Exploring weak magnetic fields with LOFAR and SKA

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Abstract. Regular magnetic field structures can be derived from the Faraday rotation measures (RM) of polarized background sources observable at 1.4 GHz with the SKA. At lower frequencies ($<250$ MHz) polarimetry of radio sources with the Low Frequency Array (LOFAR) will allow the investigation of extremely small RM, to detect and map weak regular fields in halos and outer parts of spiral galaxies, and in the interstellar and intergalactic medium. Very little is known yet about the number density of polarized sources at low frequencies. Observed distributions of polarized sources at 350 MHz and 1.4 GHz and perspectives to detect weak magnetic fields with LOFAR are presented. Test observations of polarized radio sources with the Westerbork Synthesis Radio Telescope (WSRT) and the Giant Metrewave Radio Telescope (GMRT) are discussed.

Introduction

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

Low frequency radio emission is purely nonthermal in nearby galaxies and in intergalactic (IGM) and intracluster magnetic media. Radio emission detected with present day radio telescopes allows detailed studies of a few dozens of nearby galaxies (Beck 2005). With the high sensitivity of new generation telescopes such as the Low Frequency Array (LOFAR) and the Square Kilometre Array (SKA), one can observe very weak low-frequency ($\lesssim 250$ MHz) radio emission and hence measure weak magnetic fields in the outer parts of galaxies and the IGM.

The polarimetric capabilities of LOFAR and the SKA are crucial for our understanding of magnetic fields. The required specifications are high polarization purity and multichannel spectro-polarimetry. The former will allow the detection of objects with relatively low degrees of linear polarization, while the latter will enable accurate measurements of Faraday rotation measures (RMs), intrinsic polarization 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). A range of different RM values can be observed and RM components from distinct regions along the line of sight can be separated.
Synchrotron radio emission from weak magnetic fields

Synchrotron radio emission at low radio frequencies is radiated by cosmic-ray electrons which are accelerated by supernova shock fronts in star-forming regions. The diffusion length of cosmic-ray electrons is longer at low frequencies because energy losses of electrons are smaller. The synchrotron lifetime of electrons emitting in the LOFAR bands ($30 - 240$ MHz) is $(2 - 5) \times 10^8$ yr for a magnetic field strength of $B = 5 \mu$G. Cosmic-ray electrons radiating at 50 MHz can propagate to a large distance (up to 150 kpc) from the place of origin and reach outer regions of the disk and halo of galaxies (Beck 2008). Weak magnetic fields in outer galactic regions, in the halos of clusters of galaxies, and in the intergalactic space can be traced by polarized synchrotron emission if ordered magnetic fields exist. At present, regular magnetic fields are observed in nearby spiral galaxies (Fig. 1) and in cluster relics (e.g., Govoni et al. 2005). The large scalelength and/or scaleheight of magnetic fields in the disks and halos of galaxies suggests that weak regular fields may also exist in the outer regions (Beck 2005). More sensitive radio telescopes, such as LOFAR and the low-frequency SKA array, are needed to detect a weak polarized signal from outer parts of galaxies, clusters and the IGM.

Faraday rotation measure as a tool to study weak magnetic fields

Another potential tool for studying weak magnetic fields in galaxies is the Faraday rotation measure (RM) of background polarized sources shining through the foreground galaxy. RM in galaxies are generated by regular fields of the galaxy...
plus its ionized gas, both of which extend to large galactic radii (Fig. 1). RM towards polarized background sources can trace regular magnetic fields in these galaxies out to even larger distances. However, with the sensitivity of present-day radio telescopes the number density of polarized background sources is only a few sources per square degree solid angle, so that only M 31 and the Large and Small Magellanic Clouds could be investigated in this way so far (Han et al. 1998; Gaensler et al. 2005; Mao et al. 2008). With the high sensitivity of the SKA at 1.4 GHz, we will observe the polarized intensity and RM for a huge number of faint radio sources, thus providing a high-density background of polarized point sources. This opens the possibility to study in detail large-scale patterns of magnetic fields in galaxies. By measuring RM at frequencies around 1 GHz with the SKA, simple field structures can be recognized in galaxies up to about 100 Mpc distance and will allow to test dynamo against primordial or other models of field origin for ≤ 60000 disk galaxies (Stepanov et al. 2008). For this, a source sensitivity of 0.015 µJy of integrated flux density is needed, which can be achieved within 100 h observation time with the SKA. On the other hand, the reconstruction of magnetic field structures of strongly inclined spiral galaxies would require a much higher sensitivity of the SKA (Stepanov et al. 2008). The field structures of ≈ 60 galaxies to about 10 Mpc distance can be recognized with ≥ 1000 background polarized sources which would require tens to hundred hours of integration time.

As the RM errors are smaller at larger wavelengths (ΔRM ∝ λ−2 for constant relative bandwidth) the low-frequency SKA array and low-frequency precursor telescopes like LOFAR will be ideal to study the weak magnetic fields in galaxies and intergalactic space – provided background sources are still significantly polarized at low frequencies.

Polarization properties of radio galaxies at 150 MHz

The main population of galaxies contributing to the polarized background sky at low radio frequencies are FR I and FR II radio galaxies. Schoenmakers et al. (2004) observed the double-double giant radio galaxy 1834+62 at frequencies from 600 MHz to 8.4 GHz. They found strong polarization in all four radio lobes (19% - 22%) at 1.4 GHz. The rotation measures towards four radio lobes are similar, within ∼ (3 ± 0.4) rad m⁻² of 57 rad m⁻². This difference is hard to explain by RM produced by cocoons surrounding the lobes, and it is most likely originating in the diffuse medium of the Galaxy and/or intergalactic space or intergalactic filaments.

