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Towards a New Era of Observing Cosmic Magnetic Fields

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The origin of magnetic fields in the Universe is an open problem in astrophysics and fundamental physics. Polarization observations with the forthcoming large radio telescopes will open a new era in the observation of magnetic fields and should help to understand their origin. At low frequencies, LOFAR (30–240 MHz) will allow us to map the structure of weak magnetic fields in the outer regions and halos of galaxies, in galaxy clusters and in the Milky Way. Small Faraday rotation measures can also be best measured at low frequencies. Polarization at higher frequencies (1–10 GHz) as observed with the EVLA, MeerKAT and the SKA will trace magnetic fields in the disks and central regions of nearby galaxies in unprecedented detail. The SKA pulsar survey will find many new pulsars; their RMs will map the Milky Way's magnetic field with high precision. All-sky surveys of Faraday rotation measures towards a dense grid of polarized background sources with the SKA and its precursor telescope ASKAP (project POSSUM) are dedicated to measure magnetic fields in distant intervening galaxies, clusters and intergalactic filaments, and will be used to model the overall structure and strength of the magnetic field in the Milky Way. With the SKA, large-scale patterns of regular fields in galaxies can be recognized to about 100 Mpc distance, ordered fields in unresolved galaxies or cluster relics to redshifts of $z \simeq 0.5$, turbulent fields in starburst galaxies or cluster halos to $z \simeq 3$ and regular fields in intervening galaxies towards QSOs to $z \simeq 5$.

ISKAF2010 Science Meeting - ISKAF2010
June 10-14, 2010
Assen, the Netherlands

*Speaker.

PoS(ISKAF2010)003

1. Magnetic discoveries

The history of radio astronomy is full of surprises. Karl Jansky's first radio telescope for 20.5 MHz was built to search for mysterious RFI, but in 1932 he discovered synchrotron emission from the Milky Way and hence interstellar magnetic fields. Jocelyn Bell and Anthony Hewish built a telescope for 81.5 MHz to measure radio waves from interplanetary space in 1967, but they discovered pulsars which host the strongest magnetic fields known. The Effelsberg telescope was opened in 1972 to observe the Sun and HII regions, one of its discoveries was highly polarized synchrotron emission from nearby galaxies in 1978 and large-scale coherent magnetic fields. The main driver of LOFAR is to observe the redshifted HI from the first gas structures and galaxies in the young Universe - who knows what else it will find? LOFAR goes back to the roots, to low frequencies where radio astronomy began, but with an enormously increased sensitivity and resolution. We may expect discoveries from the magnetic Universe. The enormous survey speed of the SKA at higher frequencies will further widen the phase space of radio polarimetric observations.

2. Observation of cosmic magnetism

Most of what we know about interstellar magnetic fields comes through the detection of radio waves. *Zeeman splitting* of radio spectral lines measures the field strength in gas clouds of the Milky Way [39] and in starburst galaxies [57]. 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 field component in the sky plane. The assumption of energy equipartition between these two components allows us to calculate the total field strength from the synchrotron intensity [8].

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

The intrinsic degree of linear polarization of synchrotron emission is about 75%. The observed degree of polarization is smaller due to the contribution of unpolarized thermal emission, which may dominate in star-forming regions, by *Faraday depolarization* along the line of sight and across the beam [61] and by geometrical depolarization.

At radio wavelengths of a few centimeters and below, the orientation of the observed B–vector is parallel to the field orientation, so that the magnetic patterns of many galaxies can be mapped directly [3]. At longer wavelengths the polarization vector is rotated in a magnetized thermal plasma by *Faraday rotation*. The rotation angle increases with the square of the wavelength λ^2 and with the *Rotation Measure (RM)*, which is the integral of the plasma density and the strength of the component of the field along the line of sight. As the rotation angle is sensitive to the sign of the field direction, only regular fields give rise to Faraday rotation, while anisotropic and random fields do not. Dynamo modes of regular fields can be identified from the pattern of polarization angles and RMs from multi-wavelength observations of the diffuse polarized emission of galaxy disks [27].

