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The LOFAR view of cosmic magnetism

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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 (10–240 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 via their synchrotron emission. Even weaker magnetic fields can be measured at low frequencies with help of Faraday rotation measures. A detailed view of the magnetic fields in the local Milky Way will be derived by Faraday rotation measures from pulsars. First promising images with LOFAR have been obtained for the Crab pulsar-wind nebula, the spiral galaxy M 51, the radio galaxy M 87 and the galaxy clusters A 2255 and A 2256. With help of the polarimetric technique of "Rotation Measure Synthesis", diffuse polarized emission has been detected from a magnetic bubble in the local Milky Way. Polarized emission and rotation measures were measured for more than 20 pulsars so far.

1 Origin of magnetic fields

Cosmic magnetic fields belong to the "Dark Side of the Universe". The physical processes of their generation and evolution are widely unknown. Observational data are hard to obtain because cosmic magnetic fields need "illumination", e.g. by cosmic-ray electrons. Magnetic fields in the interstellar medium are strong enough to be dynamically important, but the resolution of present-day radio telescopes is insufficient to study the interaction between gas and magnetic fields in detail. Magnetic fields form halos around galaxies and galaxy clusters which may extend much further than known today. Even intergalactic space may be magnetized, but an observational proof is extremely difficult.

The origin of the first magnetic fields in the early Universe is particularly mysterious (Widrow 2002). Any large-scale primordial field is hard to maintain in a young galaxy because differential rotation winds up the field lines during galaxy evolution and the field is rapidly destroyed by reconnection. Small-scale "seed" fields could originate from the time of cosmological structure formation by the Weibel instability (a small-scale plasma instability) (Lazar et al. 2009) or from injection by the first stars or jets generated by the first black holes (Rees 2005). The most promising mechanism to sustain magnetic fields in the interstellar medium of galaxies is the dynamo (Beck et al. 1996; Gent et al. 2012). The magnetic fields in the gaseous halos of galaxy clusters could be seeded by outflows from starburst galaxies (Donnert et al. 2008) or from AGNs, and amplified by turbulent wakes, cluster mergers or a turbulent dynamo (Ryu et al. 2008).

The Low Frequency Array (LOFAR), the planned Square Kilometre Array (SKA) (Sect. 6) and its precursor telescopes under construction, the Australia SKA Pathfinder (ASKAP) and the Karoo Array Telescopes (MeerKAT) in South Africa, are large next-generation radio telescopes with high sensitivity and high resolution. They will open a new era in studying cosmic magnetism.

2 The advantages of low-frequency radio astronomy

The low-frequency regime bears surprises, as much of this regime has been "terra incognita" until recently. Low-frequency radio waves from the Milky Way and galaxies are synchrotron emission from cosmic-ray electrons, with only a small admixture of thermal emission. Diffuse radio emission from halos of galaxy clusters is purely of synchrotron origin. Its intensity and polarization can be used to measure the strength and morphology of the interstellar and intergalactic magnetic fields. This implies several advantages in using radio telescopes at low frequencies. The

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Fig. 1 The inner LOFAR core near Exloo (Netherlands) (copyright: ASTRON).

Fig. 2 International LOFAR station seen from the lower platform of the Effelsberg 100-m telescope. Front: sparse dipole array for 10–80 MHz; back: dense array of dipole "tiles" for frequencies of 110–240 MHz (copyright: James Anderson, MPIfR).

power-law nature of synchrotron radiation with a negative spectral index means that the intensity increases towards decreasing frequencies. Furthermore, measurement of diffuse, faint emission is easier than at higher frequencies, where the lifetime of electrons is limited by various energy loss processes, so that the extent of synchrotron sources is smaller and the synchrotron spectrum is steeper.

Synchrotron emission at low frequencies is still observable from aging, low-energy electrons that have propagated far away from their places of origin. Hence, LOFAR is a suitable instrument to search for weak magnetic fields in outer galaxy disks, galaxy halos and halos of galaxy clusters (Sect. 5). "Relics" in galaxy clusters, probably signatures of giant shock fronts, have steep radio spectra and become prominent in low frequencies (Brunetti et al. 2008; van Weeren et al. 2012b).

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 is weak at low frequencies, by Faraday depolarization along the line of sight and across the telescope beam (Sokoloff et al. 1998) and by geometrical depolarization due to field bending within the beam. Faraday depolarization also occurs when polarized emission is averaged over a large bandwidth. As Faraday depolarization increases with decreasing frequency, polarized intensity is reduced and may reveal a positive spectral index at low frequencies (Arshakian & Beck 2011). Polarized emission cannot be detected from the star-forming disks of galaxies, but from regions in the outer disk or halo where the density of thermal electrons is low, magnetic fields are weak and hence Faraday depolarization is small.

Another important aspect of low-frequency observations is their sensitivity to small Faraday depths. The Faraday rotation angle $\Delta\chi$ is proportional to the "Faraday depth" (FD), defined as the line-of-sight integral over the product of the plasma density and the strength of the field component along the line of sight. Because the Faraday rotation angle increases with the square of wavelength λ^2, low frequencies are ideal to search for small Faraday depths from weak interstellar and intergalactic fields.

