The LOFAR Key Science Project on Cosmic Magnetism

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Abstract

The LOFAR Key Science Project on cosmic magnetism in the nearby Universe (MKSP) aims to investigate fundamental astrophysical questions which will help us to understand the origin of cosmic magnetism. Low-frequency observations trace regions of low magnetic field strengths and/or low-energy cosmic-ray electrons which both live longer and travel further from their acceleration sites. Consequently the LOFAR telescope will detect the weak halo fields of spiral and dwarf galaxies and will allow investigations of the unexplored domain of extremely weak magnetic fields via Faraday rotation to be measured with unprecedented precision. Detection of weak fields in stellar jets and in intergalactic filaments may become possible for the first time.

1 Introduction

Magnetic fields are present in almost every place in the Universe. Most of the luminous matter is tightly coupled to magnetic fields. Large and small-scale fields permeate the gas in the Milky Way, in galaxies and in galaxy clusters. The magnetic energy contributes significantly to the total pressure of interstellar gas, is essential for the onset of star formation, and controls the density and distribution of cosmic rays in the interstellar medium (ISM). In spite of the almost universal importance of magnetic fields, a number of fundamental questions still remain unanswered. Prime amongst these are the determination of the origin of cosmic magnetic fields, and how they were subsequently amplified; and how their evolution affects the evolution and physics of galaxies and clusters of galaxies. More specifically their role in the collimation of both protostellar and AGN outflows is still poorly constrained, as is the extent of the large-scale fields associated with galaxies and their groups. Answers to these questions require high sensitivity and angular resolution, and the opening of new frequency windows, especially at low frequencies. The LOFAR telescope is uniquely placed to do this.

2 Advantages of low-frequency observations

Most of what we know about astrophysical magnetic fields has been derived from radio astronomical observations. At low radio frequencies, such as those probed by LOFAR (10–240 MHz), most continuum emission is synchrotron radiation from relativistic electrons spiralling around magnetic field lines. Synchrotron radiation is linearly polarised, up to 75% in a fully regular magnetic field, and the degree of linear polarisation tells us the field's degree of ordering. Faraday rotation of the polarisation plane provides information on the field component along the line of sight and the *Rotation Measure Synthesis* technique can transform multifrequency polarisation data directly into Faraday depth space [2]. The information about the distribution of regular magnetic fields and ionized gas along many lines of sight that is obtained can then be used to derive a three-dimensional picture of cosmic magnetic fields [3].

Observing at low frequencies has a number of important advantages. Synchrotron emission has a steep spectrum, with its intensity increasing strongly towards low frequencies. Furthermore, the observable extent of radio emitters is often limited by the lifetime of the emitting relativistic electrons. At high frequencies the extent of synchrotron emission is limited by energy losses of the electrons to only small distances from its

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source, e.g. a few kiloparsecs in galaxies. However, low-frequency radio emission is emitted by electrons with lower energies that suffer less from energy losses and hence can propagate further away from their origins, e.g. into the outer disks of galaxies and into galaxy halos, where magnetic fields should be present as the result of outflows or dynamo action. For example, a relativistic electron radiating at 50 MHz can travel up to 200 kpc in a turbulent magnetic field of about 3 μG (0.3 nT) strength. In a regular magnetic field the travel distance is even longer, and consequently the observable extent of synchrotron haloes is expected to be considerably larger at low frequencies.

Another important tool to measure cosmic magnetic fields is the Faraday rotation of linearly polarised emission. Faraday rotation is proportional to the inverse square of the frequency, and even weak fields and low plasma densities can cause significant Faraday rotation at long wavelengths. The precision of rotation measures (RMs) increases with increasing total (not necessarily contiguous) wavelength coverage [3], so that much smaller variations in field strength can be measured at low frequencies. Using multiple RMs along various lines of sight towards polarised background sources or diffuse polarised emission allows reconstruction of the magnetic field morphology in foreground structures. Multiple structures along the line of sight may also be separated based on their Faraday dispersion functions in Faraday depth space using the powerful RM Synthesis technique.

3 Science Aims

Galactic: Polarised synchrotron radiation from the Milky Way is visible over the whole sky. At low Galactic latitudes the observed polarisation structure at low frequencies is very different to that of the total intensity due to Faraday depolarisation in the interstellar medium. At high latitudes Faraday effects are much smaller and in these regions LOFAR will be uniquely sensitive to low-energy electrons in the Galactic halo, which allows investigations of the propagation and evolution of matter and energy far from the Galactic disk [9]. Aside from increasing our understanding of the Galaxy as a foreground to extra-galactic emission, weak magnetic fields or small electron density fluctuations will become visible, both of which are of great interest for understanding important properties of the turbulent interstellar medium. The increase of thermal absorption and of depolarisation by Faraday rotation at low frequencies will be used to model the distribution of emission along the line-of-sight, leading to a three-dimensional model of the gas and magnetic fields in the solar neighbourhood.

