Magnetism in Nearby Galaxies, Prospects with the SKA, and Synergies with the E-ELT

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Abstract. Radio synchrotron emission, its polarization and its Faraday rotation are powerful tools to study the strength and structure of interstellar magnetic fields. In the Milky Way, the total field strength is about 6 μG near the Sun and 50–100 μG near the Galactic Center. Faraday rotation of the polarized emission from pulsars and background sources indicate that the regular field follows the spiral arms and has one reversal inside the solar radius, but the overall field structure in our Galaxy is still unclear. In nearby galaxies, turbulent fields are strongest in spiral arms and bars (20–30 μG) and in central starburst regions (50–100 μG). Ordered fields with spiral structure exist in grand-design, barred and flocculent galaxies. The strongest ordered fields (10–15 μG) are found in interarm regions. 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 a mean-field dynamo. Ordered magnetic fields are also observed in radio halos around edge-on galaxies, out to large distances from the plane, with X-shaped patterns. – The SKA and its precursor telescopes will open a new era in the observation of cosmic magnetic fields and help to understand their origin. The SKA will map interstellar fields in nearby galaxies in unprecedented detail. All-sky surveys of Faraday rotation measures (RM) towards a dense grid of polarized background sources with the ASKAP (POSSUM), MeerKAT and the SKA are dedicated to measure fields in intervening galaxies and will be used to model the overall structure and strength of the magnetic fields in the Milky Way and beyond. Examples for joint polarimetric observations between the SKA and the E-ELT are given.

1. Origin of cosmic magnetism

Magnetic fields are a major agent in the ISM and also control the density and distribution of cosmic rays. Cosmic rays accelerated in supernova remnants can provide the pressure to drive galactic outflows 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 cosmic magnetic fields, many important questions, especially their origin and evolution, their strength in intergalactic space, their first occurrence in young galaxies and their dynamical importance for galaxy evolution remain unanswered. The detection of ultrahigh-energy cosmic rays (UHECRs) with the AUGER observatory calls for a detailed knowledge of the magnetic field in the Milky Way to properly model the particle propagation.

The most promising mechanism to sustain magnetic fields in the interstellar medium of galaxies is the dynamo. In young galaxies a small-scale dynamo (Brandenburg & Subramanian 2005) possibly amplified seed fields from the protogalactic phase to the energy density level of turbulence within less than 10^9 yr. To explain the generation of large-scale fields in galaxies, the mean-field dynamo has been developed (Beck et al. 1996). It is based on turbu-

lence, differential rotation and helical gas flows, generated by supernova explosions (Gressel et al. 2008) or by cosmic-ray driven Parker loops (Hanasz et al. 2009). The mean-field dynamo in galaxy disks predicts that within a few 10^9 yr large-scale regular fields are excited from the seed fields (Arshakian et al. 2009), forming patterns ("modes") with different azimuthal symmetries in the disk and vertical symmetries in the halo.

2. Observation of cosmic magnetism

Magnetic fields need illumination to be detectable. *Polarized emission* at optical, infrared, submillimeter and radio wavelengths holds the clue to magnetic fields in galaxies. Optical linear polarization is a result of extinction by elongated dust grains in the line of sight which are aligned in the interstellar magnetic field (the *Davis-Greenstein effect*). The E–vector runs parallel to the field. However, light can also be polarized by scattering, a process unrelated to magnetic fields and hence a contamination that is difficult to subtract from the diffuse polarized emission from galaxies, e.g. in M 51 (Scarrott et al. 1987). Optical polarization data of about 5500 selected stars in the Milky Way yielded the orientation of the magnetic field near the Sun (Fosalba et al. 2002). Together with measurements of stellar distances, a 3-D analysis of the

Table 1. Comparison of polarization observations in the optical/near-infrared and in the radio continuum range

	Optical / infrared	radio continuum
Detectors:	special analyzers	normal receivers
A. Continuum emission processes:	scattering, dust, synchrotron	synchrotron
Sources:	ISM, galactic nuclei, jets	ISM, SNRs, galactic nuclei, jets
Degrees of linear polarization:	a few %	up to 70%
Wavelength dependence:	weak	strong at long λ (Faraday depolarization)
Spectro-polarimetry:	N/A	under development
B. Line emission processes:	Zeeman, Hanle, AMR	Zeeman
Sources:	sun, stars, planets	ISM
Spectro-polarimetry:	established	N/A

magnetic field within about 5 kpc from the Sun is possible, but more data are needed.

