

Galactic dynamos and galactic winds

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Abstract Spiral galaxies host dynamically important magnetic fields which can affect gas flows in the disks and halos. Total magnetic fields in spiral galaxies are strongest (up to 30 μG) in the spiral arms where they are mostly turbulent or tangled. Polarized synchrotron emission shows that the resolved regular fields are generally strongest in the interarm regions (up to 15 μG). Faraday rotation measures of radio polarization vectors in the disks of several spiral galaxies reveal large-scale patterns which are signatures of coherent fields generated by a mean-field dynamo. Magnetic fields are also observed in radio halos around edge-on galaxies at heights of a few kpc above the disk. Cosmic-ray driven galactic winds transport gas and magnetic fields from the disk into the halo. The halo scale height and the electron lifetime allow to estimate the wind speed. The magnetic energy density is larger than the thermal energy density, but smaller than the kinetic energy density of the outflow. There is no observation yet of a halo with a large-scale coherent dynamo pattern. A global wind outflow may prevent the operation of a dynamo in the halo. Halo regions with high degrees of radio polarization at very large distances from the disk are excellent tracers of interaction between galaxies or ram pressure of the intergalactic medium. The observed extent of radio halos is limited by energy losses of the cosmic-ray electrons. Future low-frequency radio telescopes like LOFAR and the SKA will allow to trace halo outflows and their interaction with the intergalactic medium to much larger distances.

Keywords Galaxies: halos · Galaxies: magnetic fields · Galaxies: spiral · Intergalactic medium · Radio continuum: galaxies

1 Introduction

Galactic halos are dynamical systems receiving their energy from the underlying star-forming disk. Hot thermal gas from supernova remnants or superbubbles can drive fountain outflows, but no steady wind (Breitschwerdt et al. 1991). Cosmic rays accelerated in supernova remnants can provide the pressure to drive a wind. Cosmic rays also drive buoyant loops of magnetic fields via the Parker instability (Hanasz et al. 2002) (see also Avillez, this volume) and a fast dynamo which amplifies the magnetic field (Parker 1992; Moss et al. 1999; Hanasz et al. 2004). Streaming instabilities of the cosmic-ray flow excite plasma waves in the halo and couple the gas to the outflow (Breitschwerdt et al. 1991). Magnetic reconnection can heat the gas (Zimmer et al. 1997). Outflows from starburst galaxies in the early Universe may have magnetized the intergalactic medium (Kronberg et al. 1999), but the role of present-day galaxies is still unclear. Understanding the interaction between the gas and the magnetic field in the outflow is the key to understand the physics of halos and their role during the evolution of galaxies.

2 The tools of radio synchrotron emission

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

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component in the sky plane. The degree of linear polarization can be up to 75%. Any variation of the field orientation within the beam reduces the degree of polarization. Polarized emission emerges from regular fields, which are fields having a constant direction within the telescope beam, or from anisotropic magnetic fields, which are generated from random magnetic fields by a compressing or shearing gas flow and frequently reverse their direction by 180° on scales smaller than the telescope beam. Unpolarized synchrotron emission indicates fields with random directions which have been tangled or created by turbulent gas flows.

At short radio wavelengths the orientation of the observed polarization vector is perpendicular to the field orientation. 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. 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. 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 Magnetic fields in spiral arms and bars

The total magnetic field strengths can be determined from the intensity of the total synchrotron emission, assuming energy equipartition between the total magnetic field and the total cosmic rays, and a ratio between the numbers of cosmic-ray protons and electrons in the relevant energy range (usually $\simeq 100$). The equipartition assumption seems to be valid in galaxies on large spatial and time scales, but deviations probably occur on local scales. The typical average equipartition strength of the total magnetic field in spiral galaxies is about $10 \mu\text{G}$. Radio-faint galaxies like M 31 and M 33, our Milky Way's neighbors, have weaker total magnetic fields (about $5 \mu\text{G}$), while gas-rich galaxies with high star-formation rates, like M 51, M 83 and NGC 6946, have average total field strengths of $15 \mu\text{G}$. The mean energy density of the magnetic field and of the cosmic rays in NGC 6946 is $\simeq 10^{-11} \text{ erg cm}^{-3}$, 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 (Beck 2007a).

