

Magnetic fields in galactic haloes

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Abstract Magnetic fields on a range of scales play a large role in the ecosystems of galaxies, both in the galactic disk and in the extended layers of gas away from the plane. Observing magnetic field strength, structure and orientation is complex, and necessarily indirect. Observational data of magnetic fields in the halo of the Milky Way are scarce, and non-conclusive about the large-scale structure of the field. In external galaxies, various large-scale configurations of magnetic fields are measured, but many uncertainties about exact configurations and their origin remain. There is a strong interaction between magnetic fields and other components in the interstellar medium such as ionized and neutral gas and cosmic rays. The energy densities of these components are comparable on large scales, indicating that magnetic fields are not passive tracers but that magnetic field feedback on the other interstellar medium components needs to be taken into account.

Keywords cosmic magnetism; spiral galaxies; Milky Way; magnetic fields; interstellar medium; galactic haloes

1 Introduction

Significant magnetic fields are present not only in galaxy disks, but also in the gaseous galactic halo¹. Magnetic fields in these galactic haloes can provide a significant pressure component to counteract the gravity of the halo gas (Boulares & Cox 1990). Also, they play a major role in the disk-halo interaction, influencing superbubble break-out and funneling particles out to intergalactic space. Finally, the determination of the

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¹ The term 'galactic halo' is used here to describe the medium above the galactic disk, also sometimes referred to as the thick disk. In this definition, the gaseous halo of a galaxy has not necessarily a direct relationship to the spherical stellar halo.

morphology of halo magnetic fields can shed light on the validity of various dynamo models to explain the origin and evolution of galactic magnetism.

We will first give a brief summary of the conditions in the haloes of the Milky Way and nearby spirals in Section 2 and 3. Sections 4 to 6 describe magnetic field strengths, scale heights, and structure in the Milky Way and external spiral galaxies. Finally, in Section 7 we briefly discuss the interaction of magnetic fields with other interstellar medium components.

2 Gaseous components in galactic haloes

2.1 The Galaxy

The interstellar medium (ISM) in the halo of the Milky Way consists of the three-phase medium as in the disk, but with varying filling factors and scale heights. While there is a warm neutral hydrogen layer and cold neutral hydrogen clouds at large distances from the Galactic plane (Dickey & Lockman 1990), coupled to magnetic fields through charge exchange, the most direct influence on magnetic field structure comes from the halo plasma.

Estimates for the scale height of the Warm Ionized Medium (WIM) in the Milky Way vary between ~ 1000 and ~ 1800 pc (Reynolds 1991; Gaensler et al. 2008; Savage & Wakker 2009). The volume filling factor of the WIM is believed to increase from $f \sim 0.1$ at the Galactic mid-plane to $f > 0.3$ at $|z| = 1000$ pc (Berkhuijsen et al. 2006). Whereas H II regions dominate the WIM distribution in the Galactic plane, at high latitudes H α emission from the WIM is more diffuse and pervasive (Haffner et al. 2003).

Hot, $\sim 10^6$ K gas existing inside supernova remnants and superbubbles is predicted to have a filling factor of about $\sim 20\%$ (Ferrière 1998). This estimate is confirmed by the filling factor of large neutral hydrogen holes (Heiles 1980) and observations of O VI UV absorption lines (Shelton & Cox 1994). A patchy distribution of hot gas at high latitudes is seen in fluctuations in the projected O VI column densities (Hurwitz & Bowyer 1996) and from X-ray shadows of interstellar clouds. Estimates of the hot gas scale height, from absorption lines of high-ionization ions like O VI and N V, range from about 3 to 5 kpc (Ferrière 2001).

2.2 External galaxies

Rossa & Dettmar (2003a,b) reported a mean vertical extent of 1-2 kpc of the diffuse ionized gas (DIG)² in external spiral galaxies, if they possess warm dust as indicated by the FIR $\lambda_{60}/\lambda_{100}$ ratio. This shows that gaseous haloes are connected to the star formation activity in the underlying disk. External galaxies also possess hot X-ray emitting gas with a scale height in the range 4-8 kpc (Strickland et al. 2004). Tüllmann et al. (2000) showed that this gas is again correlated with the presence of warm dust, as for the extraplanar DIG.

