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Magnetic Fields in Normal Galaxies

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Abstract

Interstellar magnetic fields are strongest in massive spiral arms of galaxies (20–30 μG) and in nuclear starburst regions (up to 100 μG). Processes related to star formation tangle the field lines, so that little polarization is observed in star-forming regions. The magnetic energy density in the inner disk of galaxies is larger than the thermal energy density, comparable to that of turbulent gas motions, and is dominant in the outer disk. Large-scale spiral patterns of the regular field are observed in grand-design, flocculent and even some irregular galaxies. In grand-design galaxies the regular fields are aligned parallel to the optical spiral arms, with the strongest regular fields (highest polarization) in interarm regions, sometimes forming *magnetic spiral arms* between the optical arms. Faraday rotation of the polarization vectors reveals patterns which are signatures of coherent large-scale fields in galactic disks, probably generated by dynamo action. The majority of field structures in galaxies requires a superposition of several dynamo modes. In barred galaxies the magnetic field is mostly aligned with the gas flow, deflected by shear and compressed in the shock. The regular field is already strong in the "upstream" region ahead of the shock. Within the circumnuclear ring the magnetic field is strong, with a regular component of spiral shape. Magnetic stress may drive inflow of gas towards the nucleus. – Present-day radio polarimetry is limited by sensitivity. The next-generation radio telescope, the Square Kilometer Array (SKA), will be able to reveal the full wealth of magnetic structures in galaxies. *Cosmic magnetism* is one of the Key Science projects for the SKA.

1 Why observing magnetic fields?

Magnetic fields contribute significantly to most physical processes in the interstellar medium. They may even affect the gas flows. Magnetic fields are essential for star formation as they enable the removal of angular momentum from the protostellar cloud. MHD turbulence distributes energy from supernova explosions (D. Breitschwerdt and M. de Avillez, this volume). Magnetic reconnection is a possible heating source for the ISM and halo gas. Magnetic fields also control the density and distribution of cosmic rays in the ISM and in galactic halos.

In this review magnetic fields in the disks of more or less *normal* galaxies are discussed. For interacting galaxies and galactic halos see M. Urbanik and M. Soida (this volume).

2 How to observe magnetic fields

Magnetic fields have regular and turbulent components. From an observer's point of view, regular fields which are unresolved by the telescope's beam and truly turbulent fields cannot be distinguished, because in both cases only unpolarized radio emission is observed. *Linearly polarized synchrotron emission* is a signature of resolved regular field components in the plane of the sky. The intrinsic degree of polarization of $\simeq$74% is reduced by the contribution of unpolarized thermal radio emission from star-forming regions, by Faraday depolarization

(Sokoloff et al. 1998), and by beam depolarization. Faraday depolarization can be used for *tomography* of Galactic regions (Beck & Gaensler 2004; R. Wielebinski, this volume). Regular field components along the line of sight, together with thermal electrons, cause *Faraday rotation* of the polarization angles. In the diffuse interstellar medium Faraday rotation is generally small at wavelengths below about $\lambda 6$ cm, so that the **B**–vectors (i.e. the observed **E**–vectors rotated by 90°) directly trace the *orientation* of the regular fields in the sky plane.

Regular fields can be *incoherent or coherent*: Compression or stretching of turbulent fields generates anisotropic turbulent (incoherent) fields which reverse direction frequently within the telescope beam. The degree of polarization is high because polarization angles are ambiguous by ±180° and hence insensitive to field reversals. Faraday rotation is a signature of coherent regular fields, and the sense of rotation reveals the *sign* of the field. Hence, radio polarimetry provides 3-D information on the large-scale interstellar magnetic field.

3 Magnetic field strength and energy density

The average strength of the total $\langle B_{\mathrm{t},\perp}\rangle$ and the resolved regular field $\langle B_{\mathrm{reg},\perp}\rangle$ in the plane of the sky can be derived from the (distance-independent) total and polarized radio synchrotron intensity, respectively, assuming *equipartition* between the energy densities of cosmic rays and magnetic fields, and the ratio K ($\simeq$100) between the number densities of cosmic-ray protons and electrons. The revised formula by Beck & Krause (2005), based on integrating the energy spectrum of the cosmic-ray protons, may lead to significantly different field strengths than the classical textbook formula which is based on integration over the radio frequency spectrum. Other sources of systematic bias are spectral steepening due to energy losses of the cosmic rays (Beck & Krause 2005) and small-scale field fluctuations (Beck et al. 2003).

