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MAGNETIC VISIONS: MAPPING COSMIC MAGNETISM WITH LOFAR AND SKA

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RESUMEN

El origen de los campos magnéticos en el Universo es un problema abierto de la astrofísica y de la física fundamental. El "Magnetismo Cósmico" ha sido aceptado como proyecto científico clave del Low Frequency Array (LOFAR, en construcción), y del planeado Square Kilometre Array (SKA). A bajas frecuencias LOFAR y SKA permitirán mapear la estructura de los campos magnéticos débiles en las regiones eternas y halos de galaxias, en cúmulos de galaxias y en la Vía láctea. Observaciones de polarización con alta resolución a frecuencias altas con SKA permitirán trazar campos magnéticos en los discos y regiones centrales de galaxias con un detalle sin precedentes. Sondeos de todo el cielo de las medidas de rotación (RM por sus siglas en inglés) de Faraday hacia fuentes de fondo polarizadas van a ser usadas para modelar la estructura y magnitud del campo magnético en la Vía Láctea, en el medio interestelar de galaxias y en el medio intergaláctico. El nuevo método de "síntesis de RM", aplicado a cubos de datos espectro-polarimétricos, separarán las componentes de las RM a diferentes distancias, permitiendo así una "tomografía Faraday" tridimensional. Los campos magnéticos en galaxias distantes y en cúmulos, así como filamentos intergalácticos, podrán ser buscados mediante imagen profunda de la emisión sincrotrón débil, y las RM hacia fuentes de fondo. Esto abrirá una nueva era en la observación de campos magnéticos cósmicos.

ABSTRACT

The origin of magnetic fields in the Universe is an open problem in astrophysics and fundamental physics. "Cosmic Magnetism" has been accepted as Key Science Project both for the Low Frequency Array (LOFAR, under construction) and the planned Square Kilometre Array (SKA). At low frequencies LOFAR and SKA will allow to map the structure of weak magnetic fields in the outer regions and halos of galaxies, in galaxy clusters and in the Milky Way. High-resolution polarization observations at high frequencies with the SKA will trace magnetic fields in the disks and central regions of galaxies in unprecedented detail. All-sky surveys of Faraday rotation measures (RM) towards polarized background sources will be used to model the structure and strength of the magnetic fields in the Milky Way, the interstellar medium of galaxies and the intergalactic medium. The new method of "RM Synthesis", applied to spectro-polarimetric data cubes, will separate RM components from different distances and allow 3-D "Faraday tomography". Magnetic fields in distant galaxies and clusters and in intergalactic filaments will be searched for by deep imaging of weak synchrotron emission and of RM towards background sources. This will open a new era in the observation of cosmic magnetic fields.

Key Words: galaxies: halos — galaxies: magnetic fields — galaxies: spiral — intergalactic medium — radio continuum: galaxies — techniques: polarimetric

1. NEW-GENERATION RADIO TELESCOPES: LOFAR AND SKA

Magnetic fields of galaxies have been a topic of intensive investigation since many years. However, many important questions, like the origin and evolution of magnetic fields in galaxies, especially their first occurrence in young galaxies, the presence of magnetic fields in elliptical galaxies without active nucleus or the small-scale structure of magnetic fields in the Milky Way remained unanswered. The intracluster gas in galaxy clusters hosts magnetic fields of considerable strength and coherence, but their origin is not known. Finally, we would like to know whether the intergalactic space is magnetized and whether outflows from galaxies or AGNs are sufficient to maintain these fields.

Most of what we know about galactic magnetic fields comes through the detection of radio waves. *Synchrotron emission* is related to the total field strength in the sky plane, while its polarization yields the orientation of the regular field in the sky plane and also gives the field's degree of ordering. Incorporating *Faraday rotation* provides information

