopes will widen the range of observable magnetic phenomena. The importance of polarimetry for the planned giant optical telescopes still needs to be established, while huge progress is expected in the radio range. The PLANCK satellite and several balloon instruments (PILOT, BLAST-pol) will improve the sensitivity of polarimetry in the submillimeter range at arcminute resolution. The Atacama Large Millimetre Array (ALMA) will provide greatly improved sensitivity at arcsecond resolution for detailed imaging diffuse polarized emission from dust grains and for detection of the Zeeman effect in molecular clouds. High-resolution, deep observations at high frequencies ( $\geq 5$  GHz), where Faraday effects are small, require a major increase in sensitivity for continuum observations which will be achieved by the Jansky Very Large Array (JVLA) and the planned Square Kilometre Array (SKA). The detailed structure of the magnetic fields in the ISM of galaxies and in galaxy halos will be observed, giving direct insight into the interaction between magnetic fields and the various gas components. High angular resolution is also needed to distinguish between regular and anisotropic (sheared) fields and to test various models of the interaction between spiral shocks and magnetic fields. The power spectra of turbulent magnetic fields could be measured down to small scales. The SKA will also allow to measure the Zeeman effect in much weaker magnetic fields in the Milky Way and in nearby galaxies.

The SKA will detect synchrotron emission from Milky Way-type galaxies at redshifts of  $z \leq 1.5$  (Fig. 51) and their polarized emission to  $z \leq 0.5$  (assuming 10% polarization). Bright starburst galaxies could be observed at larger redshifts, but are not expected to host ordered or regular fields. Total synchrotron emission, signature of total magnetic fields, could be detected with the SKA out to large redshifts for starburst galaxies, depending on luminosity and magnetic field strength (Fig. 51). However, for fields weaker than  $3.25 \mu\text{G} (1+z)^2$ , energy loss of cosmic-ray electrons is dominated by the inverse Compton effect with photons of the cosmic microwave background, so that their energy is transferred mostly to the X-ray and not to the radio domain. On the other hand, for strong fields the energy range of electrons emitting in the GHz range shifts to low energies, where ionization and bremsstrahlung losses become dominant. The mere detection of synchrotron emission from galaxies at high redshifts will constrain the range of allowed magnetic field strengths.

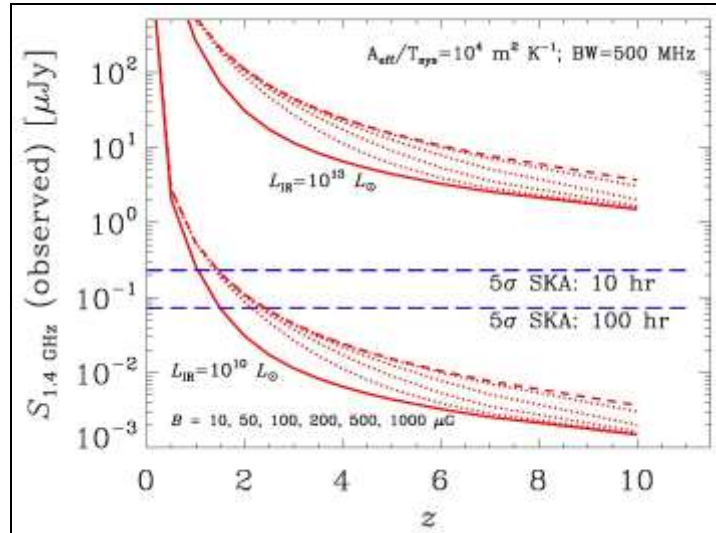


Fig. 51: Total synchrotron emission at 1.4 GHz as a function of redshift  $z$ , total magnetic field strength  $B$  and total infrared luminosity  $L_{\text{IR}}$ . The  $5\sigma$  detection limits for 10 h and 100 h integration time with the SKA are also shown (Murphy 2009).

Dynamo theory predicts timescales of amplification and coherent ordering of magnetic fields in galaxies (section 2.6). Based on models describing the formation and evolution of dwarf and disk galaxies, the probable evolution of turbulent and regular magnetic fields can be tested observationally (Arshakian et al. 2009):

- Strong isotropic turbulent fields (in equipartition with turbulent gas motions) and hence unpolarized synchrotron emission are expected in galaxies at  $z < 10$ .
- Strong regular fields (which are coherent over a scale of about 1 kpc) and hence polarized synchrotron emission and fluctuating RMs are expected in galaxies at  $z \leq 3$ .