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Distinct emitting regions located on the line of sight can generate several RM components, so that the observed RM is no longer a linear function of λ^2. In such cases, multi-channel spectro-polarimetric radio data are needed that can be Fourier-transformed into Faraday space, called *RM Synthesis* [14]. If the medium has a relatively simple structure, the 3-D structure of the magnetized interstellar medium can be determined (*Faraday tomography*). The distribution of the frequency channels across the total band and the channel width of the observation defines the *Rotation Measure Spread Function (RMSF)* [37]. Cleaning of the data cube with help of the known RMSF ("dirty beam") is similar to cleaning of synthesis data.

A grid of RM measurements towards polarized background sources is a powerful tool to study magnetic field patterns in galaxies [63] and in halos of galaxy clusters [44]. A large number of background sources is required to recognize the field patterns, to separate the Galactic foreground contribution and to account for intrinsic RMs of the extragalactic sources.

3. Origin of magnetic fields

The origin of the first magnetic fields in the early Universe is still a mystery [73]. A large-scale primordial field is hard to maintain in a young galaxy because the galaxy rotates differentially, so that field lines get strongly wound up during galaxy evolution. "Seed" fields could also originate from the time of cosmological structure formation by the Weibel instability (a small-scale plasma instability) [47] or from injection by the first stars or jets generated by the first black holes [56].

The most promising mechanism to sustain magnetic fields in the interstellar medium of galaxies is the dynamo [9]. In young galaxies without ordered rotation a small-scale dynamo [13] possibly amplified the seed fields from the protogalactic phase to the energy density level of turbulence within less than 10^9 yr. To explain the generation of large-scale fields in galaxies, the mean-field dynamo has been developed. It is based on turbulence, differential rotation and helical gas flows (α *effect*), generated by supernova explosions [34] or by cosmic-ray driven Parker loops [36]. The mean-field dynamo in galaxy disks predicts that within a few 10^9 yr large-scale regular fields are excited from the seed fields [2], forming patterns ("modes") with different azimuthal symmetries in the disk and vertical symmetries in the halo.

The magnetic fields in the intracluster medium could be seeded by outflows from starburst galaxies [24],[71] or from AGNs and amplified by turbulent wakes, cluster mergers or a turbulent dynamo [58],[65].

4. Magnetic fields in the Milky Way

Optical polarization data of stars at distances $>$1 kpc show that the magnetic field of the Milky Way is predominantly oriented parallel to the disk plane [29]. Surveys of the total synchrotron emission from the Milky Way yield equipartition strengths of the total field of 6 μG, averaged over about 1 kpc around the Sun, consistent with the HI Zeeman splitting data of low-density gas clouds [39]), and about 10 μG in the inner spiral arms (Fig. 2). Faraday and dispersion measure data of pulsars give an average strength of the local regular field of 1.4 ± 0.2 μG, while in the inner Norma arm the average strength of the regular field is 4.4 ± 0.9 μG [35]. In the synchrotron filaments near the Galactic center, oriented almost perpendicular to the plane, a break in the spectrum indicates

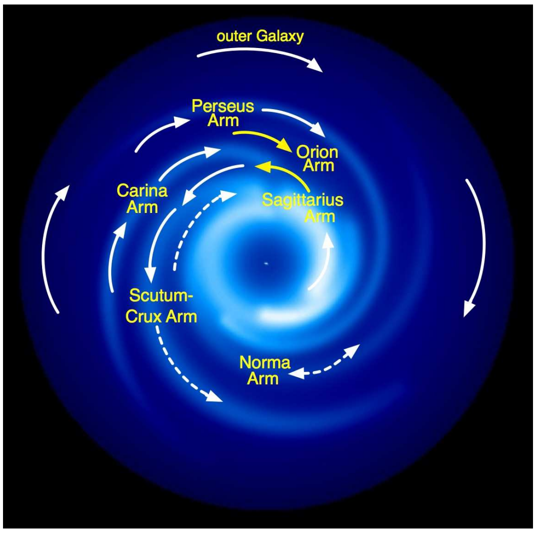

Figure 1: Sketch of the magnetic field in the Milky Way, as derived from Faraday rotation measures of pulsars and extragalactic sources. Generally accepted results are indicated by yellow vectors, while white vectors refer to results which need confirmation (from Brown, priv. comm.).