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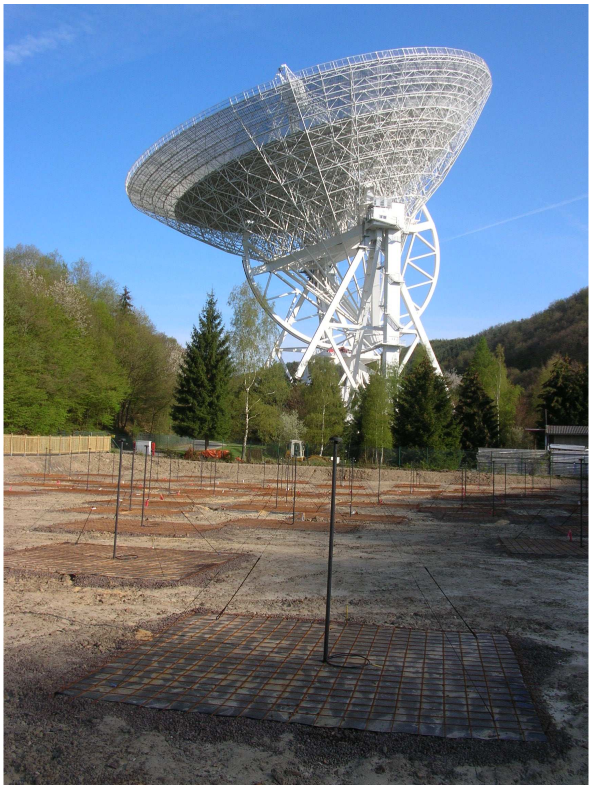

Fig. 1. The first international LOFAR station (front) with 96 low-band antennas (20–80 MHz) next to the Effelsberg 100 m telescope (back) (Copyright: MPIfR Bonn).

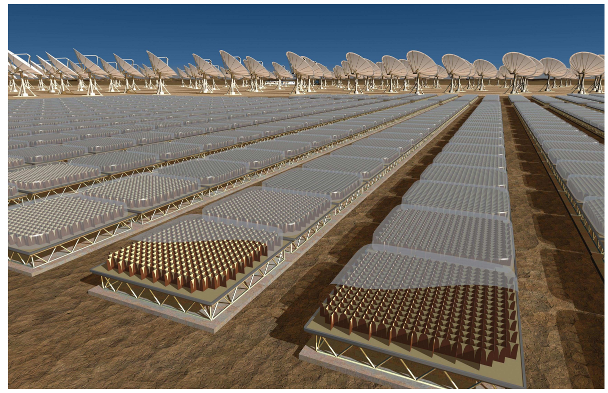

Fig. 2. SKA reference design: aperture array for low frequencies and parabolic dishes for high frequencies (Copyright: SKA Programme Development Office and XILOSTUDIOS).

on the strength and direction of the coherent field component along the line of sight.

The new generation of radio telescopes will open a new era of magnetic field studies. *Cosmic Magnetism* is the topic of Key Science Projects for LOFAR and the SKA (Gaensler et al. 2004; Beck 2007a). LOFAR (*Low Frequency Array*) is presently under construction and will lead the way for a new generation of radio telescopes consisting of a multitude of small and cheap antennas. It will work in two frequency bands, 20–80 MHz and 110–240 MHz. The radio waves are sampled digitally and the signals from the stations are transmitted over large distances to a high-performance computing facility, where the radio images are synthesized in real time. About 35 stations at distances up to about 100 km from the core will be erected in 2008–2010 in the northern part of the Netherlands. The first international station next to the Effelsberg 100 m telescope is operating since 2007 (Figura 1). Three more German stations will follow in 2008–9. Further international stations are funded in the UK, France and Sweden.

LOFAR can be considered as a pathfinder for an European participation in the SKA (*Square Kilometre Array*), the next-generation international radio telescope, which is envisaged for the years beyond 2015. The SKA is planned to cover most of the radio window accessible from the ground, from about 70 MHz to 35 GHz. The SKA Reference Design (Figura 2) aims at two different telescope arrays, one being a low-frequency digital telescope like LOFAR.

Other SKA pathfinder telescopes under construction are ASKAP (*Australian SKA Pathfinder*), consisting of two arrays operating between 80 MHz and 2 GHz, ATA (*Allen Telescope Array*, USA, 1–10 GHz), LWA (*Long Wavelength Array*, USA, 10–88 MHz) and MeerKat (*Karoo Array Telescope*, South Africa, 0.5–2.5 GHz).