The magnetic energy may even dominate in the outer disk. The strongest fields ($50\text{--}100 \mu\text{G}$) are found in starburst galaxies, like M 82 and the "Antennae" NGC 4038/9, and in nuclear starburst regions, like in the centers of NGC 1097 and other barred galaxies (Beck 2005).

Spiral arms in total radio emission appear very similar to those observed in the far-infrared. The total equipartition field strength in the arms can be up to $30 \mu\text{G}$. 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 random within the telescope beam, which typically corresponds to a few 100 pc. Strong random fields in spiral arms are probably generated by turbulent gas motions or the turbulent dynamo (Brandenburg and Subramanian 2005). In contrast, the ordered (regular or anisotropic) fields traced by the polarized synchrotron emission are generally strongest ($10\text{--}15 \mu\text{G}$) in the regions *between* the optical spiral arms, oriented parallel to the adjacent optical spiral arms. In several galaxies the field forms "magnetic arms" between the optical arms, like in NGC 6946 (Beck 2007a). These are probably generated by the mean-field dynamo (Sect. 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 M 51 (Patrikeev et al. 2006).

The ordered magnetic field forms spiral patterns in almost every galaxy, even in flocculent and bright irregular ones which lack any optical spiral structure (Beck 2005), a strong argument for dynamo action. Spiral fields are also observed in the central regions of galaxies and in circumnuclear gas rings.

In galaxies with massive bars, the field seems to follow the gas flow. As there (inside the corotation radius) the gas rotates faster than the spiral or bar pattern of a galaxy, a shock occurs in the cold gas which has a small sound speed, while the warm, diffuse gas is only slightly compressed. As the observed compression of the field in spiral arms and bars is also small, the ordered field is coupled to the warm gas and is strong enough to affect the flow of the warm gas (Beck et al. 2005). The polarization pattern is an excellent tracer of the gas flow in the sky plane and hence complements spectroscopic measurements.

4 Galactic dynamos

The origin of the first magnetic fields in the Universe is still a mystery (Widrow 2002). Protogalaxies probably were already magnetic due to field ejection from the first stars or from jets generated by the first black holes. A large-scale primordial field in a young galaxy is hard to maintain because the galaxy rotates differentially, so that field lines get strongly wound up during galaxy evolution, in contrast to the observations which show large pitch angles. This calls

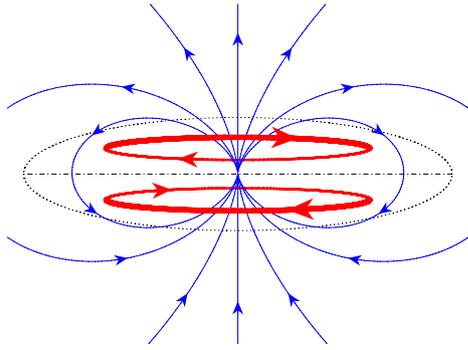


Fig. 1 Dynamo field of type A0: The toroidal field component (*thick lines*) is axisymmetric in the plane (azimuthal mode $m = 0$) and reverses its sign across the plane. The poloidal field component (*thin lines*) is of dipole type (Han 2002)

for a mechanism to sustain and organize the magnetic field. The most promising mechanism is the dynamo (Beck et al. 1996; Brandenburg and Subramanian 2005) which generates large-scale regular fields, even if the seed field was turbulent.

The regular field structure obtained in models of the mean-field $\alpha\Omega$ -dynamo, driven by turbulent gas motions and differential rotation, is described by modes of different azimuthal symmetry in the disk and vertical symmetry perpendicular to the disk plane. Several modes can be excited in the same object.

In spherical bodies like stars, planets or galaxy halos, the strongest mode is an antisymmetric toroidal field with a sign reversal across the equatorial plane, surrounded by a poloidal dipole field which is continuous across the plane (mode A0, Fig. 1). For thick galaxy disks or halos the S0 and A0 modes of strong dynamos are oscillatory, i.e. the field torus migrates radially, so that large-scale reversals in the disk at certain radii are expected (Elstner et al. 1992).

