German LOFAR - A New Era in Radio Astronomy

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Abstract

LOFAR stands for LOw Frequency ARray and is a new radio telescope under construction in the Netherlands that will operate in the frequency range between 10 and 240 MHz. In this largely unexplored domain, LOFAR will be the dominant telescope over the next decade. Because of the improvement in sensitivity and resolution by a factor of 100-1000 compared with present-day telescopes LOFAR will open a new window to the Universe. We propose a significant German participation in LOFAR with **remote stations** *and a* **science network**. *This paper outlines the LOFAR-relevant science interests of the German astrophysical community in the fields of extragalactic astronomy and surveys, Galactic astronomy, solar system science, variable and transient sources, and astroparticle physics.*

1 Introduction

LOFAR, the Low Frequency Array, is a next generation low-frequency radio telescope under construction by ASTRON in the northern part of the Netherlands. The project is funded by the Dutch government and the SNN (Samenwerkingsverband Noord-Nederland), providing a total subsidy of 74 million Euros. Construction will start in 2006, completion of the Dutch LOFAR Phase 1 is expected in 2008.

LOFAR constitutes a radical conceptional change with respect to earlier radio telescopes: classical large dishes that focus the radiation are replaced by a multitude of small and cheep antennas that sample radio waves digitally, transport them over next-generation internet connections to a fast supercomputer, where one or several large telescopes are synthesized in real time. This concept provides enormous flexibility as the electronic beam can be steered across the sky within microseconds. Also more than one beam can be formed at the same time to observe in different directions simultaneously. LOFAR antennas will have no moving parts, are cheap to build and easy to maintain. Furthermore, efficient suppression of disturbances by artificial signals (RFI) and the ionosphere is simpler with a digital telescope such as LOFAR. (For a review in German see Falcke 2004.)

The currently funded first phase of LOFAR only extends to the Dutch border. The key benefit of a German participation lies in the large baselines which, in turn, will lead to a dramatic increase of the power of this telescope and its astronomical applications. A German participation with a rather modest number of stations (at least 10) would provide an excellent spatial resolution for surveying the Universe. LOFAR will serve as the low-frequency precursor for the Square Kilometer Array (SKA), the next-generation international radio telescope, which is planned for the years beyond 2015. The SKA is to cover almost the whole radio window accessible from the ground, from 100 MHz to about 25 GHz (for the SKA Key Science Projects see Carilli & Rawlings 2004.) The experience gained with LOFAR is essential for a significant German participation at the SKA.

A number of groups at German universities and Max-Planck institutes with strong interests in LOFAR have formed a collaboration called GLOW, which stands for German LOng Wavelength Consortium. Under this umbrella a community has formed with strong interests in long wavelength observations and the related technology. The prime goal of this consortium is to coordinate the German LOFAR activities and to represent German interests within the LOFAR project.

2 Epoch of Re-ionisation

The onset of galaxy and star formation marks the time at which the early Universe emerged from the so-called "Dark Ages". At this time, which is referred to as the Epoch of Re-ionisation (EoR), the first sources start ionising the surrounding gas and eventually drive the Universe to the transition from neutral to ionised. Uncovering the timing, morphology and duration of this event is one of the most topical issues in current cosmology. The LOFAR design will provide an unprecedented observational probe into the high-redshift Universe and directly map the physical conditions of early structure formation. After recombination at a redshift of ~ 1100, the baryonic matter in the Universe remained neutral until the first stars and galaxies formed. The nature of the sources responsible for the re-ionisation of the intergalactic medium (IGM) is still the subject of a lively debate but most theoretical models adopt stellar sources. These have to be constrained on the basis of the available observations: (i) the value of the IGM temperature from the Lyman alpha forest at $z \sim 2$–4, (ii) the abundance of neutral hydrogen at $z \geq 6$ from the spectra of high-redshift quasars (QSOs), and (iii) the measurements of the Thomson scattering optical depth by the WMAP satellite. The last condition suggests that the IGM reionisation occurred at $z > 10$. An upper limit to the reionisation redshift, $z < 30$, is set by the observations of Cosmic Microwave Background (CMB) temperature fluctuations which would otherwise be suppressed. In addition to stellar-type sources, a contribution to the ionising photon budget could also come from an early population of miniquasars powered by intermediate-mass black holes. Finally, another possible contribution to re-ionisation at high redshift could come from decaying particles and neutrinos.

The radiation signature that LOFAR may be able to detect was emitted in a period preceding full re-ionisation. The signal is expected to be similar in all directions, i.e. it is a global signal. In the cool, still neutral regions of the Universe, the medium was heated by the ionising sources (stars, quasars or mini-halos) and the hydrogen spin temperature decoupled from the CMB emission. This effect caused a small step in the temperature of the background radiation. The predicted spectroscopic signature is generated at the rest frequency of the neutral hydrogen (HI) line (1420 MHz) but redshifted to LOFAR frequencies by the expansion of the Universe. Therefore, the exact frequency at which the temperature step is detected is linked to the time in the past at which it occurred.

