LOFAR-UK

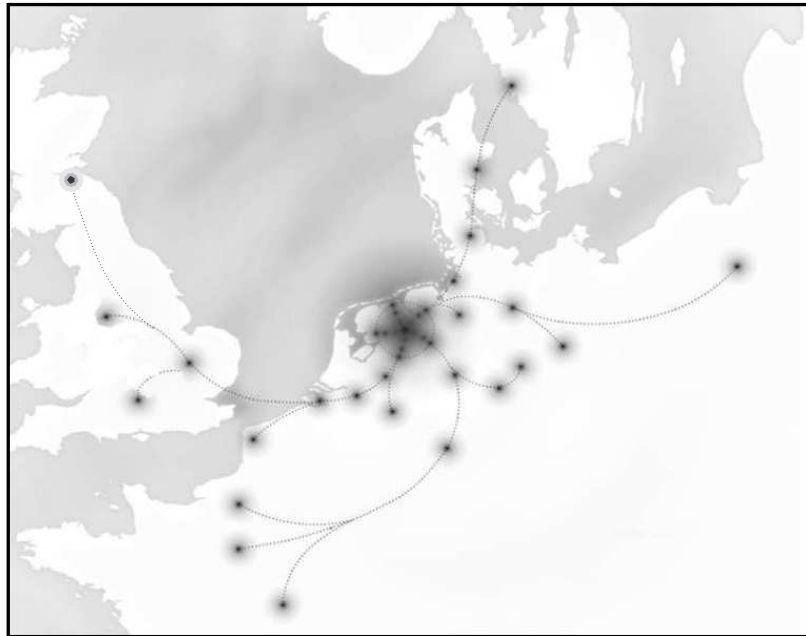## *A science case for UK involvement in LOFAR*

Assembled and edited on behalf of the LOFAR-UK consortium by

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December 2007

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1 Executive Summary

LOFAR, the **Lo**w-**F**requency **Ar**ray, is a next-generation software-driven radio telescope operating between 30 and 240 MHz, currently under construction in the Netherlands. This low frequency radio band is one of the few largely unexplored regions of the electromagnetic spectrum. The sensitivity and angular resolution offered by LOFAR will be two to three orders of magnitude better than existing telescopes, and as such it will open up this new window on the Universe. LOFAR will impact on a broad range of astrophysics, from cosmology to solar system studies: it will conduct the first studies of the Epoch of Reionisation, carry out the deepest large–sky radio source surveys ever, revolutionise the study of transient phenomena, make measurements of ultra-high energy cosmic rays via radio emission from air showers, and investigate the radio signatures of solar and interplanetary activity. In addition, history indicates that exploring new frequency windows has always led to unexpected discoveries.

There is growing European involvement in LOFAR, driven by the need to add stations far from the main core in order to improve angular resolution. LOFAR-UK is a project aimed at cementing UK participation in LOFAR via the operation of four stations within the UK, as part of a European expansion including Germany, France, Italy, Sweden and possibly other European countries. LOFAR-UK ground stations will allow the highest angular resolution LOFAR observations, reaching sub-arcsecond scales at the highest LOFAR frequencies, and as a result will also improve the (confusion-limited) sensitivity limit of the telescope for deep surveys. UK stations will also significantly enhance the instantaneous (u,v)-plane coverage, essential for snapshots of transient phenomena.

LOFAR-UK will achieve involvement for UK astronomers in a world-leading science facility operating in the immediate future. It will allow the UK to build up important scientific and technical expertise in 'next generation' radio astronomy in preparation for the Square Kilometre Array (SKA). Noting the dramatic increase in the diversity of topics addressable with the next generation of radio telescopes, LOFAR-UK will play an important role in helping to broaden the UK community that has an interest in radio astronomy: one of the key features of the LOFAR-UK consortium is that it gathers together traditional 'radio astronomy' groups with groups with very limited experience in radio astronomy, but great interest in the new science to be achievable with LOFAR and the SKA.

This White Paper outlines the strategic importance to the UK astronomy community of gaining involvement in the LOFAR project, the scientific interests of UK researchers in using the telescope, and the technical challenges that will need to be overcome.

2   Introduction

LOFAR is a next-generation software-driven radio telescope currently under construction by AS-TRON in the Netherlands. LOFAR will explore the 30-240 MHz radio sky with two to three orders of magnitude more sensitivity than previous surveys, and will have an enormous field of view facilitating semi-continuous monitoring of more than half of the entire sky at the lowest frequencies.

The Dutch LOFAR will be located entirely within a region of ~ 200 km diameter in the north of the Netherlands. It will be composed of between 36 and 50 stations (depending upon finances), approximately half of which will be located in a 10 km core close to Exloo. Each station will contain 96 low-band (30-80 MHz) and 48 high-band (120-240 MHz) antennae. These antennae will be extremely simple in design and have no moving parts (see Figure 1). They will, however, be sensitive to a large fraction of the sky, and by *beamforming* at each station can be made to 'look' in any direction on the sky. The signal from each station is transported to the LOFAR correlator (an IBM *BlueGene* supercomputer located at The University of Groningen), where it is correlated and then passed to a secondary computing cluster where images are formed and distributed to the science teams. Only data transport and computing limitations limit the number of beams available – the current LOFAR design allows for, e.g., 8×4 MHz beams, or a smaller number with larger bandwidth (greater sensitivity) up to a maximum of 32 MHz. The LOFAR stations located in the core will be able to form more beams in order to monitor a large fraction of the sky simultaneously. Figure 2 illustrates the possible LOFAR observing modes.

Progress with the construction and operation of LOFAR in The Netherlands continues apace. The LOFAR Initial Test Station (ITS) operated successfully with 16 prototype low-band antennae between 2004 and 2006. In the fourth quarter of 2006 the LOFAR Core Station 1 (CS1) was completed at Exloo in the Netherlands, close to the designated core of the full array. CS1 comprises a central cluster of 48 low-band antennae and three outliers each of 16 antennae, to a maximum baseline of 500m (in order to better simulate the operation of a full LOFAR). The design for the high-band antennae is at an advanced stage, and the *BlueGene* supercomputer correlator is fully operational. Over the next two to three years all of the Dutch stations will be constructed and connected and the Dutch array will be complete. In the meantime data is continuously being recorded and analysed as the array grows: the first official sky maps from CS1 have been publically released, and LOFAR has also detected its first pulsar (see *www.lofar.org* for more details). In November 2006 LOFAR had a Calibration Comprehensive Design Review (CDR), to which the response was positive (in particular the CDR panel were happy that issues associated with Radio Frequency Interference (RFI) would not be a show-stopper).

LOFAR is therefore an innovative technology project in an advanced stage of development, where the novel approach to data transport, data processing and associated software development will lead

Figure 1: Prototype low-band (30–80 MHz) LOFAR antennae of the type that have been deployed at the LOFAR Initial Test Station (ITS) and Core Station One (CS1). Eventually up to 5000 such antennae will be distributed across the Netherlands, in 36-50 stations each containing 96 antennae (plus 48 high-band tiles).

LOFAR observing modes

The Radio Sky Monitor (RSM)

Up to 24 beams may be formed in the core of LOFAR to tile out a large fraction of the visible sky at low radio frequencies. In this way the sky will be monitored for transient and variable radio sources.

Full−array observations

In addition up to 8 x 4 MHz beams may be formed using the full array, facilitating rapid deep surveys or pointed high sensitivity observations of regions/objects of interest.

Figure 2: The modes of operation of LOFAR. The wide-field, multi-beam capability of the telescope will allow targeted observations of specific targets, and systematic surveys, to be carried out in parallel with deep monitoring of a large fraction of the visible sky on a daily basis.

to a step-change in radio astronomy capabilities. It is certainly the most innovative and ambitious radio astronomy project prior to construction of the Square Kilometre Array (SKA), which is a long-term ($\sim$ 15yr) project for the world astronomy community and a cornerstone of the STFC Road Map. For more details about LOFAR see *www.lofar.org.*

2.1 International extensions of LOFAR

The interferometric design of LOFAR means that additional stations can relatively easily be added to the Dutch array, subject to the availability of a fast internet connection to transport the data in real-time to the *BlueGene* correlator in Groningen. There has been strong international interest in extending the LOFAR array beyond the borders of the Netherlands. The primary reason for this is that increasing the longest baselines of the array leads to a corresponding increase in the angular resolution of the observations; with international baselines, the resolution at the highest LOFAR frequencies will be below an arcsecond. Such angular resolution is important to accurately localise the detected radio sources, and allow cross-matching of these with sources detected in other wavebands. In addition, deep LOFAR observations quickly become confusion-limited, and so an increase in angular resolution translates directly to an increase in the sensitivity to which the array is able to probe.

Several European countries (Germany, France, Italy and Poland, as well as the UK) are all investigating the possibility of constructing LOFAR stations. The most advanced of these is the German Long Wavelength consortium (GLOW) which is proposing the construction of six LOFAR stations within Germany (see *www.mpifr-bonn.mpg.de/public/pr/white.paper.oct6.pdf*), with construction of the first of these at Effelsberg already underway. The French Long Wavelength consortium

(FLOW) has also produced a White Paper, proposing the construction of one LOFAR station at Nançay (see *www.lesia.obspm.fr/plasma/LOFAR2006/FLOW_Science_Case.pdf*). In combination with these, UK stations would offer both the longest baselines (highest angular resolutions) and also a significantly improvement in the instantaneous (u,v) coverage for intermediate baselines.

Since 2004, members of the UK community with an interest in LOFAR have been meeting every few months to critically appraise the possibility of a significant UK contribution to LOFAR. This has led to the establishment of the *'LOFAR-UK Consortium'*. In the space of two years the LOFAR-UK consortium has established itself as one of the broadest UK astronomy consortia. Over 100 members have voluntarily subscribed to the general LOFAR-UK mailing list, which is comparable in size to the mailing list for the Sloan Digital Sky Survey. Currently twelve UK universities have pledged funds to the project, totalling £550k. In addition two – University of Manchester and the RAL – have pledged 'in kind' contributions (fibre connections and/or land) of equivalent or greater value. An additional number of UK Universities are currently attempting to secure funds to join the consortium.

The LOFAR-UK consortium was formalised in late 2006 via the signing of a Memorandum of Understanding by the fourteen institutions, leading to the formation of the LOFAR-UK Management Council (MC). The MC has elected Rob Fender (Southampton) and Steve Rawlings (Oxford) as Project Leader and Deputy Project Leader respectively. Three project coordinators with different responsibilities have also been appointed: Science Coordinator – Philip Best (Edinburgh); e-Science Coordinator – Bob Nichol (Portsmouth); Technical Coordinator – Rob Beswick (Manchester). The University of Hertfordshire will act as treasurers for the LOFAR-UK project.

The LOFAR-UK consortium has concluded through scientific simulations that the optimal initial approach is the deployment of four LOFAR-UK stations, subtending a range of angles and baseline lengths relative to the Dutch LOFAR core. Leading candidates for these four sites are *Lord's Bridge*, *Chilbolton*, *Jodrell Bank* and *Edinburgh*. The Lord's Bridge and Jodrell Bank sites already have e-MERLIN fibre connections; for Chilbolton and Edinburgh the cost of connecting to a dark fibre network is under investigation, but in both cases a 10 Gbit/s connection to the nearest regional JANET network is possible. On a longer timescale, there is an ambition to add additional UK stations, with specific possibilities being central Wales and the north–east of England.

2.2   This document

The layout of this document is as follows. Section 3 details LOFAR's context in the overall picture of UK radio astronomy. LOFAR will build upon the UK's existing widespread expertise in radio astronomy and interferometry, and will allow the UK to develop new scientific and technical expertise in the many additional areas in which radio astronomical facilities will contribute in the coming decades. As such, LOFAR will provide the optimal stepping stone on the road to the Square Kilometer Array which, through increased sensitivity and direct redshift measurement, will totally revolutionise the field. The broad–base of the LOFAR-UK consortium demonstrates how UK involvement in LOFAR will lead to the development of a wide UK community with interest and experience in the new science to be achievable with SKA.

Sections 4 to 8 detail the specific UK science interests in using LOFAR. LOFAR is a ground-breaking experiment which has set the pace for developments in next generation radio astronomy, and will have a profound impact on a broad range of astrophysics from cosmology to solar system studies. Many of these science goals have already been well described by the Dutch Science case for LOFAR (available at *www.lofar.org/PDF/NL-CASE-1.0.pdf*), and so the emphasis in the current document is upon:

- The ways in which the main LOFAR science goals can be enhanced through UK involvement

in LOFAR, through the provision of complementary datasets and facilities available to UK researchers, and through the expertise in the UK community.

- New science capabilities that will arise from the improved angular resolution of LOFAR when UK (international) baselines are added.

- Additional science goals of interest to UK scientists.

The UK's science interests can be categorised under five broad headings:

1. The Epoch of Reionisation

2. Low Frequency Surveys of the Radio Sky with LOFAR

3. Radio Transients

4. Ultra-High Energy Cosmic Rays

5. Solar and Heliospheric Physics

These are detailed in Sections 4 to 8 respectively. The first four of these correspond to the four Dutch Key Projects for LOFAR. The fifth is an important additional research interest, which is also shared by the German GLOW consortium, and has been adopted as an International LOFAR Key Project.

Section 10 details the technical issues surrounding the LOFAR-UK project. The choice of sites within the UK for the construction of LOFAR stations is discussed, as are the technical challenges relating to connection of these sites to the main LOFAR array. In addition, since Solar and Heliospheric Physics is not one of the Key Projects identified by the Dutch LOFAR team, and hence has no pre-defined observing strategy, the observational requirements for this aspect of LOFAR-UK science are detailed. Finally, Section 11 summarises the organisation and management of the LOFAR-UK consortium, together with the current funding status.

3 LOFAR in the context of UK radio astronomy

The UK has a strong history in radio astronomy, and is looking forward to being an active and leading player in the field for the coming decades. The low-frequency radio surveys conducted at Cambridge over the past four decades have produced some of the most important and well–studied radio source samples, providing a wealth of information on the most powerful active galactic nuclei over the entire history of the Universe. Over the same period, the Jodrell Bank observatory has been at the cutting edge of the development and operation of long baseline and low frequency radio interferometers. The development of the phase-stable radio-linked interferometer led to the creation of MERLIN, the world's largest permanently connected interferometer, which has a maximum baseline length of 217km.

Current UK priorities for radio astronomy are the development of e-MERLIN and the Design Study for the Square Kilometer Array (SKADS). All of the leading institutions in these projects are members of the LOFAR-UK consortium, and fully support the project. At low radio frequencies, LOFAR is the most ambitious 'SKA Science Pathfinder'. The digital/software basis of LOFAR was the inspiration for the 'all–digital' SKA concept being developed by UK groups as part of SKADS for the low ($\lesssim 1\,\mathrm{GHz}$) frequency band. The SKA is a cornerstone of the STFC Road Map, and UK involvement in LOFAR would enable UK astronomers to build up important scientific and technical expertise.

3.1 The University of Manchester and Jodrell Bank Observatory

The University of Manchester's Jodrell Bank Observatory has been developing and operating long-baseline and low frequency radio interferometers for over 40 years, culminating in the creation of MERLIN, the largest permanently connected interferometer in the world. Initially MERLIN's prime frequency was 408 MHz, not far above the LOFAR band: some of its very first observations showed the existence of extended low frequency emission around flat-spectrum quasars, leading to the orientation-based unified scheme of flat- and steep-spectrum quasars (Orr & Browne, 1982). More recent 408 MHz observations, including a 220-km baseline to Cambridge, were made in 1994 and highlights include the detection of a large HII region in M82 (Wills et al., 1997).

MERLIN has also operated at 151 MHz, during the 1985 solar minimum. After a period of 'interference-busting', mostly involving locating sources of sporadic broad-spectrum RFI, several observing programmes were completed, notably on the bridges of radio galaxies (Leahy et al., 1989) and the extended emission surrounding the jet of 3C273 (Davis et al., 1985).

MERLIN observations are now focussed on sensitive high-resolution imaging at 5 and 1.5 GHz, with an angular resolution of 50 to 150 milli-arcseconds. The e-MERLIN upgrade involves the installation of an optical fibre network connecting the 5 remote MERLIN telescopes to Jodrell Bank at 30 Gb/s each, using 'dark fibre' and purpose-built transmission equipment. Together with new receivers, IF equipment and a new correlator, this will provide micro-Jy sensitivity. First fringes with a prototype correlator are expected in early 2008. e-MERLIN will be the natural high-resolution partner to the EVLA. e-MERLIN will also provide a natural complement to the extended LOFAR, providing sub-arcsecond imaging at 1.5 GHz for comparison with LOFAR images below 300 MHz at similar resolution. [Inclusion of LOFAR stations in the UK and in southern Germany will provide baselines of up to 1200km, providing an excellent match to e-MERLIN at 1.5 GHz].

Several of the key science goals for e-MERLIN have close parallels with the science goals for a long-baseline LOFAR, including studies of distant starburst galaxies, the co-evolution of galaxies and AGN, strong gravitational lensing, and jets from X-ray binaries. The large frequency span of e-MERLIN and the extended LOFAR at comparable angular resolution will benefit many of the programmes. Of course, e-MERLIN does not have the very wide field of view of LOFAR, but

it is wide enough (10-30 arcmin diameter) to play an important role in deep surveys, as well as follow–up observations of objects detected and studied in other LOFAR projects.

Jodrell Bank Observatory and the University of Manchester have also played a leading role in the development of data transmission for long-baseline radio astronomy using e-VLBI, carrying out some of the first UK-NL transmissions at >700 Mb/s, diagnosing bottlenecks in various e-VLBI connections, and working on transmission techniques and protocols. They are also working on direct digital connections into and out of the e-MERLIN correlator, to allow multiple e-MERLIN telescopes to transfer data to JIVE at 1 Gb/s each and to connect other European radio telescopes to the e-MERLIN correlator at 4 Gb/s. They are also heavily involved in the design and development work for the Square Kilometre Array as part of the UK technical collaboration involving Cambridge, Manchester and Oxford.

3.2 The University of Cambridge and the Mullard Radio Astronomy Observatory

The Cavendish Astrophysics Group (formerly Radio Astronomy Group) played a major role in the development of radio interferometry and the use of deep, low-frequency, radio surveys for cosmology. A variety of interferometers were developed to perform the 3C, 4C, 5C, 6C and 7C radio surveys. The Mullard Radio Astronomy Observatory has been located at Lord's Bridge near Cambridge for the past 50 years. Surveys and other experiments have operated there at frequencies from $38\,\mathrm{MHz}$ through to $15\,\mathrm{GHz}$ with the main Cambridge surveys being performed at $178\,\mathrm{MHz}$ and $151\,\mathrm{MHz}$, in the middle of the LOFAR high–frequency band. These surveys have made a considerable impact on a broad range of astrophysics. The 3C and 4C surveys detected the most powerful active galactic nuclei (AGN) over the history of the Universe, providing constraints on the evolution of the black hole activity (e.g., Longair, 1966) and acting as beacons to the most massive galaxies at all redshifts (e.g., Lilly & Longair, 1984). The 4C survey also provided crucial evidence in support of Big Bang cosmologies. Pulsars were discovered with the sensitive 81.5 MHz phased array. The One Mile and 5-km telescopes were pioneering instruments in the development of true imaging radio interferometers.

Current experimental activities in the Cavendish Astrophysics Group include radio, sub-millimetre and optical interferometry. At the Mullard Radio Astronomy Observatory the principal instrument is a telescope for blank-field Sunyaev Zel'dovich work called AMI (Arcminute MicroKelvin Imager), which is nearing completion. The observatory also hosts one of the telescopes of the MERLIN interferometer. The group also participates in the construction and exploitation of other telescopes and experiments sited around the world. They have provided common user receivers for the JCMT (most recently the heterodyne array system HARP) and are building prototype water vapour radiometers for ALMA. Experiments that they are prime contributors to include the Very Small Array, a custom-built radio telescope (operating between 26 and $36\,\mathrm{GHz}$) sited in Tenerife, for imaging primordial anisotropies of the CMB, and most recently CLOVER, a millimetre experiment for measuring CMB polarisation. They are partners with the University of New Mexico in the construction of a major new facility for optical interferometry – the Magdelena Ridge Optical Interferometer – which builds on earlier work with the Cambridge Optical Aperture Synthesis Telescope (COAST).

The Cavendish Astrophysics Group are heavily involved in the design and development work for the Square Kilometre Array as part of the UK technical collaboration involving Cambridge, Manchester and Oxford: this includes leading one of the main design studies within the European SKA Design Study with responsibility for, among other areas, technical simulations. They strongly support the push for UK involvement in LOFAR, and have extensive technical and scientific expertise to offer to the project.

3.3 LOFAR-UK as a stepping-stone to the SKA

UK astronomers have been central to the planning for the Square Kilometre Array since its inception. Peter Wilkinson (Manchester) published one of the first papers outlining the basic concept of a large interferometer for HI surveys (Wilkinson, 1991), and Wilkinson and Diamond (Manchester) have been prominent, long-standing and influential members of the International SKA Steering Committee. Rawlings (Oxford) spent 2003-2005 as vice-Chair and then Chair of the International Science Working Group: during this period he co-edited the international SKA science case (Carilli & Rawlings, 2004)

In 2004, Wilkinson was the UK coordinator for the SKA Design Study (SKADS) which culminated in a successful bid for European Community funding under the Framework 6 (FP6) programme. This proposal unifies significant activity in several EC countries (France, Germany, Italy, the Netherlands, Portugal, Spain, UK). The UK SKADS consortium was formed comprising three major University partners (Cambridge, Manchester and Oxford) alongside three minor partners (Cardiff, Glasgow and Leeds). This consortium successfully applied for PPARC funding that has resulted in a comprehensive design study incorporating science, data and network simulations, as well as a hardware design project built around the concept of an all-digital system. The UK SKADS programme will be funded from mid–2005 to mid–2009, and has built up a team of more than 20 postdoctoral researchers split across the participating UK institutions.

The UK SKADS team have led the development of the SKADS Benchmark Scenario – which couples the capabilities of phased-array technologies at low (< 1 GHz) frequencies with those of small dishes at higher frequencies – and recently costed this for consideration by the International SKA Project Office and the wider international SKA effort. They have been developing links with all of the international SKA pathfinder projects. In the low-frequency (30–300 MHz) band these include LOFAR, the Mileura Wide-field Array (MWA) and the Long Wavelength Array (LWA). In the mid-to-high frequency band (300 MHz – 20 GHz), these include the Allen Telescope Array (ATA), MWA and the Karoo Array Telescope (KAT).

In 2006, following comprehensive studies of several candidates sites, the international SKA project short-listed two sites for further consideration: Western Australia and South Africa. Some SKA pathfinder projects are being developed on these sites. The only SKA pathfinder project being developed in Europe is LOFAR. As the largest contributors to the SKADS EC project are the Netherlands and the UK, it seems natural that these countries collaborate in some way on the LOFAR project. The total cost of UK involvement in LOFAR is tiny compared to the likely UK and global investment in radio astronomy over the next two decades, but will offer a unique opportunity to obtain hands-on experience both on a technical and on a scientific level. It is also worth emphasising that the southern hemisphere locations proposed for the SKA mean that its construction will not render LOFAR redundant: we can envisage both being operated in tandem, providing full–sky surveys and transient monitoring.

4 LOFAR-UK and the Epoch of Reionisation

Protons and electrons produced in the Big Bang combined together at a redshift of $z \approx 1100$ to form neutral hydrogen. UV and X-ray radiation from the first stars and black holes (AGN) then ionised the hydrogen again[1], and later radiation from galaxies and quasars kept the bulk of the Universe highly ionised up to now. However, little is known about when and especially how the reionisation happened. LOFAR will probe the reionisation epoch by searching for the redshifted 21-cm signal that arises from neutral hydrogen in the intergalactic medium (IGM), provided that the spin temperature of the Hɪ is de-coupled from the Cosmic Microwave Background temperature. This signal disappears as the IGM gets ionised, and measurements of the distribution of neutral and ionised regions around reionisation will provide a wealth of information about the first stars and galaxies.

Study of the Epoch of Reionisation is one of the Dutch Key Projects for LOFAR, and has been one of the key drivers for the design of the telescope, in particular the concentration of a large fraction of the stations within a central core. The addition of international baselines to LOFAR is not essential for the detection of the reionisation signal *per se*, but will play an important role in the identification, localisation and spectral characterisation of the contaminating foreground signals, which are the largest impediment to the detection of the redshifted 21-cm signal. In addition to providing these long-baseline stations, the UK will bring to the LOFAR consortium extensive expertise in cosmological simulations of large-scale structure formation, galaxy formation, and radiative transfer. Providing good models for how galaxies form will be essential to maximise the information that can be obtained from the LOFAR data, and realise the full potential of having this exciting new window on the Universe.

4.1 Introduction: The Epoch of Reionisation

According to the present view of the early Universe, hydrogen atoms were first formed about a million years after the Big Bang, when the primordial matter cooled to a temperature of about 3000K. The Universe then became dark and it cooled further due to the general Hubble expansion. These "Dark Ages" came to an end many hundreds of millions of years later, when the first stars and black holes started producing light. Ionising radiation from these, and subsequently forming objects, then began to warm and ionise the Universe, until it again became highly ionised. The time at which 50% of the Universe was ionised is termed **the Epoch of Reionisation (EoR)**. Although it is important to determine the redshift of the EoR, the main scientific interest is in *how* the Universe went from neutral to ionised, and the properties of the sources that caused the transition.

Current observational constraints on the EoR are not very strong. They are based on measurements of cosmic microwave background (CMB) temperature anisotropies and polarisation, Gunn-Peterson absorption in quasar spectra, and the temperature evolution of the IGM.

1. After reionisation, free electrons Thomson-scatter CMB photons, smoothing out the temperature anisotropies on small scales. When measurements of temperature anisotropies are combined with data on the large-scale structure of galaxies, the EoR is constrained to be below $z \sim 30$. Thomson scattering also induces polarisation in the CMB, and (under the simplified assumption of a sudden reionisation history) the Wilkinson Microwave Anisotropy Probe (WMAP) team used the 3-year dataset to constrain the EoR to be around $z \sim 12$ (Figure 3; Spergel et al., 2007), although there is some degeneracy with other cosmological

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[1]Stars or AGN are by far the most likely reionising sources, but the possibility of something more exotic, such as decaying particles, cannot be excluded. In such a case, LOFAR's reionisation measurements could have fundamental implications for physics.
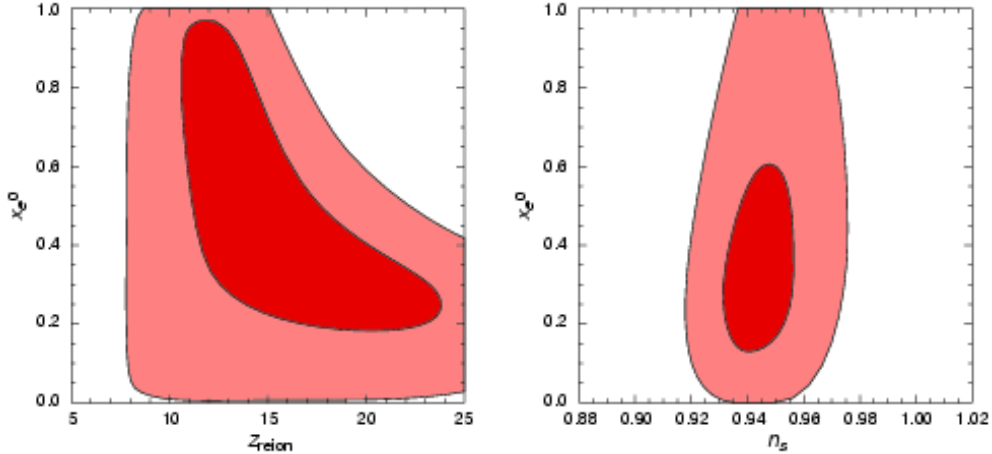
Figure 3: WMAP year 3 joint constraints on the reionisation redshift, $z_{\rm reion}$, and ionised fraction, x_e^0. These assume that the IGM became partly ionised at $z_{\rm reion}$ to an ionisation fraction of x_e^0, and then became fully ionised at $z = 7$ (from Spergel et al., 2007).

    parameters. Note that this is significantly lower than the redshift $z \sim 20$ estimated from the WMAP 1st-year polarisation data.

2. The absence of a Gunn-Peterson trough in the spectra of $z \leq 6$ QSOs shows that the IGM was highly ionised by $z \approx 6$ (e.g., Becker et al., 2001). The mean flux decrement increases rapidly before $z \approx 6$ (Becker et al., 2001; Fan et al., 2002), and indicates that the Universe is becoming more neutral. This is also indicated by the sizes of ionised regions around high-z QSOs (Mesinger & Haiman, 2007), although systematics complicate this interpretation (Bolton & Haehnelt, 2007). However, such measurements do not directly determine the redshift at which the ionised fraction was 50%.

3. As the Universe gets photo-ionised, it also gets heated. After reionisation, Compton cooling again cools the IGM and this can be used to constrain the EoR (Figure 4; Theuns et al., 2002) to $z \sim 10$, although it is dependent on assumptions about the heating rate after reionisation and the reionisation of elements heavier than hydrogen.

4. The level of UV background light post-EoR also constrains the EoR and the spectra of the sources responsible. Current models (e.g., Gnedin, 2000; Benson et al., 2006) tend to over-produce the post-EoR UV background, resulting in an IGM too transparent to Lyα scattering, as compared with the observational data. Attempts to combine the measured evolution of the mean scattered Lyα flux with numerical simulations of the IGM suggest that there is no rapid evolution of the reionising source emissivity beyond $z > 5$, and that the EoR is at $z \lesssim 11$ (Meiksin, 2005).

In summary, there are good indications that reionisation started somewhere around $z \lesssim 12$, and was mostly completed by at least $z \gtrsim 6$. However, none of the existing constraints are very tight, and current models struggle to reproduce all of the data. Improved observational constraints on the epoch and mechanism of reionisation are urgently required.

In the redshift range $6 < z < 11$, the 21-cm hyperfine line of neutral hydrogen will fall within the LOFAR high frequency band, and will be observable provided that the spin (excitation) temperature of the transition has decoupled from the CMB temperature (e.g. Madau et al., 1997). This line will disappear as the Universe gets ionised, and hence LOFAR offers an opportunity to probe in great detail the epoch of reionisation and the nature of the sources of ionising photons in the early Universe. A firm detection of the EoR by LOFAR would be of great importance, whilst even a null
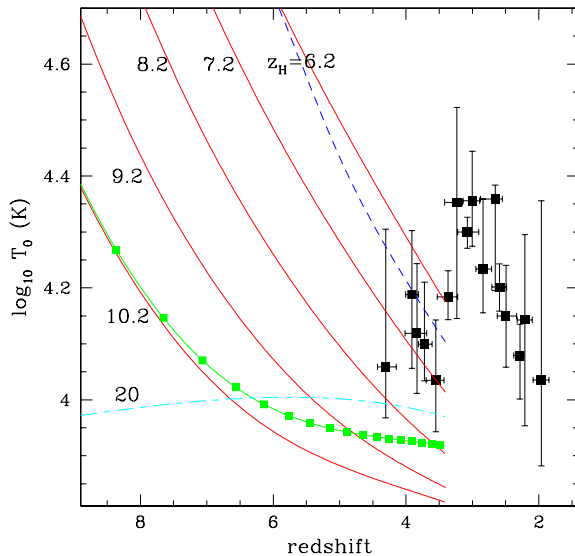
Figure 4: The evolution of the temperature, T, of the IGM. The red lines show the model predictions (not including radiative transfer) for the temperature evolution for different (labelled) H<small>I</small> reionisation redshifts, while the black points show measurements of T from quasar absorption lines. The rise in the measured temperature at $z \sim 3$ is thought to be caused by reionisation of He<small>II</small>, and so the constraint on the reionisation redshift of H<small>I</small> comes from comparing models and data at $z \sim 4$ (Theuns et al., 2002). Adiabatic expansion cooling causes the Universe to be colder than observed at $z = 4$ if the EoR is too early, while reionisation at later times fit the data better. These models assume a very high post-reionisation temperature, to show that, even for such (unrealistically) high initial temperatures, reionisation should not have happened much above $z = 10$ to avoid the IGM being to cool at $z = 4$.

detection would significantly improve our current knowledge of both the epoch and mechanism of reionisation, providing important constraints on the early history of radiation sources. The PAST and MWA (*web.haystack.mit.edu*) experiments in China and Australia, respectively, have similar goals.

Four of the most important questions that need addressing about this major event in the history of the Universe are:

- When did reionisation occur?

- How rapidly did the IGM change from being mostly neutral to mostly ionised?