Modern radio telescopes are equipped with digital correlators that allow us to record a large number of spectral channels. While radio spectroscopy in total intensity is well developed, the possibilities of spectro-polarimetry in radio continuum are explored only since a few years. The new method of "Rotation Measure Synthesis" applied to multi-frequency polarization data generates the "Faraday dispersion function" or, in short, the "Faraday spectrum" (Brentjens & de Bruyn 2005; Bell et al. 2011; Frick et al. 2011). Multiple emitting and rotating regions located along the line of sight generate several components in the Faraday spectrum. As in classical spectroscopy, the interpretation of this spectrum is not straightforward. In particular, there is no simple relation between Faraday depth and geometrical depth. Only in case of a single component in the spectrum, its Faraday depth is identical to the classical "Faraday rotation measure". A large span in λ^2 covered by observations implies a high resolution in Faraday spectra (Brentjens & de Bruyn 2005; Heald 2009; R. Beck et al. 2012), with which any foreground, intermittent or source-intrinsic features in Faraday spectra can be identified more easily.

A next major step to improve the quality of polarization images is to combine image synthesis with RM Synthesis to "Faraday Synthesis", which will soon be applied to 3-D data cubes (Bell & Enßlin 2012).

In summary, the advantages of low-frequency observations are:

- New sources with ultra-deep spectra may be discovered.
- The emission is almost purely synchrotron (no thermal admixture).
- The intensity is high because synchrotron spectra are generally steep.
- The lifetime of cosmic-ray electrons is higher and hence the extent of synchrotron sources is larger.

Fig. 3 International LOFAR station near Tautenburg/Germany. Front left: dense array of dipole "tiles" for frequencies of 110–240 MHz; front right: sparse dipole array for 10–80 MHz; back: optical Schmidt telescope (copyright: Michael Pluto, Thüringer Landessternwarte).

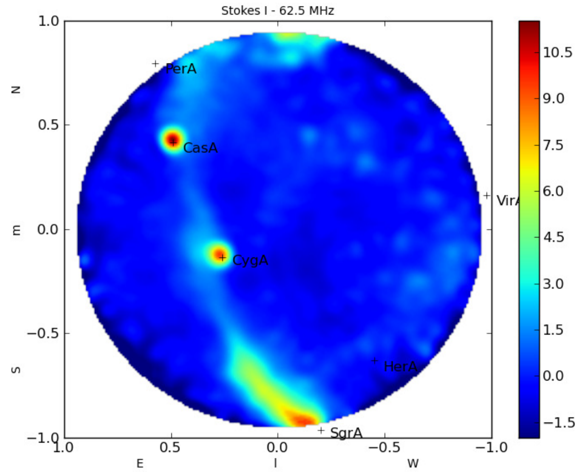

Fig. 4 All-sky image at 62.5 MHz, obtained on 2011 Aug 22 from 1.3 s observation time with the Effelsberg LOFAR station. The angular resolution is about 6°. The brightest radio sources Cas A, Cyg A and Sgr A are marked (from Jana Köhler and James Anderson, MPIfR).

– Faraday rotation angles are larger, so that smaller rotation measures (or Faraday depths, to be precise) can be measured.
– A large coverage in λ^2 and hence high resolution in Faraday spectra can be achieved with one single telescope.
– Antennas and receiving systems are relatively cheap.

3 The Low Frequency Array

The meter-wave radio telescope LOFAR (Low Frequency Array, www.lofar.org) was designed by ASTRON, the Netherlands Institute for Radio Astronomy. With its huge collecting area it is the largest online connected radio telescope ever built (Brüggen et al. 2006). LOFAR is a software telescope with no moving parts, steered solely by electronic phase delays. It has a huge field of view and can observe towards many directions simultaneously. LOFAR is an interferometric array using about 43 000 small antennas of two different designs, one for the wavelength range 10–80 MHz ("low band") and one for 110–240 MHz ("high band").

The antennas are aggregated of at least 49 stations with baselines up to more than 1000 km across Europe. 34 of these stations are distributed across the Netherlands (plus six following in 2013), five stations in Germany (plus another one following in 2013), one each in Great Britain, France and Sweden, which are jointly operated as the International LOFAR Telescope (ILT). Another three stations are planned in Poland and further stations may also be built in other European countries. The core stations are located about 3 km north of the village of Exloo in the Netherlands (Fig. 1). The angular resolution of a single international station is between 2° at 240 MHz and about 23° at 15 MHz. The total effective collecting area is up to approximately 300 000 m^2, depending on frequency and antenna configuration. The angular resolution is between 2″ (at 240 MHz) and 15″ (at 30 MHz) for the Dutch stations (up to about 100 km baselines), but can be improved by about ten times when the international baselines are included. Digital beam forming allows observation towards several directions simultaneously. The data processing is performed by a supercomputer situated at the University of Groningen/Netherlands.