To investigate this transition phase LOFAR will be equipped with dipoles optimised for the 110–250 MHz band. Because the transition is expected to occur globally, the LOFAR collecting area at these frequencies, in principle, need not be very large. The expected signal, about 15–20 mK in brightness temperature, with a spectral width of about 5–10 MHz, does not depend on aperture size. A calibration of this faint signal, however, will require a telescope with a substantial collecting area. The longer baselines of LOFAR are needed to assist in the identification and spectral characterisation of discrete sources in the field(s) of view being observed for the spectral decrement. In both cases - use of the inner portion of LOFAR to search for the spectral decrement and exploiting the high angular resolution of LOFAR to identify foreground contaminants - the broad-band nature of LOFAR will be essential. A second contaminant is the diffuse non-thermal Galactic foreground emission which is responsible for the bulk of the radio noise from the sky at LOFAR frequencies. Fortunately, this diffuse emission has very little structure on the angular scales where the global signal will be sought (~ 0.5 degree).

Prior to full re-ionisation the intergalactic medium was most likely a mixture of neutral, partially ionised, and fully ionised structures. It is believed that the low-density regions will be fully ionised first, followed by regions with higher and higher densities. A patchwork of neutral hydrogen emission will result in structures up to a degree in size. Rather than being a global, all-sky feature, this patchwork of emitting and absorbing structures will give rise to brightness temperature fluctuations in the sky on angular scales of 1'– 30' and in narrow bandwidths (a few MHz). While remaining an extremely challenging project, the detection and imaging of the 21cm intensity fluctuations with LOFAR in, both, frequency and angle will provide a three-dimensional map of re-ionisation and is within range of the planned LOFAR sensitivity. Long integration times (approaching weeks or more) may be required. However, LOFAR's multi-beaming capability enables the simultaneous imaging of large areas of sky, effectively permitting very long integrations. The biggest hurdles are the removal of discrete and diffuse foreground emission components that would otherwise dominate the signal at these wavebands. Fortunately, most these contaminants give rise to spatial but not frequency structure, while the ionisation signals have both. Moreover, any residual galactic signal is expected to show a rather non-uniform distribution over the Galaxy and should not show a preference for a particular spectral range. These are powerful discriminators between contaminants and the real cosmological signals. The output of this experiment should be a large set of narrow-band images over a wide area of the sky (hundreds of square degrees), and over a wide frequency range, containing fluctuations due to HI emission and/or absorption.

As was pointed out above, the time of the epoch of reionisation and, consequently, the frequency of the spectral decrement is uncertain. The broadband nature of LOFAR would enable a search for this effect over a finely spaced grid of frequencies, ensuring detection of the EOR transition, provided it falls in the redshift range 5–12.

3 Cosmological Large-Scale Structure in the Radio

During the formation of cosmological large-scale structure enormous amounts of energy are released. A significant fraction of this energy goes into the acceleration of particles to relativistic velocities. These particles accumulate within galaxy clusters and filaments and may constitute a large part of the energy density in these structures. Consequently, these populations of relativistic particles may play a crucial role in the formation of large-scale structures. The electron component of the relativistic population has been observed for nearly three decades in the radio band. Many clusters of galaxies host a diffuse, steep-spectrum *radio halo* that is produced by synchrotron emission of ultra-relativistic electrons in intergalactic magnetic fields. About two dozen radio halos are known and LOFAR is expected to observe thousands of new ones. The exact origin of radio halos is still shrouded in mystery. The responsible electrons have too short radiative lifetimes to be produced directly at shock waves. Therefore, they need to be either re-accelerated in situ, e.g. by turbulence, or freshly injected. A promising candidate for injection is a longlived relativistic proton population. These protons collide with the thermal gas and produce secondary electrons via pion production. In a sense a galaxy cluster can be regarded as a cosmic-sized particle detector. The shock wave acts as an accelerator for protons, the intergalactic gas as the target, and the magnetic field as a "scintillator" which produces the electromagnetic signal that can be read out with a sensitive radio telescope such as LOFAR on Earth.

Because of their low surface brightness, halo sources are difficult to find; extensive searches have so far brought to light no more than about ten. The low-frequency radio emission of these halos has a steep spectrum so that low-frequency surveys are ideal to renew the search for these enigmatic objects, especially in the thousands of clusters at $z > 0.5$ that X-ray observatories and large-area CCD cameras will find in the coming decade. The luminosities of the presently known haloes suggest that a LOFAR survey could detect several hundred halo sources in the $0.5 < z < 1$ interval, if they exist. If halo sources are a clear signature of clusters that are in the process of merging, the frequency of their occurrence will be much higher at greater distances.

