FLOW

The French LOFAR consortium

Argumentaire Scientifique pour une participation française à LOFAR

Science Case for a French participation in LOFAR

Document presented by Michel Tagger[1], Philippe Zarka[2], Nabila Aghanim[3], Monique Arnaud[4], Jean Ballet[4], Elisabeth Blanc[5], Albert Bosma[6], Gamil Cassam-Chenaï[7], Sylvain Chaty[8], Stéphane Corbel[8], Anne Decourchelle[4], Guillaume Dubus[9], Edith Falgarone[10], Chiara Ferrari[11], Katia Ferrière[12], Hector Flores[13], Yves Gallant[14], Berrie Giebels[15], François Hammer[13], Claude Mercier[2], Thierry Montmerle[9], Etienne Parizot[16], Radek Stompor[16], Steve Torchinsky[13], Wim Van Driel[13]

[1] CEA/DAPNIA/SAp/APC, [2] LESIA, Observatoire de Paris-Meudon, [3] IAS, [4] CEA/DAPNIA/SAp/AIM, [5] CEA/DASE, Bruyères le Chatel, [6] LAM/OAMP, Observatoire de Marseille, [7] Department of Physics and Astronomy, Rutgers University, USA, [8] AIM, Université Paris VII, [9] LAOG, [10] LERMA, Observatoire de Paris-Meudon , [11] Institut für Astro- und Teilchenphysics, Innsbruck Universität, Austria, [12] LATT, Observatoire Midi-Pyrénées , [13] GEPI, Observatoire de Paris-Meudon, [14] LPTA, [15] LLR, [16] APC

Summary

The present document has been written in preparation of a French involvement in the LOFAR array of radioastronomy sensors. Initially launched as a purely Dutch instrument, LOFAR is now open to contributions from other European countries, with two objectives: extending the baselines, to reach a resolution of the order of the arcsecond, and extending the scientific base necessary for the optimal exploitation of an instrument which will be revolutionary in many respects, with an expected gain of two order of magnitudes in sensitivity and angular resolution.

The breadth of the scientific fields covered, from the Solar corona and planetary magnetospheres to the largest observable scales of the universe, from the wake-up of the universe after its dark ages to the most violent and most energetic known phenomena, would be a sufficient proof of the expected scientific return. But this is even more visible in the fact that, among the contributors to this Science Case, less than a half are experienced radio-astronomers. The others, more experienced in other observational techniques, see in LOFAR an ideal complement to their usual tools for the multiwavelength approach, necessary to modern modelization efforts. This is particularly true with instruments in which the French scientific community has a strong involvement: observations with XMM-Newton, Integral and HESS which are already in operation, Planck, GLAST, Stereo, Taranis, Simbol-X, HESS 2 in the future, will strongly benefit from complementary observations with LOFAR. Conversely the expertise gained in using these instruments, and access to their data, will be of great interest to our partners in LOFAR. A participation in LOFAR, together with SKA and SKA-DS, FASR and CODALEMA, will contribute to a new age of low-frequency radio-astronomy in France.

The French involvement will thus take the form of a LOFAR remote station established in Nançay, ideally located for filling the u-v plane and where it will benefit from a protected radio environment, and from the presence of a strong expertise in low-frequency radioastronomy. It will also include the participation of French scientists, forming the FLOW consortium, in existing or new Key Science Projects, the scientific collaborations which prepare the utilization of LOFAR.

Further developments will include the establishment of a Science Data Center, providing tools and support to the French users; technical studies for a possible local extension of the LOFAR station; and, in relation with similar efforts in the Netherlands, applications in other scientific disciplines, such as precision agronomy and geophysics, of the LOFAR concept of a complex network of large arrays of sensors.

This concept is also the key to the realistic possibility, which is under active consideration, of establishing a LOFAR station on the Moon. This is a most exciting, though more remote, prospect, in which the French community will certainly wish to participate.

Introduction

LOFAR (the LOW-Frequency Array) is the precursor of a new generation of radio observatories. Designed and built by ASTRON (part of the Dutch National Research Council) in the Netherlands, it is funded by national and regional subsidies and by a consortium of Dutch universities and research agencies. It is based on recent progress which promise a gain of two orders of magnitude in sensitivity and angular resolution over present instruments in the frequency range of 30 to 240 MHz (1.25 to 10m wavelengths), and can be considered as a technical and scientific pathfinder of SKA, the *Square Kilometer Array* which, beyond 2015, will cover higher frequencies with a much larger effective area.

As an initially purely Dutch instrument LOFAR will be commissioned in 2008. It is now open to collaborations in Europe, with two main goals: extending the baselines in order to reach an arcsecond resolution, and also broadening the scientific base necessary to obtain the best scientific return from this instrument, which addresses important questions in very different fields of astrophysics, from the early ages of the Universe to the formation of new stars and planets, and to the most violent and energetic phenomena observed in the environment of accreting black holes and in cosmic explosions. Discussions are under way with Germany, the U.K., Italy, Poland and France where remote LOFAR stations could be built, giving an optimal distribution in distances and angular position with respect to the Dutch core. This will also allow scientists from these countries to join the existing scientific collaborations ("Key Projects") or to propose new ones, such as the Solar Key Project in preparation with Germany.

The design of LOFAR rests on recent progress in long-wavelength radioastronomy, such as RFI mitigation (dealing with RF parasites, mostly of human origin), accommodation of ionospheric perturbations, and rapid progress in digital electronics: this leads to the concept of LOFAR as a complex array of a large number of (relatively) simple sensors, which might also be applied to other fields such as precision agronomy or geophysics. Most of the complexity resides in the central computer where signals from the sensors are processed and recombined. For this LOFAR uses a supercomputer (IBM Blue Gene, 27 TeraFlops, equivalent to the largest computer available for public research in Europe), dimensioned to synthesize in real time as many as eight pointed beams for simultaneous observations in multiple directions for separate scientific programs, each benefiting of the whole sensitivity and resolution of the whole array. A unique capability, provided by a buffer of the data entering the correlator, is also to perform *a posteriori* pointings, in response to alerts from other instruments. Synthetic beam formation also implies a huge flexibility, with an ability to change frequencies or pointings in milliseconds. LOFAR will also provide an all-sky monitor, constantly searching the sky for transient events in Active Galactic Nuclei, microquasars, gamma-ray bursts, etc. This (although it is limited to the sky visible from Europe) is of paramount importance since the RXTE satellite, which has provided this monitoring in X-rays since 1995, is likely to cease operations in the near future.

The sensors for radioastronomy are simple, fixed antennae, organized in stations of 96 low-frequency antennae and 96 tiles of 16 high-frequency antennae, with no moving parts and limited local analogic and digital processing. The Dutch LOFAR includes 77 such stations (32 in a virtual core and 45 remote stations over baselines of 100 km). 10 to 20 additional stations are now considered in Germany, the UK, France and Poland, extending the baselines to ~ 700 kms with an ideal angular distribution around the Dutch core.

