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Galactic and extragalactic magnetic fields – a concise review

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Abstract. The strength of the total magnetic field in our Milky Way from radio synchrotron measurements is about $6\,\mu$G (0.6 nT), averaged over a radius of about 1 kpc around the Sun. Diffuse polarized radio emission and Faraday rotation of the polarized emission from pulsars and background sources show many small-scale magnetic features, but the overall field structure in our Galaxy is still under debate. – In nearby galaxies, radio synchrotron observations reveal dynamically important magnetic fields of $10-30\,\mu$G ($1-3$ nT) total strength in the spiral arms. Fields with random orientations are concentrated in spiral arms, while ordered fields (observed in radio polarization) are strongest in interarm regions and follow the orientation of the adjacent gas spiral arms. Faraday rotation of the diffuse polarized radio emission from the disks of spiral galaxies sometimes reveals large-scale patterns which are signatures of regular fields generated by dynamos, but in most galaxies the field structure is more complicated. – Strong magnetic fields are also observed in radio halos around edge-on galaxies, out to large distances from the plane. The ordered halo fields usually form an X-shaped pattern. Diffuse polarized radio emission in the outer disks and halos is an excellent tracer of galaxy interactions and ram pressure by the intergalactic medium.

1 Introduction

Magnetic fields are a major agent in the interstellar medium (ISM) and also control the density and distribution of cosmic rays. Cosmic rays accelerated in supernova remnants can provide the pressure to drive a galactic outflow and buoyant loops of magnetic fields via the Parker instability. Outflows from starburst galaxies in the early Universe may have magnetized the intergalactic medium.

In spite of our increasing knowledge of magnetic fields, many important questions, especially the origin and evolution of magnetic fields, their first occurrence in young galaxies and the existence of large-scale intergalactic fields remain unanswered. Furthermore, the detection of ultrahigh-energy cosmic rays with the AUGER observatory calls for a detailed knowledge of the magnetic field in the Milky Way to model particle propagation.

2 Measuring magnetic fields in galaxies

Magnetic fields need illumination to be detectable. Polarized emission at optical, infrared, submillimeter and radio wavelengths holds the clue to magnetic fields in galaxies. Most of what we know about galactic and intergalactic magnetic fields comes through the detection of radio waves. Zeeman splitting of radio spectral lines is the best method to directly measure the field strength in gas clouds of the Milky Way and in starburst galaxies (Robishaw et al., 2008).

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 fields, defined to have a constant direction within the telescope beam, from anisotropic fields, which are turbulent fields stretched in one dimension by compressing or shearing gas flows and frequently reverse their direction along the other two dimensions. Unpolarized synchrotron emission indicates turbulent fields which have random directions in 3-D and have been tangled or generated by turbulent gas flows.

The intrinsic degree of linear polarization of synchrotron emission is about 75%. The observed degree of polariza-

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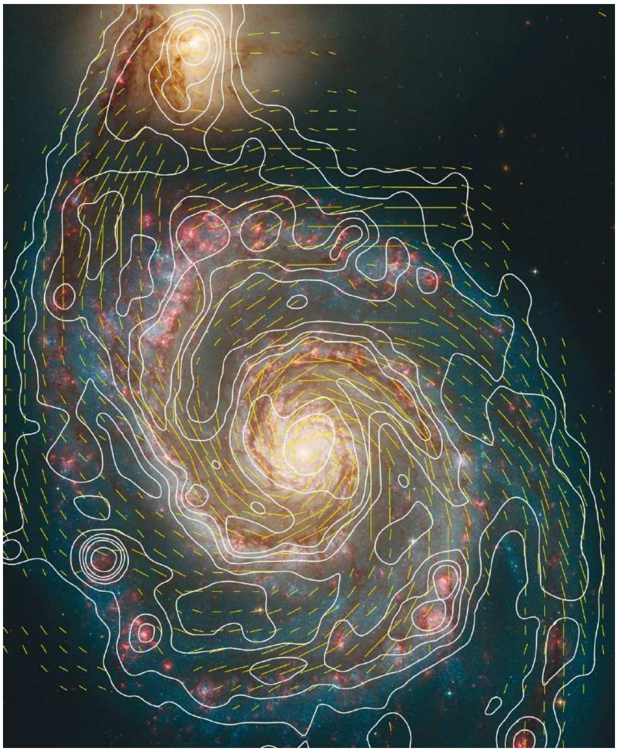

Fig. 1. Total radio emission (contours) and B–vectors of M 51, combined from observations at 6 cm wavelength with the VLA and Effelsberg telescopes and smoothed to 15” resolution (Fletcher et al., in prep.), overlaid onto an optical image from the HST (Copyright: MPIfR Bonn and Hubble Heritage Team. Graphics: Sterne und Weltraum).

tion is smaller due to the contribution of unpolarized thermal emission, which may dominate in star-forming regions, by Faraday depolarization along the line of sight and across the beam (Sokoloff et al., 1998), and by geometrical depolarization due to variations of the field orientation within the beam.

