Proceedings of *Magnetic Fields in the Universe:*
From Laboratory and Stars to Primordial Structures
Aug. 21st – 27th 2011, Zakopane, Poland
Eds. M. Soida, K. Otmianowska-Mazur, E.M. de Gouveia Dal Pino & A. Lazarian

The LOFAR Magnetism Key Science Project

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Abstract

Measuring radio waves at low frequencies offers a new window to study cosmic magnetism, and LOFAR is the ideal radio telescope to open this window widely. The LOFAR Magnetism Key Science Project (MKSP) draws together expertise from multiple fields of magnetism science and intends to use LOFAR to tackle fundamental questions on cosmic magnetism by exploiting a variety of observational techniques. Surveys will provide diffuse emission from the Milky Way and from nearby galaxies, tracking the propagation of long-lived cosmic-ray electrons through magnetic field structures, to search for radio halos around spiral and dwarf galaxies and for magnetic fields in intergalactic space. Targeted deep-field observations of selected nearby galaxies and suspected intergalactic filaments allow sensitive mapping of weak magnetic fields through Rotation Measure (RM) grids. High-resolution observations of protostellar jets and giant radio galaxies reveal structures on small physical scales and at high redshifts, whilst pulsar RMs map large-scale magnetic structures of the Galactic disk and halo in revolutionary detail. The MKSP is responsible for the development of polarization calibration and processing, thus widening the scientific power of LOFAR.

1 Introduction

Magnetic fields are pervasive throughout the Universe. Obtaining a detailed knowledge of the strength, morphology and evolution of these magnetic fields is essential not only for understanding the energetics and dynamics of numerous astrophysical phenomena, but using cosmic large scale structure as a laboratory in which to probe these fields is also the key to unlocking the even more fundamental long standing problems of magnetic evolution and structure, and ultimately to determining the origin of cosmic magnetism itself.

At radio wavelengths, magnetic fields reveal themselves indirectly in two major ways: synchrotron emission from cosmic-ray electrons (CRe) and Faraday rotation of polarized background emission due to magnetized media along the line of sight. The synchrotron radiation traces the component of the total field in the sky plane, while the Faraday rotation measure (RM) provides information on the field component along the line of sight (Sect. 5). Both of these mechanisms are enhanced at low radio frequencies due to the increased intensity of synchrotron emission and the wavelength-squared dependence of Faraday rotation, making LOFAR uniquely suited to magnetism science. The accuracy in RM measurements increases with increasing total (not necessarily contiguous) coverage in wavelength space (Brentjens & de Bruyn 2005, Heald 2009), so that much smaller variations in field strength can be measured at low frequencies. At such low frequencies CRe have longer lifetimes, traveling further from their site of generation into distant regions of low magnetic field strength and revealing rarified magnetic structures invisible at higher frequencies. These structures carry the signature of astrophysical processes that have been erased in more active regions, but which remain crucial for our understanding of cosmic history. Galaxies are expected to be much larger than their optical sizes, when observed at low radio frequencies.

A brief summary of the imaging capabilities of LOFAR was given by Heald et al. (2011).

2 Science areas

The Magnetism Key Science Project (MKSP) aims to exploit the unique abilities of LOFAR to investigate cosmic magnetic fields in a variety of astrophysical sources. The MKSP Project Plan includes an initial target list of galaxies, selected in close cooperation with the LOFAR Surveys Key Science Project (Röttgering et al. 2011), followed by deep observations of galaxies and galaxy groups. These deep fields will also serve as targets to investigate magnetic fields in the Milky Way foreground. The structure of small-scale magnetic fields will be studied the lobes of giant radio galaxies. Polarized synchrotron emission and rotation measures from pulsars and polarized jets from young stars will be observed in cooperation with the Transients Key Science Project (Fender et al. 2006, Stappers et al. 2011).

