LOFAR

Scientific Applications

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Summary

This document contains a description of the Science Case for the Low Frequency Array (LOFAR) – an advanced digital radio telescope that will operate in the frequency range from ~10 to ~250 MHz. The instrument will be developed by ASTRON (Dwingeloo, The Netherlands) and the Astronomical Community in the Netherlands, MIT/Haystack Observatory (Westford MA, US) and the Naval Research Laboratory (Washington DC, US).

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Note

The applications of LOFAR described in this document may not all be feasible with the final instrument. Discussions about the design of the instrument are ongoing. Part of these discussions is to collect convincing arguments for pushing the final design one way or another. Consequently, details found in individual contributions in this document may not accurately reflect the (current) state of the planned instrument.

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1 Introduction

1.1 Background

LOFAR's goal is to open a new, high-resolution window on the electromagnetic spectrum from ~10–250 MHz (corresponding to wavelengths of 1.5–30 m). This portion of the spectrum has been poorly explored for a number of mainly technical reasons. The most important factor has been the complicated structure of the ionosphere, which (using conventional interferometric processing) has limited the maximum baselines to a few kilometers only. This has resulted in radio maps with resolutions on the scale of arcminutes and consequently serious confusion effects which have limited imaging sensitivity to the Jansky level. Advances in wide-field self-calibration imaging procedures using powerful workstations have recently demonstrated that the NRL-NRAO 74 MHz VLA receiving system can now explore this spectral window, almost down to the instrumental sensitivity limits at the milli-Jansky level. These developments have paved the way for the exploration of this spectral region with the unprecedented imaging power of LOFAR.

1.2 Objectives

The five key areas of science to be addressed by LOFAR are:

1. **The High Redshift Universe**: the study of the most distant radio galaxies and quasars
2. **The Epoch of Reionization**: detection of the global signature, and mapping of structures
3. **Mapping Galactic Cosmic Rays**: to map the 3D distribution of the Galactic cosmic ray electron gas
4. **The Bursting and Transient Universe**: to detect short lived transient events – bursts from Jupiter-like planets, merging and interacting compact objects.
5. **Solar-Terrestrial Relationships**: to detect Coronal Mass Ejections possibly in combination with a Solar Radar, and to study the Earth’s Ionosphere.

More generally, LOFAR will be a powerful telescope for exploring the Universe for:

- coherent emission processes,
- delineating the interaction between nonthermal emitting plasmas and thermal absorbing gas, and
- differentiating between self-absorption processes.

This document contains a description of the applications currently perceived, although it is clear that scientific progress will lead to many other possibilities by the time the instrument is completed in the second half of this decade.

LOFAR hardware and software will be a key stepping stone for the development of the advanced digital signal processing technology required for the Square Kilometer Array.
In order to achieve these goals LOFAR will be a large (~360 km), electronic, broadband instrument providing fast (~1 ms) frequency selection and pointing, capable of rapidly imaging radio sources across the sky and spectrum. Multiple independent beams will herald a new approach to observing, yielding unprecedented flexibility when compared with higher cost, higher frequency ground or space-based systems. Finally, LOFAR's many orders of magnitude improved imaging power over previous instruments in its frequency range, promises new and unanticipated scientific discoveries.

1.3 Highlights of the Current Design

The most recent version of the design (agreed 10-12 July 2000 in Dwingeloo), which serves as reference for determining the approximate feasibility of proposed applications features the following elements:

- 13,365 dual polarization dipoles optimized for operation at 10-90 MHz.
- 213,840 dual polarization dipoles arranged in a 4x4 compound element array and optimized for operation at 110-220 MHz.
- Between 2 and 8 independent beams that will allow simultaneous measurement programmes to be executed.
- Maximum baselines of up to 360 km.
- All dipoles distributed over 60 to 165 stations (the number of dipoles per station varies inversely with the number of stations).
- At least 25% of the total collecting area to be located within a 2 km diameter “virtual core” where the full signal from each antenna is transported to a central processing site. These signals can be phased up to form a sensitive 2 km diameter “super-station”.
- An instantaneous RF bandwidth of 32 MHz will be digitized at the antenna level (10-90 MHz) and compund element level (110-220 MHz). The bandwidth will be reduced to 4 MHz for each of 2-8 beams for stations outside the virtual core.
- Beamforming for the virtual core together with all correlation and pipeline data processing will be carried out at a central processing site.

Approximate sensitivities of the full array are given in the table below. The sensitivities quoted are given for each beam, a single polarization, an integration time of 1s and a 4 MHz bandwidth. Resolutions are based on a station diameter of 65m, a Virtual Core diameter of 2 km and a maximum baseline of 400 km. Just under 25% of all collecting area is located within the Virtual Core. These numbers should only be taken as a guideline.

Frequency (MHz)	Effective Area (m^2)	T_{sys} in K	Sensitivity (mJy/4 MHz)		Resolution		Beamsize	
			Array	VC	Array (”)	VC (’)	Array	VC
15	1.3×10^6	131,000	98	400	12	41	1260’	90°
30	3.3×10^5	23,000	68	280	6.2	21	650’	90°
75	5.2×10^4	2450	46	190	2.5	8.3	250’	90°
120	3.3×10^5	820	2.4	10	1.5	5.2	160’	23°
200	1.2×10^5	270	2.2	9	0.9	3.1	95’	23°

Table 1-1 Approximate parameters of LOFAR

2 Key Scientific Objectives

This chapter contains a description of the five key areas of science to be addressed by LOFAR:

1. **The High Redshift Universe**: the study of the most distant radio galaxies and quasars
2. **The Epoch of Reionization**: detection of the global signature, and mapping of structures
3. **Mapping Galactic Cosmic Rays**: to map the 3D distribution of the Galactic cosmic ray electron gas
4. **The Bursting and Transient Universe**: to detect short lived transient events – bursts from Jupiter-like planets, merging and interacting compact objects.
5. **Solar-Terrestrial Relationships**: to detect Coronal Mass Ejections possibly in combination with a Solar Radar, and to study the Earth's Ionosphere.

Serendipitous discoveries, though more difficult to quantify, are virtually guaranteed for a telescope making a big step both in time and angular resolution and with such enormously increased sensitivity.

Apart from the five main topics listed above, LOFAR will have considerable applications to other fields of astronomy including the detection and study of galaxy cluster halos and their magnetic fields, the detection of fossil radio galaxies, the study of supernova remnants and their interaction with the interstellar medium, interstellar propagation effects, interstellar radio recombination lines and the detection and monitoring of pulsars and extrasolar planets. In addition, there will be applications in other fields e.g. atmospheric science. A description of these topics can be found in later chapters of this document.

2.1 The High Redshift Universe

2.1.1 Unbiased Surveys of the Sky

The importance of surveys is well-illustrated by historical sky surveys such as the Palomar Observatory Sky Survey (POSS) in the optical region of the spectrum, the 3C and Parkes surveys at radio wavelengths, the IRAS survey in the infrared and ROSAT All Sky Survey (RASS) at X-ray wavelengths. These surveys have led to countless astronomical discoveries, and in fact to much of modern astrophysics. More recently, extremely productive radio surveys have been the Westerbork Northern Sky Survey (WENSS) at 325 MHz and the NRAO VLA Sky Surveys (NVSS and FIRST) at 1400 MHz. Between them, these three surveys have resulted in the detection of millions of radio sources, including hundreds of thousands of new sources. Both have already made a valuable contribution to topics such as the study of the nature of extra-galactic radio sources and their relation to galaxy formation, the large-scale structure of the Universe and the use of galactic foreground polarization as a probe of the interstellar medium in our own Galaxy. One of LOFAR’s primary scientific objectives is to extend such survey work to lower radio frequencies, and through the combined jump in sensitivity (by two orders of magnitude) and resolution (by one order of magnitude) take radio astronomy into the last, as yet, unexplored region of parameter space.

2.1.2 High Redshift Gadio Galaxies

High redshift *radio* galaxies appear to be the oldest and most massive distant objects, providing important constraints upon early star formation epochs. They seem to be located preferentially at the centres of (forming) clusters and thus can be used to find early epoch clusters for subsequent study. Furthermore, radio galaxies are generally much more luminous than “normal” galaxies in all their component populations (stars, molecular gas, dust and relativistic plasma) often making studies at other wavelengths extremely profitable.

The most efficient method to date for finding very high redshift radio galaxies uses the correlation between radio spectrum steepness and redshift. At their rest frequency synchrotron losses generate a nonthermal continuum spectrum which steepens above ~1 GHz. For distant objects this "break frequency" is shifted to longer and longer wavelengths in the observer's frame, making them steep spectrum sources which are ideal for detection by a low frequency radio telescope such as LOFAR. The onset of additional significant energy losses at high redshifts from inverse Compton losses off the cosmic background steepen the spectra even further, leading to a class of ultra-steep spectrum (USS) sources.

A prime example of such an ultra-steep spectrum source is given in Figure 2.1. With a low-frequency spectral index of about $\alpha = -1.7$, the source TN J0924-2201 is one of the most extreme sources in the ultra steep-spectrum sample constructed from the WENSS (325 MHz), Texas (325 MHz) and NVSS (1.4 GHz) surveys. This source has been identified with a faint ($K = 21^{st}$ magnitude) object at near-infrared frequencies and its redshift was determined to be z=5.19. This object is therefore not only the most distant radio galaxy (previously 6C 0140+326 at z=4.41), but also the most distant radio source (previously the quasar GB 1428+4217 at z=4.72).

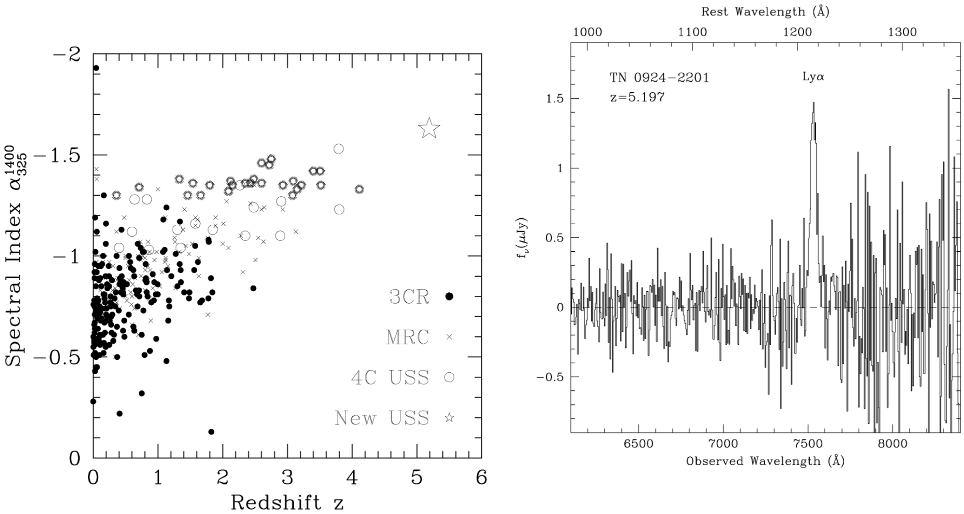

Figure 2.1 Spectral index against redshift **(left)** for two flux-limited samples (3CR and MRC) illustrating the spectral index-redshift relation and two USS samples (4C and the WN/TN sample), illustrating the effectiveness in finding very high redshift objects from such samples. The star denotes the newly discovered radio galaxy 0924-2201. A Keck I LRIS spectrum of TN J0924-2201 is shown on the **(right)**. The emission line has been identified with Lyα, indicating that this galaxy has a redshift of z=5.19.

The strategy of targeting radio sources with extremely steep spectra determined from e.g. the WENSS and NVSS surveys is at present the best way of identifying massive galaxies in the early universe. An important step forward would be to target rather fainter radio sources with steeper spectra to find significant numbers of radio galaxies with even larger redshifts (z>6). As the present steep-spectrum samples have limiting 325 MHz flux densities of a few hundred mJy, the next generation of searches should target sources with α~–2.0 and 325 MHz flux densities of only 10 mJy. However, such sources are too faint to be detected at higher frequencies and are therefore lacking in the high-frequency surveys. A survey at frequencies well below 325 MHz that can detect sources of a few hundred mJy at around 30 MHz is the only way to define such a radio-selected sample. For a reliable spectral index determination, it is essential that the LOFAR survey has a beamsize that is comparable to the available 325 MHz surveys. Although about 30% of sources in a LOFAR survey may be resolved, the expected angular sizes of z>6 candidates are typically a few arcsec. For such sources accurate spectral indices can be readily obtained. Present data suggest that the number of α~–2.0 sources in an expected survey sample size of 100,000 sources would be between ten and a hundred.

2.1.3 Starburst Galaxies

Deep, high sensitivity radio observations of relatively small regions of the sky (less than 0.3 square degree) have recently been made by the VLA (Richards et al. 1998 and Richards 2000), MERLIN (Muxlow et al. 1999) and the WSRT (Garrett et al. 2000). These studies, done at frequencies of 1.4 - 8 GHz, are throwing new light on the nature of the faint sub-mJy and microJy radio source population. The vast majority of these faint, low-luminosity (L<10^{23} Watts/Hz) radio sources are associated with star-forming disk galaxies located at cosmological distances, powered by successive generations of radio supernova remnants associated with the collapse of massive stars. These galaxies are often obscured by dust but a measurement of the relatively short-lived continuum radio flux density, relates directly to the instantaneous star-formation rate in these systems. In addition, the ratio of the radio/sub-mm continuum flux density ratio is a very sensitive redshift indicator (cf. Carilli and Yun, 1999). LOFAR will have the sensitivity to measure the radio continuum emission from starburst galaxies with star formation rates of only a few solar masses per year. In combination with sub-mm surveys (from the ground, e.g. ALMA) or from space (the FIRST satellite-mission) LOFAR will thus be capable of determining the evolving star-formation rate in the Universe up to the highest redshifts.

While the radio emission from star-forming galaxies is considerably less luminous than that of the more powerful AGN population, their sheer numbers ensure that taken together they dominate the total energy budget of the radio Universe. Extrapolations of the recent 1.4 GHz VLA and WSRT deep field observations to 200 MHz, suggest a source density (S>20μJy, about the 5 σ detection limit of LOFAR) in excess of 10 sources per square arcmin. These faint, steep spectrum radio sources will thus completely *dominate* the low-frequency, sub-mJy radio sky. The depth of the LOFAR survey, its all-sky nature and the excellent angular resolution, will therefore dwarf the existing radio surveys and open up new tools for studying a wide range of cosmological problems, especially large scale structure.

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2.2 The Epoch of Reionization

The onset of star and galaxy formation marks the time at which the early Universe emerged from the so-called "Dark Ages" and is referred to as the epoch of re-ionization (EOR). Uncovering the exact time and circumstances that gave rise to this event is one of the most important outstanding issues in cosmology, and has been the subject of much recent theoretical investigation. The LOFAR design will provide the much needed observational evidence that can specify the physical conditions during this important stage in the Universe, when the first stars and compact objects were formed.

After recombination of the elements at a redshift of ~1100, the baryonic matter in the Universe remained neutral until the first stars and galaxies started to form. At least three different types of sources have been suggested as contributing to the radiation that was responsible for reionization. These are: 1) emission from the first generation of stars, 2) radiation released in the collapse of the first galaxy-sized halos, and 3) emission from an early generation of luminous quasars. At the moment it is still unclear which sources or combination of sources or processes dominated. In fact, it is quite likely that actual measurement of the time at which re-ionization occurred will help us determine which sources played the dominant roles.

Theoretical simulations show that the process of re-ionization was probably quite rapid and could have taken place between z ~ 6 and 20 (Gnedin & Ostriker 1997; Tozzi et al. 2000). The present observational constraints are not restrictive. The EOR is not more recent than z ~ 5.8, since there is no distinctive absorption in the spectra of the highest redshift quasars due to the presence of a neutral intergalactic medium (Songaila et al. 1999; Zheng et al. 2000). The EOR could not have been earlier than z ~ 30, or there would be a suppression of the first Doppler peak in the angular fluctuation spectrum of the Cosmic Microwave Background (Tegmark & Zaldarriaga 2000; De Bernardis et al. 2000). Recent measurements of the temperature of the intergalactic medium in the Lyman alpha Forest clouds at redshift three suggest that the EOR must have occured after z ~ 10 or the clouds would have become too cool (Hui, in preparation). One further indirect constraint comes from the apparent behaviour of Dark Matter on small scales that is implied by the absence of the predicted number of intergalactic mini-halos and sub-halos of galaxies that are predicted to exist at z = 0 by simulations (Spergel & Steinhardt 2000; Kamionkowski & Liddle 2000). If these small scale structures are absent at present, the implication is that the localized star forming regions will form more slowly, which means later in the z ~ 6 to 20 window than had earlier been predicted.

2.2.1 Detection of a Global Reionization Signature

The radiation signature that LOFAR may be able to detect was emitted in the period immediately before full re-ionization. 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 ionizing sources (stars, quasars or mini-halos) and the hydrogen spin temperature decoupled from the CMB emission (from the Big Bang). 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 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.

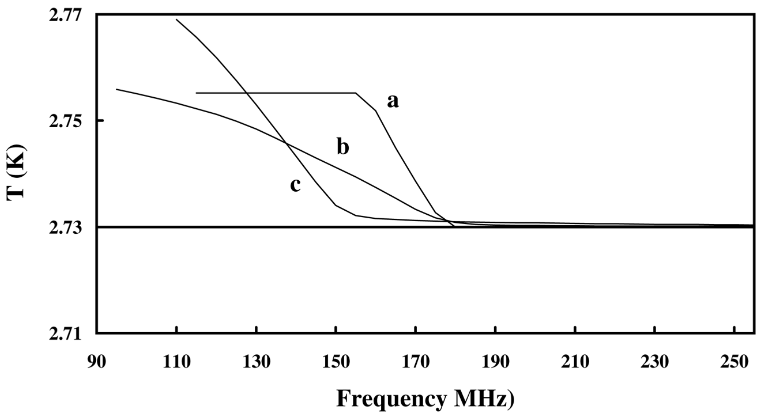

Figure 2.2 Simulations of the expected brightness temperature of the cosmic background in the vicinity of the hydrogen reionization edge as a function of observing frequency. Three cases are shown for the HI step, corresponding to different models of how the process took place. All three produce an effect that is capable of being detected by LOFAR (from Shaver et al.1999).

To investigate this transition phase LOFAR will be equipped with dipoles optimized for the 110-250 MHz band. Because the transition is expected to occur globally, i.e. in all directions at about the same time, 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.

Calibration of this faint signal, however, will dictate a telescope with a substantial collecting area (cf. Shaver et al., 1999). Collecting area and resolution are also important to deal with a crucial aspect of this experiment; which is to identify, model, and remove foreground sources that contaminate the signal. One such contaminant is the population of discrete radio sources (faint radio galaxies and, especially, starburst galaxies which make up the bulk of the faint source population) . The longer baselines of LOFAR are needed to assist in the identification and spectral characterization 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 nonthermal 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 0.5 degree angular scales at which a global signal will be sought. Faint Galactic foreground fluctuations that do exist are expected to be spectrally broad, thus permitting them to be modeled.

As was pointed out above, the epoch of reionization, and therefore the frequency of the spectral decrement, is uncertain. The broad band 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.

2.2.2 Detection of Spatial and Spectral Structure

Prior to full re-ionization the intergalactic medium was most likely a mixture of neutral, partially ionized, and fully ionized structures. It is believed that the low-density regions will be fully ionized first, followed by regions with higher and higher densities. A patchwork of neutral hydrogen emission, and possibly absorption against the cosmic background radiation (about

30 K at these redshifts), 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 appear on smaller angular scales (3'- 30') and in narrow bandwidths (few MHz). While remaining an extremely challenging project, the detection and imaging of these small-scale structures with LOFAR is a tantalizing possibility within range of the thermal noise of LOFAR (cf. Figure 2.3). 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.

As discussed above, in the description of the search for a 'global' signal, the biggest hurdles to overcome are the removal of discrete and diffuse foreground emission components. Fortunately, both of these contaminants have broad spectral energy distributions, much broader than the few MHz spectral features in the re-ionization signal. 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 the 'uninteresting' 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. The observed spatial and spectral fluctuation signals can be analyzed via standard power spectrum analysis techniques and can be compared with theoretical models for a range of cosmological models and sources of re-ionization.