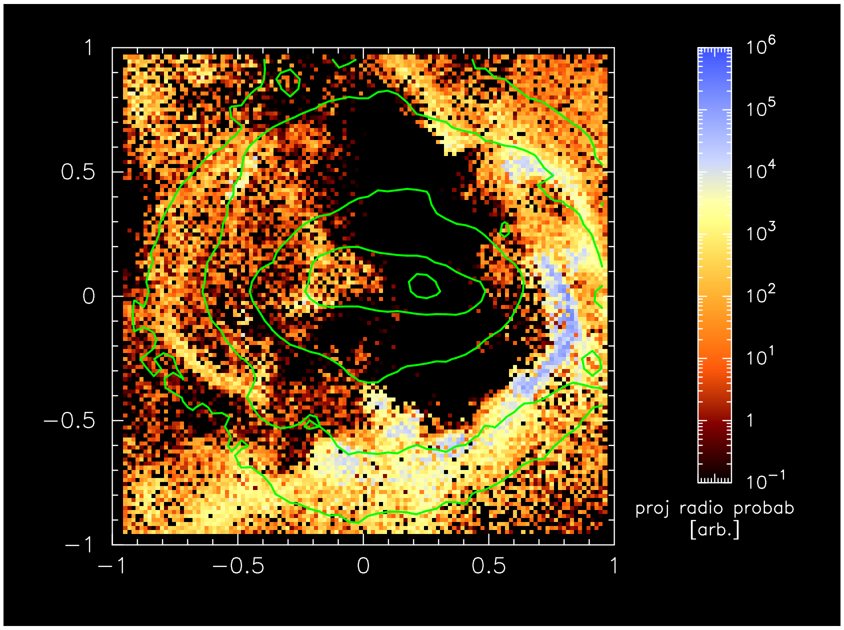

Figure 1: The projected 'potential' radio luminosities for 1.13 Gyr old radio plasma. For comparison the bolometric surface X-ray luminosity, $L_X = 1.2 \times 10^{-24}\mathrm{ergs}^{-1}\,\mathrm{m}_{\mathrm{gas}}/(\mu\mathrm{m}_\mathrm{p})\,\sum\rho_\mathrm{i}/(\mu\mathrm{m}_\mathrm{p})\,(\mathrm{kT}_\mathrm{i}/\mathrm{keV})^{1/2}$, is given. Contours are at 10^{41}, 10^{42}, 10^{43}, 10^{44} and $10^{45}\,\mathrm{erg\,s^{-1}\,h^3\,Mpc^{-3}}$. The total bolometric X-ray of the cluster is $2 \times 10^{44}\,\mathrm{erg\,s^{-1}}$ and the emission-weighted temperature is $3\,\mathrm{keV}$. For more details see Hoeft, Brüggen & Yepes (2004)

At the locations of several shocks very extended, steep-spectrum radio sources have been observed. Owing to the lack of any visible galaxy counterpart, the sources have been termed cluster radio relics. Radio relics are believed to be compressed remnants of formerly radio-emitting plasma that has been produced in large quantities by active galactic nuclei in radio galaxies. Due to the short radiative life time the radio emission of this plasma fades quickly and leaves behind a *radio ghost*. When such a radio ghost is compressed by a shock wave the electrons gain energy and the magnetic field is amplified so that the radio emission in observable bands rises again, see Fig. 3 (Hoeft, Brüggen & Yepes 2004, Ensslin & Brüggen 2002). So far only about a dozen radio relics of this kind have been observed. This points to a large gap in our knowledge of the late phases of radio galaxy evolution. However, a sensitive low-frequency radio telescope, such as LOFAR, is expected to unravel thousands of such sources. The existence of radio ghosts was confirmed very recently by high-resolution X-ray observatories which have detected spherical cavities in the surface brightness profiles of galaxy clusters. In some cases these cavities are associated with remnant, low-frequency radio emission. The cavities are interpreted as bubbles of relativistic gas that have been inflated by the central AGN. The relativistic gas has pushed away the thermal gas thus causing depressions of the x-ray emission. As these underdense but high-pressure bubbles expand and rise through the intracluster medium they do mechanical work on the ambient gas. The injected mechanical energy is eventually dissipated and heats the cluster. Recent research suggests that the energy released by the bubbles balances the radiative losses of the intracluster medium. Thus they prevent the cooling catastrophe in the cool cores of galaxy clusters and explain their temperature profiles.