Our proposal is to join this European effort by procuring a LOFAR station to be installed in Nançay, where it will benefit from a preserved radioelectric environment, from the strong local expertise in radioastronomy, and from synergies with other existing or planned instruments, including the French participation in SKA-DS, the European design study for the Square Kilometer Array. This will also give the French scientific community a unique opportunity to join the existing scientific collaborations, or to propose new ones.

The present Science Case puts together expressions of interest in various fields in which French astronomy has strong interests, ranging from cosmology to solar and planetary physics. The contributors will form the FLOW scientific consortium, which will seek active participation in the exploitation of a most exciting and promising instrument, ideally complementing major observatories (from sub-mm to extreme gamma-rays) in which France has a strong involvement.

Beyond this involvement, other exciting prospects will be considered: one will be to explore the feasibility of extending the Nançay station, by multiplying the number of antennae by factor up to eight around the same back-end. By correlation in amplitude, this would improve the sensitivity of LOFAR to faint sources, and also provide an instrument of sizable effective area (and thus sensitivity) for stand-alone research, technical developments and education. Another prospect is to promote, with the STUC research federation in Orleans, uses of LOFAR for precision agronomy and geophysics. Finally the concept of a LOFAR station on the Moon, which could be proposed to ESA for its AURORA program, is certainly the most exciting, if more remote, prospect we will consider.

The Epoch of Reionisation

After matter and radiation decoupled at recombination around z=1100, the universe became neutral with a very low residual ionisation fraction of about 10^{-4}. Observations of the Gunn-Peterson trough (e.g. Fan et al. 2003) in the line of sight of quasars with redshifts as high as ~ 6.5 however show a rapid neutral/ionised transition taking place at those redshifts. The present universe is thus in an ionized state up to z ~ 6.5. This transition undergone by the universe from the neutral to ionised state is the so-called *reionisation*. Recently, Cosmic Microwave Background (CMB) observations have added constraints on the epoch of reionisation. Through measurements of the cross-correlation between temperature and polarisation signals (Kogut et al. 2003) and more recently through the measure of the polarised signal (Page et al. 2006), the Thomson optical depth was found equal to $\tau \approx 0.09$, indicating that reionisation occurred around z=11.

Reionisation is intimately linked to the end of the dark ages since is has most likely occurred when first sources formed, whose ionising photons consumed the neutral hydrogen atoms. This period of the cosmic evolution is undoubtedly one of the less well known epochs of the evolution of the universe. As a matter of fact, we do not know what are the sources of ionising photons. Do decaying particles contribute to the ionising budget or is the latter related to the first emitting objects only? What are these first objects: mini-Black Holes, metal-free massive popIII stars, starburst galaxies? We do not know either when the reionisation occured, whether it was instantaneous, and if not and how long it lasted.

The investigation of the dark ages is still in its infancy, and very few observations support the currently available theories. However, the most promising technique to explore the evolution of the intergalactic medium during these remote times is the study of the redshifted 21 cm hyperfine triplet-singlet level transition of the ground state of neutral hydrogen (HI). This line allows the detection of the HI gas in the early universe. It thus represents a unique way to map the spatial distribution of intergalactic hydrogen (e.g. Madau, Meiksin & Rees 1997; Ciardi & Madau 2003). Therefore it permits, in principle, a reconstruction of the reionisation history as governed by the first luminous sources. The size of the structures that could be detected depends on the design of future radio telescopes. The next generation of radio telescopes such as LOFAR, in the frequency range 30-240 MHz, will have the sensitivity for HI mapping at resolutions of the order of 3 arcminutes. In a recent study, Valdes et al. (2006) have simulated observations of the reionisation signal for two (early, late) reionisation scenarios with an idealised LOFAR array, using cosmological numerical computations with radiative transfer. If reionisation occurs late, LOFAR will be able to detect individual HI structures on arcmin scales, emitting at a brightness temperature of $\approx$35 mK as a 3σ signal in about 1000 hours of observing time. In the case of early reionisation, the detection would be unlikely (see figure 1).

The redshifted 21 cm measure is not the only observational probe of reionisation. CMB is quite a powerful additional tool. Measurements of the CMB temperature and polarisation anisotropy will enable us to constrain the cosmological parameters and the underlying theoretical models. The future CMB experiment Planck will be even more powerful as it is designed to achieve the most accurate measurements of temperature anisotropies down to a few arcminute scales as well as polarisation measures. In addition to probing the cosmological model, these measurements will constrain astrophysical processes like the *reionisation*. Precise measurements (cosmic variance limited) of the E-mode polarisation power spectrum will allow us to obtain five uncorrelated numbers associated with the eigenmodes of the reionisation history (e.g. Hu & Holder 2003). This helps in tightly constraining the reionisation models and distinguishing the transition between partial and total reionisation (e.g. Holder et al. 2003). Planck will constrain partial or double reionisation to the percent level, discriminating between different models with identical optical depths (Kaplinghat et al. 2003). Secondary anisotropies are generated at small angular scales at the epoch of reionisation. Such signal at small angular scales is expected to be too weak to be detected directly.