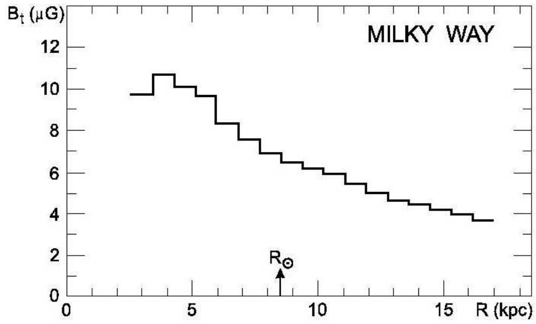

Figure 2: Strength of the total magnetic fields in the Milky Way, derived from the 408 MHz synchrotron emission, assuming equipartition between the energy densities of magnetic fields and cosmic rays (from Berkhuijsen, in [74]).

that the field strength is 50–100 μG [23]. Submm polarization observations in molecular clouds near the Galactic center reveal fields mostly parallel to the plane in dense regions, but perpendicular in regions of lower density [20].

The all-sky maps of polarized synchrotron emission at 1.4 GHz from the Milky Way from DRAO and Villa Elisa and at 22.8 GHz from WMAP and the new Effelsberg RM survey of polarized extragalactic sources were used to model the regular field [66]. One large-scale field reversal is required at about 1–2 kpc from the Sun towards the Milky Way's center, which is further supported by studies of RMs from extragalactic sources near the Galactic plane [15],[54],[69] (Fig. 1). The overall structure of the regular field is not known yet - its structure cannot be described by a simple pattern [51]. The disk field is fundamentally different from the halo field [40].

The signs of RMs of extragalactic sources and pulsars at Galactic longitudes l=90°–270° are the same above and below the plane [68]: the local magnetic field is symmetric. In contrast, the RM signs towards the inner Galaxy (l=270°–90°) are *opposite* above and below the plane. This can be assigned to an antisymmetric halo field [66] or to deviations of the local field.

Little is known about the vertical field component in the Milky Way. According to RM data from extragalactic sources, the local regular Galactic field has no significant vertical component towards the northern Galactic pole and only a weak vertical component of $B_z \simeq 0.3$ μG towards the south [49], while mean-field dynamo models predict vertical fields towards both poles.

5. Magnetic fields in spiral galaxies

The typical average equipartition strength of the total magnetic field in spiral galaxies is about

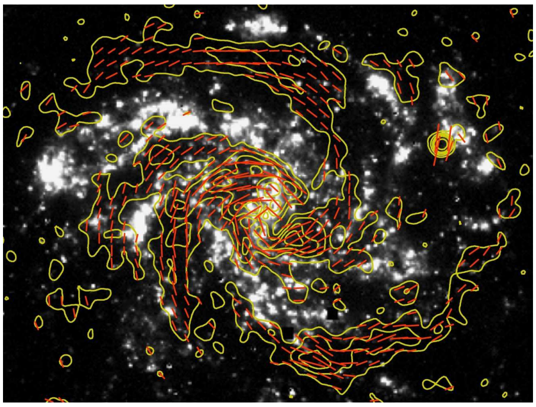

Figure 3: Polarized radio emission (contours) and *B*–vectors of NGC 6946, combined from observations at 6 cm wavelength with the VLA and Effelsberg 100m telescopes and smoothed to 15" resolution (from [7]). The background image shows the Hα emission (from [26]). Copyright: MPIfR Bonn. Graphics: *Sterne und Weltraum*.

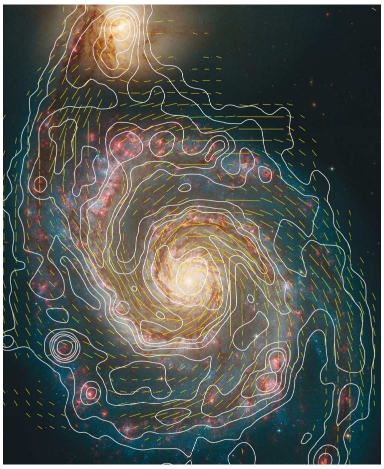

Figure 4: Total radio emission (contours) and *B*–vectors of M 51, combined from observations at 6 cm wavelength with the VLA and Effelsberg telescopes and smoothed to 15" resolution , overlaid onto an optical image from the HST. Copyright: MPIfR Bonn and *Hubble Heritage Team*. Graphics: *Sterne und Weltraum* (from [28]).

10 μG. Radio-faint galaxies like M 31 and M 33, our Milky Way's neighbors, have weaker total magnetic fields (5–7 μG), while gas-rich spiral galaxies with high star-formation rates, like M 51, M 83 and NGC 6946, have total field strengths of 20–30 μG in their spiral arms. The strongest total fields of 50–100 μG are found in starburst galaxies.