In flat objects like galaxy disks, the strongest mode (S0) is a toroidal field which is symmetric with respect to the plane and has the azimuthal symmetry of an axisymmetric spiral in the plane, without sign reversals, surrounded by a weaker poloidal field of quadrupole structure with a reversal of the vertical field component across the equatorial plane. The next strongest mode is of bisymmetric spiral shape (S1) with two sign reversals within the disk, followed by more complicated modes (Baryshnikova et al. 1987).

The standard mean-field $\alpha\Omega$ -dynamo in galaxy disks amplifies the field and builds up large-scale coherent fields within about 10^9 yr (Beck et al. 1994b). Faster amplification is possible when cosmic-ray driven Parker loops and field reconnection are involved (Parker 1992; Hanasz and Lesch 1998; Moss et al. 1999; Hanasz et al. 2004). The small-scale or fluctuation dynamo (Brandenburg and Subramanian 2005) amplifies turbulent, incoherent magnetic fields within 10^6 – 10^7 yr.

Kinematical dynamo models including the velocity field of a global galactic wind show field structures which are

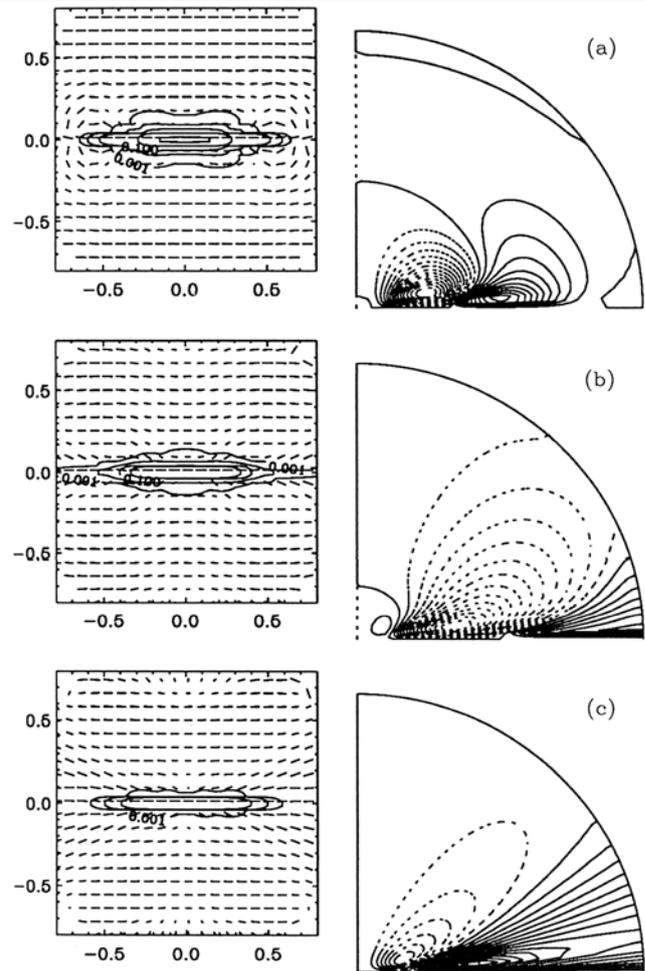


Fig. 2 Dynamo model for the galaxy NGC 891 with a galactic wind: predicted contours of polarized radio emission and vectors (*left*) and field geometry (*right*) for a radial wind with a terminal velocity of (a) 0, (b) 50 and (c) 200 km/s. The *solid* and *dashed* lines indicate different field directions; the field is oscillatory and reverses its direction along radius and height (from Brandenburg et al. 1993, Fig. 9)

parallel to the plane in the inner disk, but open radially outwards, depending on the wind speed and direction (Brandenburg et al. 1993). The model for the galaxy NGC 891 shows an oscillating field (Fig. 2), while for other galaxy models a slow wind speed of 50 km/s was found to be sufficient to change the oscillating mode into a steady one.