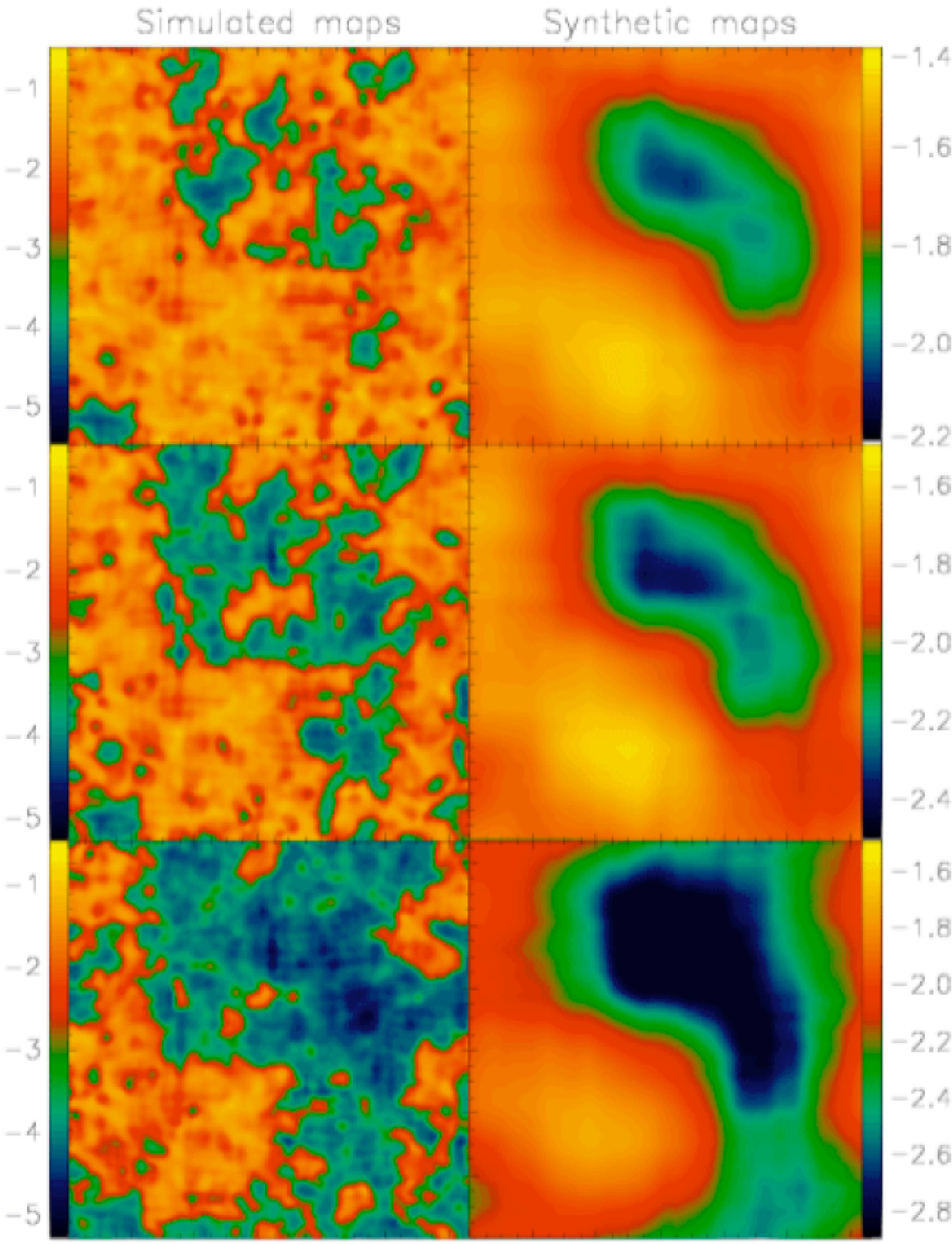

Figure 1: Logarithmic brightness temperature maps (linear size ≈11 arcmin) of the 21 cm emission for the late reionisation model at redshifts z=10.6, 9.89, 9.26 from top to bottom, respectively. Left panels: maps obtained directly from the simulation; Right: LOFAR synthetic maps From Valdes et al., 2006

Eventually, probing the reionisation of the universe requires to use different observational signatures, in combination with numerical simulations and theoretical studies. Ultimately, the best strategy is to combine the CMB data (polarisation and temperature) with direct observational probes like redshifted 21 cm line. Both signals provide a complementary view of the reionisation epoch: CMB tracing the ionised gas whereas the 21cm line traces the neutral gas. Such correlations will be possible in the near future when Planck (2008) and LOFAR (2008) data will be available. In addition to these observational probes, Lyα absorptions, metal abundances, X-ray emission, infrared background and Gamma ray bursts will permit a detailed reconstruction of the physics of reionisation.

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Large Scale Radio Emission in Galaxy Clusters: A Probe of Structure Formation

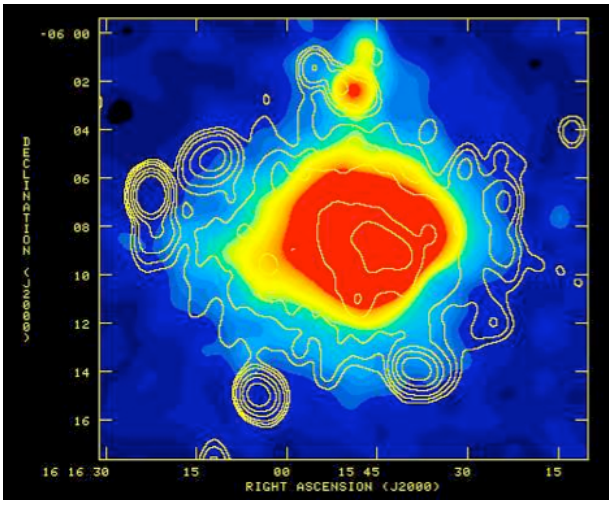

Figure 2 : The cluster A2163 as seen in X-ray (color image) and radio at 21 cm (contours) from Feretti et al. (2001) .

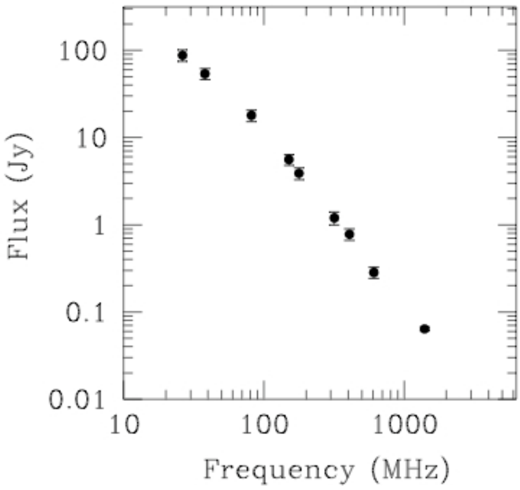

Figure 3 : Integrated spectrum of the diffuse radio source in A1914 (Bacchi et al, 2003; Komissarov & Gubanov 1994)

The main baryonic cluster component is a hot intergalactic gas, emitting in X-ray predominantly through thermal Bremsstrahlung (figure 2). This gas is heated at typical temperatures between 2 and 10 keV (depending on the cluster mass) during the hierarchical cluster formation: continuous accretion of surrounding matters and merger between clusters generate shocks that heat the gas to the virial temperature. In addition, large-scale magnetic field (B ~ 0.1 – 1μG) and relativistic electrons (E~1 – 100 Gev) are present in the intergalactic medium, as revealed by diffuse synchrotron emission observed in a fraction of galaxy clusters (figure 2 and Feretti, 2004 for a review). These extended radio sources of low-surface brightness are usually referred as “radio halos” when they show a regular morphology around the cluster center, and as “radio relics” when they are more elongated in shape and located in the cluster periphery.

Often neglected in the past, this ‘non-thermal’ component of clusters is now the subject of sustained observational and theoretical efforts, in particular in view of its importance for cosmology. Significant progresses are expected with LOFAR, whose high sensitivity and low frequency capabilities are well suited to probe the diffuse steep-spectrum radio emission in clusters (figure 3). With LOFAR we will be able to address important questions like: What are the origin and acceleration mechanism of the non-thermal population in clusters? How the energy released during hierarchical cluster formation is redistributed between the thermal and non-thermal components? Are the statistical properties of radio halos (e.g. frequency as a function of redshift) consistent with current hierarchical cluster formation scenario? Can the non thermal pressure be neglected when estimating total cluster mass (a key quantity when using clusters to constrain cosmological parameters) from X-ray observations and the hydrostatic equilibrium equation?