- Large-scale patterns of fully coherent regular fields and hence polarized synchrotron emission and large-scale RM patterns are expected in dwarf and Milky-Way type galaxies at  $z \leq 1$ .
- Giant galaxies (disk radius  $> 15$  kpc) have not yet generated fully coherent fields.
- Major mergers enhanced turbulent fields, but destroyed regular fields and delayed the formation of fully coherent fields. The lack of regular fields in nearby galaxies can be a signature of major mergers in the past.

The detections of total synchrotron emission in starburst galaxies at  $z \leq 4$  and of RMs from intervening galaxies at  $z \leq 2$  (section 4.2) are consistent with dynamo theory. Observed field patterns are so far in agreement with the predictions of the  $\alpha$ - $\Omega$  dynamo (sections 4.4 and 4.7). Progress is needed in numerical MHD simulations. Crucial tests of dynamo action will be possible in young galaxies. Detection of regular fields at  $z \geq 3$  would call for a faster process than the dynamo. On the other hand, the failure to detect global coherent field patterns in galaxies  $z \leq 1$  would indicate that the time needed for field ordering is even longer than the  $\alpha$ - $\Omega$  dynamo theory predicts, or that this theory is not applicable. If bisymmetric spiral (BSS) magnetic patterns turn out to dominate, in contrast to nearby galaxies, this would indicate that the fields could be primordial or intergalactic fields which are twisted and amplified by differential rotation.

If polarized emission of galaxies is too weak to be detected, the method of *RM grids* towards background QSOs could still be applied to measure the strength and structure of regular fields. The accuracy is determined by the polarized flux of the background QSO which could be much higher than that of the intervening galaxy. A reliable model for the structure of the magnetic field of nearby galaxies needs many RM values, hence a sufficiently large number density of polarized background sources, calling for high sensitivity. Faraday rotation in the direction of QSOs could even be measured in galaxies at distances near to those of young QSOs ( $z \geq 5$ ). The RM values are reduced by the redshift dilution factor of  $(1+z)^{-2}$ , so that high RM accuracy is needed.

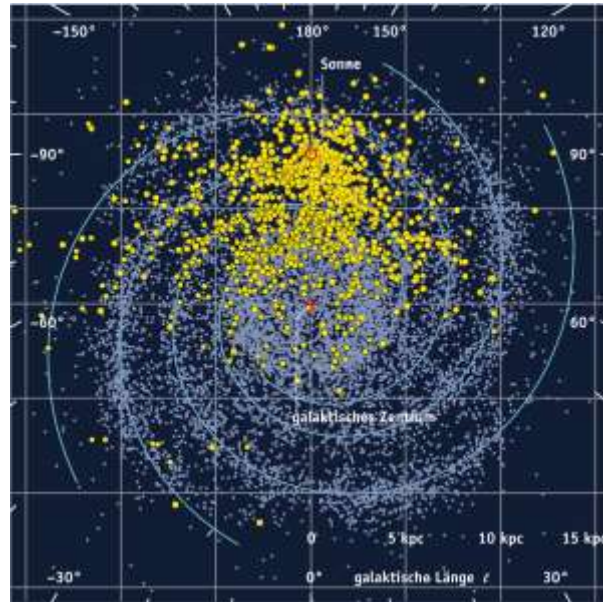


Fig. 52: Simulation of pulsars in the Milky Way that will be detected with the SKA (blue), compared to about 2000 pulsars known today (yellow) (from Jim Cordes, Cornell University). Graphics: Sterne und Weltraum