For fast global winds the advection time for the field may become smaller than the dynamo amplification time, so that the dynamo cannot operate and the field gas becomes frozen into the flow. Non-uniform local (“spiky”) winds allow dynamo action, but modify the field configuration into oscillating dipoles or quadrupoles with dominating vertical components and frequent, migrating reversals (Elstner et al. 1995). However, strong fields may back-react onto the wind. Dynamical models are needed, including the interplay between the gas flow and the magnetic field.

Dynamo modes can be identified from the pattern of polarization angles and Faraday rotation measures (RM) in multi-wavelength radio observations of galaxy disks with moderate inclination (Elstner et al. 1992; Krause 1990) or from RM data of polarized background sources (Stepanov et al. 2008). The disks of a few spiral galaxies indeed reveal large-scale RM patterns, as predicted. The Andromeda galaxy M 31 hosts a dominating axisymmetric disk field, the basic azimuthal dynamo mode S0 (Fletcher et al. 2004), which extends to at least 15 kpc distance from the center (Han et al. 1998). 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). The magnetic arms in NGC 6946 can be described by a superposition of two azimuthal dynamo modes, where the dynamo wave is phase shifted with respect to the density wave (Beck 2007a). 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 no large-scale dynamo modes exist and most of the ordered fields traced by the polarization vectors are anisotropic (with frequent reversals), due to shearing or compressing gas flows.

5 Radio halos of edge-on galaxies

Radio halos are observed around the disks of many edge-on galaxies (Hummel et al. 1991b; Irwin et al. 1999), but their radio intensity and extent varies significantly. The radial extent of radio halos increases with the size of the actively star-forming parts of the galaxy disk (Dahlem et al. 2006). 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. Dahlem et al. (1995) argue that the energy input from supernova explosions per surface area in the projected disk determines the halo size.

In spite of their largely different intensities and extents, the scale heights of radio halos observed at 5 GHz are $\simeq 1.8$ kpc (Dumke and Krause 1998; Krause 2004) and surprisingly similar. Their sample of galaxies included one of the weakest halos, NGC 4565 (Fig. 3) as well as one of the brightest, NGC 891 (Fig. 4). Assuming energy density equipartition between magnetic fields and cosmic rays, the scale height of the total magnetic field is about 4 times larger than that of the synchrotron emission, hence $\simeq 7$ kpc on average. A prominent exception is NGC 4631 with the largest radio halo (scale height of $\simeq 2.5$ kpc) observed so far (Hummel and Dettmar 1990;

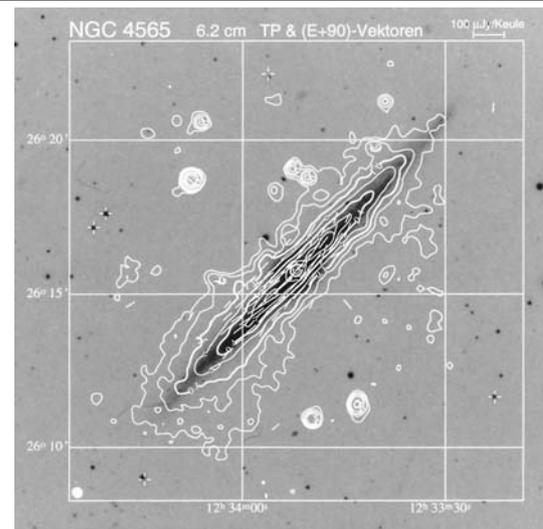


Fig. 3 Optical image of the edge-on spiral galaxy NGC 4565, overlaid by contours of the intensity of the total radio emission at 6 cm wavelength and polarization vectors, combined from observations with the VLA and the Effelsberg 100-m telescope (Dumke 1997). The field lines are mostly parallel to the disk. (Copyright: MPIfR Bonn)