LOFAR will revolutionise the observation and understanding of these high-energy components of the cosmic large-scale structure because it is ideally suited to observe extended, steep-spectrum sources in point source confused fields. Thus, astronomers will be able to study many examples of radio halos and relics in great spatial and spectral detail. LOFAR will provide us with statistically meaningful samples of these tracers of large-scale structure formation in the Universe. It will provide a powerful complement to the study of the important process of cluster formation. The large number of remnants expected at redshifts around 2–3 makes this a powerful tool of a phase in cosmic history when the IGM was moving deeper and deeper into the potential wells formed by dark matter when the X-ray emission was still building up. In Germany, there exists a vibrant community that has pioneered large parts of the science described above.

4 Cosmic Rays and Magnetic Fields in Galaxies

Models of galaxy evolution require an understanding of star formation on scales that range from star-forming cores of dense molecular clouds to feedback processes on lengths scales of the whole galaxy. The different components of the interstellar medium (ISM) trace the different stages of stellar evolution: from molecular clouds that provide the material for new stars to the metal-enriched hot medium produced by supernovae. Among the constituents of the interstellar medium, cosmic rays and magnetic fields play an important role. Cosmic rays and magnetic fields support or even drive the formation of galactic halos, and may play an important role in the formation of spiral arms.

Cosmic rays and magnetic fields are best traced by radio continuum emission. The low-frequency end of the radio spectrum is particularly important because in this regime the synchrotron component is not contaminated by the thermal component that starts to become dominant at around ~ 10 GHz. Furthermore, the emission at low frequencies comes from cosmic-ray electrons of lower energies and, hence, longer lifetimes.

One important result of previous studies is the radio continuum – far-infrared luminosity relation that characterizes the star formation rate in galactic disks. A similar relation was also found between the radio continuum and the mid-infrared luminosities, and even for the surface brightness within spiral galaxies in both spectral ranges on spatial scales below 1 kpc. This relation demonstrates the role of radio emission as an unbiased tracer of star formation. However, the origin of this relation is far from being understood, especially the effect of magnetic fields on star formation. Furthermore, it is not clear below which scales in space and time the relation breaks down. Very young starbursts may not have generated cosmic rays that radiate in the radio range; hence the first starburst galaxies in the Universe may have been radio-quiet. Galaxies in the early Universe are essential to understand the radio – IR relation.

Another discovery that was made from low-frequency observations was that many galaxies are surrounded by huge radio halos (Fig. 4), sometimes much larger than in any other spectral range. The origin of cosmic rays and magnetic fields in such halos is unclear. The relativistic particles may have diffused out from the disk, may have been advected with the gas in a galactic wind, or may have been accelerated by turbulent processes or shocks in a wind. The cosmic ray spectrum observed via the radio spectrum will shed light on the origin and propagation of cosmic rays.

The strength and structure of magnetic fields in galactic halos are problems of special interest. Equipartition arguments for estimates of the field strength may not hold in dynamic halos, so that additional data are required, e.g. from Faraday rotation and Faraday depolarization of polarized radio waves. Faraday effects decrease strongly with increasing frequency, so that at high (GHz) frequencies the degree of polarization is large. This effect, however, cannot balance the strong decrease of the radio luminosity due to the steep synchrotron spectra of halos. At low frequencies the degree of polarization is small but still observable. As a result, very little is known about the large-scale structure of magnetic fields in halos. Only a few exceptionally bright halos have been detected in polarization (Fig. 4). With multi-channel spectro-polarimetry (Brentjens & de Bruyn 2005) one can deal with Faraday

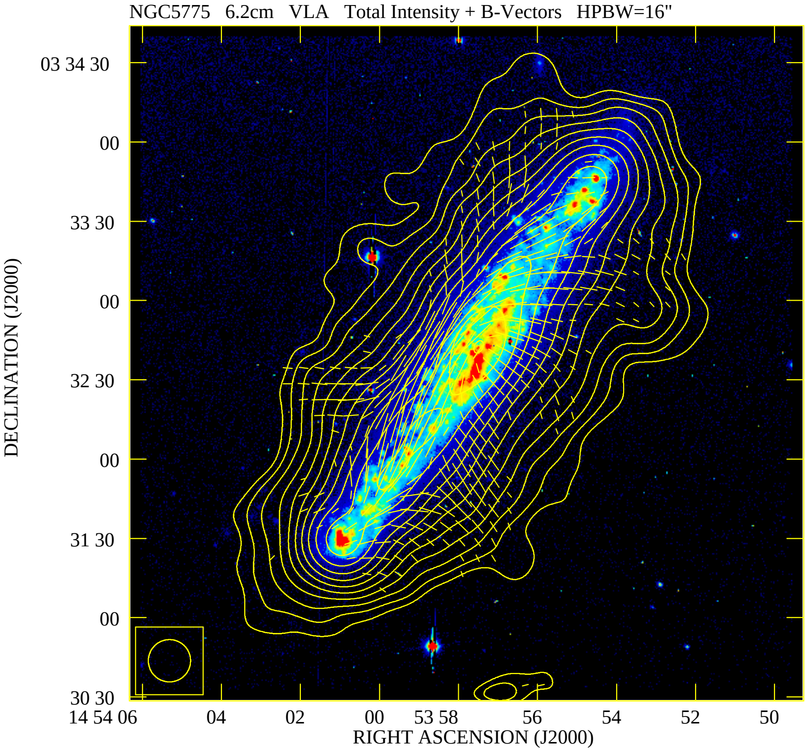

Figure 2: Total intensity (contours) and polarization (B-vectors) of NGC 5775 at λ6.2 cm from combined Effelsberg and VLA observations (Tüllmann et al. 2000).