About 50 clusters with diffuse radio emission are presently known. All present evidence of recent merger events, suggesting that these events provide the energy source of the relativistic electrons. However, the origin of the relativistic particles and the acceleration processes are far from being understood (e.g. Brunetti, 2002). A major difficulty comes from the large size of the radio halos (~Mpc). The lifetime of the electrons responsible for the emission is very short (107-108 years), must shorter than the diffusion time. The electrons must thus have been (re-) accelerated, or generated recently, by a mechanism acting at cluster scale. Several processes have been proposed and it is possible that all of them are important. These include injection of relativistic electrons from AGN or galactic winds, acceleration out the thermal pool and/or re-acceleration of low energy non-thermal electrons by shocks and/or turbulence induced during merger events, continuous injection of secondary electrons by hadronic collisions of relativistic protons with the thermal gas. This last process could be amplified during mergers. Similarly, the evolution of the intra-cluster magnetic field, from its primordial value, is poorly understood, although some recent numerical simulations now include it.

The density and energy distributions of the relativistic electrons and its connection to the thermal electron distributions are key properties to distinguish between various models. For instance, a recent comparison of VLA radio maps and Chandra temperature maps of merging clusters suggest that radio halo electrons are mostly accelerated by turbulence rather than directly by shocks (Govoni et al, 2004). More stringent constraints are given by spectral index maps. Compared with X-ray data, they provided the first confirmation that cluster mergers do supply energy to the radio halo (Feretti et al, 2004). However, such data are presently available for only five clusters (Giovannini et al, 1993; Feretti et al, 2004; Giacintucci et al, 2005; Clarke & Ensslin 2006). Dramatic progresses are expected with LOFAR, as it will allow for multi-frequency imaging at a sensitivity and resolution well matched to the spectro-imaging capability of present X-ray satellite like Chandra and XMM.

LOFAR will also play an important role in our understanding of radio relics that, compared with radio halos, are at present poorly understood. This is firstly due to a lack of statistics and detailed radio observations of these sources. Secondly, relics show a wider variety of morphologies and positions in clusters. The extended (~500-1500 kpc) relics detected in the periphery of clusters are usually linearly polarized and show straight spectra. Generally their elongated structure is roughly perpendicular to the cluster radius, and in some cases two relics located symmetrically with respect to the cluster center have been detected (Giovannini & Feretti 2004). Smaller relics (~10-100 kpc) have also been observed in clusters, possibly located near the First Ranked Galaxy (FRG), but not coincident with it. They are characterized by very steep, curved radio spectra, and a filamentary, polarized morphology. Despite their different properties, there is increasing evidence that both the sub-classes of relics are associated with shock waves produced by cluster mergers (see Feretti 2004 for a review). The electron (re-)acceleration required to produce synchrotron emission could result from Fermi-I diffuse shock acceleration of ICM electrons in the case of the elongated "giant" radio relics, or from adiabatic compression of fossil radio galaxies in the case of the less extended filamentary relics (Kempner et al. 2004 and references therein). An increase in the number of known radio relics and better radio data are essential to allow a proper study of these sources which, due to their steep spectra, are difficult to detect in the GHz domain. The low-frequency range covered by LOFAR, together with its sensitivity and resolution, will increase dramatically the statistics on the number of known radio relics. Current theories about their origin will be tested through higher resolution observations and low-frequency spectra. This will allow us to fully characterize the non-thermal component of clusters, and to fill the gap in our knowledge of the last phases of radio galaxy evolution in clusters.

A limitation of radio observation is that the synchrotron intensity depends in a degenerate way on the strength of the magnetic field and on the relativistic electron density. One can break this degeneracy by combining observations of the radio and non thermal hard X-ray emission (HXR), due to inverse Compton scattering of the CMB photons with the relativistic electrons. It will be particularly interesting to combine LOFAR data with cluster observations performed with the SIMBOL-X satellite. It will be the first satellite with imaging capability up to high energies (~ 80 keV), allowing us for the first time to detect unambiguously HXR emission in clusters and to map its properties. This project is a F/I/G collaboration under Phase A study.

Intra-cluster magnetic fields can also be measured by combining X-ray observations and Faraday rotation measures of polarized radio sources located inside or behind the cluster. The plane of polarization of linearly polarized radio waves is actually rotated when traversing the magnetized ICM by a quantity proportional to the component of the intra-cluster magnetic field along the line-of-sight, the electron number density of the ICM (derived from X-ray analysis), and the square of the wavelength of the radiation. Until now, multi-frequency polarimetric observations have been possible only for a few, very strong (Stot >~50 mJy) radio galaxies per cluster, revealing intra-cluster magnetic fields of few μG (Govoni et al. 2006a). The excellent sensitivity, high angular resolution and large number of spectral channels of LOFAR, together with new techniques of RM synthesis (Brentjens & de Bruyn 2005), will allow polarization mapping and RM studies of radio relics (usually strongly polarized), opening new possibilities to determine the intra-cluster magnetic field on larger scales. By comparing numerical and observational results Murgia et al. (2004) and Govoni et al. (2006b) have recently shown that detailed morphology and polarization information of radio halos too may provide important constraints on the strength and structure of the intra-cluster magnetic field. The higher resolution and sensitivity of LOFAR will be essential for this kind of studies, since with the present radio telescopes the detection of polarized emission from halos is extremely difficult, probably due both to Faraday rotation within the radio source, and beam depolarization.

The statistical properties of radio halos and relics provide additional diagnostics on models and can be used to test cosmological cluster formation scenario. For instance the correlation observed between the X-ray dipole power ratio (a measure of the departure of clusters from a virialised state) and the power of the radio halo is another evidence of the connection between particle acceleration and merger events (Buote 2001). Such statistical studies are presently limited to high power radio halos in the relatively nearby universe (e.g. Bacchi et al, 2003). Detailed XMM/Chandra follow-up of large representative sample of clusters from ROSAT surveys are being conducted both at low redshift (e.g Bohringer et al, 2006, in prep.) and at high redshift (e.g Maughan et al, 2006, at $0.6 < z < 1$); Arnaud et al, 2006, $z \sim 0.5$ in prep.). LOFAR has sufficient sensitivity to detect radio halos and relics in these clusters. It will be possible to establish 1) how common is the non-thermal component in clusters; e.g. do all clusters with a recent merger have radio halos/relic? do all clusters have a radio halo/relic ? 2) how the radio properties correlate with the X-ray properties; e.g. what is the most relevant X-ray property? what are the slope, dispersion and evolution of the correlations?.

