THE LOFAR MAGNETISM KEY SCIENCE PROJECT (MKSP)

INTRODUCTION

Magnetic fields are pervasive throughout the Universe. Obtaining detailed knowledge of the strength, morphology and evolution of these magnetic fields is essential for understanding the energetics and dynamics of numerous astrophysical phenomena. Using cosmic large-scale structure as a laboratory in which to probe these fields is 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: polarised synchrotron emission from cosmic ray electrons (CRe) and Faraday rotation of background emission due to magnetised media along the line of sight. 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. In addition, at such low frequencies CRe have longer lifetimes, traveling farther from their site of generation into distant regions of low magnetic field strength and illuminating rarified magnetic structures that are 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. Following the advent of Rotation Measure (RM) Synthesis (Brentjens & de Bruyn 2005, Heald 2009), such field structures can not only be mapped through their diffuse synchrotron emission but can also be separated in Faraday depth along the line of sight. For example, field reversals and turbulent fields can be recognised via their specific signatures in Faraday space (Bell et al. 2011, Frick et al. 2011). The use of RM Synthesis is a key aspect of revolutionising our 3-dimensional view of the magnetic Universe.

To address the spectrum of questions that are still unresolved in this field requires a broad range of observational work from diverse astrophysical areas. The LOFAR MKSP draws together expertise from multiple disciplines of magnetism science in order to form a coherent approach toward all of these issues. This proposal outlines the breadth of magnetism science, and variety of observational techniques, that the MKSP intends to pursue with LOFAR in order to transform our understanding of cosmic magnetism.

1. SCIENCE CASE

GALACTIC

1.1 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. Indeed, Rotation Measure (RM) Synthesis of diffuse Galactic synchrotron emission is an excellent way to disentangle various RM components, giving statistical information on the clumped magnetised ISM and on the relation of thermal electron density to magnetic field strength. LOFAR will also be an excellent tracer of the magnetised ISM due to its high angular resolution, which minimises beam depolarisation 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 (§ 1.2). Comparison of RM data to magnetic field models will shed light on the configuration of large-scale regular fields. The deep fields of nearby galaxies (§ 2.2) and of galaxy clusters 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 and in the intergalactic medium (§ 1.8).

Specific regions in the Milky Way are a mosaic of the "Fan" region of high polarisation and fields on the edges the North Polar Spur and Loop III. After exploitation of the Tier 1 surveys, we will know whether deeper, targeted LOFAR observations will be required.

1.2 The Galactic Magnetic Field from Pulsar Rotation Measures: Pulsars play a central role in detecting interstellar magnetic fields in the Galaxy. Polarisation 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 (van Leeuwen & Stappers 2010). *Polarisation 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; eg. 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, polarisation 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 polarisation 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 polarisation using both LBA and HBA.*

1.3 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. We plan to use spatially resolved polarised 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. *We plan 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 with the international LOFAR HBA.* These regions are selected to be nearby (≤ 300 pc) to allow good physical resolution and to provide contrasting samples of protostars in different stages of evolution. All three regions are located at high declination, and CF is circumpolar.

EXTRA-GALACTIC

1.4 Nearby 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. However, important questions still remain regarding the nature of the seed field and 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 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.

We plan deep total power and polarisation observations in the LOFAR highband of 10 mildly inclined spiral galaxies and strongly inclined (edge-on) galaxies.

Due to the long lifetime of low-frequency CRe, deep field total intensity observations in the LOFAR lowband will allow us to study the evolutionary history of the energetics of CRe as they interact with magnetic fields and gas in the ISM. The frequency dependence of the spectral index of such emission at LOFAR frequencies is essential for our understanding of CRe generation during star formation and their distribution in the galactic halo. Related to this, it is at low frequencies that the well-known (but poorly understood) radio–far-infrared correlation is best traced (Tabatabaei et al. 2012). *We plan LOFAR LBA observations of M31, M33 and M81/82 to address this science.*

Nearby starbursting dwarf galaxies are known not only to be substantially magnetised with large-scale magnetic fields and extended haloes, but are also recognised 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 magnetisation 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 $\approx 100\,\mathrm{Mpc}$, 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. *We plan deep total power and polarisation observations of the two brightest nearby dwarf galaxies: NGC 1569 and NGC 4449.*

1.5 Cluster and perturbed galaxies: 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 polarised emission during galaxy evolution and for the 3-D reconstruction of the cluster magnetic field.