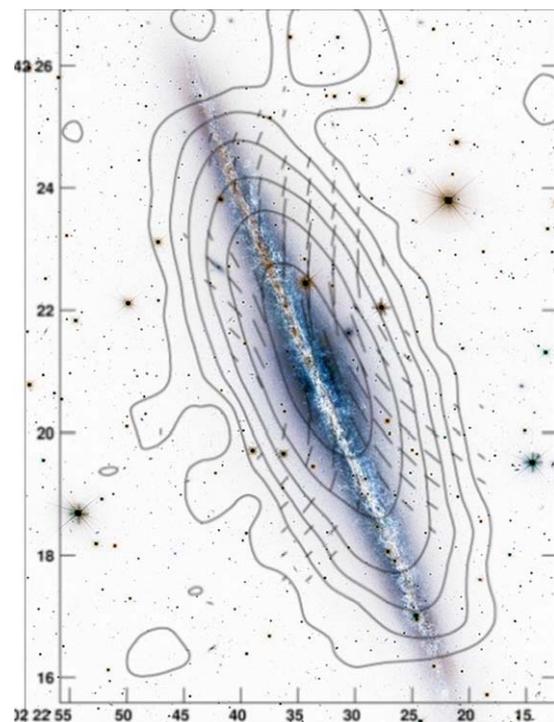


Fig. 4 Optical image of the edge-on spiral galaxy NGC 891, overlaid by contours of the intensity of the total radio emission at 3.6 cm wavelength and polarization vectors, observed with the Effelsberg 100-m telescope (Krause 2007). The field lines are parallel to the disk near the plane, but turn vertically above and below the disk. (Copyright: MPIfR Bonn)

Hummel et al. 1991a; Krause 2004) (Fig. 7). In case of energy equipartition, the scale height of the total field is at least $(3 + \alpha)$ times larger than the synchrotron scale height

(where α is the synchrotron spectral index), hence ≥ 10 kpc in NGC 4631.

The scale height may be larger if cosmic rays originate from star-forming regions in the plane and are not re-accelerated in the halo, so that the electrons lose their energy above some height and the equipartition formula yields too small values for the field strength (Beck and Krause 2005). As the degree of linear polarization increases with height above the disk midplane, the scale height of the ordered field may be even larger.

Due to its large scale height, the magnetic energy density in halos is much larger than that of the thermal gas (Ehle et al. 1998), while still smaller than the dominating kinetic energy of the wind outflow. Hence the magnetic field is frozen into the outflow and its structure is a signature of the outflow kinematics (Sect. 6).

Radio halos grow with decreasing observation frequency, which indicates that the extent is limited by energy losses of the cosmic-ray electrons, i.e. synchrotron, inverse Compton, bremsstrahlung and adiabatic losses (Pohl and Schlickeiser 1990). The stronger magnetic field in the central regions leads to larger synchrotron loss, leading to the squeezed shape of many halos, e.g. NGC 253 (Carilli et al. 1992; Beck et al. 1994a; Heesen et al. 2005) (Fig. 6), which is in contrast to its almost spherical X-ray halo (Pietsch et al. 2000). On the other hand, the exceptionally large and almost spherical radio halo above the central region of NGC 4631 (Hummel and Dettmar 1990) (see also Fig. 7) indicates that the magnetic field is weaker and/or the galactic wind is faster than in other galaxies.

The two different transport mechanisms for cosmic rays, diffusion or advection (galactic wind), can be distinguished and modeled from the variation of the radio spectral index with distance from the plane, to be determined from multi-frequency radio observations (Pohl and Schlickeiser 1990). Breaks in the spectra of total radio emission due to galactic winds were detected in several radio halos (Pohl et al. 1991a). NGC 4631 is also exceptional concerning its radio spectrum (Pohl et al. 1991b). Heesen et al. (2008) measured a transport speed of about 200 km/s in the halo NGC 253 from the radio scale height and the synchrotron loss time.

Note that most of the large-scale halo emission is missing in some VLA maps (Sukumar and Allen 1991; Carilli et al. 1992; Soida 2005), which also severely affects the polarization angles. A combination with single-dish (Effelsberg) data is indispensable for large galaxies and at wavelengths ≤ 6 cm (Figs. 3 and 6), while at ≥ 20 cm the VLA is sensitive to extended structures up to $\geq 10'$, which is sufficient to detect the halos of the largest edge-on galaxies (Fig. 7).