The mean equipartition strength of the total field for a sample of 74 spiral galaxies (Niklas 1995) is $\langle B_{\mathrm{t}}\rangle \simeq 9~\mu$G. Dwarf galaxies may host fields of similar strength as spirals if their star-formation rate is high enough (Chyży et al. 2003). In grand-design galaxies with massive star formation like M 51, M 83, and NGC 6946, $\simeq 15~\mu$G is the typical average strength of the total field. In the prominent spiral arms of M 51 the total field strength is 25–30 μG (Fletcher et al. 2004b, Fig. 1). Field compression by external forces like interaction may also lead to very strong fields (M. Urbanik, this volume). The strongest fields in spiral galaxies were found in starburst galaxies like M 82 with $\simeq 50~\mu$G strength (Klein et al. 1988), the “Antennae” (Chyży & Beck 2004) and in nuclear rings of barred galaxies (Sect. 6) with up to $\simeq 100~\mu$G strength, sufficient to drive mass inflow towards the active nucleus (Beck et al. 2005). If energy losses of electrons are significant in starburst regions or massive spiral arms, these values are lower limits (Beck & Krause 2005).

The strength of resolved regular fields B_{reg} in spiral galaxies (observed with spatial resolutions of a few 100 pc) is typically 1–5 μG. Exceptionally strong regular fields are detected in the interarm regions of NGC 6946 of $\simeq 13~\mu$G (Beck & Hoernes 1996) and $\simeq 15~\mu$G at the inner edge of the inner spiral arms in M 51 (Fletcher et al. 2004b, Fig. 1). In spiral arms the resolved regular field is generally weaker due to tangling by turbulent gas motion in star-forming regions and the expansion of supernova remnants, and the tangled+turbulent field is stronger (Sect. 4). In interarm regions the regular field is generally stronger than the tangled+turbulent field (Sect. 5).

The validity of the equipartition assumption can be tested in our Galaxy, because there is independent information about the local cosmic-ray energy density from in-situ measurements and from γ-ray bremsstrahlung data. Combination with the radio synchrotron data yields a local strength of the total field $\langle B_t \rangle$ of 6 μG and about 10 μG in the inner Galaxy (Strong et al. 2000), similar to the values derived from energy equipartition (Berkhuijsen, in Beck 2001). The revised model by Strong et al. (2004) gives somewhat weaker fields.

The relative importance of various competing forces in the interstellar medium can be estimated by comparing the corresponding *energy densities*. In the spiral galaxy NGC 6946 the energy density of the total magnetic field $E_{\rm magn}$ is one order of magnitude larger than that of the warm ionized gas $E_{\rm th}$, i.e. the ISM is a low-β plasma ($\beta = E_{\rm th}/E_{\rm magn}$) (Beck 2005). In the inner parts of NGC 6946 the energy densities of the field and the turbulent gas motions are similar, an argument for a close connection between field and gas clouds and for the action of the *turbulent dynamo* (Sect. 5). The field energy dominates over the turbulence energy of the cold gas in the outer regions of galaxies where the dynamo may be driven by the *magneto-rotational instability* (Sellwood & Balbus 1999; N. Dziourkevitch, this volume).

In the outermost parts of spiral galaxies the magnetic field energy density may even reach the level of global rotational gas motion and affect the rotation curve (Battaner & Florido 2000). Field strengths in the outer parts of galaxies can be measured by Faraday rotation of polarized background sources. Han et al. (1998) found evidence for a regular field in M 31 out to 25 kpc radius which is of similar strength as in the inner region.