² Following convention, we call the layer of ionized gas in spiral galaxies the Warm Ionized Medium (WIM) in the Milky Way, and Diffuse Ionized Gas (DIG) in external galaxies.

3 Cosmic rays

3.1 Scale height

The Galaxy: From estimates of the gamma-ray radiation from the Compton Gamma-Ray Observatory in the 1 – 30 MeV band, and isolating the inverse Compton component, Strong et al. (1996) concluded that the cosmic ray scale height is probably much larger than that of the gas. An alternative method to estimate the vertical scale height of cosmic rays is based on counts of cosmic ray nuclei such as Li, Be, and B, created in collisions of primary cosmic ray nuclei with interstellar hydrogen. Using this method, Bloemen et al. (1993) derived a cosmic ray scale height ≤ 3 kpc at the solar radius, consistent with values found by Webber et al. (1992). The cosmic ray equivalent scale height derived from observed synchrotron emissivities in the Galaxy is about 2 kpc, in agreement with the estimates above (Ferrière 2001).

Modeling of the Galactic synchrotron distribution from an all-sky survey at 408 MHz (Haslam et al. 1982) shows that the synchrotron emissivity in the Milky Way consists of a thick and a thin disk (Beuermann et al. 1985). The scale heights of these components are ~ 150 pc and ~ 1500 pc, respectively (after rescaling to a Galactocentric radius of 8.5 kpc), and 90% of the total power is emitted in the thick disk. The equipartition³ value for the cosmic ray scale height derived from this again roughly agrees with the above estimates.

External galaxies: Similarly, in external galaxies vertical profiles of the synchrotron emission can be characterized by two components, a thin disk with a scale height of 300 pc and a thick disk with a scale height of 1.8 kpc (at 4.8 GHz). These numbers are remarkably independent of the star-formation rate (Krause 2009). If we assume equipartition, the scale height of the electrons would thus be 3.6 kpc. Not much is known if the cosmic-ray nuclei and the electrons are transported together but this is generally assumed. Therefore, for electrons with an energy of a few GeV, the scale height in external galaxies agrees roughly with the ones quoted above for the Galaxy.

3.2 Cosmic-ray transport

The luminosity of X-ray emission in the center of the Milky Way can only be explained if the Galaxy possesses a wind that is hybridly driven by cosmic rays and the thermal gas (Everett et al. 2008). Due to the interaction with the ions and electron in the so-called streaming instability the cosmic rays can push out the ionized gas by momentum transfer, and – if there are sufficient ion-neutrals collisions – also the neutral gas. In a study of the resolved emission in NGC 253 it was shown that the scale height of the electrons is proportional to their lifetime leading to an estimate of 300 km s^{-1} as the cosmic-ray bulk speed. This is similar to the escape velocity in this galaxy and rather constant across the full extent of the disk, so that a “disk wind” was proposed (Heesen et al. 2009a).

³ The equipartition assumption indicates equal energy densities in the magnetic field and cosmic rays. It is often used to estimate magnetic field strengths from measured synchrotron emissivities, and generally holds well on galaxy-size scales.

4 Magnetic field scale height and strength

4.1 Scale heights

The Galaxy: From hydrostatic equilibrium considerations, Boulares & Cox (1990) determined that cosmic rays, magnetic fields, and a significant fraction of the ISM should have scale heights in excess of 1 kpc. In particular, the magnetic field strength only decreases by $\sim 30\%$ out to a distance of a kpc from the Galactic plane. A measure for the scale height of the Galactic magnetic field can also be found from the synchrotron scale height. Beuermann et al. (1985) modeled synchrotron emissivity from measurements of Haslam et al. (1981, 1982), which indicates a magnetic field scale height at the location of the Sun of about 4.5 kpc (Ferrière 2001). This scale height agrees with estimates considering hydrostatic equilibrium in the halo (Kalberla & Kerp 1998). The discrepancy with the smaller scale height of the regular magnetic field component found from Faraday rotation measurements was explained by Boulares & Cox (1990) by stating that the Galactic magnetic field becomes less regular away from the plane. Alternatively, these measurements may be explained by two separate magnetic field components with different scale heights (Andreasyan & Makarov 1988; Han & Qiao 1994), consistent with observations of a two-layer structure of the Galactic non-thermal synchrotron emission (Beuermann et al. 1985).