1.6 Giant radio galaxies: Giant radio galaxies ($> 1\,\mathrm{Mpc}$) are the largest single objects in the Universe. Observations of GRGs using the low frequencies and high resolution of LOFAR will provide insight into a range of unresolved issues: at frequencies below 150 MHz the shape of the spectrum is still unmeasured. This knowledge will allow estimation of the injection spectral energy distribution and energy losses within these objects; the diffuse cocoons thought to surround these objects are currently invisible due to observational limitations, however they will be visible with LOFAR. The high resolution of LOFAR will enable GRGs to be observed at high redshifts, thus probing the intergalactic medium (IGM). It will also be possible to probe the tenuous IGM around the lobes of these galaxies using a larger sample with known redshifts allowing measurement of both the IGM pressure and magnetic fields, as well as RM tomography using background sources. Direct observations of the Laing–Garrington effect in the jets of these galaxies using the high resolution provided by the international LOFAR baselines will allow magnetic field strengths to be derived and compared to equipartition values. *We plan polarisation observations of about 10 giant radio galaxies in both the LOFAR LBA, HBA-low and HBA-high frequency bands.*

INTER-GALACTIC

1.7 Galaxy groups: 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. Group members undergo violent interactions, often accompanied by starbursts, which transport magnetised plasma tens of kpc out of the galaxies. 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; Soida et al., in prep) 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 magnetised 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}.

We plan to correlate the results of Tier 1 survey with catalogues of known galaxy groups, which may greatly expand the list of such objects showing the intergalactic radio emission. We plan deep observations of at least three galaxy groups, SQ, HCG 37 (or HCG 60) and HCG 68 in the LOFAR high-band.

1.8 Intergalactic filaments: 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 in total power 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.

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 self-absorption polarisation effects, are required if one wants to separate the contribution of cosmic filaments from stronger intervening sources (e.g. the Milky Way foreground, see § 1.1).

We propose to investigate magnetic fields in intergalactic filaments by both detecting excess variance in RM values measured in background compact sources and by searching for faint, diffuse emission in total power. For detection of diffuse emission, we plan to study the region around the Coma cluster of galaxies, including the "Great Wall". We will develop and maintain a database of RM measurements, along with accompanying information such as source redshifts.

2. TECHNICAL CASE

2.1 RM Synthesis & Mapping of diffuse emission at 120–180 MHz: The MKSP will closely cooperate with the Surveys KSP (SKSP), processing Tier 1 survey data with the key goal of mapping diffuse total and polarised emission in various regions of interest. These data will also be processed using RM Synthesis to identify distinct components in Faraday space. These measurements will provide a catalogue of polarised sources and information on the number density of polarised background sources at low frequencies. The best cases will be selected as candidates for deep "Tier 2" mapping projects (§ 2.2). In the case of projects requiring high fidelity imaging of emission on large angular scales, visibility data for baselines shorter than about 35 m must be added using measurements from intra-station baselines. The combination is best done using international stations, which have 70 m diameter, thus providing excellent overlap in the *uv* plane. The techniques for obtaining these data are under development at the Effelsberg station and will be applicable to all stations in early 2013.

The reduction strategy will be: (1) imaging pipeline (basic calibration) on all pointings with 3–10$''$ resolution (Dutch baselines only), (2) pipeline for improved imaging (including polarisation calibration, ionospheric corrections and selfcal loops) on a subset of pointings to obtain improved maps for galaxies with the highest priority (see § 3), (3) source finding and characterisation of polarised sources, (4) pipeline for high angular resolution imaging of about 1$''$ (including the international baselines) on sub-fields centered on background point sources, (5) RM Synthesis on these data as a test for the "RM grid mode" (see below).