- What were the sources of ionisation, and how did they affect the global progression of the reionisation?

- How did reionisation affect galaxy formation?

LOFAR aims to provide the data to answer these questions, but it will be necessary to make realistic models of reionisation in order to take full advantage of all of the information that LOFAR observations will provide.

Section 4.2 discusses in some detail the signal expected from reionisation. Section 4.3 considers the issue of foreground emission sources, and the techniques needed to remove these in order to detect the reionisation signal. Section 4.4 discusses the requirements on modelling to interpret this signal, and Section 4.5 details the contribution that the UK community can offer in this respect.

4.2   Observational 21cm signatures of Reionisation

In the simplest idealised model of reionisation, the IGM everywhere changes abruptly from being neutral to ionised at the reionisation redshift, z_r. If the spin temperature (T_s) of the 21-cm hyperfine transition has already decoupled from, and been raised above, the CMB temperature (T_{CMB}) before reionisation, then this will manifest itself in 21-cm radiation as a global, all-sky spectral signal: 21-cm radiation will be detected in emission at wavelengths $\lambda \geq 21 \times (1 + z_r)$cm, but not below that (Shaver et al., 1999). If $T_s \gg T_{CMB}$, then this step in brightness temperature will have an amplitude of 10-20mK, depending only on the cosmic baryon density and the reionisation redshift, and will occur at a frequency around 130 MHz for $z_r \approx 10$. In principle, LOFAR will be easily able to detect such a signal after only a few hundred hours of observing. Measuring the frequency at which the step in emission occurs will then directly determine z_r, while the width of the step in frequency will yield the duration of the reionisation epoch. Although the reality of extracting such a signal from the foreground contamination will be non-trivial (see Section 4.3), determining these parameters is one of the key science goals of the Netherlands LOFAR consortium.

Complications to this simple picture arise because (1) the HI spin temperature needs to decouple from the CMB temperature for any 21-cm signal to be seen (in either emission or absorption), and (2) the reionisation is expected to occur inhomogeneously, with HII regions being ionised around individual sources and growing until they eventually overlap. Even within the neutral part of the IGM, the gas density and kinetic and spin temperatures will be inhomogeneous.

The HI spin temperature, T_s, can be coupled to the gas kinetic temperature, T_k, by collisions between atoms (and with ions and electrons; Scott & Rees, 1990), and by scattering of Lyman-α photons. In the absence of these processes, T_s will relax to the CMB temperature, and the HI gas will be invisible in 21-cm radiation (either in emission or absorption). Atomic collisions are likely to be important only in fairly overdense regions (e.g., Kuhlen et al, 2006), but non-ionising UV-radiation from the first galaxies can couple the spin and kinetic temperatures even in low-density gas through a process known as 'Lyman-α pumping' or the 'Wouthuysen-Field' effect. This is expected to couple T_s to T_k throughout most of the IGM, even when only a small fraction of the IGM has been reionised (Madau et al., 1997; Hirata, 2006). Several recent papers discuss these processes in detail, but reach differing conclusions: Kuhlen et al (2006) and Iliev et al. (2002) argue that a strong emission signal will be produced by collisional coupling in mini-haloes, whereas Oh & Mack (2003) suggest that Lyman-α pumping dominates the coupling under almost all circumstances. There is clearly much scope for further theoretical modelling to put the basics of the 21-cm signal on a firmer footing.

Once collisions or Lyman-α scattering have coupled T_s to T_k, the gas will appear in either emission or absorption in the 21-cm line, depending on whether $T_k > T_{CMB}$ or $T_k < T_{CMB}$. Gas in halos and filaments can be shock-heated, but for gas close to the average IGM density, the only effective heating mechanism prior to reionisation appears to be heating by X-ray photons produced by shock-heated gas in galaxy halos, by star-forming regions, by QSOs, or by mini-QSOs (Madau et al., 1997; Chen & Miralda-Escude, 2007). (Note that the energy required to have $T_k > T_{\mathrm{CMB}}$ is only 0.004 eV per particle at $z \approx 10$.) Thus, halos and filaments are expected to appear in emission in 21-cm prior to reionisation, but the lower density IGM should appear in absorption at early times, and in emission later (after it has been heated by X-rays; cf. Figure 5). Prior to full reionisation, the IGM will therefore be a mixture of ionised regions surrounding sources, embedded in partially ionised and neutral regions (Figure 6). This will lead to brightness fluctuations with structures up to a degree in size. The simulations of Tozzi et al. (2000) – see also Ciardi & Madau (2003) and Furlanetto et al. (2004) – suggest that the fluctuations in the brightness temperature should decrease with increasing angular scale (Figure 7).

Although the 21-cm signal from HI around the reionisation epoch is expected to have structure down to very small angular scales (0.1 arcmin or less), the low surface brightness of the signal
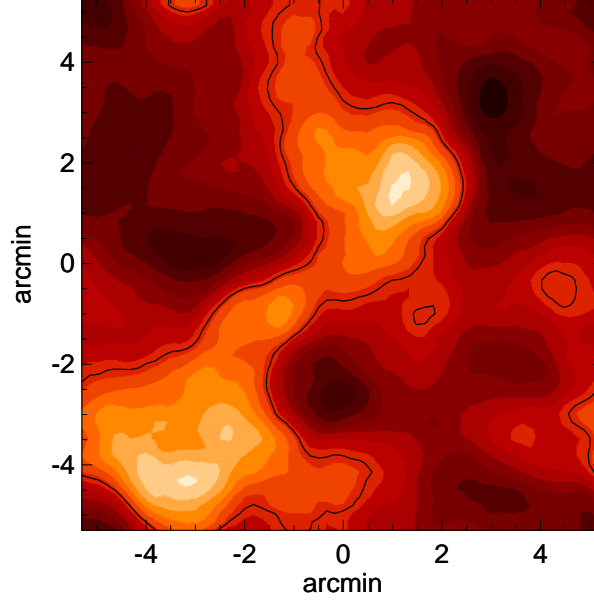
Figure 5: Radio map of redshifted 21–cm emission against the CMB at $z = 8.5$, on the scale of $20h^{-1}$ (comoving) Mpc (from Tozzi et al., 2000). The point spread function of the synthesized beam is assumed to be a spherical top–hat with a width of 2 arcmin. The frequency window is 1 MHz around a central frequency of 150 MHz. The color intensity goes from 1 to 6 μJy per beam. For clarity, the contour levels outline regions with signal greater than $4\,\mu$Jy per beam.
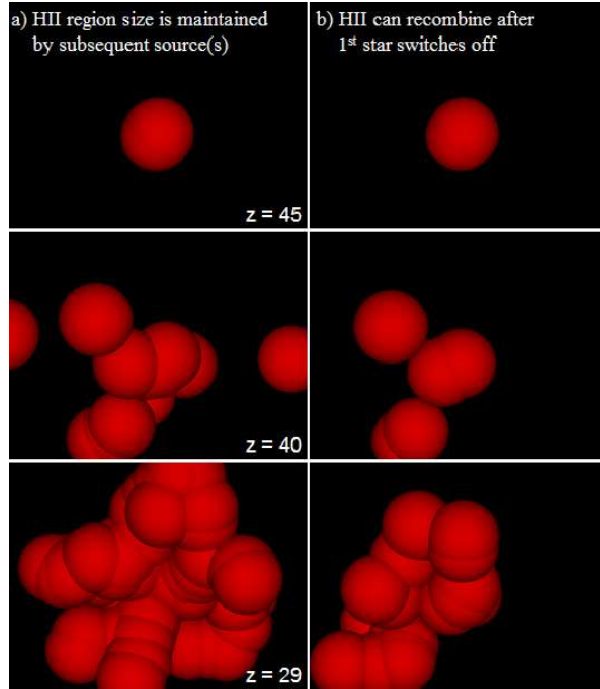
Figure 6: The growth of overlapping HII regions around early ionising sources (from Reed et al., 2005).

means that it may only be possible to detect it over receiver noise if it is smoothed over scales of a few arcminutes on the sky, which in turn implies that only the central core of the LOFAR array will be effective for measuring angular structure in the signal from the reionisation epoch. In order to provide a sufficiently large collecting area to calibrate the faint signal from the EoR, approximately half of the Dutch LOFAR stations will be located within the ($\sim 10\,\mathrm{km}$) core. The design of LOFAR
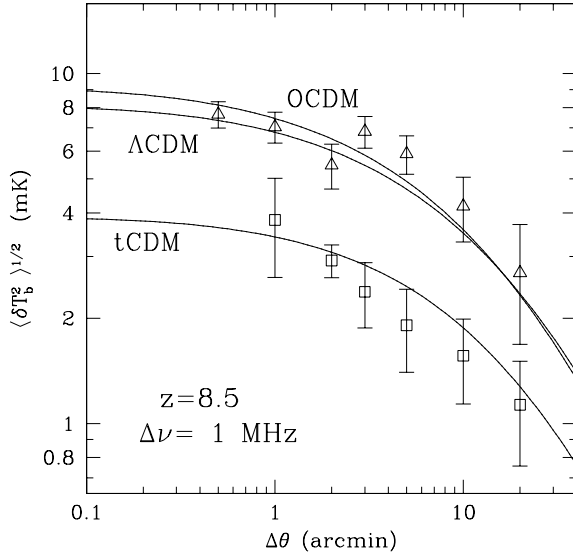
Figure 7: The predicted rms brightness temperature fluctuations as a function of angular scale (from Tozzi et al., 2000). The smooth curves show predictions based on linear theory, while the symbols show estimates based on N-body simulations.

is thus optimised to detect these fluctuations on a scale of a few arcmins at $z = 8.5$.

4.3 Removal of foreground signals and detection strategies

The biggest hindrance to the detection of an EoR signal is the contaminating foreground signals, which collectively exceed the EoR signal by 5 orders of magnitude. These comprise unresolved radio sources (the majority of which will be starburst galaxies at these low flux densities), confusion noise, free-free and synchrotron emission from the Galaxy, and free-free emission from electrons in the intergalactic medium (e.g. Di Matteo et al., 2002; Oh & Mack, 2003; Gnedin & Shaver, 2004; Morales & Hewitt, 2004; Bowman et al., 2007). Galactic and extragalactic radio recombination lines (RRLs) are also sources of contamination (Oh & Mack, 2003), but more readily manageable: the frequencies of RRLs from the Galaxy are well-known and avoidable, while the remaining extragalactic RRLs are removable as they occur over narrow frequency ranges (Gnedin & Shaver, 2004).

The most straightforward detection of the EoR is a global whole-sky signal (Shaver et al., 1999). A strategy for removing the foreground contamination would be to perform measurements over wide differences in frequency, to obtain a fiducial measurement before (or after) reionisation is complete. The most straightfoward implementations of this approach are unlikely to succeed because of the magnitude of the contamination (Gnedin & Shaver, 2004). There may, however, still be scope for developing this approach using more subtle statistical methods.

Two alternative techniques are to chop the signal over angle or over frequency (Madau et al., 1997). These methods may be used to image individual growing HII regions or to measure the fluctuations in the signal in a statistical sense (Tozzi et al., 2000). Extracting an EoR signal by differencing measurements separated by angle, however, is unlikely to adequately cancel the effects of the contaminants (Gnedin & Shaver, 2004). The most promising approach is therefore to difference the signal by frequency, for individual patches of the sky: this takes advantage of the smooth spectra of the contaminating sources, compared with the relatively large frequency variations of the 21cm signal arising from the spatial fluctuations of the IGM separated in redshift

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(Madau et al., 1997; Gnedin & Shaver, 2004). Oh & Mack (2003) point out that the changing beamwidth with frequency makes the elimination of the slowly varying (with frequency) Galactic foreground not so straightforward, but Gnedin & Shaver (2004) argue that angular correlations will facilitate the removal of the contamination, and conclude that the strategy should be successful at extracting an EoR signal for moderate angular resolution observations ($10 - 20$ arcminutes). They also argue that if Galactic synchrotron and thermal emission are structured more strongly than contaminating extragalactic point sources on small angular scales, they could be difficult to remove. Currently the angular structure of these Galactic contaminants is unknown.

In order to isolate and spectrally characterise these discrete sources, so that they may be removed from the EoR map, very long baselines (hundreds of kilometres) are crucial; these will be provided by the international extension to LOFAR. In addition, careful thought must be put into planning the observing strategy. Most of the emphasis has been on detecting the statistical fluctuations (Tozzi et al., 2000; Morales & Hewitt, 2004; Zaldarriaga et al., 2004; Bharadwaj & Ali, 2005; Bowman et al., 2007), but LOFAR is well-suited to imaging the growing and overlapping HII regions as well (Madau et al., 1997; Tozzi et al., 2000; Zaroubi & Silk, 2005). Techniques for imaging the HII regions deserve further development.

4.4 Reionisation and galaxy formation

Probing the EoR using the redshifted 21-cm line will open a new window on the very early Universe, currently out of reach of any other observatory. While measuring the redshift and duration of reionisation will provide important global constraints on the sources responsible for reionising the Universe, obtaining detailed constraints on the physical nature of these sources (e.g., their luminosities and halo masses), and connecting them to the process of structure formation, will require analysing 3D maps of the spatial and frequency structure of the 21-cm emission. Both the construction and analysis of such maps are very challenging tasks. Several recent papers discuss strategies for determining the 21-cm power-spectrum from the data, for example, Zaldarriaga et al. (2004), Morales (2005) and Furlanetto et al. (2006).

Interpreting the 21-cm data requires modelling of the sources of ionisation, and investigating how rival models can be distinguished. Necessary ingredients for the simulations are large-scale structure formation, star formation and feedback, formation and accretion onto black holes, emission and heating by X-rays, and radiative transfer of the Lyman-α and ionising radiation to compute the 21-cm signal.

The 21-cm data should be able to constrain many properties of high-redshift galaxy formation that are currently poorly-known, such as the ubiquity and initial mass function (IMF) of zero-metallicity population III stars, the presence (or not) of a substantial population of very early X-ray sources, and the escape fraction of ionising photons from small galaxies. An example calculation is illustrated in Figure 8, which shows predictions for reionisation from a physically-motivated galaxy formation model. The different curves show how the results depend on different cosmological parameters and on different assumptions about gas cooling and about the IMF of the first stars.

LOFAR can potentially constrain many of the properties of the high-z galaxies responsible for reionisation. However, it is very important to understand the limits of the models. This can only be done if a large enough range of models is investigated, by a set of relatively independent groups. Current model predictions from different groups vary relatively widely, even for basic observables such as the EoR, and much more so when realistic physics such as radiative transfer is included. In order to obtain constraints on structure formation from the LOFAR power-spectrum it will be essential to compare the data with a suite of models. An analogous situation arose with the 2dF Galaxy Redshift Survey: although little modelling was required to *measure* the 2dF galaxy-power-spectrum, mock galaxy catalogues were essential to allow cosmological constraints to be obtained
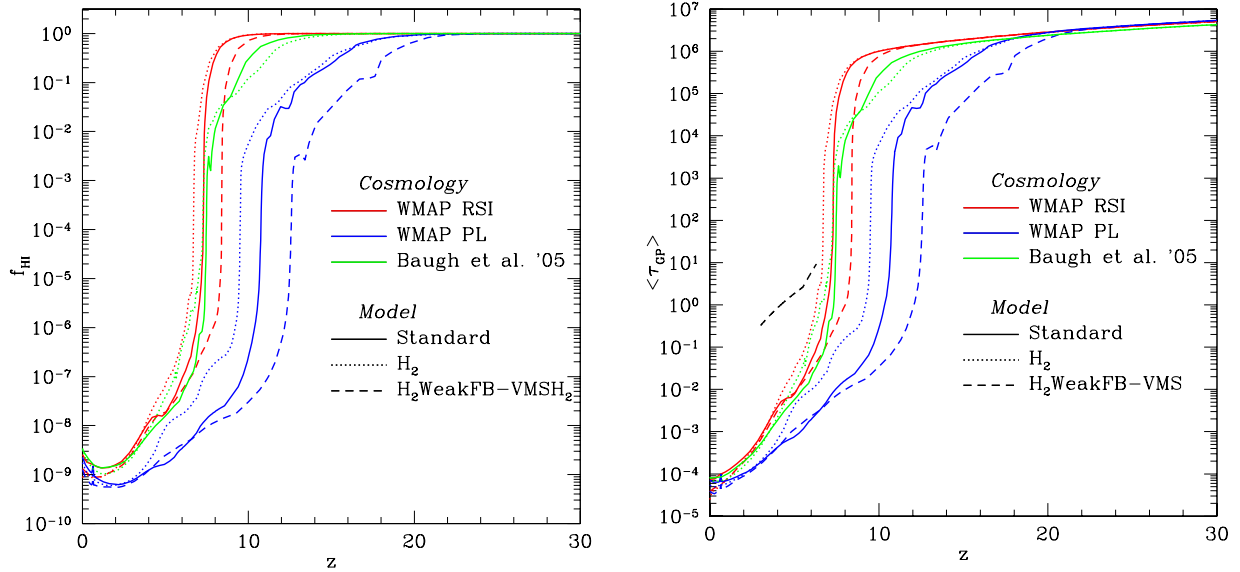
Figure 8: The mean mass-weighted H I fraction (left-hand panel) and Gunn-Peterson optical depth (right-hand panel) as functions of redshift for various models in three cosmologies (see key in figure for colour and line type coding; from Benson et al., 2006). The dashed black line in the right-hand panel indicates the fit to the mean optical depth reported by Fan et al. (2006).

from the measurements.

Finally, it is worth noting that with integration times of several beam-years, it may in principle be possible for LOFAR to measure the 21cm emission power spectrum with sufficient accuracy to detect Baryon Acoustic Oscillations (Mao & Wu, 2007). Such a detection would prove the cosmological nature of the reionisation signal, by matching the observed BAO angular scale with the reionisation brightness temperature step. The BAO signal could also be used to constrain cosmological models, particularly those that predict an early onset for dark energy.

4.5   Reionisation and the UK

The cosmology community in the UK is well placed to make a substantial contribution to interpreting and exploiting LOFAR data on the epoch of reionisation. For extracting the full cosmological information from the 21-cm maps of the reionisation epoch, it will be essential to have high-resolution numerical simulations which include all of the relevant physics of galaxy formation, radiative transfer and gas heating and cooling. Although they will not be required to determine the exact time the EoR took place, simulations and analytical models will be required to allow the full scientific impact of all the data provided by LOFAR. Moreover several key physical processes that govern the EoR are still insufficiently understood, with competing groups reaching different conclusions, demonstrating the need for further thorough theoretical investigations.

Several UK universities have a proven track-record in performing such simulations and theoretical modelling. For example, the Virgo consortium, which is a collaboration between several groups in the UK with strong links to the Netherlands (Leiden Observatory) and Germany (MPA in Garching) is a world-leader in developing simulation codes, running them on very large computers, and comparing the results in detail to data extending over the whole electromagnetic spectrum.

5 Deep Extragalactic Surveys with LOFAR-UK

"Deep Extragalactic Surveys with LOFAR" is the key project which has aroused the most widespread interest amongst UK researchers. A broad range of scientific topics can be addressed by deep and sensitive surveys of the low frequency radio sky. Many of these have already been well described by the Dutch science case for LOFAR surveys, including:

- Detecting the most distant radio galaxies in the Universe, and using these to study the most massive galaxies at early epochs, and early cluster formation.

- Studying intracluster magnetic fields, using diffuse radio emission in galaxy clusters.

- Probing galaxy evolution by studying radio–selected star forming galaxies across a wide range of cosmic epoch.

- Investigating the large-scale structure of the Universe through radio source clustering.

- Constraining the physics of radio sources, and their evolution.

- Delineating the spatial distribution of the interstellar medium (ISM) in nearby galaxies.

- Studying galactic sources, such as supernova remnants, HII regions, exo-planets and pulsars.

- Exploring new parameter space for serendipitous discovery.

The current document does not attempt to repeat these discussions, but rather focusses upon the ways in which these can be enhanced through UK involvement in LOFAR, due to (i) the improved angular resolution of the array when UK (international) baselines are added, providing new science opportunities; and (ii) the addition of complementary datasets, observing capabilities, expertise and manpower that the UK community will provide. In addition, there are a large number of additional science goals of interest to the UK community which were not discussed in the Dutch science case.

UK researchers have already formed part of the LOFAR Surveys Working Group, helping to design the format of the surveys that LOFAR will carry out. We envisage a very productive and collaborative working relationship between LOFAR-UK and the Dutch Surveys team.

5.1 Complementary observations of LOFAR deep survey regions

In the current LOFAR Sky Survey plan, it is proposed to survey the entire 2π steradians of the northern sky at frequencies of 30, 60, 120 and 200 MHz. In addition, there will be a deeper survey at 120 and 200 MHz survey over approximately 250 square degrees (hereafter referred to as 'LOFAR-deep'), reaching the confusion limit of $\approx 6\,\mu$Jy rms at 200 MHz. An even deeper survey at 200 MHz over a few square degrees, pushing into the confusion limit, is also under consideration. Given that most of the faint and distant radio population appear to have steep radio spectral indices ($\alpha \sim 1$, where $S_\nu \propto \nu^{-\alpha}$; e.g., Martínez-Sansigre et al., 2006), the 200 MHz 'LOFAR-deep' survey will have a sensitivity equivalent to $1\sigma \sim 1\mu$Jy at 1.4 GHz. Such depths have not yet been approached, requiring, in principle, a year or so of exposure with telescopes like the VLA or the GMRT, and then only over $\lesssim 1\,\mathrm{deg}^2$. The survey speed of LOFAR will outstrip even the EVLA by at least a factor of ~ 50, and will not be bettered until the SKA is operational.

The vast improvement that LOFAR will offer over previous radio surveys will undoubtedly result in a large number of significant advances in our understanding of the Universe. In modern astronomy, however, it is often the combination of datasets from different international facilities which results in

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the most significant breakthroughs. We discuss here a number of different complementary surveys of the LOFAR survey regions which the UK is currently involved in preparing or undertaking; combining these with the LOFAR survey data will greatly increase the scientific potential of the LOFAR surveys.

5.1.1 Optical and near-IR surveys of the LOFAR survey regions

At the 200 MHz confusion limit, the LOFAR-deep survey will have the sensitivity to probe volume-limited samples of AGN, as well as large populations of star-forming galaxies to high redshift (e.g., Figure 9; see Section 5.2 for details). The addition of UK and international LOFAR stations will also enable LOFAR-deep to provide sub-arcsecond angular resolution. It will detect tens of millions of objects in huge volumes of the high-redshift Universe but, crucially, only in 2D projection. We have learnt from studies of the local Universe that the shift from 2D to 3D tends to transform hints on key issues in galaxy formation and cosmology (e.g., Efstathiou et al., 1990) to firm measurements, e.g., how local galaxies trace the dark matter and hence Ω_M (e.g., Percival et al., 2001), and believable constraints on exotica like the mass of neutrinos (Elgaroy et al., 2002) and dark energy (Percival et al., 2007). A critical complement to the LOFAR surveys is thus the addition of deep optical and/or near-infrared observations.

The Wide Field Camera (WFCAM) on the United Kingdom's InfraRed Telescope (UKIRT) is an extremely powerful instrument for wide–field near-infrared studies. With four 2048x2048 Rockwell devices, it offers an exposed solid angle of 0.21 square degrees in a single shot, leading to easily the fastest survey rate of any IR instrument in the northern hemisphere. Commissioned in 2004, WFCAM is being used to carry out a number of different sky surveys, under the collective name of the UKIRT Infrared Deep Sky Survey (UKIDSS). These include two Galactic surveys (the Galactic
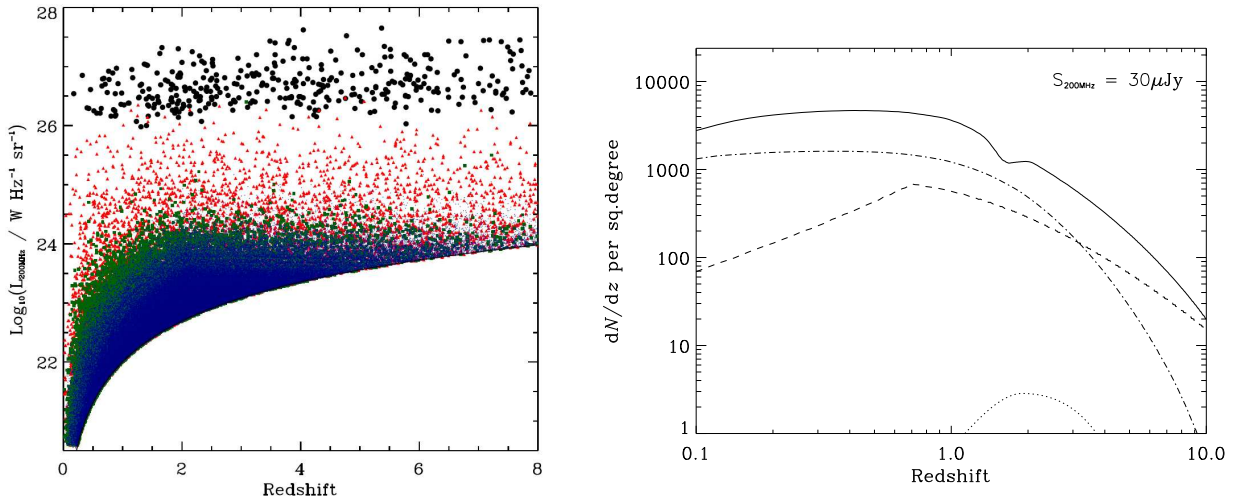
Figure 9: *Left:* A simulated $L_{200\mathrm{MHz}} - z$ (radio luminosity versus redshift) plane for 1 deg^2 of the 'LOFAR-deep' survey, to an approximate flux density limit of $S_{200\mathrm{MHz}} = 30\mu\mathrm{Jy}$. The model splits the LOFAR population into four sub-populations (Jarvis & Rawlings, 2004): starbursts (blue); radio-quiet quasars (RQQs; green), FR I radio galaxies (red); and FR II radio galaxies (black; in this case calculated for 100 deg^2). This survey will provide volume-limited samples of AGN (RQQ, FR I and FR II) out to very high redshift, and also detect most of the luminosity density in starbursts out to $z \sim 2$, and the most extreme starbursts to much higher redshift. *Right:* The number of sources per square degree in the deep LOFAR survey, split into the various sub-populations. The solid line represents the star-forming galaxies, the dot-dashed line represents the radio-quiet quasars, the dashed line shows the FR I radio galaxies and the dotted line denotes the FR II radio galaxies. One can see that such a survey is dominated by the star-forming galaxies. [NB. The slight kink in the star-forming galaxies curve is an artefact of the simplistic modelling of the evolving star-forming population.]

Plane Survey, and the Galactic Clusters Survey), and three extragalactic surveys of differing areas and depth: the Large Area Survey (LAS; 4000 deg^2 to $J = 20.0$, $H = 18.8$, $K = 18.4$), the Deep Extragalactic Survey (DXS; 35 deg^2 to $J = 22.5$, $K = 21.0$) and the Ultra Deep Survey (UDS; 0.77 deg^2 to $J = 25$, $H = 24$, $K = 23$). These surveys will be incredibly powerful when combined with the LOFAR data, particularly the northern DXS fields which offer a natural starting point for the 250 square degree deep LOFAR surveys, and the UDS which would be an obvious target for an extremely deep LOFAR pointing (as would the UltraVISTA COSMOS field, although both are equatorially located). In addition to these surveys, general observer time with WFCAM is available for smaller programmes, whilst beyond 2009 there will be a new opportunity to propose for additional large surveys. An ambition of the LOFAR-UK team is to use WFCAM to survey the full 250 square degrees of the LOFAR-deep survey regions down to $K = 20$. This is sufficiently deep as to detect essentially all of the LOFAR AGN population at $z \lesssim 2.5$ (see Figure 10a).

In the optical bands, data of great value to LOFAR will be taken by the Pan-STARRS project (Panoramic Survey Telescope & Rapid Response System; *pan-starrs.ifa.hawaii.edu/public/*). Pan-STARRS is a multi-colour optical survey to be carried out between 2008 and 2011 on a dedicated 1.8m telescope in Hawaii. The Pan-STARRS project will survey the entire 3π steradians of sky visible from Hawaii in the g, r, i, z and y bands, to a 5σ depth of $g \approx 24.6$ (1–2 magnitudes deeper than the Sloan Digital Sky Survey, which does not reach sufficient depth to get redshifts, either spectroscopically or photometrically, for the majority of the faint radio sources). The Pan-STARRS data will provide optical identifications and colour information for the majority of AGN detected by the whole suite of LOFAR surveys (e.g., see Figure 10b), and photometric redshifts for all those at $z \lesssim 1$. In addition, 10 fields of approximately 7 square degrees each will be visited many times to produce a Medium Deep Survey, with limiting depths of $g \approx 27.3$, $r \approx 26.9$, $i \approx 27.9$, $z \approx 26.3$, $y \approx 24.8$. These 10 fields have been chosen to have the best possible complementary data, particularly in the near–IR (e.g., UKIDSS-DXS and VISTA:VIDEO regions), and it is likely that many of these regions will be selected for the LOFAR deep survey fields. The Medium Deep Survey data will identify essentially all of the AGN and starburst galaxies detected by LOFAR, and provide accurate multi-band photometric redshifts for these out to at least $z \sim 2$.

The Pan-STARRS survey is a private survey, being carried out in collaboration between the University of Hawaii, Harvard University, Johns Hopkins University, Las Cumbres Observatory, the Max Planck Institutes in Heidelberg and Munich, and a UK University consortium consisting of Durham, Edinburgh and Queen's Belfast. Edinburgh and Durham are both members of the LOFAR-UK consortium, and so researchers at these universities will have access to the Pan-STARRS data. In addition, it has been agreed that the Pan-STARRS data will be made publically available approximately 1 year after the end of the survey (i.e., in about 2012), which is a timescale comparable to that on which LOFAR will be producing significant quantities of sky survey data.

In advance of this time, in collaboration with Dutch researchers, LOFAR-UK researchers (PI: Jarvis) are also proposing to use the WFI on the INT in i', r' and g' bands, to survey 18 square degrees (initially) of the LOFAR-deep survey that will also be surveyed at $1.4\,\text{GHz}$ using WSRT (see below). These observations will reach depths of $i' \approx 24.4$, $r' \approx 24.6$ and $g' \approx 25$, which are sufficient to detect old passively evolving massive ellipticals out to $z > 2$, and also to provide colours for the (typically flat spectrum) star forming galaxies and faint quasars. These data will allow early exploitation of the WSRT and LOFAR data.

Deep optical and near-IR data are essential for full optimisation of the LOFAR-deep survey because:

- We need to locate objects in 3D, requiring some sort of photometric redshifts. For LOFAR AGN, the well-known tightness of the $K - z$ relation (Figure 10a) – i.e. the fact that radio jets emerge from only the most massive galaxies (e.g., McLure et al., 2004) – means that a K data point alone is sufficient to provide a photometric redshift; for LOFAR starbursts, K plus optical will largely suffice.
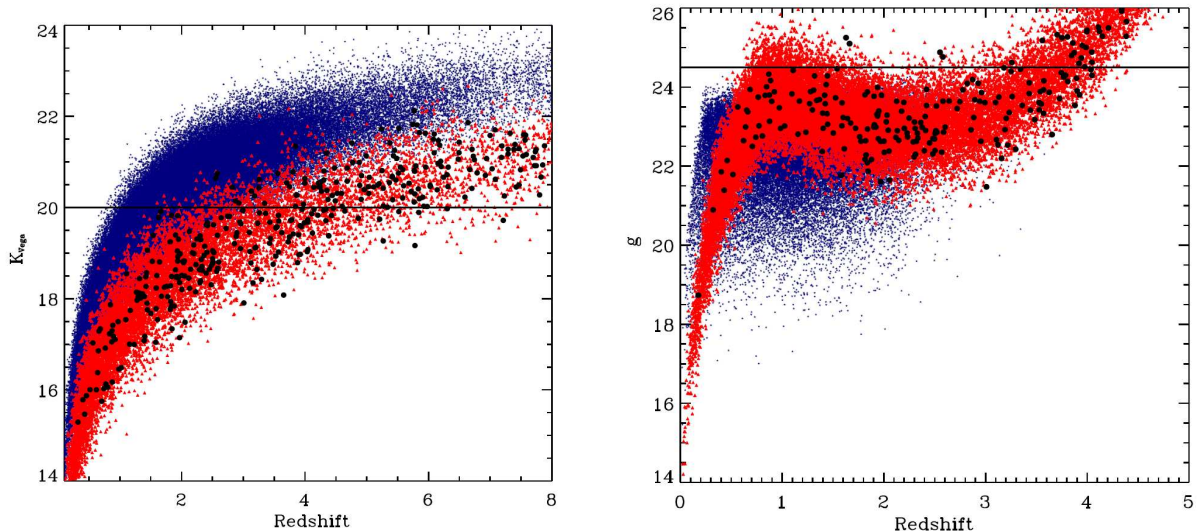
Figure 10: *Left:* A simulated $K - z$ (near-IR Hubble) diagram for 1 deg^2 (100 deg^2 for FR IIs) of the 'LOFAR-deep' survey. The LOFAR sources are separated into three sub-populations (see Jarvis & Rawlings, 2004): starbursts (blue); FR I radio galaxies (red); and FR II radio galaxies (black). LOFAR will also detect radio–quiet quasars (RQQs), which for clarity are not plotted [Type-2 RQQs will follow the locus of the FR Is; Type-1 RQQs will be brighter and be detected as sources with large point-source contributions]. The horizontal line shows the practical limit for WFCAM imaging over a ∼250 square degree area; to this limit essentially all FR Is (and RQQs) would have detections to $z \sim 2.5$. Any FR IIs (a fact determinable from radio data alone) with no K–band counterpart to $K \approx 20$ will have large redshift. *Right:* A simulated $g - z$ diagram for these same sources. The horizontal line shows the approximate limit of both the Pan-STARRS 3π survey and the proposed INT optical observations. In observations to these limits essentially all FR Is (and RQQs) would be detected at both K and g (and i), yielding, via a slight variant of the BZK method (Daddi et al., 2004), accurate photometric redshifts below $z \approx 1.2$ and a clear separation between 'red and dead' FR Is and blue starbursts in the $1.2 < z < 3$ regime. The hard upper edge to the blue points is an artefact of the simplistic modelling of the relationship between radio and (rest-frame) UV flux.