Much of what LOFAR and SKA can contribute to our understanding of magnetic fields will come from their *polarimetric capabilities*. The crucial specifications are high polarization purity and multichannel spectro-polarimetry. The former will allow detection of the relatively low linearly polarized fractions from most astrophysical sources, while the latter will enable accurate measurements of Faraday rotation measures (RMs), intrinsic polarization position angles and Zeeman splitting. The method of *RM Synthesis*, based on multichannel spectro-polarimetry, transforms the spectral data cube into a data cube of Faraday depth (Brentjens & de Bruyn 2005). This allows to measure a large range of RM values and to separate RM components from distinct regions along the line of sight. If the structure of the medium along the line of sight is not too complicated, this can be used for *Faraday tomography*.

2. LIMITATIONS OF OBSERVATIONS WITH PRESENT-DAY RADIO TELESCOPES

2.1. *Extent of galactic magnetic fields in galaxies and galaxy clusters*

The observation of radio synchrotron emission from galaxies only reveals magnetic fields illuminated by cosmic-ray electrons (CRE) accelerated by supernova shock fronts in regions of strong star formation. As the propagation of CRE is limited, radio images at centimeter wavelengths (synchrotron + thermal) are mostly similar to images of star-forming regions, as observed, e.g., in the far-infrared.

NGC 6946 is one of the best studied spiral galaxies in radio continuum. Its synchrotron emission is observed until 25 kpc distance from the center (Beck 2007b), limited by the extent of the star-forming disk, while neutral gas is detected until twice larger radius (Boomsma et al. 2005). Magnetic fields may extend far away from star-forming regions where the magneto-rotational instability (MRI) (Sellwood & Balbus 1999) serves as an energy source of turbulence and field amplification.

The spectacular synchrotron ring of the Andromeda galaxy M 31 is the result of an extended magnetic field of considerable regularity illuminated by CRE generated in the relatively narrow ring of star-formation at about 10 kpc from the center (Fletcher et al. 2004). Faraday rotation measurements towards polarized background sources showed that the regular field of M 31 exists also inside and outside the ring (Han et al. 1998). However, the Faraday method could not be applied to more galaxies because the number density of polarized background sources is too small with the sensitivity of present-day radio telescopes (Stepanov et al. 2008).

The observable size of radio halos around (almost) edge-on galaxies generally increases with decreasing observation frequency, which indicates that the extent is limited by energy losses of the CRE, i.e. synchrotron, inverse Compton, bremsstrahlung and adiabatic losses (Pohl & Schlickeiser 1990), and by the advection velocity of the outflow from the disk. NGC 253 is a prominent example (Figura 3). The halo extent is smallest in the inner region where the magnetic field is strongest and hence the synchrotron loss is highest (Heesen et al. 2009). The X-shaped pattern of the B-vectors in the halo of NGC 253 is typical for edge-on galaxies, possibly a signature of a galactic wind with a radial component.

The vertical profile of radio halos of most edge-on galaxies observed at 5 GHz can be described by an exponential decrease with about 2 kpc vertical scaleheight (Krause 2004). This corresponds to a scaleheight of the magnetic field of about 8 kpc, assuming equipartition between the energy densities of the field and the total cosmic rays and a constant ratio of CR protons to electrons. However, this ratio is expected to increase with increasing distance from the disk due to the energy losses of the CRE, so that the field's scaleheight is larger than 8 kpc. A similar argument refers to the radial scalelengths of the radio disks.

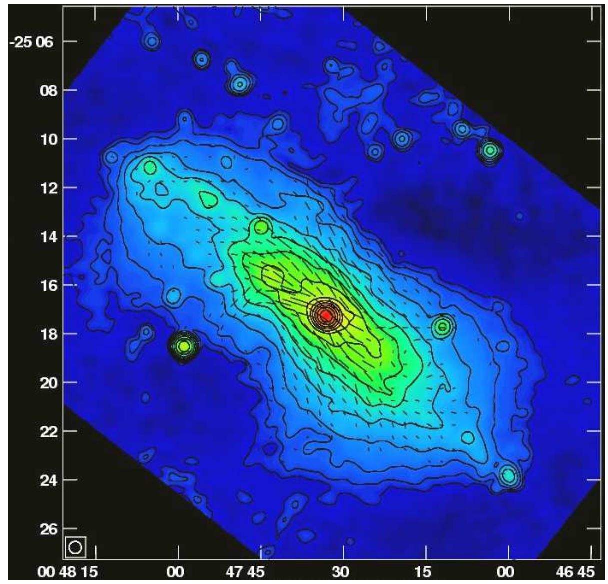

Fig. 3. Total radio emission (contours) and polarization B-vectors of the almost edge-on spiral galaxy NGC 253, combined from observations at 6 cm wavelength with the VLA and the Effelsberg 100 m telescope and smoothed to $30''$ resolution (Heesen et al. 2009) (Copyright: AIRUB Bochum).