LOFAR will detect nearly all pulsars within 2 kpc of the Sun and discover about 1000 new nearby pulsars at high latitudes. Most of these are expected to emit strongly linearly polarised signals at low frequencies. This allows us to measure their RM which will give a unprecedented picture of the structure of the magnetic field near to the sun and thus complement the observations of diffuse Galactic emission [7]. The strong polarisation of pulsars also makes them ideal calibrators for polarisation observations of much weaker sources.

Jets from young stars are thought to be down-scaled analogues to the jets from active radio galaxies, but located much closer to Earth. The circular polarisation from gyro-synchrotron radiation in these objects will allow us to investigate the magnetic field strength along the jet beam, the magnitude of which is dynamically important for magnetic collimation models of stellar outflows [8]. These polarisation observations will require highly accurate polarisation calibration and imaging from the LOFAR long baselines.

Extra-galactic: 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 their sources (probably supernova remnants). As described in § 2, at the low frequencies measured by LOFAR the extended haloes and outer regions of nearby and dwarf galaxies become visible. These observations are vital for understanding the origin and propagation of cosmic rays, their energy loss processes and the effect of magnetic fields; as well as clarifying the origin of magnetic fields in galaxies by differentiating between the action of dynamo fields and galactic winds. Diffuse polarised emission from the inner disk will be mostly suppressed by Faraday depolarisation, but may be detectable in the outer disk and halo where interaction between galaxies and ram pressure with the IGM can amplify the magnetic fields. RM grids will allow us to detect regular magnetic fields both within and at the outskirts of galaxies and groups and to constrain the contribution of galactic winds and outflows to the magnetisation of the inter-galactic medium [1].

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. [5]) 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. GRGs are expected to be highly polarised even at low frequencies, and the low-energy electrons responsible for this emission can propagate large distances from their origins in the central core or lobe hotspots, resulting in large radio cocoons. 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.

The search for magnetic fields in the intergalactic medium (IGM) is of fundamental importance in cosmology as the prediction of a large-scale Cosmic Web is one of the defining characteristics of large-scale structure simulations. Placing limits on the magnetic field strengths in this web will provide powerful observational constraints on the origin of cosmic magnetism. Simulations suggest that the field strengths in the cosmic web will be very low, and are optimally observed at the very low frequencies measured by LOFAR. Although it is possible that we will detect these fields directly it is likely that a statistical analysis of their power spectrum using cross-correlation with other large-scale structure indicators like the galaxy density field will provide the strongest constraints [4].

4 Observing Programme and early results

The core of the MKSP is to deeply map both **diffuse total and polarised emission and its Faraday rotation distribution**. Diffuse emission from e.g. extended disks and halos around nearby galaxies, is best detected at low resolutions of 10–60 arcsec. High resolution may be needed to avoid beam depolarisation, but after RM Synthesis and subtraction of the Galactic foreground smoothing to lower resolution can be applied to detect weak diffuse polarised emission. The main depolarisation effect is likely to be RM gradients within individual sources and from the Galactic foreground. To resolve these internal RM gradients we will require angular resolutions of a few arcseconds; the brightest nearby galaxies will allow polarisation mapping with LOFAR international baselines at resolutions of about 1 arcsec.

Measuring the **RMs of a grid of polarised background sources** is 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. Furthermore, depolarisation by RM gradients in the foreground source is less severe as long as the angular extent of the background source is similar or smaller than the beamsize. Detecting RM signals from intergalactic magnetic fields is a challenge which requires a very high sensitivity in addition to a well behaved Galactic foreground. These requirements overlap with those of the LOFAR Epoch of Reionization (EoR) Key Science Project and it is intended that commensurate observing between the projects will be proposed for this aspect of the MKSP science plan.

The first detection of polarisation from LOFAR data was found conclusively towards pulsar PSR J0218+4232, which has a known rotation measure of -61 $\mathrm{rad\,m^{-2}}$ [6]. LOFAR observations centred around a frequency of 129 MHz measured a value of $-60.5\,\mathrm{rad\,m^{-2}}$. Since its original RM detection this pulsar has been used for development of the LOFAR RM-Synthesis pipeline which is under active development by the MKSP but is already useable for data sets consisting of multiple LOFAR sub-bands. It has also been used to demonstrate the effect of ionospheric variations on polarisation data, an important first step in the correction and calibration of such effects.

5 Conclusions

With the angular resolution and sensitivity of LOFAR, it will be possible to obtain low-frequency maps providing completely new information on magnetic fields and cosmic ray populations. 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. LOFAR's sensitivity allows us to detect much fainter emission at these frequencies. In addition, an even more sensitive technique to detect regular magnetic fields by observing a grid of Faraday rotation measurements towards polarised background sources, independent of the presence of cosmic rays, will allow us to detect regular fields at radial and vertical distances larger than the detection limit of the synchrotron emission in extended haloes and the inter-galactic medium for the first time.

As of the beginning of 2011, the MKSP Project Team consists of 27 full members from 6 countries, who have agreed to invest a significant fraction of their time for the project, plus another 43 associated members from 10 countries. The Project is led by a German/Dutch/Irish management team. The MKSP website may be found at: `http://www.mpifr-bonn.mpg.de/staff/rbeck/MKSP/mksp.html`.

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