The first German station was built in 2007 next to the 100-m Effelsberg radio telescope and completed in July 2009 (Fig. 2), the second near Tautenburg (Thüringen) (Fig. 3) was completed in November 2009, the third German stations near Garching (Unterweilenbach) in 2010, the fourth and fifth stations in Bornim near Potsdam and in Jülich in 2011. Another station in Hamburg will be built in 2013. The 12 participating German institutes are organized in GLOW (German Long Wavelength Consortium). Their main scientific interests are the Epoch of Reionization, when the first cosmic gas structures formed, magnetic fields and cosmic rays in our Milky Way, in galaxies and in jets, pulsars and solar radio emission (see www.lofar.de).

LOFAR was officially opened by the Dutch Queen on 12 June 2010. Regular science observations with 33 Dutch stations, five German stations and the stations in the UK and France started in December 2012.

The sensitivities and spatial resolutions attainable with LOFAR will allow several fundamentally new studies:

– search for the signature of the reionization of neutral hydrogen in the distant Universe ($6 < z < 10$), making use of the shift of the 21 cm line into the LOFAR high band window;
– detect the most distant massive galaxies and study the processes of formation of the earliest structures in the Universe: galaxies, galaxy clusters and active galactic nuclei;

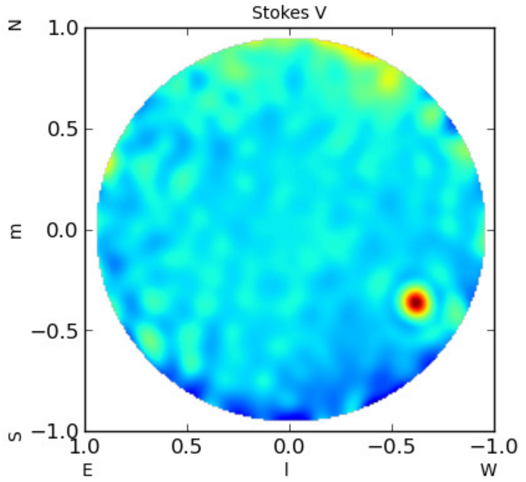

Fig. 5 All-sky Stokes V image at 32 MHz with Jupiter on bottom right, obtained on 2012 Aug 3 from 1.3 s observation time with the Dutch LOFAR station CS002. The degree of circular polarization is 57 % at this frequency (from Jana Köhler and James Anderson, MPIfR).

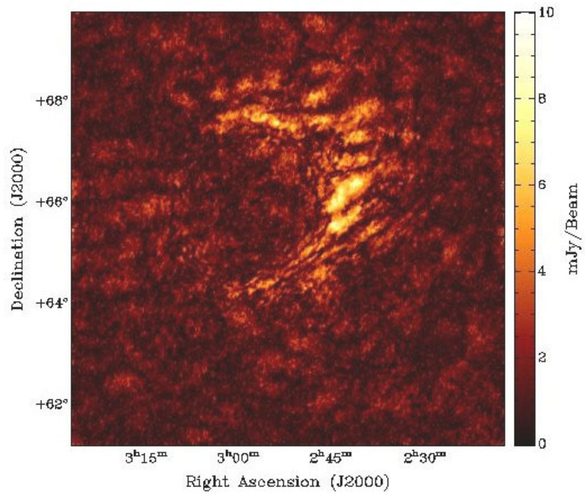

Fig. 6 A region of $15^\circ \times 15^\circ$ in the "Fan" region of the Milky Way's plane centered at $l = 137^\circ, b = +7^\circ$ was observed with LOFAR at 110–174 MHz with $139'' \times 126''$ resolution. The polarized intensity of a slice through the Faraday data cube at Faraday depth –2 rad m^{-2} is shown (from Marco Iacobelli, University of Leiden, and the MKSP commissioning team).

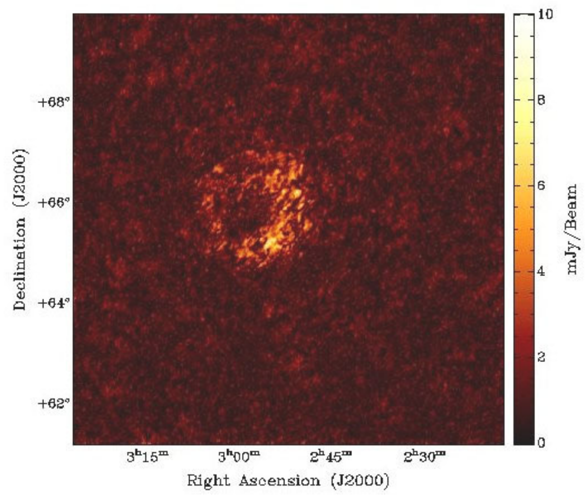

Fig. 7 Same as Fig. 6, but at Faraday depth –5 rad m^{-2} (from Marco Iacobelli, University of Leiden, and the MKSP commissioning team).

- map the three-dimensional distribution of magnetic fields in our own and nearby galaxies, in galaxy clusters and in the intergalactic medium (Sect. 4);
- discover about 1000 new pulsars within a few kiloparsecs from the Sun (Fig. 10);
- detect flashes of low-frequency radiation from the outer solar planets and from pulsars, search for bursts from Jupiter-like extrasolar planets and for short-lived transient events produced by e.g. stellar mergers or black hole accretion;
- detect ultra-high energy cosmic rays entering the Earths atmosphere;
- detect coronal mass ejections from the sun and provide large-scale maps of the solar wind;
- explore the low-frequency spectral window, to make unexpected "serendipitous" discoveries.