Linearly polarized emission from elongated dust grains at infrared and submillimeter wavelengths is not affected by scattered light. The B–vector is parallel to the magnetic field. The field structure can be mapped in gas clouds of the Milky Way (e.g. Tang et al. 2009) and in galaxies, e.g. in the halo of M 82 (Greaves et al. 2000).

In the optical and near-infrared lines, the Zeeman and Hanle effects are the main polarization mechanisms, and spectro-polarimetric observations ("probing the third dimension", Oudmaijer & Harries 2008) have enormously increased our knowledge about magnetic fields in stars (Beryugina 2009). The *Atomic Magnetic Realignment (AMR)* (Yan & Lazarian 2008) mechanism predicts a few % polarization e.g. in the optical and UV lines of OI, SII and TiII, but has not yet been detected.

Most of what we know about interstellar magnetic fields comes through the detection of radio waves. *Zeeman splitting* of radio spectral lines directly measures the field strength in gas clouds of the Milky Way (Heiles & Troland 2005) 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. The assumption of energy equipartition between these two components allows us to calculate the total magnetic field strength from the synchrotron intensity (Beck & Krause 2005).

Polarized emission emerges from ordered fields. As polarization "vectors" are ambiguous by 180°, they cannot distinguish *regular (coherent) fields*, defined to have a constant direction within the telescope beam, from *anisotropic fields*, which are generated from turbulent fields by compressing or shearing gas flows and frequently reverse their direction along the other two dimensions. Unpolarized synchrotron emission indicates *turbulent (random) fields* which have random directions in 3-D and have been amplified and tangled by turbulent gas flows.

The intrinsic degree of linear polarization of synchrotron emission is about 75%. The observed degree of polarization 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 can be mapped directly (e.g. Beck 2005). At longer wavelengths, the polarization vector is rotated in a magnetized thermal plasma by *Faraday rotation*. The rotation angle increases with the square of the wavelength λ^2 and with the *Rotation Measure (RM)*, which is the integral of the plasma density and the strength of the component of the field along the line of sight. As the rotation angle is sensitive to the sign of the field direction, only regular fields 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. Dynamo modes of regular fields can be identified from the pattern of polarization angles and RMs of the diffuse polarized emission of galaxy disks (e.g. Fletcher et al. 2004).

Distinct emitting regions located on the line of sight can generate several RM components, so that the observed RM is no longer a linear function of λ^2. In such cases, multi-channel spectro-polarimetric radio data are needed that can be Fourier-transformed into Faraday space, called *RM Synthesis* (Brentjens & de Bruyn 2005, Heald 2009). If the medium has a relatively simple structure, the 3-D structure of the magnetized interstellar medium can be determined (*Faraday tomography*).

A grid of RM measurements towards polarized background sources is a powerful tool to study magnetic field patterns in galaxies (Stepanov et al. 2008). A large number of background sources is required to recognize the field patterns, to separate the Galactic foreground contribution and to account for intrinsic RMs of the extragalactic sources.

Table 1 summarizes the main properties of the observation methods.