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 randomly oriented within the telescope beam, the width of which typically corresponds to a few 100 pc. Turbulent fields in spiral arms are probably generated by turbulent gas motions related to star formation activity.

The ordered (regular and/or anisotropic) fields traced by the polarized synchrotron emission are generally strongest (10–15 μG) in the regions *between* the optical spiral arms and oriented parallel to the adjacent spiral arms, in some galaxies forming *magnetic arms* (Fig. 3), probably generated by a mean-field dynamo. In galaxies with strong density waves some of the ordered field is concentrated at the inner edge of the spiral arms (Fig. 4). The ordered field forms spiral patterns in almost every galaxy [3], even in ring galaxies [21] and in flocculent galaxies without massive spiral arms [60]. Spiral fields with large pitch angles are also observed in the central regions of galaxies and in circum-nuclear gas rings of barred galaxies [10].

Spiral fields can be generated by compression at the inner edge of spiral arms, by shear in interarm regions, or by dynamo action. Large-scale patterns of Faraday rotation measures (RM) are signatures of coherent dynamo fields and can be identified from polarized emission of the galaxy disks [27] or from RM data of polarized background sources [63]. The Andromeda galaxy M 31 and several other galaxies host a dominating axisymmetric disk field, as predicted by dynamo models. Dominating bisymmetric fields are rare, as predicted by dynamo models. Faraday rotation in

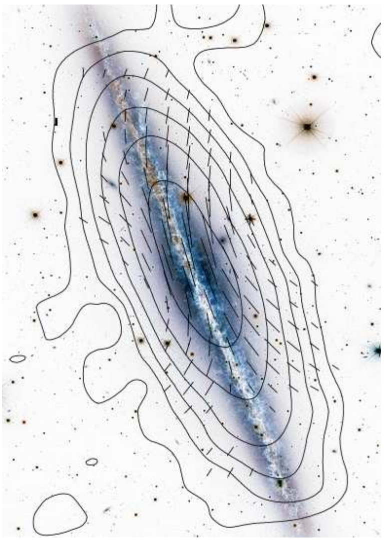

Figure 5: Total radio emission (84” resolution) and *B*–vectors of the edge-on galaxy NGC 891, a galaxy similar to the Milky Way, observed at 8.4 MHz with the Effelsberg telescope. The background optical image is from the CFHT. Copyright: MPIfR Bonn and CFHT/Coelum (from [45]).

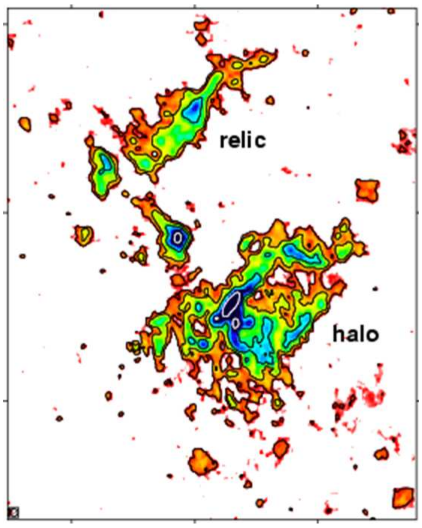

Figure 6: Total radio emission from the cluster A 2255, observed at 1.4 GHz with the VLA. The field size is about 20’ x 25’ (from [33]).

NGC 6946 and in other similar galaxies with magnetic arms can be described by a superposition of two azimuthal dynamo modes [4]. In many galaxy disks no clear patterns of Faraday rotation were found. Either the field structure cannot be resolved with present-day telescopes or the generation of large-scale modes takes longer than the galaxy’s lifetime [2].

Large-scale field reversals were discovered in the Milky Way (Sect. 4), but nothing similar has yet been detected in spiral galaxies, although high-resolution RM maps of Faraday rotation are available for many spiral galaxies. A satisfying explanation is still lacking.

Nearby galaxies seen edge-on generally show a disk-parallel field near the disk plane. High-sensitivity observations of NGC 253 [38], NGC 891 (Fig. 5), NGC 4631 [45] and other galaxies revealed “X-shaped” fields in the halo. The field is probably transported from the disk into the halo by an outflow emerging from the disk.