External galaxies: The scale heights in external galaxies can be estimated from the synchrotron scale height. If we assume equipartition, we obtain that the magnetic field scale height is a factor of 4 larger than the synchrotron scale height and thus about 6 kpc.

4.2 Field strengths

The Galaxy: Much is still unknown about the magnetic field strength and structure in the Milky Way at large distances from the Galactic plane. Sun et al. (2008) modeled the magnetic field in the Galactic halo as a plane parallel field superimposed on a turbulent component, based on synchrotron emissivity and Faraday rotation data. They found that the halo field is unrealistically high with a 1 kpc scale height, but when using a scale height of 1.8 kpc, their estimate of the regular magnetic field strength in the Galactic halo goes down to reasonable values of $2 \mu\text{G}$.

External galaxies: Using the energy equipartition condition the total magnetic field strength in galaxies is $9 \pm 3 \mu\text{G}$ (Niklas & Beck 1997). From the linear polarization one can derive the regular magnetic field strength as typically $1 - 5 \mu\text{G}$ in the disk (Krause 2009). In the halo, the magnetic field is dominated by the regular component as opposed to the disk. The regular component in the halo is of the order of the disk component, if we neglect stronger fields that are found in the interarm regions in the disk such as in NGC 6946 (Beck 2007, Beck, this volume).

5 Magnetic field structure in the Galaxy

Galactic magnetic fields are maintained and amplified by dynamo action (see Brandenburg et al, this volume). The simplest model is that of the $\alpha - \omega$ dynamo, which

amplifies the radial magnetic field component through differential rotation, and amplifies the azimuthal and poloidal components of the field by turbulent loops twisted by the Coriolis force. Although the $\alpha-\omega$ dynamo is believed to act in the Sun (Ossendrijver 2003), it is considered unable to sufficiently amplify galactic magnetic fields to observed values (eddy diffusion time scales are much shorter than time scales for amplification of the regular field, thereby suppressing turbulent motions, and quenching the dynamo). Various solutions to this problem are discussed in Widrow (2002). For a flat disk-like galaxy which is differentially rotating, mean-field dynamo theory predicts a quadrupolar magnetic field configuration, where the direction of the azimuthal magnetic field is the same above and below the plane, but the direction of the vertical magnetic field component reverses with respect to the plane. However, for a spherical, weakly rotating structure – such as a Galactic halo – the dipolar configuration is more easily excited, i.e. an azimuthal magnetic field with reversing direction across the Galactic plane, while the vertical field is directed in the same way above and below the plane (see Figure 1).

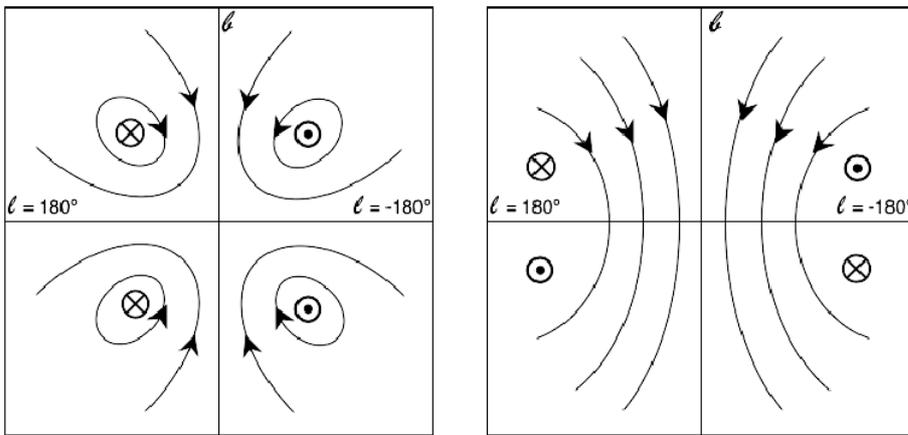


Fig. 1 Quadrupole (left) and dipole (right) large-scale magnetic field configurations of the Milky Way as a function of Galactic longitude and latitude. Magnetic field towards the viewer is denoted by a dot, field away from the observer as a cross.