4 Magnetic fields and gas clouds

The correlation between radio continuum emission and infrared emission from galaxies (far infrared as well as mid infrared) is tight and valid under a wide range of physical conditions. The relation holds for total luminosity of galaxies, from nearby objects (Niklas 1997) out to redshifts of at least $z \simeq 1$ (Appleton et al. 2004), as well as for surface brightness within individual galaxies, e.g. in NGC 6946 (Frick et al. 2001). However, on small spatial and time scales the radio–infrared correlation can be violated. For example, very young starburst galaxies are radio-deficient (Roussel et al. 2003). Either the production of cosmic rays or the amplification of magnetic fields via the dynamo mechanism is delayed with respect to the onset of the starburst.

The physical background of the relation is hardly understood. Over most of the observable frequency range the total radio emission is dominated by nonthermal synchrotron emission which increases with the square of the total field strength $B_{\rm tot}$ (or even more in case of equipartition between magnetic and cosmic-ray energy densities), so that even small variations in $B_{\rm tot}$ lead to strong variations in radio intensity. Interstellar magnetic fields are probably coupled to dense, mostly neutral gas clouds, which are mixed with the dust. Photoionization generates free electrons of sufficient density in the outer regions of gas clouds to hold the magnetic field lines. Hence, $B_{\rm tot}$ is highest in spiral arms where the density of clouds is highest. Niklas & Beck (1997) and Hoernes et al. (1998) proposed a scaling $B_{\rm tot} \propto \rho^{1/2}$ where ρ is the average density of the neutral gas (atomic + molecular) within the telescope beam, similar to the scaling observed in molecular clouds (R. Crutcher, this volume).

5 Spiral magnetic fields in galaxies: signatures of dynamo action

Radio polarization observations show that in most galaxies the resolved regular field follows the spiral structure seen in the stars and the gas (Figs. 1 and 2; I. Patrickeyev, this volume), though the regions of strongest regular fields are generally *offset* from the spiral arms. In the spiral arms, polarized emission is generally weak, because the regular field is unresolved in the spiral arms due to field tangling by increased turbulent motions of gas clouds or by supernova shock fronts, and, at longer wavelengths, due to Faraday depolarization. Turbulent fields, indicated by unpolarized emission, are generally enhanced in spiral arms, following the general scaling with gas density (Sect. 4).

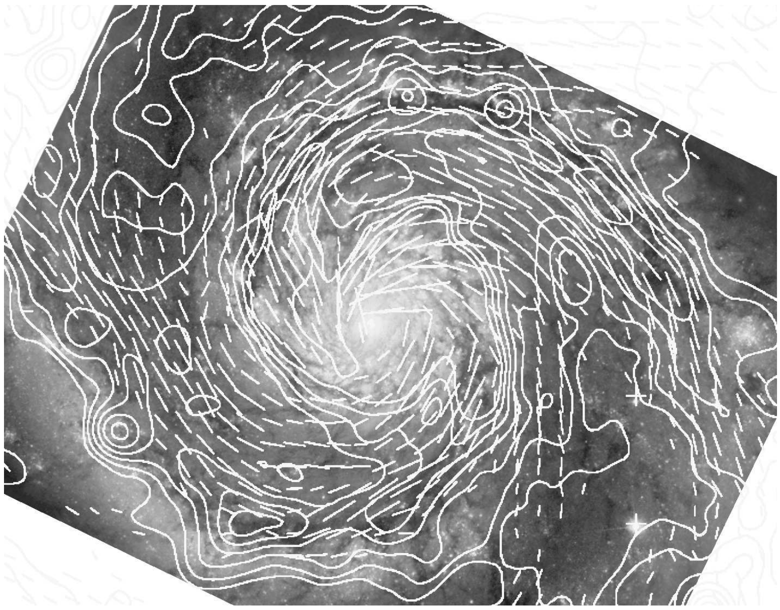

Figure 1: Total radio emission (contours) and B–vectors from the inner disk of M 51 at $\lambda 6$ cm, combined from VLA and Effelsberg observations (Fletcher et al. 2004b). The field size is 4' x 3', the beam size 6". The background image shows the optical emission observed with the Hubble Space Telescope (Hubble Heritage Project)