Interaction between galaxies or of a galaxy with the 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 cluster spirals are strongly compressed on one side of the galaxy (Vollmer et al. 2007; Weżgowiec et al. 2007). The lobes of the Virgo spiral NGC 4569 reach out to at least 25 kpc from the disk and are highly polarized (Figura 4), probably a remainder of interaction in the past.

The centers of some galaxy clusters host halos of radio synchrotron emission (Feretti et al. (2004); Brunetti 2009). They are probably created by turbulent wakes by the motion of galaxies through the intracluster medium. The polarization of cluster halos is low. Weak synchrotron emission was also detected

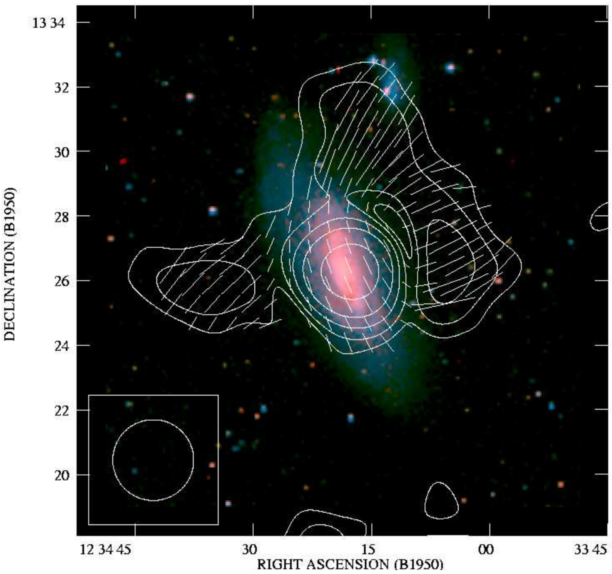

Fig. 4. Polarized radio emission (contours) and B-vectors of the spiral galaxy NGC 4569 in the Virgo Cluster, observed at 6 cm wavelength with the Effelsberg telescope (Chyży et al. 2006) (Copyright: Cracow Observatory).

around a group of radio galaxies (Kronberg et al. 2007). Synchrotron radiation from regions of large-scale shocks in clusters, where the intergalactic magnetic fields are compressed and cooled pools of formerly highly relativistic particles are re-accelerated, are called *relics* (Enßlin 2009). Their radio emission is characterized by strong polarization (Govoni et al. 2005). There may be large numbers of exhausted radio sources, with "starved" AGN. Due to their steep spectra, all of these structures are best detectable at low radio frequencies.

Polarized radio emission is an excellent tracer of interactions in the intergalactic and intracluster medium. 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.

To overcome the limitations by CRE lifetime, two observation methods will be applied:

1. *Low frequencies:* CRE losses are smaller, and the extent of galactic magnetic fields into intergalactic space can be traced. The lifetime of CRE due to synchrotron losses increases with decreasing frequency ν and decreasing total field strength B: $t_{\rm syn} = 1.1 \times 10^9$ yr $(\nu/{\rm GHz})^{-0.5}(B/\mu G)^{-1.5}$. In a 5 μG field the lifetime of electrons emitting in the LOFAR bands is $2-5\times10^8$ yr. In turbulent magnetic fields, cosmic rays propagate by diffusion, with a diffusion speed equal to the Alfvén speed. In the hot medium of galaxy or cluster halos (electron density $n_e \simeq 10^{-3}$ cm^{-3}), the Alfvén speed is about 70 km/s $(B/\mu{\rm G})$. In field strengths above 3.25 $\mu G \cdot (z+1)^2$ where synchrotron loss is stronger than loss due to Inverse Compton with CMB photons, CRE radiating at 50 MHz can travel huge distances of about 330 kpc $(B/\mu G)^{-0.5}$.

Polarized synchrotron emission traces ordered magnetic fields which can be generated from turbulent fields by compressing or shearing gas flows. Low frequencies will reveal such effects at larger distances out to the intergalactic medium.