These two configurations can be observationally distinguished by the directions of the azimuthal magnetic field component above and below the Galactic plane, and by the directions of the vertical field components above and below the plane. Firstly, measurements of Faraday rotation of extragalactic sources show a pronounced anti-symmetric “butterfly pattern” with respect to the Galactic plane and the meridian through the Galactic center (Simard-Normandin & Kronberg 1980), only visible in the inner Galaxy (first and fourth Galactic quadrants). This has been interpreted as a reversal of the direction of the azimuthal magnetic field with respect to the Galactic plane indicative of a dipolar magnetic field configuration and an A0 dynamo (Han et al. 1997), but can possibly also be due to the influence of local structures on large angular scales (Wolleben et al. 2010; Stil et al. 2011). Secondly, a vertical component of the Galactic magnetic field is predicted by Boulares & Cox (1990) to provide a magnetic tension term that can balance other pressure components in the Galactic disk and halo (see also Andreasyan & Makarov 1988). Mao et al. (2010) tried to measure this

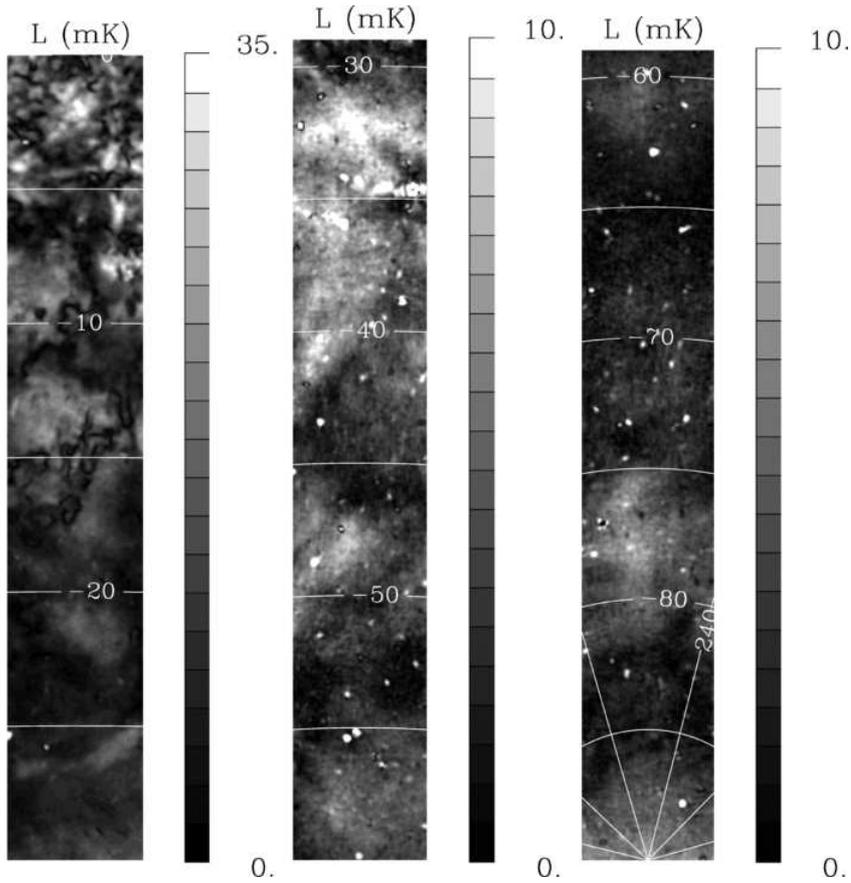


Fig. 2 Linearly polarized intensity from the Parkes Galactic Meridian Survey (Carretti et al. 2010) at 2.3 GHz shows small-scale structure in linear polarization at all Galactic latitudes, indicating small-scale structure in the electron-density weighted magnetic field.

vertical magnetic field component at high latitudes. At the solar radius, they found a small vertical magnetic field component of $B_z = 0.31 \pm 0.03 \mu\text{G}$ towards negative Galactic latitudes but not towards positive latitudes, indicating smaller-scale structure in the halo magnetic field. These conclusions agree with the structure in the X-ray halo (Ferrière 2001) and with star light polarization measurements. Taylor et al. (2009) include the North Polar Spur region in their determination of vertical magnetic field strengths and do find a small vertical magnetic field component $B_z = -0.14 \pm 0.02 \mu\text{G}$, while their estimates towards the southern sky agree with Mao et al. (2010).