6 Magnetic field structure in halos

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 NGC 891 (Fig. 4), NGC 5775 (Fig. 5), NGC 253 (Fig. 6) and M 104 (Krause et al. 2006) show vertical field components which increase with increasing height z above and below the galactic plane and also with increasing radius, so-called X-shaped magnetic fields (Krause 2007).

The observation of X-shaped polarization patterns is of fundamental importance to understand the origin of magnetic fields in halos. The X-shape is inconsistent with the predictions from standard dynamo models without wind flows (Sect. 4), so that the field has to be transported from the disk into the halo. A uniform wind would just lift up the disk field and can also be excluded. A superwind emerging from a starburst nucleus, as predicted for NGC 253 (Heckman et al. 1990), would produce a radial pattern, which is not observed. The most probable explanation is a wind emerging from the disk which is modified by differential rotation in the halo and dynamo action.

The analysis of the highly inclined galaxy NGC 253 (Fig. 6) allowed a separation of the observed field into an axisymmetric disk field and a halo field inclined by about 50° (Heesen et al. 2008). Similar tilt angles are also observed at large heights in other edge-on galaxies.

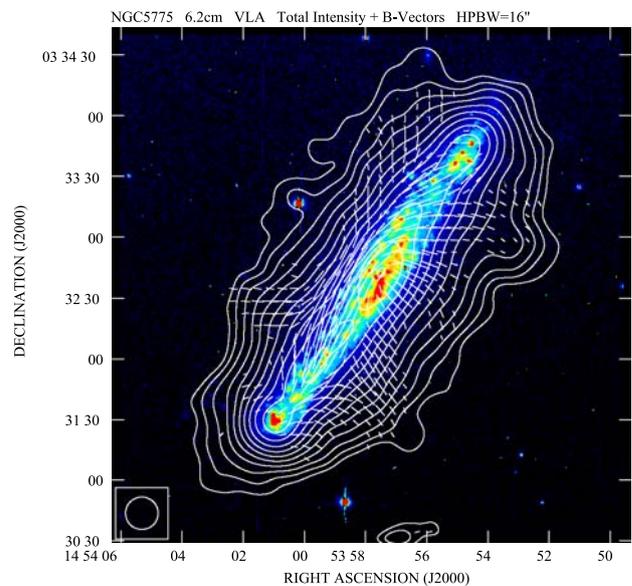


Fig. 5 $H\alpha$ image of the edge-on spiral galaxy NGC 5775, overlaid by contours of the intensity of the total radio emission at 6 cm wavelength and polarization vectors, observed with the VLA (Tüllmann et al. 2000). The field lines are parallel to the disk near the plane, but become increasingly vertical away from the plane. (Copyright: Cracow Observatory)

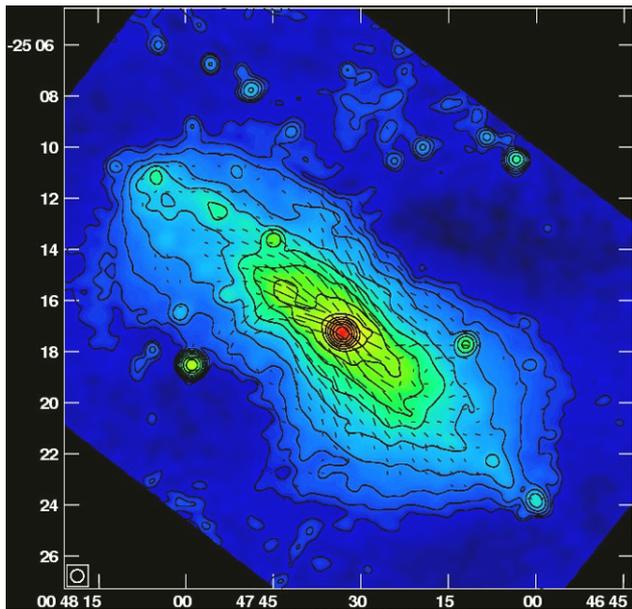


Fig. 6 Total radio emission at 6 cm wavelength and polarization vectors of the almost edge-on spiral galaxy NGC 253, combined from observations with the VLA and the Effelsberg 100-m telescope (Heesen et al. 2005). (Copyright: AIRUB Bochum/MPIfR Bonn)