While the azimuthal symmetry of the dynamo modes is known for many galaxies, the vertical symmetry is much harder to determine. The RM patterns of symmetric and antisymmetric modes cannot be distinguished in mildly inclined galaxies. The symmetry type becomes only visible in strongly inclined galaxies, as a reversal of the RM sign above and below the plane. Only symmetric fields were found so far (in M 31, NGC 253, NGC 891 and NGC 5775) which is in agreement with the prediction of dynamo models (Sect. 3). The RM data of NGC 253 further indicate a symmetric quadrupolar field in the halo, consistent with the symmetric field near the disk.

Near the disk plane, ordered fields of nearby galaxies seen edge-on are preferably oriented parallel to the plane [45]. As a result, polarized emission can also be detected from unresolved galaxies if the inclination is larger than about 20° [64]. This opens a new method to search for ordered fields in distant galaxies.

The integrated flux densities of total radio continuum emission at centimeter wavelengths (frequencies of a few GHz), which is mostly of nonthermal synchrotron origin, and far-infrared (FIR) emission of star-forming galaxies are tightly correlated. This correlation extends over five orders of magnitude [11] and is valid to redshifts of at least 3 [59]. It requires that magnetic fields and star formation are connected [52],[53]. The total radio emission serves as a tracer of star formation and of magnetic fields in the early Universe.

6. Galaxy clusters

Some fraction of galaxy clusters, mostly the X-ray bright ones, has diffuse radio emission [19], emerging from diffuse *halos* and steep-spectrum *relics* (Fig. 6). The diffuse halo emission is almost unpolarized and emerges from turbulent intracluster magnetic fields. RMs towards background sources show a vanishing mean value and a dispersion which decreases with distance from the cluster center [22]. Relics can emit highly polarized radio waves from anisotropic magnetic fields generated by compression in merger shocks [25]. A polarized region of about 1 Mpc size was discovered in Abell 2255 [33].

Equipartition strengths of the total magnetic field range from 0.1 to 1 μG in halos, and are higher in relics. On the other hand, Faraday rotation data towards background sources behind cluster halos reveals fields of a few μG strength fluctuating on coherence scales of a few kpc [32] and even fields of 40 μG in the cores of cooling flow clusters [18] where they may be dynamically important. The reason for the difference in the field strength determinations is still under discussion.

High-resolution RM maps of radio galaxies embedded in a cluster allowed to derive the power spectra of the turbulent intracluster magnetic fields which are of Kolmogorov type and have coherence scales of about 1–5 kpc [72].

7. Intergalactic filaments

The search for magnetic fields in the intergalactic medium (IGM) is of fundamental importance for cosmology. All "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. Models of structure formation predict strong intergalactic shocks which enhance the field.

Various mechanisms have been suggested for the origin of a magnetic field in the cosmic web. The field could be produced via the Weibel instability at structure formation shocks [50]. Another possibility is the injection from galactic black holes (AGNs) and outflows from starburst galaxies [71]. In each case the field is subsequently amplified by compression and large-scale shear-flows [16]. Ryu et al. [58] have argued that highly efficient amplification is possible via MHD turbulence, with the source of the turbulent energy being the structure formation shocks themselves. Estimates of the strength of the turbulent field in filaments obtained from MHD simulations with a primordial seed field range typically between 0.1 μG and 0.01 μG, while regular fields are weaker.

To date there has been no unambiguous detection of a general magnetic field in the IGM. In an intergalactic region of about 2° extent west of the Coma Cluster, containing a group of radio galaxies, enhanced synchrotron emission yields an equipartition total field strength of $0.2-0.4$ μG

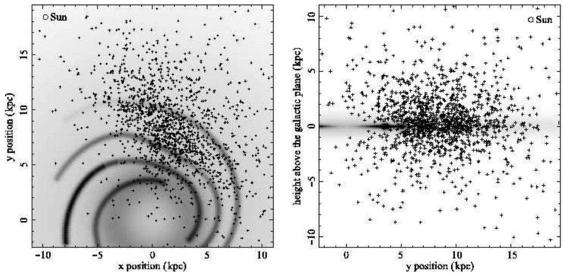

Figure 7: Simulation of the 1000+ pulsars that LOFAR is expected to find in a 60-day all-sky survey, shown in a Galactic plane projection (left) and an edge-on view of the Galactic plane (right) (from [70]).