Schnitzeler et al. (2007) also find a small, varying vertical magnetic field component at intermediate positive latitudes in the outer Galaxy. De Bruyn et al. (2006) conclude from radio polarimetric measurements at high Galactic latitudes that there must be significant variations in the vertical component of the Galactic magnetic field on the level of $1\mu\text{G}$, similar to the strength of the random magnetic field component at high Galactic latitudes (Mao et al. 2010). However, the studies by Schnitzeler et al. (2007)

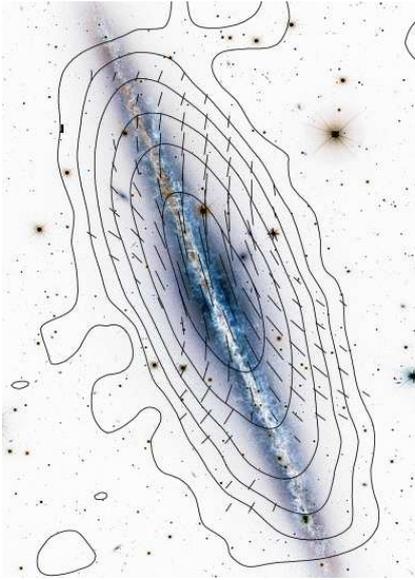


Fig. 3 Radio continuum emission of the edge-on spiral galaxy NGC 891 at $\lambda 3.6$ cm (8.35 GHz) with the 100 m Effelsberg telescope with a resolution of $84''$ HPBW. The contours give the total intensity, the vectors the intrinsic magnetic field orientation (Copyright: MPIfR Bonn). The radio map is overlaid on an optical image of NGC 891 from the Canada-France-Hawaii Telescope/(c)1999 CFHT/Coelum. From Krause (2009).

and De Bruyn et al. (2006) were performed at low frequencies, which indicates that they may be probing mostly nearby structure. The higher-frequency Parkes Galactic Meridian Survey at 2.3 GHz detects polarized emission from a larger path length and shows that even towards the southern Galactic pole, there is still small-scale structure in radio polarization, indicating structure in the density-weighted Galactic magnetic field on scales of degrees (Carretti et al. 2010, see Fig. 2).

Small-scale structure in the high latitude magnetic field is confirmed by measurements of linear polarization of starlight. Starlight which propagates through asymmetric dust grains aligned in a magnetic field will become partially polarized with a polarization angle in the average direction of the magnetic field perpendicular to the line of sight in the dusty regions between the star and the observer. Berdyugin and co-workers published a series of papers (e.g. Berdyugin & Teerikorpi 2001; Berdyugin et al. 2001, 2004) on polarization directions of stars at high latitude, which probe mostly the direction of the field component parallel to the Galactic plane. They concluded (1) that this magnetic field towards the southern Galactic pole is oriented towards $l \approx 80^\circ$, in agreement with a spiral magnetic field, and (2) that smaller-scale structure towards the northern Galactic pole precluded any conclusions about the ordered field component there. As the polarization percentages keep increasing towards higher distances from the plane, out to their furthest stars at about 500 pc, they concluded that Galactic magnetic fields reach at least to 500 pc without significant decrease.

6 Magnetic field structure in external galaxies

6.1 Field orientation

The magnetic field is mainly aligned parallel to the disk in regions close to the mid plane. In the halo, the vertical component becomes stronger with increasing height