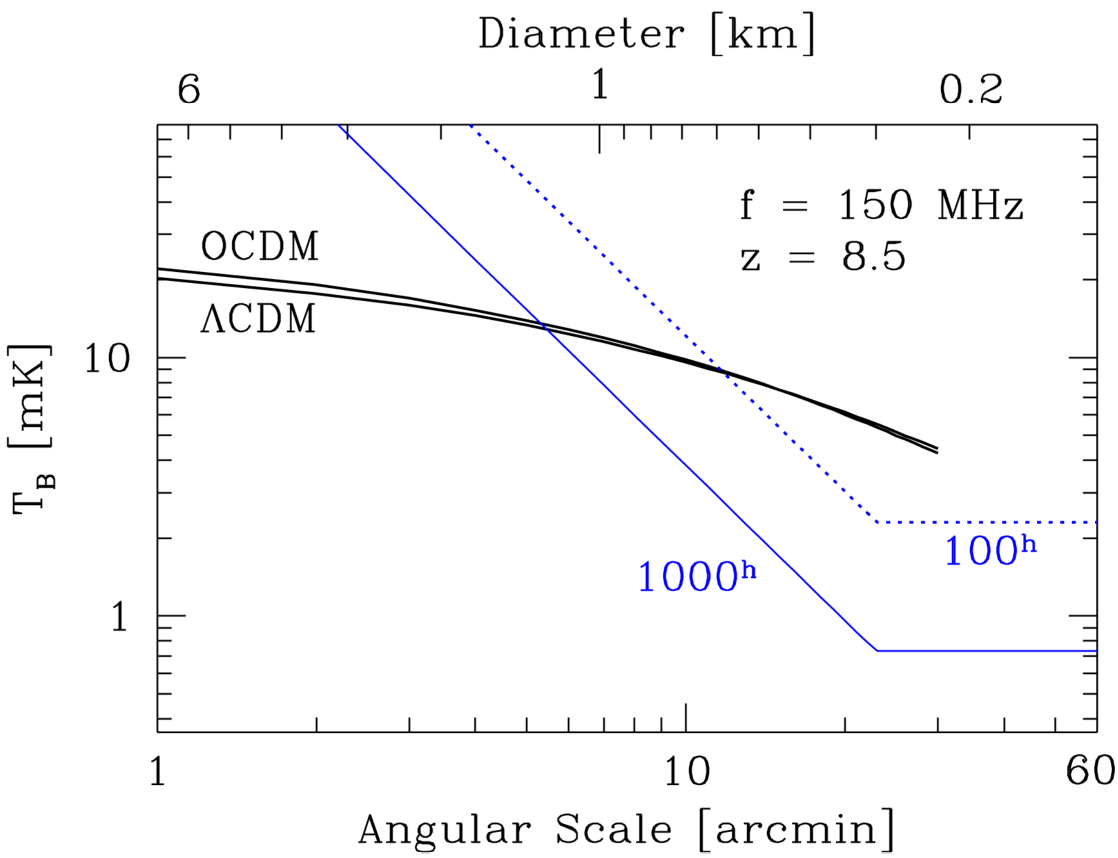

Figure 2.3 Comparison of the predicted brightness fluctuations as a function of angular scale with the sensitivity attainable after integrations of 100 and 1000 hrs with a compact sub-aperture of LOFAR. The simulationed fluctuation spectra show the amplitude of the 3 sigma

peaks in sky brightness computed by Tozzi et al (1999), for two different cosmological models. The sensitivity lines represent a confidence level of 5 times the noise level attained after the indicated integration time. The flat portion of the sensitivity curves at the right side of the plot indicate the response of a fully filled aperture of diameter equal 300m to brightness fluctuation on angular scales greater than 22 arcminutes. Dispersing the same number of elements over a wider area to obtain better angular resolution causes the sensitivity to surface brightess to fall off as denoted by the diagonal line, so that once the aperture is diluted over a 1.5 km diameter area, the instrument should still detect the background peaks at 5 times the noise level on angular scales of 6 arcminutes after 1000 hours of integration.

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2.3 Mapping Galactic Cosmic Rays

Cosmic rays are atomic nuclei and electrons that have been accelerated to energies (much) greater than their rest mass energies and form a collisionless, nonthermal gas. Their energy density is approximately 1 eV cm^{-3} – equivalent to a number density of 10^{-9} cm^{-3} – and they are energetically important, containing at least as much energy as the other phases of the interstellar medium.

The origin of Galactic cosmic rays is one of the oldest outstanding questions in astrophysics. The current explanation for their origin is that cosmic-ray particles are shock accelerated, probably in supernova remnants. (They then diffusively propagate through the Galaxy, being scattered by small-scale magnetic field fluctuations, before perhaps escaping from the Galaxy altogether.) There is little observational confirmation of this scenario, however. X-ray and gamma-ray observations of a small number of remnants (e.g., SN 1006 and IC 443) have indeed been able to identify localized regions whose nonthermal spectra are consistent with ongoing shock acceleration. X-ray and gamma-ray observations typically have poor angular resolution (> 1') and low sensitivity, so that only the most efficient regions of particle acceleration can be identified. A complementary approach is to demonstrate that the Galactic distribution of cosmic rays is consistent with the presumed sources, namely supernova remnants. Obviously, any deviations might indicate additional, as yet unrecognized sources.

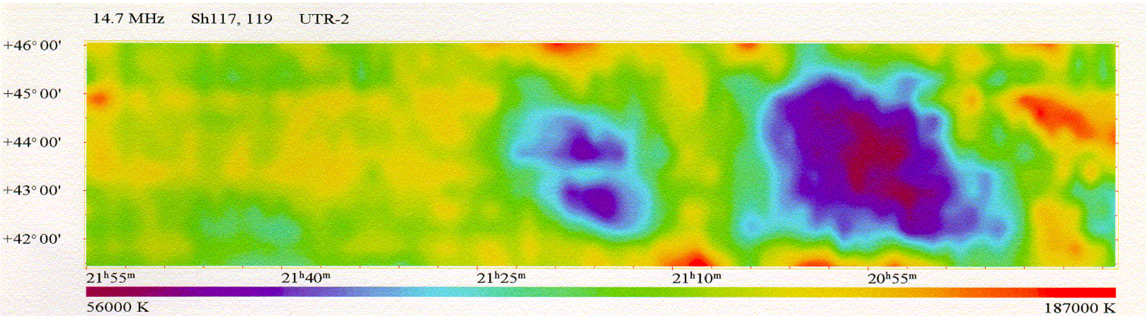

Figure 2.4 UTR-2 at 15 MHz: HII regions Sharpless 117 and 119 in absorption, angular resolution ~ 2 degrees.

LOFAR will play an important role by mapping the space distribution and energy spectrum of cosmic-ray electrons. In the approach described by Longair (1990), Webber (1990), and others, optically thick thermal sources at known distances are observed in absorption; a technique that can be exploited only at low frequencies and yields directly line-of-sight cosmic-ray synchrotron emissivities. Comparisons with observations at higher frequencies, including the distributed Galactic gamma-ray emission (such as observed by OSSE and EGRET and with the proposed GLAST mission) follow naturally, and provide important tools for decoupling the matter, cosmic-ray, and magnetic field distributions in the Galaxy.

The Galactic nonthermal synchrotron emission arises from the interaction of cosmic-ray electrons with the Galactic magnetic field. Using the radio emission to trace the distribution of the cosmic-ray electrons has long been of interest to cosmic-ray physicists as well as radio astronomers interested in the magnetic field distribution. Unfortunately, determining the synchrotron emission at centimeter wavelengths is fraught with problems. There is a mixture of thermal and nonthermal emission, along with the discrete sources that confuse the single dish observations required to detect the distributed emission. Furthermore, such measurements are sensitive to the entire line-of-sight emission, making interpretation very difficult.

At low frequencies one detects only the nonthermal emission, and with sufficient resolution an interferometer can avoid discrete sources. Moreover, in the approach favored by Longair (1990) and Webber (1990), observations towards optically thick HII regions whose distances are known kinematically, provide the line-of-sight synchrotron emmissivity along well-determined path lengths. The technique is most robust in directions towards the first and fourth Galactic quadrants where the background radiation field is high, but observations over the widest range of possible longitudes is desired. Unfortunately, past low-frequency observations have had such poor resolution that only nearby H II regions can be utilized. Figure 2.4 shows as an example of this technique—two large H II regions appearing as absorption “holes” in maps made by the UTR-2 telescope at 15 MHz. Unfortunately the 2 degree resolution reflects the pre-LOFAR state of low-frequency astronomy, and so only a few such measurements of nearby H II regions have been made. These have been useful for determining the properties of the local low-energy cosmic-ray electron spectrum (which cannot be measured near the Earth because of the solar wind) and magnetic field, but can say nothing about elsewhere in the Galaxy.

Figure 2.5 indicates how the hundreds to thousands of H II regions, which could be observed (in absorption) by LOFAR, could be used to map out the 3-D distribution of the cosmic-ray electron gas. High sensitivity, to 0.1 mJy or below is required, as one is utilizing the background emission, with $T_b \sim 10^4$ K, to “shadow” the H II regions. This compares to typical discrete emission sources with $T_b \sim 10^8$ K and higher. Moreover, an array with versatile angular resolution is required, since the ideal measurement is made when the synthesized beam is matched to the size of the H II region. Thus, a versatile array would be able to make use of the wide variety of H II regions throughout the Galaxy for such measurements.

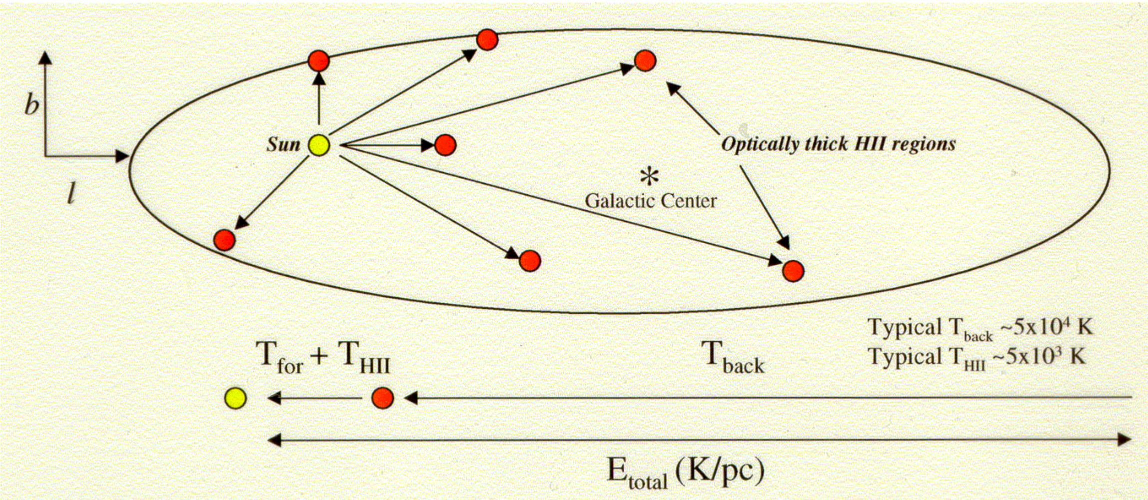

Figure 2.5 Mapping out the cosmic ray electron gas using Galactic HII regions at known distances. This permits decoupling of the foreground and background components of the synchrotron emission along many lines of sight. Absorption hole "flux densities" will range from µJy to mJy and higher depending on the size and Galactic coordinates of the target HII region. More sensitive observations will probe a larger volume of the Galaxy and on smaller (<1') scales.

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2.4 The Bursting and Transient Universe

Mainly for practical reasons, most existing radio sky surveys have been made at relatively low frequencies. From these surveys have come both serendipitous discoveries (for example, pulsars) and the catalogues of sources used for high-resolution mapping at high frequencies. Serendipitous discoveries often provide the greatest opportunities for advances in our understanding of the physics of astronomical objects. LOFAR would be an excellent instrument for the study of bursting and transient radio sources. The large instantaneous field of view means that LOFAR can effectively monitor a large fraction of the sky at all times, averaging on many different time scales. This makes possible for the first time a sensitive unbiased survey for astronomical transients. The factor of 100 increase in collecting area over previously operated instruments and the array's capability for data buffering and rapid electronic pointing, assisted at the lower frequencies by plasma delays, will also for the first time make possible prompt follow-up of transients detected with LOFAR and other instruments.

2.4.1 An Unbiased Survey for Transient Astronomical Radio Sources (STARE)

The inner compact configuration of LOFAR will consist of 25% of the array's collecting area arranged in a circle of 2 km diameter. All signals from the individual receptors will be brought to the central processor, allowing for synthesis mapping of a substantial fraction of the entire field of view of the receptors (the receptor field of view is an area of about 100 degrees diameter for the low frequencies, and about 25 degrees diameter for the high frequencies).These images will be examined in real time for transient events, and averaging will provide information on a range of time scales. This activity will represent the first unbiased survey for bursting and transient sources carried out with a radio telescope with a large collecting area and with sophisticated interference mitigation capabilities. Large-area monitors for transient sources at other wavelengths in astronomy have been very productive. For example, such observations led to the discovery of gamma-ray bursts and of samples of supernovae useful for cosmological studies. A low-frequency radio survey is likely to reveal processes giving rise to coherent emission, and has great discovery potential.

2.4.2 The Physics of Collapse and Explosion

2.4.2.1 Radio Supernovae

Radio studies of SNe have shown that multi-frequency monitoring of the rapid radio turn-on is critical to determining the early phases of the explosion, the physical mechanisms at work (e.g., SSA vs. f-f absorption) and the structure and density of the final, pre-supernova stellar mass-loss stages. For very rapidly evolving SNe, only at low frequencies does one have sufficient warning to obtain high quality turn-on information, since a transition seen at 100 MHz takes ~15 times as long from explosion to peak flux density as it does at 5 GHz. For example, SN 1987A reached 5 GHz peak already at age ~1 day and 840 MHz peak at age ~3 days, which led to very poor radio turn-on sampling of this once in 400 year event. Follow-up, long-term, frequent (at least initially) monitoring at multiple frequencies is then needed to establish the properties of the last periods of stellar mass-loss before explosion. At cm wavelengths the presupernova mass-loss evolution for periods of ~20,000–30,000 years before the explosion can be measured. However, only at long wavelengths does the radio emission remain sufficiently bright that one can study the mass-loss history from even earlier epochs.

Unfortunately, due to the competition between rapidly declining optical depth, slowly decreasing flux density with time, and increasing flux density at lower frequencies due to the nonthermal spectrum, there is a rough equality of peak flux density at all frequencies. Thus, the peak spectral luminosity even at LOFAR frequencies is unlikely to exceed $L_R \sim 10^{27}$ erg s^{-1} Hz^{-1} (flux densities of a few mJy for objects at or closer than the Virgo Cluster) except for unusual cases. Also, because of rapid evolution in the early phases, sensitivity of <1 mJy (5 sigma) in ~30 minutes is desirable with resolution of ≤1 arcsec to reduce confusion with background emission from the parent galaxy.

Radio supernovae are also candidates for targeted searches with LOFAR since they are known to occur in dusty starburst galaxies (exemplified by the enigmatic objects in M82) with no optical counterpart. To find and study such objects one must carry out continuous, or at least frequent, monitoring of the radio structure of many nearby galaxies to look for the appearance of new radio point sources. Such observations would improve the rather poorly established supernova rates in different galaxy types.

2.4.2.2 Giant Pulses

The strong magnetic fields associated with neutron stars in pulsars are believed to be responsible for the nonthermal processes that produce the observed radio pulses. In two cases, these pulses are exceedingly strong, and appear as “giant pulses”. Giant pulses have been detected from the Crab pulsar and from the millisecond pulsar PSR B1937+21, both in our Galaxy. In the case of the Crab pulsar, a giant pulse occurs on average once every ten seconds. The flux density distribution of the giant pulses has a power-law distribution above 200 Jy. Although the lower flux density cutoff has been determined to be about 50 Jy, no upper flux density cutoff has been seen. Individual giant pulses with flux densities exceeding 1000 Jy have been detected, and some giant pulses can outshine the entire Crab Nebula. Pulsars emitting giant pulses with these properties could be detected at least to the galaxies in the Local Group and potentially even further. Indeed, giant pulse-emitting pulsars offer the best hope for detecting pulsars beyond the Magellanic Clouds.

Detecting more giant pulse-emitting pulsars would have a number of scientific applications. First, detecting a new Galactic pulsar(s) with giant pulses may make the study of such pulses easier. The strong intensity of the Crab Nebula makes study of the individual “normal” pulses, and some giant pulses, difficult. Second, the two known giant pulse-emitting pulsars are quite dissimilar: The Crab pulsar is a young, strong-field pulsar while PSR B1937+21 is a (presumably) old, recycled, millisecond pulsar. It is not clear to what extent conclusions determined for one can be applied to the other. Third, existing observations suggest that the giant pulses from the Crab pulsar occur in the same region as the “normal” pulses, but result from a short modulation of the pulse emission process. Additional pulsars would both test this model as well as provide additional constraints on the nature of this modulation mechanism. Finally, the dispersion and rotation measures for pulsars in other galaxies would allow us to probe their interstellar media and potentially place constraints on the intergalactic medium in the Local Group.

2.4.2.3 LIGO Events

The detection of gravitational waves will represent one of the most important measurements in the history of physics. Evidence for the reality of such signals, and of their astrophysical origin, may be provided by other instruments operating in coincidence. Evidence for coincidence is, of course, not necessary to prove the existence of gravitational waves, but has the potential to strengthen greatly the case for astrophysical gravitational wave sources, and to provide complementary information on the sources.

The most promising sources for the gravitational wave detectors under construction are the coalescence of two compact objects in a binary system, including those composed of two neutron stars (NS-NS binaries), a neutron star and a black hole (NS-BH binaries), and two black holes (BH-BH binaries). NS-NS binaries have been most extensively studied theoretically. Predicted event rates are highly uncertain, but it has been estimated that coalescence will occur at a rate of 3 per year (distance / 200 Mpc)^3 for the initial LIGO system.

Predictions for LIGO II are even more uncertain since at the LIGO II levels of sensitivity NS-BH and BH-BH events are expected to dominate. Current estimates give LIGO II rates of once per week for NS-BH events and once per hour for BH-BH events. For a typical coalescing system, the time during which gravitational radiation is emitted within the detector bandwidth is approximately 15 minutes, during which time there are approximately 16,000 cycles. Hansen and Lyutikov (2000) have examined the possibility of radio emission from NS-NS coalescence. They model the system as a conducting sphere (one neutron star) moving through an external magnetic field (due to the other neutron star). They compute induced currents and the acceleration of charged particles drawn off the neutron star, and by assuming the energy of the charged particles is converted to radio waves with the same efficiency as in pulsars, they predict a flux density of $F_\nu \approx 2.1$ mJy (ε/0.1) (D/100 Mpc)$^{-2}$ $B_{15}^{2/3}$ $a_7^{-5/2}$ where ε is the efficiency of energy conversion, D is the distance, B_{15} is the magnetic field in units of 10^{15}G, and a_7 is the semi-major axis in units of 10^7 cm. Again, we emphasize this prediction is highly uncertain. However, it does give a plausible mechanism for the generation of radio waves in NS-NS coalescence.

One would expect any radio emission to be modulated at the orbital period of the NS-NS binary. This is roughly given by the dynamical time scale of about a millisecond, though the signal will be chirped as the binary merges. In analogy with pulsars, one would expect the radio emission to be polarized, and the time dependence of the polarization would provide important information on the geometry of the system.

2.4.2.4 Gamma Ray Bursts - Prompt Radio Emission

Many of the currently viable models of gamma-ray bursts (GRBs) postulate NS-NS or NS-BH coalescense as the energy source for the burst. In these models, the possibilities for radio burst generation by neutron star motion through a magnetic field are similar to those described for the LIGO events above. Another possible source of radio bursts is in the magnetized wind that may flow from the binary system (Usov and Katz 2000). The very large magnetic field associated with these winds is supported by a surface current at the boundary of the wind and the ambient medium, and variations in this current may drive coherent emission of low frequency electromagnetic waves. This radiation peaks at frequencies fundamentally set by the proton gyrofrequency, and for typical burst parameters the peak occurs around 1 MHz. The high-frequency tail may be detectable by LOFAR; Usov and Katz estimate that flux densities as high as 100 Jy at 30 MHz may be produced.

2.4.2.5 Gamma Ray Bursts - Flares and Afterglows

Radio emission following GRB's has been detected in about 40% of the objects for which observations have been possible. This radio emission is usually in the form of “afterglows”, which last for a number of days after the GRB. Shorter lasting (one or two day) “flares” have also been seen in a few objects. Both radio phenomena show strong absorption at low frequencies which indicate that only the very brightest radio events might be detectable with LOFAR. These detections would test flare and afterglow models involving forward and reverse shocks in a frequency range where the models have not yet had to confront data.