- With ∼arcsecond beam sizes and complicated radio source structures (e.g., Simpson et al., 2006), reliable 'follow-up' spectroscopy of LOFAR sources with fibre instruments like FMOS would be inefficient without optical or near-IR identifications.

- A fundamental property of any astronomical object is its mass. The K-band traces old stellar populations so that K-band selection broadly maps onto a stellar-mass selection criterion. On the scales of galaxies, this is a good proxy for halo (dark-matter) mass selection.

- Optical and near-IR data allow a characterisation of the environments of the radio sources (e.g., Stanford et al., 2005; van Breukelen et al., 2006; Strazzullo et al., 2006). Near–IR data reaching $K \sim 20$ would allow sub-L_* luminosities to be probed at $z < 2$, and thus offer a sensitivity which reaches well below those of the richest clusters detected by X-ray and Sunyaev Zel'dovich (SZ) surveys.

5.1.2   Westerbork and GMRT surveys of LOFAR deep

LOFAR-UK and LOFAR-NL have begun jointly to survey 18 square degrees of the LOFAR deep field region using the Westerbork telescope at 1.4 GHz, to a roughly uniform rms sensitivity of 11μJy. This will provide $\gtrsim 1\sigma$ detections of the majority of $S_{200\text{MHz}} \gtrsim 30 \mu$Jy source in the deep LOFAR surveys. The LOFAR-UK consortium has agreed to manage the effort of calibrating and reducing these data, on the understanding that reduced data products will be made available to the whole LOFAR-NL + LOFAR-UK survey team prior to any science exploitation.

Although this WSRT survey covers only a subset of the region that will be surveyed by the LOFAR deep survey, the sky area is large enough to sample the full range of environments (from richest clusters to voids) over a wide range of cosmic epochs. The survey covers the northern Spitzer Wide-area InfraRed Extragalactic (SWIRE) survey regions ($\approx$ 9deg^2 in the Lockman Hole, $\approx$ 9deg^2 in Elais-N1), which are the only large sky patches in the northern sky with comprehensive multi-waveband datasets, and will therefore be likely targets of the first wide and deep LOFAR surveys. As well as the mid-IR SWIRE data (at 3.6, 4.5, 5.8, 8.0, 24.0, 70 & 160μm), deep GMRT radio data ($\sim$60μJy rms sensitivity at 610 MHz) have been taken by members of the LOFAR-UK consortium, whilst other datasets are currently being built up, or planned, and will become available for exploitation whilst the WSRT survey is underway (e.g., the UKIDSS-DXS survey in the near-IR, and the optical INT survey discussed above).

The WSRT survey will take place over the period 2007-2009, and has a number of different goals:

- In combination with the existing 610 MHz GMRT data, the WSRT data will allow the radio spectra of the brightest $\sim 10^5$ radio sources in this sky region to be determined, prior to the onset of the LOFAR surveys. These will provide an accurate sky model for calibration of the LOFAR array, greatly aiding early observations.

- In combination with the LOFAR data, the WSRT data will determine the radio spectra of the objects in the deep LOFAR surveys (both spectral indices and curvature), allowing separation of flat- and steep-spectrum objects in the deep LOFAR surveys as soon as they become available. This is an essential first step in the characterisation of the LOFAR population and will allow, with full photometric redshift information, the first robust calculation of the radio luminosity function (e.g., Dunlop & Peacock, 1990) and hence the cosmic heating effect of radio sources (e.g., Rawlings, 2003). This will also allow the isolation of rare but interesting sub-populations of objects (e.g., most distant AGN, cluster haloes etc) from the LOFAR data.

- The WSRT observations will provide a dataset deep enough to allow 'stacked' analyses of sub-populations of distant AGN and starbursts, selected in non-radio wavebands, before any LOFAR data have been taken. This will allow the generation of a full simulated LOFAR sky, deviations from which in the real data will pinpoint exotic objects quickly.

- The WSRT survey will provide an early target list for follow-up observations, for example, for spectroscopic surveys with FMOS.

Whilst the Westerbork survey will accomplish these important goals, it still only covers a small proportion of the LOFAR deep survey area. Therefore, in collaboration with Dutch researchers, the LOFAR-UK consortium has submitted (and had the first 120 hours of time allocated for) a GMRT proposal (PI: Green) to survey the entire 250 deg^2 at 610 MHz to an rms sensitivity of 70μJy. This will combine and extend the various distinct GMRT surveys that UK and Dutch researchers have so far carried out (totalling about 30 deg^2 in different well-studied regions). As with the surveys discussed above, the LOFAR-UK Universities will make fully reduced data available to the entire LOFAR consortium.

This GMRT survey will provide radio spectral index information for all of the brighter sources within the LOFAR deep survey region. Although it is impossible with GMRT to reach the same effective sensitivity level as the 200 MHz LOFAR data over such a large sky area, the GMRT survey does reach the sensitivity level required for optimal comparability with the whole suite of LOFAR surveys. LOFAR surveys at 30, 60, 120 and 200 MHz will be available over the entire 250 square degrees, and the least sensitive of these will be the 60 MHz survey. This has a (1σ) rms sensitivity of ≈ 0.33 mJy beam^{-1} which, for a typical non-thermal spectral index of 0.7, corresponds to 70μJy beam^{-1} at 610 MHz. Thus, for typical radio sources detected at each of 30, 60, 120 and 200 MHz, the GMRT data will add a valuable flux density measurement at 610 MHz.

5.2 Starforming galaxies in the deepest radio surveys

For many years, radio surveys have been known for their ability to find the rarest most powerful active galactic nuclei (AGN) out to very high redshifts, and lower power examples in the nearby Universe. However, the next generation of radio surveys conducted with the new radio telescopes will break into new parameter space for extragalactic surveys. Due to the massive increase in sensitivity of LOFAR over previous telescopes, the most numerous extragalactic sources will no longer be the AGN, but starburst galaxies. A 200 MHz LOFAR-deep survey to a 30μJy flux density limit will detect galaxies with star formation rates of $10M_\odot$ per year out to redshift $z \approx 2$, whilst objects with more extreme star formation rates of $100M_\odot$ will be detectable out to $z \sim 6$.

Using the radio-luminosity functions derived from previous low-frequency surveys for the more powerful radio source populations, such as the Fanaroff & Riley Class I and II radio galaxies (FR Is and FR IIs; Fanaroff & Riley, 1974), along with a prescription for the radio luminosity of radio-quiet quasars derived from the X-ray luminosity function of Ueda et al. (2003), we are able to estimate the contribution of the AGN to any LOFAR survey. This follows the work described in Jarvis & Rawlings (2004) for the Square Kilometre Array (SKA). Furthermore, we are also able to estimate the contribution to the total source population from star-forming galaxies using the luminosity function from Yun et al. (2001) along with an assumed evolution which ensures that the source counts at both mid- and far-infrared wavelengths are not exceeded (see Blain et al., 1999). Assuming that a deep LOFAR survey could reach an rms sensitivity of $\approx$6 μJy at 200 MHz, this would imply a total source density of around 20,000 per square degree. As shown in Figure 9b, the vast majority of these sources (about 80 per cent) will be star-forming galaxies.

An alternative method of estimating the source density and population mix expected for deep LOFAR surveys is to consider the results of existing deep radio surveys. Muxlow et al. (2005) analysed deep 1.4 GHz MERLIN and VLA observations of an 8.5×8.5 arcmin area centred upon the Hubble Deep Field North, and detected 92 radio sources to a detection threshold of 40 μJy. Around 70% of radio sources fainter than about 100μJy are associated with star-forming or composite AGN-starburst galaxies. In deep *HST* ACS z-band images of this same area, $\sim$13,000 galaxies are detected. Whilst the vast majority of these galaxies are not individually detected at radio wavelengths, it is possible to statistically detect these faint optical systems in the deep radio data. The left panel of Figure 11 shows the binned radio flux of $\sim$8000 of these sources (excluding radio sources >20μJy and all potentially confused sources) versus their optical brightness. Optical sources as faint as 25th magnitude are statistically detected at the level of a few microJansky; this is illustrated by a 'stacked' average image of the radio emission from $\sim$1000, 23rd magnitude galaxies, shown in the right panel of Figure 11. These results imply that approximately half of the $\sim$2700 galaxies brighter than 24th magnitude will have radio flux densities of greater than 4 μJy at 1.4 GHz within this 8.5×8.5 arcmin field. Assuming that the radio emission arising from this faint radio source population is related to star-formation with a radio spectral index $\sim$0.7, the LOFAR-deep survey with a detection limit of 30μJy at $\sim$200 MHz will detect a couple of tens of thousands of 'normal' star-forming galaxies per square degree.

Obviously, with these source densities, confusion becomes a major issue. This is particularly true with the current Netherlands-only LOFAR, where the spatial resolution is $\sim 3 - 4$ arcsec, limiting the depth to which any deep survey could reach. However, with UK and other international long baselines, LOFAR would be able to probe to much deeper fluxes; a deep LOFAR survey with international baselines, pushing into the confusion limit, could conceivably probe star formation rates approaching a solar mass per year at $z \sim 2$. This is a depth that will probably not be feasible with other telescopes (radio or otherwise) over such large areas of sky until the SKA is operational.

It is not only the flux density limit to which star-forming galaxies can be detected that is improved by the addition of international baselines, but also the angular resolution with which they are observed. Increasingly it is being recognised that, to understand astrophysical phenomena, a pan-
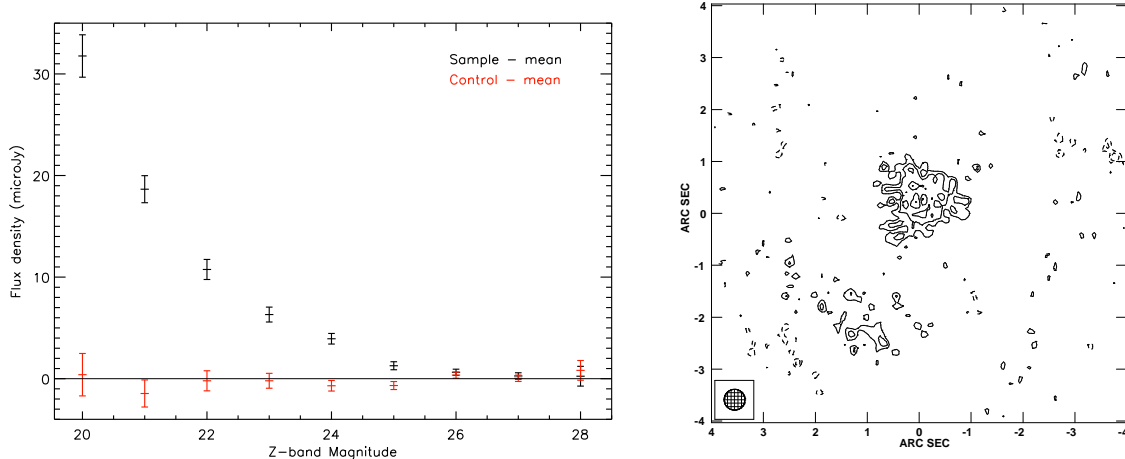
Figure 11: *Left:* Statistical detection of the μJy radio emission from >8000 optically selected galaxies within an 8.5×8.5 square arcminute field centred on the HDF-N (excluding all radio emission brighter than 20μJy beam^{-1}). Radio emission is statistically detected from galaxies brighter than magnitude 25. The red points represent a control sample of randomly selected positions away from any catalogued source. *Right:* The average radio emission from 957 galaxies in the HDF-N with magnitudes between 22.5 – 23.5. The contours are $\sqrt{2}$ times 340 nJy beam^{-1}.

chromatic view of the Universe is required. LOFAR will uniquely contribute to this view by providing high-sensitivity observations of the little-explored low frequency Universe. The radio flux density is closely related to the star formation rate (e.g., Condon, 1992), and will provide one of the most reliable ways of measuring the star formation rates of high redshift galaxies; LOFAR will thus provide an extremely powerful additional piece of information in the multi-wavelength studies of galaxy formation and evolution being undertaken using both current and next-generation astronomical instruments (e.g., e-MERLIN, EVLA, eVLBI, ALMA, NGST, VLTI, Spitzer, Herschel, Chandra, Swift, etc). In order to achieve this, however, LOFAR observations must have comparable angular resolutions to these other instruments (i.e., ideally < 1arcsec) and also must be able to be astrometrically aligned with sub-arcsecond precision. Increasingly, as higher sensitivity observations are made at all wavelengths and fields become more crowded with sources, it is essential that observations are able to both separate and correctly identify sources at different wavelengths.

5.2.1 The star-formation history of the Universe

As discussed above, a 200 MHz LOFAR-deep survey to a 30μJy flux density limit will detect galaxies with star formation rates of $10 M_\odot$ per year out to redshift $z \approx 2$, which is the epoch at which the cosmic star formation history is believed to have peaked. Combining such radio data with deep optical and near-IR data (e.g. from UKIDSS DXS) will enable considerably more detailed study of star formation at this key epoch.

In order to fully understand the basic features of galaxy formation and evolution, one must understand the volume-averaged star formation rate as a function of epoch, its distribution function within the galaxy population, and its variation with environment. Surveys of the star-formation rate as a function of epoch suggest that the star-formation rate density rises as $\sim (1+z)^4$ out to at least $z \sim 1$ (e.g. Lilly et al., 1996) then flattens around $z \sim 2$, although different star-formation indicators still give widely different measures of the integrated star-formation rate density (see Smail et al., 2002). The problem is that currently used star formation indicators either need large corrections for dust (e.g. the UV flux), large extrapolations for faint sources below the sensitivity

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limit (e.g. sub-mm sources), or are based on small-field surveys with large uncertainties due to the effects of large-scale structure and cosmic variance. Use of the radio flux density as a star formation rate indicator in wide-field LOFAR surveys would overcome all of these issues.

It is not only the global average star formation rate which is important for our understanding of galaxy formation and evolution, but more crucially the nature and distribution of the star forming galaxies at high redshifts. Many recent results point towards the star formation in the most massive galaxies occurring earlier than that in lower mass galaxies – so-called 'down-sizing', or anti-hierarchical growth (e.g. Cowie et al., 1996). Massive galaxies must therefore form stars rapidly at an early epoch, and then have their star formation truncated, for example by feedback from AGN (e.g. Bower et al., 2006; Croton et al., 2006; Best et al., 2006). Determining the characteristic mass at which star formation begins to be truncated, as a function of cosmic epoch, would determine the physical processes involved in the downsizing activity and place tight constraints upon galaxy formation models. At low redshift, the star formation rates of galaxies are also greatly influenced by the environment in which they reside, with star formation strongly suppressed in dense environments. To what extent is it the build-up of galaxies into groups and clusters since $z \sim 1$ that drives the decline in the cosmic star formation rate?

These issues can only be addressed by examining how the relationships between star-formation rate and both galaxy mass and environment evolve with redshift. Deep LOFAR radio data would provide star-formation rates for large samples of galaxies over the redshift range $z = 0$–3, across the peak star formation epoch, for which deep optical and near-IR observations (e.g. from UKIDSS, VISTA surveys, Pan-STARRS) are providing photometric redshift and stellar mass estimates, and from these also estimates of environment. Such data would provide a uniquely powerful tool for measuring the growing influence of environment on star-forming galaxies, and determining how the characteristic stellar mass of star forming galaxies changes with both environment and epoch. Such observations would yield key tests of current galaxy formation models (e.g. Benson et al., 2000; Baugh et al., 2005; Bower et al., 2006).

An extremely deep LOFAR pointing in the UKIDSS UDS or UltraVISTA COSMOS field would enable such studies to be extended back to the earliest cosmic times, $z \gtrsim 6$. The UDS will have near-IR data from WFCAM to $J = 25$, $H = 24$, $K = 23$, over 0.77 sq. deg., together with extremely deep Subaru SuprimeCam data at optical wavelengths, and longer wavelength data from Spitzer. These will permit accurate photometric redshifts and stellar mass estimates out to $z > 4$ (cf. Cirasuolo et al., 2007). UltraVISTA will have even deeper IR data from VISTA, to $Y = 26.7$, $J = 26.6$, $H = 26.1$, $K = 25.6$, over 0.75 sq. deg., together with existing deep multiwavelength data, further extending the redshift range of study. Although both of these fields are at equatorial locations, the exquisite complementary data provides a strong argument for carrying out exceptionally deep LOFAR 200MHz observations, probing into the confusion limit. Not only will this allow detection of galaxies with more typical star formation rates out to higher redshift, but also through radio stacking analyses it will be possible to determine mean star formation rates as a function of galaxy properties (redshift, mass, environment, colour, etc) out to $z \sim 6$.

5.2.2 Comparison with sub-millimetre and mid-to-far infrared surveys

The SCUBA-2 instrument for the JCMT is due to be commissioned in 2008, and will be the first large-format "CCD-like" camera for sub-millimetre astronomy. It will allow large areas of sky to be mapped simultaneously at 850 and 450μm, at speeds up to a thousand times faster than the current SCUBA camera. A number of legacy surveys will be carried out using SCUBA-2, of which the most relevant for LOFAR studies of distant starbursts is the SCUBA-2 Cosmology Survey.

In the first two-year plan, the SCUBA-2 Cosmology Survey aims to map 20 square degrees of sky at 850μm down to the confusion limit at an rms level of 0.7 mJy/beam. This survey will be carried out in fields with existing multi–wavelength data (XMM-LSS, Lockman Hole, Chandra Deep Field

South, ELAIS N1, COSMOS, and Bootes). The best weather conditions will be used to map a smaller area to a much deeper depth at 450μm (where the confusion limit is deeper due to the higher angular resolution): this will reach 0.5 mJy/beam at 450μm over 0.6 deg^2 (GOODS-N, GOODS-S, UDS, and COSMOS). Ultimately it is proposed to extend these surveys to 70 and 2 square degrees at 850 and 450μm respectively.

Deep LOFAR observations of the SCUBA-2 Cosmology Survey regions will allow the host galaxies of essentially all of the sub-mm sources to be identified. Previous radio surveys to a limit of around 7μJy/beam rms at 1.4 GHz have succeeded in identifying over two-thirds of the sub-mm sources (e.g., Ivison et al., 2007). GMRT observations at 610 MHz have demonstrated that the radio spectra of sub-mm sources show no evidence of turning over at lower radio frequencies (Ibar et al., 2007), and so 200 MHz observations to an rms level of 6μJy/beam will effectively reach a factor of ~ 5 deeper than current 1.4 GHz limits.

Radio identifications of the sub-mm sources are of great importance because they provide accurate astrometric positions of the sub-mm sources: at 850μm the beam size of the JCMT is 14 arcsec, and so without follow-up identifications it is impossible to reliably identify the host galaxy of most sub-mm sources. The international baselines of LOFAR are extremely beneficial in this respect, and in some case necessary, in order to provide sufficiently high astrometric accuracy. For example, only by using very accurate absolute positions from radio observations was it possible to identify the brightest sub-mm source in the Hubble Deep Field North (HDF850.1; Muxlow et al., 2005; Dunlop et al., 2004) with an optically faint, and extremely red, $z \sim 4$ galaxy situated within ~ 1 arcsec of several brighter, nearby elliptical galaxies (Figure 12, left panel). In addition, radio detections of the sub-mm sources provide an immediate redshift estimate, since the radio to sub-mm flux ratio is a sensitive indicator of redshift (cf. Figure 12, right panel; e.g., Carilli & Yun, 1999). This is because of the strong positive k-correction at sub-mm wavelengths.

The radio data will be equally valuable in identifying sources detected by the Spitzer, Herschel and Akari satellites. Spitzer is currently operational, and there is strong UK involvement in the
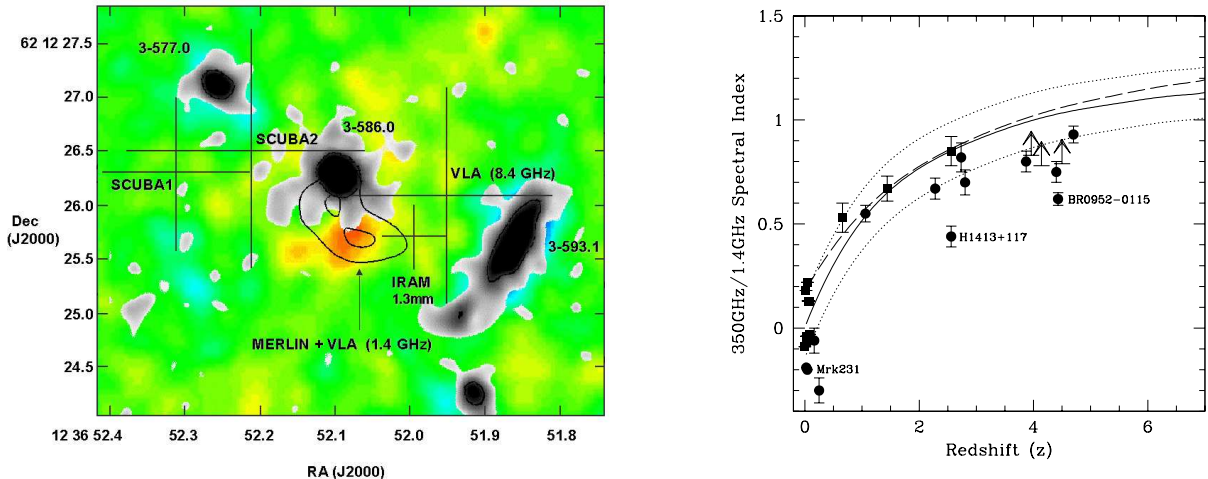
Figure 12: *Left:* Positional information on HDF850.1, overlaid on a $K - I$ colour image of the field (from Dunlop et al., 2004). The SCUBA1 and SCUBA2 crosses represent position estimates from two different reductions of the SCUBA data. The positions from VLA 8.4 GHz and IRAM PdB 1.3 mm detections are also shown. In all cases the size of the cross indicates the 1σ error in the relevant position. The contours show a high resolution MERLIN+VLA 1.4 GHz radio map. Only with this sub-arcsec resolution was the host galaxy of HDF850.1 able to be associated with an optically faint extremely red galaxy. This demonstrates the need for international baselines to increase the angular resolution of LOFAR. *Right:* The modelled and observed radio to sub-mm flux ratio as a function of redshift (from Carilli & Yun, 2000). This flux ratio allows a reliable redshift estimate out to $z \sim 3$.

Spitzer SWIRE Legacy Program which has imaged over 50 square degrees in seven infrared bands between 3.6 and 160μm. Akari (previously Astro-F), a Japanese satellite with UK involvement, was launched in 2006 and has begun mapping the entire sky in 6 infrared bands from 9 to 180μm, with especially deep observations in the North Ecliptic Polar (NEP) region. The Herschel satellite is due to be launched in 2008, and will carry out deep infrared surveys between 60 and 500μm. In each of these cases, the resolution at far-IR and sub-mm wavelengths is such that high angular resolution follow-up will be essential to identify the host galaxies: LOFAR will provide this.

5.2.3 Gigamasers: pinpointing luminous starbursts at very high redshift

Powerful OH masing is relatively common amongst IR-luminous galaxies: the most recent survey (Darling & Giovanelli, 2002) found that at least a third of ultraluminous IR galaxies (ULIRGs, $L_{\rm FIR} \geq 10^{12} L_\odot$) support megamasers or gigamasers ($L_{\rm OH} \geq 10 L_\odot$ or $L_{\rm OH} \geq 10^3 L_\odot$, respectively). If starbursts are responsible for a significant fraction of the luminosity of ultraluminous and hyperluminous IR galaxies, as currently thought (e.g., Farrah et al., 2002), then the associated turbulence may enable low-gain unsaturated masing (Burdyuzha & Komberg, 1990). The earliest OH maser-line observations appeared to demonstrate a quadratic relationship between OH and far-IR (FIR) luminosities, $L_{\rm OH}$ and $L_{\rm FIR}$. This is believed to be due to the abundant flux of FIR photons pumping an OH population inversion in the star-forming molecular gas (Baan, 1985, 1989). Since FIR and radio luminosities ($L_{\rm rad}$) are well correlated (e.g., Helou et al., 1986), emission stimulated by the background radio continuum would then yield $L_{\rm OH} \propto L_{\rm FIR} L_{\rm rad} \propto L_{\rm FIR}^2$.

Townsend et al. (2001) argued that this quadratic dependence would yield OH masers detectable amongst the high-redshift sub-mm galaxy population, with peak luminosity densities up to two orders of magnitude greater than those seen in current samples. This would allow us to determine an accurate and relatively unbiased redshift distribution for sub-mm galaxies, as well as constraining the mass of their black holes, determining their geometric distances, and even probing the evolution of fundamental constants (e.g., Barvainis & Antonucci, 2005; Lo, 2005; Kanekar et al., 2005; Caproni et al., 2006). Although there remains some dispute about the precise dependence of $L_{\rm OH}$ on $L_{\rm FIR}$ — correcting large maser samples for Malmquist bias (Kandalian, 1996) favours a weaker dependence ($L_{\rm OH} \propto L_{\rm FIR}^{1.2\pm0.1}$; Darling & Giovanelli, 2002), but using a smaller, complete sample continues to suggest a quadratic relationship ($L_{\rm OH} \propto L_{\rm FIR}^{2.3\pm0.6}$; Klöckner, 2004) — it is reasonable to expect OH maser emission from a high proportion of distant starbursts, with $L_{\rm OH}$ in the range $10^{4-5} L_\odot$ for $L_{\rm FIR} \sim 10^{13} L_\odot$ and mJy-level peak flux densities.

Maser searches have clear advantages over other methods of detecting distant starbursts: i) the bandwidth requirement for blind detection of OH megamasers is low, <1 GHz ($\nu_{\rm obs} = 165$–835 MHz for $z = 1$–10), with $z \sim 7$ accessible to LOFAR at 200 MHz; ii) the instantaneous survey area is limited only by the primary beam (>1 deg^2 for an OH line search with LOFAR at 200 MHz); iii) interferometry permits some rejection of radio-frequency interference; iv) the position of an emission line can be pinpointed accurately, on the sky and in redshift space; finally, v) the dual-line 1665/1667 MHz OH spectral signature can act as a check on the line identification and the reality of detections.

Ivison (2006) tested this technique using a well-studied, FIR-luminous galaxy, with a well-determined redshift. LOFAR, with its large instantaneous bandwidth, will enable the first *blind* search for high-redshift gigamaser emission. It will capable of probing starburst galaxies at $z \sim 7$, the progenitors of the luminous quasars found by SDSS at $z \sim 6$, and will be able to do so whilst conducting its deep sky surveys. The improved angular resolution that international baselines will provide will be beneficial in determining accurate positions, to allow detailed follow-up observations of any high-redshift gigamasers discovered.

5.2.4 Extending the radio–infrared correlation to lower radio frequencies and luminosities

Over 25 years ago it became clear that the radio and global infrared emission from galaxies were tightly correlated. In the 1980s, data from the IRAS satellite demonstrated that this correlation extended over many orders of magnitude, from nearby dust-rich dwarfs to ultra-luminous infrared galaxies (ULIRGs). More recently, comparisons of observations from NASA's Spitzer IR satellite and radio observations have extended this correlation both to the mid-IR and over a still wider range of luminosities (see Figure 13; Appleton et al., 2004; Beswick et al., 2006). This correlation can be extended to even fainter luminosities ($L_{25\,\mu m} \approx 10^{20}\,\mathrm{W\,Hz^{-1}}$) by considering discrete regions within individual nearby star-forming galaxies (Murphy et al., 2006). The correlation between the radio and infrared emission arises because both are related to the star formation processes; the infrared emission is produced from dust heated by photons from young stars, while the radio emission arises from synchrotron radiation produced by the acceleration of charged particles from supernova explosions.

While recent deep field observations at radio (using MERLIN, VLA & the WSRT) and IR (primarily using Spitzer) wavelengths have made significant advances in understanding the relationship between decimetre radio emission and mid-IR emission in star-forming galaxies (both nearby galaxies and out to z~4; e.g., Garrett, 2002), the relationship between the infrared emission and that at low radio frequencies is still unexplored. LOFAR will explore the lower frequency (30-240 MHz) radio emission from millions of star-forming galaxies and, in conjunction with the current generation of IR satellites such as Spitzer, will extend the radio-IR correlation to lower radio frequencies and luminosities, allowing the investigation of any evolution of this relationship with redshift, luminosity and radio frequency.

Although surveys using LOFAR with 100 km baselines would be able to detect a large number of sources and contribute to this work, the lack of resolution will result in the confusion limit being quickly reached and hence significantly reduce both the number and luminosity range of sources that can be observed. The addition of international baselines would be of great benefit.
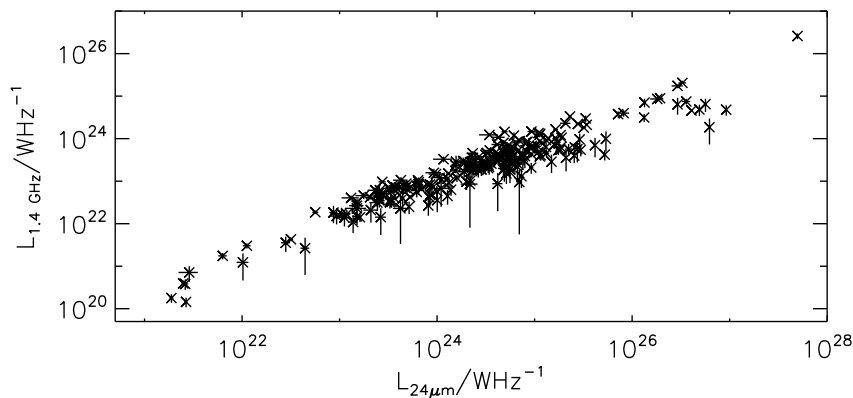

Figure 13: The 20 cm radio versus 24 μm IR luminosity correlation for 24 μm selected Spitzer sources within the Hubble Deep Field North. Luminosities have been *k*-corrected in the IR assuming a SED slope equivalent to Arp220 and in the radio assuming a $(1+z)^{0.7}$ boosting (from Beswick et al., 2006).

5.3 Radio–loud AGN and their influence on galaxies and the large–scale environment

It is now crystal clear that even the most basic features of the local galaxy population, such as its luminosity function, cannot be understood by studying stellar populations in isolation. It has become apparent that AGN play a key role in galaxy evolution, with AGN outflows being responsible for controlling or terminating the star formation of their host galaxies. At least two modes of feedback are needed: a slow accretion mode (Croton et al., 2006; Bower et al., 2006), the observational manifestation of which is the Fanaroff & Riley (1974) Class I (FR I) radio galaxy population, and a fast accretion mode associated with quasars (e.g., Silk & Rees, 1998). To understand galaxies we need to identify and quantify the physical processes which control the AGN feedback process, including the AGN duty-cycle, as well as to determine the influence of the AGN on the large-scale properties of clusters and protoclusters. As one must study all this as a detailed function of both epoch and environment, adequate sampling of the highest redshifts and rarest environments demands the use of much larger sky areas than are available in existing 'deep fields'.