2.1 Milky Way

LOFAR's broad coverage of low frequencies makes it uniquely suited to studying weak magnetic fields and low-density regions in the halo of the Milky Way, where such studies can address both the disk-halo interaction and interstellar medium (ISM) energetics. In addition to probing the origin and evolution of Galactic magnetism through the regular field component and interstellar turbulence though small-scale structure, Galactic halo magnetic field investigations also importantly address the confusing effect of Galactic emission as a Faraday screen when studying distant extended galactic and extragalactic objects: at LOFAR frequencies foreground influence is expected in all directions and must be properly separated for a correct interpretation of extragalactic data. High-resolution 3-D simulations of Galactic emission components will be used for this purpose (Sun et al. 2009). Rotation Measure (RM) Synthesis of diffuse Galactic synchrotron emission is an excellent way to disentangle various RM components, giving statistical information on the clumped magnetized ISM and on the relation of thermal electron density to magnetic field strength.

LOFAR will also be an excellent tracer of the magnetized ISM due to its high angular resolution, which minimizes beam depolarization effects, and due to its coverage at low frequencies enabling it to detect aged electrons high in the Galactic halo that emit at low frequencies. Within a few kpc the 3-D structure of the Galactic magnetic field will be mapped with unprecedented accuracy, complementary to pulsar RMs (Sect. 2.2). Comparison of RM

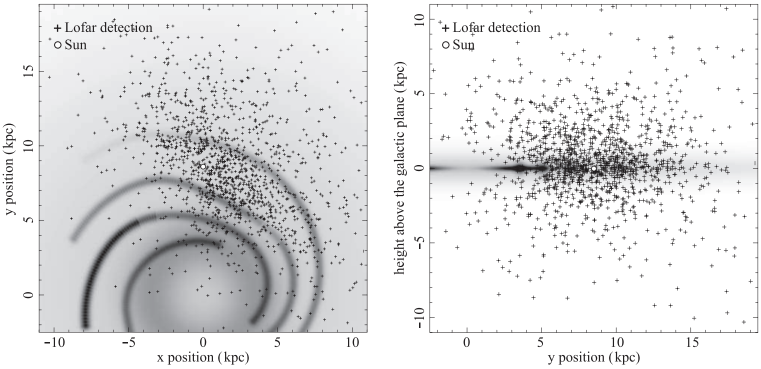

Figure 1: Simulation of the 1000+ pulsars that LOFAR is expected to find in a 60-day all-sky survey, shown in a Galactic plane projection (left) and an edge-on view of the Galactic plane (right) (from van Leeuwen & Stappers 2010).

data to magnetic field models will shed light on the configuration of large-scale regular fields. The deep fields of nearby galaxies (Sect. 2.3) with a minimum of Galactic foreground contamination will be used to make a statistical comparison of RMs and redshifts in order to investigate the presence and properties of magnetic fields in the Galactic halo.

The targets of observation for the deep observations of galaxies (Sect. 2.3) will lie at intermediate and high Galactic latitudes and will also be used to probe the magnetized Galactic halo. Here, less is known about the Galactic magnetic field, even though this field is important in the disk-halo energy exchange and for the propagation and scattering of extragalactic ultrahigh-energy cosmic rays (UHECRs).

2.2 Pulsars

Pulsars play a central role in detecting interstellar magnetic fields in the Galaxy. Polarization observations of hundreds of pulsars have already been used to map large-scale features in the Galactic magnetic field (e.g. Noutsos et al. 2008): the field's magnitude and direction along the line of sight to each pulsar can be determined by using the pulsar RMs. One large-scale field reversal was found, possibly more exist but cannot be confirmed with the present data. LOFAR pulsar searches will benefit from both high sensitivity and an increasing pulsar brightness at low frequencies. This is expected to result in the discovery of a new population of dim, nearby and high-latitude pulsars too weak to be found at higher frequencies: roughly 1,000 pulsar discoveries are expected from LOFAR (Fig. 1). Polarization observations of these pulsars will approximately double the current RM sample (≈ 700 RMs). When combined with the catalogue of $\approx 38,000$ extragalactic-source RMs (Taylor et al. 2009), this will provide the strength and direction of the regular magnetic field in previously unexplored directions and locations in the Galaxy; e.g. very little is known about the magnetic field properties of the Milky Way beyond a few hundred parsecs from the Galactic plane. RMs of high-latitude pulsars and extragalactic sources are crucial for determining fundamental properties such as the scale height and geometry of the magnetic field in the thick disk and halo, as well as providing the exciting prospect of discovering magnetic fields in globular clusters.