LOFAR will be able to detect ~ 1000 halos and relics, of which 25% are expected to be at redshift larger than 0.3 (Ensslin & Röttgering, 2002). New deep X-ray cluster surveys are being made with XMM, like the XCS (Romer et al, 2001) or the XMM-LSS (Pierre et al, 2006); and the SZ cluster survey with Planck should detect ~10000 clusters in the whole sky up to z~1-2. Combining all these surveys and using the radio data as tracers of recent dynamical evolution, will allow us to test cosmological models of cluster formation.

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Observations of galactic magnetic fields

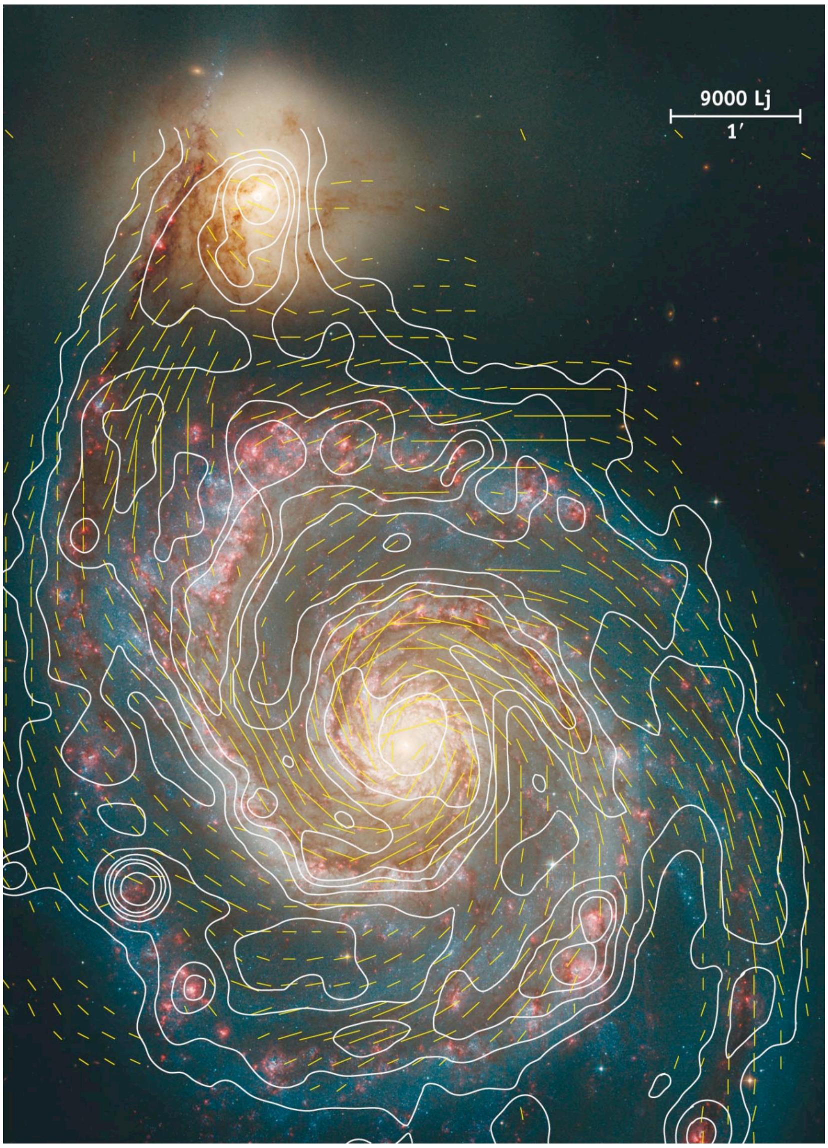

Figure 4 : The magnetic field of M51, observed at 6 cm from Effelsberg and the VLA. Optical image: Hubble Heritage Project (Fletcher, Beck, et al., to appear in A&A. 2007)

The properties of interstellar magnetic fields in our Galaxy are not well established yet, and neither their exact origin nor their precise effects on the other components of the ISM are well understood. Our current observational knowledge of Galactic magnetic fields largely relies on radio observations of Faraday rotation and synchrotron emission. LOFAR will be capable of carrying out both types of observations with much better sensitivity and resolution than present-day telescopes, and in an as yet poorly explored low-frequency range.

The Faraday rotation of a linearly polarized radio wave increases with wavelength squared times the so-called rotation measure, $RM = C \int n_e B_{//} ds$. With its low-frequency range and its wide-band polarization facility, LOFAR will be able to measure RMs well below the current threshold (down to ~ 0.1 rad m^{-2}), and thus detect very weak magnetic fields as well as magnetic fields in regions of low electron density. In particular, LOFAR will offer the opportunity to trace interstellar magnetic fields in the Galactic halo.

Furthermore, LOFAR's multi-channel capability will make it possible to perform spectro-polarimetry (RM synthesis). Because Faraday depolarization, which is particularly severe at LOFAR's low frequencies, depends on wavelength, different wavelengths probe different layers of polarized emission. Therefore, putting together measurements at various wavelengths will lead to a three-dimensional tomographic view of the local interstellar magnetic field.

Faraday tomography with LOFAR will also provide a tool to investigate the properties of magneto-ionic turbulence in the local ISM. In addition, LOFAR's high resolution will make it possible to measure modulations in the polarized radio background, and hence to study the underlying fluctuations in magnetic field strength and in electron density, on very small scales (down to a few 10^{-3} pc).

Another task awaiting LOFAR will be to survey the Galactic radio sky in different frequency bands. The large number of available channels will allow an accurate determination of the spectral index of the diffuse Galactic emission across the sky as well as the separation of synchrotron emission from thermal emission. Because synchrotron emission increases towards lower frequencies, LOFAR will be particularly well suited to measure its intensity, and from it deduce the magnetic field strength, in regions with weak magnetic fields and/or few cosmic-ray electrons, such as the Galactic halo.

LOFAR will also have access to regions harboring a population of only low-energy cosmic-ray electrons (those responsible for the low-frequency synchrotron emission). Such regions naturally arise as low-energy cosmic-ray electrons, which are less affected by radiation losses, manage to propagate farther away from their sources, thereby illuminating larger zones. These larger zones – which range from the extended vicinity of individual supernova remnants to the entire synchrotron halo of the Galaxy – will be observable with LOFAR.

Finally, let us mention the possibility of performing synchrotron tomography with LOFAR. The idea is that radiation at low radio frequencies is efficiently absorbed in HII regions, so that the synchrotron intensity measured by LOFAR toward an optically thick HII region will only represent the contribution from the line-of-sight segment in front of the HII region. In consequence, synchrotron measurements toward HII regions located at various distances from the Sun will give access to the three-dimensional distribution of synchrotron emission, and by implication that of the interstellar magnetic field, in the local ISM.

Observations of nearby galaxies

LOFAR will open up the study of nearby galaxies, mainly spirals, at low frequencies. The issues to be studied usefully complement the study of the magnetic field in our Galaxy, and similar scientific goals can be formulated.