In *grand-design* galaxies with strong density waves like M 51 (Fig. 1) three components of the regular field can be distinguished. One component fills the interarm space. The second component is strongest at the positions of the prominent dust lanes on the inner edge of the gaseous spiral arms, as expected from field alignment by compression. However, the arm-interarm contrast is low, which is in conflict with classical shock compression models and calls for new models of spiral arm formation (e.g. Gómez & Cox 2002). The third component of regular field coincides with the outer spiral arms, without signs of compression. In M 83 (Fig. 2) regular fields are located at the inner edges of the inner optical arms, in some interarm regions, in the outer optical arms, and also at the outer edges of the small bar (see however Sect. 6). Other grand-design galaxies like M 81 (Krause et al. 1989b) show little signs of field compression; regular fields occur mainly in the interarm regions.

The gas-rich spiral galaxy NGC 6946 reveals a regular distribution of polarized emission with two symmetric *magnetic arms* located in interarm regions, without any association with observable gas or stars, and running almost parallel to the adjacent optical spiral arms (Beck & Hoernes 1996). These magnetic arms do not fill the entire interarm spaces like the polarized emission in M 81, but are less than 1 kpc wide. Their degree of polarization is exceptionally high (up to 50%); the field is *almost totally aligned.* Magnetic arms between the optical arms have been found in several other galaxies, e.g. in M 83 (Fig. 2). Regular magnetic fields may also be disconnected from the optical spiral pattern, e.g. in IC 342 (Krause et al. 1989a) and in NGC 3627 (Soida et al. 2001; M. Urbanik, this volume).

Large-scale patterns in Faraday rotation measures *RM*, as observed e.g. in M 31 (Berkhuijsen et al. 2003), show that the regular field in these galaxies has a *coherent* direction and hence is not generated by compression or stretching of turbulent fields in gas flows. The

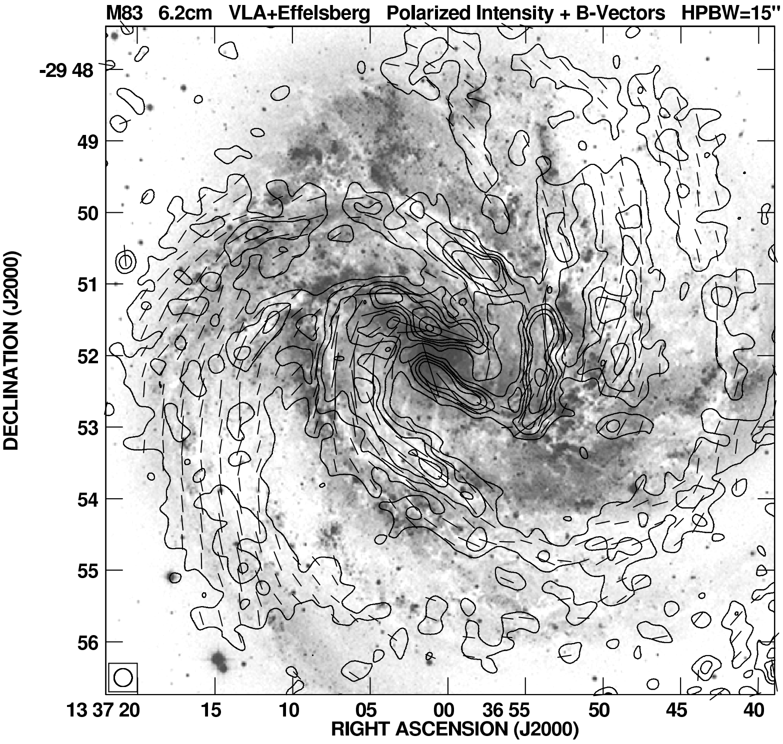

Figure 2: Polarized radio emission (contours) and B–vectors of M 83 at $\lambda6$ cm with 15" beam size, combined from VLA and Effelsberg observations (Beck, Ehle & Sukumar, unpublished); the background optical image is from the Anglo Australian Observatory (Malin, priv. comm.)

turbulent dynamo mechanism (Beck et al. 1996; see also A. Brandenburg and K. Ferrière, this volume) is able to generate and preserve coherent magnetic fields, and these are of appropriate spiral shape. However, the pitch angle of the field spiral depends on the dynamo number, *not* on the pitch angle of the gaseous spiral. The observed alignment of magnetic pitch angles with those of the gaseous arms can be achieved by inclusion of the shear flow around spiral arms (e.g. Elstner et al. 2000; D. Elstner, this volume).