As well as delivering a transformational increase in radio survey speed, the low radio frequency of LOFAR is also liable to be crucial. Although there are many complications in the physics of radio sources (e.g., Blundell & Rawlings, 2000), it remains crudely true that the observed, as opposed to intrinsic, duty cycle of radio-jet and radio-starburst activity increases with decreasing frequency: this is because of the longer synchrotron lifetimes of the lower-energy relativistic particles probed at lower frequencies. LOFAR frequencies may well be low enough to probe all, or at least most, of both modes of AGN feedback in the observable Universe.

5.3.1 The nature and evolution of radio–AGN feedback on galaxy scales

Substantial progress in understanding the process of radio–AGN feedback in the nearby Universe has recently been made by Best et al. (2005), who combined the Sloan Digital Sky Survey (SDSS) with the NVSS and FIRST radio surveys to determine the statistical relationships between radio activity and galaxy / black hole mass. They found that the fraction of galaxies that host radio–loud AGN (with $L_{1.4\mathrm{GHz}} > 10^{23}\,\mathrm{W\,Hz}^{-1}$) is a strong function of stellar mass, rising from nearly zero below a stellar mass of $10^{10}M_{\odot}$ to more than 30% at stellar masses of $5 \times 10^{11}M_{\odot}$ (see Figure 14a). Best et al. (2005) also showed that this steep mass dependence of the radio-loud fraction mirrors the mass dependence of the expected accretion rates on to the central black hole from gas in the hot haloes surrounding massive elliptical galaxies. They argued that low luminosity radio–loud AGN are fuelled by cooling of this hot gas. Best et al. (2006) took this argument one step further by using estimates of the mechanical energy output associated with radio–loud AGN activity to calculate the time–averaged energy output associated with recurrent radio source activity in a galaxy of given mass. They showed that, for massive elliptical galaxies, the radio–source heating roughly balances the radiative energy losses from the hot gas surrounding the galaxy (Figure 14b), and that the recurrent radio–loud AGN activity may therefore offer a self-regulating feedback mechanism capable of controlling the rate of growth of galaxies.

To complete this picture, it is now essential to trace the evolution of these relations: how does the fraction of galaxies hosting a powerful radio source evolve with redshift, as a function of stellar or black hole mass?; how does the balance between radiative cooling and AGN heating vary with redshift, mass and environment? Sadler et al. (2007) have begun to address these questions by demonstrating that the radio luminosity function of luminous red galaxies (LRGs; i.e., the most massive galaxies) evolves out to $z \sim 0.5$ as $(1 + z)^2$, but further study is hampered by the lack of depth in both optical and radio datasets. The LOFAR deep survey is sufficiently deep that it will detect essentially all radio–loud AGN in the Universe out to very high redshifts. Combining these data with deep optical and/or near-infrared data, particularly those from the Pan-STARRS
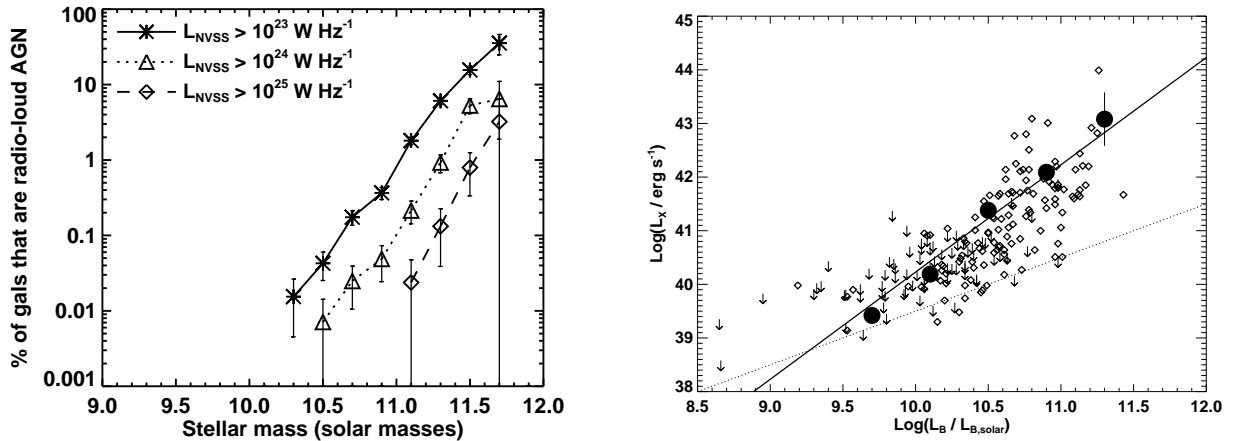
Figure 14: *Left:* the fraction of galaxies which are radio–loud AGN, as a function of stellar mass, for different cuts in radio luminosity. The radio-loud AGN fraction is a remarkably strong function of stellar or black hole mass and has the same slope at all luminosity limits (from Best et al., 2005). *Right:* The radio-AGN heating versus radiative cooling balance in elliptical galaxies (from Best et al., 2006). The data points show bolometric X-ray luminosity (L_X; the rate at which elliptical galaxies radiate energy away from their hot gas haloes), versus optical luminosity (L_B) for elliptical galaxies from the sample of O'Sullivan et al. (2001). The large filled circles show the mean values of L_X for galaxies in 5 bins of L_B. The solid line shows the prediction for the amount of heating produced by recurrent radio-loud AGN activity: this balances radiative cooling losses remarkably well, across the full range of optical luminosities (masses).

Medium Deep Survey, will provide both photometric redshifts and stellar mass estimates. It will be therefore be possible to make definitive measurements of how the mass–radio relations, the radio source duty cycle, and the heating rate vary as a function of epoch across most of the age of the Universe.

Important questions that will be addressed include:

- Do the high redshift samples show the same steep mass dependence of the radio-loud AGN fraction as the $z \sim 0$ SDSS sample (implying that the same physical processes are at work)?

- Does the location of the relations evolve with redshift? This would imply either an evolution in the efficiency of production of radio emission, or an evolution in the fuelling rate. This is the key input for parameterising AGN feedback in galaxy formation models.

- Does the balance between AGN heating and radiative cooling losses change?

The combination of sensitivity and high angular resolution offered by LOFAR (with international baselines) will also allow a more detailed investigation of the mechanisms by which AGN energy may be transferred from radio-loud AGN to their galaxy (and cluster) environments. Recent X-ray observations with Chandra and XMM-Newton have revealed that several mechanisms are in operation, including heating by strong and weak shocks and by subsonic expansion (e.g., Kraft et al., 2003; Fabian et al., 2003; Croston et al., 2003; Forman et al., 2005). To date, the only clear examples of heating by strong shocks are in massive elliptical galaxies, where small (few kpc-scale), over-pressured radio sources can inject amounts of energy comparable to the thermal energy of the galaxy ISM, permanently increasing its entropy (Kraft et al., 2003; Croton et al., 2007).

The FIRST radio survey (currently the best available) is only able to resolve these low-luminosity galaxy-scale radio sources (like Centaurus A) sufficiently that they are identifiable as double-lobed, and allow a minimum pressure to be calculated, out to redshifts $z \sim 0.04$. As such, only a small number of these sources are known, and their importance for galaxy feedback is unclear. However,

given their lifetimes of $\sim 10^6$ years, they may constitute an important population. The detection of similar radio-lobe sources in a few active spiral galaxies (e.g., Gallimore et al., 2006) increases the importance of understanding this type of low-luminosity radio outburst. LOFAR, with international baselines, will enable us to detect and resolve these radio sources to a redshift of $z \sim 0.5$, over large sky areas, enabling population statistics to be compiled for the first time. Studies of the environmental dependence of this type of radio outburst will be crucial to understand whether they are triggered by galaxy mergers (as hinted at by the examples known to date), and to constrain their impact in different host galaxy populations.

5.3.2 Feedback from FR IIs?

The local Universe SDSS surveys do not contain many sources more powerful than $L_{1.4\text{GHz}} \sim 10^{25}\text{W Hz}^{-1}$, due to the rarity of these sources and the small volume studied. Above this luminosity, most radio sources are FR IIs. The origin of the dichotomy between FR I and FR II sources is still a matter of debate, with both intrinsic properties (black hole spin or accretion flow) and the extrinsic environment (jet disruption through interactions) argued to play a role (see discussion in Snellen & Best, 2001). The strong correlation seen between radio and emission-line AGN activity in powerful FR II sources indicates that the fuelling (and hence triggering) method may be very different from that postulated for the FR I sources in the SDSS study. In such a case, it is reasonable to assume that the mass dependence of the radio–loud fraction would break down. However, this remains untested, and the role that FR II sources may play in AGN feedback is also unknown.

In addition to determining the fraction of low luminosity radio sources as a function of galaxy mass at moderate redshifts, the LOFAR surveys will provide significant samples of radio sources more powerful than the FR I – FR II divide (cf. Figure 9a). The radio–loud fraction versus mass relation for the FR II sources can therefore be determined, and compared to that of the FR I sources at the same redshift, in order both to quantify the role that the FR II sources play in AGN feedback, and also to greatly enhance our understanding of the differences between the two radio classes.

5.3.3 AGN feedback and the larger–scale environment

Gas in the central regions of clusters of galaxies often has a radiative cooling timescale very much shorter than the Hubble time. In the absence of a heating source, a cooling flow would be expected to develop, whereby the temperature in the central regions of the cluster drops and gas flows inwards at rates of up to $\sim 1000 M_\odot \text{yr}^{-1}$ (see Fabian, 1994, for a review). However, recent XMM-Newton and Chandra observations of cooling flow clusters have shown that the temperature of cluster cores does not fall below $\sim 30\%$ of that at large radii, and that the amount of cooling gas is only about 10% of that predicted for a classical cooling flow (e.g. Peterson et al., 2001; David et al., 2001; Tamura et al., 2001; Kaastra et al., 2001). This implies that some heating source must balance the radiative cooling losses, preventing the gas from cooling further.

Heating by radio sources associated with the brightest cluster galaxies (BCGs) has gained popularity in recent years, as X–ray observations have revealed bubbles and cavities in the hot intracluster medium of some clusters, coincident with the lobes of the radio sources (e.g. Böhringer et al., 1993; Carilli et al., 1994, cf. Figure 15). These are regions where relativistic radio plasma has displaced the intracluster gas, creating a low–density bubble of material in approximate pressure balance with the surrounding medium, which then rises buoyantly and expands. For some clusters the (pV) energy contained within the evacuated bubbles has been shown to be sufficient to balance the cooling losses, at least for a short period of time (a few $\times 10^7$ yr; e.g. Fabian et al., 2003; Bîrzan et al., 2004; Dunn et al., 2005).

In some clusters, such as Perseus and Hydra-A, extended cavity systems are seen, with the inner cavities filled with radio plasma but the outer cavities being radio-quiet (cf. Figure 15). These
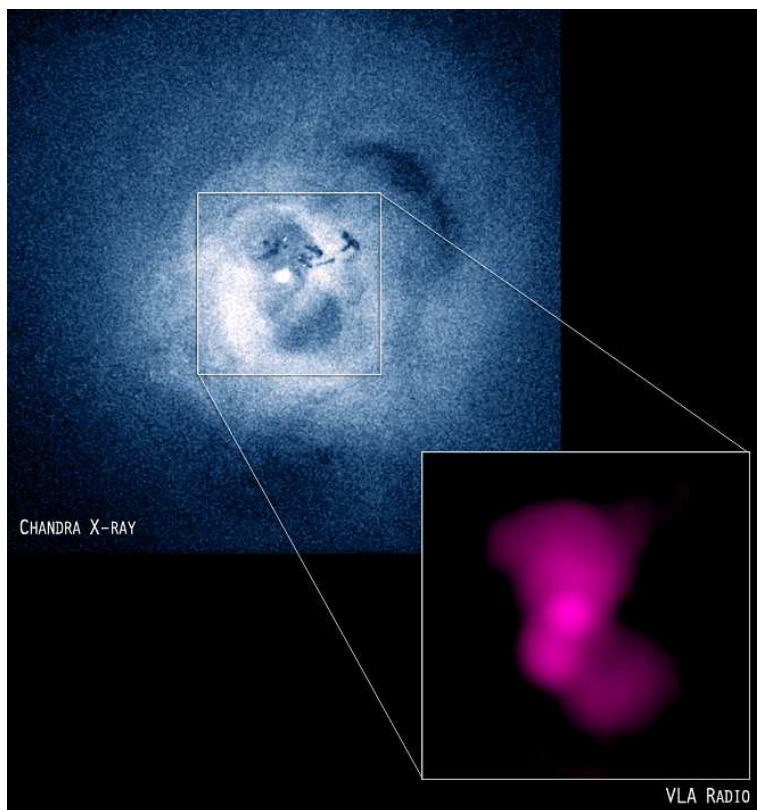
Figure 15: A Chandra X-ray image of the Perseus cluster (credit: A. Fabian) together with the 328 MHz VLA image of the same region (credit: G. Taylor). Evacuated cavities are clearly visible in the central regions of the X-ray image of the cluster, co-incident with the location of the radio emission. An older, radio-quiet, cavity is also visible towards the north-west of the cluster.

larger radius cavities may be associated with previous radio outbursts; their older ages mean that the relativistic electrons will have lower Lorentz factors, and so emit at lower frequencies: characterisation of these radio-quiet cavities using LOFAR observations will help to determine the duty cycle of the radio-AGN activity of the BCGs. LOFAR will also have the sensitivity to probe the diffuse cluster sources out to much higher redshifts, which is important to understand the evolution of clusters and cooling flows.

There are only a few high-redshift precursors of the Abell cluster population (the largest collapsed dark-matter haloes) per square degree (e.g., van Breukelen et al., 2006), but the 250 square degrees of the proposed LOFAR-deep survey is sufficient to obtain samples of ~ 25 clusters in each of ten small ($\Delta z = 0.1$) redshift bins over the range $0.5 \leq z \leq 1.5$. These proto-clusters can be identified using the near–IR and optical surveys of this region (Pan-STARRS, for example, will select clusters out to $z \approx 1$ in the 3π survey and to $z \approx 1.5$ in the Medium Deep Survey regions); the LOFAR deep survey will then enable a definitive measurement of the how the mass–radio relation, the radio source duty cycle and the heating rate vary as a function of environment and epoch. Studies using clusters selected from the SDSS data suggest that, locally, the radio–AGN feedback is stronger in richer environments (Best et al., 2007): how does this environment–activity relation evolve out to earlier cosmic epochs? These investigations are important to understand the extent to which radio AGN feedback can be responsible for the substantially lower rates of star formation activity in dense environments (cf. Rawlings & Jarvis, 2004).

We note that it is essential that the individual patches of the LOFAR deep survey are large enough to ensure that we can investigate superclustering – the clustering of these clusters. Even on half-arcminute scales the surface density of old passively evolving galaxies at high redshift varies by several tens of percent (e.g., Yamada et al., 2005), whilst significant overdensities in quasi-linear

structures on scales up to ~ 100 Mpc (corresponding to angular sizes of $\sim 2 \times 2$ deg^2 at $z \sim 1$) have previously been detected by radio surveys (Brand et al., 2003). This suggests that patch sizes of $\gtrsim 5$ by 5 degrees will be necessary and sufficient, both to detect the boundaries of individual superclusters and to measure the statistics needed to confront models with data (cf. Swinbank et al., 2007). This is an important measurement because the space density of superclusters is one of the sharpest discrepancies between theory and observation in the local Universe (Einasto et al., 2006).

5.3.4 Radio galaxy structure and electron energy distributions

To understand the large-scale energy input from radio-loud active galaxies into the IGM and into the hot baryonic atmospheres of groups and clusters of galaxies (e.g., Croton et al., 2006; Bower et al., 2006; Roychowdhury et al., 2004; Ruszkowski et al., 2001), it is vital to understand the details of the radio-loud AGN 'feedback' process: how much energy is transported by an observed AGN jet, in what form (or forms) is it stored in the observed jets and lobes, and how is it transferred to the external medium?

The observed radio-through-X-ray synchrotron and X-ray inverse-Compton emission from jets and lobes tells us that the lobes contain, at a minimum, electrons, positrons and magnetic field. The e^+e^- population is somewhat energetically dominant (e.g., Croston et al., 2005) and has a roughly power-law energy distribution with a steep index: thus the low-energy electrons completely dominate the relativistic particle component of the lobe energy density and pressure. The relativistic particles are thought to be accelerated at relatively compact sites (predominantly in the jets for low-power radio galaxies; predominantly in compact hot spots at the ends of the jets for high-power objects). The size scales of these regions are of the order of a few kpc, compared to hundreds of kpc for the large-scale lobes.

By providing arcsec-scale (kpc-scale for typical radio galaxy distances) resolution at low frequencies, LOFAR + UK long baselines will address two critically important issues. Firstly, it will allow us to observe, via synchrotron emission, the population of low-energy leptons in the lobes (with $\gamma \approx 1000$, where γ is the electron Lorentz factor) which are currently only observable by their X-ray inverse-Compton emission (e.g., Hardcastle & Croston, 2005). Direct comparisons between the structures of synchrotron and inverse-Compton emission for electrons at these energies will be possible and this will tell us about the distribution of energy density in the other component of the relativistic plasma, the magnetic field. Secondly, it will allow us to probe much lower-energy electrons in the high magnetic field regions of particle acceleration, the jets and hotspots. Existing observations hint at the possibility of a low-energy cutoff in particle acceleration at energies around $\gamma = 500 - 1000$ (Carilli et al., 1991; Hardcastle et al., 2001), but the difficulty of making these observations at high resolution means that the evidence comes from only a few bright (and atypical) sources. LOFAR will probe electron energies down to $\gamma \approx 100$ in the high-field acceleration regions of many radio sources. Measurement of the low-energy electron spectrum in the acceleration regions will not only tell us the energy spectrum that is injected into the lobes, which is required if we are to understand the energetically dominant lepton population, but also constrain the still poorly understood particle acceleration mechanism(s); this will give clues about how the bulk kinetic energy of jets is translated into the internal energy of the observed relativistic plasma. The high resolution provided by the long international baselines is vital to both problems, to allow the compact particle acceleration regions to be separated from the lobes and to allow point-to-point mapping of the lobe electron spectra and magnetic field strength. UK involvement in LOFAR will therefore enable the resolution of a number of long-standing problems in radio-galaxy physics, that are crucial to understanding galaxy feedback.

5.3.5 High redshift quasars and the link to star formation

It can be seen from Figure 9 that the LOFAR sensitivity will be adequate to detect all the quasar activity, even from so-called 'radio-quiet' quasars (RQQs), out to very high redshift. Many of these radio–quiet quasars are type-2 quasars, where the central AGN is obscured at optical wavelengths. Indeed, this population is already being discovered in small numbers by the cross-matching of deep radio (VLA / GMRT) and Spitzer catalogues (Martínez-Sansigre et al., 2005). Matching of these objects to X-ray datasets has revealed that the majority are Compton thick and either present only in the hardest X-ray bands of XMM, or absent altogether (Simpson et al., 2006; Martínez-Sansigre et al., 2007). This strongly implies that most high-redshift quasar activity has yet to be detected directly.

A near-IR survey to $K \approx 20$ will identify the host galaxies of essentially all of these radio-quiet quasars out to $z \gtrsim 2$ (see Figure 10), whilst the addition of the optical datasets will provide optical detections (and hence photometric redshifts for the type-2 objects) out to a similar redshift. This will allow accurate measurements of how the quasar activity evolves with redshift, which is vital for studies of black hole growth, quasar feedback, and the link with star formation, as well as more esoteric things like the gravitational wave background.

A prediction of all quasar feedback theories (e.g., Silk & Rees, 1998) is a strong link between quasar and starburst activity, and there is evidence that this occurs in individual objects. Coupling the LOFAR-deep survey with deep K–band data (plus probably some high-resolution radio follow-up with e-MERLIN) it will be possible to study directly, and in precise detail, how quasar activity occurs alongside star formation as a function of both epoch and environment. The radio emission of starburst galaxies measures the time-averaged star-formation rate, independent of dust, and LOFAR's sensitivity and frequency range will provide a unique resource for mapping this out across the huge areas needed to obtain representative samples of environments at each epoch.

5.3.6 Evolution of the radio luminosity function and high-redshift radio galaxies

In combination with optical and near–IR data to provide photometric redshifts out to $z \gtrsim 2$, the LOFAR surveys will enable the evolution of the radio luminosity function (RLF) to be measured down to radio luminosities an order of magnitude fainter than previous studies (cf. Clewley & Jarvis, 2004), and with a sample size two orders of magnitude larger. This will therefore provide a definitive measurement of how strongly the evolution of the RLF varies with radio luminosity: in the optical and X-ray wavebands, large differences in evolution are being found between the epoch of peak activity of high luminosity and low luminosity sources (e.g., Hasinger et al., 2005), and so determining whether the same holds for radio–loud AGN will address the question of what makes an AGN radio-loud. Comparing the cosmic evolution of the FR I and FR II radio sources at the same radio luminosity will also shed light on the origin of the different morphological classes of radio source (an intrinsic property of the central engine, or an environmental effect; cf. Snellen & Best, 2001; Rigby et al., 2007).

Another critical question is the evolution of the radio luminosity function beyond $z \approx 2.5$, where there has been much debate in the literature as to the presence or absence of a high redshift cut-off (e.g., Jarvis et al., 2001). This is important to determine because, since strong radio activity is only produced by the most massive black holes ($M \gtrsim 10^9 M_\odot$; e.g., Dunlop et al 2002), the cosmic evolution of powerful radio sources offers the cleanest way to constrain the evolution of the top end of the black-hole mass function. To a 30μJy flux density limit at $200\,$MHz, we expect to detect ~ 100 radio–loud AGN per square degree with $z \gtrsim 4$ (cf. Figure 9). Extremely deep optical and near-IR data will be available over a few tens of square degrees of the LOFAR deep survey (e.g., in the Pan-STARRS Medium Deep Field regions), producing a sample of several thousand $z > 4$ radio source candidates, identified through photometric redshifts. At these redshifts Lyα

is easily observable within the optical band, and so measuring the redshifts of candidate high-redshift sources, and thus determining the space density of radio sources at $z \sim 4$ (which would unambiguously answer the question of the high redshift cut-off), is an eminently achievable goal.

Since high-redshift radio galaxies are among the brightest known galaxies in the early Universe (De Breuck et al., 2002), follow-up studies of these $z \sim 4$ radio galaxies will constrain the evolution of such massive galaxies. Recently, it has been discovered that powerful radio galaxies are often surrounded by significant galaxy overdensities, whose structures have sizes of a few Mpc and velocity dispersions of a few hundred km s^{-1} (e.g., Venemans et al., 2002); the inferred masses of these structures are several $\times 10^{14}$ M$_\odot$, consistent with them being the precursors of rich clusters (proto-clusters). Deep optical and near-IR data are a vital starting point for studying the environments of these $z > 4$ radio galaxies, which will constrain the formation of clusters at the earliest epochs.

5.3.7 Powerful radio galaxies within the Epoch of Reionisation

Particularly interesting would be the discovery of powerful radio galaxies at $z \gtrsim 7$, since this would allow studies of the interstellar medium through redshifted 21 cm absorption studies at the end of the reionisation epoch (cf. Carilli et al., 2002). Figure 9a shows predictions for the number of FR II radio sources expected in the LOFAR-deep survey and, as this is predicated on the most reliable estimates we have for the decline in the space density of radio sources at high redshift, this is highly encouraging. Although the uncertainties in this rate of decline are extremely large (e.g., Jarvis et al., 2001), the LOFAR-deep area of 250 square degrees is large enough to virtually guarantee objects at $z \gtrsim 7$, even if the decline is, say, ten-times more severe than the current extrapolation.

These $z \gtrsim 7$ objects will be blank in the deep optical imaging and in near-IR observations to $K \approx 20$, but such datasets are deep enough that other blank–field radio sources will be rare. Since there exist radio properties that are predictive of high radio power or high redshift (FR II, steep-spectral index etc; e.g., De Breuck et al., 2000; Cruz et al., 2006, and references therein), the candidates for $z \gtrsim 7$ will be able to be promptly followed up spectroscopically on 8-m telescopes. There is therefore an excellent chance that radio-loud objects will be found in the EoR, and a chance that one will be found with a high enough radio flux density to allow H I absorption measurements with LOFAR (Carilli et al., 2002).

5.4 Cosmology with the LOFAR sky surveys

5.4.1 Spectroscopic follow-up of LOFAR-deep, and Dark Energy

The detection of the signatures of Baryon Acoustic Oscillations (BAO) at low redshift (e.g., Percival et al., 2007) has led to the realisation that they can be used to determine the dark energy component of the Universe, if better statistics can be achieved in the large cosmic volumes available at high redshift. State-of-the-art BAO surveys (e.g., with AAΩ on the Anglo-Australian telescope) are aiming to provide information on the dark energy parameter, $w(z)$, at redshifts $z \sim 0.7$. To complement this, a key future goal is to measure the BAO length-scale to an accuracy of $\sim 2\%$ at redshift $z \gtrsim 1$; to achieve this, redshifts for a well-defined sample of at least several hundred thousand galaxies will need to be measured.

The UK has a broad interest and strong scientific leadership in the study of BAO. It is also involved in the development of the required instrumentation to pursue these studies at $z \gtrsim 1$, namely the next generation of multi-object near-infrared fibre spectrographs, such as FMOS (Dalton et al., 2006) and WFMOS (Smee et al, 2006). The FMOS spectrometer, currently under commissioning at Subaru, has been built by a consortium of UK, Australian and Japanese groups, and provides a 30$'$

field sampled with 400 fibres by a pair of NIR OH-Suppression spectrographs covering $0.9-1.8\,\mu$m. Utilising emission lines like Hα, deep FMOS observations will be sensitive to even moderately ($\sim 1M_\odot$ yr^{-1}) star-forming galaxies at $z \gtrsim 1$. If the down-sizing scenario proves to be predictive, this means that FMOS will spectroscopically identify all but the most massive systems via their emission lines, whilst the most massive systems should be bright enough in continuum to allow the measurement of absorption-line redshifts. The UK–Japan agreement for FMOS means that the UK will get access to FMOS for 30% of the nights that FMOS is operational on Subaru. WFMOS will be a successor to FMOS.

The LOFAR-deep survey will provide an ideal dataset from which to select targets for BAO surveys with FMOS and WFMOS, for a number of reasons. As demonstrated in Figure 9b, LOFAR-deep delivers above the critical density dn/dz of objects (~ 2000 deg^{-2}) that is needed for power-spectrum measurements at $z \approx 1.5$ to be cosmic-variance (rather than shot-noise) limited. In addition, the objects identified are those that, through their radio emission, are known to be either starbursts or AGN, and therefore likely to have narrow Hα emission; this means that redshifts can be obtained in relatively short spectroscopic observations. Furthermore, the few hundred square degree coverage proposed for the LOFAR-deep survey is approximately the size needed to produce the required $\sim 2\%$ accuracy in the BAO length-scale measurement. Finally, the LOFAR population peaks in precisely the redshift regions to be targeted by FMOS and WFMOS. The LOFAR-deep survey can thus be an extremely valuable resource for future BAO surveys, such as the proposed joint UK / Japan / Australian FMOS survey *FastSound*.

One critical constraint on the LOFAR-deep survey for BAO work, however, is that because the angular scale of BAOs is relatively large (around 2.5 degrees at $z \sim 1$) contiguous regions of at least 5 by 5 square degrees are required, and even larger regions are preferable. In order to avoid aliasing issues, it is better if the deep fields are nearly symmetrical, and for optimal follow-up the fields should be widely spread in right ascension.

Optical and near-IR surveys of the LOFAR-deep regions play two crucial roles with regard to BAO studies. Firstly, they will provide accurate positions for each LOFAR source, allowing precise positioning of spectroscopic fibres. Secondly, they can be used to select $z > 1$ blue emission-line targets, whilst ensuring that a narrow range of mass (constant K at a given z) is targeted. This is important as mixing populations of different, unknown, bias could easily distort the BAO features in the power spectrum.

5.4.2 Strong gravitational lensing

Strong-gravitational lenses are systems in which the gravitational field of a foreground galaxy multiply images a background source. They are important because studies of lens systems probe mass profiles of galaxies, including the dark matter, and are beginning to give us major insights into galaxy structure and evolution. For example, on the scale of a few kiloparsecs, lensing studies, in some cases together with stellar dynamical information, have shown that the total (baryonic + dark) mass profiles of $z \sim 0.5$ galaxies are approximately isothermal (e.g., Cohn et al., 2001; Wucknitz et al., 2004; Koopmans et al., 2006). We are even at the stage where the light and dark matter profiles may be separable using combined HST imaging and lensing studies (e.g., Warren & Dye, 2005).

About 120 lens systems are currently known. The largest number ($\sim$40) have been discovered in the Sloan Lens ACS (SLACS) survey (Bolton et al., 2006) based on identification of multiple-redshift systems in the SDSS. A further $\sim$40 have been discovered in radio surveys, the largest number (22) in the Cosmic Lens All-Sky Survey (CLASS) of flat-spectrum radio sources (Myers et al., 2003; Browne et al., 2003). SLACS survey lenses are well suited for mass profiles, since the background sources are extended; CLASS lenses have been used for mass determinations but also, via variability studies, for extraction of the Hubble constant (e.g., Biggs et al., 1999; Fassnacht

et al, 2000; Wucknitz et al., 2004).

Although they make up one-third of known lens systems (a fraction which will decrease in the short term as surveys such as SLACS and CFHTLS increase) radio lenses are very important in two major areas.

First, CDM simulations of galaxy formation are just beginning to have the resolution to probe sub-galactic scales and make predictions about the internal structure of galaxies. For example, they over-predict the number of Galactic satellites (Moore et al., 1999; Klypin, 1999) and an immense amount of work has been devoted to understanding this. Recent work (e.g., Moore et al., 2006) has addressed the important role of baryons in the centres of galaxies, and secure theoretical predictions may be available in the next decade. Gravitational lenses are vitally important for providing observational tests of these theories, as they are the only way of detecting lumpy dark-matter substructure in $z \sim 0.5$ galaxies. This is possible because lumps of dark matter close to the line of sight to a lensed image will perturb its position and, especially, its magnification in such a way that the lens can no longer be modelled by a simple, smooth model (Mao & Schneider, 1998; Dalal & Kochanek, 2002; Metcalf, 2002). Radio lenses are important here because the fluxes of the components are much less affected by micro-lensing by stars in the lens galaxy, because radio sources are bigger than optical quasars. The big problem is the small number (8) of four-image radio lenses. A larger sample is urgently needed for progress in this area.

Second, images forming close to the centre of the lens galaxy allow probes of its gravitational potential within the central $100\,\mathrm{pc}$ (Wallington & Narayan, 1993; Rusin et al., 2001; Winn et al., 2003). This is only possible in radio lenses, as the optical picture is contaminated by light from the lensing galaxy. The lensed image becomes stronger as the central potential becomes less singular, and this therefore offers a probe of the steepness of the central stellar cusp together with the mass of the central black hole. Furthermore, central black holes may produce additional images which, if detectable, measure black hole masses more directly.

In terms of practicalities, about 1 in 700 radio sources at $z \geq 1$ are lensed. The major requirement for a radio survey is therefore a large number of sources, which LOFAR will provide: in 10^8 sources one expects 100,000 lenses. Direct identification of the lenses requires high angular resolution, however, since the typical separation of lensed images is only about $0.5''$: the higher the resolution, the more lenses will be identified. Surveys at lower (2-$3''$) resolution are still useful, and in conjunction with optical data can be used to vastly increase the efficiency of targeted searches with the EVLA/e-MERLIN (Jackson & Browne, 2007), but surveys with long-baseline LOFAR with $\sim 1''$ resolution could be expected to find many lens systems directly. How many could be found immediately depends critically on the stability of the PSF, but it is likely that between 50 and 100 systems would be found straightforwardly (Jackson, 2002; Wucknitz et al., 2006). Note that direct surveys with the EVLA, limited to 1 in 700 efficiency, cannot be done without unreasonably large amounts of observing time. Pre-filtering using a large-area LOFAR survey with long baselines could increase the efficiency by an estimated factor of 10, making a further EVLA survey practical.

5.4.3 Weak lensing with LOFAR

Weak gravitational lensing represents an important tool for probing the dark matter distribution in the Universe. Background galaxy images are distorted (sheared, or flexed) by the gravitational potential of the intervening dark matter distribution, causing an overall alignment in the appearance of galaxy images at all wavelengths. This allows detailed measurements of the projected gravitational potential throughout a vast (typically $z = 0 \rightarrow 1$) region of the cosmos. Furthermore, one can examine the dark matter profile of mass concentrations in the Universe, such as galaxies and clusters (e.g., Hoekstra et al., 2004).

Weak lensing provides a surprising variety of cosmological information on a wide range of scales.