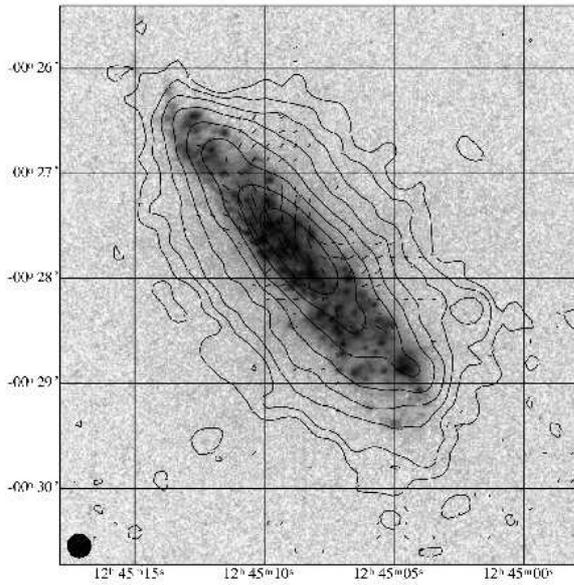


Fig. 4 Radio continuum emission of NGC 4666 at $\lambda 6$ cm from VLA observations with $14''$ HPBW. The vectors show the magnetic field orientation where the length is proportional to the polarized emission. The background shows $H\alpha+N[II]$ emission, showing the spatial correlation of optical emission line and (polarized) radio synchrotron emission from the halo. From Dahlem et al. (1997).

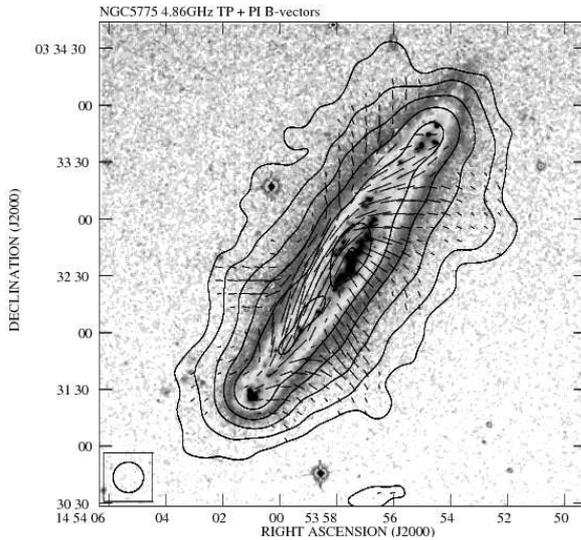


Fig. 5 Radio continuum emission of NGC 5775 at $\lambda 6$ cm from VLA observations with $14''$ HPBW. The vectors show the magnetic field orientation where the length is proportional to the polarized emission. The background shows $H\alpha$ emission. From Tüllmann et al. (2000).

above the disk. Also the magnetic field is more ordered as indicated by the higher polarization degree in the halo. Galaxies that have a radio halo possess also vertical fields.

Several disk galaxies viewed edge-on show X-shaped magnetic fields in their haloes as shown in Fig. 3 for the case of NGC 891. The orientation of the magnetic field aligns with the X in the four quadrants and the polarized emission is enhanced there. Some galaxies have distinctive sites with significant vertical magnetic field components that are referred to as “radio spurs”. They correlate in position with filamentary $H\alpha$ emission

sticking out from the disk into the halo. Examples for this are NGC 4666 (Dahlem et al. 1997) and NGC 5775 (Tüllmann et al. 2000). This is illustrated in Figs. 4 and 5.

The reason for this structure is not yet clear. It could be related to the flow of gas in the halo that has X-shaped structure as well (Dalla Vecchia & Schaye 2008). The energy densities of the magnetic field and the gas are comparable, so that interaction between the two is possible. Heesen et al. (2009b) showed that NGC 253 also has an X-shaped field. This is in so far remarkable as the halo field can only be revealed after subtraction of a model field for the disk, because this galaxy has an inclination angle of 78° and is therefore not exactly edge-on. In the case of NGC 253, Heesen et al. (2009b) suggested that the halo magnetic field may be enhanced by compression due to expanding hot gas in the halo that is visible as a conical outflow in X-ray emission (see Fig. 6). Consequently, radio spurs should align with the boundary of the outflow cone and the magnetic field be roughly tangential to it.