The field structure obtained in *mean-field* α–Ω *dynamo models* is described by modes of different azimuthal and vertical symmetry (Beck et al. 1996). Several azimuthal modes can be excited, the strongest being $m = 0$ (an axisymmetric spiral field), followed by the weaker $m = 1$ (a bisymmetric spiral field), etc. These generate a Fourier spectrum of azimuthal *RM* patterns (Krause 1990). The axisymmetric mode with even vertical symmetry (quadrupole) is excited most easily. M 31 hosts a dominating axisymmetric field (Fletcher et al. 2004a), extending to at least 25 kpc radius (Han et al. 1998). A bisymmetric $m = 1$ mode dominates in M 81 (Krause et al. 1989b). Magnetic arms like in NGC 6946 can be described as a superposition of a $m = 0$ and a $m = 2$ mode. For most of about 20 nearby galaxies observed so far, the *RM* data indicate a mixture of magnetic modes which cannot be reliably determined due to low angular resolution and/or low signal-to-noise ratio.

In *flocculent galaxies*, regular magnetic fields with strengths similar to those in grand-design spiral galaxies have been detected, e.g. in M 33 (Buczilowski & Beck 1991), NGC 3521 and NGC 5055 (Knapik et al. 2000), and in NGC 4414 (Soida et al. 2002). The mean degree of polarization (corrected for different spatial resolutions) is similar between grand-design and flocculent galaxies (Knapik et al. 2000). Spiral patterns are observed in all flocculent galaxies, indicative that the dynamo works without assistance from density waves. The multi-wavelength data of M 33 and NGC 4414 call for a mixture of dynamo modes (Fletcher et al. 2000, Soida et al. 2002).

The Large Magellanic Cloud shows indications of an axisymmetric field (B. Gaensler, this volume). In the slowly rotating, Magellanic-type irregular galaxy NGC 4449, the field is partly regular with some spiral pattern (Chyży et al. 2000), while in chaotically rotating irregular galaxies like NGC 6822 the field is mostly tangled (Chyży et al. 2003). Such galaxies require field amplification e.g. by the *fluctuation dynamo*, producing only turbulent fields (Subramanian 1998; A. Schekochihin, this volume).

6 Magnetic fields in barred galaxies: mapping the gas flow

10 northern galaxies with large bars were observed with the Very Large Array (VLA) and 10 southern barred galaxies with the Australia Telescope Compact Array (ATCA) (Beck et al. 2002). The symmetry of the velocity fields in these galaxies is distorted by the bar's gravitational potential, leading to enhanced velocity shear of the gas streaming.