In addition to providing an indirect probe of Galactic magnetic structure, polarization surveys of pulsars at low frequencies will provide a new view of intrinsic pulsar physics. These include the effects of scattering, which are prominent at LOFAR frequencies but have until now only been studied at higher frequencies (e.g. Noutsos et al. 2009); pulsar polarization spectra, which are expected to turn-over in the LOFAR band (100 − 400 MHz), and constraints on the geometry of pulsar magnetospheric emission. We intend to observe every pulsar detected with LOFAR in polarization using both LBA and HBA.

2.3 Nearby galaxies

It is now generally accepted that galactic magnetic fields result from the amplification of a seed magnetic field by a hydromagnetic dynamo, rather than having a merely primordial origin. Turbulent "seed" fields in young galaxies can originate from the Weibel instability in shocks during the cosmological structure formation (Lazar et al. 2009), injected by the first stars or jets generated by the first black holes (Rees 2005). The turbulent dynamo can further amplify the field on small timescales (Schleicher et al. 2010), followed by the large-scale dynamo (Beck et al. 1996, Arshakian et al. 2009).

Important questions still remain regarding the amplification process, as well as the configuration of the large-scale field in evolving galaxies (e.g. Moss et al. 2012) and the field structure in galactic halos (Braun et al. 2010). The expected number density of background sources seen by LOFAR will for the first time enable systematic studies of galactic field structures using Faraday rotation of background sources (Stepanov et al. 2008). "Faraday spectra" generated by RM Synthesis (Sect. 5) will allow a detailed 3-D view of regular magnetic fields and their reversals (Bell et al. 2011, Frick et al. 2011) and enable a clear measurement of magneto-ionic turbulent fluctuations and their scale spectrum. These will give us a handle on the properties of the turbulent motions responsible for dynamo action, allowing us to address outstanding key questions: such as whether magnetic fields are dynamically important in the ISM of galaxies at different evolutionary stages. LOFAR's sensitivity to regions of low density and weak field strengths will also allow us to measure the magnetic structure in the outer disks and wider halos of spiral galaxies. It is here that star formation activity is low, and processes additional to dynamo action, such as gas outflows from the inner disk, the magneto-rotational instability, gravitational interaction and ram pressure by the intergalactic medium are imprinted on this magnetic structure.

Outside of the optical extent of a galaxy, little synchrotron emission is detected at high frequencies because the highly relativistic electrons responsible for the emission rapidly lose energy as they travel away from the acceleration sites in supernova remnants, which are concentrated in the inner disk of galaxies where the star formation rate is highest. Radio halos are detected around edge-on galaxies. The "X-shaped" structure observed in polarization indicates action of a galactic wind (Krause 2009). In a few spectacular cases, huge radio lobes were discovered, e.g. around NGC 4569 which is located in the dense Virgo cluster of galaxies (Fig. 2). Such phenomena should be much more frequent at low frequencies.

Nearby starbursting dwarf galaxies are recognized for their poor containment of magnetic fields and CRe (Klein et al. 1991). This has led to the suggestion that they may contribute considerably to the magnetization of the IGM (Bertone et al. 2006), and may be responsible for generating large-scale ordered magnetic fields through their disturbed kinematics. LOFAR will be able to resolve the structure in nearby dwarf galaxies out to distances of ≈ 100 Mpc, where it will be possible to detect CRe streaming into the extended halos and place constraints on the generation mechanisms of the magnetic fields in these regions.