3. Nearby Universe: Projects with the Square Kilometre Array

The SKA will allow us to investigate the interstellar medium (ISM) in nearby galaxies with much higher resolution and/or much higher sensitivity than with present-day telescopes. Several projects are discussed (e.g. Carilli & Rawlings 2004):

- HI line: Turbulence spectrum of the ISM in the Milky Way down to scales of a few AU
- HI line: ISM structure ≤ 100 pc in galaxies up to ≈ 20 Mpc distance
- HI line: Low-density gas in outer parts of galaxies
- HI line: High-velocity clouds around galaxies and in the IGM
- Zeeman effect (HI, OH and H_2O lines): Magnetic fields in nearby galaxies
- Thermal emission: Structure of ultracompact HII regions up to ≈ 1 Mpc distance and super star clusters up to ≈ 20 Mpc distance
- Thermal emission: Stellar winds and stellar jets
- Recombination lines: Structure of thermal gas in nearby galaxies
- Methanol lines: Parallaxes of masers in nearby galaxies
- Synchrotron emission: Structure and variability of knots in SNRs and of galactic nuclei
- Pulsars in the Milky Way and nearby galaxies: Testing theories of gravity and detection of gravitational waves
- Polarized synchrotron emission and Faraday rotation: Origin and evolution of cosmic magnetism.

The last two topics with underlying fundamental physical questions were chosen as Key Science Projects. The pulsar project is described elsewhere (Kramer, this volume). A summary of the SKA magnetism project is given in Section 6.

4. Magnetic fields in the Milky Way

Optical polarization data of stars at distances >1 kpc show that the magnetic field of the Milky Way is predominantly oriented parallel to the disk plane (Fosalba et al. 2002). The orientations of the polarization vectors from more nearby stars are chaotic around 80° Galactic longitude, which points to the direction of the local field.

Surveys of the total synchrotron emission from the Milky Way yield equipartition strengths of the total field of 6 μG, averaged over about 1 kpc around the Sun, consistent with the HI Zeeman splitting data of low-density gas clouds (Heiles & Troland 2005), and about 10 μG in the inner spiral arms (Berkhuijsen, in Wielebinski 2005). Faraday and dispersion measure data of pulsars give an average strength of the local regular field of $1.4 \pm 0.2 \mu$G, while in the inner Norma arm the average strength of the regular field is $4.4 \pm 0.9 \mu$G (Han et al. 2002).

In the synchrotron filaments near the Galactic center, oriented almost perpendicular to the plane, a break in the
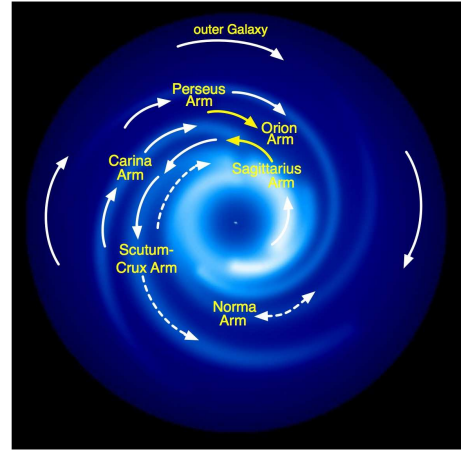
Fig. 1. Model of the magnetic field in the Milky Way, derived from Faraday rotation measures of pulsars and extragalactic sources. Generally accepted results are indicated by yellow vectors, while white vectors refer to results which are probable but not fully confirmed (from Brown, priv. comm.).

spectrum indicates that the field strength is 50–100 μG (Crocker et al. 2010).

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 large-scale field reversal is required at about 1–2 kpc from the Sun towards the Milky Way's center, which is also supported by the detailed study of RMs from extragalactic sources near the Galactic plane (Van Eck et al. 2010, Fig. 1). The overall structure of the regular field is not known yet - its structure cannot be described by a simple dynamo-type pattern (Men et al. 2008). A larger sample of pulsar and extragalactic RM data is needed.

The signs of RMs of extragalactic sources and of pulsars at Galactic longitudes l=90°–270° are the same above and below the plane (Taylor et al. 2009): the local magnetic field is part of a symmetric field structure. In contrast, the RM signs towards the inner Galaxy (l=270°–90°) are *opposite* above and below the plane. This can be assigned to an antisymmetric halo field (Sun et al. 2008) or to deviations of the local field.