At radio wavelengths of a few centimeters and below, the orientation of the observed B–vector is parallel to the field orientation, so that the magnetic patterns of many galaxies could be mapped directly (Beck, 2005). The orientation of the polarization vectors is changed in a magnetized thermal plasma by Faraday rotation. The rotation angle increases with the plasma density, the strength of the component of the field along the line of sight and the square of the observation wavelength. As the rotation angle is sensitive to the sign of the field direction, only regular fields can give rise to Faraday rotation, while anisotropic and random fields do not. Measurements of the Faraday rotation from multi-wavelength observations allow to determine the strength and direction of the regular field component along the line of sight. Its combination with the total intensity and the polarization vectors can yield the three-dimensional picture of the magnetic field and allows to distinguish the three field components: regular, anisotropic and random.

3 Strengths of galactic magnetic fields

The typical average “equipartition” strength of the total magnetic field in spiral galaxies is about $10\,\mu$G (1 nT), assuming energy equipartition between cosmic rays and magnetic fields. Radio-faint galaxies like M 31 and M 33, our Milky Way’s neighbors, have weaker total magnetic fields (about $5\,\mu$G, 0.5 nT), while gas-rich spiral galaxies with high star-formation rates, like M 51 (Fig. 1), M 83 and NGC 6946, have total field strengths of $20-30\,\mu$G ($2-3$ nT) in their spiral arms. The mean energy densities of the magnetic field and of the cosmic rays in NGC 6946 and M 33 are $\simeq 10^{-11}$ erg cm^{-3} and $\simeq 10^{-12}$ erg cm^{-3}, respectively (Beck, 2007; Tabatabaei et al., 2008), about 10 times larger than that of the ionized gas, but similar to that of the turbulent gas motions across the whole star-forming disk.

The strongest total fields of $50-100\,\mu$G ($5-10$ nT) are found in starburst galaxies, like M 82 and the “Antennae” NGC 4038/9 (Chyży and Beck, 2004), and in nuclear starburst regions, like in the centers of NGC 1097 and other barred galaxies (Beck et al., 2005). In starburst galaxies the equipartition field strength is probably underestimated due to strong energy losses of the cosmic rays (Thompson et al., 2006) which was recently confirmed by Zeeman measurements of OH maser lines (Robishaw et al., 2008).

The degree of radio polarization within the spiral arms is only a few %; hence the field in the spiral arms must be mostly tangled or randomly oriented within the telescope beam, the width of which typically corresponds to a few 100 pc. Turbulent fields in spiral arms are probably generated by turbulent gas motions related to star formation activity.

4 Structure of galactic magnetic fields

The ordered (regular and/or anisotropic) fields traced by the polarized synchrotron emission are generally strongest ($10-15\,\mu$G) in the regions between the optical spiral arms and oriented parallel to the adjacent spiral arms, in some galaxies forming magnetic arms. These are probably generated by a mean-field dynamo (Beck et al., 1996). In galaxies with strong density waves some of the ordered field is concentrated on the inner edge of the spiral arms (Fig. 1). The ordered magnetic field forms spiral patterns in almost every galaxy (Beck, 2005) and also in the central regions of galaxies and circum-nuclear gas rings (Fig. 2).

In galaxies with massive bars the field lines follow the gas flow (Fig. 2). As the gas rotates faster than the bar pattern of a galaxy, a shock occurs in the cold gas which has a small sound speed, while the flow of warm, diffuse gas is only slightly compressed but sheared. The ordered fAS-2009-10-1.pdffield is also hardly compressed. It is probably coupled to the diffuse gas and strong enough to affect its flow (Beck et al., 2005). The polarization pattern in spiral arms and bars