Previous studies of nearby galaxies at these frequencies are scarce, so that the potential to learn new things is rather high. Israel & Mahoney (1990) studied a number of spiral galaxies at 57.5 MHz, and found some evidence for increasing free-free absorption of the non-thermal emission as function of the inclination of the galaxy. However, the analysis became more complicated when a strong central source was present. Such studies can be done routinely with LOFAR at adequate resolution to separate the central source from the disk emission.

From studies at higher frequencies, we can extrapolate to see what can be expected at the lower frequencies. A lot of the work in this area has been done by the Bonn group (Beck et al.), and it does not seem reasonable to duplicate effort. Briefly, their work shows several configurations of the magnetic field structure in galaxies (axisymmetric or bi-symmetric) which might be expected if galactic dynamos are generated. There are frequently striking enhancements in the continuum emission distribution, coinciding with dust lanes, which are thought to outline large scale shocks in the gas flow, due to spiral arms or bars. For edge-on galaxies, there are outflow regions in galaxies with a high current star formation rate, and the magnetic field orientation can be determined there. These issues can be addressed with LOFAR at lower frequencies, where the signal is stronger, and where a good angular resolution can be reached.

A recent study of the radiocontinuum in a number of galaxies has been done by Braun et al. (2006) in the framework of the Spitzer SINGS legacy project. Their data go deeper than previous data on the same objects, and some surprising results were found. E.g. the galaxy NGC 5055 showed two arcs of emission spanning about 60 degrees, well away from the center, and not associated with anything else in the galaxy. The galaxy NGC 4569 in the Virgo cluster shows a double structure quite like the well known anomalous arms in the galaxy NGC 4258. Such novel findings can be expected likewise in the LOFAR data. An attempt has been made in Murphy et al. (2006) to link the synchrotron emission in the radio bands to the present rate of star formation in a galaxy as measured by other indicators. Such studies can be put on a firmer basis when more data at lower frequencies become available.

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High-energy γ-ray AGNs

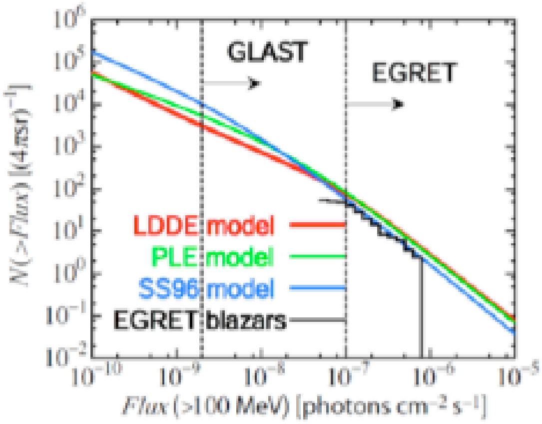
Blazars are amongst the few astronomical sources known to emit radiation across the whole electromagnetic spectrum, from meter radio to γ-rays of tens of TeV. The emission is thought to be synchrotron and inverse Compton from particles accelerated to very high energies (VHE) in a relativistic outflow aligned with the line-of-sight. Understanding the processes through which energy is liberated into non-thermal channels provides insights into the physics close to a black hole, notably how accretion and ejection are related.

Blazars are characterized by strong variability at all wavelengths. The activity is thought to be linked to relativistic ejections of matter from the vicinity of the massive black hole. For instance, in the internal shock scenario [12], shells ejected with different speeds collide and produce VHE particles at the relativistic shock, as in gamma-ray bursts. VHE particles subsequently cool, are possibly re-energized away from the core and eventually inject power into the IGM.

LOFAR usefully complements the current multiwavelength view of blazars. Electrons emitting incoherent synchrotron at LOFAR frequencies have long lifetimes (days with B ~1 G as appropriate for compact sources) compared to those responsible for the high energy emission. Low-frequency lightcurves combined with measurements at higher energies, can yield important information on how particles cool [9, 4]. LOFAR monitoring can also provide alerts to blazar activity supplementing those currently given in X-rays by the RXTE ASM, or replacing it after the end of RXTE operation. Intraday variability at low ν during flares would lead to exceedingly high brighness temperatures ($T_b \propto \lambda^2$, $T_b > 10^{18}$ K) which, in our present understanding, can only be alleviated by very large relativistic boosts [13]. With good angular resolution, ghosts of past jet activity may appear as large-scale low-frequency synchrotron emission in much lower B fields. Extending radio spectra to low frequencies can identify cutoffs associated with the particle distribution (γ_{min}) or due to radiative processes (Razin effect, synchrotron self-absorption), providing better estimates of energy densities and magnetic fields [6].

LOFAR can provide invaluable help in expanding the number of known γ-ray emitting extragalactic sources. Nearly all identified EGRET sources are blazars, establishing those as major sources in the GeV sky [7]. EGRET blazars are typically strong, polarised, flat-spectrum radio sources with $S_{1\ GHz} >$ 0.25 Jy. About 170 of the 271 EGRET sources remain unidentified due to insufficient angular resolution (sub-degree). GLAST (launch late 2007) will cover the same energy range (~ 0.1 - 30 GeV) but with arcmin localisation and a ~100-fold improvement in sensitivity. GLAST is expected to recover the EGRET sources within a couple of days and to return a catalog of several thousand GeV sources in its lifetime. Many of the high-latitude sources will be faint blazars at high redshift (FSRQ, BL Lac) or closer M87-like radio galaxies that will need proper identification and follow-up (figure 5). This sample can be used to study the correlation between radio and γ-ray luminosities found with EGRET [5] to lower fluxes, with consequences e.g. on beaming; the luminosity function will allow new insights into AGN evolution.

The surveying ability, sensitivity and resolution of LOFAR are ideally suited to identify distant counterparts for high-latitude GLAST sources. GLAST is US-led with participation from Italy, France and Sweden. The GLAST source catalog is a deliverable of CEA-Saclay and scientists at IN2P3, who have developed major parts of the GLAST science analysis software, have a strong interest in blazar physics. Involvement in LOFAR would put the French community in a privileged position to initiate projects with these instruments. Furthermore, the French VHE community is also strongly involved via HESS in ground-



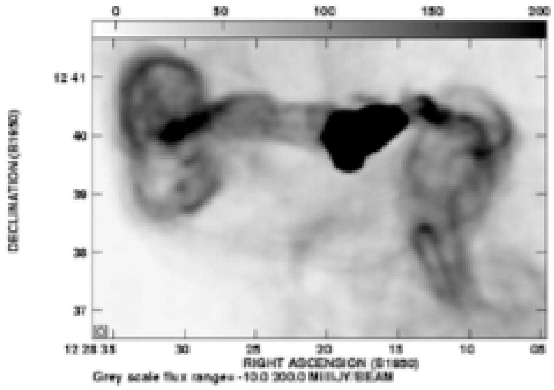


Figure 5: Left: Expected luminosity function of GLAST-detected blazars assuming various evolutionary models [10]. GLAST will see at least several thousand blazars for which LOFAR can provide identifications, typing and follow-up monitoring. Right: 90cm VLA observation of the nearby radio galaxy M87, showing the bubbles inflated by the relativistic jet. The energy input in the bubble is inferred to exceed that in the X-ray jet [11]. M87 has recently been confirmed as a TeV emitter by HESS, extending known γ-ray emitting sources to a new class of AGN [3].