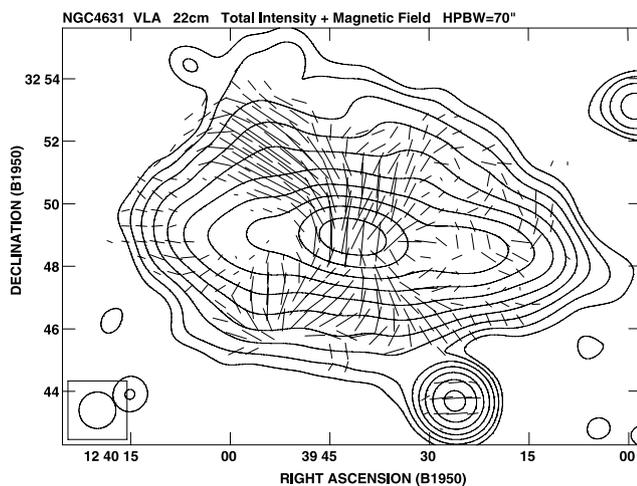


Fig. 7 Total radio emission at 22 cm wavelength of the edge-on spiral galaxy NGC 4631, observed with the VLA (Beck 2005). The polarization vectors are corrected for Faraday rotation. The lack of polarized emission near the plane is due to Faraday depolarization. (Copyright: MPIfR Bonn)

The field lines in the outer halo of NGC 4631 suggest a dipole field (Fig. 7), but Faraday rotation measures do not support this interpretation (see Sect. 7). The radio halo above the inner disk is composed of almost vertical magnetic spurs connected to star-forming regions (Golla and Hummel 1994). The observations support the idea of a strong “spiky” galactic wind which is driven by regions of star formation in the inner disk (Elstner et al. 1995). Furthermore, differential rotation is small in the inner disk, so that ver-

tical field lines are less twisted. At larger radii, where star formation is weaker and differential rotation is larger, the field becomes parallel to the disk. Another galaxy with vertical fields away from the plane and hence a strong wind is NGC 4666 (Dahlem et al. 1997; Soida 2005).

7 Faraday rotation and depolarization in halos

Polarization “vectors” are ambiguous by 180° and hence cannot distinguish between a halo field which is sheared into elongated Parker loops or a regular halo field generated by a dynamo. A large-scale regular field can be measured only by Faraday rotation measures (RM). In external galaxies, the vertical field symmetry could not yet been determined from existing RM data with sufficient accuracy. RM values in halos, e.g. in NGC 253 (Beck et al. 1994a) and in NGC 4631, are small and do not show large-scale patterns. Indirect evidence for preferred symmetric toroidal fields follows from the possible dominance of the inward-directed radial field component in the disk (Krause and Beck 1998). Such a dominance of is in conflict with a reversal of the toroidal field across the plane¹ in which case the observed field direction would depend on the aspect angle and no preference would be expected for a galaxy sample.

In the Milky Way, the pattern of rotation measures from pulsars and polarized background sources indicates a symmetric local magnetic field, but an antisymmetric field in the halo, i.e. the toroidal field reverses its sign across the plane (dynamo mode A0, Fig. 1) (Han et al. 1997; Han 2002; Sun et al. 2008).

Faraday depolarization is another method to detect magnetic fields and ionized gas in galaxy halos. In NGC 891 and NGC 4631 the mean degree of polarization at 1.4 GHz increases from about 1% in the plane to about 20% in the upper halo. This was modeled by depolarization due to random magnetic fields of $10 \mu\text{G}$ and $7 \mu\text{G}$ strength, respectively, and ionized gas with densities in the plane of 0.03 cm^{-3} and 0.07 cm^{-3} and scale heights of 0.9 kpc and 1.3 kpc, respectively (Hummel et al. 1991a).