The data gathered to date suggest that the gamma rays are beamed and the radio afterglows are not. Constraints on the size of the opening angle and the observed rate at which GRB's show radio afterglows (40%) indicate that for every gamma-ray burst beamed in our direction there should be 40 radio afterglows. Since, these afterglows last for days, the transient survey area covered during their time “on” should be at least half the sky, meaning about 20 radio afterglows per day will fall at some time in the LOFAR field of view. The difficulty will be in detecting the afterglows. Absorption greatly reduces the flux at 150 MHz, from about 100 microJy for the typical afterglow to about 2 microJy. The reduced flux means that only about 0.3% of the volume out to a redshift of 1 (the typical redshift of a GRB) will be surveyed by LOFAR. Assuming a uniform and isotropic distribution of GRB sources, this brings the number of detectable afterglows to about 22 per year. These LOFAR-detected afterglows would provide a valuable sample for GRB afterglow studies.

2.4.3 X-ray Binaries with LOFAR

Observations of X-ray binaries at low frequencies have been rarely made and yet can provide strict constraints on the spectral and energy properties of the radio emitting jets. LOFAR therefore opens up a unique spectral window in the study of transient X-ray binaries. Below we briefly summarise the potential of LOFAR for the study of transient compact radio sources, notably X-ray binaries within our Galaxy and the Local Group.

2.4.3.1 X-ray Binaries

X-ray binary systems, of which currently ~250 are known, produce radio emission in synchrotron-emitting jets, which can be considered to be scaled-down versions of the powerful jets associated with AGN. The radio emission qualitatively comes in two forms; relatively weak (~10 mJy at GHz frequencies), steady, flat-spectrum emission (believed to arise in quasi-continuous self-absorbed jets) and transient, bright (sometimes >1 Jy at 1 GHz) events which rapidly evolve to an optically thin state.

2.4.3.2 X-ray Transients

In Figure 2.6 we show the peak radio fluxes (scaled to 5 GHz assuming a spectral index α = -0.5, where $S_\nu \propto \nu^\alpha$) of the 20+ transient events which have been observed simultaneously in both radio and X-rays. Assuming that the electron distribution extends to low enough energies (see below) to extend the optically thin synchrotron spectrum to 150 MHz, then $S_{150\ MHz}/S_{5\ GHz} = (5000/150)^{0.5} = 5.8$, ie. events will peak at flux densities about six times higher at 150 MHz. Therefore we will be able to extend the range of detectable radio luminosities by almost an order of magnitude (assuming we achieve ~1 mJy sensitivity at 150 MHz in a typical run). Given that by 2005/6 the Japanese ASM instrument onboard the ISS will push down the sensitivity of all-sky X-ray monitoring by an order of magnitude, LOFAR would provide an important follow-up instrument. As well as detecting sources not measurable at higher frequencies, simultaneous measurements with LOFAR and at higher (e.g. GHz) radio frequencies will be extremely sensitive for testing whether there are contributions from radiative (ie. Synchrotron and/or inverse Compton) losses to the decay of radio emission from these events (in which case the spectrum will steepen gradually), or whether (as it seems at present, with limited spectral coverage) the losses are dominated by adiabatic expansion (which produces no spectral change).

2.4.3.3 The Extent of the Nonthermal Electron Spectrum

The synchrotron emission observed from X-ray binaries follows (probably!) a power-law $N(E)dE \propto E^{-p}$, where $2 \leq p \leq 3$. The magnetic fields estimated for the ejected plasma at peak (via equipartition) are typically of order 0.05 Gauss; hence emission at 5 GHz arises (primarily) from electrons with γ~150. Detection of a continuation of the synchrotron spectrum as low as 150 MHz would imply we were observing electrons with γ~25. Since, for an outflow with bulk relativistic motion, the energetics will be dominated by the kinetic energy of the (presumed) ‘cold’ protons (unless of course it is a pair plasma), determination of this minimum γ is of great importance (indeed it has long been recognised for AGN that determination of the *low-frequency* tail of the synchrotron spectrum is fundamental for the energetics of [baryonic] outflows).

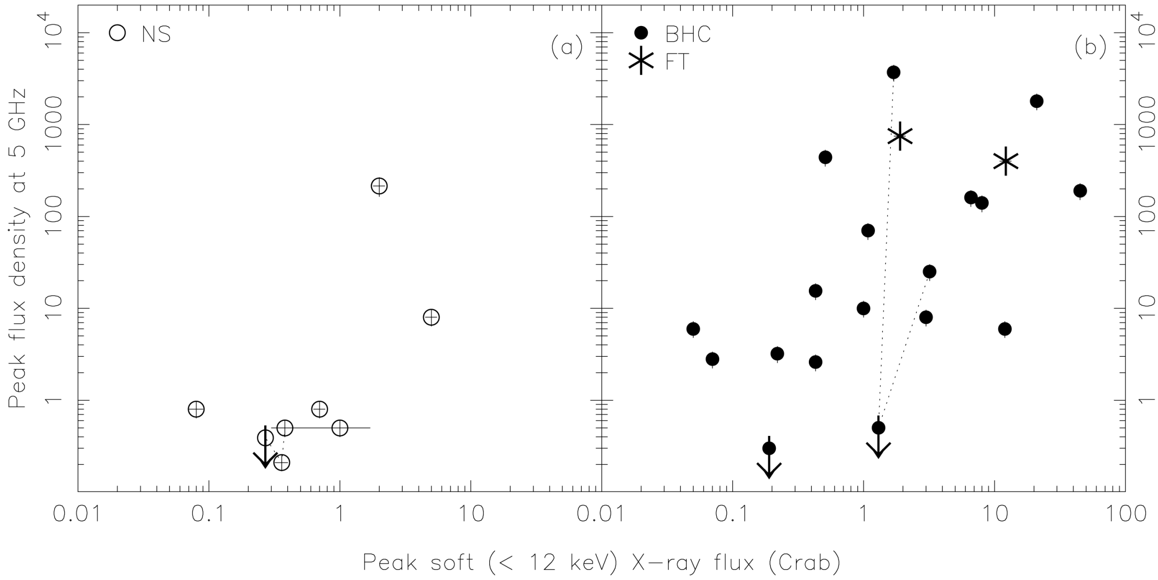

Figure 2.6 Peak radio and X-ray flux densities of transient XRBs

2.4.3.4 Relic Radio 'Lobes'

The radiative efficiency of both XRB and AGN jets appears to be in the range 1–10%. In AGN it is known that most of the remaining 90% is deposited in lobes, where kinetic energy is converted into internal energy of electrons at a shock. In X-ray binaries such lobes have almost never been found (perhaps in 4/30 or so cases), and so the eventual site and form of release of the jet power is unknown. Given that the jet may be the primary power output channel for the accretion and/or compact object spin energy, this is a fundamental question. The spectrum of the known 'lobes' (in 1E1740.7-2942, GRS 1758-258, SS433/W50 and perhaps XTE J1748-288) are steep, and they have low surface brightness. Hence observations at low frequencies have the potential to reveal these postulated sites of kinetic energy release. The long baselines proposed for LOFAR also provide the potential to map in detail the structure of these lobes, should we find them.

2.4.3.5 Requirements

The science roughly outlined above would (modestly) require an r.m.s. of ~1 mJy at 150 MHz within a reasonable (≤12 hr) integration time, and would preferably have an angular resolution of order one arcsecond. The ability to do rapid follow up and long term monitoring have already proved instrumental in improving our knowledge of the radio emission from XRBs. The possibility that a LOFAR beam might be available to observe the transient events from XRBs is therefore of great interest.

References

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Usov V.V. and Katz J.I., astro-ph/0002278 – Submitted to ApJ, 2000.

2.5 Solar-Terrestrial Relationships

There is great interest in developing a means of detecting and predicting the arrival times of Earthward-directed Coronal Mass Ejections (CMEs), generally believed to be the main cause of increasingly costly geomagnetic storms. Until now the best way of studying CMEs has been from space, which is expensive and often unreliable. Furthermore, as Figure 2.7 illustrates, space-based coronagraphs are not well suited for studying Earthward-bound CMEs. A revolutionary ground-based technique of detecting and tracking CMEs with a long-wavelength solar radar is now being considered, and LOFAR would be an ideal imaging receiver for such experiments. LOFAR's pioneering of the technique of Solar radar in conjunction with a suitably equipped transmitting facility could open up an entirely new and exciting field of solar research. There are related LOFAR radar applications in both ionospheric and magnetospheric physics. We describe here only the solar radar application

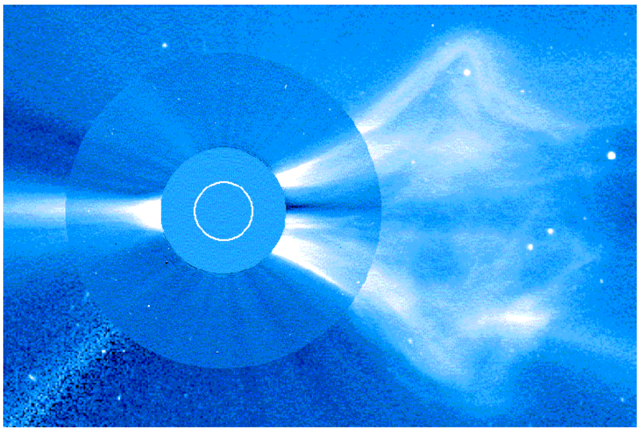

Figure 2.7 A LASCO coronagraph image of a transversely directed CME, obtained from the SOHO spacecraft located at the Earth-Sun L1 point. Coronagraph images are most effective for determining transverse motions of CMEs. Figure courtesy of NRL, Code 7600.

The El Campo radar (see Figure 2.8), built by the Lincoln Laboratory, detected 38 MHz radar echoes from the Sun for a period of 9 years in the 1960's. Huge, rapidly-moving targets were occasionally observed but this was before the space-borne coronagraph discovery of coronal mass ejections (CMEs), and the physical nature of these “targets” was a mystery. It is now thought that CMEs were being observed.

The reliable detection and monitoring of CMEs is of great practical importance. CMEs that impact the Earth's magnetosphere can result in hundreds of millions of dollars in damage to spacecraft, communications, and electrical power systems. A low-frequency transmitter coupled with a high-angular-resolution receiving array would form an extremely cost-effective system to detect and track CMEs. Rodriguez (1996) has summarized the potential of 10-80 MHz radar systems for detecting CMEs; Figure 2.9 illustrates the basic principle. The Doppler shift introduced by different parts of an outward-moving CME will result in a characteristic frequency- and time-dependent signature in the reflected signal. The rich information inherent in this measurement could open an entirely new window on CME studies, yielding their angular distribution, ranges, and line-of-sight velocities.

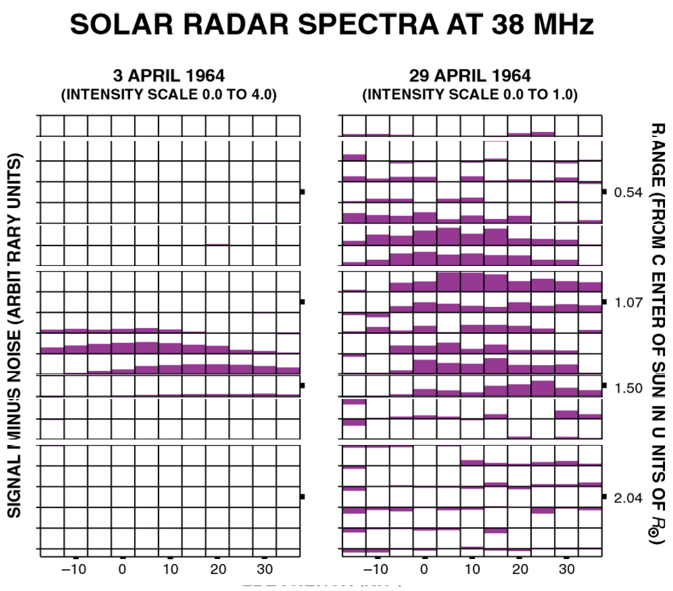

Figure 2.8 Two examples of solar radar spectra observed by James in 1964.The data from 3 April are typical of 70 percent of El Campo spectra.The data from 29 April shows two scattering regions;the signal from the upper (more distant)region is likely caused by radar waves refracted to and from regions lying near the edge of the solar disk.At times James also observed echoes from regions lying up to 5 solar radii from the center of the sun (one solar radius equals 700 Mm).The availability today of extensive,high quality supporting observations,in combination with future radar imaging observations with the LOFAR,would allow identification of the source regions and scattering mechanisms of solar radar echoes. After James (1968).

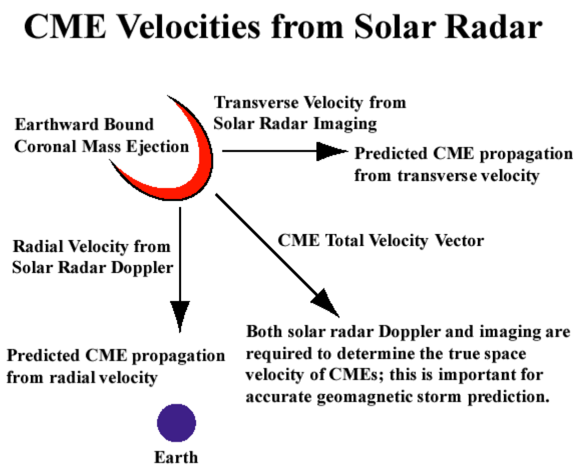

Figure 2.9 Constraining CME velocities from solar radar imaging and Doppler.

Figure 2.9 shows that combining the radial velocity obtained from the Doppler shift with the transverse velocity obtained from imaging is required to determine the CME total velocity vector. This would allow for accurate predictions of CME Earth-arrival times. Transmitting facilities now exist (e.g. Arecibo Observatory and over-the-horizon radars that are no longer required for military purposes), but adequate receiving facilities are needed for such a project.

Currently, space-based coronagraphs are used to detect and track CMEs. However, space-borne white-light coronagraphs detect the Thomson-scattered light from the CME material and therefore are less sensitive to structures propagating at large angles out of the plane of the sky, such as Earth-directed CMEs. An array of coronagraphs in the Earth's orbit could provide the stereoscopic view to determine this information, but at significant cost and a limited, somewhat unpredictable lifetime. A cheaper and more reliable low-frequency radar system (incorporating LOFAR as its prototype imaging receiver) offers a great cost advantage over such space-based CME monitoring schemes.

Aside from the macroscopic physics of direct interest to the space weather program, there is great potential in unraveling the microscopic physics of the solar radar scattering mechanism. An understanding of this mechanism is key to solving the puzzles of the spectral shape, the large Doppler spread, the Doppler shift, and the variation in solar radar cross section. Various mechanisms have been suggested, including turbulence in the local medium, fluctuations in the altitude of the plasma resonance level due to electron density fluctuations in the solar wind, ion acoustic waves, and coherent lower hybrid waves. The possibility of coherent coronal plasma waves is especially intriguing as it is a topic of current interest, and a search for such waves was included in the observing program for the Solar and Heliospheric Observatory (SOHO) spacecraft.

Once the microphysics is understood, solar radar could become a probe of the solar plasma on a par with the modern coherent and incoherent radars used to probe the earth's ionosphere. In particular, the astonishingly accurate plasma physical theory of incoherent scatter radar has allowed a detailed and productive study of our nearest space plasma in a way undreamed of before its discovery. A similar scientific potential may be hidden in the coronal scattering mechanism.

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3 Additional Astronomical Applications

3.1 Protogalaxies and Galaxy Evolution: HI Absorption

In the nearby Universe, neutral gas traces gravitational potential wells. The 21cm line of atomic hydrogen (HI) provides radio astronomers with a unique tool for measuring gas kinematics and the distribution of dynamical mass in galactic systems. Observations of radio emission from galaxies with the Westerbork telescope produced the earliest and strongest evidence for the existence of dark matter.

At low redshift, cold neutral gas represents only a small fraction of the total mass in baryons – much less mass than in stars or in the ionized intergalactic medium. As a reservoir for fueling star formation, HI appears to be nearly used up. Conditions were very different in the distant past, at redshifts greater than 3, when the neutral gas outweighed the stars. From quasar absorption line studies, there is no doubt that the comoving HI mass density of the Universe was at least a factor of five higher at these early times (when the Universe was one tenth its present age) than now.

The most successful theoretical models for evolution of the Universe's large scale structure and for the formation of large galaxies has the galaxies building up in mass by merging and accretion of small protogalactic mass clumps. This process is especially vigorous in the time period over redshifts from 2 to 1, implying that the still earlier times (z=3-6) will have special importance for measuring the properties of the protogalactic clumps. The neutral gas is known to be there, and the crucial question is whether the 21cm line can still be used as a tracer to determine the depths of the evolving potential wells (the dynamical mass) and the spatial extent of the HI rich objects. These are basic tests of the theories of galaxy formation and evolution.

We cannot detect ***emission*** in the HI line from high redshift because the line flux received at Earth falls off as d_L^2 as the luminosity distance (d_L) increases toward high redshift. In contrast, ***absorption*** lines depend on the surface brightness of the background source for their detectability, and as long as samples of bright high redshift radio sources exist at higher z than the redshift of interest, the prospects for using the redshifted 21cm line in absorption are good. Such samples exist and are still growing, with a current record redshift of 5.2. High redshift, steep spectrum radio galaxies are especially attractive since they have more extended structure than flat spectrum quasars.

The extended structure is necessary (as illustrated in Figure 3.1) in order to probe multiple lines of sight through the intervening absorber, effectively mapping the 21cm optical depth, measuring the spatial extent of the HI layer, and giving the kinematics of the absorber. For absorbers like the one against 3C196, the most desirable observation would be to actually map the absorber with a high resolution radio telescope. This z=0.437 galaxy has a linear extent of more than 50 kpc (10 arcseconds), and it is clear that to test theories of galaxy evolution, the radio telescope must be sensitive to structures of 10 kpc and more. Some follow up of this object has been done with European VLBI Network baselines, but they turn out to be too long, and very little background radio emission remains unresolved to interferometer baselines as short as WSRT Effelsberg. Shorter baselines not exceeding a few hundred kilometers – are ideal!

For the frequency range covered by the high-frequency LOFAR, 120-300 MHz, we can search for absorption in the redshift range from z=3.5 to z=11. The highest redshift radio source is at z=5.2 although QSO's have now been seen out to z=5.8. At present only four radio sources (cf. De Breuck) have a redshift high enough to make them suitable targets to search for intervening HI absorption in the frequency range below 300 MHz.

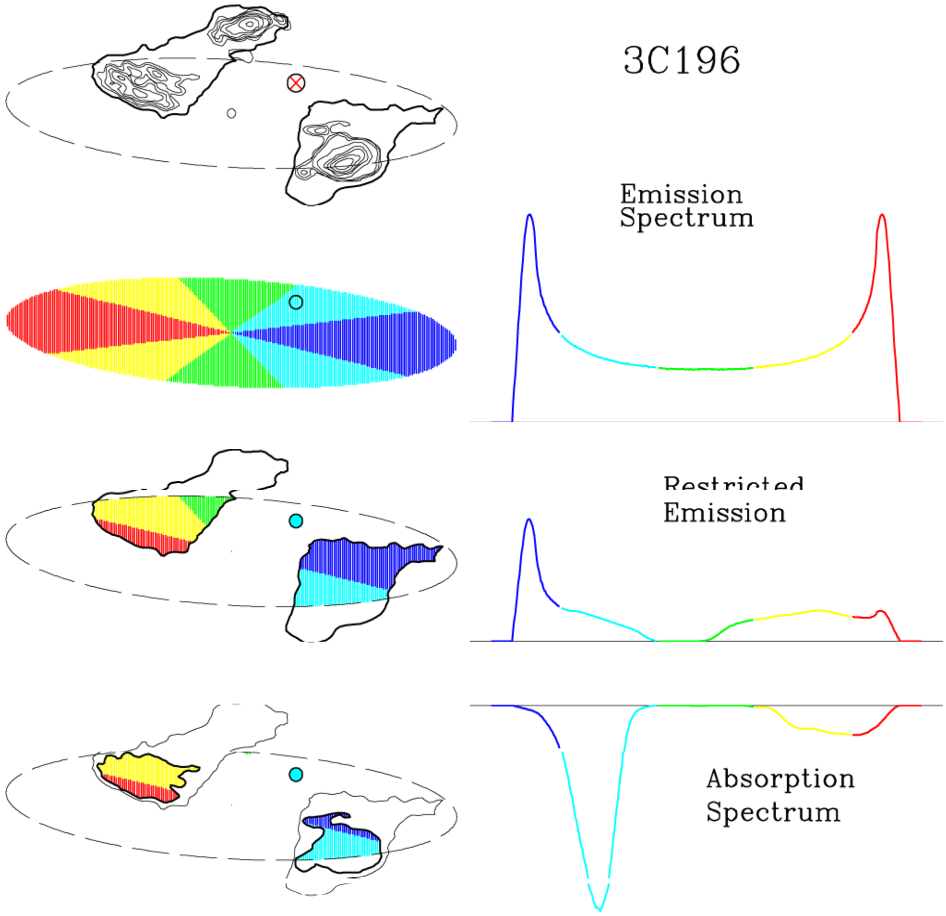

Figure 3.1 The figure demonstrates how mapping of the absorption works for an intermediate redshift (z_{abs}=0.437) galaxy that happens to lie in front of the double lobed radio quasar 3C196 (z_{em}=0.871). Recent WSRT observations with the UHF system have shown a complex absorption profile and indications that the spatial extent of the gas must cover part of both the lobes. An HST image shows an L* barred spiral galaxy whose optical extent and orientation is indicated by the color coded velocity field. A simple model can account for the observed absorption profile, with the implication that this well formed, intervening galaxy at an age half that of nearby galaxies, has a rotation speed of 180 to 250 km/s and falls close to the Tully Fisher relation that applies to z ~ 0 galaxies.