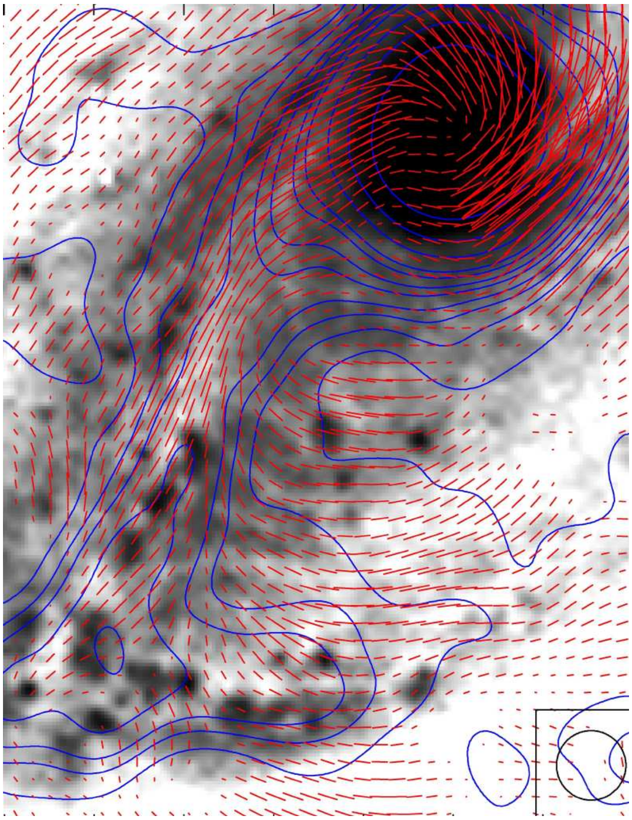

Fig. 2. Total radio emission (contours) and B–vectors of the barred galaxy NGC 1097, observed at 6 cm wavelength with the VLA and smoothed to 10” resolution (Beck et al., 2005). The background optical image is from Halton Arp (Copyright: MPIfR Bonn and Cerro Tololo Observatory).

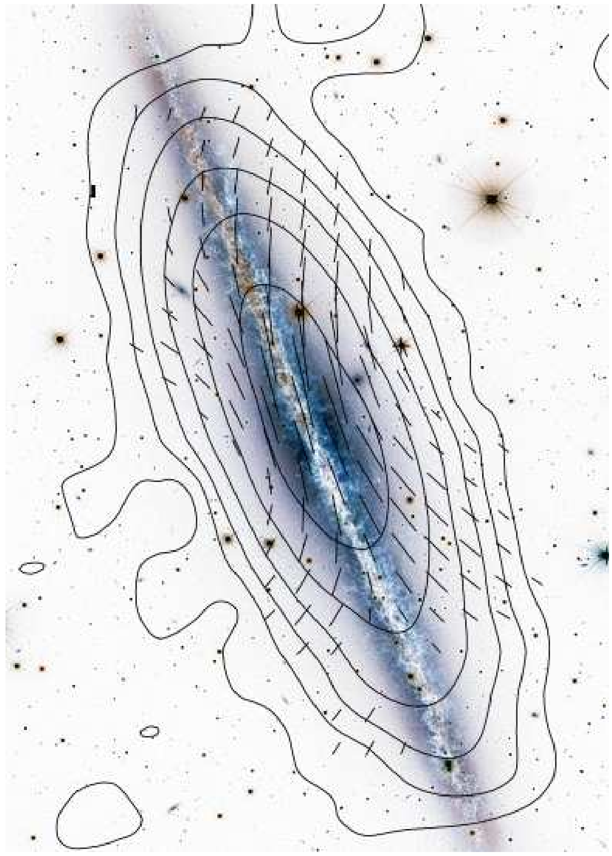

Fig. 3. Total radio emission (84” resolution) and B–vectors of the edge-on spiral galaxy NGC 891, observed at 3.6 cm wavelength with the Effelsberg 100m telescope (Krause, 2008). The background optical image is from the CFHT (Copyright: MPIfR Bonn and CFHT/Coelum).

can be used as a tracer of shearing gas flows in the sky plane and hence complements spectroscopic measurements.

Spiral fields can be generated by compression at the inner edge of spiral arms, by shear in interarm regions, or by dynamo action (Beck et al., 1996). Large-scale patterns of Faraday rotation measures (RM) are signatures of regular dynamo fields and can be identified from polarized emission of the galaxy disks (Krause, 1990) or from RM data of polarized background sources (Stepanov et al., 2008). The Andromeda galaxy M 31 hosts a dominating axisymmetric disk field (Fletcher et al., 2004), as predicted by dynamo models. Other candidates for a dominating axisymmetric disk field are the nearby spiral IC 342 (Krause et al., 1989) and the irregular Large Magellanic Cloud (LMC) (Gaensler et al., 2005). However, in many observed galaxy disks no clear patterns of Faraday rotation were found. Either several dynamo modes are superimposed and cannot be distinguished with the limited sensitivity and resolution of present-day telescopes, or the timescale for the generation of large-scale modes is longer than the galaxy’s lifetime.