The SKA will be able to detect  $1 \mu\text{Jy}$  sources and measure about  $10^4$  RMs per square degree at 1.4 GHz within 12 h integration time. The SKA Magnetism Key Science Project plans to observe an all-sky RM grid with 1 h integration per field (Gaensler et al. 2004) which should contain about 20 000 RMs from pulsars in the Milky Way with a mean spacing of  $30'$  (Fig. 52) and several 100 extragalactic pulsars. At least  $10^7$  RMs from compact polarized extragalactic sources at a mean spacing of about  $1.5'$  are expected, about 10 000 in the area around M31 (Fig. 53). This fundamental survey will be used to model the structure and strength of the magnetic fields in the foreground, i.e. in the Milky Way, in intervening galaxies, and in the intergalactic medium. A pilot all-sky survey called POSSUM with the

Australian SKA Precursor (ASKAP) is planned. MeerKAT, the South African SKA precursor, and APERTIF, the Dutch SKA pathfinder telescope, will have a higher sensitivity but a smaller field of view and will concentrate on measuring RM grids centered on individual objects.



*Fig. 53: Simulation of RMs towards background sources (white points) in the region of M31 observable with the SKA within 1 h integration time. Optical emission from M31 is shown in red, diffuse total radio continuum intensity in blue and diffuse polarized intensity in green (from Bryan Gaensler, Sydney University).*

Progress is also expected at low radio frequencies. Present-day measurements of galactic magnetic fields by synchrotron emission are limited by the lifetime and diffusion length of the cosmic-ray electrons which illuminate the fields. With typical diffusion lengths of only 1 kpc away from the acceleration sites in star-forming regions, the size of galaxies at centimeter wavelengths is not much larger than that in the optical or infrared spectral ranges. There is indication that magnetic fields probably extend much further into the intergalactic space (section 4.7). The Low Frequency Array (LOFAR), and the Murchison Widefield Array (MWA), the Long Wavelength Array (LWA) and the low-frequency part of the planned SKA will be suitable instruments to search for extended synchrotron radiation at the lowest possible levels in outer galaxy disks and halos and investigate the transition to intergalactic space. While most of the disk is depolarized at low frequencies, polarization should be detectable from the outer regions. Faraday rotation in the Earth's ionosphere and in the Milky Way foreground is strong and need to be corrected for.

The filaments of the local Cosmic Web may contain *intergalactic magnetic fields*, possibly enhanced by IGM shocks, and this field may be detectable by direct observation of total synchrotron emission or by Faraday rotation towards background sources. For fields of  $10^{-8} - 10^{-7}$  G with 1 Mpc coherence length and  $10^{-5} \text{ cm}^{-3}$  electron density,  $|RM|$  of  $0.1-1 \text{ rad m}^{-2}$  are expected. An overall intergalactic field is much weaker and may only become evident as increased  $|RM|$  towards QSOs at redshifts of  $z > 3$  by averaging over a large number of sources. As the Faraday rotation angle increases with  $\lambda^2$ , searches for low  $|RM|$  should preferably be done at low frequencies.

In summary, the SKA and its pathfinders (EVLA, LOFAR, LWA, MWA, APERTIF) and precursors (ASKAP, MeerKAT) will measure the structure and strength of the magnetic fields in the Milky Way, in intervening galaxies, and possibly in the intergalactic medium. Looking back into time, the future telescopes could shed light on the origin and evolution of cosmic magnetic fields. The observational methods are:

- RM grids of extragalactic sources and pulsars to map the detailed 3D structure of the Milky Way's magnetic field (0.2–1 GHz)
- High-resolution mapping of total and polarized synchrotron emission from galaxy disks and halos of nearby galaxies at high frequencies ( $\geq 5$  GHz)
- Mapping of the total and polarized synchrotron emission from the outer disks and halos of nearby galaxies and galaxy groups at low frequencies ( $\leq 0.3$  GHz)
- Reconstruction of 3D field patterns in nearby galaxies by RM Synthesis of the diffuse polarized emission



- Reconstruction of 3D field patterns in nearby galaxies from RMs towards polarized background sources
- Recognition of simple patterns of regular fields in galaxies from RMs towards polarized background sources (at  $z \leq 0.02$ )
- Search for polarized synchrotron emission from distant galaxies (at  $z \leq 0.5$ )
- Search for total synchrotron emission from distant starburst galaxies (at  $z \leq 3$ )
- Search for regular fields in very distant intervening galaxies towards QSOs (at  $z \leq 5$ ).