4 Prospects of magnetic field observations with LOFAR

4.1 Jupiter's magnetosphere

The outer gas planets of the solar system are strong radio emitters, producing by various processes diverse radio components with complex dynamic spectra (Zarka 2004a). The most intense radio emissions of Jupiter below about 40 MHz are related to the aurorae and the moon Io and are generated by electrons accelerated to keV energies in the magnetosphere, via a well studied nonthermal coherent process: the Cyclotron Maser Instability (CMI). This emission is strongly elliptically polarized. Jupiter is the brightest low-frequency source in the sky in total intensity and by far the dominating source in Stokes V (Fig. 5). Intense synchrotron emission (incoherent and thus less intense than auroral emission) is also produced from MeV electrons trapped in Jupiter's radiation belts. Atmospheric lightning is accompanied by the emission of broadband radio bursts (Zarka et al. 2004).

Detailed studies of Jupiter planned with LOFAR (Zarka 2004b) are crucial for the extrapolation to radio emissions from exoplanets. Dynamic spectra have already been studied with single stations and with the longest LOFAR baselines and will be used soon to investigate the position and motion of the emitting electrons (Wucknitz & Zarka, in prep.).

4.2 Polarization of the Galactic foreground

LOFAR's broad coverage of low frequencies makes it uniquely suited to studying weak magnetic fields and low-

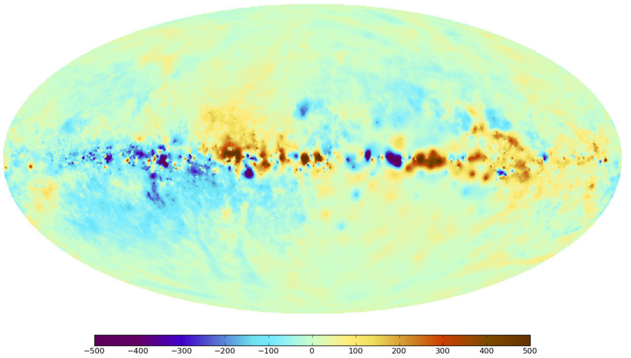

Fig. 8 Model of the RM sky looking through the Milky Way (in Galactic coordinates), based on 41 330 RMs from polarized background sources (from Oppermann et al. 2012).

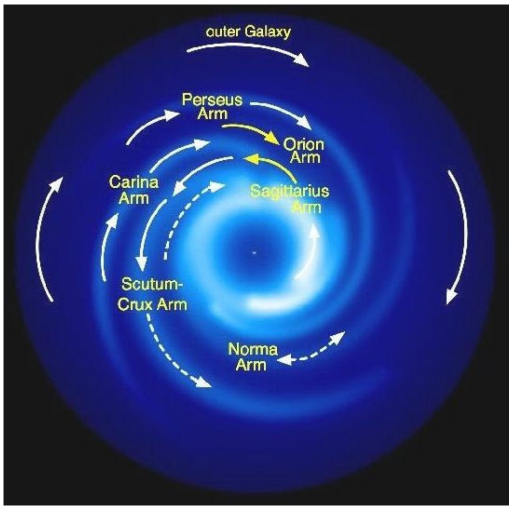

Fig. 9 Sketch of the magnetic field in the Milky Way, as derived from Faraday rotation measures of pulsars and extragalactic sources. Generally accepted results are indicated by yellow vectors, while white vectors refer to results which need confirmation (from Jo-Anne Brown, Calgary).

density regions in the halo of the Milky Way, where such studies can address both the disk-halo interaction and the energetics of the interstellar medium. Emission and Faraday rotation from magnetic fields in the Galaxy affect the measurement of distant, extended objects. At LOFAR frequencies this foreground influence must be properly separated for a correct interpretation of data from extragalactic sources. RM Synthesis (Sect. 2) of diffuse Galactic synchrotron emission is an excellent way to disentangle various components in the Faraday spectrum, giving statistical information on the clumped magnetized ISM and on the relation of thermal electron density to magnetic field strength. Data from regions 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.

Faraday depolarization is strong at low frequencies. Polarized emission from the Milky Way can be detected only from nearby magnetized objects. These rotate the polarization angle of background emission and hence act as a "Faraday screen". The Canadian/German Galactic Plane Survey (Landecker 2010) revealed a wealth of structures in polarized emission which are invisible in total intensity.

One of the first detections of polarized emission with LOFAR was achieved from a huge gas bubble in the "Fan" region of the Milky Way (Iacobelli 2013). Figures 6 and 7 show slices through the Faraday data cube at two different Faraday depths, corresponding to two different geometrical depths. The ring is part of a magnetized bubble structure, possibly a relic (Iacobelli et al. 2013).