It affords measurements of the overall density of dark matter (e.g., Brown et al., 2003) and dark energy (Heavens et al., 2006); equally, it has recently been shown that higher-order (flexion) weak lensing statistics can efficiently probe small-scale structure on the scale of tens of kpc (Bacon et al., 2006). In addition, correlations between lensing-based dark matter maps and light maps will allow detailed understanding of galaxy bias (Taylor, 2004).

LOFAR is potentially well-placed to explore the dark matter distribution using weak lensing, as it is able to observe a substantial density of background sources ($n \simeq 30$ per square arcmin at 200 MHz, $n \simeq 10$ per square arcmin at 120 MHz) on which lensing can be measured. However, galaxy shape information needs to be accurately assessed in this technique, and this will not be possible with standard LOFAR. A Netherlands-only LOFAR has a beam size of 3–4 arcsec at 200MHz (~ 6 arcsec at 120MHz), which is much larger than the typical size of the radio sources that will dominate the deep LOFAR surveys: Muxlow et al. (2005) showed that the extremely faint radio sources in the Hubble Deep Field and Flanking Fields (1.4 GHz flux densities down to 40μJy) have angular sizes in the range 0.2 to 3 arcsec.

For this reason, there is a strong motivation from weak lensing studies for a UK contribution expanding the baseline of LOFAR to ~ 1000km. This would lead to a beam size of $\simeq 0.5$arcsec at 200MHz, providing sharper galaxy shape information than is available with any ground-based optical lensing survey. Even at 120MHz, the beam size would be sub-arcsec, comparable to the effective PSF for most optical surveys (c.f. CFHTLS, Hoekstra et al., 2006).

In addition, the large survey areas projected for LOFAR will make its lensing results competitive with the next generation of optical lensing surveys (e.g., Pan-STARRS). Two LOFAR surveys in particular are of interest. Firstly, 120 and 200 MHz surveys covering 2π steradians, with reasonable source density and beam size described above, will allow a full-sky map of the projected dark matter distribution, with an accuracy equivalent to $\simeq 10^{13} M_\odot$ on 1Mpc scales at z=0.2. The shear power spectrum, simply related to the dark matter power spectrum, will additionally be measured with S/N>5 on *each mode* of the power spectrum from l=60 to 440; averaging over modes allows measurement of the power to, e.g., one percent accuracy for 10–100Mpc scales at $z = 1$.

Secondly, the deeper 200MHz survey covering 250 square degrees is also of interest: while this will not provide such accurate statistics for the overall dark matter distribution, the higher number density of sources makes this survey suitable for 3-D dark matter maps (Bacon & Taylor, 2003) and dark matter evolution studies (Bacon et al., 2005). The size of the survey makes photometric (e.g., Pan-STARRS deep surveys, WFCAM on UKIRT) and spectroscopic redshift follow-up plausible for this purpose.

5.5 LOFAR studies of local galaxies

5.5.1 Low frequency observations of nearby starburst galaxies

Starburst galaxies are galaxies which have a rapid and efficient star-formation rate which cannot be maintained for the galaxy's lifetime. The centres of these sources are generally heavily obscured at optical wavelengths by large reservoirs of dust and gas which fuel the ongoing star-formation. Observations at radio wavelengths are one of the few ways in which the on-going physical processes can be studied: supernovae, supernova remnants and compact Hɪɪ regions can all be observed at radio wavelengths. Nearby starburst galaxies provide an ideal laboratory within which large samples of these sources can be investigated.

The radio emission from starburst galaxies comprises a mixture of thermal and non-thermal radiation. At decimetric and centimetric wavelengths, the radio spectra of star-forming galaxies is dominated by non-thermal synchrotron radiation from accelerating charged particles associated with supernova explosions and supernova remnants. At higher frequencies, free-free radio emission
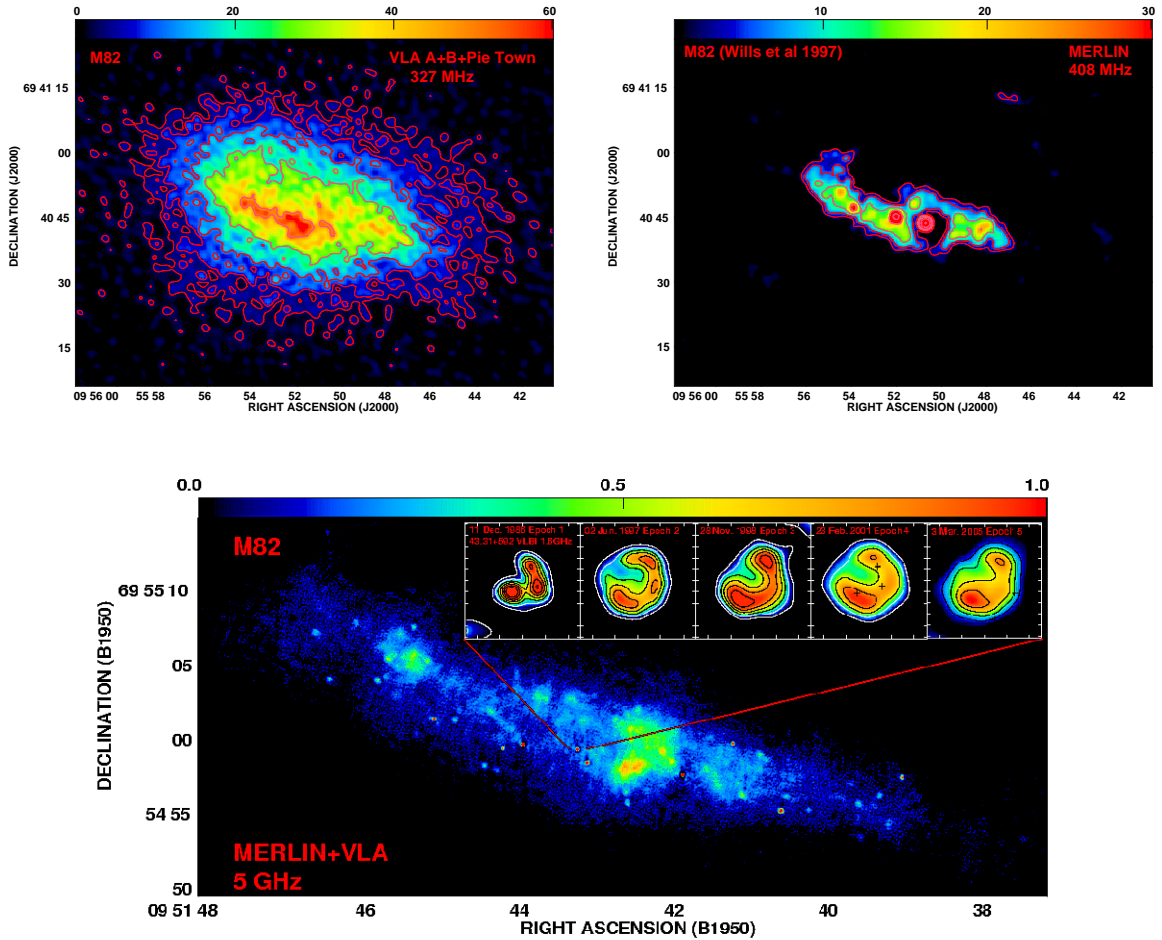
Figure 16: *Top Left:* M82 at 327 MHz with a angular resolution of ∼2 arcsec, observed with the VLA A+B configuration and including the VLBA antenna at Pie Town (Noglik, 2003). *Top Right:* A MERLIN image of M82 at 408 MHz with an angular resolution of 0.5 arcsec. *Bottom:* A combined MERLIN plus VLA 5 GHz image of M82. This image is convolved with a synthesised beam of 100 milliarcsec. Insert images show the expansion of the RSNe 43.31+592, as observed with VLBI over the last 20 years.

and emission from dust become dominant. At the lowest radio frequencies ($\lesssim 1\,$GHz) this radio emission is absorbed by intervening ionised foreground material, via free-free processes. When directly compared with higher frequency observations, observations of the radio emission in the LOFAR band can therefore be used to provide a vital high resolution probe of the ionised material in the centres of galaxies.

At 1.6 GHz, e-MERLIN will be able to observe nearby starburst galaxies at angular resolutions of ∼0.2″, with μJy sensitivities. LOFAR will provide similarly sensitive observations with (when international baselines are included) sub-arcsecond angular resolution, but, crucially, at previously unexplored low radio frequencies. The direct complementarity of these two instruments will provide a unique and powerful probe of the ionised interstellar medium in galaxies. For example, the nearby (3.2 Mpc) prototypical starburst galaxy M82 contains ∼50 compact radio sources embedded within a diffuse radio halo (see Figure 16). Currently the deepest, high-resolution, low radio frequency (327 MHz) observations made using the VLA, and including the VLBA antenna at Pie Town, are just able to begin to image the clumpy nature of the ionised foreground material within the centre of this starburst (Figure 16; Noglik, 2003). However, these observations only achieve angular resolutions of ∼2 arcsec, which is not adequate to resolve the ionised gas in fine-detail. At somewhat higher resolution (∼0.5 arcsec), but with lower sensitivity, MERLIN 408 MHz observations of M82

(Wills et al., 1997) were able to separate several of the compact radio supernova remnants from the diffuse background and hence allow the free-free absorbing column to be measured against these sources (Figure 16). However, these observations had insufficient brightness temperature sensitivity to detect all but the brightest regions of extended emission. These MERLIN and VLA studies represent the best high-resolution, low-frequency observations that can be achieved with today's radio telescopes. LOFAR will revolutionise such observations by providing a large leap in the sensitivity and angular resolution achievable at the lowest radio frequencies.

LOFAR will be able to image the radio emission of starburst galaxies like M82 in great detail between 30 and 230 MHz. When such observations are coupled with higher frequency observations, from instruments such as e-MERLIN, they will enable the free-free absorption of the foreground ionised gas within these galaxies to be mapped against the background radio continuum on linear scales of a few parsecs, as well as allowing the radio spectra of the individual compact radio sources to be determined.

5.5.2 Jet-powered radio nebulae around extragalactic microquasars

Relativistic jets in AGN are well-known for inflating lobes filled with a magnetised relativistic plasma emitting radio synchrotron radiation. X-ray binaries producing jet flows, so-called microquasars, should in principle create similar structures when their jets interact with the ISM. A few microquasars in the Galaxy seem to contain such radio synchrotron lobes (Rodríguez et al., 1992; Mirabel et al., 1993; Corbel & Fender, 2002), which have been interpreted as structures very similar to the lobes of radio galaxies (Begelman et al., 1980). However, the conditions in the ISM for the formation of radio synchrotron lobes around microquasar jets are not always favourable (Heinz, 2002). Another method of detecting the presence of jet-powered lobes is to look for the radio bremsstrahlung emitted by the shock-compressed, and at least partially ionised, ISM around the lobe surface. This technique was successful in detecting the lobe inflated by one of the jets of Cyg X-1 (Gallo et al., 2005). Detection of radio lobes can place important constraints on the time-averaged energy transport rate of microquasar jets, which are otherwise not obtainable. In the case of Cyg X-1 we now understand, thanks to the discovery of the jet-powered lobe, that the energy transported by the jets is at least comparable to the energy radiated away by the material in the accretion disc (Gallo et al., 2005).

Detecting radio lobes in the Galaxy is complicated by the expected large size of these structures, combined with the large number of confusing radio sources, e.g., HII regions, in the Galactic plane. We can, however, expect to detect radio lobes around microquasars in other galaxies, where these problems are reduced. Microquasars are likely to be associated with regions actively forming stars. Hence, even in other galaxies, their radio lobes are expected to be located close to confusing HII regions and supernova remnants. The position of microquasars in other galaxies can be obtained from X-ray observations. To then identify the radio lobes as connected to the microquasar, good spatial resolution is needed. In the case of lobes emitting sufficient synchrotron radiation, the identification is simplified due to the characteristic spectrum. This, however, requires good spatial resolution at more than a single frequency. To date, at least one example of a non-thermal radio source with properties consistent with an interpretation as a jet-powered radio lobe has been associated with an ultra-luminous X-ray source in the galaxy NGC 5408 (Soria et al., 2006).

The typical properties of the ISM and the expected jet powers of microquasars infer an expansion speed of the radio lobe of roughly $100\,\mathrm{km\,s^{-1}}$ (Kaiser et al., 2004). X-ray binaries containing an accreting black hole are expected to have typical ages of 10^6 years, thus implying a typical size of the radio lobe of around 100 pc. Placing such a source into a nearby galaxy within a distance of 10 Mpc then suggests a typical angular size of the lobe of roughly $1''$. At the highest observing frequency of LOFAR (240 MHz) resolving such a radio lobe would require a baseline of at least 260 km. Ideally we need to resolve the lobe at lower frequencies as well, which would require somewhat longer

baselines. Clearly LOFAR stations located in the UK would allow such observations, while they are impossible with LOFAR restricted to the Netherlands. Taking the radio nebula in NGC 5408 (Soria et al., 2006) as a guide, sensitivity is not an issue for these observations as the source has a flux density of roughly 0.3 mJy at 4.8 GHz, suggesting a comfortable 6 mJy at 240 MHz (assuming a spectral index of -1, as measured at GHz frequencies).

5.6   Cosmic Magnetism

Magnetic fields fill interstellar and intracluster space, and play a vitally important role in many aspects of astrophysics, from the onset of star formation to the evolution of galaxies and galaxy clusters. Despite their importance, little is still known about the origin, structure and evolution of magnetic fields. When were the first magnetic fields generated in the Universe? Are they primordial, or was their generation associated with early structure formation? How did magnetic fields evolve as galaxies evolve? These are all unanswered questions.

Radio emission offers the best probe of astrophysical magnetic fields. The intrinsic polarisation of a radio source yields information about the orientation and degree of ordering of the magnetic field. Faraday rotation of the polarisation vector as the radio wave passes through the magnetised medium between the radio source and the observer gives a view of the magnetic field along the line of sight. However, magnetic field strengths are typically weak, so only the nearest or brightest objects have so far been studied. LOFAR's high sensitivity will permit these studies to be extended into much weaker field regimes, such as galaxy haloes, galaxy clusters, and the intergalactic medium. LOFAR's multichannel spectropolarimetric capabilities will be essential in this aim, as they will enable accurate measurements of rotation measures and intrinsic polarisation position angles in a single observation in a single (up to 32MHz) frequency band.

Polarisation information in the Survey data will allow: Faraday tomography of the interstellar medium in the Milky Way and in the disks and central regions of nearby galaxies; studies of the extensions of galaxies into their halos or intergalactic space, due to the effects of interactions and galaxy winds; tracing of the full extent of magnetised halos in galaxy clusters; study of the origin of magnetic fields in the intracluster medium of galaxy clusters; measuring the magnetic fields in galaxies out to $z \sim 2$. The UK has considerable expertise in radio polarimetry, both on galactic and extragalactic scales. In addition to the scientific results that LOFAR will produce, studying the weak magnetic fields that LOFAR will see will enable UK researchers to develop the technical and scientific analysis tools that will be essential for polarisation studies with the SKA, which will be able to probe to significantly deeper depths.

6 LOFAR-UK and Radio Transients

The very wide field of view of LOFAR, particularly in the low band, makes it ideal for the discovery and monitoring of variable radio sources. This has been identified by ASTRON as a key science area for LOFAR, in the form of the Transients Key Project (Fender et al., 2006). The potential temporal scales are from microseconds to years.

The UK has a strong history and interest in variable radio sources, primarily focussed around high-energy astrophysical phenomena associated with relativistic objects such as neutron stars and black holes. The UK can also bring considerable additional benefits to the transients project, in particular due their access to the RoboNet Telescopes (the Liverpool and Faulkes telescope) which are able to acquire transient sources such as Gamma Ray Bursts within one minute of an alert being generated. RoboNet is coordinated by the Liverpool John Moores University (LJMU), which is part of the LOFAR-UK consortium. LJMU has considerable access to these telescopes, which is offered for optical follow-up of any LOFAR transients as part of LOFAR-UK's "in-kind" contribution. LOFAR-UK anticipates a clear and productive working relationship with the Dutch LOFAR Transients Key Project team.

6.1 X-ray binaries / microquasars

X-ray binaries are binary systems in which accretion of material from a more or less 'normal' companion star onto a collapsed relativistic object (neutron star or black hole) results in an enormous release of gravitational potential energy in the form of both radiation and powerful relativistic jets. These jets are ubiquitously associated with radio emission, resulting from shock-accelerated leptons spiralling in magnetic fields and producing synchrotron emission. Clear patterns of behaviour in the radio band have been linked to changes in the luminosity and 'state' (geometry and radiative efficiency of the accretion flow) of the accretor (e.g., Fender et al., 2004). Studying such objects not only provides us with valuable insight into the physics of accretion and jet formation, but has been shown to be scaleable to accretion onto Active Galactic Nuclei (e.g., McHardy et al., 2006).

We can imagine observations of X-ray binaries with LOFAR proceeding in two ways,

(a) daily monitoring of known sources (including those discovered by LOFAR itself), providing a unique resource.

(b) discovery of new X-ray binary transients in the radio band.

Procedures for the detection and identification of new X-ray binary transients with LOFAR are currently under development by the LOFAR transients project team. LOFAR will be able to both scan a large fraction of the sky daily *and* localise new transients with arcsec accuracy, by a stepwise ramping up of baselines from core to full array, and frequency from 30 to 240 MHz. It may well become the most productive source for the discovery of new transients, following the likely demise of the all-sky monitor (ASM) on-board the RXTE mission within two years.

The international baselines provided by the UK will be primarily of use in imaging the transient radio structures associated with relativistic ejection events (cf. Figure 17). Such events have been mapped on angular scales from milli-arcsec (with GHz VLBI, and beyond the capabilities of even an Europe-wide LOFAR) to several arcmin. Regularly tracking the ejecta to large angular scales will allow us to measure deceleration and shock acceleration as the jet and ISM interact and exchange energy.

UK expertise in the variable radio counterparts of X-ray binaries (also known as 'microquasars') includes phenomenological models of disc-jet coupling, and theory and modelling of outbursts and
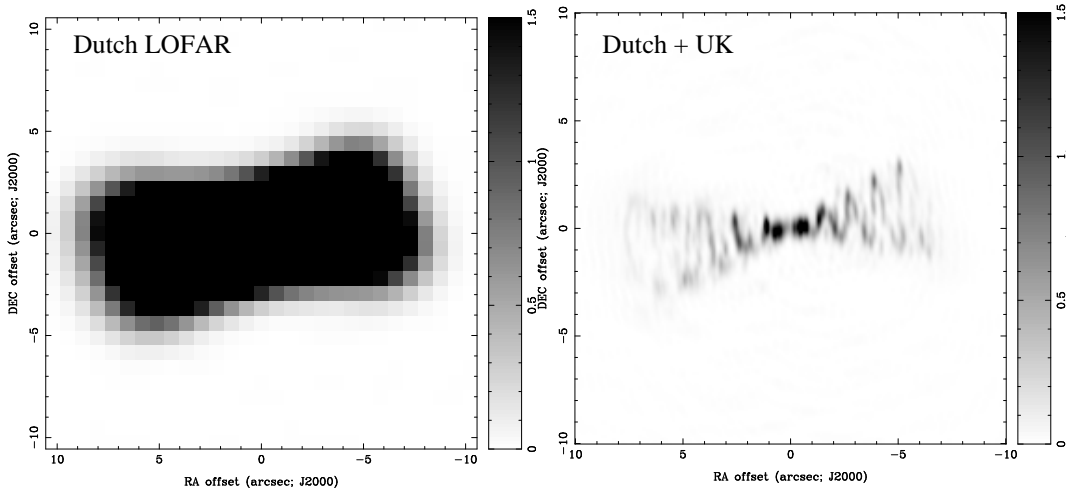
Figure 17: A simulated image of the SS433 jet, based on a 4hr exposure with a Netherlands-only LOFAR (left panel), and with the addition of UK baselines (right panel). Credit: Mark Hill and Faye Cashman.

jet formation. Observational support for UK involvement will include observations of new transients with e-MERLIN and optical to X–ray follow up with RoboNet and SWIFT.

6.2 AGN outbursts and variability

LOFAR will open up a new window for studying radio-emission from AGN in the time domain. Whilst at low frequencies the radio emission from most AGN is dominated by large-scale steep-spectrum lobes, which will be very steady in the LOFAR band on timescales of decades or longer, some AGN are highly variable on much shorter timescales (sometimes less than days). In some cases this is attributable to scintillation and/or relativistic beaming, but in other cases it is clear that variability is physically associated with the accretion/jet process itself. It is now thought that AGN jets play a crucial role in regulating the growth of massive galaxies and galaxy clusters, and variability is an essential tool to probe these jets close to their origin.

Using two bands in the ~hundred MHz range, LOFAR can cleanly separate the wavelength-dependent interstellar scintillation effects from intrinsic jet variability. LOFAR's sub-mJy sensitivity on day time-scales will enable, for the first time, the study of the variability of faint AGN jets known to exist in 'radio-quiet' AGN such as Seyfert galaxies, radio-quiet quasars and low-luminosity AGN (LLAGN), as well as hundreds of more distant and powerful radio-loud objects. X-ray studies of AGN have led to the identification of characteristic time-scales of variability, which scale with black hole mass and inversely with accretion rate (McHardy et al., 2006). With LOFAR we will determine if similar scalings hold in the radio for thousands of AGN, allowing definitive tests of how jet sizes scale with mass and accretion rate; this will provide the key physical parameters for models of how jets affect the galactic and intergalactic environments. LOFAR will also be sensitive to variability in the relativistically beamed jets of hundreds of blazars to large look-back times. We can determine whether jet variability evolves with redshift, as might be expected if the black holes are still growing, or their environment is changing.

As well as studying variability in the known AGN population, LOFAR will be sensitive to transient extragalactic sources which are impossible to find using conventional radio telescopes. For example, it has long been suspected that the 'quiescent' supermassive black holes (SMBH) harboured by every galaxy should occasionally flare up as they tidally disrupt, and then accrete, material from a star that has wandered too close. These events are sufficiently rare that, to date, only a handful of candidate events have been seen (in the X-ray band), in otherwise 'normal' galaxies. Given that

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accreting SMBH (i.e. AGN) are known to emit in the radio in the form of jets, it is likely that LOFAR will be sensitive to these stellar tidal disruption events. Tidal disruption rates are a strong function of black hole mass, and the stellar environment: measurement of these event rates will provide constraints on models for the environments close to SMBH, as well as the SMBH mass function in the local Universe. The events themselves will be of special astrophysical interest, as we watch how the accretion of the stellar remnants unfolds. The flaring emission should last for at most a few years, but can rise from zero within weeks, making LOFAR ideally suited to detecting these events compared to more sparsely sampled surveys. Given the expected frequency of stellar tidal disruption events in the local Universe, and assuming the same scaling of radio and X-ray luminosity as seen in normal AGN (e.g. Merloni et al., 2003), we expect LOFAR might detect a few tens of these events each year. This would revolutionise this whole area of research.

6.3 Gamma-ray bursts

Gamma-ray bursts (GRBs) are amongst the most luminous events in the Universe. They are short flashes of gamma rays, coming from random directions, that instantaneously outshine every other gamma-ray source in the sky including the Sun. They are currently detected at the rate of about one per day, by all-sky monitors on orbiting satellites. They are often followed by "afterglow" emission at longer wavelengths, from X–rays through to radio wavelengths.

The phenomenologically rich radio afterglows of GRBs arise from synchrotron emission from electrons accelerated in shocks, a consequence of the collision between an ultra-relativistic outflow from the GRB event – the "fireball" – and the external medium into which it expands. As such, it is a crucial indicator of the physical parameters of the blast wave, providing constraints on the energetics of the explosion itself and the density and structure of the circumburst medium with which it interacts (e.g., Wijers & Galama, 1999). Despite synchrotron self-absorption limiting the low-frequency visibility of the afterglow at early times, a combination of factors nevertheless work in LOFAR's favour as an instrument for detecting and following-up GRBs.

Firstly, the afterglow evolves on a much longer timescale at lower frequencies than in the optical and X-ray regimes. Therefore, not only is one afforded a "slow-motion" view of events such as the "prompt emission" – an early ($\sim$1–2 day) flare due to a reverse shock (e.g., Kulkarni et al., 1999) whose optical equivalent occurs too rapidly ($\sim$1 minute) for systematic study – but also the evolution can be tracked out to much later times than at high frequencies. As the fireball expands, the afterglow spectral peak shifts to longer wavelengths at later times. Thus the radio afterglow does not immediately exhibit the power-law decay seen in the optical and X-rays, but rises to a peak and declines slowly thereafter. Indeed, at the lowest frequencies, the light curve does not peak until months or years after the burst. This means that LOFAR will be able to track the brightest afterglows, such as GRB030329 (Figure 18; van der Horst et al., 2007), for years after they have ceased to become visible in the optical.

Secondly, the radio component is relatively insensitive to the geometry of the relativistic fireball (Frail et al., 2000). It is thus possible to detect the more isotropic radio emission from GRBs whose high energy emission is confined to a beam that, in the majority of cases, lies out of our line of sight. Models predict that the true rate could outnumber the observed (beamed) rate by a factor $\sim$50–100 (e.g., Guetta et al., 2005). The all-sky monitoring capability of LOFAR thus provides an unbiased census of GRB beaming statistics, and a measure of their true rate.

There is also an intriguing possibility that the rate of low luminosity (and hence low redshift) bursts could be much larger (of order 100 times larger) than that of classical cosmological GRBs (Pian et al., 2006; Soderberg et al., 2006). Such a low-z burst would not be seen in gamma-rays but, even if the GRB itself is not seen (and consequently no X-ray or optical afterglow is found), it is possible to detect the radio emission from the afterglow since, at late times, the radio emission is isotropic.
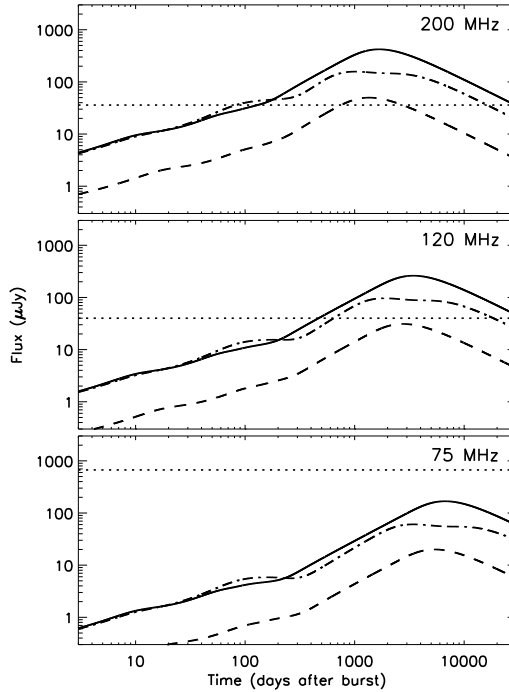
Figure 18: The predicted light curve of the $z = 0.16$ GRB 030329 at three frequencies within the LOFAR observing range (from van der Horst et al., 2007). The solid and dash-dot line correspond to two different models for the afterglow emission, whilst the dashed line gives the corresponding light curve if the GRB were located at $z = 1$. The horizontal dotted line shows the limiting sensitivity of LOFAR in a four hour integration.

Emission line spectra of the host galaxies will be within reach of 8m class telescope. This would confirm the low redshift nature of these bursts and establish whether or not they represent a class distinct from cosmological GRBs.

Bright, nearby bursts such as GRB030329 (z=0.1685) are expected to peak, at 100–200MHz, 5–10 years after the event itself, and should be detectable in this frequency range with LOFAR (Figure 18). At increasing redshift, an "inverse k-correction", analogous to that encountered for sub-mm galaxies, compensates to some extent for luminosity distance dimming, as one probes a higher rest-frequency and an earlier time in the light curve (Ciardi & Loeb, 2000). Thus, although events of the magnitude of GRB030329 are rare, the lack of dependence of radio emission on beaming geometry, combined with their detectability out to $z \sim 1$ (Figure 18) and the protracted evolution at low frequency, make it feasible that LOFAR could detect as many as 20 such bursts per year. It will also be possible to obtain accurate localisation of past bursts that have, in the LOFAR bands, yet to reach their peak. This will enable the study of afterglows that were missed in the optical, and therefore allow us to assess statistically whether the faintness of these "dark bursts" was intrinsic, or due merely to survey incompleteness. The long baselines provided by UK LOFAR stations would be particularly important in this respect, to provide high positional accuracy for the bursts.

The progenitors of short-duration GRBs are also predicted to give rise to radio flares, detection of which would be a potential test of progenitor models. The majority of short bursts are thought to result from the coalescence of either neutron-star-neutron-star or neutron-star-black-hole systems. Low frequency radio flares, which may be detectable by LOFAR, are predicted to arise from such systems in two ways: (1) currents induced by the motion, prior to coalescence, of one neutron star through the magnetic field due to the other (Hansen & Lyutikov, 2001); (2) variations in the surface currents associated with the relativistic magnetised wind flowing from the binary, which, though peaking at ∼1MHz, may have a high-frequency tail that is detectable in the low-frequency LOFAR

bands (Usov & Katz, 2000). UK researchers have developed very advanced numerical simulations of the merging of these binary systems of compact stars (e.g., Ruffert & Janka, 2001), and detailed LOFAR observations will enable testing and refinement of these models.

6.4   Pulsars and related phenomena

Pulsars are steep spectrum objects whose pulsed flux density usually peaks in the 100–200 MHz range. With an unprecedented sensitivity in exactly this frequency range, LOFAR will make an excellent instrument for studies of pulsars and their use as galactic probes. Moreover, as the emission process of pulsars is still only poorly understood, the observed radiation properties, as well as simply the presence or absence of low-frequency emission from pulsars, will serve as powerful constraints on models of the pulse emission process.

How many pulsars LOFAR will discover depends on the low-end of the pulsar luminosity function. There are indications that the luminosity function turns over in the range 0.3–$1 \, \mathrm{mJy \, kpc^2}$, but at the same time it is likely that existing (high-frequency) surveys are already incomplete at the $10 \, \mathrm{mJy \, kpc^2}$ level. The extremely high sensitivity of LOFAR will be able to measure the low-end of the pulsar luminosity function significantly better than any previous survey. Understanding this function is vital for our knowledge of how many pulsars there are, which in turn constrains the massive star population and supernova rate in the Galaxy.

Recent pulsar surveys have moved to higher and higher frequencies to escape the deleterious effects of dispersion due to the passage of the pulses through the interstellar medium. However, the natural frequency decimation of LOFAR, combined with the significant processing power available, means that these effects can be limited. This means that scattering in the interstellar medium will be the limiting factor in determining the distance to which pulsars are seen with LOFAR. Even with the most conservative estimates, one finds that a pulsar survey with LOFAR of the entire Galaxy (i.e., those parts visible from Northern Europe) will find $\approx$1500 new pulsars, almost doubling the total number of pulsars known (see Figure 19). This large addition to the known population will allow us to better test the period distribution of pulsars, which is an important ingredient in understanding supernova physics and the physics of neutron stars. LOFAR will also provide an improved spatial distribution of pulsars in the Galaxy – this is in particular true in the Northern hemisphere – and thus at distances well above and below the Galactic plane.

The apparent detection of a few pulsars only at frequencies near or below 100 MHz, and the existence of pulsars like B0943+10 (which have flux-density spectra with a spectral index steeper than -4) and millisecond pulsars (which have steep spectra which do not turnover even down to frequencies of 30 MHz; see Figure 20) suggests that there is a large number of pulsars that are detectable only at low frequencies. This behaviour could be either intrinsic to the emission mechanism of pulsars or due to geometrical effects. The latter reason seems more likely, given that the pulsar emission cone width increases at lower frequencies. Indeed, the increase in the pulsar emission cone size could become quite significant at low frequencies, leading to a large increase in the 'beaming fraction' of the illuminated sky near 100 MHz. Thus, pulsars which are not beamed towards us at higher frequencies may well be detectable at low frequencies. If there is a significant population of such sources then LOFAR will be in a unique position to detect them. Detection of these pulsars would provide an improved understanding of the emission process and a clearer understanding of the total population of radio pulsars. Moreover, the shear number of pulsars that will be discovered by LOFAR provides for the possibility that the sample will include some exotic systems, like double neutron stars, double pulsars, or pulsars with planets.