Long integration times will be necessary to detect the feeble redshifted 21cm absorption lines. The multi beaming capability of LOFAR will therefore be an extremely powerful feature: LOFAR will, ultimately, provide many hundreds of hours of integration on ALL the low frequency sources in more than half the sky.

If it could also provide this for the full range of the high-frequency LOFAR (i.e 200-300 MHz) one can do blind searches for HI absorption. Any absorption line in this frequency range is most likely due to HI and immediately points to a very high source redshift. This technique is truly optically blind as we would not be dependent on a spectroscopic Ly-α redshift determination. If dust is abundant in high redshift radio galaxies this is the only unbiased probe of high z HI.

References

De Breuk C., PhD Thesis, University of Leiden, p144, 2000

3.2 Mpc-Sized Radio Galaxies at z>1

Giant Radio Galaxies (GRGs) are the largest single objects found, with projected linear dimensions >1.0 Mpc. At low redshifts (z < 0.3) these very large objects number about thirty. The most extreme of these is 3C 236 which has a projected linear size of 5.7 Mpc. Why are these radio galaxies so enormous? Is it because of an unusually tenuous environment, because of high jet powers, or simply because of old age? GRG's have expanded well out of the denser central regions of their parent clusters into the much less dense InterGalactic Medium (IGM). They can thus be utilized as probes of the IGM far from the host galaxies, where it is inaccessible to current X-ray instruments. Their central AGN engines must be approaching the endstage of their active radio phase, so that they may tell us how AGN's die. Finally, many of these large sources are identified with quasars (e.g. 4 C 34.47) or Broad Line Radio Galaxies (e.g. 0319+412) which makes them into important testcases for orientation-dependent radio-loud AGN unification schemes (Barthel 1989) which predict that quasars will not have large projected linear sizes.

If, like luminous radio galaxies and quasars, GRGs exist in large numbers at high redshifts, their study will provide valuable new information on the cosmological evolution of radio sources. In order to study the cosmological evolution of the IGM, we need a large sample of GRGs covering a broad redshift range. Since IGM densities are expected to evolve as fast as $(1+z)^5$, this evolution should be quite obvious in the envisioned sample. Up to about 50 GRGs have been found with redshifts 0.5<z<1 and, serendipitously, even one at z=1.9. This present sample is, however, hard to use for constraining either IGM models or dying radio source models because of selection bias. Presently, high-z candidates are selected by apparent hotspot separation, but sources with relatively faint hot spots are missed. Needed are therefore low-frequency radio images of sufficient sensitivity to show the lobe emission *between* the hotspots. The resolution need not be better than 30 arcsec.

Finally, the exciting possibilities provided by detailed studies of GRG's is well-illustrated by the case of WNB 2147+816. At a redshift of 0.15, its projected linear size of 3.7 Mpc makes it the second largest radio source known (see Figure 3.2) Of particular interest is the radio emission seen between the lobes which is associated with the backflow and side shock emanating from the jet, together forming a cocoon. Several of the trends noted for similar objects by Subrahmanyan et al. (uniform environment, low local IGM density, interrupted central activity) are related to the properties of such cocoons. Since these radiate predominantly at low frequencies, LOFAR resolutions of 10 arcsec would be ideal to study them.

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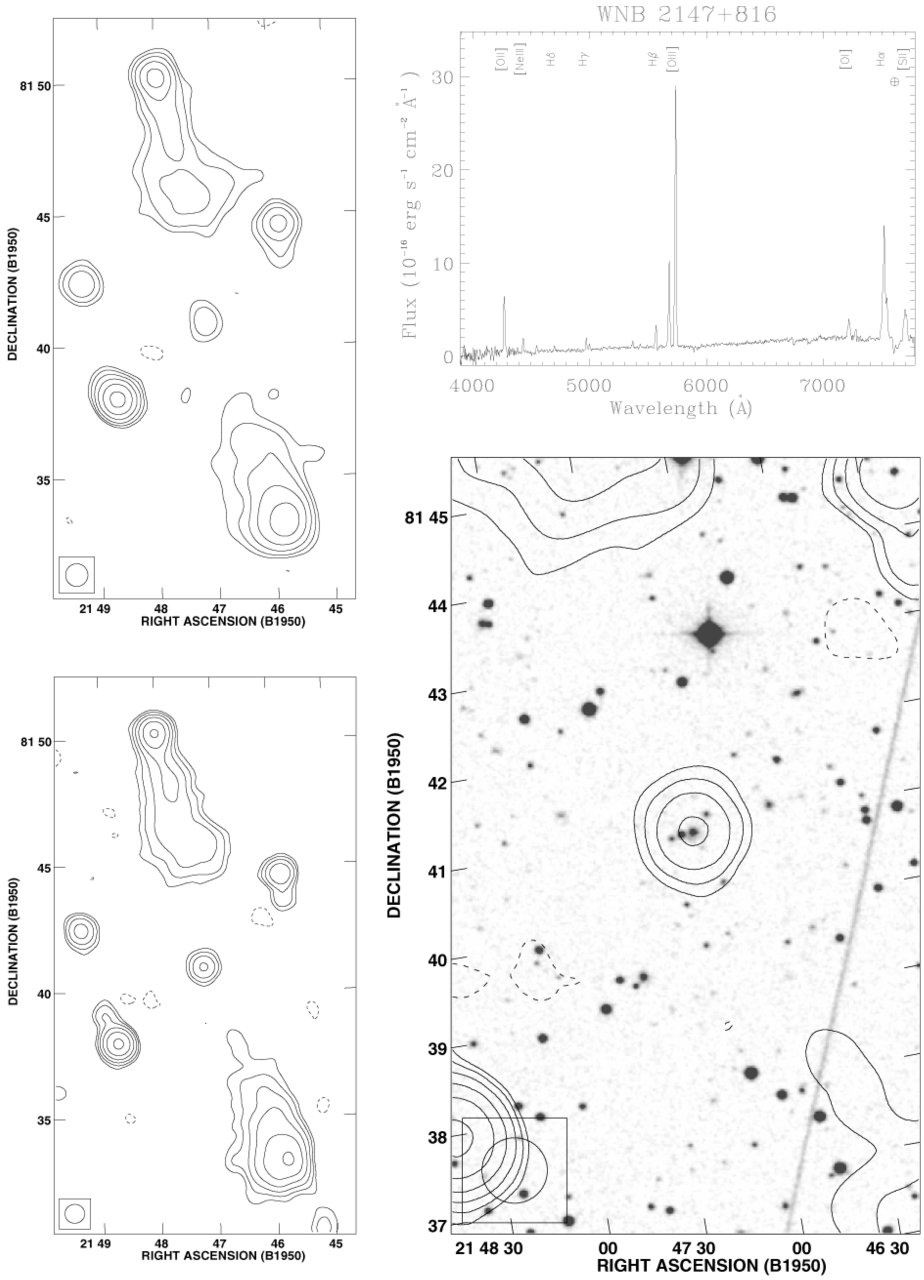

Figure 3.2 WNB 2147+816: The WENSS (upper) and NVSS (lower) radio contour plots, an overlay of the NVSS radio map (contours) with an optical image (greyscale) and the optical spectrum of the host galaxy.

3.3 Radio Halos

Radio halos are regions of smooth extended radio-emitting plasma, with sizes of the order 1 Mpc. They are found in rather remarkable clusters that: (i) are very rich, (ii) have unusually few (~ 10%) spiral galaxies, (iii) exhibit a large velocity dispersion ~1000 km s^{-1}, (iv) have large X-ray luminosities L ~ 10^{44} - 10^{45} erg/s and large core radii >0.3 Mpc and (v) lack cooling flows. Prime examples are A2556 and A3667. Most of these characteristics may be explained by the assumption that these clusters are experiencing a massive merger, heavily distorting the morphology of the radio sources in the cluster (Röttgering et al. 1994 and references therein).

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 ($\alpha << -1.0$) 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. Measuring the halo emission from these distant objects will help explain the halo phenomenon and also help unravelling merging activity associated with possibly still forming clusters. 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 indeed mark clusters in the process of merging and forming, the frequency of their occurrence might well be much higher at greater distances.

Several models have sought to explain the origin of the relativistic electrons causing the extended emission (see reviews by Jaffe 1992, Feretti & Giovannini 1995), involving (i) particle collisions (Vestrand 1982), (ii) galactic wakes (Roland 1981), (iii) intracluster turbulence and shocks (Harris et al. 1980; Tribble 1993), or (iv) active galactic nuclei. High-resolution LOFAR observations of a number of nearby haloes will distinguish between these different models.

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3.4 Thomson Scattering by Cluster Gas and the IGM

Clusters of galaxies have a significant Thomson scattering depth (typically about 0.001-0.01) which reveals itself through the scattering of MWB photons. This so-called S-Z effect has become an important method to study the gas content and density profiles of clusters WITHOUT strong radio sources. In those cases where a strong steep spectrum (large and hence old) radio source is embedded within the cluster, a Thomson scattering halo is produced. The scattering process leads to a significant and characteristic polarization pattern allowing it, in principle, to be separated from any intrinsic halo emission (Sunyaev, 1982; Wyse and Sarazin, 1990).,

For a 10 Jy source, not uncommon at 100 MHz for a central cluster source, a halo with flux density of (0.001-0.01) x 10 Jy or 10-100 mJy is expected. This is far above the noise level attainable by LOFAR. The detection of these haloes is therefore mainly a matter of dynamic range and confusion by cluster and background sources (a Thomson scattered halo has probably been detected in WSRT 21cm observations of the Perseus cluster (de Bruyn, in preparation). The older the source the larger the scattering halo: thus a 10^7 year old source will extend out to 3 Mpc projected radius. The shape and spectrum of the halo carries important information on the time-evolution of the central radio source, which can be reconstructed once the gas density has been obtained using X-ray images. Other diagnostics provided by this type of study are the beaming of the central source and the intra-cluster magnetic field.

In a more speculative application of this mechanism the integrated effect of tens of Mpc of intergalactic medium on a high redshift radio source. E.g. the z=4.25 source 8C41.35, with a strength of 10 Jy at 150 MHz, would produce a giant (0.5 degree) halo of about 10 mJy for a Universe with 5% baryons in the IGM. The detection of such haloes would present a real challenge at the low frequencies of LOFAR.

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3.5 The Fossil Radio Universe, AGN Duty Cycles and Cluster Formation

Radio galaxies are among the biggest and most spectacular objects in the Universe. They have existed for almost a Hubble time: from a record redshift of 5.2 to the local Universe. Radio galaxies were particularly common at redshifts of z=2-3, often called the 'quasar era'. This era is thought to be marked by galaxy mergers which are expected to enhance AGN activity through increased fuelling. On the basis of both evolutionary arguments and energetic considerations it is considered unlikely that the active phase, (the 'dutycycle') can have lasted for a Hubble time. Radiative ages at GHz frequencies are at most 10^8 years, although this does not exclude the possibility that the 'physical' age of the radio source is larger. In fact evidence for recurrent activity in a small fraction of radio galaxies is mounting (Schoenmakers et al, 2000).

It is therefore believed that the Universe is filled with aged remnants of radio galaxies whose nuclei have stopped being active.These 'so-called' relic sources have a low surface brightness and probably a very steep radio spectral index. The fading process, which commences once the supply of fresh energy from the nucleus stops or slows down, is thought to be particularly fast at high redshift due to the steep increase of Inverse Compton losses off the MWB photons ($\propto (1+z)^4$). High redshift fading radio galaxies are therefore more luminous in X-rays than at radio wavelengths.

The 'fossil' universe, contains a historic record of invaluable information. Ensslin and collaborators (1998, 2000) have drawn attention to various diagnostics provided by old/dormant/fossil/relic radio sources. Once 'overtaken' by large scale shockwaves, both in clusters and at the edges of clusters, the fossil sources will be 'revived' and start radiating at the lower frequencies.

Thusfar surprisingly few relic sources have been discovered. This points to a large gap in our knowledge of the late phases of radio galaxy evolution. The excellent sensitivity for steep spectrum emission and low surface brightness features makes LOFAR the instrument of choice for the study of this fossil universe. It will reveal the location and number density of dormant AGN and will shed light on the causes of the cessation of nuclear activity.

In combination with sensitive X-ray images from Chandra and XMM/Newton LOFAR could revolutionize the study of this largely 'invisible' but energetically important component of the IGM. 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.

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3.6 Large Scale Structure

Since the number density of powerful radio galaxies was more than a factor of a hundred larger at redshifts z~1 than it is today, any flux-density limited catalogue of radio sources samples the universe out to redshifts z>1. Therefore, large flux-limited samples of radio sources potentially provide a powerful tool for investigating the clustering properties of galaxies at cosmological distances. Evidence for anisotropies in the distribution of radio sources has been found in flux-limited samples of radio sources from surveys conducted at Green Bank Survey, the VLA and the WSRT (WENSS). For instance, the brighter radio sources seem to be more clustered than the fainter ones, but why this would be so is not clear. A LOFAR survey will provide a different source population that is intrinsically bright as opposed to bright by dopler boosting, one might expect a strong clustering signal, perhaps further boosted by a relatively high fraction of sources in dense, clusterlike environments. The WENSS experience indicates that of a few hundred thousand sources are needed to probe the clustering signal.

3.7 Thermal and Nonthermal Emission in Nearby Galaxies

Radio continuum emission from galaxies provides significant information on the properties of the interstellar medium. At low frequencies radio emission will be dominated by the synchrotron mechanism. At frequencies between 20 and 300 MHz one predominantly observes the old population of relativistic electrons present in the disks and haloes (or thick disks) of galaxies, i.e. the aged version of the relativistic electrons which were supposedly generated by supernovae and associated events (such as the supernova shocks ploughing through the interstellar medium).

Imaging the radio emission of galaxy disks at low frequencies will enable us to separate better the thermal and non-thermal emission. This is done best by comparing many images spanning a large range in frequency rather than images at only a few frequencies as has been done until now. Escpecially high resolution imaging below 300 MHz will provide a much more robust determination of the non-thermal component, and by implication the thermal component in higher-frequency images. This is important, because it provides us with one of the least biased views of star formation in galaxies. Low-frequency imaging at the same time provides detailed information on spectral index variations across galaxies, which in turn function as important clues to location-dependent aspects of relativistic electron production and evolution.

Only a few low-frequency surveys of galaxies presently exist at 80 and 160 MHz (Slee 1972a,b; 1977) and at 57.5 MHz (Israel and Mahoney 1990), all with limited resolutions too poor to resolve any spatial structure. However, they do imply the frequent occurrence of significant spectral flattening also at the low-frequency end, with spectral turnovers in the 100 - 1000 MHz range. This flattening may be explained by relativistic electron energy losses or free-free absorption of synchrotron emission by the ionized interstellar medium. Israel & Mahoney (1990) have shown that in the latter case, galaxies must have a pervasive presence of well-mixed clumpy thermal/nonthermal gas, with an ionized component at temperatures well below $T_e = 10^3$ K. This component might correspond to the ionized fraction of the cold neutral interstellar medium. Alternatively, the observed spectral turnovers could be caused by relativistic electron energy losses in large-scale galactic winds (Hummel 1991; Pohl et al 1991). At least in the case of the Local Group galaxy M33, Israel et al. (1992) found that free-free absorption is the most probable cause of the observed low-frequency spectral flattening.

Either explanation is extremely interesting. If free-free absorption is the dominant process, further low-frequency observations provide one of the few ways, if not the only one, of studying a major but hitherto virtually inaccessible component of the interstellar medium. If galactic winds apply, low-frequency observations again provide one of the few ways of studying the large-scale energetics and disk-halo interactions of spiral galaxies. Further progress in this field requires accurate determination of integrated galaxy spectra in the frequency range 20 – 1000 MHz, with good spectral sampling. LOFAR would play the essential role at the lower end of this range. In addition, low-frequency imaging of e.g. edge-on galaxies is also powerful discriminating tool as galactic wind models predict a spectra steepening away from the galactic plane, whereas the free-free absorption model predicts little or no spectral change perpendicular to the plane. In the plane itself there will be strong absorption by ionised gas in HII regions.

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3.8 Compact Sources in Nearby Galaxies

With sufficient resolution and sensitivity, LOFAR images of large nearby galaxies (M 33, M 31, M 101, M 82, M 81, M 51, NGC 6946 etc) may be used to search for compact nonthermal sources. The majority probably would be supernovaremnants (such as Cas A or the Crab (Taurus A)), but among these one could perhaps also detect pulsars. A particular interesting subject is the search for compact low-frequency nuclear emission. Such compact sources have been found in M 31 and in the Milky Way centre. Their nature is yet uncertain.

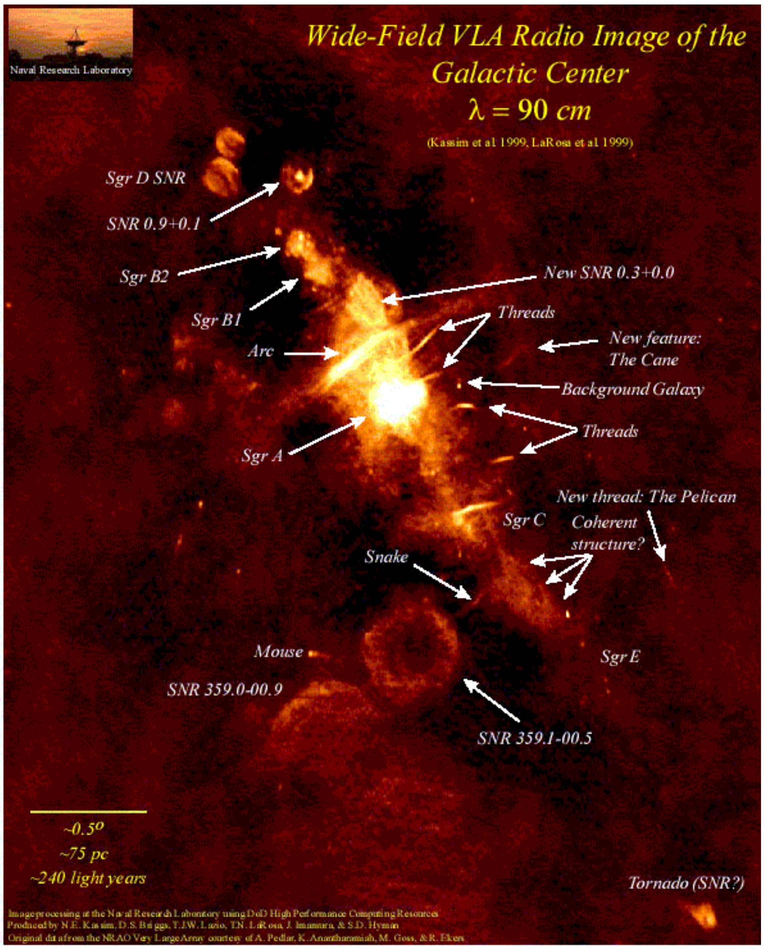

Figure 3.3 330 MHz wide-field VLA image of the Galactic center (LaRosa et al. 2000. Among the new sources discovered were the SNR G0.3+0.0 (Kassim & Frail 1996), and new nonthermal filaments the Cane and the Pelican (Lang et al. 1999).

3.9 Supernova Remnants and the Distribution of Ionized Gas in the ISM

The nonthermal spectra and extended morphologies of Galactic SNRs ideally match LOFAR's unprecedented, low frequency surface brightness sensitivity. The naturally large fields encompass the largest, individual Galactic SNRs and efficiently survey whole populations in nearby galaxies. Continuum spectrum studies are more accurate because of wide frequency coverage, and thermal absorption and scattering effects can only be measured at LOFAR frequencies.