Little is known about the vertical field component in the Milky Way. According to RM data from extragalactic sources, the local regular Galactic field has no significant vertical component towards the northern Galactic pole and only a weak vertical component of $B_z \simeq 0.3 \mu$G towards the south (Mao et al. 2010), while mean-field dynamo models predict vertical fields towards both poles.

5. Magnetic fields in spiral galaxies

The typical average equipartition strength of the total magnetic field in spiral galaxies is about 10 μG. Radio-faint galaxies like M 31 and M 33, our Milky Way's neighbors, have weaker total magnetic fields (5–7 μG), while
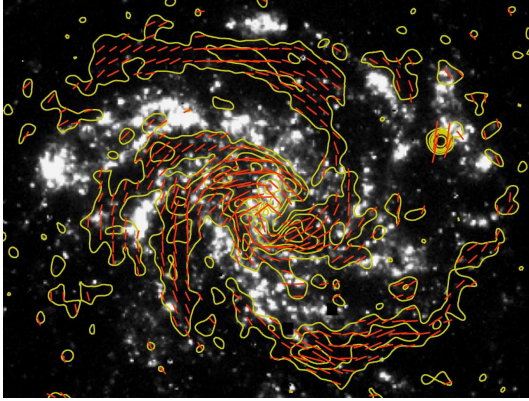
Fig. 2. Polarized radio emission (contours) and B–vectors of NGC 6946, combined from observations at 6 cm wavelength with the VLA and Effelsberg telescopes and smoothed to 15" resolution (from Beck & Hoernes 1996). The background image shows the Hα emission (from Ferguson et al. 1998). Copyright: MPIfR Bonn. Graphics: *Sterne und Weltraum*.
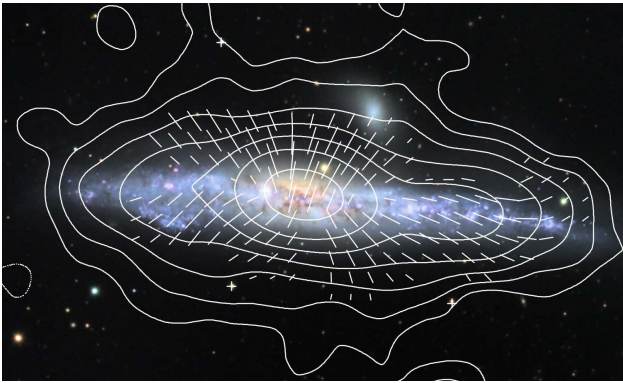
Fig. 3. Total radio emission (84" resolution) and B–vectors of the edge-on irregular galaxy NGC 4631, observed at 3.6 cm wavelength with the Effelsberg 100-m telescope. The background optical image is from the Misti Mountain Observatory. Copyright: MPIfR Bonn (from Krause 2009).

gas-rich spiral galaxies with high star-formation rates, like M 51, M 83 and NGC 6946, have total field strengths of 20–30 μG in their spiral arms. The strongest total fields of 50–100 μG are found in starburst galaxies, e.g. in M 82 (Klein et al. 1988).

The ordered fields traced by the polarized synchrotron emission are generally strongest (10–15 μG) in the regions *between* the optical spiral arms and oriented parallel to the adjacent spiral arms, in some galaxies forming *magnetic arms* (Fig. 2), probably generated by a mean-field dynamo. In galaxies with strong density waves some of the ordered field is concentrated at the inner edge of the spiral arms (Fletcher et al. 2010). The ordered field forms spiral patterns in almost every galaxy (Beck 2005), even in ring galaxies (Chyży & Buta 2008) and in flocculent galaxies without massive spiral arms (Soida et al. 2002). Spiral fields are also observed in the central regions of galaxies and in circum-nuclear gas rings (Beck et al. 2005).