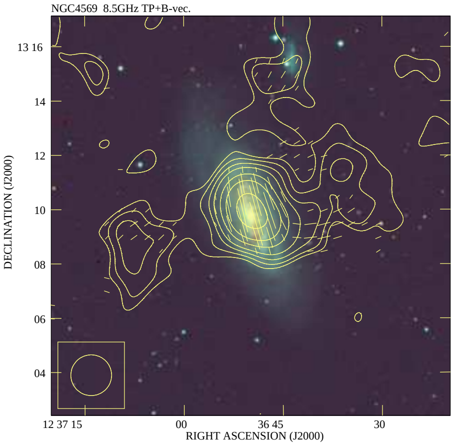

Figure 2: Contours of total emission and polarization B-vectors of the spiral galaxy NGC 4569, observed at 8.4 GHz and 90" resolution with the Effelsberg telescope. Vector lengths are proportional to the polarized intensity (from Chyży et al. 2006).

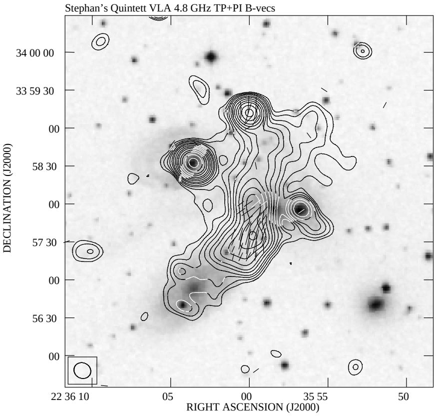

Figure 3: Contours of the total power and B-vectors of Stephan's Quintet observed with the VLA at 4.8 GHz, overlaid upon an image from the blue DSS. Vector lengths are proportional to the polarised intensity (from Soida et al., in prep.).

Compression and shear can modify magnetic field structures. The effects of these processes are most visible in tidally interacting systems (e.g. the Antennae: Chyży & Beck 2004) and in galaxies interacting with intracluster gas (Vollmer et al. 2010). LOFAR will provide information on the strength and structure of magnetic fields ejected into intergalactic space during such interactions. In particular, observations of the Virgo Cluster galaxies will enable extensive statistical studies of the effects of ram pressure stripping by the intracluster gas and high-velocity tidal interactions. This will yield conditions for further MHD numerical simulations of the large-scale magnetic field and polarized emission during galaxy evolution and for the 3-D reconstruction of the intra-cluster magnetic field.

Galaxies at redshifts up to $z \approx 6$ tend to cluster on the scale of nearby groups (Conselice 2007); the conditions in nearby compact groups may resemble those among field galaxies at $z \approx 1$–2. Consequently these groups constitute unique laboratories for testing the evolution of galaxies and intergalactic plasma. "Magnetic enrichment" of the IGM may be most efficient in galaxy groups where bursts of star formation occurred in the member galaxies. Diffuse synchrotron emission from colliding galactic winds and amplified magnetic fields should be detectable with LOFAR. Some groups even contain intergalactic gas pools (e.g. Mulchaey et al. 2003) with large-scale shocks. Indeed, recent observations of the groups HCG 15 and Stephan's Quintet (SQ; Fig. 3) show the presence of partly ordered intergalactic magnetic fields with an energy density comparable to that of the thermal gas. The low frequencies provided by LOFAR will be highly sensitive to such steep-spectrum shock-like features, resembling relics in clusters, and knowledge of their 3-D magnetic field structures from RM Synthesis will allow us a vastly improved understanding of intergalactic gas dynamics: regular and anisotropic fields produce clearly differentiated Faraday spectra. Low-frequency studies may also reveal magnetized tails and cocoons with steep radio spectra, providing essential information on how magnetic flux field structure is supplied to intergalactic space beyond the group. Improved knowledge of the intergalactic magnetic and CR pressure affects the estimation of dark matter content within groups and consequently the estimates of the mass parameter, Ω_{M}.