based Cherenkov arrays that operate above 100 GeV with great sensitivity. There is Nançay monitoring (limited to meridian transit) of a few blazars of interest to HESS [2]. Since it is a pointed instrument, HESS would benefit from GLAST+LOFAR identifications of new extragalactic targets (e.g. low-redshift blazars through which attenuation of γ-rays on the extragalactic background light can be studied, [8]). Inversely, although limited by its Northern location, LOFAR may help identify counterparts to newly discovered HESS sources in the Galactic plane, notably the dark accelerators with no obvious counterparts away from the TeV regime [1].

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Probing the non thermal flaring Universe

Black holes and neutron stars in compact Galactic X-ray binaries are variable on many timescales ranging from ms to years; they have proven to be ideal targets to investigate the accretion – ejection coupling in accreting compact objects, general relativity in strong gravitational fields, or the equation of state of nuclear matter in neutron stars. Their transient X-ray outbursts are usually associated with synchrotron radio emission, originating from high energy particles interacting with the magnetic field of relativistic jets. These jets are now known to come in two flavours: the powerful self absorbed compact jets and the transient impulsive superluminal ejection events that are usually observed during state transitions [1]. With a factor 100-1000 improvement in sensitivity and spatial resolution, LOFAR can achieve major advances in understanding the violent nature of these cosmic explosions. The interaction of the jets with the interstellar medium is also responsible for the formation of large scale lobes, which accelerate particles up to very high energy [2]. As noted in the section on AGN, the new high energy observatory GLAST (Gamma-ray Large Area Space Telescope), designed to cover the energy range 20 MeV to 300 GeV, is expected to be launched in fall 2007 and will therefore be in action simultaneously with LOFAR. Compared to the previous instrument (EGRET) in the same energy range, GLAST will be able to provide an all sky map in one day, with sensitivity similar to EGRET during its entire lifetime. One of the main scientific objectives of GLAST includes the identification and the nature of high energy particle accelerators (AGN, compact objects, GRB, solar flare…) in the Universe, which is also one of the main focus points of LOFAR. The SAp at CEA Saclay, with associated scientists at IN2P3, is responsible for the production of the GLAST catalogue and delivery of the science analysis software. Compared to previous telescopes, GLAST and LOFAR will provide a two-order of magnitude improvement in terms of daily sensitivity. As some of their primary objectives are similar, it is important to be able to explore both databases in a timely manner.

LOFAR as a radio all sky monitor:

A fundamental task of the LOFAR array is to provide a daily monitoring of the active radio sky. The results of this program and the detection of new transients will be made available to the community. Automatic reconfiguration of the telescope will allow arcsecond localisation of new transient sources. Currently, new active X-ray binaries are detected by their X-ray emission with the All Sky Monitor aboard RXTE (RXTE/ASM). RXTE/ASM provides alert to the scientific community allowing follow-up observations by pointed observatories in space (XMM-Newton, Chandra, Spitzer …) or on ground (optical, radio …). RXTE has a finite lifetime and is expected to be terminated in years 2008-09, a period in which LOFAR will be fully operational. There is no plan for a replacement of the RXTE/ASM. As an all sky monitor with sensitivity 10 times higher than current X-ray all sky monitor, LOFAR will therefore fulfil a role of prime importance for the high-energy astrophysics community by providing the alert for Target-Of-Opportunity pointed observations. In addition to existing X-ray missions, such as INTEGRAL or XMM-Newton, SAp/Saclay is currently initiating the next generation of high energy observatories with SIMBOL-X. Relying on two spacecrafts in a formation flight configuration, SIMBOL–X will use for the first time a ~ 30 m focal length X–ray mirror to focus X–rays with energy above 10 keV (up to 80 keV), also resulting in a two orders of magnitude improvement in angular resolution and sensitivity in the hard X-ray range with respect to non focusing techniques. The revolutionary instrumental capabilities of

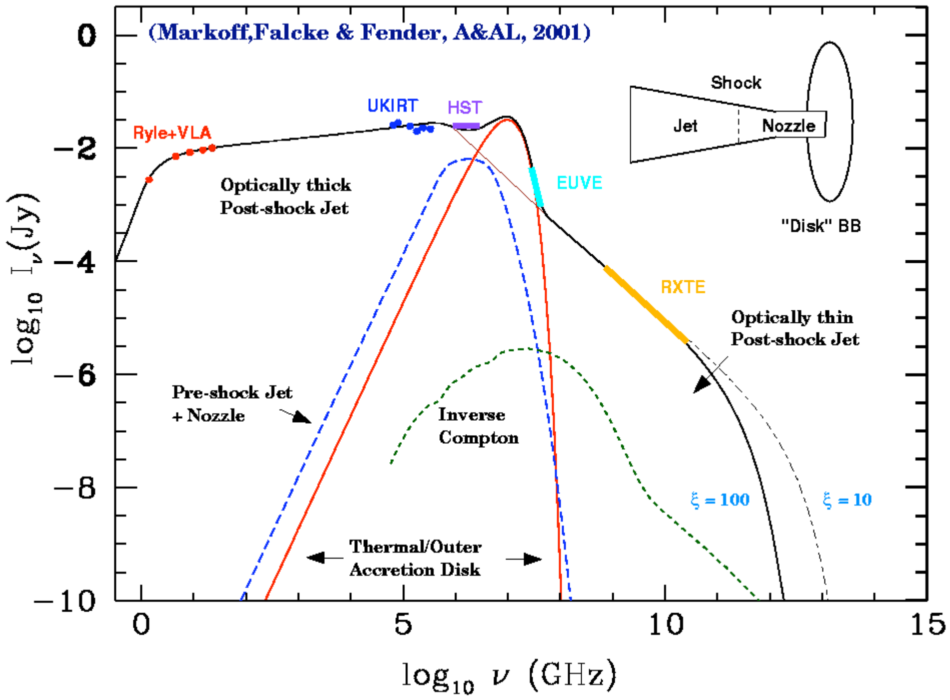

Figure 6: Broadband spectral energy distribution of XTE J1118+480 during a hard state in 2000.