3.9.1 Discovering New SNRs

Catalogs are severely selection effect limited and incomplete at surface brightness levels ~10^{-20} W m^{-2} Hz sr^{-1} (Green 1991), which LOFAR will exceed by two orders of magnitude. Catalogs under-sample both older SNRs and bright, compact, young SNRs, required for understanding SN/SNR birthrates, statistics, ISM energy input, and for comparison with progenitor populations. Sensitive (< 1 mJy/beam) LOFAR Galactic plane surveys will easily reveal many (>100) new SNRs and PSR/SNR associations, critical to studies of the radio lifetime of SNRs and PSR birth kinematics (Frail et al. 1994). LOFAR will also reveal unique sources such as the SS433 jet system within W50 and as seen in the Galactic center. The

330 MHz VLA image in Figure 3.3 presents an unprecedented combination of resolution and surface brightness sensitivity and has detected many new exotic sources (Kassim & Frail 1996, Lang et al. 1999, LaRosa et al. 2000). However it falls short of detecting emission on scales large enough to connect with structure seen on single dish maps (Sofue 2000) and linked to Galactic center black hole activity. LOFAR's dense uv coverage will achieve this and provide equally spectacular inner Galaxy maps in many more directions.

3.9.2 Spectral Studies

SNR radio continuum spectra trace the energy spectra of shock accelerated relativistic electrons and test predictions of shock acceleration theory, probing the complex modulation of blast-wave physics by the pre-existing environment into which remnants evolve. Theory is presently very poorly constrained, since models predict varieties of subtle variations which current observations are too inaccurate to test (Jones et al. 1998). Increasingly believable evidence of spectral variations is emerging, but the poor accuracy of the primitive lowest frequency data remains the weakest link and guarantees that LOFAR will have a powerful impact.

LOFAR will revolutionize the accuracy of SNR spectra where Fermi theory predicts curvature and strongly constrains magnetic fields. Present spectra are inaccurate at low frequencies, and believable curvature is suggested towards only a few sources (Reynolds & Ellison 1982). Integrated spectra also test Van der Laan theory where controversial bends are linked to cosmic ray gas compression (Green 1990). Spatial spectral variations test theory in greater detail, e.g. steep spectrum breakout regions interpreted as weaker shocks (Pineault et al 1998). But curved electron spectra, magnetic field gradients, particle acceleration/diffusion and other effects weave a complex relationship which present maps are too crude to constrain. This is despite the maturity of spectral analysis (Anderson & Rudnick 1993, Zhang et al 1997) utilizing new techniques (e.g. spectral tomography, Katz-Stone et al. 2000) robust against calibration errors. But they cannot overcome the poor resolution and sensitivity of the lowest frequency images. LOFAR spectra will distinguish remnant morphologies (e.g. composites and barrels, Dwarakanath 1991, Gaensler, 1998) and reveal the influence of pulsar winds (Frail et al 1994). A preeminent mystery is the missing Crab shell, demanding explanation in context of blast wave physics/ISM properties. LOFAR will improve the best limit (Frail et al 1995) by two orders of magnitude.

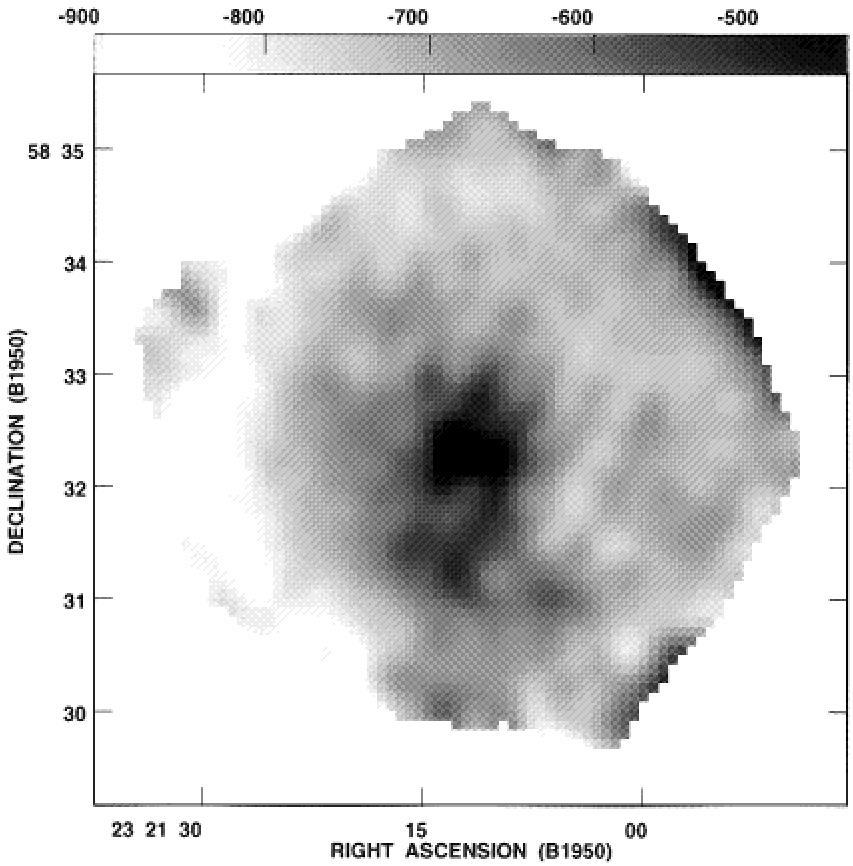

Figure 3.4 74-330 MHz spectral index grey-scale map of Cas A made with the VLA. Dark corresponds to a flatter spectrum, a region of absorption caused by free-free absorption from unshocked ejecta interior to the reverse shock (Kassim et al 1995).

3.9.3 Absorption & ISM Studies

The surprising discovery of SNR internal absorption at 74 MHz implies LOFAR will detect thermal material inside numerous remnants. The Cas-A absorption (Figure 3.4) is only the second detection of unshocked ejecta inside a young SNR (Kassim et al 1995). It is expected from theory and provides a crucial probe of reverse shock physics in young SNRs. The Crab also shows thermal absorption from its foreground thermal filaments, constraining their location relative to the pulsar powered nonthermal emission (Bietenholz et al 1997). Extending SNR thermal absorption measurements beyond these pathologically bright sources requires LOFAR.

SNR integrated spectra reveal low frequency turnovers (Kassim 1989) due to extrinsic thermal absorption. This offers a powerful constraint on the distribution of ionized ISM gas, including hard upper limits on the Warm Ionized Medium density ($\leq 0.26\ cm^{-3}$) which can be greatly improved by lower frequency (≤ 50 MHz) LOFAR measurements. The patchy absorption is consistent with Extended HII Region Envelope absorbers suggested by stimulated low frequency recombination lines (Anantharamaiah 1986) which LOFAR will also be uniquely sensitive too. However existing spot frequency data are at primitive resolution (>15'), with the 74 MHz VLA image in Figure 3.5 being the first spatially resolved detection of ISM absorption against a Galactic SNR (Lacey 2001). A >100 times more sensitivity, frequency versatile LOFAR will redefine this field of study. For inner Galaxy complexes the contrast between absorption and emission will disentangle the relative superposition of HII regions and SNRs as in W30 (Kassim & Weiler 1990) and the Galactic center (Pedlar et al 1989), but in most cases is impossible without LOFAR.

Scattering measurements test blast wave physics which predicts turbulence near SNR shocks. These are accessible to LOFAR through measurements of background sources, with broadband coverage distinguishing between competing absorption effects. VLBI has explored for such effects, e.g. the heavily scattered line of sight towards 1849+005 passing coincidentally ~10' near SNR G33.6+0.1 (Spangler et al 1986), but connections remain unproven. The myriad, sub-mJy background sources and the λ^2 dependence of scattering will allow many more measurements by LOFAR.

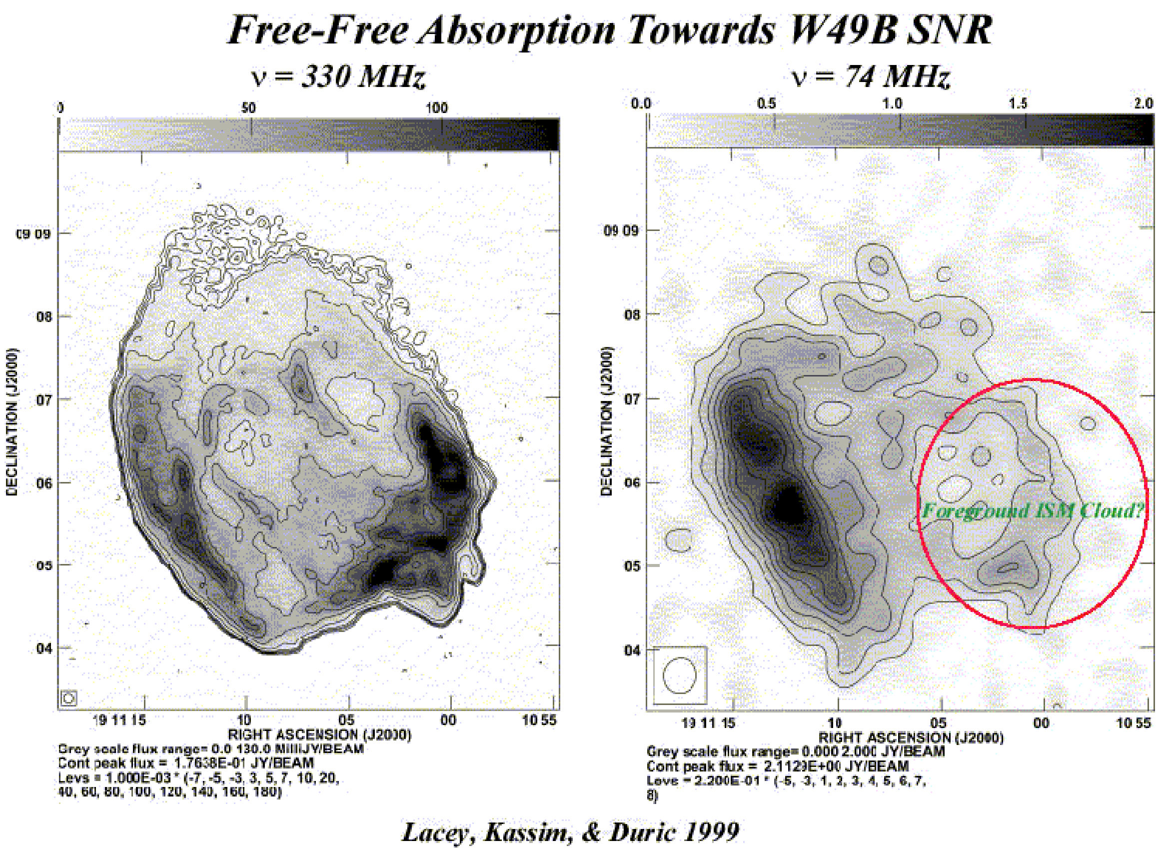

Figure 3.5 74-330 MHz spectral index map of W49B revealing the first spatially resolved detection of ISM thermal absorption towards a Galactic SNR (Lacey et al. 2001).

3.9.4 Extragalactic SNR Studies

Nearby galaxies provide powerful statistical samples of co-distant SNRs (Jones et al 1998). LOFAR will find new SNRs and anchor spectral and morphological identifications made at higher frequencies. Many SNRs show extrinsic turnovers at higher frequencies (≥ 100 MHz) than towards Galactic SNRs. At 408 MHz in M82 this implies ionized gas with emission measures ~10^6 cm^{-6} pc, comparable to giant HII regions (Wills et al. 1997). This places the discrete sources relative to the host galaxy ISM, and measures particle acceleration efficiency, relates cosmic ray origin to specific SNe types, and measures SN rates, star formation, and ISM properties (Duric et al 1995, Jones et al 1998). Lower frequency observations are crucially required but without LOFAR have insufficient resolution.

In summary, LOFAR will offer unique insights into SNRs and their interaction with the ISM, with its surface brightness sensitivity and field of view well matched to SNR spectra and morphology. Intrinsic absorption seen by the 74 MHz VLA imply LOFAR will trace thermal material within many more SNRs, and it will complete SNR catalogs by uncovering many (>100) new remnants and SNR-PSR associations. Its broad-band response and high resolution will empower shock-acceleration studies where sensitive, spatially resolved spectral index maps trace synchrotron emitting relativistic electron energy spectra. Comparisons with higher frequency images will measure spectral variations at unmatched accuracy to test theoretical predictions, and will re-define integrated spectra. LOFAR will be a powerful diagnostic of ISM gas, with SNRs and background sources providing a grid against which to map the ISM through absorption and scattering processes. LOFAR SNR applications extend to nearby galaxies, mapping the ionized ISM with respect to the discrete sources. Powerful, co-distant sampled LOFAR SNR images and spectra will provide powerful constraints on the star formation history, ISM energetics, and cosmic ray gas properties of nearby galaxies.

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3.10 H II Regions

Observations at 330 MHz have demonstrated that measurements of optically thick H II regions can constrain source electron temperatures, emission measures, and filling factors. At lower frequencies these regions appear as cooler regions against a much hotter Galactic background, allowing kinematic distance ambiguities to be resolved and the superposition of thermal and nonthermal sources to be separated along complex lines of sight through the Galaxy. A classic example is the 330 MHz VLA observation that revealed the thermal Galactic center source Sgr A West in absorption against the nonthermal Sgr A East supernova remnant, constraining the superposition of these sources along the most confused Galactic line of sight. Along other lines of sight, kinematic-distance ambiguities resulting from radio-recombination-line measurements can be resolved using the detection, or non-detection, of H

II regions in absorption below 100 MHz, because foreground ("near") H II regions would be much more prominent absorption features on low-frequency LOFAR images than distant ("far") ones.

3.11 Interstellar Propagation Effects

All Galactic and extragalactic radio sources are observed after their radiation has propagated through the Galactic plasma (Rickett 1990). Variations in the plasma density produce refractive index fluctuations, scaling as ν^{-2}, which in turn scatter the radiation. The magnitude of radio-wave scattering from the interstellar plasma is strongly direction dependent, but the effects can remain significant at frequencies as high as 10 GHz or higher. The density (refractive index) microstructure responsible for interstellar scattering occurs on scales of order 1 AU. The density fluctuations, in turn, are thought to arise from velocity and/or magnetic field fluctuations. In addition to their corrupting effects, interstellar propagation effects are a powerful sub-parsec probe of the interstellar plasma, can provide a tracer of energy input into the ISM, can serve as a filter to find extremely compact sources, and may be linked to cosmic ray propagation. The strong frequency dependence of interstellar scattering means that studies of it are optimized with high-resolution, low-frequency observations.

LOFAR would prove useful for interstellar scattering studies in a number of respects. The most recent compilation of scattering observations contained 223 sources, a number that will be greatly increased by LOFAR. Not only will LOFAR increase the number of known pulsars by a large amount, but it will also enable scattering observations in less intense scattering regions. The vast majority of scattering studies have been conducted using compact extragalactic sources viewed through regions of intense scattering (e.g., Cygnus), where the scattering effects can be detected at frequencies near 1 GHz on baselines of length 50–5000 km, typically with VLBI. The use of VLBI has also restricted most scattering studies to relatively bright sources. Because of the λ^2 dependence of scattering and LOFAR's sensitivity a much larger volume of the Galaxy will be opened for scattering studies.

Of particular interest is the distribution of the scattering material near the Sun and its spatial spectrum. There are conflicting claims for the detection of a signature from the boundary of the Local Bubble. The interior of the Local Bubble is a hot, nearly fully ionized gas whereas the gas outside is cooler and perhaps only partially ionized. At the interface, one might expect some amount of turbulence and an increased level of scattering. However, the generally weak level of scattering near the Sun means that a signature of this interface is difficult to detect at frequencies near 1 GHz. The magnitude of scattering observables, e.g., angular broadening, depends not only upon the total rms electron density fluctuations toward a source, but also upon their distribution along the line of sight. Thus, multi-frequency scattering observations of nearby pulsars may resolve the local structure of the interstellar medium.

Current shock-acceleration theories, relevant to the origin of cosmic rays, also suggest that upstream of a SNR should be an ideal site for the generation of the density fluctuations responsible for interstellar scattering. High-frequency searches for the signatures of such upstream turbulence have a mixed record. The λ^2 dependence of interstellar scattering would allow much more stringent tests to be applied.

Compact incoherent extragalactic sources should be limited by the inverse Compton catastrophe to brightness temperatures of no more than about 10^{12} K. Nonetheless, various sources have been identified that have inferred brightness temperatures well in excess of the Compton limit (by factors of 10^2–10^3). The primary means for identifying these sources has been via their variability: Low frequency variables (LFVs) are sources that vary on time scales of order 1 year at frequencies below 1 GHz while intraday variables (IDVs) are sources that vary on time scales of order hours at frequencies near 5 GHz. Various lines of evidence, including a dependence on Galactic latitude, suggest that the variability is *extrinsic* in origin and results, either partially or entirely, from refractive interstellar scintillation (RISS). The variations are caused by AU-scale density fluctuations drifting past the line of sight and focusing and defocusing the background source. The effective velocity of the density fluctuations is determined by a combination of the Earth's velocity and motions within the interstellar medium. Just as in the case of optical scintillation in the Earth's atmosphere (“stars twinkle, planets don't”), in order to display RISS a source must be less than a characteristic size. The implied diameters of LFV and IDV sources are of order 10 µas to 10 mas, well below can be probed even with current space-based VLBI at the relevant frequencies. Thus RISS, via LFV and IDV, can serve as a probe of the interstellar medium on AU-scales and a filter on source diameter selecting milliarcsecond- and sub-milliarcsecond-diameter sources.

Monitoring programs typically indicate that only a small fraction, ~1%, of sources are compact enough to display LFV. IDV is a more recently recognized phenomenon, but initial monitoring programs suggest that the proportion of IDV sources might be much higher. Although no detailed comparison of IDV and LFV has been done, other than the possible proportion of variable sources, sources displaying either of the two phenomena have a number of similarities. Most notable is that flat-spectrum sources are most likely to display either IDV or LFV. With notable exceptions, LFV monitoring programs have consisted of measuring the flux density of sources at only a few epochs. Sampling a large number of sources relatively frequently might reveal that a much larger fraction of sources really are LFVs. Such a monitoring program would also elucidate motions of the Earth relative to the local interstellar medium potentially as well as motions within the interstellar medium. An exemplar of this kind of monitoring program is that of Bondi et al. (1994) who were able to determine the Earth's motion relative to the local interstellar medium by finding annual variations in the level of variability. Their analysis relied on only 43 sources; with a sufficiently large number of sources one could consider differences in the level of annual variations in different directions, which would presumably indicate motions within the medium.

With its relatively large beams LOFAR would be a powerful monitoring instrument. It is not implausible that any given region of the sky (and the sources within it) would be observed on average once a week. Over the lifetime of the instrument, 5–15 year light curves with nearly weekly sampling could be produced on a considerable number of sources. Such light curves would be powerful diagnostics of RISS-induced (and intrinsic) variability. The results of a monitoring program could also be used to define a homogeneous sample from which to probe other aspects of LFV. For example, is there a redshift dependence on the likelihood for a source to display LFV? The presence (or absence) of such a dependence would probe the evolution of radio sources. The long time scales of LFV, as opposed to those of IDV, make its identification easier in large samples of sources. In an individual source, IDV can be identified relatively quickly, but with current single-beam, high-frequency instruments monitoring a large number of sources is demanding on telescope resources. Conversely multi-beam, high-frequency instruments, such as the proposed Square Kilometer Array, are scheduled to become operational around 2010, after LOFAR is projected to have been operational for approximately 5 years. Light curves from a combined SKA and LOFAR monitoring program would be complimentary means of exploring and contrasting IDV and LFV.

LOFAR may also probe novel regimes of scattering. Typical analyses of scattering assume that the scattering medium extends an infinite distance transverse to the line of sight. At low frequencies, as the scattering diameter increases, the scattering diameter may begin to approach the size of the scattering region. If so, the assumption of an infinite scattering region is no longer appropriate. Such spatially-limited scattering, if detected, would result in the apparent structure of the source being determined by the scattering region. To date, scattering observations have focused on the Galactic plasma. At low frequencies, intergalactic scattering may become detectable. The dominant source of intergalactic scattering toward distant sources is probably the interstellar media of intervening galaxies, however, at high redshifts or low frequencies effects from dense Lyα clouds may also become detectable.