With the angular resolution and sensitivity of LOFAR, it will be possible to obtain low-frequency maps providing completely new information on the cosmic-ray electrons in nearby galaxies. The cosmic-ray spectrum, derived from the radio synchrotron spectrum, allows us to study and to understand the origin and propagation of cosmic rays, the energy loss processes and how the propagation is affected by the magnetic fields. Deep LOFAR observations of a sample of spiral and dwarf galaxies are planned to observe diffuse polarized emission and its Faraday rotation from the outer disks and halos. LOFAR's sensitivity allows us to detect much fainter emission than with present-day telescopes. An even more sensitive technique to detect regular magnetic fields in galaxies is to observe a grid of Faraday rotation measurements towards polarized background sources. This method is independent of the presence of cosmic rays in the galaxy and may allow us to detect regular fields at radial and vertical distances larger than the detection limit of the synchrotron emission. The MKSP Project aims to clarify the origin of magnetic fields in galactic halos. Proposed models are dynamos which can generate large-scale regular fields, or galactic winds where magnetic fields from the disk are blown out and amplified by the outflow.

First LOFAR maps for M 51 and NGC 4631 are presented by Mulcahy et al. (this volume).

2.4 Intergalactic filaments

The search for magnetic fields in the intergalactic medium (IGM) is of fundamental importance in cosmology. The prediction of a large-scale "Cosmic Web" is one of the defining characteristics of large-scale structure simulations. The warm–hot intergalactic medium (WHIM) contained in this web may account for the missing two thirds of baryon density in the Universe expected from concordance cosmology and studying the largely unknown nature of the magnetic fields in these environments is essential for understanding the origin and evolution of magnetism in the Universe. With LOFAR it will be possible to search for synchrotron radiation from the Cosmic Web at the lowest possible levels. Such emission probes the existence of magnetic fields in the most rarefied regions of the IGM, and measuring their intensity provides a means of investigating both their origin and relation to large-scale structure formation in the Universe. Faint emission has previously been detected around the Coma cluster (Kronberg et al. 2007), although it is debated whether this emission can truly be attributed to filamentary plasma. Deep LOFAR observations of Coma, sensitive to a wide range of angular scales, will be crucial for confirming the current data, and for definitively detecting ultra-steep-spectrum emission associated with an aging relativistic electron population.

LOFAR is well suited for the search for intergalactic magnetic fields. If the Cosmic Web outside clusters also contains a magnetic field (Fig. 4) we can hope to detect this field by either direct observation of synchrotron emission or the Faraday rotation of polarized emission from background sources. Detection of this field, or placing stringent upper limits on it, will provide powerful observational constraints on the origin of cosmic magnetism. The high Faraday depth resolution provided by the broad wavelength-squared coverage of LOFAR will also allow detection of weak magnetic fields in the cosmic web using RMs. Akahori & Ryu (2011) predict that the variance in the RM due to intergalactic magnetic fields will be of order $1\,\mathrm{rad/m^2}$, meaning that precise RM measurements, with spectral filtering to take account of

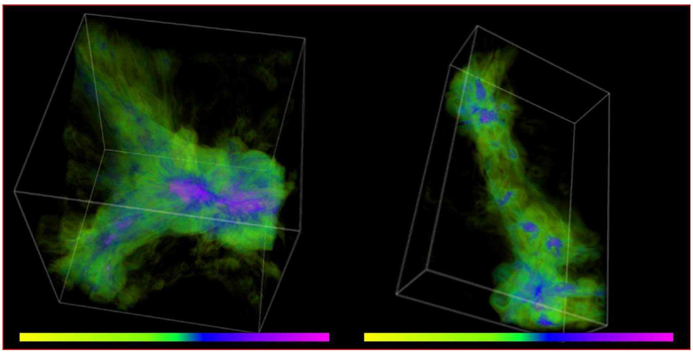

Figure 4: Simulation of magnetic fields in the Cosmic Web at $z = 0$ in a volume of $25\,h^{-1}\,\mathrm{Mpc}^3$ centered around a cluster complex (left panel) and in a volume of $25 \times 15.6 \times 6.25\,h^{-1}\,\mathrm{Mpc}^3$ which includes a number of galaxy groups along a filament (right panel). The color codes the magnetic field strength (logarithmically scaled) from 0.1 nG (yellow) to 10 μG (magenta). Clusters and groups are shown with magenta and blue, while filaments are green (from Ryu et al. 2008).