2. *Faraday rotation:* The halos of galaxies and galaxy clusters contain hot gas which causes Faraday rotation of the polarized emission from background sources if some fraction of the magnetic field has a coherent component along the line of sight. As Faraday rotation increases with the square of wavelength, low frequencies are again preferable. In the outer halos of galaxies and in the intracluster medium, we expect electron densities of $n_e \simeq 10^{-3}$ cm^{-3} and field strengths of about 1 μG with 1 kpc coherence length, causing a rotation measure of 0.7 rad m^{-2} which should be easily detectable with LOFAR and the low-frequency SKA.

The key platform on which to base the SKA's studies of cosmic magnetism will be the *all-sky RM survey* at around 1 GHz which can yield RMs towards about 10^7 compact polarized extragalactic sources (Gaensler et al. 2004). This data set will provide a grid of RMs at a mean spacing of just $\simeq 1-2'$ between extragalactic sources.

2.2. *Dynamical effects of magnetic fields in galaxies*

Surprisingly, large-scale shock fronts in the gas, found in spiral arms and bars from spectral line observations, have only weak counterparts in polarized synchrotron emission: The ordered field avoids the shock. Striking examples are the spiral galaxy M 51 (Patrikeev et al. 2006) (Figura 5) and the barred galaxy NGC 1097 (Figura 6). Beck et al. (2005) argued that the field is connected to the diffuse gas which has a large sound speed and is not shocked. As the energy density of the field is comparable to that of the diffuse gas, the gas velocity may be affected by the field. The circumnuclear ring of NGC 1097 (Figura 6, top right) is another case of field-gas interaction: the field is strong enough for an inward deflection of about one solar mass of gas per year, sufficient to feed the active nucleus (Beck et al. 2005).

Another indication for the dynamical importance of interstellar magnetic fields comes from the comparison of energy densities in the spiral galaxy

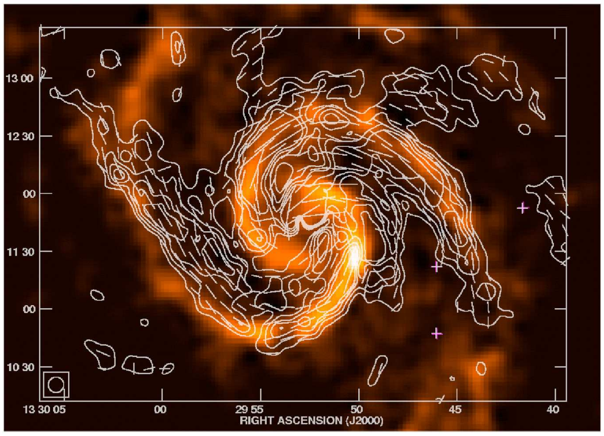

Fig. 5. Polarized radio emission (contours) and B-vectors of the spiral galaxy M 51, combined from data at 6 cm wavelength from the VLA and the Effelsberg 100 m telescopes and smoothed to $8''$ resolution (Fletcher et al. 2008). The background image shows the integrated CO(1-0) line emission (Helfer et al. 2003) (Copyright: MPIfR Bonn).

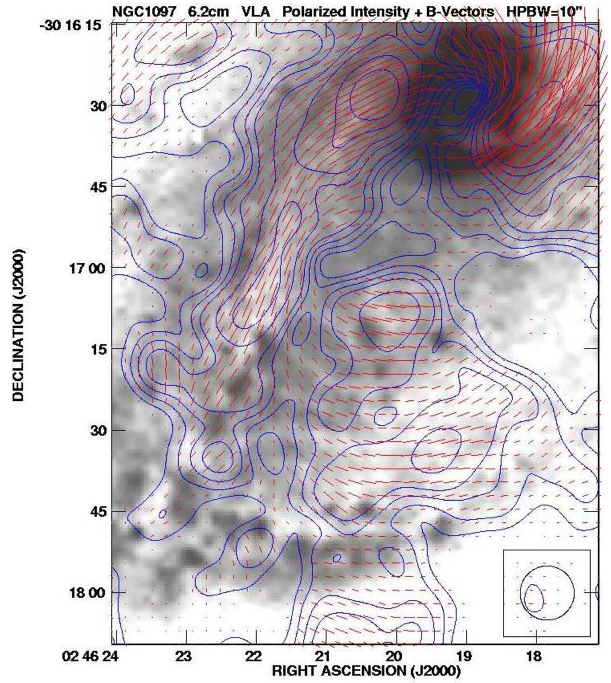

Fig. 6. Polarized radio emission (contours) and B-vectors of the barred galaxy NGC 1097, smoothed to $10''$ resolution, observed at 6 cm wavelength with the VLA (Beck et al. 2005). The background optical image is from Halton Arp (Copyright: MPIfR Bonn and Cerro Tololo Observatory).