Fundamental questions are waiting to be answered:

- When were the first magnetic fields generated: in young galaxies, in protogalactic clouds, or are they relics from the early Universe before the galaxies were formed?
- How and how fast were magnetic fields amplified in the interstellar medium?
- Did magnetic fields affect the evolution of galaxies?
- How important are magnetic fields for the physics of galaxies, like the efficiency to form stars from gas, the formation of spiral arms or the generation of outflows?
- Can outflows from galaxies magnetize the intergalactic space?
- How strong and how ordered are magnetic fields in intergalactic space?
- What is the large-scale structure of the Milky Way's magnetic field?
- How strongly are extragalactic ultrahigh-energy cosmic rays deflected in the Milky Way and in intergalactic space?

## Appendix

### A.1 Catalogue of radio surveys of the Milky Way

Table 2: All-sky or all-hemisphere radio total intensity surveys

Frequency	Beam	Reference
45 MHz	$\approx 4^\circ$	Guzmán et al. 2011
150 MHz	$3^\circ.6$	Landecker & Wielebinski 1970
408 MHz	$2^\circ$	Haslam et al. 1982
1.4 GHz	$0^\circ.6$	Reich 1982; Reich & Reich 1986; Reich et al. 2001
2.3 GHz	$0^\circ.33$	Jonas et al. 1998 (southern hemisphere)
2.7 GHz	$0^\circ.33$	Reif et al. 1987 (northern hemisphere)
23 – 94 GHz	$0^\circ.8 - 0^\circ.2$	Hinshaw et al. 2009

Table 3: All-sky or all-hemisphere radio polarization surveys

Frequency	Beam	Reference
408 MHz	$7.5^\circ$	Wielebinski et al. 1962 (northern hemisphere)
	$2^\circ$	Berkhuijsen & Brouw 1963 (northern hemisphere)
	$7.5^\circ$	Wielebinski & Shakeshaft 1964 (northern hemisphere)
	$\approx 1^\circ$	Mathewson & Milne 1965 (southern hemisphere)
300 MHz – 1.8 GHz	$30' - 60'$	Wolleben et al. 2009; 2010a (northern hemisphere)
1.4 GHz	$36'$	Wolleben et al. 2006; Testori et al. 2008
1.4 GHz	$\approx 13'$	Rudnick & Brown 2009 (northern hemisphere)
23 – 94 GHz	$0^\circ.8 - 0^\circ.2$	Kogut et al. 2007; Hinshaw et al. 2009

Table 4: Radio surveys of the Galactic plane with angular resolutions of a few arcminutes

Frequency	Beam	Area (Galactic coordinates)	Reference
325 MHz	$\approx 4'$	selected areas	Wieringa et al. 1993
350 MHz	$\approx 5'$	selected areas	Haverkorn et al. 2003; 2004
408 MHz	$\approx 1'$	$147.3^\circ > l > 74.2^\circ$ $-7.7^\circ < b < 8.7^\circ$	Taylor et al. 2003
1.4 GHz	$\approx 1'$	$147.3^\circ > l > 74.2^\circ$ $-3.6^\circ < b < 5.6^\circ$	Taylor et al. 2003
1.4 GHz	$\approx 1'$	$67^\circ > l > 18^\circ$ $b \pm 1^\circ.5$	Stil et al. 2006
1.4 GHz (PI)	$\approx 1'$	$358^\circ > l > 253^\circ$ $b \pm 1^\circ.5$	Haverkorn et al. 2006
1.4 GHz (PI)	$\approx 1'$	$175^\circ > l > 66^\circ$ $-3^\circ < b < 5^\circ$	Landecker et al. 2010
1.4 GHz	$9'$	$162^\circ > l > 93^\circ$ $b \pm 4^\circ$	Kallas & Reich 1980
1.4 GHz	$9.4'$	$240^\circ > l > 95.5^\circ$ $-4^\circ < b < 5^\circ$	Reich et al. 1990a; 1997
1.4 GHz (PI)	$9'$	selected areas	Uyaniker et al. 1999
1.4 GHz	$\approx 1'$	$332.5^\circ > l > 325.5^\circ$ $-0.5^\circ < b < 3.5^\circ$	Gaensler et al. 2001
2.4 GHz	$10.4'$	$238^\circ > l > 365^\circ$ $b \pm 5^\circ$	Duncan et al. 1995
2.4 GHz (PI)	$10.4'$	$238^\circ > l > 5^\circ$ $b \pm 5^\circ$	Duncan et al. 1997
2.7 GHz	$4.3'$	$357.4^\circ < l < 76^\circ$ $b \pm 1.5^\circ$	Reich et al. 1984
2.7 GHz (PI)	$6'$	$74^\circ > l > 4^\circ.9$ $b \pm 1.5^\circ$	Junkes et al. 1987
2.7 GHz	$4.4'$	$76^\circ > l > 358^\circ$ $b \pm 5^\circ$	Reich et al. 1990b
2.7 GHz	$4.4'$	$240^\circ > l > 76^\circ$ $b \pm 5^\circ$	Fürst et al. 1990
2.7 GHz (PI)	$4.3'$	$74^\circ > l > 4^\circ.9$ $b \pm 5^\circ$	Duncan et al. 1999
5 GHz (PI)	$9'$	$129^\circ > l > 122^\circ$ $b \pm 5^\circ$	Sun et al. 2007
5 GHz (PI)	$9'$	$230^\circ > l > 129^\circ$ $b \pm 5^\circ$	Gao et al. 2010
5 GHz (PI)	$9'$	$122^\circ > l > 60^\circ$ $b \pm 5^\circ$	Xiao et al. 2011
5 GHz (PI)	$9'$	$60^\circ > l > 10^\circ$ $b \pm 5^\circ$	Sun et al. 2011