self-absorption polarization effects, are required if one wants to separate the contribution of cosmic filaments from stronger intervening sources (e.g. the Milky Way foreground, see Sect. 2.1). A statistical analysis is needed like the measurement of the power spectrum of the magnetic field of the Cosmic Web (Kolatt 1998) or the cross-correlation with other large-scale structure indicators like the galaxy density field.

2.5 Giant radio galaxies

Giant radio galaxies (GRGs), defined as objects with dimensions larger than about 1 Mpc, are the largest single objects in the Universe (see e.g. Machaski et al. 2006) and are extremely useful for studying a number of astrophysical problems. These range from understanding the evolution of radio sources, constraining the orientation-dependent unified scheme for AGN, to probing the intergalactic and intercluster medium at different redshifts.

The low-energy electrons responsible for the low-frequency emission can propagate large distances from their origins in the central core or lobe hotspots, and large radio cocoons are expected to surround many objects. Using high angular resolution observations with the full international LOFAR array should help us to learn more about the low-energy electron population in these objects, and hopefully to better understand the acceleration mechanisms which produce the relativistic electrons responsible for synchrotron emission.

Because of the low density in and around these giant sources, with lobes located far outside the gaseous spheres of the parent galaxies, GRGs can be expected to be highly polarized even at low frequencies. The high degree of polarization of giant radio galaxies also makes them ideal polarization calibrators for the observation of weaker sources.

2.6 Stellar jets

Jets from young stars are one of the most striking manifestations of star formation. A crucial part of the accretion/ejection mechanism, they are ubiquitous across low and high mass star formation. Emission indicative of high magnetic field strengths, attributed to both synchrotron (Carrasco-González et al. 2011) and gyrosynchrotron (Ray et al. 1997, Scaife et al. 2011) has been seen from a number of objects. We plan to use spatially resolved polarized structure (linear & circular) in these jets to examine the magnetic field structure of outflows and to investigate the impact of magnetic fields on the launching and evolution of protostellar jets. The MKSP plans to use the large FoV of LOFAR to observe multiple objects simultaneously by targeting three regions with a high density of star formation: the Taurus, Perseus & Cepheus Flare (CF) molecular clouds, at sub-arcsecond resolution. These regions are selected to be nearby ($\leq$ 300 pc) to allow good physical resolution and to provide contrasting samples of protostars in different stages of evolution.

3 MKSP observing program

The core of the MKSP is to deeply map in the LOFAR highband (120–180 MHz) the diffuse total and polarized emission and its Faraday rotation (RM) distribution from selected regions in the Milky Way, a variety of nearby galaxies, selected galaxy groups, and the galaxies of the Virgo cluster. The diffuse total emission from extended disks and halos around nearby galaxies is best detected at low resolutions of 10”–60”.

Sub-areas of the deep fields centered on polarized background sources will be imaged with high resolution (about 1”) to obtain RM grids. LOFAR presently has 8 international stations with baselines up to about 1000 km, providing sub-arcsecond resolution (Heald et al. 2011). RM grids are the most sensitive way to detect weak regular fields because the signal-to-noise ratios are much higher than that of the diffuse galactic emission. A minimum of about 10 background sources is needed to recognize a large-scale field pattern in a galaxy (Stepanov et al. 2008). High angular resolution is needed here, too. The deep fields around galaxies will be located at different Galactic latitudes and will also be analyzed with respect to the properties of the small-scale magnetic field in the foreground of the Milky Way, e.g. by computing the structure functions as a function of Galactic latitude.