To study the polarization properties of this source at lower frequencies we conducted observations with the WSRT at 150 MHz and 350 MHz (joint project with Ger de Bruyn) with resolutions of 130” and 55”, respectively. Preliminary results show that the inner lobes are depolarized at 350 MHz, while the outer lobes still show 13% polarization. At 150 MHz the outer lobes are more depolarized, to < 5%. Fractional polarization of outer lobes at 150 MHz is ≥ 2 times smaller than at 350 MHz and ≥ 4 times at 1.4 GHz suggesting that beam and/or depth depolarization is stronger at 150 MHz. Therefore, the number density of polarized sources will be low, at least for large beams.

The polarized sky was observed within the primary beam of the GMRT (using the experimental software backend) near 150 MHz at 20” resolution. Pen et al.
Density of polarized background sources at 350 MHz

LOFAR can in principle measure very small Faraday rotation measures (below \( \lesssim 1 \, \text{rad} \, \text{m}^{-2} \)) and hence very weak magnetic fields and/or small electron densities in the outer disks of galaxies (\( RM < 10 \, \text{rad} \, \text{m}^{-2} \)), galaxy halos, cluster relics and in intergalactic filaments (\( RM \sim 1 \, \text{rad} \, \text{m}^{-2} \)), and, possibly, also in the general intergalactic medium (\( RM \lesssim 0.1 \, \text{rad} \, \text{m}^{-2} \)).

As the flux density decrease with frequency (for steep-spectrum sources), one should expect more polarized background sources to be detected at lower frequencies. On the other hand, the depolarization is stronger at low frequencies which weakens the polarized signal. Deep low-frequency polarization surveys are needed to determine the cumulative source counts.

Because of the lack of polarization surveys at low frequencies (<600 MHz), we used several fields observed with the WSRT at 350 MHz (Haverkorn et al. 2003a,b; Schnitzeler 2008; Schnitzeler et al. 2009) to compile a sample of 104 polarized extragalactic sources. The number counts of polarized sources at 350 MHz (Fig. 2 black squares) is one order of magnitude lower than that at

![Figure 2. Observed integral number counts of polarized background point sources at 350 MHz (black squares) and 1.4 GHz (Taylor et al. 2007, solid line). The dashed line is the extrapolation of number counts at 350 MHz down to flux density level of 0.01 mJy. The two vertical solid lines represent the 5\( \sigma \) detection limits with the LOFAR Dutch Full Array within 1 h observation time for 20 (right) and 36 LOFAR stations (left). The three vertical dotted lines are the 5\( \sigma \) detection limits with the Dutch Full Array and International Full Array (36+14 stations) in the “high-band” (110–240 MHz) within 1 h (right), 10 h (middle) and 100 h (left) observation time.](image-url)
1400 MHz (Fig. 2; solid line). This suggests that at low frequencies depolarization is larger than the spectral increase and reduces the polarized flux, and hence the observable number of polarized background sources. Extrapolation of the number counts down to 0.01 mJy (the dashed line in Fig. 2) shows that with a sensitivity of 0.5 mJy the high-band LOFAR will detect \( \lesssim 1 \) polarized source per 1 deg\(^2\) and \( \approx 5 \) sources in 1 hours integration time with the Dutch and International Full Array (DFA and IFA) configurations, respectively. From 10 to 30 polarized sources will be detected with IFA in 10 to 100 hours of integration time.

RM mapping with LOFAR is possible for nearby sources with large angular sizes covering a sky area of several square degrees. The high-band antennae (110-240 MHz) are preferable because calibration is easier while detection of polarization in the low-band (30-80 MHz) will be much harder. The Coma Cluster of galaxies covers an area of about 50 deg\(^2\), and LOFAR (high-band) will detect \( \approx 500 \) background polarized sources towards the cluster in 10 hours of integration time, thus allowing detailed RM mapping and studying of the structure of the large-scale magnetic fields. About 30 polarized sources can be detected behind a filamentary structure (\( \approx 3 \) deg\(^2\)), found in the central part of the Coma cluster at 408 MHz [Kronberg et al. 2007], and about 80 polarized sources behind the nearest galaxy, M31, with 100 hours of integration time. The latter number of background sources is four times larger than that detected with the VLA at 1.4 GHz [Han et al. 1998], thus allowing the detailed structure of the field to be investigated.

**Summary**

Extremely small RM values can be measured in the LOFAR high-band (110-240 MHz), thus providing a powerful tool to measure weak magnetic fields. Recognition of simple magnetic field structures of foreground objects is realistically possible with \( \gtrsim 10 \) polarized background sources per object. Depolarization is stronger at lower radio frequencies which leads to a strongly reduced number density of polarized point sources. Therefore, recognition and detection of weak magnetic field structures is only possible for nearby sources with large angular sizes covering a sky area of several square degrees (nearby galaxies, clusters and filaments), while distant objects (or objects with small angular sizes) require much observation time (\( \gtrsim 100 \) h). For objects with small angular sizes, the diffuse polarized emission from the objects themselves has to be detected to measure their RM.

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