(PI): with polarization data

## A.2 Catalogue of radio polarization observations of nearby galaxies

In radio continuum the typical degrees of polarization are much higher than those in the other spectral ranges, and further benefit comes from the development of large instruments and sensitive receivers. This is why almost all of our knowledge on interstellar magnetic fields in galaxies is based on their polarized radio emission and Faraday rotation.

A list of spiral, barred, irregular and dwarf galaxies detected in radio polarization until year 2010 is given in Tables 5, 6 and 7. Most detections were made in the wavelength range 2–13 cm where Faraday depolarization is small. At  $\lambda \approx 20$  cm, the polarized intensity is generally smaller by a factor of several (Fig. 3). At wavelengths of more than 20 cm, no detection of polarized emission from spiral galaxies has been reported so far.

Table 5: Radio polarization observations and magnetic field structures of galaxies with low or moderate inclination

Galaxy	Telescope & $\lambda$ (cm)	Structure	Reference
M33	E21,18,11,6,3	BSS	Bucsilowski & Beck 1991
	E6,4, V21	ASS+BSS+QSS	Tabatabaei et al. 2008
M51	W21,6	Spiral	Segalovitz et al. 1976
	V21,18	Spiral	Horellou et al. 1992
	E6,3, V21,6	ASS+BSS (disk) +ASS (halo)	Neininger 1992; Berkhuijsen et al. 1997
	W21	BSS (halo)	Heald et al. 2009
	E6,4, V21,6,4	ASS+QSS (disk), +BSS (halo)	Fletcher et al. 2011
M81	E6, V21	BSS	Krause et al. 1989b
	E6, V21	BSS (+ASS)	Sokoloff et al. 1992
	V21,6	Interarm fields	Schoofs 1992
M83	V21	Spiral	Sukumar & Allen 1989
	P6	Spiral	Harnett et al. 1990
	E6,3	BSS?	Neininger et al. 1991; 1993
	A13	Magnetic arms	Ehle 1995
	V6	Magnetic arms + $\parallel$ bar	Beck 2005
M101	E11,6,3	Spiral	Gräve et al. 1990
	E11,6	Spiral	Berkhuijsen et al., unpubl.
NGC0628	W21	Incomplete spiral	Heald et al. 2009
NGC0660	V6	$\parallel$ polar ring +X-shape	Drzazga et al. 2011
NGC0877	V6	Spiral	Drzazga et al. 2011
NGC1097	V21,18,6,4	ASS+BSS+QSS + $\parallel$ bar +nuclear spiral	Beck et al. 2005a
NGC1365	V21,18,6,4	ASS+BSS+QSS + $\parallel$ bar +nuclear spiral	Beck et al. 2005a
NGC1559	A13,6	$\parallel$ bar	Beck et al. 2002
NGC1566	A21,13,6	Spiral, interarm	Ehle et al. 1996
NGC1569	W21, V6,3	Spiral, bubbles, loops	Kepley et al. 2010
NGC1672	A13,6	Spiral, interarm	Beck et al. 2002
NGC2207	V6	Spiral +radial streamers	Drzazga et al. 2011
NGC2276	V21,6	BSS?	Hummel & Beck 1995
NGC2403	E11,6	Spiral	Beck unpubl.
	W21	Diffuse	Heald et al. 2009
NGC2442	A13,6	Spiral + $\parallel$ bar	Harnett et al. 2004
NGC2841	W21	Two arcs	Heald et al. 2009
NGC2903	E6,3, V21	Spiral	Beck, unpubl.
	W21	Spiral	Heald et al. 2009
NGC2997	V21,6,4, A13	Spiral +inner ASS?	Han et al. 1999
NGC3521	E3	Spiral, compressed	Knapik et al. 2000
NGC3627	E3	Spiral + $\parallel$ dust lane	Soida et al. 1999
	V6,4	Anomalous arm	Soida et al. 2001
	W21	Spiral	Heald et al. 2009
	E11	Spiral	Nikiel-Wroczyński et al. 2013a
NGC3938	W21	Spiral	Heald et al. 2009
NGC4038	V21,6,4	$\parallel$ tidal arm	Chyży & Beck 2004