Nearby galaxies seen “edge-on” generally show a disk-parallel field near the disk plane. High-sensitivity observations of edge-on galaxies like NGC 891 (Fig. 3) and NGC 253 (Heesen et al., 2009) revealed vertical field components in the halo forming an X-shaped pattern. The field is probably transported from the disk into the halo by an outflow emerging from the disk.

5 Magnetic fields in the Milky Way

Surveys of the total synchrotron emission from the Milky Way yield equipartition strengths of the total field of 6 μG (0.6 nT), averaged over a radius of about 1 kpc around the Sun, and about 10 μG (1 nT) in the inner Galaxy (Berkhuijsen, in Wielebinski, 2005). Faraday RM and dispersion measure data of pulsars give an average strength of the local regular field of $1.4 \pm 0.2\,\mu$G (0.14 nT) (Rand and Lyne, 1994). In the inner Norma arm, the average strength of the regular field is $4.4 \pm 0.9\,\mu$G (0.44 nT) (Han et al., 2002).

The all-sky maps of polarized synchrotron emission at 1.4 GHz from the Milky Way from DRAO and Villa Elisa and at 22.8 GHz from WMAP and the new Effelsberg RM survey of polarized extragalactic sources were used to model the regular Galactic field (Sun et al., 2008). One field reversal is required at about $1-2$ kpc from the Sun towards the Milky Way's center, which also agrees with the detailed study of RMs from extragalactic sources near the Galactic plane (Brown et al., 2007). Models for a simple regular field structure of the Milky Way (Han et al., 2002) could not be confirmed by statistical tests (Men et al., 2008). Similar to external galaxies, the Milky Way's regular field probably has a complex structure which can only be revealed by a larger sample of pulsar and extragalactic RM data.

RMs of extragalactic sources and of pulsars do not show a reversal across the plane at Galactic longitudes $l=90°-270°$: the local field is part of a symmetric (quadrupolar) field structure. However, towards the inner Galaxy ($l=270°-90°$) the RM signs are opposite above and below the plane which was assigned to an antisymmetric halo field (Sun et al., 2008).

Little is known about the vertical structure of the magnetic field in the Milky Way. The exponential scale height of the thick disk of synchrotron emission from the Milky Way is about 1 kpc, similar to that in external spiral galaxies which, in case of energy equipartition, corresponds to a scale height of the total magnetic field of about 4 kpc. The local regular Galactic field has only a weak vertical component of $B_z \simeq 0.2\,\mu$G (0.02 nT) (Han and Qiao, 1994).

While the kpc-scale regular field is much more difficult to measure in the Milky Way than in external galaxies, Galactic observations can trace magnetic structures to scales down to a few pc (Wielebinski, 2005). Small-scale and turbulent field structures are enhanced in spiral arms compared to interarm regions (Haverkorn et al., 2006). The all-sky and the Galactic plane polarization surveys (Reich, 2006) show a wealth of structures on pc and sub-pc scales: filaments, canals, lenses and rings. Their common property is to appear only in the maps of polarized intensity, but not in total intensity. Some of these are artifacts due to strong depolarization of background emission in a foreground Faraday screen, called Faraday ghosts, but carry valuable information about the turbulent ISM (Shukurov and Berkhuijsen, 2003; Fletcher and Shukurov, 2006). Faraday rotation in foreground objects (e.g. supernova remnants, planetary nebulae, pulsar wind nebulae or molecular clouds) embedded in diffuse polarized Galactic emission may generate a Faraday shadow or Faraday screen which enables to estimate regular field strengths of more than $10\,\mu$G (1 nT) (Reich, 2006).

Measurements of the Voyager spacecrafts indicate that the interstellar magnetic field outside the heliosphere is strong ($4-5\,\mu$G, $0.4-0.5$ nT) but oriented at an angle of $60°-90°$ with respect to the Galactic plane (Opher et al., 2009) which is no surprise in view of the complicated structure of galactic magnetic fields.

6 Conclusions and outlook

Our knowledge about magnetic fields in the Milky Way and external galaxies has significantly increased during the last decade, but the fundamental questions about the origin of magnetic fields and their dynamical role for the evolution of galaxies remain unanswered. Future high-resolution, high-sensitivity observations at high frequencies with the Extended Very Large Array (EVLA) and the Square Kilometre Array (SKA) will show the detailed field structure and the interaction with the gas. The new Low Frequency Array (LOFAR) will be suitable to search for extended synchrotron radiation at the lowest possible levels in outer galaxy disks, halos and clusters, and the transition to intergalactic space. Low frequencies are also ideal to search for small Faraday rotation from weak interstellar and intergalactic fields (Beck, 2008). "Cosmic magnetism" is the title of Key Science Projects for LOFAR and SKA.

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