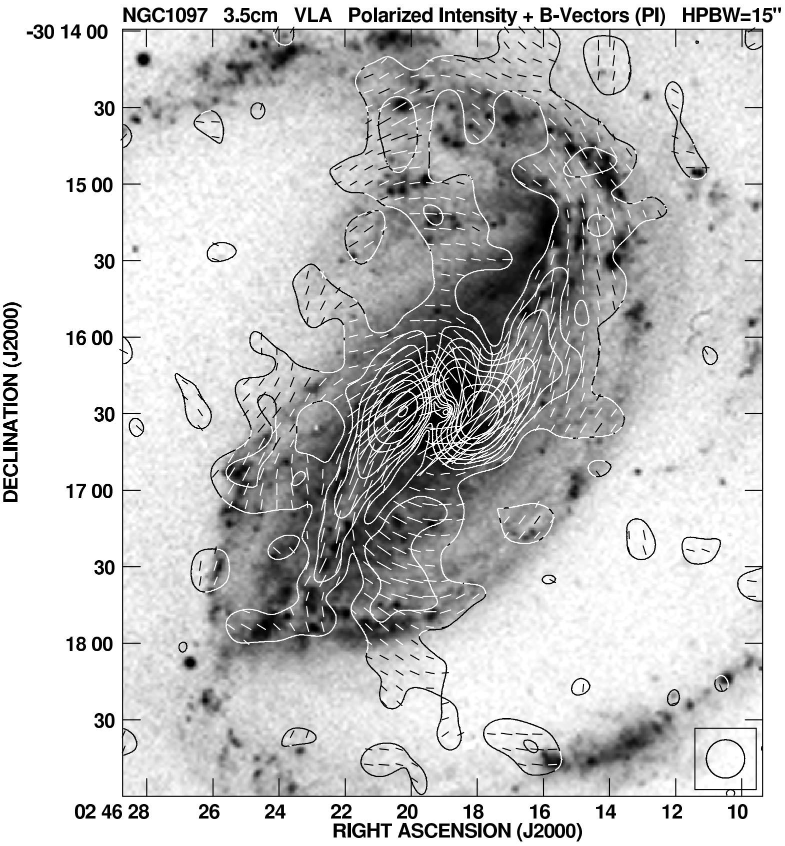

Figure 3: Polarized radio emission (contours) and B–vectors of the barred galaxy NGC 1097 at $\lambda3.5$ cm with 15" beam size, observed with the VLA (Beck et al. 1999, 2002). The background optical image is from the Cerro Tololo Observatory (Arp, priv. comm.)

NGC 1097 hosts a huge, radio-bright bar of about 16 kpc length. The total radio intensity is strongest in the region of the bar's dust lanes, consistent with shock compression. High polarized intensities (strong regular fields) occur outside of the bar ("upstream"), and the field lines are oriented at large angles with respect to the bar (Fig. 3). The general similarity of the B–vectors in NGC 1097 and gas streamlines around the bar as obtained in numerical simulations (Athanassoula 1992) is striking. This suggests that the regular magnetic field is aligned with the shearing flow (Beck et al. 1999). The "upstream" and the compression regions ("downstream") in the southern bar are separated in polarized emission by a strip of low polarized intensity where the regular field changes its orientation by almost 90° (Fig. 3). This observation implies that the region of strongest shear in the magnetic field is located $\simeq 800\,\mathrm{pc}$ in front of the dust lanes, in contrast to the velocity field predicted from the numerical simulations. Either the regular field is not coupled to the dense gas and avoids the shock, or the existing simulations are insufficient to model magnetized shocks. High-resolution observations of the velocity field and MHD models are required.

Galaxies with large bars often host circumnuclear rings which are sites of intense star formation, sometimes with an active nucleus in its center. NGC 1097 hosts a large ring of 1.5 kpc diameter. A regular magnetic field of spiral shape extends between the ring and the nucleus, with a large pitch angle similar to that of the spiral dust filaments visible on optical images. Magnetic stress in the ring with its strong field can drive mass inflow which is sufficient to fuel the activity of the nucleus (Beck et al. 1999, 2005).

7 Prospects

High-frequency radio polarization observations have revealed the large-scale properties of the interstellar magnetic fields in most nearby galaxies. Polarization observations at lower frequencies in our Galaxy (M. Haverkorn and R. Wielebinski, this volume) are complementary to extragalactic observations as they trace structures of pc and sub-pc sizes. However, the physical connection between the features at large and small scales is not yet understood. Radio polarization observations of external galaxies at better angular resolution and of selected Galactic regions at higher frequencies are needed to map the full wealth of magnetic structures in galaxies. Furthermore, the velocity field of the gas should be measured in more detail, to provide input for dynamo and MHD models.

The *Square Kilometer Array* (SKA) will be able to map nearby galaxies with at least 10x better angular resolution compared to present-day radio telescopes, or 10x more distant galaxies with similar spatial resolution as today (Beck & Gaensler 2004). Magnetic field structures will illuminate the dynamical interplay of cosmic forces. The SKA's sensitivity will allow to detect synchrotron emission from the most distant galaxies in the earliest stage of evolution and to search for the earliest magnetic fields and their origin. *Cosmic Magnetism* is one of the Key Science Projects for the SKA (Gaensler et al. 2004).

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