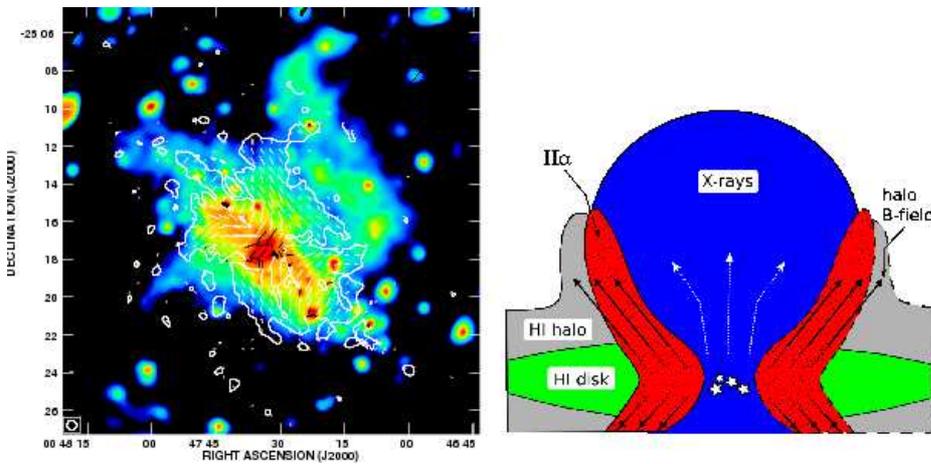


Fig. 6 Left: halo magnetic field in NGC 253 overlaid on diffuse X-ray emission. Contours show the intensity of the polarized emission of the halo magnetic field. Vectors show the orientation of the halo magnetic field where the length is proportional to the polarized intensity. Right: proposed halo structure of NGC 253. The superbubble, filled with soft X-ray emitting gas, expands into the surrounding medium (indicated by dotted lines with arrows). The halo magnetic field is aligned with the walls of the superbubble. Dashed lines denote components that are not (or only weakly) detected in the southwestern half of NGC 253. Figures from Heesen et al. (2009b).

An example of non-X-shaped fields is NGC 4631 with a rather more dipolar field structure, where the vertical component of the magnetic field dominates as shown in Fig. 7. This may be a case where the field is dominated by an interaction with a nearby companion or where differential rotation is weak and thus the A0 dynamo mode is excited (Golla & Hummel 1994). Deviations from the X-shaped field structure are also found for galaxies which do not have star formation driven outflows. NGC 4258 (Krause & Löhner 2004) and NGC 4569 (Chyży et al. 2006) are examples for jet magnetic fields. There the magnetic field is vertically aligned to the disk and parallel to the outflow in the jet.

Vertical magnetic fields are also indirectly detected. M 82 has vertical filaments and gaps in the radio continuum emission at $\lambda 20$ cm with a width of 100 pc (Reuter et al.



Fig. 7 Radio continuum emission of NGC 4631 at $\lambda 3.6$ cm with $84''$ HPBW from observations with the 100 m Effelsberg telescope. The vectors show the magnetic field orientation where the length is proportional to the polarized emission. The background is an optical image taken at the Misti Mountain Observatory (Copyright: MPIfR Bonn). From Krause (2009).

1992; Wills et al. 1999). Vertical fields were detected with radio continuum polarimetry in this galaxy albeit at a lower resolution, which likely prevented the detection of filaments (Reuter et al. 1994). Wills et al. (1999) tried to connect the filaments to chimney structures, i.e. blow outs by clustered supernovae, but the outflow visible in CO line emission was only related to a weaker minimum in the continuum emission. Duric et al. (1998) found vertical “tentacles” of a flat spectral index component protruding from the disk into the halo in NGC 5775. If they are interpreted as outflows of young cosmic-ray electrons, there needs to be some vertical alignments for which magnetic fields are the favored mechanism. There are other indicators of vertical fields like vertical dust filaments in NGC 253 (Sofue et al. 1994). These filaments are thin (≤ 50 pc) compared to the resolution of the available radio maps and are thus far not detected in the continuum or polarized emission.

Nuclear outflows are a good site to study filaments in the radio continuum, because they are very bright and allow us to use high resolution. Although they are not located in the halo, they are at the base of the conical outflows discussed above. They may be also a source for vertical fields. An example for nuclear outflow is NGC 3079 which has a prominent bowl-shaped structure visible as $H\alpha$ filaments. The polarized emission is concentrated in filaments bordering the outflow cone and is tangential to it (Cecil et al. 2001). Similarly, the outflow cone in NGC 253 is bordered by continuum filaments with a scale height of 150 ± 20 pc with the field orientation parallel to the filaments (Heesen et al. 2011). The magnetic field may collimate the nuclear outflows and thus explain the small opening angles $\sim 30^\circ$ of the cones.