NGC 6946. Beyond 5 kpc radius, the magnetic energy density seems to be larger than the thermal energy density and the kinetic energy density of turbulent cloud motions (Beck 2007b). "Super-equipartition" fields may result from the *magneto-rotational instability* (MRI) which transfers energy from the shear of differential rotation into turbulent and magnetic energy (Sellwood & Balbus 1999).

Battaner & Florido (2000, 2007) proposed that 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. Fields in the outer regions can best be measured by Faraday rotation of polarized emission from background sources with LOFAR and SKA.

If the magnetic field is dynamically important, dynamo and other MHD models have to include the back-reaction onto the gas flow. Further observational evidence should be provided by detailed comparisons between field structures and gas velocity fields at spatial resolutions of better than 100 pc. Present-day telescopes do not provide sufficient sensitivity at such resolutions because the signal from extended sources decreases with the beam area.

The best spatial resolution in synchrotron polarization achieved so far in galaxies is about 10 pc in the LMC (Mao et al., in prep.). 100 pc can be reached in M 31, but only a few regions provide signals significantly above the noise level. M 33 is faint in polarization due to weakly ordered fields. IC 342 allows 200 pc resolution and reveals bright polarized filaments, some of them unrelated to gas structures (Beck 2005). These data are too sparse for a systematic study of the dynamical importance of magnetic fields in galaxies. *Higher sensitivity* is needed to allow studies at higher resolution.

2.3. *Magnetic field structure of the Milky Way*

The small-scale and large-scale structure of the magnetic field of the Milky Way is topic of numerous investigations since several decades. Nevertheless, no consistent picture could yet be established.

Polarized synchrotron emission from the Milky Way and RM data from polarized extragalactic sources were used by Sun et al. (2008) to model the large-scale Galactic field. One large-scale reversal is required about 1–2 kpc inside the solar galactocentric radius. This confirmed the previous analysis of Brown et al. (2007) that the local field runs clockwise (seen from the northern Galactic pole) but reverses to counter-clockwise towards the next inner spiral arm, the Sagittarius-Carina arm, and is still counter-clockwise in the inner molecular ring. Sun et al. (2008) claimed that the direction of the disk field is continuous across the Galactic plane, but they needed a second field component, called halo field, which is strongest at 1 kpc distance from the plane and reverses its direction across the plane.

A model of the Galactic field based on 554 pulsar RM values collected from several telescopes indicated reversals at several Galactic radii, possibly between each spiral arm and the adjacent interarm region (Han et al. 2006). The fields in the main inner arms (Carina-Sagittarius, Scutum-Crux and Norma) run counterclockwise, while the fields run clockwise in the interarm regions, in the solar neighborhood and in the outer Perseus arm. On the other hand, Noutsos et al. (2008), based on independent measurements of 150 pulsar RMs with the Parkes telescope, found safe evidence for two reversals. The first is located about 1 kpc inside the solar galactic-centric radius, between the local field (clockwise field) and the Carina arm (counter-clockwise). The second reversal occurs between the Carina and Crux arms at 2–4 kpc distance from the sun towards the Galactic center. Noutsos et al. (2008) found the field in the Carina arm to reverse from counterclockwise to clockwise beyond about 4 kpc distance from the sun, contrary to Han et al. (2006). However, sub-samples of RM values above and below the Galactic plane in several regions revealed different field reversals, which calls for caution with interpreting the data.