In face-on galaxies, structures in the halo may become visible via depolarization of the underlying disk emission, e.g. in M 51 (Berkhuijsen et al. 1997). A large depolarized region above the disk of NGC 6946 may be due to a strong vertical field (Beck 2007a).

¹Note that the observed Faraday rotation measure RM is *not* zero along a line of sight passing through a disk containing a field reversal in its midplane if cosmic-ray electrons and thermal plasma are mixed in the disk. In this case RM is half of that from a disk without a reversal, and the sign of RM traces the field direction in the layer which is *closer* to the observer.

8 Interactions

Interaction between galaxies or with a dense intergalactic medium imprints unique signatures onto magnetic fields in galaxy halos and thus onto the radio emission. The Virgo cluster is a location of strong interaction effects. Highly asymmetric distributions of the polarized emission shows that the magnetic fields of several spirals are strongly compressed on one side of the galaxy (Vollmer et al. 2007; Weżgowiec et al. 2007).

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 NGC 4569 reach out to at least 25 kpc from the disk and are highly polarized (Chyży et al. 2006). However, there is no indication for a recent starburst, so that the radio lobes are probably a signature of activity in the past.

Polarized radio emission is an excellent observational tracer of interactions. As the decompression timescale of the field is very long, it keeps memory of events in the past. These are still observable if the lifetime of the illuminating cosmic-ray electrons is sufficiently large. Radio observations at low frequencies are preferable.

9 Summary and outlook

Total and polarized radio emission of edge-on galaxies is a powerful tool to study the physics of galaxy halos. The extent and spectral index of radio halos gives information on the transport of cosmic-ray electrons and their origin in star-forming regions in the disk. Estimates of the electron lifetime allow an estimate of the transport speed. The shape of the halo and the field structure may allow to distinguish a global wind driven by star formation in the disk from a superwind emerging from a central starburst. The field structure in the halo reflects the interaction between the outflow and differential rotation. Shock fronts between colliding halo outflows may re-accelerate cosmic rays and enhance the radio emission. Halo fields compressed by galaxy interactions or ram pressure with the intergalactic gas are observable via polarized emission. Faraday rotation measures trace regular fields and can test dynamo models (Stepanov et al. 2008). Faraday rotation and depolarization are also sensitive tools to detect ionized gas in galaxies and in the intergalactic space.

Future radio telescopes will widen the range of observable phenomena around galaxies. High-resolution observations at high frequencies with the Extended Very Large Array (EVLA) and the planned Square Kilometre Array (SKA) are required to show whether the halo fields are regular or composed of many stretched loops. Forthcoming low-frequency radio telescopes like the Low Frequency Array

(LOFAR), Murchison Widefield Array (MWA), Long Wavelength Array (LWA) and the low-frequency SKA will be suitable instruments to search for extended synchrotron radiation at the lowest possible levels in the outer galaxy halos, the transition to intergalactic space and in galaxy clusters and will give access to the so far unexplored domain of weak magnetic fields in galaxy halos (Beck 2007b, 2008). The detection of radio emission from the intergalactic medium will allow to probe the existence of magnetic fields in such rarified regions, measure their intensity, and investigate their origin and their relation to the structure formation in the early Universe.

As Faraday rotation angles increase with λ^2 , low-frequency telescopes will also be able to measure very small Faraday rotation measures (RM) and Faraday depolarization, which allow to detect weak magnetic fields and low-density ionized gas in galaxy halos. The present limit in electron densities of about 0.003 cm^{-3} can be reduced by at least one order of magnitude.

The planned all-sky RM survey with the SKA at about 1 GHz will be used to model the structure and strength of the magnetic fields in the intergalactic medium, the interstellar medium of intervening galaxies and in the Milky Way (Beck and Gaensler 2004). With deep polarization and RM observations the origin and evolution of galactic magnetic fields will be investigated. “Cosmic magnetism” has been accepted as Key Science Projects for both, LOFAR and SKA.

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