4.3 Large-scale magnetic fields of the Milky Way

Faraday rotation measures (RMs) of polarized background sources reveal an image of the regular magnetic fields averaged along the lines of sight. RMs are positive around $l \approx 250^\circ$ and negative around $l \approx 80^\circ$ (Fig. 8), so that the magnetic field of the local spiral arm is directed clockwise and is symmetric with respect to the Galactic plane. The different RM signs above and below the Galactic plane around $l \approx 30^\circ$ may indicate an antisymmetric field component towards the inner galaxy or in the Galactic halo, but this could also be the effect of a nearby magnetized cloud.

Pulsars play a central role in detecting interstellar magnetic fields in the Galaxy. RM surveys of polarized pulsars were used to model the large-scale regular field of the Milky Way (Van Eck et al. 2011; Noutsos 2012). One large-scale field reversal is required at about 1–2 kpc from the Sun towards the Milky Way's center (Fig. 9); more reversals possibly exist but cannot be confirmed with the present data. Nothing similar has yet been detected in other spiral galaxies, although high-resolution RM maps of Faraday rotation are available for many spiral galaxies. Large-scale field reversals may be relics of seed fields from the early phase of a galaxy which were stretched by differential rotation (Moss et al. 2012).

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. LOFAR will detect almost all pulsars within 2 kpc of the Sun; at least 1000 pulsar discoveries are expected from LOFAR, especially at high latitudes (Fig. 11). Most of these are expected to emit strong, linearly polarized signals and will allows us to measure their RMs. This should approximately double the current RM sample ($\approx$700 RMs). When combined with the catalogue of extragalactic-source RMs (Fig. 8), this will provide the strength and direction of the regular magnetic field in previously unexplored directions and locations in the Galaxy.

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

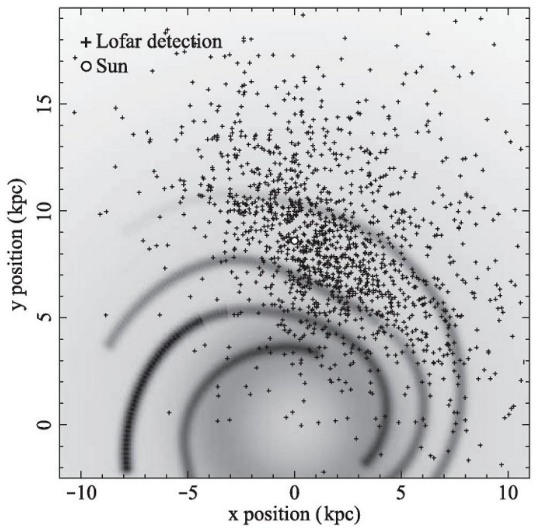

Fig. 10 Simulation of the 1000+ pulsars that LOFAR is expected to find in a 60-day all-sky survey, shown in a Galactic plane projection (from van Leeuwen & Stappers 2010).

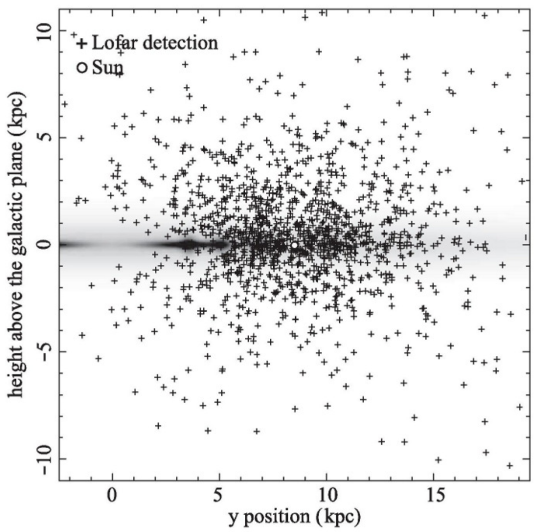

Fig. 11 Same as Fig. 10, but as an edge-on view of the Galactic plane.

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 allow to study the effects of scattering in the interstellar medium, which are prominent at LOFAR frequencies but have until now mostly been studied at higher frequencies (Noutsos et al. 2009); pulsar polarization spectra, which are expected to turn-over in the LOFAR high band, and constraints on the geometry of pulsar magnetospheric emission.

Polarized emission and rotation measures have been measured with the LOFAR pulsar observation mode for more than 20 pulsars so far (Sobey & Noutsos, in prep).