Whereas interaction in the interstellar medium can explain the distribution of the fields in filaments, it does not *generate* vertical magnetic fields. For this the galactic dynamo is a favorite process. Vertical magnetic fields may also be generated by the Parker instability where cosmic-ray gas inflates magnetic field lines that reconnect and give rise to the fast Parker dynamo (Parker 1992). These magnetic fields would be expected to be anisotropic with frequent field reversals. This configuration is expected to have reversals in the line-of-sight component which can be detected in Faraday rotation.

6.2 Field direction

The halo rotation measures (RMs) are difficult to measure, because they can overlap with the RMs in the disk which dominate the polarized emission. Recent papers have tried to separate the contributions from the disk and halo by using models of the magnetic field structure. Heesen et al. (2009b) found in NGC 253 a magnetic field that points outward on the near side of the halo, but the data is not conclusive for the halo behind the bright polarized emission in the disk. The field direction has some consequence for the dynamo models because in the presence of a galactic wind the parity of the disk and halo field are expected to be identical (Moss et al. 2010).

Braun et al. (2010) explained the asymmetry of the polarized emission with respect to the receding and approaching side of the galaxy with halo fields. In their sample of 21 galaxies detected in polarization (Heald et al. 2008) they found directions that resemble both the quadrupolar type of fields and dipolar radially directed fields. The magnetic field structure in the halo is also of interest for angular momentum transport. If the field lines are stiff and we do not measure any azimuthal component then we know that we are below the Alfvénic point. The higher up the Alfvénic point the more angular momentum is transported from the disk into the halo (Zirakashvili et al. 1996).

The Parker fast dynamo would see RM reversals as part of Parker loops. Such a reversal was observed in the nuclear outflow in NGC 3079 (Cecil et al. 2001). In NGC 1569 the vertical magnetic field borders an outflow bubble and is also accompanied with a field reversal (Kepley et al. 2010). In principle it is possible to distinguish between the anisotropic and the isotropic component of the halo field by comparing the field strengths from the RM and equipartition. This was attempted by Heesen et al. (2009b) where they found the field component from the RM to be only 50% lower than that from equipartition. This would mean that the halo field has only a small anisotropic component generated by Parker loops.

7 Interaction of the magnetic field with the interstellar medium

Interstellar magnetic fields are in constant interaction with the other components in the interstellar medium. Magnetic fields are mostly directly frozen into the ionized gas component, but also closely interact with the neutral gas through charge exchange (for an example, see McClure-Griffiths et al. 2006). On large scales, the magnetic field energy density is comparable to the cosmic ray energy density and the turbulent gas energy density (see Heiles & Haverkorn this volume; and Beck, this volume). This means that any of these components can only be fully understood if the interaction with the other components is taken into account.

Therefore, gas dynamics is greatly influenced by magnetic fields. Numerical simulations show that expansion of supernova remnants in a magnetized medium will be anisotropic (Stil et al. 2009) and slower (Ferrière et al. 1991) than in the non-magnetized case. Magneto-hydrodynamic turbulence can be a significant source of heating in the ISM (e.g. Scalo & Elmegreen 2004), as can magnetic reconnection (Zimmer et al. 1997).

Magnetic fields play a large role in the hydrostatic equilibrium of the Milky Way. Thick gas disks, as observed in the Milky Way, with purely azimuthal magnetic fields, have a tendency to become unstable (e.g. Parker 1969). Boulares & Cox (1990) show

that magnetic tension in a small vertical component of the magnetic field may stabilize this configuration and so help to keep the thick gas layer from collapsing onto the disk.

Cosmic rays are tightly coupled to galactic magnetic fields. These charged particles gyrate around magnetic field lines with a Larmor radius depending on their energy and the magnetic field strength. Therefore, magnetic fields effectively trap all except the most energetic cosmic rays in galaxies and fully determine their trajectories. Also, magnetic fields are a major factor in acceleration of these charged particles to their relativistic velocities. For more details, see Aharonian et al. (this volume).

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