The average pulse profiles of radio pulsars are made up of the superposition of a large number of sub-pulses. These sub-pulses are believed to have a very strong link to the emission process. In some pulsars these sub-pulses are observed to drift in an organised fashion through the pulse window
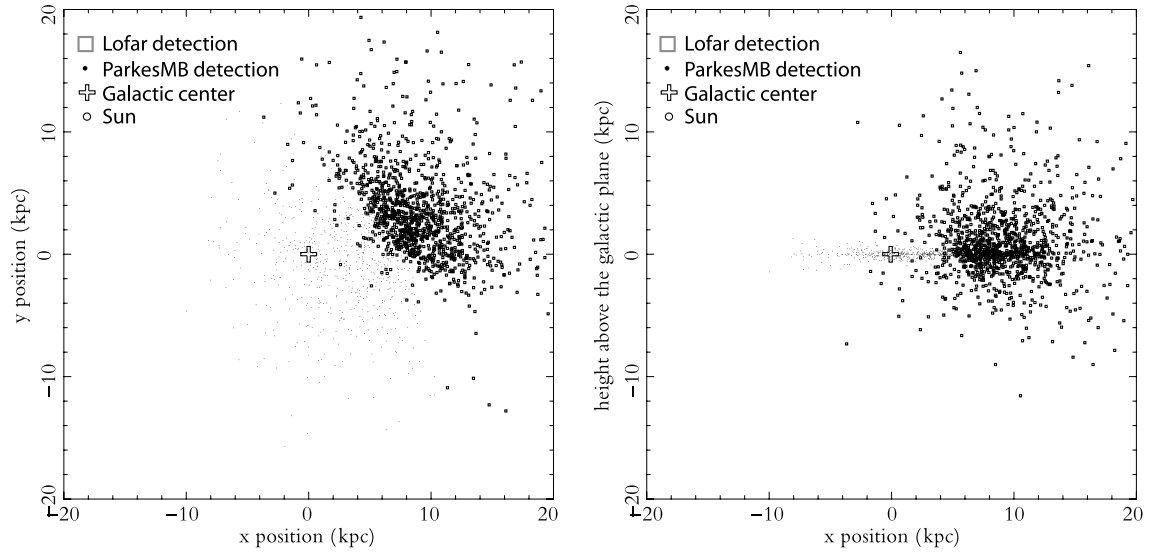
Figure 19: Simulated detections of pulsars in the LOFAR surveys (compared to Parkes Multibeam) for 1-hour LOFAR pointings. The left panel shows these projected on the Galactic plane, whilst the right panel shows them projected on the plane through the Galactic centre and sun, perpendicular to the disk (from Stappers et al., 2007).
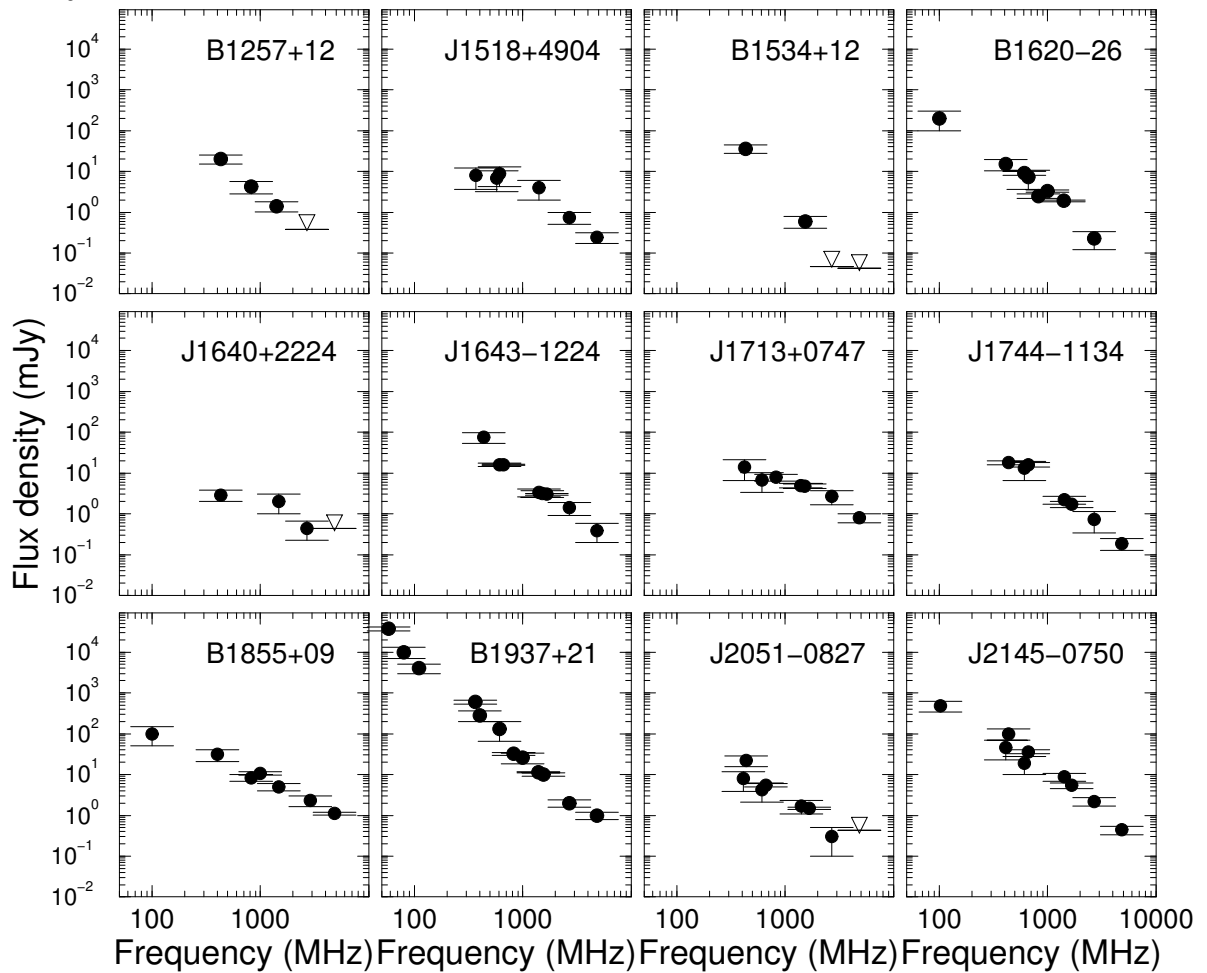
Figure 20: Example flux density spectra of millisecond pulsars (from Kramer et al., 1999), demonstrating that the flux density spectrum of many millisecond pulsars seems to continue rising to the lowest frequencies.

Figure 21: The low frequency pulse profile of a millisecond pulsar as observed with Westerbork, demonstrating that low frequency observations can be comparable to, or even better than, high frequency observations.

and this is thought to be due to properties within the pulsar magnetosphere. Some pulsars show significant frequency evolution in the properties of these drifting sub-pulses and observations at low-frequencies, which probe a very different sight line across the emission, can be used to reconstruct the d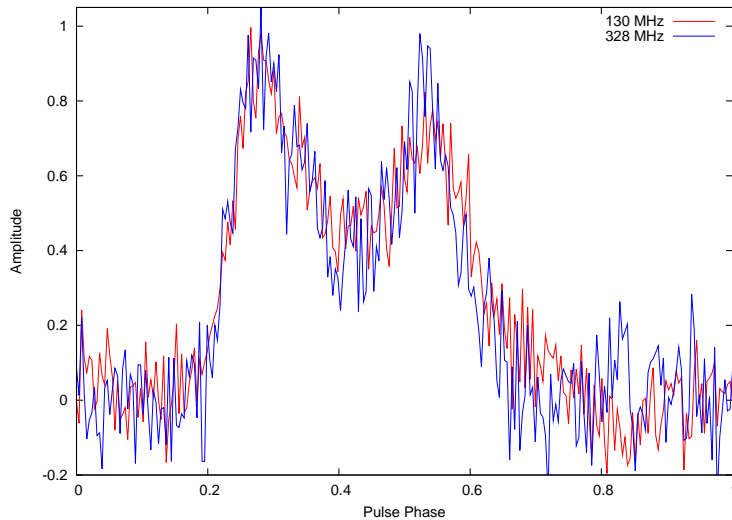istribution of emission within the magnetosphere. Greater constraints can be obtained by simultaneous observations at different frequencies across the LOFAR bands, and in combination with high frequency facilities. This will reveal how the "radius-to-frequency mapping" (i.e., the dependence of emission height on radio frequency) manifests itself in the drifting sub-pulses, and will determine whether the drifting is more or less organised at the low frequencies. There is also some evidence that both pulse intensities and drifting are less stable at low frequencies. The greatly increased sample of pulsars for which single pulse studies with LOFAR are possible will help to confirm or refute this evidence.

Single pulses from radio pulsars provide us with the best view of the emission process. The fact that LOFAR will enable us to detect single pulses from so many more sources is a great step forward. Low frequencies are particularly interesting because micro-structure (quasi-periodic emission seen in some pulsars, with periods and widths of the order of microseconds) and sub-pulses tend to be stronger at low frequencies (cf. Figure 21), where we would expect the density imbalance and plasma dynamics to be the most noticeable. Observations such as these have potentially high payoff, because they come closest to the timescales and predictions that can be made by theoretical models of the emission region. The high time resolution requirement of these observations will limit the sources because of interstellar scattering, but there are still many tens of sources for which studies can be made.

Pulsars are excellent probes of the ionised component of the interstellar medium through scintillation, dispersion measure, and Faraday rotation studies. Scintillation studies have been revolutionised in the last five years by the discovery of faint halos of scattered light extending out to 10–50 times the width of the core of the scattered image. This, in turn, gives a wide-angle view of the scattering medium with milli-arcsecond resolution, and the illuminated patch scans rapidly across the scattering material because of the high pulsar space velocity. Some of the most interesting effects are visible at low frequencies, and LOFAR's combination of sensitivity, frequency coverage, and signal flexibility are an excellent match to this new science. As such, LOFAR will also make important contributions to traditional dispersion measure and rotation measure determinations. By almost doubling the number of known pulsars, the proposed survey will add a dense grid of new sight lines through the Galaxy to those that already exist. Combining the dispersion measures of
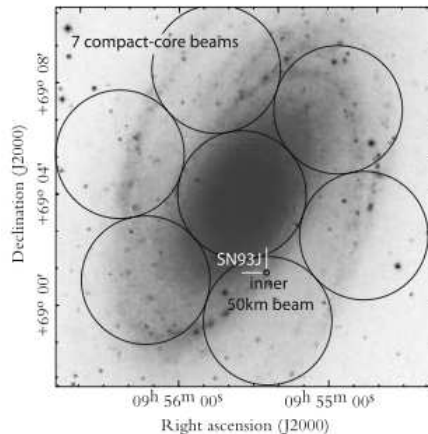
Figure 22: Coherently formed beams from the compact core and the inner 50-km of LOFAR, projected on the core of M81, the second best candidate galaxy for an extragalactic survey and the home of supernova 1993J.

this new sample with those already known will improve our global model of the distribution of the ionised ISM. Putting this together with the rotation measures of a large fraction of the new and known pulsars will place important constraints on the overall magnetic field structure of the Milky Way, which is still not well characterised. At LOFAR frequencies it is also possible to determine the very small rotation measures of the nearby population of pulsars, providing an unprecedented tool for studying the local magnetic field structure. The large number of new sight lines will also allow statistical studies of small-scale fluctuations of electron density and magnetic field variations.

6.4.1 Extragalactic pulsars

Due to its sensitivity, LOFAR can be the first telescope to find extragalactic pulsars, besides those in the Magellanic Clouds (cf. Figure 22). If spiral and irregular galaxies (which will host young, bright, Crab-like pulsars) are observed face-on and located away from the Galactic disk, the scatter broadening will be relatively low and a LOFAR survey will have excellent sensitivity for pulsars of all spin periods. There are at least 20 galaxies for which LOFAR will have good sensitivity to their pulsar population: for a relatively close galaxy like M33, LOFAR could detect all pulsars more luminous than 50Jy kpc^2, above which level the Milky Way hosts 10 pulsars. Complementary to this normal pulsar emission, some pulsars show ultra-bright 'giant pulses' that could be visible in even more remote galaxies (e.g. McLaughlin & Cordes, 2003).

A survey for extragalactic pulsars would allow us to investigate if the bright end of the pulsar distribution in other galaxies differs from that in our galaxy, and how the pulsar distribution depends upon galaxy type and star formation history. Extragalactic pulsars can also help the understanding of the missing baryon problem, the history of massive star formation in these galaxies and also, if sufficient numbers can be found, they can be used to probe the turbulent intergalactic medium.

6.5 Extrasolar planets

Extrasolar planets is one of the most dynamic and exciting areas of astrophysics, engaging both astronomers and the general public. New discoveries as to the structure and formation of extrasolar planets are being made at a rapid rate, and LOFAR will make important advances in this field, particularly concerning the magnetic field and magnetosphere of extrasolar planets.

As of March 2007, there are over 200 known extrasolar planets, with orbital periods ranging from

just over 1 day up to several years. The derived planetary masses range from around 6 Earth masses up to the brown dwarf limit. A significant number of these planets also have high orbital eccentricities, and it is clear that many of the extrasolar planetary systems are rather different from the solar system.

With LOFAR we expect to detect the magnetospheres of extrasolar planets, and this will give us a unique chance to investigate the magnetic field strengths of extrasolar planets, planetary rotation (which may be very difficult to access via any other means), and also possibly the presence of moons orbiting the planet. We expect to do this based on extrapolations from the solar system, where 5 planets (the Earth and the 4 giant planets) have been detected at low frequencies, either from the ground or from space-based observations. The radio emission from the solar system planets is coupled to the solar wind, and the radio flux is proportional to the amount of solar wind incident on the planetary magnetosphere. Consequently, the level of radio emission depends on planetary parameters, such as the magnetic moment and the orbital period (which determines how much solar wind is incident on the magnetosphere), and also stellar parameters (such as the solar wind mass-loss rate and wind velocity).

The low frequency radio emission is due to electron cyclotron maser emission, with an upper cut-off frequency determined by the magnetic field strength close to the surface of the planet. For Jupiter, emission is observed extending up to around 40 MHz, and the Jovian low frequency emission was one of the early surprises of radio astronomy. For the other planets the emission is at frequencies below the ionospheric cut-off frequency for the Earth, and these have only been detected from space. We expect the frequency of emission from extrasolar planets to be related to planetary mass, with higher mass planets having emission extending up to higher frequencies. Further to this, the electron cyclotron maser may also play a role in the poorly understood radio emission from brown dwarfs (Hallinan et al., 2006), where the masses are higher and the emission is at GHz frequencies.

We can easily estimate the level of radio flux by using the measured flux from the solar system objects (most notably Jupiter) and using parameters appropriate for the extrasolar planetary systems (see, for example, Lazio et al., 2004; Stevens, 2005). We expect the brightest exoplanets to have fluxes in the range of a few mJy and for a substantial number to have fluxes accessible with LOFAR. The highest level of emission is expected to come from massive planets, orbiting at short periods around stars with strong stellar winds (which translates to younger stars). The very short period planets will be tidally locked and this may affect the level of radio emission (and this would be one aspect where LOFAR will make a contribution).

In addition to studying known extrasolar planets, there is also the aspect of serendipitous detection of extrasolar planets. We expect the emission to be primarily in the range of 10-150 MHz, to be broad-band in nature, and also to show strong bursts. There have been several searches for extrasolar planets at 150MHz (using the GMRT) and the VLA (74MHz) but no detections have been made (Farrell et al., 2002; George et al., 2007). One possible problem is distinguishing between emission from the star and from the planet. This will be achievable because we expect the planetary emission to be highly polarised, while the stellar emission will not be.

The initial goal of using LOFAR in the study of extrasolar planets will be to obtain a number of detections of the known extrasolar planets. Using these, we can investigate the systematics of low frequency radio emission from planets outside our solar system. Once we have a number of measurements of each planet then, by analogy with Jupiter, we can investigate the presence of periodicities, which are indicators of planetary rotation and the presence of moons (Io in the case of Jupiter). Whether we can disentangle these without additional information may be challenging. The wide spectral band of LOFAR will be important in understanding the magnetospheres of extrasolar planets. Identifying the high frequency emission cut-off will enable us to determine the magnetic field strength and magnetic moment of extrasolar planets (assuming the spectral characteristics are similar to those of solar system objects), which are not accessible by other

means.

In summary, we confidently expect to detect a number of extrasolar planets with LOFAR, opening up a new field of study. These detections will enable us to investigate extrasolar planets in ways that are simply not possible at other wavelengths. In addition, we are confident (and hopeful) that the low frequency radio emission from extrasolar planets will throw up a number of surprises.

6.6 Search for Extraterrestrial Intelligence

It is generally believed that communications from an extraterrestrial intelligence will come in two forms. The first may be a civilisation more advanced than ours, that has the technology and power to broadcast signals across the Galaxy specifically for others to detect (a "beacon"). The second are technologically younger civilisations, like ours, that are just beginning to use advanced communications which are leaking into space for others to eavesdrop on. As outlined in Penny (2004), radio frequencies are the most natural place to look for both types of signal and, therefore, a majority of past, present and future searches for extraterrestrial intelligence are in the radio (microwave) range of the electromagnetic spectrum.

The most ambitious search for extraterrestrial beacons was the Phoenix Project, which ran for nearly ten years (from 1995 to 2004), and observed 800 stars (out to 240 light years) with Arecibo, Parkes and the Green Bank Telescopes (1.2 - 3 GHz ranges). Alternatively, the BETA project used a 26m radio telescope to perform an all-sky, narrow-band, microwave search for extraterrestrial beacons in the so-called "Water Hole" from 1400 to 1720 MHz (a radio–quiet region between the hydrogen line and the strongest hydroxyl line). In both cases, no unusual radio signals were detected.

The future for the Search for Extraterrestrial Intelligence (SETI) is to push beyond our nearest stars, and survey a much larger volume of our Galaxy. We already know from the detection of hundreds of extra–solar planets, that other planetary systems exist relatively nearby, e.g., the nearest known extra-solar planet is only 10.5 light years away around a sun-like star called Epsilon Eridani. The number of such systems will increase rapidly with new missions like Kepler, which is predicted to find up to 640 inner-orbit planets by monitoring 10^5 nearby main–sequence stars; ~ 35 of these will be Earth-like planets in the habitable zone (see Perryman et al., 2005). Therefore, it is possible that life does exist relatively nearby.

The next generation of SETI experiments will soon be underway with the full Allen Telescope Array (ATA; 350 antennas) becoming operational in 2008. The ATA plans to survey 10^6 stars out to 900 light years for extraterrestrial signals within the range of 1 to 10 GHz. Beyond the ATA, the Square Kilometre Array (SKA) should provide the sensitivity to explore up to 10^8 stars looking for powerful radio signals similar to those presently used by humans (see Tarter, 2004; Penny, 2004).

Recently, Loeb & Zaldarriaga (2007, LZ07) have raised the issue of looking for extraterrestrial intelligence in the 100 MHz regime of the radio spectrum, rather than at GHz frequencies around the 21cm hydrogen line (as with ATA and the Phoenix Project above). The rationale for this idea is two-fold. First, humans communicate mostly in the 100 MHz regime, e.g., through television and radio. Second, the search for the "Epoch of Reionisation" (EoR) has pushed the next generation of radio observatories (MWA-LFD, PAST, LOFAR) towards large surveys in the 80–300 MHz range, to detect redshifted 21cm emission from the first galaxies at $z \sim 6$ to 15. LZ07 therefore note that a SETI project could "piggy-back" on such EoR surveys.

In their paper, LZ07 focus on military radar as one of the most powerful sources of radio "leakage" into space from Earth. The radar employed by the US Ballistic Missile Defence System (BMDS) can generate isotropic radiation with a total power of 2×10^9W, or two orders of magnitude higher if beamed (LZ07). Likewise, "over-the-horizon" radar, that bounces signals off the ionosphere, can reach similar power output (Tarter, 2004). Using such signals as a blueprint for possible

extraterrestrial radio emission, LZ07 predict that LOFAR could detect civilisations like ours out to a distance of ~ 70pc, containing up to $\sim 10^5$ stars.

The challenge would be finding such a signal in the LOFAR data-stream, as it would appear as a faint spectral line whose frequency would not coincide with any known atomic or molecular transition. Furthermore, the line would be Doppler shifted by both the orbital (around the star) and rotational (spin on axis) motions, as well as a possible modulation in the strength of the line if the emission was not uniformly spread over the entire surface of the planet. The emission may also be switched on and off, or be beamed "lighthouse" fashion. The detection of such an unusual signal requires new algorithms and extensive computational resources, as the analysis must run on the raw data-streams with as much frequency resolution as possible.

In summary, LOFAR has the sensitivity to detect human-like radio signals out to the nearest Sun–like planet systems. Therefore, LOFAR (alongside ATA and other 21cm surveys) will provide the first real opportunity to detect serendipitous radio emission from the communications of advanced extraterrestrial civilisations. Even if no signal is detected, a LOFAR SETI initiative would provide important training for the SKA, especially in the development of the required computational techniques and resources.

6.7 Exploration of the Unknown

The challenges outlined in the LOFAR science case are today's problems: will they still be the outstanding problems that will confront astronomers in the next decade and beyond? If history is any example, the excitement of LOFAR will not be in the old questions which are answered, but by the new questions that will be raised by the new types of observations it will permit.

Most of the phenomena we observe today using telescopes across the electromagnetic spectrum were unknown a few decades ago, and to an amazing extent were discovered by scientists using increasingly powerful instruments and following their curiosity when they found the unexpected. Examples include non-thermal radiation, radio galaxies, quasars, pulsars, gravitational lensing, cosmic evolution, extra-solar planetary systems, cosmic masers, molecular clouds, dark matter, and the cosmic microwave background. These discoveries have changed the whole face of astronomy in fundamental ways. Some discoveries came about as a result of more sensitivity, others from better spatial or temporal resolution, still others by observing in a new wavelength band or even from misguided theory. Many involved recognising a new phenomenon and being able to distinguish it from a spurious instrumental response.

How can we plan for discovery? Despite the apparent capriciousness of our aim, history tells us that a basic requirement is to carry out systematic work with one or more observing capabilities (sensitivity; spatial, temporal or spectral coverage; spatial, temporal or spectral resolution) having at least an order of magnitude improvement over what has been achieved before. LOFAR will greatly enlarge known parameter space as a result of: i) a much greater sensitivity at low radio frequencies; ii) a very large instantaneous field-of-view; iii) multiple, independently steerable, beams. The sensitivity and sky coverage advances combine to make a large the volume of space accessible – and hence the chances of finding intrinsically rare objects in large scale surveys will be much enhanced. LOFAR is therefore well-placed to make serendipitous discoveries.

LOFAR's design means that it will be a highly multiplexed instrument involving multi-beaming on a massive scale as compared with current telescopes. The multiple beams provide users with a highly flexible and responsive instrument and will inevitably lead to changes in observing style. The challenge to LOFAR is to develop a philosophy of operations and data archival which allows individuals, small groups, and larger communities the freedom to innovate, and encourages users to explore completely new ways of collecting, reducing and analysing data: in other words, to allow for discovery as well as explanation. Some possible considerations for LOFAR planners are:

- Award some time to successful groups or collaborations on the basis of their past record – a 'rolling time allocation grant' which can be sustained or closed down on the basis of performance integrated over several years.

- Allow high-risk or unproven new-style observations. The availability of independent beams will help to make this feasible without compromising conventional observing programs.

- Maintain technical expertise in the community. In the lead up to LOFAR and then the SKA, innovative research and development is re-invigorating the world-wide community and involving a new generation of engineers and students. However, when first LOFAR and then SKA are completed, it is vital to allow a cadre of technical people world-wide to gain continuous access to parts of the system for continuous experimentation.

7 Ultra-High Energy Cosmic Rays and Neutrinos with LOFAR-UK

Ultra-high energy cosmic rays (UHECRs) are predominantly protons and heavy nuclei with energies far exceeding those in terrestrial particle accelerators. The mechanism by which these particles are accelerated to such high energies is not known, but candidates include the most extreme processes in the Universe, such as Active Galactic Nuclei (AGN) and Gamma Ray Bursts. They could even arise from the decay of unknown massive particles, often predicted in Grand-Unified Theories (GUTs), or from topological defects arising during the period of inflation after the Big Bang.

Although the spectrum of charged cosmic rays has been measured over 14 orders of magnitude (Abbasi et al., 2005; Mantsch et al., 2005; Shinozaki et al., 2006), no diffuse cosmic neutrino spectrum has yet been observed. Unlike cosmic rays, neutrinos are undeflected by magnetic fields and so will point back to their source. They also travel cosmological distances unattenuated. A multi-messenger approach that includes data from cosmic rays, neutrinos and gamma rays, will be necessary to further our understanding of the origin of UHECRs and the mechanisms that drive their acceleration. In addition, the interactions of neutrinos with energies above 10^{17} eV, in any detection medium, occur at centre-of-mass energies that exceed those seen in the high energy particle accelerators on Earth. These interactions thus offer the opportunity to probe new particle physics phenomena at energies approaching the GUT scale, for example, the presence of extra spatial dimensions, which would enhance the neutrino-nucleon interaction cross-section.

UHECRs produce a particle shower when they impact the atmosphere, and currently the most important methods for detecting such showers have been observations of the fluorescence light emitted by the air showers, or directly detecting the shower particles that reach the surface of the Earth. However, the UHECR-initiated air showers also produce a radio signature. When the secondary charged particles in the air shower are deflected in the Earth's magnetic field, they produce radiation that is emitted in the forward direction, and is coherent for wavelengths that are larger than the size of the shower front, i.e., for frequencies less than 100 MHz. These radio signatures from cosmic rays were first detected over forty years ago (see Weekes, 2001, for an historical overview). The unprecedented size of the LOFAR array allows this technique to be applied to neutrino detection for the first time. Air showers from neutrinos can be distinguished from showers from other particles if the neutrino path is highly inclined with respect to the down-going direction. At those angles, the atmosphere filters electromagnetic energy from cosmic rays showers produced at high altitudes, while neutrinos can penetrate deeper into the atmosphere and produce a detectable cascade at lower altitudes. The high effective area provided by LOFAR's antennae would offer a greatly improved sensitivity to the radio signature produced by air showers from both ultra-high energy cosmic rays and neutrinos (Falcke et al., 2004).

Additionally, LOFAR has a unique opportunity to detect ultra-high energy neutrinos through a different radio signature that they would produce in their interactions with the moon. This radio Cerenkov signature was first proposed by Gurgen Askaryan. When a neutrino interacts in matter and produces a shower, that shower will develop a charge asymmetry, at the level of approximately 20%. This can be viewed as a ball of negative charge travelling faster than the speed of light in that medium, which results in Cerenkov radiation. For wavelengths longer than a transverse size of the shower, of order 10 cm, the signal is coherent. That coherence occurs in the radio microwave region. At the same frequencies, there exist media that occur naturally in large volumes and are transparent to this signal. Ice, salt and sand are three such media and past, present and future experiments that use this technique all use one of those media. The GLUE experiment was the first to search for ultra-high energy neutrinos by viewing the sandy surface of the moon (the regolith) with a radio antenna (Gorham et al., 2003). LOFAR, with its antennas pointed at the moon, would be sensitive to the same signature.

LOFAR offers the opportunity to extend the search for cosmogenic neutrinos into a higher energy regime than is possible with existing and proposed detectors. The UCL HEP LOFAR group (Connolly, Lancaster, Nichol, Waters) has expertise in the simulation of neutrino interactions and the associated radio signal, through their participation in the ANITA radio high-energy neutrino experiment, which is expected to be the first experiment to find evidence for UHE neutrinos in the energy region below LOFAR. This expertise will be applied to the neutrino-moon interactions that LOFAR has sensitivity to, with a view to probing predictions of the neutrino flux to 10^{22} eV and identifying any sources, should a flux be observed.

8 Solar and Heliospheric Physics with LOFAR-UK

The Sun is a powerful emitter at radio wavelengths, not only during intense bursts of activity related to phenomena such as solar flares and coronal mass ejections (CMEs), but also during times when it is considered quiet at other wavelengths. The radio domain provides a particularly sensitive diagnostic tool for accelerated particles on the Sun because even weak disturbances, such as the tiny events thought to be related to coronal heating, can give rise to detectable radio signatures via coherent plasma emission. Radio emission from energetic and dynamic phenomena such as solar flares and CMEs is of particular interest, as they are major drivers of space weather and can affect the Earth's space environment. Flares and CMEs are also challenging physical phenomena to be understood in their own right.

In the solar context, LOFAR will open up an unexplored window of radio observations, that is particularly useful for studying particle acceleration and large-scale dynamics. It will enable the study of accelerated particles, from very weak to very energetic events, and allow us to address key topics, especially when combined with multi-wavelength observations from other terrestrial- and space-based observatories. With LOFAR, dynamic processes involved in solar flares and CMEs can be studied from their origins on the Sun as they propagate out through the solar atmosphere. Using radio interplanetary scintillation measurements, CMEs can be tracked, and the solar wind and interplanetary magnetic field conditions analysed, from the outer solar corona to the Earth and other planets. Furthermore, radio observations with LOFAR will provide powerful diagnostics of the Earth's ionosphere and magnetically-linked regions of its magnetosphere. Uniquely, in the radio domain, LOFAR will enable much of the Sun-Earth system to be probed with a single instrument facility.

LOFAR's native angular resolution is a few arcseconds, and this, in combination with its enhanced sensitivity and time resolution, makes for a solar radio instrument far superior to any previous. Prime benefits of LOFAR to solar physics will be its increased sensitivity and its ability to perform radio imaging spectroscopy, scanning rapidly in many frequencies, and following dynamic sources as they propagate through the corona on (sub)second timescales (for comparison, the Nançay Radioheliograph has 5 channels between 150 MHz and 450 MHz, and occasional VLA solar imaging is also done in only 3 or 4 channels). A major advantage of LOFAR will be the opportunity to examine phenomena for which radio signatures occur preferentially at low wavelengths, such as coronal shock waves and radio noise storms.

Sources of radio waves close to the plasma frequency in the solar corona are broadened by plasma and wave turbulent scattering (Bastian, 2004). For example, sources at double the local plasma frequency, near 200 MHz, should have a size of around $100''$. While this means that it may not always be possible to exploit the full spatial resolution capabilities of LOFAR for solar studies, it does allow the study not only of the source structure (for sources emitting at higher than the local plasma frequency) but also of the effects of propagation and refraction of radio waves in the solar corona.

Solar and heliospheric physics stands to benefit greatly from LOFAR's increased capabilities. The UK has large, internationally-leading, solar and heliospheric physics communities that are active in theory, modelling and data analysis from gamma-rays to radio wavelengths, of phenomena occurring below the solar photosphere, through the solar atmosphere, into the solar wind and on to the atmospheres and surfaces of the planets. These communities host considerable expertise in radio methods and are well-placed to take advantage of LOFAR to study the genesis of solar disturbances and their effect on the Earth and the other inner planets. Radio studies will naturally be augmented by multi-wavelength observations of the dynamic corona available to us from other STFC-supported missions such as STEREO and Hinode (Solar-B).

The programmes of study included in this science case cover a wide range of solar physics and

Sun-Earth connections, from eruptive activity and coronal shock waves on the Sun, through to the propagation and evolution of structures in the solar wind and the signatures of disturbances in the magnetosphere and ionosphere of the Earth, as well as the connection between cosmic rays and atmospheric electricity. Below we outline the main science case for solar physics, heliospheric physics and terrestrial/planetary physics.

8.1   Solar Flares

Solar flares are complex, extremely energetic and often dynamic phenomena. Among other things they produce immense bursts of energetic electrons, the source and acceleration of which is not well-understood. The primary diagnostics for these accelerated electrons are hard X-rays and radio waves. In the metric and decametric regime, their emission is dominated by coherent radiation at the local plasma frequency and/or its harmonics. This is mode-converted plasma radiation from unstable distributions, such as non-thermal beams of particles. These beams, moving at ~0.2–0.5c outwards into interplanetary space and, more rarely, sunwards, produce emission drifting rapidly in frequency: type III bursts, reverse-drift type III bursts and bi-directional beams. There are many other, less explored, types of radio emission, which may be closely related to the main flare energy release, such as radio spike bursts and pulsations (e.g., Isliker & Benz, 1994). Together, these give unique insight into the production of non-thermal distributions in the corona.

With LOFAR we can also study flare electrons in large-scale magnetic structures that are difficult to see at other wavelengths. U-bursts, which are sometimes observed below 200 MHz (e.g., Bastian et al., 1998), are produced by electrons travelling up and then down along large magnetic loops. Sometimes such large loops are visible in X-ray and EUV images of the solar corona (e.g., Khan & Hudson, 2000; Pohjolainen et al., 2001; Foullon et al., 2005). We also expect to see incoherent gyro-synchrotron of thermal or mildly-relativistic electrons in magnetic fields of up to 10G, corresponding to coronal loops on the scale of a solar radius. Imaging with LOFAR will reveal the properties and development of large-scale, low density closed coronal loops: how they form, erupt and reform, and their relation with active regions, flarings and the CME structures. The incoherent radiation will provide estimates of the energy distribution and numbers of particles in these structures.