Though the spatial resolution with present-day radio telescopes in external galaxies is much lower, typically a few 100 pc, large-scale field reversals in the RM maps of diffuse polarized emission should have been observed if they persist over at at least a few kpc and their vertical extent is similar to that of the synchrotron-emitting disk. However, only two large-scale reversals were found, one in the flocculent galaxy NGC 4414 (Soida et al. 2002) and one in the barred galaxy NGC 1097 (Beck et al. 2005). In both cases the line of reversal runs at about constant azimuthal angle, different from the reversals claimed for the Milky Way. Field reversals on smaller scales are probably more frequent but also more difficult to observe in external galaxies because the signal-to-noise ratios are quite low. Only in the barred galaxy NGC 7479, where a jet serves as a bright polarized background, several reversals on 1–2 kpc scale could be detected in the foreground disk of the galaxy (Laine & Beck 2008). Either the Galactic reversals are not coherent over several kpc, or they are restricted to a thin region near the Galactic plane, or the Milky Way is special.

All Galactic field models so far assumed a constant pitch angle. However, experience from external galaxies shows that the field's pitch angle is not constant along the spiral arm and that the field may even slide away from the spiral arms, as observed e.g. in M 51 (Patrikeev et al. 2006), but this cannot explain the discrepancy between the Galactic and extragalactic observations.

A reliable model for the large-scale Galactic magnetic field needs a much higher number of pulsar and extragalactic RM, hence much larger sensitivity. The SKA "Magnetism" Key Science Project plans to observe an all-sky RM grid (§ 2.1) which should contain about 10^4 pulsar values with a mean spacing of $\simeq 30'$.

While the large-scale field is much more difficult to measure in the Milky Way than in external galaxies, Galactic observations can trace magnetic structures to much smaller scales. The 1.4 GHz all-sky polarization map by Wolleben et al. (2006) reveals a wealth of details, but suffers from Faraday depolarization near the Galactic plane. Future polarization surveys will either observe at higher frequencies (e.g., the Parkes S-PASS at 2.3 GHz, Carretti 2009) or observe at 1.4 GHz in the spectro-polarimetric mode with a large number of channels (e.g. the Arecibo GALFACTS survey, Taylor et al.). Multichannel data allow to apply the method of RM Synthesis (Brentjens & de Bruyn 2005). Faraday depolarization can be reduced and features at different distances can be separated. If the medium has a relatively simple structure, *Faraday tomography* along geometrical depth will be possible.

2.4. *Search for intergalactic magnetic fields*

The search for magnetic fields in the intergalactic medium (IGM) is of fundamental importance for cosmology. All of "empty" space in the Universe may be magnetized. Its role as the likely seed field for galaxies and clusters and its possible relation to structure formation in the early Universe, places considerable importance on its discovery. A magnetic field already present at the epoch of re-ionization or even at the recombination era might have affected the processes occurring at these epochs (Subramanian 2006). To date there has been no detection of magnetic fields in the IGM; current upper limits on the average strength of any such field suggest $|B_{\rm IGM}| \leq 10^{-8} - 10^{-9}$ G (Kronberg 1994).

Structure formation led to strong intergalactic shocks. Fields of $B \simeq 10^{-9} - 10^{-8}$ G are expected along filaments of 10 Mpc length with $n_e \simeq 10^{-5}$ cm^{-3} electron density (Kronberg 2006). This yields Faraday rotation measures of RM $\simeq 0.1 - 1$ rad m^{-2}. Their detection is a big challenge, but possible. LOFAR has a realistic chance to measure intergalactic magnetic fields *for the first time.* With LOFAR and SKA, the synchrotron background emission from intergalactic shocks may also become detectable below 500 MHz via their angular power spectrum (Keshet et al. 2004).

If the all-pervading magnetic field will turn out to be even weaker, it may still be identified through the planned all-sky RM grid with the SKA (§ 2.1). The correlation function of the RM distribution provides the magnetic power spectrum as a function of cosmic epoch (Blasi et al. 1999).

Primordial fields existing already in the recombination era would induce Faraday rotation of the polarized CMB signals of the cosmic microwave background (CMB) (Kosowsky & Loeb 1996; Kosowsky et al. 2005) and generate a characteristic peak in the CMB power spectrum at small angular scales. The detection is challenging but possible with an instrument of superb sensitivity like SKA.