NGC4214	V6	No ordered field	Kepley et al. 2009
	E6	Fragment of a spiral	Drzazga 2008
NGC4258	W21, V21	In anomalous arms	van Albada & van der Hulst 1982
	V21,6	anomalous arms	Hummel et al. 1989
	V4, E3	nuclear jet + an. arms	Krause & Löhner 2004
NGC4414	V6,4	ASS+BSS+QSS	Soida et al. 2002
NGC4449	E6,3	opt. filaments	Klein et al. 1996
	V6,4	Spiral+radial field	Chyży et al. 2000
NGC4490/85	E6,4	Radial halo field	Knapik et al. in prep.
NGC4736	V6,4	Spiral, ASS?	Chyży & Buta 2008
	W21	Outer lobe	Heald et al. 2009
NGC5033	W21	Inner disk	Heald et al. 2009
NGC5055	E3	Spiral	Knapik et al. 2000
	W21	Spiral	Heald et al. 2009
NGC5426/7	V6	Spiral +spiral	Drzazga et al. 2011
NGC6822	E11,6,3	No ordered field	Chyży et al. 2003; 2011
NGC6907	V6	Spiral	Drzazga et al. 2011
NGC6946	E11,6,3	ASS?	Ehle & Beck 1993
	V21,18,6,4	ASS+QSS	Beck 1991; 2007
	W21	ASS (halo)	Heald et al. 2009
NGC7479	V21,6,4	spiral jet	Beck et al. 2002; Laine & Beck 2008
NGC7552	A6	Spiral +   bar	Beck et al. 2002
IC10	E11,6,3	H $\alpha$ filament	Chyży et al. 2003; 2011
	V6	Filaments	Heesen et al. 2011a
	V6,4	Filaments	Chyży 2005
IC342	E11,6	ASS	Gräve & Beck 1988
	E6, V21	ASS	Krause et al. 1989a
	E6, V21	ASS	Sokoloff et al. 1992
	V6,4	Magnetic arms	Beck unpubl.
IC1613	E11,6	No ordered field	Chyży et al. 2011
UGC813/6	V6	⊥bridge	Drzazga et al. 2011
UGC12914/5	V6	bridge	Drzazga et al. 2011
Holmberg II	E11,6	No ordered field	Chyży et al., unpubl.
SMC	P21,13	main ridge	Haynes et al. 1986
	A21	Pan-Magellanic?	Mao et al. 2008
LMC	P21,13,6	Magn. loop near 30 Dor	Haynes et al. 1991; Klein et al. 1993
	A21	ASS	Gaensler et al. 2005
	P21, A21	filaments, even-symmetry halo field	Mao et al. 2012
Leo Triplet	E11	No intergalactic field	Nikiel-Wroczyński et al. 2013a
Stephan's Quintet	E4, V21,6	Intergalactic field	Nikiel-Wroczyński et al. 2013b
PKS1229-021	V21,6,2	BSS?	Kronberg et al. 1992