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3.12 Polarimetry

The magnetic field is a major source of pressure in the ISM and controls the flow of charged particles in and out of the Galactic disk. Radio continuum polarization data carry important, and often unique, information about the strength and topology of the large scale Galactic magnetic field, plasma turbulence and the ionized components through the measurement of Faraday rotation. As such, these observations complement the line-of-sight measurements of interstellar scattering. Moreover, additional observational constraints would help motivate further MHD modelling, particularly now that computational power is approaching what is needed to do the complex simulations. Polarization studies could provide insight in the following areas: (1) Disk/halo emission (Parker instabilities, bubbles); (2) Cosmic ray origin and propagation; (3) Particle acceleration via reconnection processes; (4) Origin of the Galactic magnetic field (wound up by differential rotation from a primordial seed field?); (5) The existence of large-scale currents (e.g., those thought to be required by the Galactic center filaments); and (6) Distribution and temperature of ionized gas (10^3–10^7 K).

A recent additional motivation for the study of the diffuse polarized emission of disk galaxies is the recognition of its importance for high-redshift galaxies. The microJansky population of radio sources (at a few GHz) appears to be dominated by starforming galaxies at high redshift. The radio luminosity of these galaxies is generated probably by synchrotron emission from their disks. The sources of particles responsible for this emission seem clear (massive star formation, OB stars, SNe and pulsars). However, it is less clear how the magnetic field was formed and how strong it is. Understanding the field in our Galaxy (i.e., a prototypical z = 0 galaxy) is essential to infer correctly the properties of high-z, young disk galaxies.

3.13 Recombination Lines

In the 20-100 MHz range both hydrogen and carbon recombination lines occur from high quantum number transitions (in contrast to the $n < 200$ transitions observed at centimeter wavelengths). At such high quantum numbers, atoms have radii of order 0.1 mm and are extremely sensitive to their surroundings, making them excellent probes of the ambient physical conditions. Furthermore, at these low frequencies, most of the observed recombination lines are due probably to carbon rather than hydrogen. Sufficiently broad backends will allow simultaneous observations of various line sequences. At the lowest frequencies, the level populations are determined by collisions with free electrons rather than by radiative transitions; the lines are thermalized and can be seen in absorption against background sources. The quantum number at which the lines change from being in emission to absorption depends on the balance of collisional excitation (temperature and density) and radiative excitation (local radiation field).

A number of Galactic regions that produce these lines have been found, including a large region that stretches 40° along the Galactic plane in the inner Galaxy. Recombination line observations in the direction of individual sources, notably Cas A, have yielded important information on the condition of the diffuse interstellar medium at low densities, $n_e < 1$ cm^{-3}, and temperatures, $T_e < 100$ K. However, all observations of these lines have been made with filled apertures with extremely low angular resolutions. The complexity of the analysis requires resolutions better than 1” for further progress. This is needed in particular to discriminate between two sets of models, one corresponding to a cold ISM phase associated with molecular hydrogen, and one corresponding to a slightly warmer ISM phase associated with neutral atomic hydrogen. The very central portion of LOFAR will have sufficient surface brightness sensitivity for detection of these lines and would provide much needed angular resolution to map their distribution. The sensitivity of the LOFAR will also be sufficient to extend such studies to nearby galaxies.

3.14 Neutron Stars and Their Environments

Over the last 30 years, a comfortable picture has emerged in which a supernova forms both a supernova remnant (SNR) and a rapidly rotating neutron star. The neutron star produces opposed beams of radio emission – when these beam cross our line of sight we observe the neutron star as a pulsar. A neutron star also produces a relativistic wind, which interacts with the ambient medium to form an observable pulsar wind nebula (PWN), of which the Crab Nebula is the best-known example.

However, there are many aspects of this picture which are not understood. What fraction of supernova explosions produces neutron stars? How many pulsars are beaming away from us so that we do not see them? How do neutron stars deposit their energy into their associated PWNe? Furthermore, a flurry of recent discoveries have forced us to concede that there are many products of core-collapse besides radio pulsars, all very different from “normal” radio pulsars. Just how these new classes of object relate to each other and to pulsars is still not clear.

Both pulsars and SNRs have steep radio spectra, and the latter are generally of low surface brightness. Thus with its capability to form high sensitivity images at low frequencies, LOFAR will excel at finding and studying SNRs and pulsars, and thus can make important contributions to the study of neutron stars and their environments. Specific problems that LOFAR will address are outlined below.

3.14.1 Associations Between Neutron Stars And SNRs

Most of what we know about young neutron stars comes from those few cases where we can also identify the SNR formed in the same explosion. Most fundamentally, associations with SNRs provide independent estimates of neutron star ages and distances, from which birth-rates, initial periods and luminosities of the neutron star population can be calculated (Frail, Goss & Whiteoak 1994). The offset of a neutron, star from the SNR's center also lets one calculate the projected velocity with which the former was ejected from its supernova explosion.

Many young neutron stars lack associated SNRs – deep imaging towards these sources with LOFAR can result in new associations with SNRs, the properties of which can further add to our understanding of the neutron star population (Gaensler, Gotthelf & Vasisht 1999; Crawford et al. 2001). In cases where no surrounding SNR is detected, the upper limits on surface brightness can be used to calculate the lifetimes of SNRs and their ambient densities (Braun, Goss & Lyne 1989).

Imaging of SNRs already proposed to be associated with neutron stars can also shed new light on such systems (Frail, Goss & Whiteoak 1994; Yusef-Zadeh et al. 2000). Some associations are problematic because the neutron star is on the edge of or even outside the SNR. However, LOFAR may reveal low-surface-brightness extensions to a SNR, which may demonstrate its extent to be further than previously thought, and cause a corresponding association with a neutron star to be re-assessed.

3.14.2 Searching For Point Sources In PWNe

A pulsar wind nebula is an unambiguous indicator that a young and energetic pulsar resides within. PWNe are thus obvious places to look when searching for such pulsars. There are sufficiently few young pulsars known that any such detection is interesting in its own right (Strom 1987). But more fundamentally, when the whole population of PWNe is considered, the statistics of detection and non-detection of central pulsars can be used to calculate pulsar luminosities and beaming fractions (Frail & Moffet 1993).

PWNe are flat-spectrum sources, while their central pulsars have steep spectra. Thus at the low frequencies and high spatial resolution offered by LOFAR, a young pulsar beaming towards us should be detectable as a central point source within a PWN (Kassim et al. 1993). Any point source thus identified can then be subjected to pulsation searches to confirm its identity, while the position of such a source relative to wisps, jets and other features seen within the PWN can help determine the energetics of the nebula.

3.14.3 Ghost Nebulae

While it is thought that all pulsars generate relativistic winds, only in a small fraction of cases do these winds generate observable PWNe. Pulsars with radio-bright PWNe are usually traveling at high velocity or are inside SNRs, presumably because their winds are confined by their high pressure environments. Deep searches around the remainder of the pulsar population have failed to find any associated PWNe, but the consequent upper limits cannot rule out the existence of large, faint "ghost nebulae", resulting from pulsar winds expanding into low density environments (Blandford et al. 1973; Frail & Scharringhausen 1997; Gaensler et al. 2000).

Because of its excellent surface brightness sensitivity and sampling of the largest spatial scales, LOFAR will be able to make much deeper searches for radio nebulae around pulsars than has previously been possible. Detection of such nebulae can provide the first real insight into how the overall pulsar population deposits its energy into the ambient medium.

3.14.4 PWNe Around Radio Quiet Neutron Stars

While the vast majority of neutron stars so far discovered are seen as radio pulsars, there are also a small but increasing number of “radio quiet neutron stars” (RQNS), seen as unpulsed X-ray sources but not detected in radio waves. Many RQNS have been associated with SNRs, and are thus probably quite young objects.

The nature of RQNS is hotly debated. It has been proposed that RQNS are either neutron stars with large initial periods and/or high magnetic fields (Vasisht et al. 1997), or that they are simply energetic young radio pulsars, but whose beams do not cross our line of sight (Brazier & Johnstone 1998). One way to distinguish between these possibilities is to search for a PWN around a RQNS (Gaensler, Bock & Stappers 2000) – the detection of a PWN with typical properties would argue that a particular RQNS is a pulsar beaming away from us, while an unusual PWN or a non-detection would favor more exotic explanations. With LOFAR's surface brightness sensitivity, far deeper searches for PWNe around RQNS than previously possible could be carried out.

3.14.5 Spectral Variations Across PWNe

The spectral index of synchrotron emission can be directly related to the energy spectrum of the emitting electrons. Any spatial variation in the spectral index of a PWN thus results from the processes of injection, acceleration and diffusion within the nebula, all of which are poorly understood. Types of spectral variation which might be expected include regions of flatter spectrum in which renewed acceleration is occurring, a gradual steepening of the spectrum with increasing radius due to synchrotron losses, and a steeper spectrum around a PWN's perimeter, representing shock acceleration at a surrounding SNR blast wave.

Studies of the Crab Nebula over a frequency range of 74 to 5000~MHz have shown little spectral variations across the nebula (Bietenholz & Kronberg 1992; Bietenholz et al. 1997). However, such studies are limited by the spatial resolution and sensitivity at the lowest frequency, which prevent a search for spectral variations on the smallest scales or towards other, fainter, PWNe. In particular, the so-called “low frequency break” PWNe have very different spectral properties to the Crab Nebula, and may fundamentally differ in their energetics (Woltjer et al. 1997). LOFAR will have the sensitivity and spatial resolution to make detailed studies of spectral index variations for the Crab Nebula and for many other PWNe, which will allow us to better probe the variations in the electron distribution throughout the nebula.

3.14.6 Searching for SNRs around PWNe

Since supernova explosions are believed to form both neutron stars and SNRs, a young pulsar and its associated PWN are expected to be surrounded by a SNR. While the majority of PWN are indeed found within SNRs, there are approximately 10 PWNe (including the Crab Nebula) for which deep imaging of their environments shows no surrounding SNR (Reynolds & Aller 1985; Frail et al. 1995). The most likely explanation is that these ``naked'' PWNe are evolving into low density regions of the ISM so that there has been no significant interaction between the supernova blast wave and surrounding material.

The obvious way to test this model, and to further investigate these sources, is to search for SNRs surrounding these PWNe. The size and shape of a surrounding SNR delineates the position of the supernova blast wave, traces the interaction with ambient material, and allows one to estimate physical parameters such as the age of the system, the energy in the initial explosion and the ambient density (Slane et al. 2000). Furthermore, the results from searches for SNRs towards these sources can be used to estimate what fraction of supernova explosions produces faint and/or undetectable SNRs, a result which affects estimates of the SNR birth-rate and of the filling factor of the hot low-density component of the ISM (Gaensler & Johnston 1995). Since SNRs have steep radio spectra, low-frequency searches with LOFAR for shells around PWNe will be far more sensitive than previous efforts.

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3.15 Studying Pulsars

Pulsars were discovered using a low-frequency instrument (81 MHz, Hewish et al. 1968), and most searches for radio pulsars to date have searched for dispersed, pulsed emission at frequencies of 400-1400 MHz. Alternate search techniques will need to be employed at lower frequencies, as pulse broadening from interstellar scattering will become increasingly important. At 100 MHz only nearby pulsars – those with dispersion measures DM ≤ 100pc/cm^3 – will suffer pulse broadening less than 1s and be seen as sources of pulsed emission; at 30 MHz only a handful of the very nearest pulsars, DM ≤ 10pc/cm^3, will be seen as sources of pulsed emission (Cordes 1990), though there may be important exceptions to these limits in certain directions.

Even so, LOFAR will provide important new capabilities for pulsar studies, which we summarize in this section.

3.15.1 Spectral Turnover

The generally steep spectra of pulsars is observed to have a low-frequency turnover, typically at frequencies between 100 and 250 MHz (e.g., Malofeev et al. 1994). However there is a small fraction of pulsars for which no such spectral break has been observed, to frequencies as low as 50 MHz. High- sensitivity, low-frequency studies are ideal in two respects for constraining further radio emission models, first by enabling additional single-pulse studies of pulsars known to emit below 100 MHz and, second by using LOFAR to find pulsars below 100 MHz.

3.15.2 Searching for New Pulsars

The apparent detection of the Geminga pulsar only at the specific frequency of 100 MHz (Malofeev & Malov 1997; Kuzmin & Losovskii 1997; but see Kassim & Lazio 1999), and the existence of pulsars like B0943+10, which have flux-density spectra with a spectral index steeper than -4.0 (Deshpande & Radhakrishnan 1994), suggests that there may be quite a 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, as indicated by the radius-to-frequency mapping and the dipole geometry. The increase in the pulsar emission cone width could become quite significant at low frequencies, leading to a large increase in the “beaming fraction” below 100 MHz. Thus, pulsars which may not be beamed towards us at higher frequencies may be detectable at low frequencies. Detection of these pulsars would provide an improved understanding of radius-to-frequency mapping and a clearer understanding of the total population of radio pulsars.

Even for the normal population of pulsars, given the projected sensitivity of the LOFAR (~36 K/Jy a 150 MHz, with an effective area of about 95,000 m^2) and the currently known luminosity function for pulsars, it turns out that we will be able to discover about 1300 new pulsars in the Galaxy! This number would double the currently known population of radio pulsars in the Galaxy. (For comparison the recent Parkes multi-beam survey is expected to discover roughly 750 pulsars.) We have arrived at this estimate with a Monte Carlo simulation. We injected a large number of objects in the Galaxy with an assumed distribution in their Galactic coordinates, and magnetic field strength and rotation period, and computed the fractional population of pulsars “detectable” by the LOFAR (above the declination of –25 degrees). The detection of such a large number of pulsars (or even the lack of such a large number of new pulsars) will provide a unique opportunity to understand the fainter side of the luminosity distribution of pulsars.

The possibility of low frequency or ultra-steep-spectrum radio emission from high magnetic field pulsars such as the magnetars (e.g., Kouveliotou et al. 1998) and anomalous X-ray pulsars (AXPs, e.g., Israel et al. 1999) is also a very exciting one. Furthermore, there are also a large number of supernova remnants (SNRs) that have no compact counterparts; the absence of such a central compact source could potentially be due to steep-spectrum radio pulsars. A survey of SNRs, as well as those neutron stars not yet detected at high radio frequencies, with a sensitive instrument such as a LOFAR would probe both the SNR-pulsar connection as well as possible new radio emission mechanisms (from magnetars and AXPs). However, while dispersion smearing of the pulse profile can be corrected (by "coherent de-dispersion"), interstellar pulse broadening can be significant, as it depends on the observing frequency as $\nu^{-4.4}$. Therefore, for the short pulse periods (which the AXPs and magnetars do not have), we will definitely be probing only the local population.

For all these survey projects, a telescope with N beams allows a survey to reach a specified sensitivity level N times faster or to go N times deeper in the same amount of time.

3.15.3 Emission Physics

Given the sensitivity of LOFAR in the frequency range of 150-250 MHz, it becomes a very attractive instrument for studying individual pulses. To understand the radio emission mechanism in its full detail, it is very important to have high-time resolution single pulse observations. It is also important to aim for high-resolution polarimetry. Problems related to the ionospheric Faraday rotation will be solved as part of the procedure to solve for the rafraction problems as a function of time.

These high-resolution observations will also help to understand some of the fundamental problems, such as the behaviour of "mode changing" at low frequencies, and nature and the mechanism of the giant pulses. The frequency dependence of these properties can also be effectively studied by complimentary high-frequency observations with the other telescopes.

For pulsars like 0329+54 and 1133+16, where the interstellar scattering effects are small enough at frequencies of 150-250 MHz, the estimated signal to noise ratio of single pulses observed with the LOFAR could easily be a few hundreds! Therefore, LOFAR gives a unique opportunity to study and understand the behaviour of these very short temporal structures in great detail for a large number of pulsars.

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3.16 Jupiter

3.16.1 Magnetosphere

Jupiter has powerful radiation belts which produce bright synchrotron radiation. Although measurements at a variety of radio frequencies have been used to determine the energy spectrum of the radiating electrons, a number of questions about their distribution and source remain uncertain. The emission has been extensively mapped at cm wavelengths and reconstructed in 3 dimensions using tomographic techniques (de Pater & Sault 1998; Sault et al. 1997). This synchrotron emission was also recently detected at 74 MHz using the VLA (dePater 1999). Above about 1 GHz, the spectrum shows a standard power law with a spectral index of ~ -0.5 but it flattens and then turns over at lower frequencies. This spectrum has been empirically fit with a four parameter model (van Allen 1976) but refinement of the fitting parameters and their relation to physical conditions remain to be explored. The most generally accepted causes of the decrease in low energy electrons are pitch angle scattering, radial diffusion processes, and accleration at instabilities in the field and plasma. These processes can all vary with position in the magnetosphere and the presence of satellites.

It is thus very important to image Jupiter's magnetosphere at several frequencies below 300 MHz, where the spectrum is changing, at the same time and with the same spatial frequency coverage. This is the only way that the different effects can be separated and their importance evaluated. The requirement for similar timing is necessary because, as well as possible long term variations with solar distance, Jovian seasons (small but present), and solar stimulation (Klein et al. 1998), the inclined and offset magnetic dipole significantly changes the observed emission with Jupiter's 10-hour rotation period. In addition to helping understand the energetics of Jupiter's magnetosphere, these data may have inplications for establishing how the effects of space weather may get transferred through the earth's magnetosphere.

3.16.2 Decameter Bursts

The source of bursts of radio emission from Jupiter at decameter wavelengths still remains a mystery more than 40 years after their discovery. Many observational parameters have been determined but we still don't know the actual location of the source nor the detailed emission mechanism. Until we have the high angular resolution afforded by LOFAR we will not be able to determine the key positional information.

These bursts of decametric radio emission occur from frequencies below the ionospheric cutoff up to 40 MHz. Their repetition is tied to the spin rate of the planet with modulation caused by the viewing aspect from earth plus the location of the satellite Io, and to a lesser extent some of the other inner satellites, with respect to the line of sight to earth. Many of these data indicate that the radiation may be highly beamed. Any possible solar dependence is unconfirmed. Early VLBI experiments showed that the source size is small, probably less than about 500 km, but they had no phase reference and so the source locations remain unknown (Dulk 1970; Lynch et al. 1972).

Jovian storms have typical bandwidths of a few MHz, drift either up or down in frequency with rates of about 1 MHz/minute, and can last for tens of minutes. Individual pulses, however, can have bandwidths of only tens of kHz and last for fractions of a second. The brightness peaks at a fequency of about 10 MHz; typical flux densities at 20 MHz would be about 10^6 Jy (see e.g. the review by Carr & Desch 1976).

The detailed emission mechanism is not known. The radiation is highly circularly polarized which may suggest cyclotron radiation from energetic electrons orbiting Jupiter's magnetic field lines in the ionospheric regions of the planet. They appear to be dumped there through perturbations by the satellites passing through Jupiter's extensive magnetosphere. The coupling between Io's orbital motion and Jupiter's ionosphere, the instability mechanism which can amplify the electromagnetic waves, and the propagation of the radiation through the plasmasphere are still problems to be resolved.

Clearly, a knowledge of specifically where the source lies plus its variation with rotation and Io's location will greatly aid efforts to characterize the interrelated mechanisms resoponsible for these decameter bursts from Jupiter. The good resolution of LOFAR – about 1/10th of Jupiter's disk for a 400 km baseline at 30 MHz - would be very valuable for monitoring changes in the source position with time. The emission is strong so that individual bursts can be characterized as well as whole storms. For example, does the position shift as the frequency drifts, how far are the feet of the active flux tubes from Io's position, etc.?

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3.17 Extrasolar Planets

The recent detections of extrasolar planets have stimulated the imagination of many astronomers and members of the public as well. The existence of places possibly similar to the earth brings up the question of our uniqueness and all the implications thereof. The results to date, however, are surprising in that all the detected planets appear to be many Jovian masses and to lie well within 1 a.u. of their parent stars. It is difficult to understand how they could have formed in such tight orbits without tidal disruptions or have been perturbed into stable orbits that close to a more massive object. It may be that such planets are rare and have been detected by observational selection but maybe the solar system is the unusual case. The method of detecting cyclic variations in radial velocity of a star to indicate orbital motion, requires a large mass for the planet and a small orbital radius in order to produce a detectable shift in the star's motion. Detection of decameter bursts similar to those from Jupiter might offer a way of detecting lower mass planets at any distance from their stars.

Five solar planets have magnetospheres although only Jupiter produces strong decameter bursts. The intensity of these bursts should depend on the magnetic moment of the planet which is likely proportional to the mass and also the rotation rate. Injection from the stellar wind is at least partly responsible for the magnetospheric particle population; this, in turn, is proportional to the inverse square of the distance from the parent star and the stellar activity. Finally, the passage of satellites through the magnetosphere affects the dumping of the particles into the ionosphere. It is clear that we need to study Jupiter thoroughly with LOFAR to find the location of its burst radiation which will help us to more thoroughly assess the emission processes and better choose other candidates for detection of similar planetary systems.