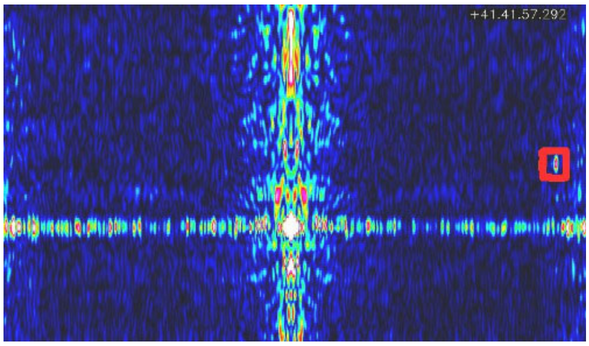

Fig. 12 Slice through a RM Synthesis cube at the declination of the pulsar PSR J0218+42, made from 5 min worth of LOFAR data. The plot has Faraday depth (FD) on the x-axis ($\pm 70\,\mathrm{rad\,m^{-2}}$) and right ascension on the y-axis. The pulsar at a FD of $61\,\mathrm{rad\,m^{-2}}$ is highlighted by a red box. At around $0\,\mathrm{rad\,m^{-2}}$ and at the position of a strong source at RA = $2^{\mathrm{h}}\,34^{\mathrm{m}}\,30^{\mathrm{s}}$ there is significant instrumental polarization (vertical and horizontal stripes). With improved calibration the instrumental polarization will be reduced, but already at this stage the pulsar can be easily picked out (from A. Horneffer, MPIfR Bonn, and M. R. Bell, MPA Garching).

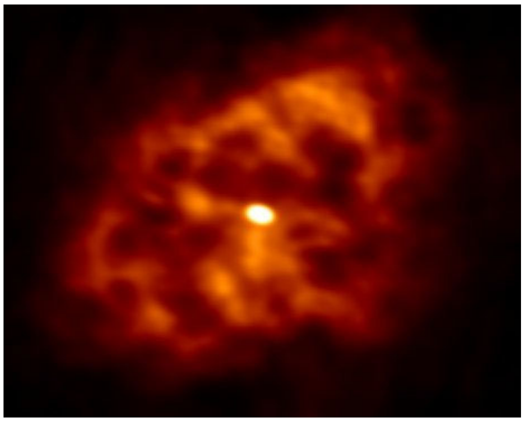

Fig. 13 Total synchrotron intensity of the Crab nebula, observed with the Dutch LOFAR stations in the high band (115–150 MHz). The resolution is $9'' \times 14''$, the field size is $7.5' \times 6'$ (from Olaf Wucknitz, MPIfR).

Pulsars are also visible in Faraday spectra of imaging observations as strongly polarized sources (Fig. 12).

4.4 Magnetic fields in the Crab Nebula

The Crab pulsar-wind nebula was one of the early targets of LOFAR observations in February 2011 (Fig. 13). The structure is very similar to that at higher frequencies (Bietenholz & Kronberg 1990), so that the radio spectral index is constant across the nebula. This suggests that the dominant accelerator of the relativistic electrons is the central pulsar. The magnetic field strengths in the filaments are not known, probably a few 100 μG (Bietenholz & Kronberg 1991).

Observing with the long baselines of the international LOFAR stations, the radio signal is dominated by the pulsar, which served as a point-like calibrator source. This calibration was then used to image the shorter baselines from

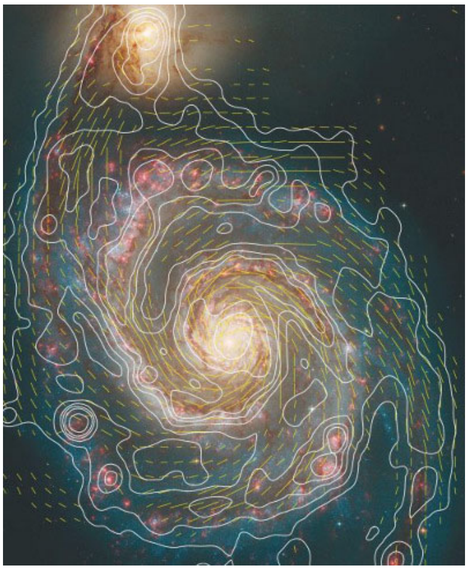

Fig. 14 Total radio intensity (contours) and B-vectors of M 51, combined from observations at 4.8 GHz with the VLA and Effelsberg telescopes and smoothed to 15″ resolution, overlaid onto an optical image from the HST. Copyright: MPIfR Bonn and Hubble Heritage Team. Graphics: "Sterne und Weltraum" (from Fletcher et al. 2011).

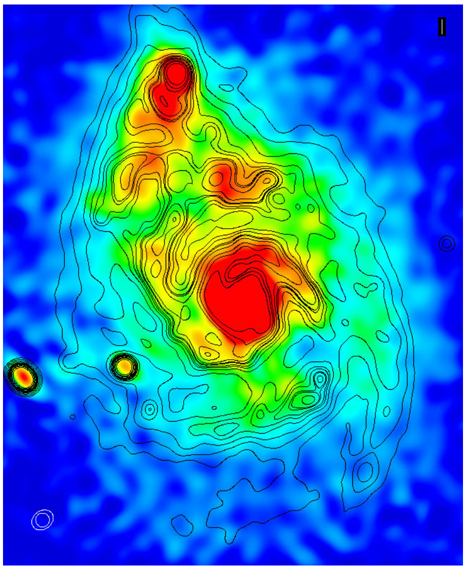

Fig. 15 Contours of total emission of M 51, observed at 1.4 GHz with the VLA (from Fletcher et al. 2011), superimposed on a colour image of the total radio intensity at 120–181 MHz, observed with LOFAR at 20″ resolution (from David Mulcahy, MPIfR Bonn, and the MKSP commissioning team).

the Dutch stations to reveal the structure of the nebula. The long baseline data themselves allowed to study the polarization of the pulsar, which turned out to be much lower than in earlier observations with the Westerbork telescope at similar frequencies (Wucknitz et al., in prep).