Table 6: Radio polarization observations and magnetic field structures of galaxies with high inclination (almost edge-on)

Galaxy	Telescope & $\lambda$ (cm)	Structure	Reference
M31	E21,11,6 V21,6 E11,6, V21	Even-symmetry ASS Spiral (inner region) Even ASS (+QSS)	Beck 1982; Beck et al. 1989 Beck et al. 1998 Berkhuijsen et al. 2003; Fletcher et al. 2004
M82	V6,4 E1	Radial halo field   disk +vertical halo field	Reuter et al. 1994 Wielebinski 2006
M104	V21,6	disk +X-shaped halo field	Krause et al. 2006
NGC253	P6,3 V21,6 E6,3 E6,4, V21,6 V21,6,4	plane   plane   plane, halo spurs Even ASS disk field +even halo field Helical field in outflow cone	Harnett et al. 1990 Carilli et al. 1992 Beck et al. 1994 Heesen et al. 2009a; 2009b Heesen et al. 2011b

NGC891	V6	plane +halo spurs	Sukumar & Allen 1991
	V21	plane +halo spurs	Hummel et al. 1991
	E3	plane +tilted	Dumke et al. 1995
	E4	Even ASS disk field	
		+X-shaped halo field	Krause 2009
NGC1808	V21,6	Halo spurs	Dahlem et al. 1990
NGC3079	V6	Extraplanar jet	Duric & Seaquist 1988
NGC3432	E6	Vertical, weak	Drzazga 2008
NGC3628	V21	Fragments of ord. field	Reuter et al. 1991
	E3	plane	Dumke et al. 1995
	E4	plane	
		+X-shaped halo field	Krause, unpubl.
	E11	plane	Nikiel-Wroczyński et al. 2013a
NGC4217	V6	X-shaped halo field	Soida 2005
NGC4236	E6	No ordered field	Chyży et al. 2007
NGC4565	V21	plane	Sukumar & Allen 1991
	E3	plane	Dumke et al. 1995
	E6,4, V6   plane		
		+X-shaped halo field	Krause 2009
NGC4631	V21	⊥plane	Hummel et al. 1991
	V6,4	⊥plane, spurs	Golla & Hummel 1994
	V21,18	X-shaped halo field	Beck 2009
	E4	plane +vertical central field	
		+X-shaped halo field	Krause 2009
	W21	X-shaped halo field	Heald et al. 2009
NGC4656	E6	No ordered field	Chyży et al. 2007
NGC4666	V21,6	X-shaped halo field	Dahlem et al. 1997
	V6	X-shaped halo field	Soida 2005
NGC4945	P6,3	Halo spurs	Harnett et al. 1989; 1990
NGC5775	V21,6	X-shaped halo field	Tüllmann et al. 2000
	V4	Even ASS disk field	
		+X-shaped halo field	Soida et al. 2011
NGC5907	E6, V21	plane	Dumke 1997
	E4	plane +X-shape?	Krause, unpubl.
NGC7331	E3	plane	Dumke et al. 1995
	W21	X-shaped halo field	Heald et al. 2009
Circinus	A21, 13	radio lobes	Elmouttie et al. 1995
IC2574	E6	No ordered field	Chyży et al. 2007

Table 7: Radio polarization observations and magnetic field structures of galaxies in the Virgo cluster