The LOFAR frequency range corresponds to plasma densities of 10^7 to $7 \times 10^8 \, \text{cm}^{-3}$, present between about 1.15 to 2.5 solar radii (cf. Figure 23). In some flares, the *source* of the electrons which generate type III emission will lie in this range. This is particularly the case for events where magnetic reconnection is believed to occur high above the flare kernel, say at the top of large loop system, as proposed in the break-out model (Antiochos, 1998; Antiochos et al., 1999). In many cases the type III emission from upward-propagating electrons can be studied, for example, in comparison with the downward-propagating electrons which give rise to hard X-ray emission. With spatial and spectral observations of type III sources we can address:

- What is the starting location (i.e., the all-important acceleration site) and propagation path of electrons producing type III and other coherent bursts?

- How do the burst spectra change as a function of time and position? This is a diagnostic of local plasma conditions, e.g., the presence of low frequency turbulence.

Another coherent radio signature, radio spike bursts, are believed to be produced by accelerated electrons at, or very close to, the energy release site. Khan & Aurass (2006) found, using Nançay Radioheliograph data, that the spikes appeared high in the corona apparently in response to compression of magnetic structures by an ongoing CME. This suggests a direct link between MHD disturbances and electron acceleration, which we can study further with LOFAR.
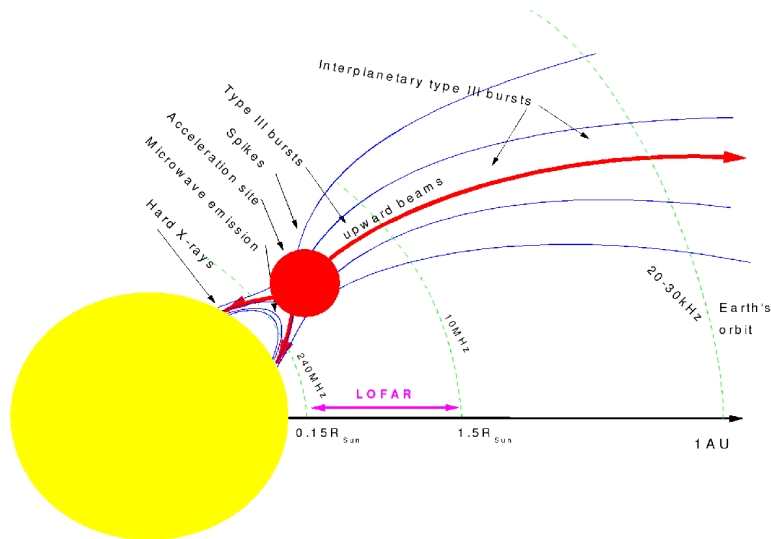
Figure 23: The approximate location of different types of solar radio emission, in the context of the flare magnetic geometry

8.2 Coronal Mass Ejections

Coronal mass ejections (CMEs) are important for the production of interplanetary (IP) shock waves and particle acceleration, and are one of the most significant space weather phenomena affecting the Earth's environment. CMEs are studied to determine the physical processes that precede and cause them, their intrinsic properties and their consequences, as well as how to identify the most geo-effective events. CMEs have been imaged at radio frequencies (e.g., Bastian et al., 2001, cf. Figure 24) at heights below two or three solar radii. In these cases, the emission appears to be thermal and non-thermal gyro-synchrotron emission, providing immediate information on the electron energy distribution and the magnetic field strength in a CME. However, with comparatively few events analysed so far, we know little of their origins or consequences.

With LOFAR, combined with imaging and spectroscopy at other wavelengths, we can address the following questions:

- What are the trajectories of CMEs, and what are their effects on the surrounding corona?

- What can we learn about the physical structure (density, field strength) and driver of the CMEs?

- What are the relations between CMEs and flares?

- Is the eruption of hot large loop structures in the solar corona a major component of the later CME?

- What is the relation between CMEs and shock waves seen in the corona and in interplanetary space?

8.3 Coronal shock waves

A familiar radio signature of a shock wave in a metric to decametric dynamic spectrogram is a broad spectral feature drifting slowly to lower frequencies. This so-called type II radio burst is
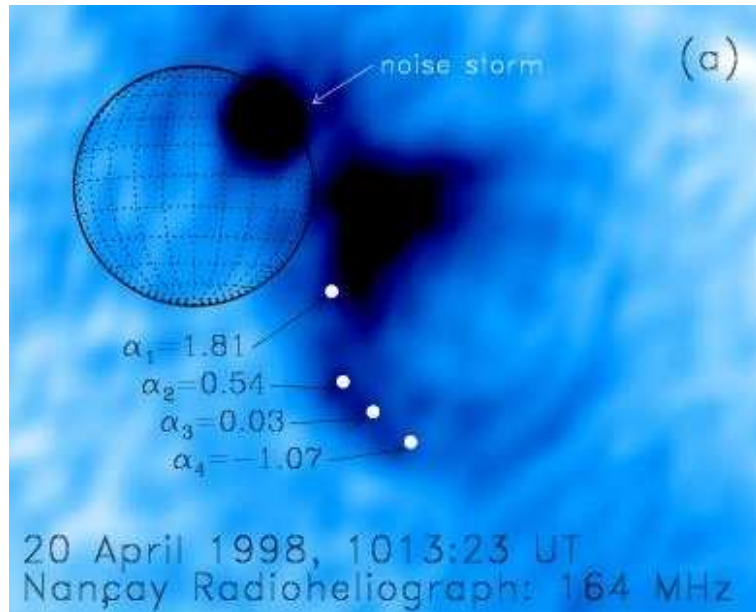
Figure 24: The radio signature of a coronal mass ejection from the Nançay Radioheliograph (Bastian et al., 2001).

believed to be due to plasma emission from electrons accelerated at an outward-propagating shock wave (Wild & Smerd, 1972).

Radio observations from LOFAR will enable us to follow the coronal type II bursts and determine the physical structures (density, magnetic field strength) associated with them. Studies of coronal shock waves will seek to understand the physical origin of coronal type II radio bursts and their relation to interplanetary type II bursts and shock waves. Regarding the origin of the shock waves, we aim to determine if the shock waves are launched by, e.g., a piston of moving matter or a pressure pulse. We will also investigate the association with flares or CMEs, and seek to determine whether they are directly–driven or freely–propagating shocks.

Studying shock waves on the Sun is important not only for understanding them in their own right, but also for understanding their effects on other solar phenomena. It is known that large-scale shock waves may disturb filaments (Moreton, 1964), initiate eruptions (including CMEs), and trigger 'sympathetic' flares, all at remote locations. Khan & Hudson (2000) identified a new class of coronal mass ejections associated with the eruption of large-scale trans-equatorial loops attributed to the passage of a shock wave. In addition, shocks are probably also the drivers of oscillations observed in coronal loops (Hudson & Warmuth, 2004; Ballai et al., 2005). Studies of coronal shock waves will seek to determine their propagation characteristics and their effects on the surrounding corona and other solar structures.

It should be noted that type II radio bursts preferentially occur at low wavelengths (typically $<150\,\mathrm{MHz}$) and, consequently, comparatively few type II bursts have been studied to date. The potential for discovery in the study of coronal type II radio bursts and large-scale coronal shock waves with LOFAR is very high.

The investigation of both large- and small-scale shock waves in radio data will augment the pre-eminent UK effort in the detection and analysis of MHD waves at X-ray, EUV and optical wavelengths. Since shock waves are ubiquitous in astrophysical plasmas, advances in understanding solar coronal shock waves and their role in particle acceleration will also be of interest to the wider astrophysics community.
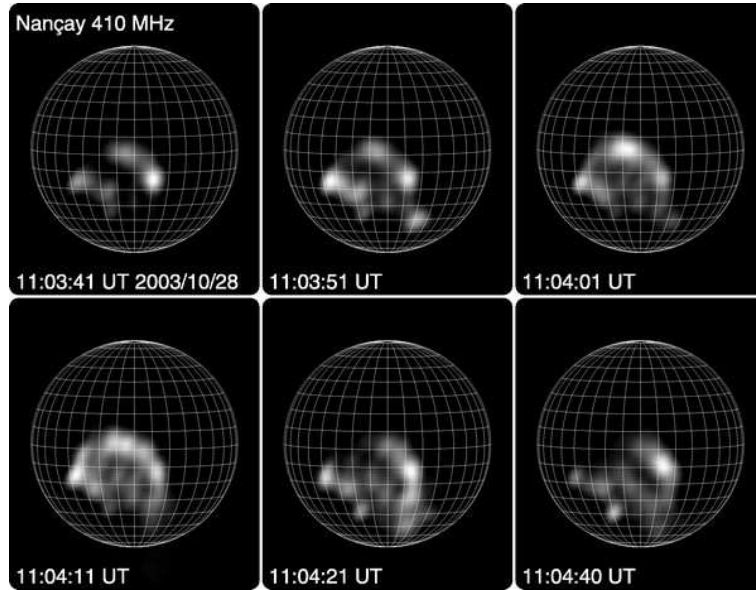
Figure 25: The radio signature of a shock wave propagating through the solar corona (Pick, 2005).

8.4 Non-flaring active region energy release

The corona of an active region evolves continuously under the action of sub-photospheric driving, and we suspect that it sustains a permanent population of non-thermal electrons (as has been observed for active dwarf stars; Kundu et al., 1987). Small micro-flares occur every few minutes when there are active regions on the disk (Lin et al., 1984), many of them producing non-thermal particles (Lin et al., 2001), and the ubiquitous presence of non-flare-associated type III bursts may also reveal streams of enhanced density associated with multi-million degree coronal jets (e.g., Aurass et al., 1994; Kundu et al., 1995). The quasi-continuous occurrence of even smaller events has been proposed as the mechanism that maintains the hot corona (Parker, 1988). High brightness temperature radio noise storms are a signature of accelerated electrons lasting for hours or even days, in correlation with identifiable events in active region evolution (Bentley et al., 2000). These are a major source of solar radio emission at low frequencies, outside of the times of flares and CMEs. The origins of the noise storms, in particular how the accelerated population of electrons is produced and maintained, are not yet understood. Noise storms, like type II radio bursts, preferentially occur at low frequencies and so LOFAR will be particularly useful in their study. Small numbers of quiet–time non–thermal electrons, hard to observe or invisible in other energy ranges (optical, X-ray), should be sufficiently bright via coherent emission to be imaged with LOFAR. Such studies will address fundamental issues in solar coronal physics: the occurrence of non-thermal electron distributions in non-flaring active regions; the partitioning of energy between heating and particle acceleration; the role of nano-flares in coronal heating and in the 'gradual' evolution of active regions.

8.5 Radar mapping of the solar corona, and plasma turbulence

Using LOFAR as a receiver for future active experiments on the solar corona could open a new era of radar studies of the Sun, such as is already used to probe the Earth's ionosphere. The solar corona is a unique example of a turbulent plasma medium yet to be fully explored. Electromagnetic emission is effectively scattered by electron plasma waves, whereas absorption at the local plasma frequency is strongly determined by the anisotropy of the turbulence spectrum (Khotyaintsev et al., 2006). Early active experiments (James, 1970) show that the radar signal reflected from the corona can
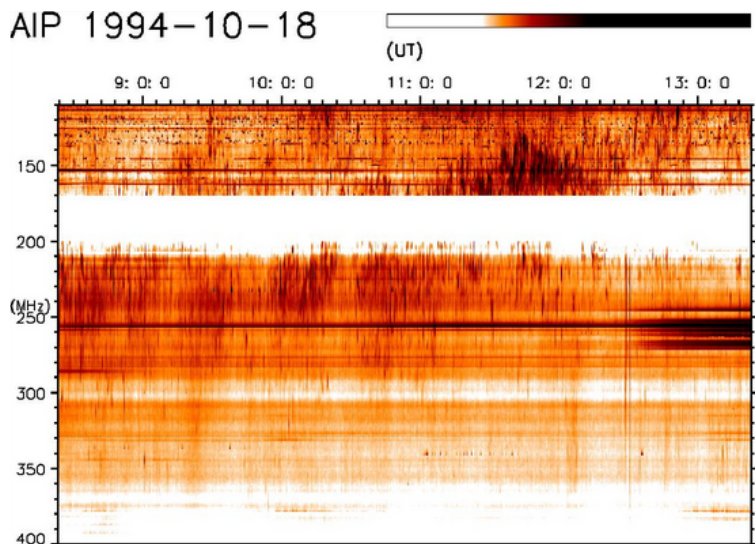
Figure 26: An example of a solar radio noise storm on 18 October 1994 as seen in a radio spectrogram (courtesy the Astrophysikalisches Institut Potsdam). The numerous short-duration, narrow-band bursts are noise storm emission and indicate continued particle acceleration.

vary by a few orders of magnitude, implying a highly anisotropic medium. The radar echoes at 38 MHz imply ever-present compressional waves in the corona, which may be associated with coronal heating. LOFAR will answer crucial questions about Langmuir wave spectra in the solar corona, inaccessible by in-situ measurements. Such an approach in the ionosphere successfully identifies the parameters of Langmuir turbulence (Kontar & Pecseli, 2005), and similar efforts may be possible with the solar atmosphere. In addition, passive observations of sub-second radio emission provides a diagnostic tool to measure the magnetic field and main plasma parameters (Stepanov et al., 2004). There is growing international interest in active radar studies of the Sun (e.g., the LOFAR Outrigger In Scandinavia (LOIS): *www.lois-space.net*).

8.6 Radio scintillation observations of the 3D solar wind

The solar wind is the medium by which solar disturbances, such as coronal mass ejections and fast solar wind stream interaction regions, are conveyed to the Earth and the other planets. It is also representative of the stellar winds surrounding other mid-life cool stars and interacting with any planets they might possess. The plasma processes operating in the solar wind are the same as those found in the atmospheres of other Sun-like stars and are relevant to other astrophysical processes, while the evolution of the large-scale structure of the solar wind is fundamental in determining the manner in which it couples to planetary environments in the solar system. Current instruments – and currently planned instruments – can only give a partial view of solar wind structure. LOFAR has the potential to provide a high-resolution view of density and velocity structures in the solar wind from inside the orbit of Venus to beyond Earth orbit. The science questions we hope to address with LOFAR are:

- How do structures within coronal mass ejections (CMEs) interact, and how does this affect the interaction between the CME and the background solar wind?

- How do the interaction regions between CMEs and stream-stream co-rotating interaction regions (CIRs) develop, and how important is this in determining the geo-effectiveness of CMEs?

- How does large-scale structure in the solar wind evolve in the inner solar system?

- How do small-scale structures (turbulence) in the solar wind evolve with increasing distance from the Sun, and how rapidly is energy transported between scales?

To do this, we would use LOFAR as a multi-beam interplanetary scintillation (IPS) telescope, measuring the small variations in apparent intensity of astronomical radio sources arising from scattering of the signal by small-scale density irregularities in the solar wind. As the irregularities are being carried out from the Sun by the solar wind, IPS measurements provide information on both (relative) solar wind density and solar wind outflow speed, as well as providing estimates of other solar wind parameters (Coles, 1996). The technique of IPS, using modulation of signals from astronomical radio sources by the solar wind, has been used to study the density and outflow velocity structure of the solar wind for over forty years (e.g., Hewish et al., 1964; Armstrong & Coles, 1972; Kojima & Kahinuma, 1977). In the last ten years there have been considerable advances in the technique, allowing it to realise its full potential as a tool for untangling the evolving structure of the solar wind (e.g., Coles, 1996; Breen et al., 1999, 2006).
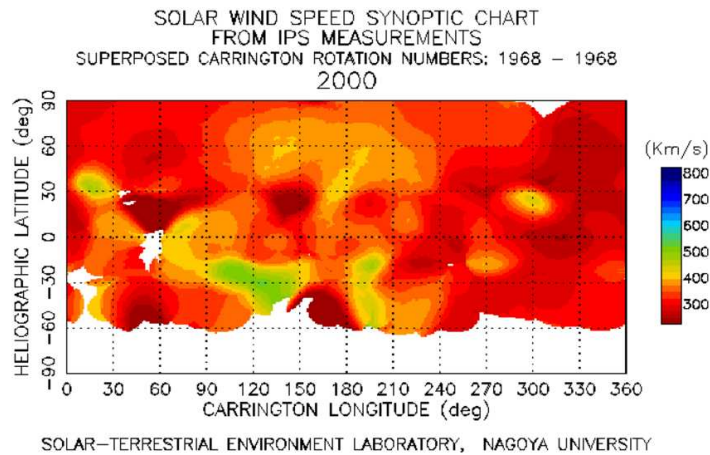

Figure 27: An overview map of solar wind velocity structure over one solar rotation near solar maximum (credit: M. Kojima)

LOFAR possesses the features necessary to provide a view of the solar wind with sufficient resolution to image in detail the passage of CMEs and the development of stream-stream interactions, and thereby to gain the full scientific benefit from the next generation of space missions, such as the Solar Orbiter. These observations require large numbers of density and velocity measurements, with good velocity resolution (Breen & Woan, 2003), over a large number of radio sources across the inner heliosphere each day. LOFAR has the collecting area and sampling rate (100 Hz minimum) to detect the many weak, and weakly-scintillating (at the 1-10% level), radio sources necessary to do this. The construction of UK stations as part of the LOFAR programme will provide the long baselines needed for accurate measurements of solar wind speed. This combination of sufficient spatial resolution to image the internal structure of solar wind disturbances and accurate measurements of their velocity would represent a huge advance on the capabilities of any current system, and will provide entirely new information on the solar wind.

LOFAR will be able to provide measurements of solar wind density and velocity from ∼80 solar radii out to beyond 230 solar radii, spanning the distance range from within the orbit of the ESA Solar Orbiter mission to beyond Earth orbit, and covering the regions in which the structure of the solar wind seen in the outer regions of the corona is transformed into that sweeping across the orbit of the Earth. It will be able to provide information on the large-scale 3-dimensional structure of the inner solar wind, both to place high-resolution coronal and in-situ measurements in their
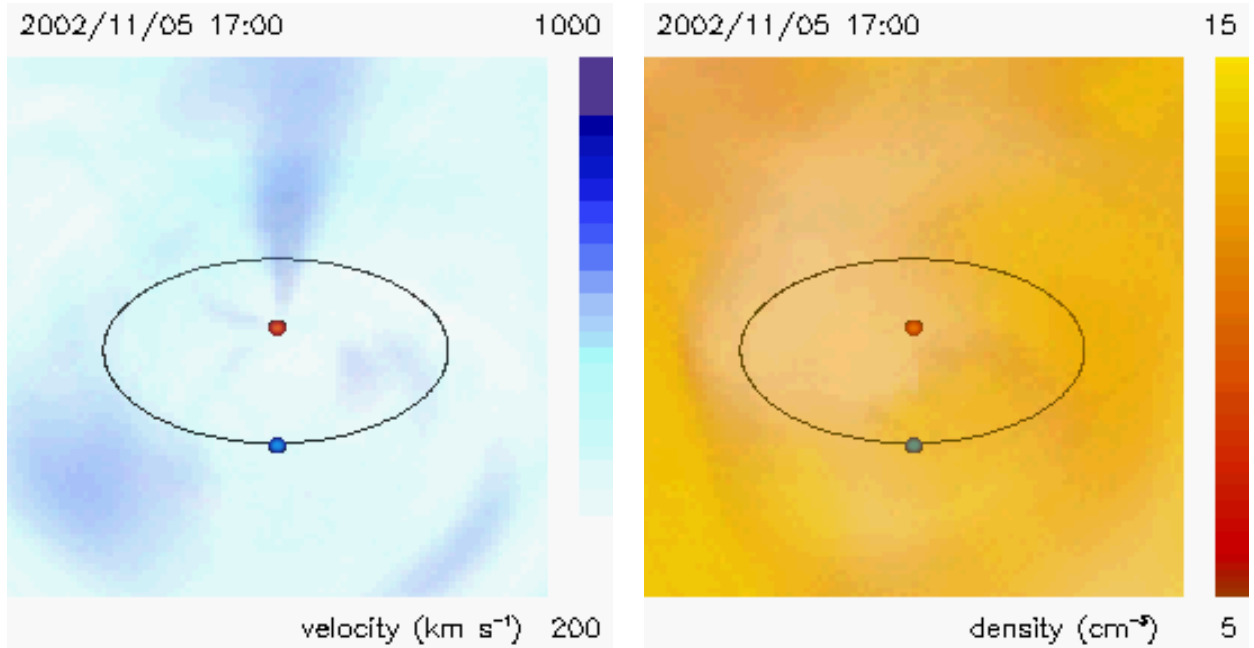
Figure 28: Tomographic reconstructions of 3D solar wind velocity (left) and density (right) structure, using Nagoya STELab IPS data (from Hick & Jackson, 2001).

broader context (how do structures elsewhere relate to those observed in detail?) and to study the evolution of the solar wind in velocity and density with latitude, longitude, distance from the Sun and phase of the solar cycle. Specifically, LOFAR will:

- provide information on the large-scale structure of the solar wind, and particularly on the interaction regions between streams of fast and slow solar wind and between coronal mass ejections and the background solar wind (a large number of observations per day are required for this). The high sensitivity of IPS measurements to electron density, together with their ability to measure velocity, will provide an overlapping dataset which will be the ideal complement to white-light coronal density measurements of the inner heliosphere;

- provide context for high-resolution IPS (EISCAT, MERLIN, VLBA) and in-situ measurements, by revealing the large-scale structure of the solar wind at interplanetary distances. The results will be especially valuable in providing context for Solar Orbiter measurements;

- provide information for 3D tomographic reconstruction of the solar wind;

- provide density and velocity information for solar wind and heliospheric modelling.

The multiple-frequency capabilities of LOFAR will also make it possible to probe differences in behaviour between different scales of irregularities, building on the recent work of Fallows et al. (2006). The IPS mode for LOFAR would be capable of providing information suitable for operational space weather monitoring, although this would not be the primary purpose of these observations.

A great advantage of LOFAR as an IPS instrument is its multi-beam capability, which will enable routine IPS observations to be run without contention for telescope time. This will make synoptic observations of the solar wind practical. The large number of observations required to image density structures would be made by using the whole collecting area of the telescope to observe scintillation of many weak sources. Velocities could be estimated from those source-observations with high signal-to-noise, using the method developed by Woan (1992), with velocity calibration achieved by using widely-separated LOFAR station groups to observe a more limited number of strong sources

simultaneously, allowing use of a 2-site cross-correlation approach to velocity estimation (e.g., Coles, 1996; Breen et al., 1999, 2006). LOFAR will provide a unique opportunity to study the large-scale structure of the interplanetary solar wind – a field of science where the UK is already one of the world leaders.

8.7   Riometric Observations of the terrestrial space environment

The Earth's ionosphere and magnetosphere form a coupled plasma system, strongly influenced by the external drivers of the solar wind and coronal mass ejections. While it is carrying out astronomical observations, LOFAR will also be able to diagnose conditions in the ionosphere, thus providing large-scale, high-resolution measurements of the magnetically-linked inner magnetosphere, specifically the so-called 'slot region' between the Earth's inner and outer radiation belts. Studying this crucial zone, not currently covered by any existing instrumentation, will advance, in particular, our understanding of how relativistic particles respond – are accelerated and lost – as geomagnetic and electric fields vary.

The science questions we hope to address with LOFAR are:

- What is the morphology of the F-region plasma at latitudes equatorwards ("sub-auroral") of the auroral oval during storms and sub-storms?

- What is the extent of relativistic electron loss to the ionosphere across the outer radiation belt?

- What is the morphology of the sub-auroral ionosphere during sub-storms?

- What is the cause, and the spatial and temporal structure, of electron precipitation from the slot region during geomagnetic storms?

- By how much does solar radio emission degrade absorption measurements in the auroral regions?

As radio signals pass through the ionosphere they are attenuated, primarily by increased electron density. Although this is a hindrance for astronomical observations, it is this loss of signal that provides a mechanism for observing the ionosphere. By utilising the loss of signal, LOFAR can act as a large-scale riometer (relative ionospheric opacity meter) at the same time as it is making astronomical observations. At 30 MHz the beam width is 5.5°, corresponding to a spatial resolution of ∼8km in the ionospheric D-region. This is on a par with the detail provided by the new ARIES (Advanced Rio-Imager Experiment in Scandinavia) system recently deployed at Ramfjord, Norway. However, the latitude of LOFAR means that it will probe a different, lower-latitude, part of the ionosphere from ARIES, and one in which the attenuation is expected to be due to very high energy electrons leaking from the radiation belt, or to very low energy electrons from the Earth's plasmasphere – the region of cold, dense plasma trapped on field lines which rotate with the Earth.

The essence of using LOFAR as a riometer is to extract the raw signal from each beam before any corrections are applied to compensate for ionospheric attenuation. This can then be compared to a quiet day signal. The technique will work best for frequencies in the 20–60 MHz band; at higher frequencies the smaller absorption values will be hard to distinguish from the noise level. This is especially important for monitoring the subtle increases and decreases in absorption in the F region, associated with, e.g., the loading of the F-region when the Earth's plasmasphere is eroded during geomagnetic storms, or the decreases due to nightly ionospheric flows. The longitudinal coverage of LOFAR will provide large-scale images of the ionosphere with high temporal and spatial resolution. This is something that satellites are currently not able to do – for example, 4 point measurements in 90 minutes is typical for a polar orbiting satellite.

Since riometers are essentially sensitive radio receivers, they suffer when the sun is emitting additional radiation at their operating frequency, and when high-energy solar protons produce so-called polar-cap absorption events that mask the true ionospheric absorption. LOFAR will provide a measure of the solar radio emission when the sub-auroral ionosphere is inactive, so that corrections can be made to riometer data from other, high-latitude, instruments.

8.8 LOFAR as an ionospheric sensor

The mid-latitude ionosphere is far from being understood and is the key region showing a dramatic response to solar storms. Newly-discovered ionospheric phenomena include storm enhance density (SED) and the associated sub-auroral polarisation stream (SAPS). GPS ionospheric monitoring (Foster & Vo, 2002; Yin et al., 2004) has aided the understanding of the phenomena over the US and Europe. However, only very few storms over the last solar maximum have been studied. One problem is the lack of mid-latitude instrumentation – many ionospheric instruments have been decommissioned and there is increasing reliance on data from satellites that are not guaranteed to be in the right location at the right time.

There are two key areas where LOFAR can aid in modern ionospheric studies. The first is that the unprecedented sensitivity of LOFAR to radio signal delay will allow measurements of path delay to less than 1 cm. The same types of techniques that have already been developed to use GPS signals to image wide regions of the mid-latitude ionosphere are directly applicable to LOFAR signals, resulting in thousands of simultaneous and accurate measurements to be used in multi-instrument data assimilations. Simultaneous with the ionospheric response, the solar radio bursts will also be detected, allowing high-temporal and spatial resolution studies of solar–terrestrial storms. In addition, the capability to observe at high resolution across a wide-area will expand the observable spectrum of ionospheric waves.

The second area, an even more novel use of LOFAR, is as a passive mid-latitude backscatter radar, using signals-of-opportunity as a system to monitor the expansion of the polar cap during highly-disturbed space–weather events and to allow the density and velocity of the plasma over Europe to be monitored continuously. This would provide a substantial European contribution to support the science goals proposed in US satellite missions such as 'Living with a Star Ionosphere-Thermosphere Storm Probes'.

8.9 Radio from Lightning Flashes and Cosmic Rays: Natural Radio Waves in the Earth's Atmosphere

Naturally occurring lightning flashes and cosmic rays transmit bursts of invisible electromagnetic waves into the Earth's atmosphere, similar to radio broadcasting stations. It was recently suggested that lightning flashes may be initiated by energetic cosmic rays (Gurevich & Zybin, 2005). The physical properties of lightning flashes and cosmic rays can be inferred from simultaneous measurements of electromagnetic waves with LOFAR and extremely low frequency radio wave magnetometers.

The proposed study of radio waves from lightning flashes and cosmic rays is based on the comparison of simultaneous electromagnetic wave recordings from lightning flashes and cosmic rays. The experimental observation of radio waves builds on the expertise with remote sensing at the University of Bath (Fullekrug, 2004), while the observation of radio bursts from ultra-high energy cosmic ray air showers (UHECRs) is based on the expertise of ASTRON (Falcke et al., 2005). The naturally occurring electromagnetic waves will be observed with radio wave antennae at Extremely-Low Frequencies (ELF), from 10 Hz to 4 kHz, in collaboration with the British Geological Survey (BGS) in Edinburgh. The BGS operates a geophysical observatory at Eskdalemuir in Scotland,

which is remotely located, away from human activity, and hence ideally suited to record naturally occurring radio waves. The observation of cosmic rays can be done with LOFAR.

8.10 Other science areas

There is considerable interest within the UK solar, heliospheric (and solar system) science communities in other opportunities for exploiting LOFAR. These include studies of small-scale structure in the terrestrial ionosphere using the technique of ionospheric scintillation, and active radar studies of space plasma processes, with LOFAR acting as a network of receiving arrays.

9 LOFAR-UK as a stand-alone array

There will be times when some or all beams from the international LOFAR stations will not be correlated with those of the Dutch LOFAR stations, either because they are not required (e.g. when EoR observations are carried out using only the Dutch core stations), or because of limitations of the correlator. In these circumstances, beams from individual LOFAR-UK stations can be used independently, or may be correlated with the other international stations (and any unused Dutch stations) as a sparsely-sampled array. There are a number of valuable science goals that could be carried out in this way.

9.1 Pulsar observations with individual LOFAR stations

The individual LOFAR stations have sufficient sensitivity to be able to do very interesting monitoring observations of some known pulsars and other transient radio emitting neutron stars. They could be used to perform regular timing observations of a few dozen radio pulsars which are known to glitch. One of the keys to understanding the equation of state of the super dense material of a neutron star is seeing how often neutron stars suffer starquake-like glitches and, when they do occur, how the rotation rate recovers from the glitch. The frequent monitoring that would be possible with individual LOFAR stations would allow us to catch more glitches and to sample them more regularly. Presently less than a handful of pulsars are monitored frequently enough to be able to study their glitches in sufficient detail. These timing observations could also be used to form timing ephemerides of the brightest pulsars which could be used by high energy satellites like GLAST to look for gamma-ray emission.

Recent discoveries have highlighted two new interesting classes of radio-emitting neutron stars. These are the RRATs and the intermittent pulsars. RRATs are characterised by infrequent bright single pulses (typically a few per hour). Monitoring of these sources may greatly improve the number of pulses detected and thus allow us to better determine the nature of the sources. Moreover by implementing a trigger algorithm on the station data we could also perform piggy-back searches for more of the short duration pulses that characterise these sources, and thus potentially greatly increase the number known. The wide field-of-view of a LOFAR station will greatly facilitate this search. These observations would also be sensitive to short duration pulses like the one recently discovered in the direction of the Magellanic Clouds but which is believed to be at more than a Mpc away. The origin of this single very bright burst is at present unknown but there are suggestions that there could be hundreds per day. Their brightness means that they could be detected by an individual LOFAR station.

The intermittent pulsars are the other new class of sources which could be studied with a LOFAR station. They are pulsars which are seen to emit radio waves from anything from a few days to years and then turn off for similarly long periods. Intriguingly during the off periods they are seen to exhibit different spin properties to when they are on, thus providing a unique probe of the emission mechanism itself. To better understand the phenomenon we need better statistics on the repitition timescale of the source turning on and off. It is also of interest to know what happens exactly at the moment when the on-off or off-on transition happens. The monitoring capabilities of a LOFAR station are again ideally suited to this task.

9.2 Solar observations with individual LOFAR stations

As discussed in Section 8, one of LOFAR's Key Science Projects is concerned with observing and studying the properties of the Sun. However, such observations will only be carried out for a subset of the time. Although the angular resolution of an individual LOFAR station will be low, it will

be able to operate as a very sensitive, high temporal resolution and high frequency resolution solar radio spectrograph, greatly increasing the capabilities for solar activity monitoring. Spectrographic observations are essential to make sense of the solar radio emission in the full-LOFAR Solar imaging observations, because a variety of radio bursts have been classified according to their form in spectrograms and these, in turn, have been related to various physical phenomena. Moreover, several very interesting fine structures have been seen in recent spectrogram data. LOFAR acting as a very sensitive spectrograph will very likely reveal much more information on the detailed spectral behaviour of solar radio emissions, and thus on the details of the particle accelerations and plasma process involved.

Continual solar spectroscopic monitoring would also allow burst-trigger-mode observations, whereby the entire LOFAR array could be triggered to observe the Sun at relatively short notice if an interesting burst is detected in the radio spectrograms. Furthermore, relatively crude centroiding images from the LOFAR-UK stations would provide useful information (in the absence of better radio imaging) for large-scale phenomena such as CMEs and shock waves.