2.2 Deep mapping of diffuse emission and RM grids: A selection of targets will be chosen from the Tier 1 survey. These targets will include: 15 galaxies (selected together with the SKSP team) to include a variety of spiral, edge-on galaxies and dwarf galaxies (§ 1.4), tidally stripped or interacting galaxies (§ 1.5) and compact galaxy groups (§ 1.7); 10 giant radio galaxies (§ 1.6); 3 Galactic star formation regions (selected together with the SKSP team; § 1.3); 3 Galactic fields including the Fan region, North Polar Spur and Loop III (§ 1.1).

For all projects, data analysis will be performed in two modes: (1) imaging of the diffuse total and polarised emission with an angular resolution of about 10$''$; (2) high angular resolution ($\approx 1''$) imaging for RM grids. Because imaging of the entire field of view at full resolution is unfeasible, we intend to image sub-fields of every pointing, where each sub-field will be centered on the point sources detected in the first mode. We will process each individual sub-field using RM Synthesis. In this way we will build up an RM grid for every pointing. The second mode requires the use of both Dutch stations and international stations. GRGs and star formation regions will be mapped at high resolution ($< 1''$) using the international baselines.

2.3 Pulsars: The polarisation observations for this project will require the ephemerides of all pulsars discovered with LOFAR. Currently known pulsars with undetermined RMs will also be observed at LOFAR frequencies. The project aims for $S/N \approx 100$ for each pulsar, in order to minimise the statistical uncertainties in the RM determination. At present, these observations can be adequately performed with the "Superterp" (6 stations), but we also intend to include the remaining Dutch core stations (total of 24 stations) as they become operational under a single clock; the required observing time will be then reduced by a factor of 16. We intend to combine LBA and HBA data, spreading the available bandwidth over the accessible bands: this will maximise the bandwidth across which we can detect changes in polarisation flux and scattering and will also increase the precision of RM measurements. When possible, instead of performing separate HBA and LBA observations, we will simultaneously observe in the two bands by selecting two different station sub-arrays, each corresponding to a band, targeted at the pulsar. Finally, for the purposes of polarisation calibration, we will simultaneously observe known, bright pulsars as ionospheric calibrators, with a secondary beam targeted at the calibrator source. We will perform the standard polarisation calibration to correct for parallactic angle rotation and other geometrical and systematic effects during observations. The Pulsar Working Group (PWG) of Magnetism KSP maintains a close collaboration with the PWG of the Transients KSP (TKP). The data products of the proposed project will be shared between the two KSPs.

During the first semester, the Pulsar Working Groups of the MKSP and TKP will prioritise on the brightest, most polarised pulsars in the northern sky (see list in TKP proposal). For that semester, we request ≈ 70 hours for HBA and LBA observations with the Superterp. During the next 2–3 years, if only the Superterp is available, we will need a total of ≈ 350 hours for an all-sky census of known and discovered polarised pulsars; if more Tied Array stations become available, the required time will be less.

2.4 Large Area Mapping: For studies of diffuse emission from inter-galactic filaments (§ 1.8), we will work with the SKSP Tier 1 and Tier 2 surveys that include the Coma field. Even the planned Tier 1 survey is an order of magnitude deeper than previous observations. Following an initial investigation of Tier 1 data, deeper follow-up investigations will be made with the Tier 2 survey. These investigations will focus on a ≈ 100 sq. degree area centered on the Coma cluster of galaxies. For this project sensitivity to a vast range of spatial scales is required: from tens of arcseconds to degrees. Long baselines are required in order to identify and produce high-quality images of field sources with small angular sizes; it is important that such sources are carefully removed from the data. Any emission associated with sheets and filaments will span several degrees. Confidently mapping such large-scale emission will require the inclusion of intra-station baselines, for combination with the standard interferometric data, as described above.

For Faraday rotation studies of IGM filaments, all Tier 1–3 survey fields falling within the SDSS survey area ($120^\circ \leq \mathrm{RA} \leq 240^\circ$, $0^\circ \leq \delta \leq 60^\circ$ J2000) will be analysed in order to determine the Faraday RM corresponding to each background point source. With these RMs in hand, a statistical detection of excess RM variance due to magnetic fields within filaments will be possible. The studied fields must lie within the SDSS footprint to supply redshift information to our RM data. We will make use of the structural reconstruction and classification performed by Jasche et al. (2010).