As a quick assessment of the relative possibilities for detection of bursts from extrasolar planets, we note that Jupiter has the strongest magnetic field but the other planets also have different geometrical effect: the earth is closer to the sun but does not have any satellites within its magnetosphere; Saturn does have weak hectometric bursts detected by Voyager but its magnetic axis is aligned with its rotational axis rather than tilted and it is further from the sun; Uranus and Neptune have highly tilted magnetic as well as rotational axes so both their stimulating and viewing geometries may be unfavorable.

One good planet in the solar system with decameter bursts readily detectable by LOFAR is very promising, however, particularly if we wish to begin the search for extrasolar planets like those detected to date by the radial velocity techniques. They have larger masses than Jupiter (and thus likely larger magnetic fields) and are closer to their parent stars (with thus a greater cross section for the stellar wind). A reasonable detection rate is certainly possible.

It should be noted that the sun produces noise storms of comparable brightness in the same frequency range but they are much more sporadic and do not have the precise repetition with rotation rate. Thus, it will be necessary to monitor each candidate for a few months to search for periodicities appropriate for a planetary rotation, say a few hours to several days.

With typical bursts of about 10^6 Jy at 20 MHz for a planet at Jupiter's distance, (they can be a factor of 10 higher) we can expect 0.4 mJy at 1 pc or 4 microJy at 10 pc. This may make detections marginal as we have only about 5 MHz bandwidth and a few minutes per burst.

4 Solar Applications for LOFAR

4.1 Passive Solar Emission Studies

In addition to solar radar, there are direct as well as indirect means by which LOFAR will be capable of studying a wide range of important solar phenomena through conventional passive emission imaging. These include detecting radio emission directly from CMEs and detecting and tracking CMEs and interplanetary shocks through scattering measurements. In addition, LOFAR will provide high quality, dynamic images of solar flares, bursts, and storms, many of which result in powerful coherent emission at LOFAR frequencies. The lack of any currently operational, high dynamic range, broad-band, high resolution imaging radio heliograph operating below 150 MHz makes LOFAR passive emission studies of CME and related solar phenomena particularly attractive at this time.

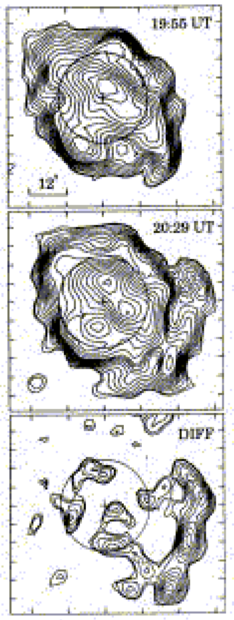

Figure 4.1 Clark Lake detection of the CME of 1986 February 16 observed by the coronagraph aboard the Solar Maximum Mission satellite. The upper panel shows the quiet Sun at 73.8 MHz prior to the formation of the CME seen lifting off from the sun approximately 30 minutes later in the middle panel. The bottom panel is the difference of the two.

4.1.1 Direct Detection of Emission from CMEs

There are only two reported cases of ground-based radio detection of thermal emission from CMEs in the literature, and both of these were at LOFAR frequencies < 100 MHz. Sheridan et al. (1978) detected a CME at 80 MHz using the Culgoora radio heliograph while Gopalswamy and Kundu used the Clark Lake Radio Observatory to detect a CME at 73.8 MHz. This Clark Lake CME detection is shown in Figure 4.1. The radio emission from these CMEs was in the form of optically thin bremmstrahlung or free-free radiation.

The difficulty in detecting thermal radio emission directly from CMEs is one of dynamic range: the CME must be detected over the thermal emission from the quiet Sun itself. At frequencies from 200-2000 MHz the CME thermal emission is a factor of 10-1000 weaker than the quiet Sun emission, respectively, requiring high dynamic range for detection. But as the Culgoora and Clark Lake CME detections demonstrated, the CME emission becomes comparable to or greater than the quiet Sun emission at frequencies below 100 MHz. (Note that at 74 MHz the quiet sun is only a ~2000 Jy source, approximately an order of magnitude less bright than some cosmic sources, e.g. Cas A and Cyg A.) This makes the frequency range of LOFAR advantageous for passive imaging of CMEs, and the spatial filtering capabilities of an aperture synthesis instrument can be tuned to selectively "resolve out" the much more extended emission from the quiet Sun. LOFAR's electronic sophistication will provide rapid, broad-band dynamic spectra and images of quickly evolving solar phenomena.

CMEs are also known to have nonthermal emission. For example CME's in the form of Moving Type IV bursts have been observed on many occasions, and Interplanetary Type II emission observed below 2 MHz by space-borne radio receivers has also been associated with the propagation of CME's through the interplanetary medium. It is possible that LOFAR might detect nonthermal radio emission generated directly by CME-driven shocks. For example, Type II bursts are caused by blast waves in the corona and were in fact long thought to result from CME-driven shocks. These bursts have been observed from the Earth's surface down to ~20-30 MHz and fall well within the detectable frequency range of LOFAR. There is excellent reason to expect CMEs to drive shocks which would accelerate particles and generate similar steep-spectrum nonthermal emission.

4.1.2 Studies of Solar Flares and Bursts

Two well known types of solar radio emissions, Type II and Type IV bursts, are well known at LOFAR frequencies and could certainly be monitored from the Earth's surface by LOFAR. While the once-held notion that flares "cause" CMEs is almost certainly not true, flares, CMEs, and the interplanetary shocks are clearly related in a complex, as yet poorly understood manner. With the current lack of high resolution radio heliographs operating at frequencies below 150 MHz, LOFAR would re-establish the ability to map solar radio bursts from the Earth's surface. These could be correlated with radio-spectrographs (which "detect and monitor" solar bursts, but have no position-finding capability) and space-based CME coronagraph observations (including STEREO) as well as with possibly related interplanetary shocks detected by satellites. This would go a great way towards further developing the phenomenological relationship between flares, CMEs, and interplanetary shocks, and for space weather applications to develop better models of geomagnetic storm prediction.

4.1.3 Detection and Tracking of CMEs and Interplanetary Shocks Through Scattering Measurements

A key limitation in understanding the connection between solar activity and the interplanetary disturbances which eventually produce storms has been the difficulty in linking coronagraph observations near the Sun with the shocks which are detected at greater distances and at later times by satellites near the Earth. Here LOFAR scattering measurements against the numerous cosmic background sources in the natural LOFAR sky can bridge this gap.

The CMEs and the interplanetary shocks that they generate cause turbulence, radio wave scattering and scintillation, and an increase in solar wind speed. These effects can be measured with LOFAR by radio-wave scattering measurements. While existing small-aperture arrays can and do measure the effects of CME-driven interplanetary shocks when they are far from the Sun through amplitude scintillation ("twinkling") measurements of background sources, they lack the angular resolution to make the angular broadening measurements which are required to see the effects of this turbulence when it is near the Sun. This means that by the time the shock is detected by intensity scintillations it is already a long way from the Sun, and its association with coronal phenomena is no longer clear. However a sensitive and broad-band LOFAR would have the angular resolution and frequency versatility to both 1) track CMEs near the Sun by measuring the angular broadening of background sources, and 2) detect and continue to track their effects further from the Sun through scintillation measurements. This capability would make LOFAR unique in its ability to follow the propagation of CMEs, and perhaps also interplanetary shock waves and Co-rotating Interaction Regions.

In summary, there are a variety of solar passive emission studies which LOFAR can uniquely carry out, and when combined with complementary observational data from space (e.g. STEREO) will provide an extremely powerful and dynamic data base capable of establishing a connection between passive emission phenomena and directly observed CME or interplanetary shock and particle measurements.

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4.2 Active Solar Studies

See Section 2.5 for a description of active solar applications for LOFAR

5 Ionospheric Applications for LOFAR

5.1 Passive Ionospheric Studies

5.1.1 Characterizing Ionospheric Waves

The ability to measure dynamic ionospheric structure and variability over a wide range of scale sizes would greatly improve operational models of navigation and communications and improve developing closely interdependent models of atmospheric, ionospheric, and space weather physics and prediction. On the largest scales, global models of the "smooth" ionosphere as characterized by the Total Electron Content (or TEC, a measure of column density typically ~10^{17} m^{-2}) are being revolutionized by Global Positioning System of Satellites (GPS) measurements . For example a GPS based ionospheric model developed by NRL and NRAO at the 74 MHz VLA has resulted in a dynamic ionospheric model which can predict the TEC to within ~10% over a large region of the sky (Erickson et al. 1996, 2000). Other sophisticated GPS-based TEC models using data from a world-wide network of ground receivers are now also available.

However, superimposed on the smooth TEC component is a common and rich variety of wave-like structures (for example Travelling Ionsospheric Disturbances or TIDs) whose basic phenomenology is very poorly understood. LOFAR is a unique and powerful way of measuring these waves because it is extremely sensitive to variations in TEC at accuracies exceeding a fraction of a percent. For example, at a generic LOFAR frequency of 74 MHz, even a 1% cyclical variation in ionospheric column density moving at a speed of 100 km/h with a 30 km wavelength would cause a 10 radian phase differential between two stations 30 km apart, with a phase rate of 1 radian per minute. Alternatively, a horizontal gradient in the TEC of 10^{13} /cm^{-2} km would produce a 1 radian phase shift over a 10 km baseline. Variable gradients of this magnitude comprising ~0.1% of the TEC per km are very common.

Jacobson and Erickson (1992) have already used the 330 MHz VLA to demonstrate how a meter wavelength array can be used as a powerful diagnostic of wave-induced TEC variations which have a wide spectrum of spatial and temporal scales, while Kassim et al. (1993) have used the 74 MHz VLA to show that such techniques are easily extended to LOFAR frequencies. These studies rely on measuring the refractive effects of the TEC variations on cosmic background sources which are numerous and bright at LOFAR frequencies. While the VLA-based ionospheric studies made significant advancements over previous studies by smaller aperture radio arrays, the 35 km VLA is too small to track these often large wave, e.g. the naturally occurring acoustic gravity waves with scale sizes > 50 km. Here the tremendous size of a 500 km LOFAR and its ability to monitor families of cosmic radio sources across the sky and spectrum would provide a direction finding and tracking capability for these waves.

Figure 5.1 illustrates the sensitivity of a low frequency interferometer to the TEC gradients imposed by an ionospheric wave. The thick line is the 74 MHz VLA phase of a background point source, as measured on a ~20 km baseline, and in the absence of ionospheric effects would normally remain constant over the 5 minute time period shown. However an ionospheric wave has introduced a time varying (though regular) difference in TEC between the two interferometer elements corresponding to over a full 360 degree turn in interferometer phase over this period. The thin line shows the compensating phase derived by self-calibration from simultaneous higher frequency observations which are then applied to the 74 MHz phase in order to "unwind" the ionospheric effects as shown by the dotted line. This technique shows that it is possible to derive differences in TEC from a low frequency interferometer to extremely high accuracy. A much larger aperture LOFAR is required to also provide a direction finding capability for these waves.

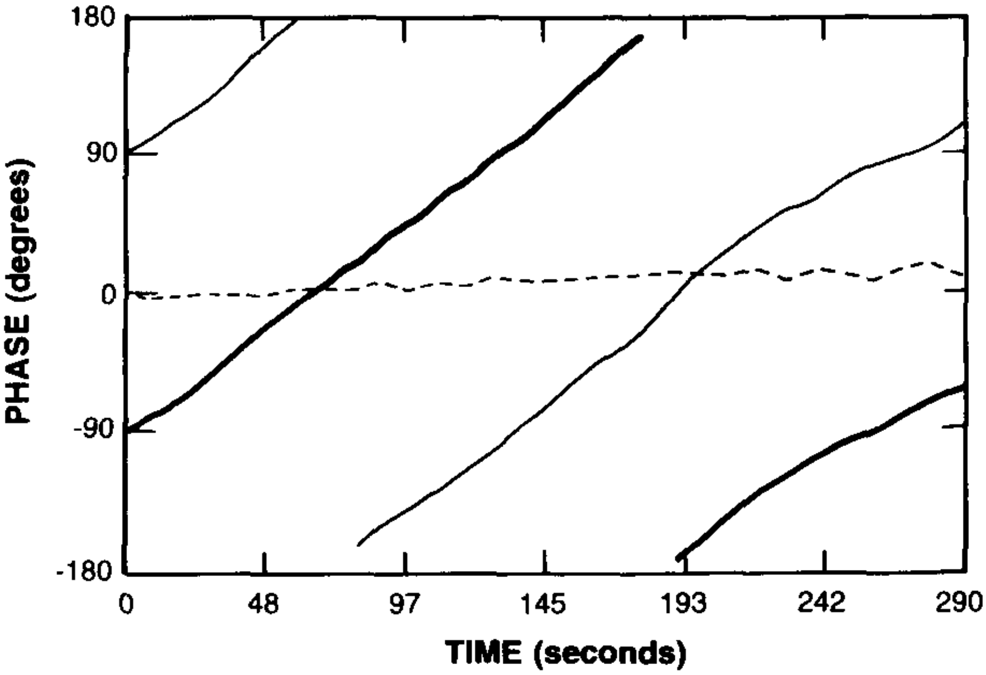

Figure 5.1 The effects of an ionospheric wave on interferometer phase as measured by the 74 MHz VLA, see text for details (adapted from Kassim et al. 1993).

5.1.2 Man-made Ionospheric Disturbances

In addition to natural phenomena such as thunder storms or geomagnetic storms, ionospheric waves also result from man-generated phenomena such as atmospheric explosions and rocket launches. The refractive effects of waves generated by rocket launches at Vandenberg Air Force Base in northern California were detected by low frequency observations (<100 MHz) through the fluctuating phase of the natural background sources with the ~3 km Clark Lake Interferometer east of San Diego. Similarly, atmospheric disturbances produced by man-generated explosive events over the White Sands missile base in eastern New Mexico were detected further west by meter-wavelength observations with the VLA near Socorro. In both cases, however, the causal link between the explosive atmospheric events and the detected ionospheric waves were inferred from their temporal correlation. The short baselines rendered them incapable of determining the direction of origin of these large (>50 km) ionospheric waves. LOFAR will provide such a direction finding capability without an a-priori knowledge of the physical origin of the atmospheric perturbation. A real-time LOFAR ionospheric wave tracking and detection capability thus offers a unique and passive means of detecting man-generated atmospheric disturbances.

Already in the mid 1970's it was discovered, somewhat unexpectedly, that electromagnetic radiation from ground-based HF radio transmitters can, if powerful enough, create irregularities in the otherwise smooth overhead ionosphere. These “artificial” irregularities have scale lengths ranging from meters to tens of kilometers and are the result of the non-linear and turbulent interaction of the radiation with the ionospheric plasma (Robinson, 1989). Since the power density required for the excitation of such irregularities are comparable to those emitted by today's major HF broadcasting stations, there is a growing concern about the possible harmful impact on the Earth's upper atmosphere by such human activities on the ground. Experimental studies of these “artificial” irregularities are currently being carried out with the use of purpose-built radio and radar facilities operating mainly in the HF and VHF frequency ranges. Using the unparalleled resolution capability of LOFAR while receiving probing radio signals which traverse the regions with "artificial" irregularities, it should be possible to perform systematic, repeatable experiments which will provide data of such irregularities of a dramatically higher quality than is possible in any other experiments. This much needed new and better observational data will be invaluable input to the theoretical modelling which has proved to be unusually difficult (Gurevich et al., 1995). Once a good theoretical model is obtained, one can with confidence apply this model to similar processes both near and far away from the Earth and provide new insights into the important problem of turbulent layers in space.

Other applications of an ionospheric wave detection capability must await a more complete understanding of the rich phenomenology associated with these traveling disturbances. Here an analogy may be drawn with the power of modern seismology to monitor man-generated energy releasing geological events such as underground nuclear explosions which trigger global seismic activity. Today's operational technology for sophisticated seismic measurements was originally driven by the need to understand natural seismic phenomena such as earthquakes. LOFAR will provide the information to make similar advances in our understanding of both natural and unnatural atmospheric/ionospheric phenomena. These measurements will develop the scientific phenomenology and understanding to contribute to real-time ionospheric models with direct impact on strategic and environmental operational models.

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5.1.3 Ionospheric Radio Tomography

The nature of the ionospheric studies supported by LOFAR will depend on the facility's location. Ionospheric structure driven by magnetosphere-ionosphere coupling mechanisms including electric fields, ExB plasma advection, or particle precipitation, can be significant at mid-latitude locations, while ionospheric enhancements associated with the poleward expansion of the equatorial anomaly region will impact a more equatorward-situated site. Both sub-auroral and low-altitude large-scale ionospheric density structures have scale sizes of hundreds to thousands of kilometers, but are subject to the formation of a broad spectrum of density irregularities and radiowave scintillation at frequencies between 1 MHz and 1 GHz. The highly-directional and narrow-beam capabilities of LOFAR, as well as its ability to image separate parts of the sky simultaneously, will enable it to contribute to passive-propagation studies of such ionospheric structure and irregularities which constitute important space weather research topics.

Radio signal traveling through the ionosphere undergo both time delay and phase rotation. Both of these effects are proportional to the integral of electron density along the path. Ray based tomography inverts the data from multiple ground based receivers (wiith a baseline of a 100 km or more) to obtain a 2D or 3D map of electron density in the ionosphere (e.g. Austen, 1988). Since 1993 there have been multiple tomography campaigns which have utilized this technique to image the electron density in the ionosphere (e.g. Bust, 1994). Ray tomographic receiver chains have been developed and deployed in order to use this technique as a regular ionospheric diagnostic (e.g. Pryse and Kersley, 1992; Foster et al., 1994, Kronschnabl et al., 1995). Receiver sites are spaced by several hundred km, and only large and meso-scale structures (tens of kilometers) can be resolved. Dual-frequency navigation satellites of the Navy Transit series (150 MHz and 400 MHz) are often.

In addition to the time delay and phase rotation it is possible to have phase and amplitude scintillation caused by small scale electron density irregularities. Diffraction tomography measures the coherent phase (amplitude) with multiple receivers spaced across a few kilometer baseline and inverts this information to obtain specificacion of the electron density of small scale irregularities (Kunitsyn and Tereschenko, 1992).

The technique of adaptive calibration of the LOFAR instrument is fundamental to its usefulness in many areas of research. The technique successfully removes the effects of the ionosphere by estimating the distortion introduced by the ionosphere. For large and medium scale features, this calibration information (i.e. the phase delay) represents a relative measurement of the integral electron density or total electron count (TEC) along the path between each receiver and the calibration source. The measurement is relative to an overall constant due to the fact that a uniform shift of the electron density is does not affect the calibration. The TEC across the array for a given calibration direction, can be used directly to investigate horizontal structure of medium and large-scale waves in the ionosphere. When the calibration is done for many sources over the entire field of view, the TEC data can be used with a Computerized Ionospheric Tomography (CIT) algorithm to produce a 3D specification of ionospheric electron density. The sampling time of such 3D images of the ionosphere would be given by the time to make adaptive calibrations across the entire field of view. The resulting 4D (3 spatial dimensions plus time) images of electron density would provide a unique, data source for detailed investigations of the 3D structure of TIDS, daily variations of the ionosphere and other long-term studies.

The TEC measurement would allow a specification of the electron density over the location of the LOFAR installation at spatial and temporal resolutions, which are today not possible. The spatial resolution is limited by the diffraction scale size for the frequency of interest. This fine level of detail would aid in understanding the spatial and temporal variations in the ionosphere. The measurements would act as a unique tool in validating first-principles based physics models of the ionosphere.

The spatial measurement of the ionosphere will be limited by the number of sources that have been cataloged, the number of receive antennas on the ground, and most importantly the processing power which is available for the adaptive calibration. It may be that in various configurations LOFAR will not be concerned with covering large regions of the sky therefore it will be necessary for the ionospheric/calibration processor to be able look at the raw data coming from the digitizers to be able to form whole sky snapshots of the electron density.

5.1.4 Diffraction Tomography

When ionospheric irregularities are present, phase and amplitude scintillation are observed on the received signal. The adaptive correction method will provide the phase fluctuation information for each receiver in the array for a given calibration direction. The phase fluctuation from receivers within a few kilometers of each other, can be inverted through a diffraction tomography algorithm to produce a 2D map, perpendicular to the line-of-sight between receivers and calibration source, of ionospheric irregularities. Such maps produced from several clusters of receivers with differing lines-of-sight will allow investigation of the spatial distribution of the irregularities. Since such maps can be made continuously in time, with a sampling time determined by the time to produce the calibration, the phase fluctuation data represents a unique opportunity to investigate the spatial-temporal dynamics of small-scale ionospheric irregularities. In addition, these types of spatial-temporal irregularity maps will be available for several distinct frequencies in the HF-VHF band. Finally, if several calibration source directions are used over a short time period, even more complex diffraction tomography algorithms can be applied, allowing for the possibility of some 3D diffraction tomography inversions. Even if the array is located at mid-latitudes, where small scale ionospheric dynamics is less important, the data set will still be invaluable for magnetospheric storms when small scale dynamics does penetrate to mid latitudes, sporadic E investigations, and for investigations of the mid latitude irregularities observed at Arecibo and reported by Kelley, Bust and others.