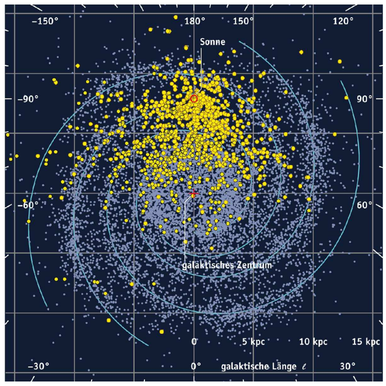

Figure 8: Simulation of about 20 000 pulsars (blue) in the Milky Way that will be detected with the SKA, compared to about 2000 pulsars known today (yellow). Graphics: *Sterne und Weltraum* (from Cordes, priv. comm).

[46]. Xu et al. [75] observed an excess of rotation measures (RM) towards two super-clusters which may indicate regular magnetic fields of $< 0.3\ \mu$G on scales of order 500 kpc. Gamma-ray halos around active galactic nuclei can be used to measure the strength of the intergalactic field [1], but the observed halos could also be instrumental effects. Lee et al. [48] found indications for a statistical correlation at the 4σ level of the RMs of background sources with the galaxy density field which may correspond to an intergalactic field with about 30 nG strength and about 1 Mpc coherence length. However, the current data are probably insufficient to constrain the amplitude and distribution of large-scale intergalactic fields [62].

8. Prospects with LOFAR and the SKA

Next-generation radio telescopes will widen the range of observable magnetic phenomena. 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 outer galaxy disks and the transition to intergalactic space [5] and in steep-spectrum cluster halos [17].

LOFAR will detect all pulsars within 2 kpc of the Sun and discover about 1000 new nearby pulsars, especially at high latitudes (Fig. 7). Most of these are expected to emit strongly linearly polarised signals at low frequencies. This allows us to measure their RM which will give an unprecedented picture of the structure of the magnetic field near to the Sun.

High-resolution, deep observations at high frequencies, where Faraday effects are small, require a major increase in sensitivity for continuum observations which will be achieved by the Extended Very Large Array (EVLA) and the planned Square Kilometre Array (SKA). The detailed structure of the magnetic fields in the ISM of galaxies, in galaxy halos, in cluster halos and in cluster relics can then be observed. The turbulence power spectra of the magnetic fields can be measured. Direct insight into the interaction between gas and magnetic fields in these objects will

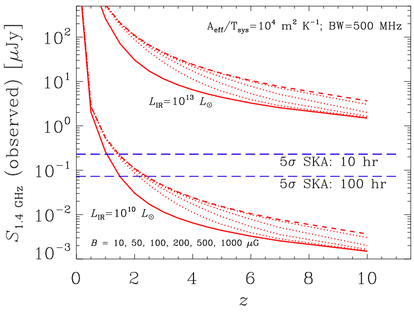

Figure 9: Synchrotron emission at 1.4 GHz as a function of redshift z and magnetic field strength B, and the 5σ detection limits for 10 h and 100 h integration time with the SKA (from [52]).

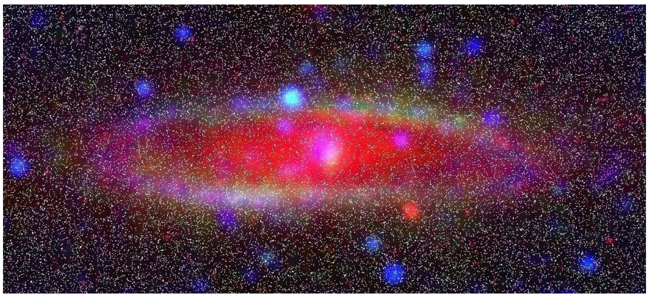

Figure 10: Simulation of RMs towards background sources (white points) in the region of M 31 observable with the SKA within 1 h. Optical emission from M 31 is shown in red, diffuse radio continuum intensity in blue and diffuse polarized intensity in green (from Gaensler, priv. comm.).

become possible. The SKA will also allow to measure the Zeeman effect in much weaker magnetic fields in the Milky Way and in nearby galaxies.

Detection of polarized emission from distant, unresolved galaxies will reveal large-scale ordered fields [64], and statistics can be compared with the predictions of dynamo theory [2]. The SKA at 1.4 GHz will detect Milky-Way type galaxies at $z \leq 1.5$ (Fig. 9) and their polarized emission at $z \leq 0.5$ (assuming 10% percentage polarization). Bright starburst galaxies can be observed at larger redshifts, but are not expected to host ordered or regular fields. Cluster relics are also detectable at large redshifts through their integrated polarized emission.