depolarization and increase the polarized signals significantly. With LOFAR's high sensitivity and large number of spectral channels this method can be applied to much fainter and much more distant galaxies.

The low-energy/low-frequency regime is not well studied, mainly because few experiments have sufficient angular resolution at these wavelengths to resolve galaxies. With the angular resolution and sensitivity of LOFAR it will be possible to obtain low-frequency maps to provide completely new information on cosmic rays in nearby galaxies. LOFAR observations could also solve the problem of missing cosmic rays in dwarf galaxies. If their spectra are very steep, existing radio telescopes may just have missed the emission. LOFAR may also detect polarized emission from galactic halos, which would enable us to understand the origin of large-scale magnetic fields.

Studies on galaxy structure in the radio continuum, optical and infrared spectral ranges as well as theoretical studies on galaxy structure and evolution have a strong tradition in German astronomy. The Effelsberg 100-m telescope had been most successful instrument for the study of magnetic fields in galaxies and in the Milky Way (Wielebinski & Beck 2005). The access to LOFAR would strengthen these activities and help maintain their internationally recognized position.

5 The Milky Way

Low-frequency high-resolution observations of Galactic emission with LOFAR will complement several aspects of Galactic high-frequency work as carried out, e.g., at the Effelsberg 100-m telescope of the MPIfR (Fig. 5). LOFAR covers the relatively unexplored low-frequency range where some key information about the interstellar medium can be obtained.

At frequencies below 100 MHz thermal gas that exists in diffuse form throughout the Galaxy as well as in discrete HII regions becomes optically thick and, depending on electron density and temperature, absorbs emission from background sources. Here, it is essential to know the thermal state of the gas along the line of sight. Cold thermal gas close to about 1000 K is known to exist from recombination line observations. This fully or partially ionised low-density gas (1–10 cm^{-3}) has a size of 50–200 pc and surrounds HII regions. Its distribution and contribution to the total ionised gas mass is unknown and its effects on the ISM dynamics remain to be determined. By combining Faraday Rotation Measure (RM) data (see below) with thermal emission in the direction of supernova remnants, the magnetic field strength and its dependence on thermal electron density and temperature can be estimated. For RM determinations, high-frequency polarisation observations will be combined with future LOFAR data for a common interpretation.

Another application of thermal absorption is *tomography* of the total synchrotron emission. At low frequencies HII regions absorb all synchrotron radiation. As a result, any remaining synchrotron emission must come from regions between the observer and the nearest optically thick HII region. Thus HII regions at different distances provide a tool to trace the synchrotron emissivity as a function of distance. With a sufficiently large number of HII regions with known distances to be observed by LOFAR, a detailed distribution of the synchrotron emissivity within a few kpc distance from the Sun can be derived. Modelling the radio emission of the Galaxy requires precise knowledge of its local distribution. Recent Effelsberg results indicate that the local emissivity has been significantly underestimated previously. As a consequence, the size of the halo of our Galaxy is smaller or its emissivity is lower than assumed so far.

The polarization capabilities of LOFAR for a wide frequency range open new possibilities to study details of the local Galactic magnetic field on subparsec scales. In the Galactic plane detection of low-frequency polarized emission is limited to a few hundred parsec (or even less) due to Faraday depolarization effects, while the total emission is a superposition of components extending over the entire Galaxy. Detailed structures of the local magnetic field become visible in linear polarization, complementing studies of larger scales in nearby galaxies (see above).

Faraday rotation provides additional information of the magnetic field component along the line of sight. Faraday rotation increases with λ^2 and becomes rather strong in LOFAR's frequency range. Narrow channel polarimetry as will be provided by LOFAR allows a precise determination of Rotation Measures (RM) components along the line of sight (Brentjens & de Bruyn 2005). In this way *polarization tomography* of the local magneto-ionic medium can be performed. Note that bandwidth depolarization becomes significant for a channel width of 1 kHz at 30 MHz only for RMs exceeding about 100 rad m^{-2}.