Detecting RM signals from intergalactic magnetic fields is a challenge which requires a very large areal source density and hence a very high sensitivity. Studies of diffuse emission from intergalactic filaments (Sect. 2.4) will use the SKSP Tier 1 and Tier 2 surveys that include the Coma field. Deeper follow-up investigations will be made with the Tier 2 survey. These investigations will focus on a $\approx$100 sq. degree area centered on the Coma cluster of galaxies. Proof for an intergalactic origin of (part of) the RM could come from a statistical comparison with source redshift. The best candidates are deep fields around compact galaxy groups with minimum Galactic foreground contribution.

Furthermore, polarization of selected giant radio galaxies will be observed in three frequency bands, and polarization of a few stellar jets in the highband.

4 Polarization calibration

Polarization calibration for LOFAR is mostly a matter of dealing with the ionosphere. The typical Faraday rotation introduced by the Earth’s ionosphere is 1–3 rad/m^2. In order to calibrate the angle of linear polarization to within 10° on the sky at 120 MHz, the ionospheric Faraday rotation must be corrected to better than 1% of its absolute value for each LOFAR station. As polarized emission is significantly weaker than total emission, and as there are few strongly polarized sources for use as calibrators, ionospheric Faraday rotation calibration is a challenge for LOFAR.

Many observing plans for LOFAR polarimetry need the wide field of view to simultaneously measure hundreds of sources, or to measure large sources in single pointings. These observations require accurate polarization calibration across the entire LOFAR beam, including the individual antenna beams, the high band tile beams, the phased-array station beams, and potentially tied-array beams. Science targets of interest often have polarized emission a factor of 10 or 100 times weaker than the total emission. Hence, the polarization calibration of the leakage terms of the LOFAR beams must be accurate to better than one percent in order to prevent leakage of the total intensity into polarization intensity through mis-calibration from dominating the real signal.

5 RM Synthesis

Successful low frequency observations need digital backends with numerous narrow-frequency channels to cope with man-made interference signals and to reduce depolarization by Faraday rotation across the observing band. Multi-channel polarization data are used for the technique of *Rotation Measure Synthesis*. It Fourier-transforms multifrequency polarization data into a data cube with Faraday depth as the third coordinate (Brentjens & de Bruyn 2005, Heald 2009). The Faraday depth (FD) is the integral of the plasma density times the field strength along the line of sight. Information about the distribution of regular magnetic fields and ionized gas along lines of sight is obtained and, with help of some modeling, a 3-D picture of cosmic magnetic fields can be derived (Bell et al. 2011, Frick et al. 2011).

LOFAR RM data cubes will have Faraday depth dimensions of perhaps tens of thousands of pixels. A full RM cube from a single pointing with international LOFAR baselines would be well over 100 Petabytes in size. Data processing will have to be performed in faceted chunks for many years. Adding to the computational challenge is the need to deconvolve ("CLEAN") the RM cube in Faraday depth space as well as position space (Heald 2009). The MKSP Team is developing single-dimensional deconvolution algorithms for LOFAR, with 3-D deconvolution methods planned for future research (Bell & Enßlin 2011).

LOFAR observations with large signal-to-noise in the highband (120–180 MHz) will allow the detection of FD with precisions well below $1\,\mathrm{rad/m^2}$. This is sufficient to detect fields below $1\,\mu$G (0.1 nT), which has never been possible to date. In the LOFAR lowband range (15–70 MHz), the FD accuracy is formally even better, but the calibration is more difficult and the sensitivity is lower than in the highband range.

The first successful LOFAR detection of polarized emission and RM from the pulsar J0218+4232 was presented by Heald et al. (2011).

6 Project Team

At the beginning of 2012, the Project Team consists of 29 full and 54 associated members from 14 countries. The Project is led by a German/Dutch/UK management team.

MKSP website: http://www.mpifr-bonn.mpg.de/staff/rbeck/MKSP/mksp.html

Acknowledgements. LOFAR, the Low Frequency Array designed and constructed by ASTRON, has facilities in several countries, that are owned by various parties (each with their own funding sources), and that are collectively operated by the International LOFAR Telescope (ILT) foundation under a joint scientific policy. – This research is supported by the DFG Research Unit 1254.

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