Unpolarized synchrotron emission, signature of turbulent magnetic fields, can be detected with the SKA out to very large redshifts for starburst galaxies, depending on luminosity and magnetic field strength (Fig. 9), and also for cluster halos. However, for fields weaker than 3.25 μG $(1+z)^2$, energy loss of cosmic-ray electrons is dominated by the inverse Compton effect with CMB photons, so that their energy appears mostly in X-rays and not in the radio range. On the other hand, for strong fields the energy range of the electrons emitting at a 1.4 GHz drops to low energies, where ionization and bremsstrahlung losses may become dominant. In summary, the mere detection of synchrotron emission at high redshifts will constrain the range of allowed magnetic field strengths.

If polarized emission from galaxies, cluster halos or cluster relics is too weak to be detected, the method of *RM grids* towards background QSOs can still be applied. Here, the distance limit is given by the polarized flux of the background QSO which can be much higher than that of the intervening galaxy. A reliable model for the field structure of nearby galaxies, cluster halos and cluster relics needs RM values from a large number of polarized background sources, hence large sensitivity and/or high survey speed. The POSSUM survey at 1.4 GHz with the planned Australia SKA Pathfinder (ASKAP) telescope with 30 deg^2 field of view [31] will measure about 100 RM values from polarized extragalactic sources per square degree within 10 h integration time. Similarly long integrations with the EVLA and with MeerKAT will show about 5 times more sources, but their fields of view are small.

The SKA "Magnetism" Key Science Project plans to observe a wide-field survey (at least 10^4 deg^2) around 1 GHz with 1 h integration per field which will detect sources with 0.5–1 μJy flux density and measure at least 1500 RMs deg^{-2}. This will contain at least 2×10^7 RMs from compact polarized extragalactic sources at a mean spacing of $\simeq 90''$, plus at least 10^4 RM values from pulsars with a mean spacing of $\simeq 30'$ [30]. More than 10 000 RM values are expected in the area of M 31 (Fig. 10) and will allow the detailed reconstruction of the 3-D field structure in this and many other nearby galaxies, while simple patterns of regular fields can be recognized out to distances of about 100 Mpc [63] where the polarized flux is too low to be mapped. The magnetism of cluster halos can be measured by the RM grid to redshifts of about 1 [44].

The SKA pulsar survey will find about 20 000 new pulsars which will be mostly polarized and reveal RMs (Fig. 8), suited to map the Milky Way's magnetic field with high precision.

Faraday rotation in the direction of QSOs allows us to determine the strength and pattern of a regular field in an intervening galaxy [12]. This method can be applied to distances of young QSOs ($z \simeq 5$). Mean-field dynamo theory predicts RMs from regular galactic fields at $z \leq 3$ [2], but the RM values are reduced by the redshift dilution factor of $(1+z)^{-2}$. If an overall IGM field with a coherence length of a few Mpc existed in the early Universe and its strength varied proportional to $(1+z)^2$ [73], its signature may become evident at redshifts of $z > 3$. Averaging over a large number of RMs is required to unravel the IGM signal. The goal is to detect an IGM magnetic field of 0.1 nG, which needs an RM density of ≈ 1000 sources deg^{-2} [42].

If the filaments of the local Cosmic Web outside clusters contain a magnetic field [58], possibly enhanced by IGM shocks, we hope to detect this field by direct observation of its total synchrotron emission [41] and possibly its polarization, or by Faraday rotation towards background sources. For fields of $\approx 10^{-8} - 10^{-7}$ G with 1 Mpc coherence length and $n_e \approx 10^{-5}$ cm^{-3} electron density, Faraday rotation measures between 0.1 and 1 rad m^{-2} are expected. A 30 nG regular field on a coherence scale of 1 Mpc [48] generates about 0.2 rad m^{-2}, which cannot be detected directly. Promising is a statistical analysis like the measurement of the power spectrum of the magnetic field of the Cosmic Web [42] or the cross-correlation with other large-scale structure indicators like the galaxy density field [62]. Detection of a general IGM field, or placing stringent upper limits on it, will provide powerful observational constraints on the origin of cosmic magnetism.

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