The distribution of polarized Galactic emission is also affected by the various Faraday depolarization effects. Measurements of *Faraday dispersion* can yield estimates of the size and spectrum of turbulent cells in the magnetized ISM. If magnetic fields, thermal gas and cosmic rays are mixed, the effect of *differential Faraday rotation* causes total cancellation of polarized signals at certain values of the observed mean RM which may mimic filamentary magneto-ionic structures ("canals", see Fig. 5). These, however, do not correspond to real features. With LOFAR's multi-channel capability one can analyze differential Faraday rotation as a broad distribution of RM values around its mean value along the line of sight. Real magnetic filaments, on the other hand, should generate sharp RM signals along the line of sight.

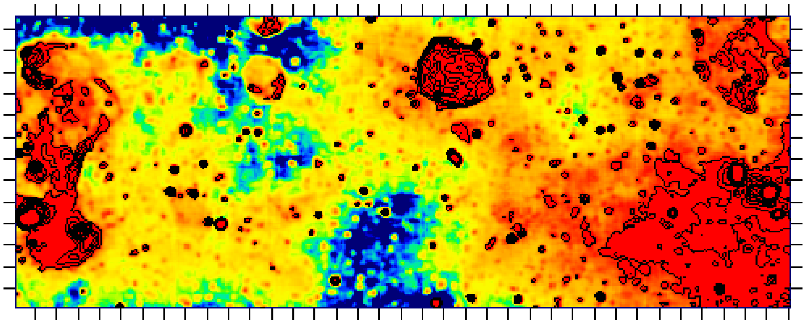

Figure 3: Total radio emission from a $24^o x 9^o$ section of the 1.4 GHz (λ21 cm) Effelsberg Medium Latitude Survey centered at $l, b = 162^o, 0^o$, with large-scale emission added from the Dwingeloo survey (Reich et al. 2004).

If Faraday rotation occurs in the magneto-ionic medium in front of the emitting source, this is described as a *Faraday screen.* Variations in electron density and/or magnetic field strength, e.g. by HII regions, planetary nebulae or supernova remnants, are reflected as modulations of the polar-

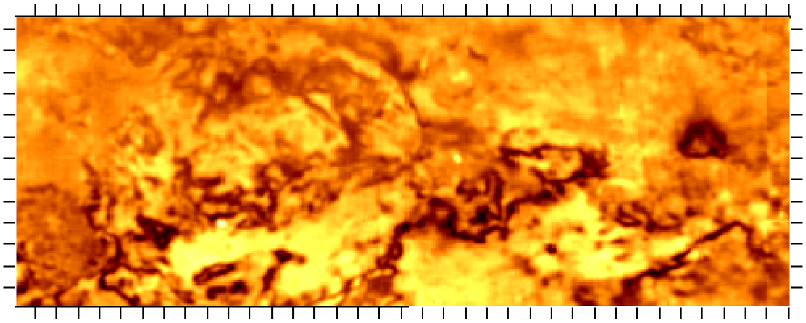

Figure 4: Polarized radio emission from the same region as in Fig. 5 (Reich et al. 2004).

ized background by the foreground screen (Fig. 5). The excellent resolution of LOFAR in its full extent allow a study of such fluctuations on previously unprecedented scales of a few 10^{-3} pc.

At high Galactic latitudes RMs are very low and observations at long wavelengths are needed to trace them. The existence of thermal gas at high latitudes is known from Hα surveys. The mechanism of excitation of high Galactic latitude gas is not well understood at present. The thermal electron density decreases with latitudes, while its filling factor increases on average as derived from pulsar dispersion measures. RM studies could provide more detailed information of the distribution, density and filling factor of thermal gas. In areas where Hα surveys have insufficient sensitivity, thermal gas e.g. of density 10^{-3}cm^{-3}, distributed over 1 kpc in a regular magnetic field of 1μG, causes a RM of just 0.8 rad m^{-2}. This is undetectable with present-day instruments, but can easily be traced with LOFAR in the frequency range below 150 MHz.

6 Surveys

One of the purposes of LOFAR is to survey the galactic and extra-galactic radio sky. Multi-channel all-sky surveys at low frequencies, with unresolved compact extragalactic sources removed, will result in detailed spectral index information of the diffuse Galactic emission across the sky. Diffuse Galactic emission consists of a mixture of thermal radiation and synchrotron emission, whose fraction varies as a function of Galactic coordinates.

All-sky diffuse Galactic radio emission and spectral index information, together with the magnetic field structure derived from radio polarization data, will constrain models of the origin and propagation of Galactic cosmic rays. The distribution of cosmic rays over geological times at the position of the Sun has received renewed attention from the geosciences since effects of cosmic rays may well result in a contribution to climate changes on Earth.

LOFAR will also set new benchmarks for surveys of radio sources in the low-frequency regime, extending the sensitivity by two orders of magnitude and the resolution by one order of magnitude. In addition, LOFAR will revolutionise survey work by exploring the *time* domain as a new survey parameter. Intensity variations of radio sources can be detected on timescales from seconds to years, and even the detection of variations on timescales of decades is in the realm of possibility.