Spiral fields can be generated by compression at the inner edge of spiral arms, by shear in interarm regions, or by dynamo action. Large-scale patterns of Faraday rotation measures are signatures of coherent dynamo fields and can be identified from polarized emission of the galaxy disks (Fletcher et al. 2004) or from RM data of polarized background sources (Stepanov et al. 2008). The Andromeda galaxy M 31 and several other galaxies host a dominating axisymmetric disk field, as predicted by dynamo models. However, in many observed galaxy disks no clear patterns of Faraday rotation were found. Either the field structure cannot be resolved with present-day telescopes or the generation of large-scale modes takes longer than the galaxy's lifetime (Arshakian et al. 2009).

Nearby galaxies seen edge-on generally show a disk-parallel field near the disk plane. High-sensitivity observations of NGC 4631 (Fig. 3), NGC 253 (Heesen et al. 2009) and other galaxies revealed "X-shaped" fields in the halo. The field is probably transported from the disk into the halo by an outflow emerging from the disk. Faraday RM data of NGC 253 indicate a symmetric quadrupolar field, consistent with mean-field dynamo models.

Polarized emission can also be detected from unresolved galaxies if the inclination is larger than about 20° (Stil et al. 2009). This opens a new method to search for ordered fields in distant galaxies.

6. Prospects with the SKA and its Precursors

Future radio telescopes will widen the range of observable magnetic phenomena. Low-frequency radio telescopes like the Low Frequency Array (LOFAR) and the planned Murchison Widefield Array (MWA), Long Wavelength Array (LWA) and the low-frequency part of the SKA will be suitable instruments to search for extended synchrotron radiation at the lowest possible levels in outer galaxy disks and the transition to intergalactic space (Beck 2009).

High-resolution, deep observations of the detailed field structure in the ISM of galaxies at high frequencies, where Faraday depolarization is small, require a major increase in sensitivity for continuum observations that will be achieved by the EVLA and especially by the SKA.

If polarized emission from galaxies is too weak to be detected, the method of RM grids towards background sources (QSOs) can still be applied. The *POSSUM* survey at 1.4 GHz planned with the Australia SKA Pathfinder (ASKAP) telescope with 30 deg^2 field of view (Gaensler et al. 2010) will measure about 100 RM values per square degree from polarized extragalactic sources within 10 h integration time. Measuring RM grids for a survey of nearby galaxies has been proposed for MeerKAT, the SKA precursor in South Africa. The SKA "Magnetism" Key Science Project plans to observe a wide-field survey (at least 10^4 deg^2) around 1 GHz with 1 h integration per field, which will measure at least 1500 RMs per deg^2 and a total RM number of at least 2×10^7 (Gaensler et al. 2004). More than 10^4 RM values are expected in the area of M 31 and will allow the detailed reconstruction of the

Table 2. Synergies on magnetic field investigations in the Milky Way and nearby galaxies

	SKA	E-ELT
Detailed field structure in the ISM	Sync pol	Optical or NIR pol
Field structure in molecular clouds	Sync pol	NIR pol
Field strengths in molecular clouds	Sync pol & Zeeman	NIR pol
Field ordering by gas flows	Sync pol & HI velocities	Opt./NIR pol & velocity fields
Stellar jets	Sync pol	Emission lines
Galactic Center & AGNs	Sync pol	Opt./NIR pol & emission lines

3-D field structure in this and many other nearby galaxies. Large-scale field patterns can be recognized out to distances of about 100 Mpc (Stepanov et al. 2008).

The SKA pulsar survey will find about 20 000 new pulsars which will be mostly polarized and reveal RMs, perfectly suited to measure the Milky Way's magnetic field with high precision (Noutsos 2009).

7. Synergies with the E-ELT

Polarization observations in radio continuum with the SKA and in the optical or near-infrared with the E-ELT have a lot of synergy potential (Table 2). Polarization is a standard observation mode for the SKA (Gaensler et al. 2004), but polarimetry modes with the E-ELT still need to be developed (Strassmeier & Ilyin 2009). The weak signals of optical polarimetry need large collecting areas and hence can best be done from ground, and photometric nights are not needed. *The E-ELT needs polarimeters!*

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