4.5 Magnetic fields in spiral 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). In young galaxies a small-scale dynamo possibly amplified the seed fields from the protogalactic phase to the energy density level of turbulence within less than 10^8 yr (Schleicher et al. 2010; A. Beck et al. 2012), followed by a large-scale dynamo which generates a spiral field pattern (Beck et al. 1996; Hanasz et al. 2009; Arshakian et al. 2009). Field seeding by supernova explosions and amplification of small-scale fields operates over the whole lifetime of a galaxy and may affect the regularity of the field pattern (Moss et al. 2012).

Turbulent as well as ordered magnetic fields have been detected in the disks and halos of many galaxies (Beck 2012a). The field lines mostly follow the material spiral arms in galaxies, e.g. in M 51 (Fig. 14). The strongest regular fields are often located between the arms, e.g. in NGC 6946 (Beck 2007). 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 (Fletcher et al. 2011) or from RM data of polarized background sources (Stepanov et al. 2008). Many spiral galaxies host a dominating axisymmetric disk field, while dominating bisymmetric fields are rare, as predicted by dynamo models. Faraday rotation can be described in most galaxies by a superposition of two or three azimuthal dynamo modes (Fletcher et al. 2011). 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.

Important questions still remain regarding the amplification process, as well as the configuration of the large-scale field in evolving galaxies (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 enable systematic studies of galactic field structures using Faraday rotation of background sources (Stepanov et al. 2008). "Faraday spectra" generated by RM Synthesis (Sect. 2) 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 gas 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 out-

Fig. 16 Total synchrotron intensity of the radio galaxy M 87, observed with LOFAR at 115–162 MHz and overlaid onto an optical SDSS image. The size of the shown field is $19' \times 19'$, the resolution is $21'' \times 15''$ (from de Gasperin et al. 2012).

flows from the inner disk, the magneto-rotational instability, gravitational interaction and ram pressure by the intergalactic medium are imprinted on the magnetic structure.

The first LOFAR maps of nearby galaxies (M 51 and NGC 4631) were published by Mulcahy et al. (2012). More recent observations show an extended radio disk around M 51 (Fig. 15).

4.6 Magnetic fields in the radio galaxy M 87

M 87 = Vir A is one of the nearest radio galaxies, the fourth brightest radio source in the northern sky and hosts in its nucleus one of the most massive black holes discovered so far. The low-frequency emission from M 87 forms a huge halo around the galaxy (Fig. 16). The similarity to the radio images at higher frequencies indicates that the halo is confined by the pressure of the intergalactic medium. The emitting cosmic-ray electrons in the lobes are freshly provided by the active nucleus (de Gasperin et al. 2012).

4.7 Magnetic fields in galaxy clusters

Some fraction of galaxy clusters, mostly the X-ray bright ones, have, diffuse radio emission, emerging from diffuse halos and steep-spectrum "relic" sources at the periphery of clusters. The diffuse halo emission is unpolarized and emerges from intracluster magnetic fields. In contrast to the interstellar medium, the magnetic energy density is much smaller than that of the thermal gas in the intracluster medium. Still, intracluster fields affect thermal conduction in the halo gas, give rise to instabilities and hence can modify the structure of the intracluster medium (see Brüggen 2013).

RMs towards background sources show a vanishing mean value and a dispersion which decreases with distance from the cluster center (Clarke et al. 2001; Bonafede et al. 2011). The intracluster fields are turbulent with correlation lengths of several 10 kpc (Murgia et al. 2004).

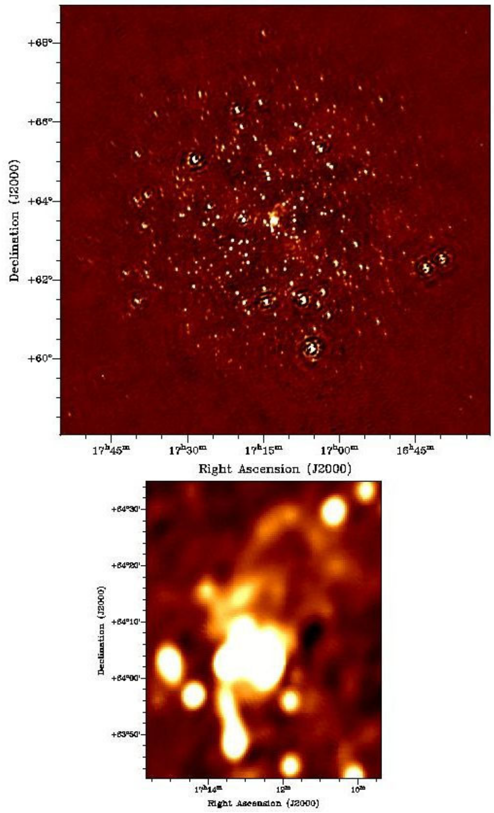

Fig. 17 *Top panel*: total synchrotron intensity around the galaxy cluster A 2255, observed with LOFAR at 110–190 MHz. The field size is $11^\circ \times 11^\circ$, the resolution is $2'$. Bottom panel: zoom into the inner 1° with the extended cluster halo, the relic source at the right periphery of the halo and a radio galaxy to the south (from Roberto Pizzo, ASTRON).