LOFAR's harvest from surveys will be a great variety of galactic and extragalactic sources. There will be discoveries of objects from known classes as, for example, radio galaxies, which harbour supermassive black holes in their centres. Because of their steep radio spectra with maximum emission at rest frequencies of ≈ 1 GHz, detections at very high redshifts ($z > 4$) require low-frequency surveys. The vast majority of the extragalactic radio population at mJy level and below will consist, however, of faint, low-luminosity radio sources ($L < 10^{23}$ W/Hz), associated with star-forming disk galaxies. The study of these objects will open a new opportunity to disentangle the role of star formation and black holes during galaxy evolution at cosmological distances.

LOFAR's capability to detect transient sources and to follow processes varying in time will prompt patrol surveys to detect radio bursts, for example, from active stars, exo-planets, Gamma-ray bursts, or radio supernovae. The harvest will also contain yet rare specimens of extragalactic objects, such as Mpc-sized radio galaxies, radio remnants from past radio galaxy activity periods, and radio halos in galaxy clusters, which are known only in small numbers today.

If the history of scientific discovery is any example, the excitement of LOFAR will not only be in the study of well known or emerging populations, but in the yet to be made discoveries of new phenomena. It is this prospect that makes the time-consuming and extensive work on surveys a fascinating field of research.

7 The Sun

The Sun is a very intense radio emitter in space. The non-thermal radio emission is a sensitive indicator of solar activity. There is a huge variety of solar activity concerning spatial and temporal scales, the 11-year cycle being the best-known signature of solar variability. During flares a huge amount of energy is suddenly released within a period of a few hours. Here, magnetic field energy is transferred into plasma heating, particle acceleration, and mass flows. Furthermore, a large amount of coronal material is injected into interplanetary space, a phenomenon called Coronal Mass Ejections (CME). All these different phenomena of solar activity have their special signatures in the radio band. Thus, the study of solar radio emission provides very important information on magnetic energy release, electron acceleration, coronal shock waves, coronal mass ejections. All these processes are of general astrophysical interest but can be studied best on the Sun.

Generally, it is assumed that the solar radio emission in the low-frequency range is generated by plasma emission. Here, energetic electrons excite high-frequency electrostatic plasma waves that interact with the background plasma to produce electromagnetic waves with frequencies near the local electron plasma frequency. In the gravitationally stratified solar atmosphere, the high and low frequencies are emitted in the low and high corona, respectively. LOFAR will be able to measure the emission in the frequency range between ~ 10 and 240 MHz. These frequencies correspond to radial distances of 1.2 and 2.5 solar radii, respectively. Thus, LOFAR will be able to monitor the corona and the region of its transition into the near-Sun interplanetary space. This region is very important since this is the region where the solar processes that are relevant for the solar-terrestrial relationship take place. Solar activity influences Earth's space environment in mainly two different ways: CMEs can impinge on the Earth's magnetosphere in a period of 1-3 days after their launch in the corona. This leads to magnetic storms disturbing the navigation of ships and airplanes as well as the intercontinental radio communication. In summary, LOFAR will provide the possibility to use the Sun as a plasma physics laboratory and at the same time be a useful tool in space weather research.

8 Astroparticle Physics

It has recently been realized that radio telescopes such as LOFAR are ideal experiments for direct detections of the highest cosmic rays. The detection of ultra-high energy cosmic rays (UHECR) with energies up to and beyond 10^{20} eV is the main aim of many astro-particle physics experiments. The nature and physics of these particles is one of the big mysteries in astrophysics today. When UHECR collide with particles in the Earth's atmosphere, the collision has a centre-of-mass energy well above what can be achieved in the largest particle accelerators on Earth. In the form of an extensive air shower, the resulting particle cascade rushes through the atmosphere and can be detected with particle or optical air fluorescence detectors. The rather lower incidence of these relativistic particles, however, requires large detector arrays. Leading experiments in this field with significant German participation are KASCADE-Grande in Karlsruhe/Germany and the Pierre Auger Observatory in Argentina.

As the air shower intersects the Earth's magnetic and electric field (the latter only being relevant during thunderstorms), the particles are deflected and start producing radio emission. Since the thickness of the emitting shower "pancake" (a few meter) is less than the wavelength at frequencies below 100 MHz, the radio emission is coherent and greatly amplified. This process has been simulated extensively with a new Monte Carlo code developed at the MPIfR in Bonn. An experimental test of the radio emission from extensive air showers is under way with the LOPES experiment at the Forschungszentrum Karlsruhe. The experiment utilizes LOFAR prototype antennas in conjunction with the particle detectors of the KASCADE array. First successful detections have been made (Falcke et al. 2005).