9.3   Heliospheric Physics with individual LOFAR stations

The UK has considerable expertise in indirect imaging of the interplanetary medium using scintillation techniques. These methods have proven effective in monitoring the solar wind, providing alerts for the possible onset of geomagnetic activity and determining the connections between solar activity and interplanetary weather. In addition these data have direct relevance to satellite and spacecraft operations, the commercial operation of high-latitude electric power grids and radio communication. Near real-time monitoring of the solar wind has significant potential in all these fields but has been hampered by the lack of suitable radio telescopes on the ground, capable of monitoring several hundred compact extragalactic radio sources per day and measuring their scintillation levels. However, each LOFAR station has the sensitivity, collecting area and bandwidth to perform these stand-alone scintillation measurements, necessary for solar wind imaging. Indeed, the beam-forming capabilities of a single LOFAR station are far superior to any low frequency array currently in operation worldwide and offer the opportunity to exploit this technique to the full for the first time.

Measurements of density structures do not need interferometric baselines, so this task could be performed by a single UK LOFAR station. With more than one station, intensity correlation analyses will reveal the motion of the scintillation pattern over the ground and therefore the velocity of the solar wind. Long-baseline intensity correlation observations combining data from UK station(s) with measurements from non-core LOFAR sites in Germany and France would provide high-precision measurements of solar wind speed and direction. LOFAR will offer a unique combination of imaging of density structures in the solar wind together with long-baseline, high-precision velocity measurements, and will provide an entirely new view of the evolving interplanetary medium. Again, these observations can be performed without relaying data back to the LOFAR data processing facility in Groningen.

9.4   Ionospheric diagnostics with individual LOFAR stations

As LOFAR operates at low radio frequencies, its performance will be sensitive to conditions in the Earth's ionosphere. In order to ensure optimal performance from LOFAR, adequate ionospheric diagnostics will be required. The UK has a record of expertise in ionospheric radio science, and this will be drawn on to map ionospheric structures above LOFAR in near real-time. This would provide the information necessary to correct for ionospheric effects, even during periods of geomagnetic disturbance. This capacity could be developed with a single UK LOFAR station.

9.5 Correlating E-LOFAR stations for early long-baseline surveys

The $u - v$ plane coverage of an international array of 8-10 European LOFAR stations will be sufficient to make reasonable images at $1''$ resolution. Although these observations will not have the sensitivity of the full array, they should be able to observe every source in the 1.4-GHz FIRST survey (Becker et al., 1995) to a flux limit of 1 mJy at 1.4-GHz, in just a few beam-months. The correlation requirement would be relatively modest, despite the high resolution, because the FIRST survey tells us exactly where the sources are; only a small area around each source need be correlated, resulting in greatly reduced requirements on channel width and integration time. Ionospheric calibration would be done by observing only in fields around bright ($>$200-mJy) point-source calibrators. The amount of sky that can be covered depends critically on the ionospheric stability at the time of observations, but for typical isoplanactic patch sizes we expect 30–50% coverage should be possible.

There would be a number of key advantages in such a programme. First, the entire FIRST survey could be examined for gravitational lenses. These have typical dimensions of $< 2''$ (so require E-LOFAR's resolution), and are of importance for studying mass distributions in galaxies and galaxy evolution, as discussed in Section 5.4.2. The numbers of lenses which could be detected would depend on assumptions about source structure, but we note that the CLASS survey (Myers et al., 2003) discovered 22 lenses out of the currently known ∼150 by a radio survey of flat-spectrum radio sources to the 30-mJy level. A $1''$–resolution survey at this depth would also push into new parameter space for the study of radio source populations.

Second, it is almost certainly imperative for the planning of a full-scale survey with the whole E-LOFAR array to have a pilot survey on long baselines. Such a survey, in addition to producing scientific output, would allow us to optimize observing strategies given the calibration problems produced by the ionosphere. This will be crucial, because the full E-LOFAR survey will in any case require increased computing/correlator resources, both because it will have more long baselines and also because it will be a blind survey, without the advantage of prior knowledge of source positions. Considerable experience with the pilot survey will therefore be necessary before this is carried out.

10 Technical Case

10.1 The locations of UK LOFAR stations

Scientific simulations, plus considerations of practicalities, have led to the conclusion that the optimal approach for LOFAR-UK would be the deployment of four UK LOFAR stations, subtending a range of angles and baseline lengths relative to the Dutch core. Leading candidates for the sites of these stations are *Jodrell Bank*, *Lord's Bridge*, *Chilbolton*, and *Edinburgh*. The rationale for the choice of these sites is discussed below. Numerous simulations have been carried out of the *u-v* coverage that would be provided by various subsets of these sites, for sources of different declinations in both snapshot and full 12-hr synthesis observations. A full suite of these simulations is available at *www.jb.man.ac.uk/∼rbeswick/LOFAR/*; two illustrative sets of examples are shown in Figures 29 and 30. It is clear that the proposed UK stations will: (i) increase the maximum baselines in the *u-v* plane, leading to an increase in the angular resolution of the array by a factor of ∼ 2 compared to LOFAR with just Dutch and German stations (and a factor of several compared to Dutch-only LOFAR); (ii) allow much more uniform coverage of intermediate baselines, providing smoother and more symmetric beam-shapes.

The Jodrell Bank and Lord's Bridge sites are natural choices for UK LOFAR stations, for a number of reasons. These are locations where, as discussed in Section 3, there is a long history of radio astronomical facilities, and thus extensive local technical expertise. Land has been donated to the LOFAR-UK project at these sites by the University of Manchester and the University of Cambridge, respectively. The proposed stations are also close to e-MERLIN fibres, thus minimising the additional cost of fibre connections. The sites have recently been RFI surveyed by the LOFAR team, and initial findings show that in both cases the interference environment is better than other LOFAR sites in Holland.

The Chilbolton Observatory site, close to STFC Rutherford Appleton Laboratory, also offers excellent potential to host a LOFAR-UK station. RFI surveying of this site by the LOFAR team has demonstrated that this is also better than other LOFAR sites in Holland. In addition, the majority of facilities required to support the establishment of a LOFAR station are present. The only notable short-coming is the lack of a connection to dark fibre. Connection to dark fibre is thought to be a more cost effective method of providing data transport than using the Chilbolton Observatory's connection to the BT fibre network. The South East England Development Agency (SEEDA) are very enthusiastic about the location of a LOFAR station in this part of the country and may provide financial support (see Section 11) to assist in data connectivity.

A Scottish LOFAR station has the clear benefit of providing both the longest possible UK baselines, and also a different subtended angle relative to the main LOFAR core, providing improved coverage of the *u-v* plane. There is also the possibility that funding for a Scottish station could be provided directly from the Scottish Funding Council. The currently-favoured site for a Scottish LOFAR station is about 10 km south of Edinburgh, close to the Edinburgh Technopole Science Park. A 10 Gb/s fibre connection is available from this science park, connecting directly into the SuperJanet 5 fibre network. Investigations of precise site locations, and the cost of installing the final 1-2 km fibre connection, are still in progress. The nearby location of the Astronomy Technology Centre may be beneficial in terms of technical support.

Other potential sites for LOFAR stations within the UK are still under consideration. In particular, the possibility of siting a LOFAR station in Central Wales, as part of a larger funding bid to the Welsh Assembly for fast-fibre connectivity of that region, is currently being investigated. There have also been informal discussions with the Regional Development Agency and other funding sources in the North-East of England related to the construction of a LOFAR station there.
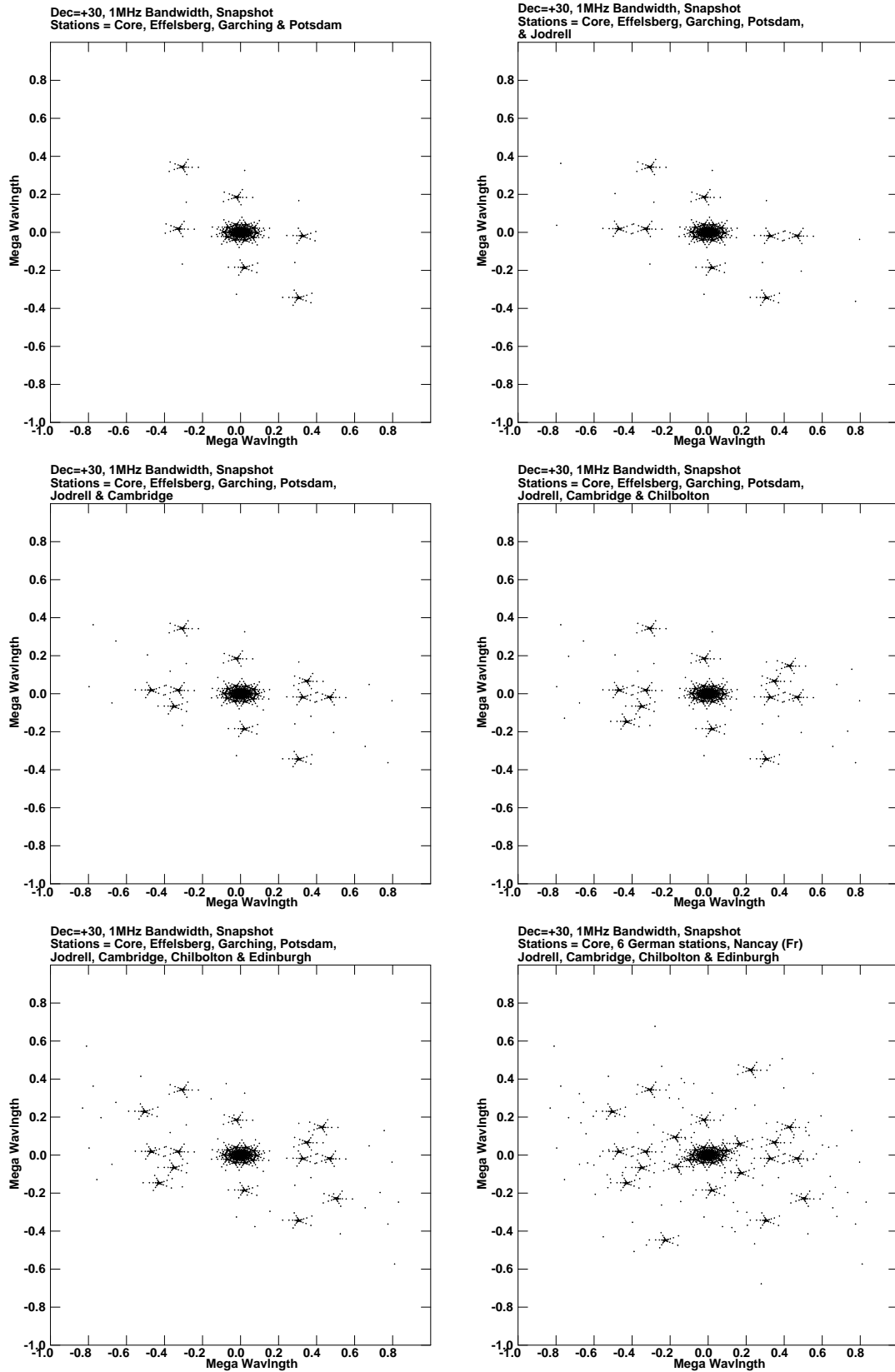
Figure 29: The simulated *u-v* coverage for snapshot observations at 230 MHz (other frequencies only change the axis scalings), with 1 MHz bandwidth, of a source at 30° declination. The top-left plot shows the *u-v* coverage provided by the Dutch LOFAR plus three fully-funded German stations. The subsequent four plots show the improvement in *u-v* coverage when various subsets of UK stations are added. The lower-right plot finally shows the *u-v* coverage produced if all proposed international stations (6 German, 1 French and 4 UK) are included.

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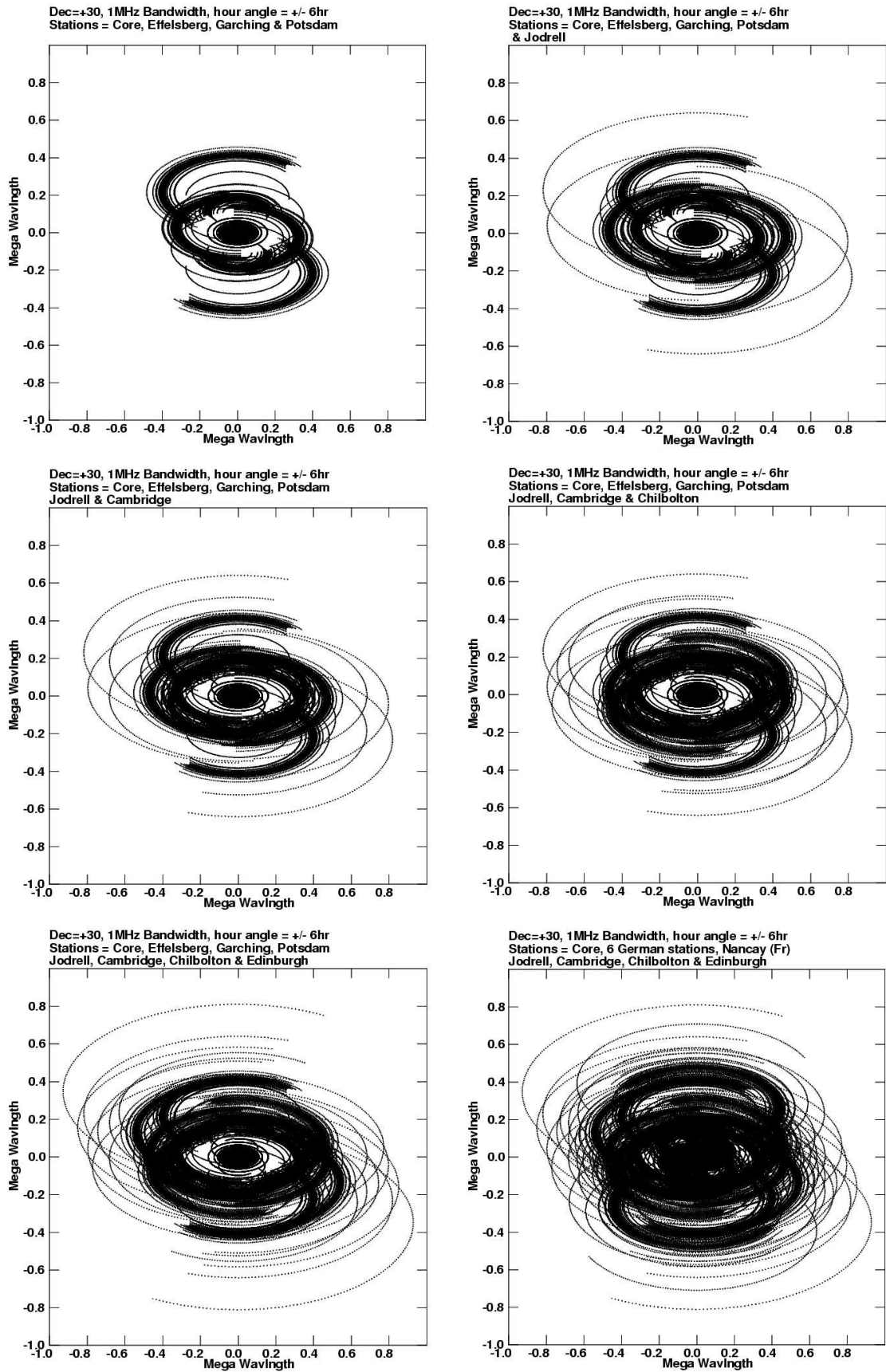Figure 30: The simulated *u-v* tracks for full 12 hr (hour angle ±6) synthesis observations of a source at 30° declination, at 230 MHz with 1 MHz bandwidth. The various combinations of LOFAR stations are as described in Figure 29.

10.2   Data transport

The anticipated data rate from a LOFAR station outside the central core is 2 Gb/s, based on a total bandwidth of 32 MHz, which can be divided in up to 8 beams, in each of 2 polarisations, with 12-bit sampling, and allowing up to 512 Mb/s for formatting and framing overheads along with control and monitoring data. For LOFAR within the Netherlands, the data will be transmitted from each station across a dedicated Wide Area Network using Gigabit Ethernet protocols to the central processor. Connecting stations from outside this dedicated WAN will require additional work and resources.

For remote stations in the UK, we expect that the LOFAR station data can be transmitted across the SuperJanet 5 (SJ5) network, which has trunk data rates and access points at 10 Gb/s, to interconnect with the Geant network (the EC-funded network which connects the various European research networks) for transmission to Amsterdam. Subsequent transmission to the LOFAR central processing facility will be handled by Surfnet in the Netherlands. A similar route is currently being used for regular e-VLBI experiments, where data from radio telescopes at Jodrell Bank, Cambridge (via radio link to Jodrell Bank), Torun (Poland), Medicina (Italy), Westerbork (Netherlands) and Onsala (Sweden) are transmitted at data rates of up to 512 Mb/s to the EVN data processor at JIVE (located in Dwingeloo, in the Netherlands) for real-time correlation there. Data are transmitted using standard IP protocols across national research networks and Geant. Scientists and engineers at Jodrell Bank Observatory, the MERLIN/VLBI National Facility and the High Energy Physics group at the University of Manchester have played important roles in the development of e-VLBI and are engaged in a number of research projects to develop the technique and capabilities still further. Currently, data transmission from Jodrell Bank also makes use of the UKLight connection from Manchester to Amsterdam, provided by Janet(UK). The last two years have seen a rapid development of this e-VLBI capability, with sustained data rates climbing from 32 Mb/s to 512 Mb/s, and an EC-funded project EXPReS is currently tasked with making 1 Gb/s real-time operations a routine procedure for the European VLBI Network. Sustaining continuous transmission across production networks at these rates is a real challenge and a very active area of research in terms of processing and throughput bottlenecks, data protocols and switching and routing techniques.

Issues for data transport from LOFAR-UK stations include the initial connection from the station to the SJ5 network, and consideration and optimisation of the data rate and management of the data flow across SJ5 and Geant to Amsterdam. For the Jodrell Bank site, a 2.5 Gb/s connection to Manchester already exists, funded through e-MERLIN and a PPARC grant for e-VLBI, with operational costs currently met by MERLIN. Equipment is currently being installed to upgrade this connection to 10 Gb/s. For the Cambridge site, there may be options to make use of the e-MERLIN dark fibre connection to connect with national trunk fibre networks and then SJ5. Other sites will require fibre rental or new optical fibre cables to be installed over distances of up to a few kilometres.

The nature of the data flow from a LOFAR-UK station needs to be considered in detail. While the 12-bit sampling depth is a specification for the LOFAR core and stations in the Netherlands, and may be appropriate for the combination of stations where there are considerable correlated interfering signals present, it may be possible to reduce this sampling depth at remote stations where the interfering signals are much more independent. In addition, it may be possible to increase the amount of local signal processing in order to reduce the transmitted data rate. In the end, this comes down to issues of cost: for the LOFAR core, it is cheaper to transmit larger volumes of data and do the processing centrally, while for the most distant stations it may be more cost effective to do more processing locally and reduce the data rate. As data transmission becomes cheaper and easier, it will be possible to increase the data rate, number of beams and sampling depth, even for the remote stations.

The management of the data flows within the UK, and the interconnections with Geant and Surfnet, will require close interaction with Janet(UK), Dante, Surfnet and LOFAR staff.

10.3 Long-baseline calibration

The calibration and imaging of wide fields of view at high resolution and at low frequencies is one of the key technical challenges facing LOFAR. Substantial effort is being invested by the LOFAR team to study, develop, implement and test calibration and imaging strategies, algorithms and software. Extending LOFAR to long baselines, especially with isolated stations, makes some of these issues more challenging. Solving these issues will not be the first priority of the Dutch LOFAR team and so it will be important for the UK to contribute effort in this area.

The principal issue for LOFAR calibration will be the number of sources per station beam. Even for the 'Minimum Ionosphere Models' developed by Noordam, this number is likely to be 20-30. Longer baselines will resolve a significant fraction of these sources, reducing the number of calibration points per field of view and hence the accuracy with which the ionosphere can be characterised above those stations. Shorter baselines benefit from the coherence of the ionospheric fluctuations on length scales of 100km; longer baselines are likely to require denser calibration observations on the sky in both time and space. Keeping track of the whole number of turns of phase delay introduced by the ionosphere for remote long baseline stations may also be more problematic.

The LOFAR calibration strategy involves solving for instrumental and ionospheric parameters at the locations of individual bright sources and then subtracting these accurately from the data. The brightest sources in the sky (Category 1, roughly the A-team of radio astronomy: Cyg A, Virgo A, etc) are subtracted wherever they are in the sky. The next brightest sources (Category 2) within the beam are used to calibrate and are then subtracted; their solutions are then interpolated over the whole field of view.

Longer baselines require the data to be correlated in narrower frequency channels and with shorter integration times. In general, to keep the field of view constant, the number of sample points has to increase as the square of the baseline length. The increase in correlator output data rate has consequences for calibration, and in particular the (discrete Fourier transform) subtraction of category 1 and 2 sources. The data processing for imaging also increases with the correlator output rate and the size of the image in pixels. It will be worthwhile investigating how to optimise the calibration and data processing techniques for long baselines to the UK and other international partners.

10.4 Operational requirements for Solar and Heliospheric observations with LOFAR

Solar and Heliospheric Physics are not part of the Dutch Key Science plan for LOFAR, and so we discuss here the observational requirements for this aspect of the LOFAR-UK science case. There are clear differences between the operational requirements of these two sets of studies: solar observations (flares, CMEs and coronal shocks, quiescent energy release and solar radar studies of plasma turbulence) will require dedicated observing modes with beams tracking the Sun, whereas the majority of the heliospheric applications require many radio sources across a wide area of the sky to be observed near-simultaneously. Further details are provided below.

Since Solar and Heliospheric Physics is not one of the Dutch Key Science Projects, the European partners will also be responsible for archiving the LOFAR data for this project. We are aware that the Astrophysical Institut Potsdam (AIP) intends to host a LOFAR Solar Data Archive. The University of Glasgow is also exploring the possibility of supporting the archiving of the solar data

from LOFAR, in close discussion with AIP. Considerations for the support of the Helipspheric data are also underway.

10.4.1 Solar observational requirements

Observing the Sun with LOFAR will differ in technique from observations of other astronomical objects. Solar observations with LOFAR require observations taken in four "modes": spectrograph-mode, snapshot-mode, burst-trigger-mode, and campaign-mode, which are described below. Since we are interested in observing and understanding phenomena which are frequency- and time-dependent on the Sun, a spectrographic capability for LOFAR is required to be available alongside the LOFAR radio imaging observations.

For spectrograph mode, we propose using one, or a few, ground stations to have LOFAR operate as a very sensitive and high temporal resolution solar radio spectrograph. Spectrographic observations are essential to make sense of solar radio emission during imaging observations in burst-trigger-mode and campaign-mode. The reason for this is because a variety of radio bursts have been classified according to their form in spectrograms and these, in turn, have been related to various phenomena. Moreover, several very interesting fine structures have been seen in recent spectrogram data. LOFAR acting as a very sensitive spectrograph will very likely reveal much more information on the detailed spectral behaviour of solar radio emissions.

Snapshot-mode solar observations with LOFAR are imaging observations taken, ideally, at a several wavelengths, regularly throughout daylight hours every day. The cadence of the images is to be negotiated, but we initially suggest one set of images every three minutes. These provide 'snapshots' of solar phenomena which will be useful for general and long-term studies.

In addition to snapshot-mode, we also require burst-trigger-mode observations. That is, at certain times, LOFAR would be available to respond to requests to observe the Sun at relatively short notice if bursts are detected. Since the majority of bursts of interest occur infrequently, this approach will be more effective for the solar science than simply allocating time for high resolution observations during which no interesting phenomena may occur. One way in which we envisage this mode might operate is as follows. Radio spectrographs of the Astrophysical Institut Potsdam detect the onset of an interesting radio burst in the LOFAR frequency range. This information is then rapidly communicated to LOFAR, and at the same time a request is made for LOFAR to observe this burst with the highest possible temporal and spatial resolution. The typical total duration of most solar radio bursts of interest will be a few minutes or a few tens of minutes. Ideally the images should be taken with sub-second (millisecond?) cadence and, preferably, in at least two (ideally more) frequencies. This mode will allow us to adequately observe highly dynamic important solar phenomena.

The other mode of observations we propose is campaign-mode. In the solar community, multi-wavelength, multi-instrument, internationally co-ordinated observations are sometimes carried out. These observations are planned typically weeks to months in advance. We would like LOFAR to participate in such campaign observations. These will involve higher cadence observations than in snapshot mode, and most likely a number of frequencies. The specific time intervals and cadence will be specified well in advance of the observations, to allow co-ordination between all instruments. This mode may be used to study, for example, the evolution and development of a solar active region.

Most solar images (e.g., during snapshot mode) will require observations in a relatively small region of the sky, several degrees across, but in some situations (e.g., detailed study of CMEs) larger fields of view might occasionally be required.

10.4.2 Heliospheric observation requirements

Radio scintillation observations of the solar wind, riometric studies of magnetosphere-ionosphere coupling and ionospheric studies all require observations of many weak radio sources over the course of a day, with both the amplitude and phase of the signals sampled rapidly. In the case of radio scintillation observations, the total power received from each radio source must be sampled at 100 Hz across a bandwidth of several MHz, centred near the upper limit of LOFAR frequencies, with the source observed for around 15 minutes in order to build up a well-defined spectrum. The demands of riometric and ionospheric observations would be slightly lower, as regards sampling rate, but once again large numbers of sources would need to be observed.

In order to successfully image solar wind density and velocity structures, a radio scintillation experiment running on LOFAR would need to be able to record scintillation patterns for a large number of astronomical sources lying within about 40° degrees in the sky from the Sun. Most of these sources would be relatively weak, so as a guideline it can be assumed that we would need to observe point-like sources with flux densities of a few Jy at $\sim$200 MHz (the choice of a frequency band near the upper limit of LOFAR capabilities is to optimise the observations to study the solar wind inside the orbit of the Earth, and to reduce the effects of ionospheric scintillation). As the variation in power due to scintillation is of the order of a few per cent of the total flux strength, the observations would be required to have rms noise levels of a few mJy in order accurately measure the scintillation. As the scintillation patterns vary only slowly with frequency, a wide bandwidth is advisable for successful scintillation observations – of the order of a few MHz (most current IPS systems use bandwidths of 10 MHz or more). The collecting area of the LOFAR core should be amply capable of fulfilling these requirements, provided that wide-bandwidth measurement is possible.

Interplanetary scintillation is characterised by rapid variations in signal power, on timescales of less than 0.1s to more than 10s. Estimates of solar wind speed are particularly sensitive to the high-frequency limit of the spectrum, so it is necessary to sample rapidly: sampling should be at 100 Hz at least, and it is generally desirable to sample more rapidly and subsequently integrate to reduce the effects of stochastic noise. For the weaker sources it will take about 15 minutes to build up a well-defined power spectrum for the scintillating flux, and this is what sets the required duration of each source-observation. As many sources need to be observed to build up an image of solar wind structures, the use of multiple beams is highly desirable, but the wide bandwidth and rapid sampling are essential to successful scintillation observations. The best science value would be obtained by running radio scintillation experiments on LOFAR in campaign mode, choosing one or two intervals a year and attempting to construct maps of solar wind density and velocity over a solar rotation (27 days) – these intervals would be selected to offer the best complementarity with other (mainly space-based) observations. A baseline for usage might be 150 sources observed every other day (preferably every day during intervals of higher solar activity) over 27 days, no more than once a year. The requirement to observe a source for 15 minutes to build up a good spectrum of scintillations thus indicates a need for at least 4 beams to observe all of the sources within a 12 hour period, and ideally more beams for a shorter period to increase simultaneity.

11 The LOFAR-UK Consortium

11.1 Consortium members and management

The LOFAR-UK consortium comprises UK university departments and research institutes who plan to work with funding agencies, educational organisations, industry, and the main LOFAR team, to operate a number of LOFAR stations within the UK. It will also initiate and coordinate LOFAR-based and LOFAR-related scientific research, both within the UK and in wider collaborations involving the whole LOFAR team. It plans to coordinate the exploitation of UK skills and resources to maximise the UK's participation in, and scientific return from, LOFAR.

In late 2006, fourteen institutions signed a Memorandum of Understanding which formalised the LOFAR-UK consortium, and led to the formation of a Management Council (MC); a fifteenth has recently also signed up. The institutions, and their representatives on the Management Council, are listed in Table 1. Rob Fender (Southampton) has been elected as the overall Project Leader of LOFAR-UK, and Steve Rawlings (Oxford) as the Deputy Project Leader. These Project Leaders are responsible for representing the interests of the whole LOFAR-UK consortium, both internally within the consortium, and externally through negotiations with the main LOFAR collaboration and other international partners, and with funding agencies. The MC has additionally appointed three project coordinators to oversee various aspects of the LOFAR-UK effort. Philip Best (Edinburgh) has been appointed as Science Coordinator, with responsibility for coordinating the UK White Paper, the UK science effort, and the scientific optimisation of UK stations. Rob Beswick (Manchester) is the Technical Coordinator, with responsibility for managing the technical effort, such as the issues of data transport (liaising with Janet(UK)), long-baseline calibration, and site testing (liaising with ASTRON). Finally, Bob Nichol (Portsmouth) is the LOFAR-UK e-Science coordinator, responsible for investigating novel approaches to data archiving and interrogation, and GRID computing, as well as maintenance of LOFAR-UK email lists and web pages.

Institution	LOFAR-UK representative
Aberystwyth University	Andy Breen
Cardiff University	Steve Eales
Durham University	Alastair Edge
Liverpool John Moores University	Chris Simpson
Open University	Glenn White
STFC (RAL)	Brian Ellison
University College London / MSSL	Catherine Brocksopp
University of Cambridge (Cavendish)	Paul Alexander
University of Edinburgh	Philip Best
University of Glasgow	Graham Woan
University of Hertfordshire	Matt Jarvis
University of Manchester	Simon Garrington
University of Oxford	Steve Rawlings
University of Portsmouth	David Bacon
University of Southampton	Rob Fender

Table 1: Participating institutions of LOFAR-UK, and their representatives on the Management Council.

11.2   Estimated costs and funding of LOFAR-UK

The cost of purchasing all of the hardware associated with a LOFAR station, and installing this on the ground, is currently estimated at £610k per station. This excludes the cost of acquiring and preparing the land, and of providing a fibre connection for the station. Running costs include: fibre rental to transport the data to the Netherlands – this differs from site to site, being upwards of £20k per annum; electricity costs at £10k per annum; technician support and other maintenance at around £10k per annum; yet-to-be-finalised contributions towards central processing costs, likely to be of order £40k per annum per station.

Currently thirteen UK universities have pledged funds to the LOFAR-UK project, totalling £600k. In addition, the University of Manchester, the University of Cambridge, and the STFC (RAL) have all pledged land for LOFAR stations, with e-MERLIN fibre connections already available at the Jodrell Bank and Lord's Bridge sites. Further universities have expressed interest in joining the LOFAR-UK consortium, and are currently attempting to raise funds. Bids are also submitted or in preparation for the additional funding required to reach the UK's target of four LOFAR stations. These include:

- A bid to the Scottish Funding Council, submitted in July 2007, as part of a larger SUPA2 initiative. This would make a substantial contribution towards the initial purchase, installation and commissioning costs of a Scottish LOFAR station.

- A bid to HEFCE as part of the SEPNET 'ASCE' initiative, to include more south-eastern Universities in the LOFAR initiative, provide installation support for the Chilbolton site, and provide computing support for the LOFAR-UK effort.

- A bid for ≈ £100k, to be submitted to the South-East England Development Agency (SEEDA), to support the operation of a station at the Chilbolton site.

- A bid to STFC, in preparation, to support the remainder of the construction and first three-year running costs of the four LOFAR-UK stations, together with postdoctoral and FTE support for addressing the technical challenges associated with long-baseline calibration and data transport, and building a UK LOFAR archive.

It is envisaged that funding of the stations beyond the initial 3-year period will be drawn from either European Union funding through the Framework Programme 7, or through STFC Rolling Grants of the LOFAR-UK consortium members.

ASTRON has indicated that there will be two phases or purchasing of LOFAR stations, in Winter 2007-8 and Winter 2008-9. LOFAR-UK already has sufficient funding in place that it is proceeding with the purchase of a single LOFAR station in the Winter 2007-8 round. The goal is to follow this with the purchase of three more stations next year. On a longer timescale, there are aspirations to further increase the number of UK LOFAR stations, with other funding sources being investigated.

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