5.1.5 Passive Radar Applications for Ionospheric Radio Science

Passive radar is a technique for observing targets of interest using radio signals already present in the environment. By intercepting both the signal radiated by a transmitter and the scatter from targets of interest it is possible to make traditional radar measurements. The range, doppler shift, and bearing of a target can all be determined with an accuracy that depends on the nature of the illuminating waveform and the characteristics of the passive radar system.

In most cases the signals used by a passive radar will be generated by non-cooperative illuminators such as FM radio or television stations. Such illuminators are present in most of the world, radiate significant power, and often transmit signals well suited to radar applications. The technique can also be applied to signals from a cooperative illuminator such as an active radar system. In this case, it is similar to more traditional forms of bistatic or multistatic radar.

Many investigations into the requirements and potential of passive radar have been made although only a few are publicly available (Ringer et al., 1999). Experimental systems have been described using UHF television for aircraft tracking (Howland, 1994), and using FM radio signals for ionospheric investigations (Sahr and Lind, 1997).

For ionospheric radio science passive radars are useful for observing E-region irregularities (Lind et al., 1999). These irregularities are created at altitudes between 95 and 120 km by a two stream instability that occurs for sufficiently strong electric fields. The irregularities commonly occur in association with the aurora surrounding the Earth's poles, at the equator in association with the equatorial electrojet, and occasionally at mid-latitudes where the phenomenon is known as sporadic-E. A summary of the phenomenon, theory, and experiment for auroral regions is available in Sahr and Fejer (1996).

The passive HF radar method has been utilised in ionospheric experiments for diagnosing both natural and “artificial” ionospheric irregularities and found to provide indispensable data. With this method, supplemented by other diagnostics, it was recently discovered that aurorae can be triggered when strong radio waves interact with the lower layers of the ionosphere (Blagoveshchenskaya et al., 1999). As this is the first evidence of an anthropogenic ionosphere-magnetosphere coupling it is particularly important to study these phenomena further. Environmental monitoring by radio methods of this kind are expected to be increasingly important in the future. The experimental limits set by the modest HF/VHF receiving facilities used today will be essentially removed by using the LOFAR facility.

E-region irregularities are a manifestation of large scale electric field structures in the ionosphere. They play an important role in ionospheric energy dissipation, particularly in the auroral regions where the electric fields are generated by interactions between the solar wind and the Earth's magnetic field. The irregularities are also an active part of the larger Space Weather environment. Experimental investigation of the irregularities provides a way to measure ionospheric electric fields and to relate them to observations of other ionospheric, magnetospheric, as well as space weather phenomenon. For example, the irregularities cause scintillation of communications and navigation signals passing through the ionosphere (Vats et al, 1995). This can be especially important to accurate navigation using GPS systems and for radio communication with satellites at VHF, UHF, and L-band frequencies.

A radio telescope such as LOFAR has the potential to perform well as a passive radar. The basic technology of the LOFAR digital beamforming phased array is appropriate for passive radar. LOFAR's large aperture should also allow for detection of weak scatterers while excluding the direct signal from the illuminator. For passive radar applications the LOFAR receivers will need to be synchronous, stable, and have high dynamic range. It is likely that the raw output from the additive beamforming process would be needed for use in the passive radar signal processing.

FM radio signals (88-108 MHz) are the best illuminators available for passive radar in LOFAR's proposed 10-300 MHz frequency range. However, these same signals are a major source of interference for LOFAR and the current design avoids them explicitly through antenna design and by filtering. It is probably best to site LOFAR in a "radio quiet" location away from such illuminators. This would not prevent LOFAR from being used as a passive radar if the filtering can be removed for the passive radar mode or a cooperative transmitter is used to generate the desired signal. Transmitter to receiver baselines of several hundred kilometers are known to work for ionospheric observations, and baselines of up to 2000 km are conceivably useful. Large baselines will require intercept of the transmitter signal using a separate receiver system close to the point of transmission.

As was pointed out before, ultra-stable HF radio signals in the 10-30 MHz range have already been used for passive radar investigation of ionospheric irregularities.

The final location of LOFAR will have a large impact on what ionospheric phenomenon are observable using the system as a passive radar. Ionospheric scintillations due to E-region irregularities will be a source of interference for the radio astronomy applications of LOFAR. Because of this, it is also best to site the system in the least interesting location possible for regular investigation of E-region irregularities. In such a location LOFAR could still use passive radar to detect scatter from sporadic-E and meteors.

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5.2 Active Ionospheric Studies

To study the fundamental physical principles governing the solar-terrestrial environment, powerful ground-based instruments are required. Satellite observations can only provide a limited set of local snapshots from this environment and must be complemented by observations of processes taking place on large spatial scales and over extended time periods. Furthermore, many regions of solar-terrestrial space can only be probed by instruments sensing the processes remotely.

A judiciously designed radio facility such as LOFAR is versatile and flexible enough to allow the study of a large variety of physical phenomena in virtually all space regions of central interest for present and future space physics, from the Earth's neutral atmosphere to the Sun and even beyond, with one and the same instrument. A multi-purpose LOFAR facility has the attractive feature of being able to operate as a world-class radio observatory of a new kind for use in ground-based space physics, astrophysics and environmental research.

Ever since the pioneering experiments in the early part of the 20th century, many active radio and radar techniques have been developed for the study of near Earth space. The literature describing this development and the employment of the various technique is plentiful. Suffice it here to mention the monographs by Hunsucker (1991) and by Kohl et al. (1996).

For many years, the probing techniques used were based on the idea of minimum interaction between the probing signals and the ionospheric plasma, while the past three decades has seen the emergence of interacting probing techniques, much the same as those used in non-linear optics, allowing new insights into processes in space plasma, particularly when it is in a non-equilibrium state.

Among the outstanding questions that are currently being addressed in space physics, one can mention the following:

- How do the large variations in the Sun's activity, mediated to the Earth via the natural solar radiation and the solar wind, affect the state of the ionosphere and/or the upper atmosphere and the technological infrastructures on Earth and in space?
- How can we understand the mechanisms responsible for the generation of the copious amounts of natural electromagnetic radiation in the Earth's magnetosphere that continuously “bombard” the ionosphere from above?
- Can we learn anything from the electromagnetic radiation observed in our own space habitat? Can such knowledge be applied to help interpret the physical processes that generate the electromagnetic radiation received from distant astronomical sources of radio emission (e.g. pulsars and supernova remnants in our own Galaxy, but also distant radio galaxies and quasars)?
- Have the natural physical processes that take place in the Earth's magnetosphere and ionosphere, located at hundreds to thousands of km altitude, any measurable connection with processes in the atmosphere at much lower altitudes, or perhaps even on the Earth's weather system and climate?
- Does the electromagnetic radiation from the tens of thousands of broadcast, TV, utility and radar stations deployed on the ground by man over the past century have any effect on the ionosphere? If so, is this an adverse or a positive effect? Or, if measurable at all, is it negligible? Compared to the ionosphere over densely populated and heavily industrialised regions, the pristine parts of the Earth's near plasma are ideally suited for comparative studies of such effects.

With LOFAR, used as a single instrument or in combination with existing and future transmitter facilities, it will be possible to:

- Perform ground-based radio and radar studies of space surrounding Earth much further out and on much larger spatial scales than with any other existing ground-based instrument. One aim is to investigate the plasma processes which give rise to natural waves, turbulence, non-linear structures and chaos, of which we have only limited knowledge today, but which in a decisive way influence the atmosphere and near space and, hence, conditions for life on Earth.
- Develop and utilise new experimental techniques, based on modern linear and non-linear physics and technology, for high-precision studies of both natural, spontaneous processes, as well as systematic phenomena created under controlled, reproducible conditions, analogous to the way physical phenomena are studied in earth-bound laboratories.
- Perform solar, lunar, planetary, and astrophysical radio observations with unprecedented accuracy and sensitivity within a largely unexplored low radio frequency range.
- Detect electromagnetic radiation with new methods which enable us to determine, to a very good precision and with a high dynamic range, all characteristics (amplitude, phase, spectral distribution, direction of arrival, and state of polarisation) of the signal received.

A flexible transmitter installation near LOFAR or at a remote site allows radar experiments far out into space within the near zone of the LOFAR antenna. This opens up completely new possibilities for ultra-precision determination of the near-Earth plasma properties.

Of particular interest is to use LOFAR in combination with so called ionospheric HF interaction facilities. Such facilities are relatively simple to build, using commercially available HF radio transmitters and antennas. Existing systems today include the high-latitude facilities HAARP and HIPAS, Alaska, and EISCAT/Heating, Norway, and the mid-latitude Sura facility, Russia. For nearly 30 years, a low-latitude facility was available at the Arecibo Observatory, Puerto Rico. A few years ago it was destroyed in a hurricane. There are now advanced plans to build a new HF interaction facility at Arecibo. Similar facilities have been proposed for equatorial latitudes both in Africa and in Asia.

We emphasise that a major objective for the future space physics is to further investigate into the possibility that human activities near the Earth may give rise to hitherto unidentified anthropogenic effects.

5.2.1 Meteor Shower Research

There is increasing interest in the effects of meteors on the upper atmosphere and ionosphere. Active research programs include studying the chemistry, meteor trails and electrodynamics of meteors on the medium. Several radars are currently studying this including Arecibo, Millstone Hill and ALTAIR. LOFAR with its wide frequency range and high resolution coupled with an active transmitter should bring new information to meteor research.

5.2.2 High-altitude Magnetospheric Studies

Studies of magnetospheric physics are important for understanding the intricate interplay in the solar-terrestrial system, and in the plasma environment around our planet. The optimum frequency for such studies is a compromise between the need not to resolve structures in the plasma while ensuring penetration of the ionosphere. The optimum appears to be somewhere between 10 and 30 MHz, although frequencies as high as 85 MHz are not excluded.

5.2.2.1 Diagnostics by Linear Coherent Scatter

Space-borne experiments have indicated that very strong turbulence is present in the magnetosphere of the auroral regions at altitudes of between 4000 and 13000 km. This turbulence is believed to be due to geomagnetic field-aligned currents that produce a whole host of effects including spatial irregularities, ion-cyclotron and ion-acoustic instabilities and double layers. There are suggestions that the latter are responsible for auroral phenomena such as auroral arcs in the lower ionosphere, ion beams and conics, and inverted V events in the magnetosphere. A LOFAR, suitably equipped with a radar transmitter, and with access to the auroral zones, could be used to study the properties and excitation of this turbulence, its dependence on the field-aligned currents and its significance for auroral particle acceleration.

By operating LOFAR as part of a magnetospheric radar set-up, it should be possible to perform the following measurements:

- Enhanced turbulence plasma line observations to estimate the magnetospheric electron density profile
- Measurement of ion-acoustic turbulence and double layers at altitudes of several thousand kilometres
- Measurement of parallel plasma velocities and of perpendicular electric fields by using an inclined beam.

These continuous “full-volume” measurements can be compared with discrete, single point measurements from satellites as well as with other, supplementary instruments (rockets, radars, magnetometers, optical instruments).

Experimental evidence of coherent scattering off magnetospheric turbulence was reported from the Russian facility Sura by Gurevich et al. (1992). Near the so-called trough regions at high latitudes, the ionosphere can sometimes be extremely dilute, particularly during solar minimum. An experiment during such conditions was performed at the EISCAT/Heating facility near Tromsø, Norway, in 1995. The facility was set up to operate in a radar mode with an ERP of about 1 GW at 8 MHz while the critical frequency of the overhead ionosphere was transparent to all frequencies above 1.5 MHz. Clearly detectable, coherent echoes from about 3000 km altitude were observed (Thidé, private communication).

5.2.2.2 Diagnostics by Linear Incoherent Scatter

Incoherent Scatter Radar (ISR) facilities generally operate at frequencies substantially higher than the LOFAR range, although exceptions (like the Jicamarca radar in Peru, and the MU Radar in Kyoto, Japan) do exist. These high frequencies (of a few hundred MHz) are optimised for studies of the central ionosphere. However, for probing the more tenuous plasma in the upper part of the ionosphere, much lower frequencies are preferred. Potential conditions for study at the lowest LOFAR frequencies (i.e. below ~30 MHz) include the topside auroral ionosphere and lower magnetosphere at times of auroral activity. In addition the study of the ionosphere above the polar cap is also of interest. It is clear that these experiments would favour a LOFAR located as far north as possible. Non-linear interactions between a powerful radar beam at VHF or UHF frequencies give rise to inelastic scattering off electromagnetically pumped, collective modes which fall in LOFAR's frequency range.

5.2.3 Non-linear Probing of the Near-Earth Plasma

One of the major discoveries in the exploration of space was that space plasma are highly structured and that their behaviour are far from textbook-like. While space plasma respond linearly when perturbed very gently, be it in a “natural” way or through human activities, they will all exhibit a clear non-linear behaviour for typical levels of perturbation. It is therefore futile to hope that linear models would have a chance of even crudely explaining the processes observed.

For the development of more correct models which are able to accurately describe, and, more importantly, to predict the behaviour of space plasma under a broad range of conditions, we need to be guided by empirical studies in which the non-linearities are easy to observe and to isolate. Hence, we need to improve our experimental knowledge of the fundamental linear as well as non-linear physics of space plasma. This is one of the important objectives of fundamental space physics research.

Another important objective is to develop better radio diagnostic methods in order to obtain improved knowledge of the ionosphere which constitutes an important link in the atmosphere-ionosphere-magnetosphere-heliosphere chain which defines the conditions for life on Earth.

Our understanding of the physical mechanisms which manifest themselves in the spontaneous, natural occurrence of plasma waves, turbulence, cavities, and radiation in planetary ionospheres are, at best, sketchy. To a large extent this is due to the fact that neither the external source nor the the response of the plasma to the external perturbation is known well enough. Yet another objective is therefore to study these fundamental physical phenomena under controlled conditions and to make detailed studies of the effects of the interaction between an external source and the ionospheric plasma in order to achieve a better understanding of the underlying physical processes.

Non-linear probing of the near-Earth plasma can be used for ground-based measurements of parameters that cannot be determined accurately enough or at all with conventional linear diagnostic techniques. The techniques available for these measurements include: beat wave excitation of resonant plasma modes, stimulated scattering off ion and electron modes, and the stimulated electromagnetic emission (SEE) process. This last technique (SEE) is based on the analysis of secondary electromagnetic radiation generated within a space plasma region pumped by powerful radio waves transmitted from a suitable ionospheric HF interaction facility (Thidé et al., 1982). A compilation of articles describing the current development in this area can be found in the December, 1997, issue of Journal of Atmospheric and Solar-Terrestrial Physics.

While the general concept of the conversion of electrostatic turbulence into electromagnetic waves is a well established one, its concrete manifestation in ionospheric modification experiments in the form of Stimulated Electromagnetic Emissions has led to such an enormous richness of phenomena that it has essentially opened up a new field of research, both experimentally and theoretically. Plasma self-organisation within a wide range of scale-lengths, growth times, saturation levels, and orientations with regard to the external terrestrial magnetic field, has been observed in the experiments. In addition to the methods based on the conversion of electrostatic into electromagnetic waves and vice versa, this self-structuring has been investigated by a variety of diagnostic techniques and facilities on the ground, for instance by means of the methods of Bragg scatter, anomalous absorption of HF waves, wave scintillations, and optical and EM emissions caused by accelerated electrons. It is physically reasonable to assume that SEE-like emission mechanisms are responsible for some of the collective, non-thermal radiation in some astrophysical objects.

Experiments have shown that the SEE signals can be observed more than a thousand kilometres distant from the ionospheric region where they are generated. Remote observations and analysis with LOFAR will definitely provide new and more sensitive results than is possible with any existing or planned radio observatory. In recent ionospheric experiments in the auroral zone it has been noted that SEE-type emissions have many similarities in common with the natural noise-like emissions associated with auroral activity.

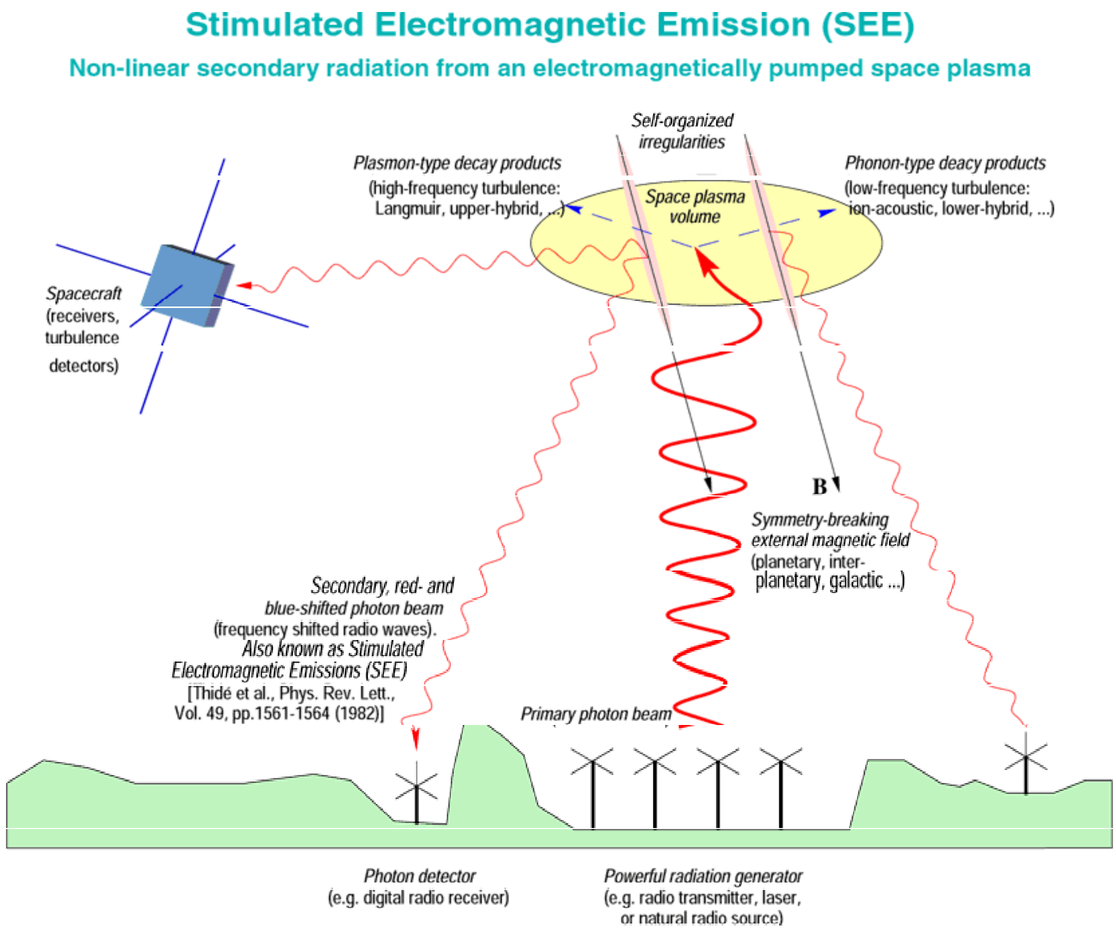

Figure 5.2 A schematic diagram which shows the set-up used to generate and observe stimulated electromagnetic emission from a volume of space plasma.

A natural extension to the SEE method is to utilise the nonlinearity of the near-Earth plasma medium to generate combination frequency emissions. By illuminating a common region of the ionosphere by more than one transmitter separated in frequency by a characteristic resonance frequency in the ionospheric plasma peak, it is possible to excite emissions which carry with them vital importance on the plasma region from which they emanate. The possibility of this promising new diagnostic method was demonstrated in experiments performed at St. Santin and Nancay, France (Lavergnat et al., 1977). Following these pilot investigations, no conclusive results have emerged since, possibly due to the technical and experimental complexity of such experiments. However, both these experiments and theoretical investigations show that this phenomenon has considerable potential for delivering very accurate diagnostics of space plasma. The low frequencies of LOFAR will favour the technique, compared with the UHF band in which the French experiments were carried out.

As has been demonstrated in ionospheric experiments in Puerto Rico, Norway, and Russia, certain combinations of the frequencies from two transmitters will produce extremely narrow emissions at the arithmetic mean frequency. Since these narrow emissions are generated in the plasma, and therefore act as tracers, natural bulk plasma motions can be precisely determined by Doppler analysis of these emissions. LOFAR will be an excellent facility in such measurements.

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