Galaxy	Telescope & $\lambda$ (cm)	Structure	Reference
NGC4192	E6,4	ASS? +halo field	Weżgowiec et al. 2012
	V21,6	disk +inclined	Vollmer et al. 2013
NGC4254	E6,3	Spiral	Soida et al. 1996
	V21,6,4, E6,3	ASS (+BSS), tidally stretched	Chyży 2008
NGC4294	W21	Spiral	Heald et al. 2009
	V21,6	Halo field, inclined to disk	Vollmer et al. 2013
NGC4299	V21,6	Fragments of a spiral	Vollmer et al. 2013
NGC4298/ NGC4302	E6,4	disk+intergal. bridge, locally vertical	Weżgowiec et al. 2012
NGC4302	V21,6	Mostly   disk	Vollmer et al. 2013
NGC4303	E6,4	ASS?	Weżgowiec et al. 2012
	V21,6	Spiral	Vollmer et al. 2013
NGC4321	V21,6	Spiral	Vollmer et al. 2007; 2010
	W21	Spiral	Heald et al. 2009
	E6,4	BSS? +  bar	Weżgowiec et al. 2012
NGC4330	V21,6	Mostly   disk	Vollmer et al. 2013
NGC4388	E6,4	Inclined to disk	Weżgowiec et al. 2012
	V21,6	disk +incl. in halo	Vollmer et al. 2007; 2010
NGC4396	V21,6	disk +  NW tail	Vollmer et al. 2007; 2010

NGC4402	V21,6	disk in southern halo, incl. in northern halo	Vollmer et al. 2007; 2010
NGC4419	V21,6	disk +X-shaped	Vollmer et al. 2013
NGC4424	V6	X-shaped	Vollmer et al. 2013
NGC4438	E6	disk, $\perp$ outflow	Weżgowiec et al. 2007
	V6	disk, displaced from disk in the east	Vollmer et al. 2007; 2010
NGC4457	V21,6	Spiral	Vollmer et al. 2013
NGC4501	E6,3	disk, asymmetric	Weżgowiec et al. 2007
	V21,6	Compressed along SW disk edge	Vollmer et al. 2007; 2010
NGC4522	V21,6	plane, compressed	Vollmer et al. 2004
NGC4532	V6	Huge halo field, inclined +vertical, X-shaped	Vollmer et al. 2013
NGC4535	V21,6,4	Spiral	Beck et al. 2002
	E6,4	Spiral, asymmetric	Weżgowiec et al. 2007; 2012
	V21,6	spiral arm, asymmetric	Vollmer et al. 2007; 2010
	E4	ASS?	Weżgowiec et al. 2012
NGC4548	E6	$\perp$ bar	Weżgowiec et al. 2007
NGC4567/ NGC4568	V21,6	Intergal. bridge	Vollmer et al. 2013
NGC4569	E6,4	disk +  outflow	Chyży et al. 2006
	W21	disk +  outflow	Heald et al. 2009
	V21,6	disk +  outflow	Chyży et al. in prep.
NGC4579	V21,6	bar, spiral in outer disk	Vollmer et al. 2013
NGC4654	E6,4	SW arm +  gas tail	Weżgowiec et al. 2007
	V21,6	arms, bending out towards gas tail	Vollmer et al. 2007; 2010
NGC4689	V21,6	Fragments of a spiral	Vollmer et al. 2013
NGC4713	V21,6	Spiral	Vollmer et al. 2013
NGC4808	V21,6	Vertical, asymmetric	Vollmer et al. 2013

Instruments: E = Effelsberg 100-m, V = Very Large Array, A = Australia Telescope Compact Array,  
P = Parkes 64-m, W = Westerbork Synthesis Radio Telescope

Wavelength codes: 21 = 20-22 cm, 18 = 18.0 cm, 13 = 12.5-13.4 cm, 11 = 11.1 cm, 6 = 5.8-6.3 cm, 4 = 3.6 cm,  
3 = 2.8 cm, 2 = 2.0 cm, 1 = 9 mm

Field structures: ASS = axisymmetric spiral, BSS = bisymmetric spiral, QSS = quadrisymmetric spiral,  
MSS = multimode spiral

### A.3 Links to the SKA project and its precursor and pathfinder telescopes

<http://www.skatelescope.org>  
[http://www.scholarpedia.org/article/Square\\_kilometre\\_array](http://www.scholarpedia.org/article/Square_kilometre_array)  
<http://www.atnf.csiro.au/SKA>  
<http://www.ska.ac.za>  
<http://www.aoc.nrao.edu/evla>  
<http://www.lofar.org>  
<http://www.astron.nl/general/apertif/apertif>  
<http://www.phys.unm.edu/~lwa>  
<http://www.mwatelescope.org>

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