Alternatively, one can use LOFAR itself as a large cosmic ray detector. LOFAR's design has been modified in order to make this possible. Estimates indicate that LOFAR can observe cosmic rays over the entire range from 10^{15} to 10^{20} eV making it a very competitive cosmic ray experiment. Its advantages are that the power in radio pulse from the geomagnetic effect should be directly proportional to the energy of the primary particle squared. Since radio photons do not suffer absorption in the atmosphere, all particles in the shower will contribute. Thus, even highly inclined showers can be seen.

The range of particle energies that can be observed with LOFAR can be greatly expanded in the future, once one is able to use isotropic signals, such as radar reflections, from the ionisation trails of air showers. This is applicable to energies above 10^{20} eV and is based on a much larger detector volume.

9 Synergy with other projects

The LOFAR project can provide interesting and fruitful interconnections between existing research programmes in Germany. Some are listed below:

- **The Forschungsverbund Astro-Interferometrie:** The following four institutions located in Nordrhein-Westfalen (NRW) have recently formed a competence cluster ("Forschungsverbund") for interferometry: the I. Physikalisches Institut at the University of Cologne, the Astronomical Institute at the University of Bochum, the Astronomical Institute at the University of Bonn, and Max-Planck-Institut für Radioastronomie Bonn.

- **The D-Grid programme** is an initiative of the "Bundesministerium für Bildung und Forschung (BMBF)" to support the development of e-science and Grid middleware for scientific applications in Germany. Starting in autumn 2005 the D-Grid Integrations Project managed by the Forschungszentrum Karlsruhe aims: 1. to build a robust, flexible and sustainable technical Grid infrastructure for e-science applications 2. to develop e-science services for scientific communities and 3. to enhance the scientific efficiency.

- **EISCAT** stands for European Incoherent Scatter Scientific Association. It was established more than 25 years ago for studies of the Earth's ionosphere and upper atmosphere in polar regions. The EISCAT observatories, located in northern Scandinavia and on Spitzbergen/Svalbard, operate high power radars with high-gain dish antennas and sophisticated digital radar control, data acquisition and analysis systems. EISCAT is presently in the stage of preparing a new generation radar system that will apply interferometry, imaging and digital beam forming techniques. A close collaboration on technology and digital signal processing between the communities of LOFAR/GLOW and EISCAT is planned.

10 Organization

Figure 5: Model of a LOFAR station with low-frequency antennas (by courtesy of ASTRON).

In the previous sections we have outlined the broad impact that LOFAR is going to have on astrophysical research in Germany. These science cases make a strong case for an active involvement by German institutions in the LOFAR project. In detail, this involvement may look as follows:

Early LOFAR Remote Stations are essential for gaining the necessary experience with LOFAR observations and to conduct tests over long baselines with the stations in the Netherlands. Single stations will permit new kinds of experiments, like all-sky surveys for transients. Furthermore, student education and training has to establish the knowledge for future science with LOFAR and finally the SKA.

The cost of a Remote Station (estimate by ASTRON from March 2005) consists of the antennas and station electronics which make up 460k Euro. The station infrastructure such as housing, power supplies, etc. are estimated as 80k Euro. The manpower needed for test and integration forms part of the station costs 50k Euro. Local storage and processing costs of the order of 30k Euro should be added to this. The total cost to budget for a Remote Station excluding land and external connections is 620k Euro. Important subsystems (receiver unit, high band antenna) still have large cost uncertainties. For that reason a contingency of 10% is used, giving a total of 686k Euro per station. The cost of land, connection to the power grid and the Wide Area fibre connection are not specified here, since they heavily depend on the local situation. We assume that the land for the station will be provided by the host institutes.

In addition to a participation in the hardware and infrastructure of the telescope, a scientific backbone needs to be provided that ensures that LOFAR data is readily available and can be used effectively by astronomers in German institutes.

The *LOFAR Science Network* is envisaged to form a virtual organization that concentrates competence in the various fields and administrates a distributed user community with inhomogeneous access rights to the available facilities. The resources are the telescope time, the operational modes for observations, the data storage to buffer the incoming flow of raw data, the computational facilities to process the data, and the data bases for final and public data products. There will be users of the system with a spectrum of different roles as scientists organized in different sub-projects, software developer to build and maintain the data processing pipelines, administrators of the various resources, guests and trainees from schools and universities, and the general public accessing the public archive. The now initiated German GRID initiative of the BMBF is going to evaluate, to bundle, and to install the required software and administrative infrastructure to facilitate such virtual organizations. The GLOW consortium will therefore be one of the first applicants in Germany of this new concept of distributed collaboration and thereby a driver for further development of technology-based organizational tools in scientific projects.

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Figure 6: Locations of the LOFAR core near Dwingeloo and the proposed early remote stations in Germany. Further stations in Garching and Göttingen are under consideration.