3. SEMESTER 1 PROPOSALS

(1) The brightest, most polarised pulsars in the northern sky (70 hours for HBA and LBA observations with the Superterp).
(2) A "Tier 0" survey of 48 high-priority targets (12 galaxies), proposed jointly with the Survey KSP.
(3) All-sky, full polarisation data products from TBB imaging, combined with simultaneous polarised pulsar observations for calibration (200 hours of single, international station time: two epochs of 25 hours for each of the LBA and HBA low, mid, and high frequency ranges).
(4) Long (international) baseline observation of T Tau polarised outflows (6 hours HBA).

References:

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PRIORITY TARGET LIST

76 NEARBY GALAXIES FOR IMPROVED IMAGING OF THE TIER 1 HBA SURVEY (63 POINTINGS)

IC10 • IC1613 • IC2574 • NGC0224 (M31) • NGC0598 (M33) • NGC0628 (M74) • NGC0660 • NGC0891 • NGC1156 • IC0342 • NGC1569 • NGC2146 • NGC2276 • NGC2366 • NGC2403 • HOII (UGC04305) • NGC2683 • NGC2814/2820 • NGC2841 • NGC2903 • NGC2976/3031/3034/3077 (M81/M82) • NGC3079 • NGC3183 • NGC3239 • HARO2 (MRK33) • NGC3344 • NGC3351/3368 (M95/M96) • NGC3359 • NGC3432 • NGC3486 • NGC3556 • NGC3593/3627/3628 (M66) • NGC3938 • NGC3953 • NGC4096/4217 • NGC4214 • NGC4236 • NGC4258 (M106) • NGC4395 • NGC4414 • NGC4418 • NGC4449 • NGC4490 • NGC4491 • NGC4559 • NGC4565 • NGC4605 • NGC4618 • NGC4631/4656 • NGC4736 (M94) • NGC4676A/4676B • NGC4826 (M64) • NGC4861 • NGC5055 (M63) • NGC5194/5195 (M51A/B) • NGC5457 (M101) • NGC5775 • NGC6503 • NGC6946 • NGC7331 • NGC7479 • UGC813/816 • UGC12914/12915

49 VIRGO CLUSTER GALAXIES (3X3 HBA POINTINGS)

NGC4064 • NGC4123 • NGC4178 • NGC4189 • NGC4192 (M98) • NGC4212 • NGC4216 • NGC4254 (M99) • NGC4298/4302 • NGC4294/4299 • NGC4303 (M61) • NGC4321 (M100) • NGC4330 • NGC4383 • NGC4388 • NGC4394 • NGC4396 • NGC4402 • NGC4406 (M86) • NGC4419 • NGC4424 • NGC4438 • NGC4450 • NGC4457 • NGC4486 (M87) • NGC4501 (M88) • NGC4517 • NGC4522 • NGC4527 • NGC4532 • NGC4535 • NGC4536 • NGC4548 (M91) • NGC4552 (M89) • NGC4567/4568 • NGC4569 (M90) • NGC4571 • NGC4579 (M58) • NGC4596 • NGC4607 • NGC4651 • NGC4654 • NGC4689 • NGC4698 • NGC4713 • NGC4808 • NGC4866

PRELIMINARY LIST OF 15 TARGETS FOR THE DEEP TIER 2 HBA SURVEY (WILL BE SPECIFIED ACCORDING TO RESULTS FROM TIER 1 SURVEY)

10 mildly inclined (e.g. M33, M51, M81, M101, M106) and edge-on galaxies (e.g. M31, M82, NGC 891, NGC 4631, NGC 4656); 2 starbursting dwarfs: NGC 1569 and NGC 4449; 3 galaxy groups: Stephan's Quintet, HCG 37 (or HCG 60), HCG 68

3 GALAXY TARGETS FOR THE DEEP TIER 2 LBA SURVEY

M31, M33, M81/M82

3 TARGETS FOR STELLAR JETS (HBA)

Cepheus Flare (L1251), Perseus Molecular Cloud (NGC1333), Taurus Molecular Cloud

3 TARGETS IN THE MILKY WAY

"Fan" region (HBA and LBA), Loop III (particularly pointings around A2255 - HBA only), high-latitude part of North Polar Spur (HBA only).