Relic sources can emit highly polarized radio waves from anisotropic magnetic fields generated by compression in merger shocks (Enßlin et al. 1998; Iapichino & Brüggen 2012). A polarized region of about 2 Mpc size was discovered in the cluster 1RXS J0603.3+4214 at a redshift of 0.225 (van Weeren et al. 2012b).

A 2255 is a nearby, rich cluster, which shows signs of undergoing a merger event. It hosts a diffuse radio halo and a highly polarized "relic" source at its periphery (Govoni et al. 2005; Pizzo & de Bruyn 2009). The LOFAR image (Fig. 17) confirms the diffuse halo and the relic source, and shows several radio galaxies in the neighborhood of the cluster. Another giant cluster halo, around the nearby cluster A 2256, was mapped with the LOFAR low band between 18 MHz and 67 MHz (van Weeren et al. 2012a), to give the first image of a galaxy cluster at frequencies below 30 MHz.

5 The Magnetism Key Science Project

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 (Anderson et al. 2012). At the end of 2012, the MKSP Project Team consisted of 86 members from 13 countries and is led by a German/Dutch/UK management team. MKSP website: http://www.mpifr-bonn.mpg.de/staff/rbeck/MKSP/mksp.html

The MKSP Project Plan includes an initial target list of galaxies, selected in close cooperation with the LOFAR Survey Key Science Project (Röttgering et al. 2011), to be followed by deep observations of the diffuse total emission and the Faraday spectra from selected regions in the Milky Way, a variety of nearby galaxies, selected galaxy groups and the galaxies of the Virgo cluster. Sub-areas of the deep fields centered on polarized background sources will also be imaged with high resolution (about $1''$) to obtain grids of RM values derived from background sources. 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 to reduce depolarization within the telescope beam. The international LOFAR stations provide baselines currently up to about 1300 km, yielding sub-arcsecond resolution (Heald et al. 2011). 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.

The structure of small-scale magnetic fields will be studied in 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). The radio polarization of galaxy clusters will be studied by the LOFAR Survey Key Science Project, in cooperation with the MKSP.

Detecting Faraday rotation signals from intergalactic magnetic fields is a challenge which requires a very large number density of sources and hence a very high sensitivity. Studies of diffuse emission from intergalactic filaments will use the LOFAR surveys that include the Coma field, followed by deeper observations. Primary targets are a $\approx$100 deg^2 area, centered on the Coma cluster of galaxies, and compact galaxy groups with minimum Galactic foreground contribution. Proof for an intergalactic origin of specific components of the Faraday spectrum could come from a statistical comparison with source redshifts.

6 Outlook: the Square Kilometre Array

High-resolution, deep observations at high frequencies, where Faraday depolarization is small, require a major increase in sensitivity for continuum observations, which will be achieved by the planned Square Kilometre Array (SKA, www.skatelescope.org) (Garrett et al. 2010; Beck 2012b). 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. Direct insight into the interaction between gas and magnetic fields in these objects will become possible. The SKA will also allow us 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, and statistics can be compared with the predictions of dynamo theory (Arshakian et al. 2009). The SKA at 1.4 GHz will detect Milky-Way type galaxies at about $z \leq 1.5$ (Murphy 2009) and their polarized emission at about $z \leq 0.5$. Bright starburst galaxies can be observed at larger redshifts, but are not expected to host ordered 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 in starburst galaxies, depending on luminosity and magnetic field strength, and also in cluster halos.

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 and will allow us to determine the field strength and pattern in an intervening object. 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. Regular fields of several μG strength were already detected in distant galaxies (Bernet et al. 2008; Kronberg et al. 2008). Mean-field dynamo theory predicts RMs from evolving regular fields with increasing coherence scale at $z \leq 3$ (Arshakian et al. 2009). 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. POSSUM, the RM survey around 1 GHz with the planned Australia SKA Pathfinder (ASKAP) telescope with 30 deg^2 field of view, will measure about 100 RM values from polarized extragalactic sources per square degree.

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 measure at least 1500 RMs deg^{-2}, or at least 2×10^7 RMs at a mean spacing of $\simeq 90''$ (Gaensler et al. 2004). More than 10 000 RM values are expected in the area of M 31 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 (Stepanov et al. 2008). The magnetism of cluster halos can be measured by the RM grid to redshifts of about 1 (Krause et al. 2009). Finally, the SKA pulsar survey should find more than 10 000 new pulsars, which will be mostly polarized and reveal RMs, suited to map the Milky Way's magnetic field with high precision (Noutsos 2012).

Construction of the SKA is planned to start in 2017. In the first phase (until about 2020) about 10 % of the SKA will be erected (SKA$_1$), with completion of construction at the low and mid frequency bands by about 2025 (SKA_2), followed by construction at the high band.

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LOFAR, 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.

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