2.5. *Origin of magnetic fields in galaxies*

Radio observations of polarized synchrotron emission showed that the large-scale field structures in almost all nearby galaxies are spiral with pitch angles similar to those of the optical spiral arms (Beck 2005). Spiral fields were also detected in galaxies without optical spiral structure and in circumnuclear gas rings. This indicates the action of *dynamos* in rotating galaxies, where the Coriolis force organizes turbulent gas motions, amplifying a weak seed field and generating coherent field structures (Beck et al. 1996). However, the physics of galactic dynamos is far from being understood. The build-up of large-scale fields requires that small-scale helicity is removed from the galaxy by outflows (Sur et al. 2006). Even under favorable conditions, the timescale for the growth of large-scale fields is several galactic rotation periods.

Primordial or protogalactic fields, generated in the early Universe or during galaxy formation, would be twisted by differential rotation and destroyed by reconnection and diffusion within a few rotation periods. Turbulent gas flows are needed to maintain the field strength (de Avillez & Breitschwerdt 2005). Compressing and shearing gas flows, e.g., by spiral density waves, can generate coherence on a scale of about 1 kpc (Otmianowska-Mazur et al. 2002). To obtain coherence on larger scales, the dynamo is the only available model.

The regular field structures obtained in models of the *mean-field $\alpha\Omega$-dynamo*, driven by turbulent gas motions and differential rotation, are described by modes of different azimuthal symmetry in the disk. Such modes can be identified from the pattern of polarization angles and Faraday rotation measures in multi-wavelength radio observations of galaxy disks (Krause 1990; Elstner et al. 1992) or from RM data of polarized background sources (Stepanov et al. 2008) and were found in the disks of a few nearby spiral galaxies (Beck 2005). However, in many galaxy disks no clear patterns of Faraday rotation were found. Either many 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 produced by compressing or shearing gas flows. Again, *higher sensitivity* is needed because the Fourier analysis of dynamo modes requires high-resolution RM data, as planned by the SKA "Magnetism" Key Science Project (Beck & Gaensler 2004). The SKA will offer the chance to recognize these patterns with help of Faraday rotation measures to at least 100 Mpc distance (Stepanov et al. 2008).

Measurements of magnetic fields in distant galaxies (at redshifts between $z \approx 0.1$ and $z \approx 2$) with SKA will provide direct information on how magnetized structures evolve and amplify as galaxies mature. The linearly polarized emission from galaxies at these distances will often be too faint to detect directly. Faraday rotation within these sources holds the key to studying their magnetism. Available RM data of quasars at $z = 2-3$ indicate that their galaxy environment was already magnetized at μG levels (Kronberg et al. 2008). Distant, but extended polarized sources like radio galaxies also provide the ideal background illumination for mapping Faraday rotation in galaxies along the same line of sight.

The mean-field $\alpha\Omega$-dynamo needs a few galactic rotations or about 10^9 yr to build up a coherent field of galactic scale (Beck et al. 1996). The failure to detect coherent fields in distant galaxies would indicate that the growth timescale is larger than the galaxy age. If "bisymmetric" magnetic patterns turn out to dominate, this would indicate that primordial or protogalactic fields were twisted and amplified by differential rotation. If, on the other hand, coherent fields are observed in young galaxies, this would indicate that protogalactic fields were strong and possibly already partly coherent.

At yet larger distances, with the sensitivity of the deepest SKA fields, we expect to detect the synchrotron emission from (unresolved) young galaxies and protogalaxies, since the turbulent dynamo needs about 10^7 yr to build up a galactic field of μG strength (Brandenburg & Subramanian 2005). Unresolved galaxies will exhibit polarized radio emission if their fields are ordered and their inclination is larger than about 30° (Stil et al. 2008).

Radio telescopes operating at low frequencies (LOFAR, ASKAP-MWA and the low-frequency SKA array) may also become very useful instruments for field recognition or reconstruction with the help of background RMs. The Faraday rotation angle increases with RM $\cdot\lambda^2$, so that much smaller RM values can be detected at low frequencies. However, the number density of polarized sources at low frequencies is expected to be lower than at high frequencies due to Faraday depolarization within the source and in the intervening medium.

3. CONCLUSIONS

Observing cosmic magnetism with present-day radio telescopes is limited by low sensitivity and low resolution. Pushing these limits requires large telescope arrays with large collecting areas, as planned for LOFAR, SKA and the SKA pathfinders. Low frequencies and spectro-polarimetry (RM Synthesis) can break the limits and open the window to the magnetic Universe.

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