SIMBOL–X will permit to elucidate outstanding questions in high energy astrophysics. SIMBOL-X would be flying in the years 2013+, i.e. during the LOFAR lifetime. A by-product of the radio all sky monitoring is a better understanding of the distributions of X-ray binaries in the Galaxy and a significant input into population synthesis models. Potential examples of interesting LOFAR targets include:

Compact jets

The self absorbed compact jets are now believed to be an ubiquitous property of accreting black holes and neutrons star at low accretion rates [1]. The discovery of the fundamental plane of black hole activity has brought to light a similar coupling in AGN, underlying a possible unification of the physical properties of all accreting compact objects [3, 4]. The synchrotron emission of the compact jets (figure 6) extends from radio up to the near infrared with a possible extension up to X-rays [5]. Inverse Compton emission at the jet base on seed photons from the accretion disk or from the synchrotron jet photons (SSC) may contribute to observable and detectable gamma-ray emission in the GLAST energy range [6]. Such emission has not been detected in any accreting binary system at energies greater than a few MeV, but if detected it will be of prime importance to disentangle between the various models of accreting binaries. The ability to combine radio observation of the synchrotron emission with the X- and gamma-ray emission from these processes, due to the same populations of electrons, will be the key to constrain models of the physics at the base of the jet and in the disk corona.

Relativistic ejections events

Relativistic ejections are almost unpredictable events due to their transient nature and have been proven to be difficult to observe due to the low-availability of radio telescopes and the

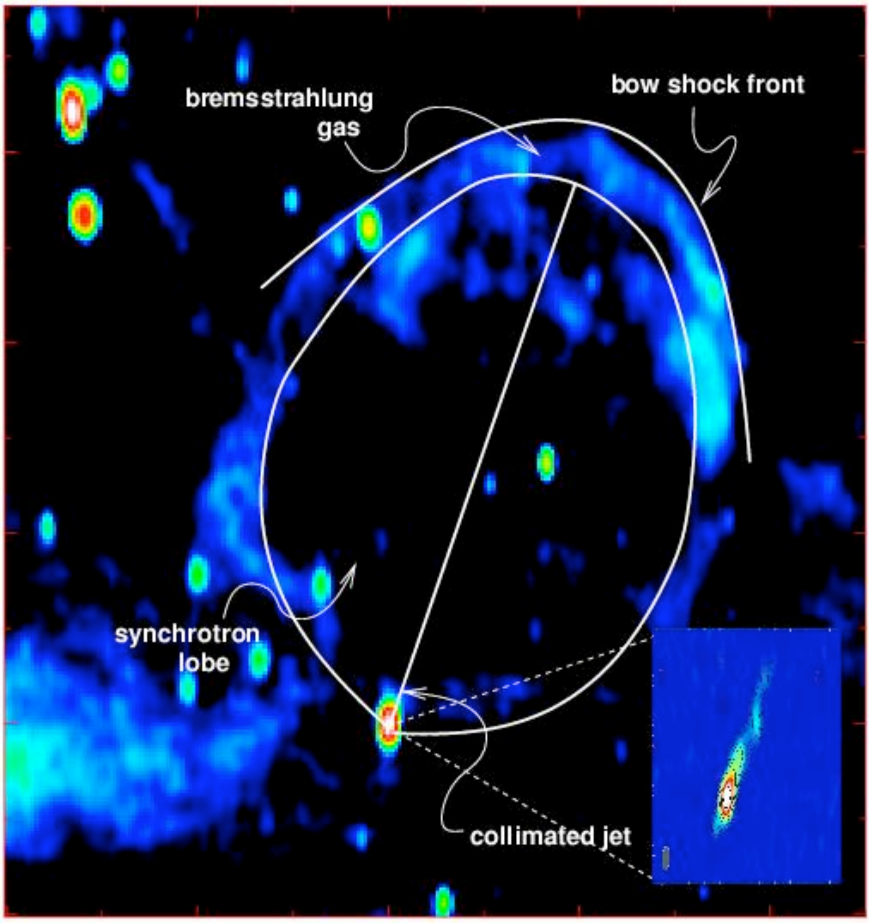

Figure 7: The ring of Cygnus X-1 [8] is the result of a strong shock that develops at the location where the pressure exerted by the collimated milliarcsec-scale jet, shown in the inset, is balanced by the interstellar medium. The jet particles start to inflate a synchrotron-emitting lobe which is overpressured with respect to the surrounding gas, thus the lobe expands sideways forming a spherical bubble of shock-compressed bremsstrahlung-emitting gas.

fast decay of the associated GHz radio emission. With LOFAR, such events could not be missed (even if opacity effects, and hence delay, would have to be taken into account) as LOFAR will be the first all (North) sky monitor at radio frequency. Any relativistic ejection from a given source will be detected by LOFAR with a delay of several days after activation. Very rapid detection will be possible for the very bright cases or if the event is initially optically thin. 1 to 10 transients are expected to be monitored every year by LOFAR. It is also accepted that transients as far as the M31 galaxy could be detected. In a few cases, the jets would be expected to point toward the observers. Relativistic beaming effects would imply that the superluminal jets may appear as a radio source with fast and intense variation of flux density with possible high energy emission as in the extragalactic blazars[7]. The combination of LOFAR and GLAST should be ideally optimized for the first detection and characterization of a microblazar.

Serendipitous discovery

More importantly, any time a new observing window has been opened; unexpected discoveries have been made, such as the unidentified EGRET sources, the recent repeating radio transients or the giant flares of magnetars. LOFAR and GLAST will have unprecedented sensitivities and capabilities compared to previous instruments in their energy ranges. It is therefore expected that important serendipitous discoveries will be made. Identification at low and/or high energy would be of prime interest to reveal the nature of the new phenomena. It has also to be noted that LOFAR has a unique capability to focus “a posteriori” on some specific events (such as a GRB or a blazar flare).

Key scientific LOFAR contributions

Low frequencies radio observations are important for many aspects. First of all, observations in this frequency range are currently extremely rare. LOFAR will allow measuring the extent of the non thermal electron spectrum down to low frequencies. With an electron distribution N(E)dE a E-p, the radio emission usually observed at typical radio frequency (e.g. 5 GHz) have Lorentz factor γ_e of the order of 150; at LOFAR frequency (e.g. 150 MHz) those electrons will have only a Lorentz factor γ_e of ~25. The determination of the minimum Lorentz factor is important to estimate the total energetic budget of jets if they are dominated by the kinetic energy of cold proton in the jets. Simultaneous observations at low and high radio frequency of an ejection events can identify whether the energy loss mechanisms are driven by radiative or expansion losses by comparing the observed decay rates. Additionally the conversion of jet kinetic energy into internal energy during collision processes with the ISM (with shock reacceleration) lead to the formation of large scale radio lobes with a steep radio spectrum that should be very bright at low frequency. Using the lobes as a calorimeter (e.g. Cyg X-1 in figure 7 [8]) allows an independent estimation of the power times lifetime of the jet by measuring the total energy deposited in the lobes. Finally, LOFAR observations are important to measure absorption processes (Razin or free-free) that are dominant at low frequency, which allow a determination of the magnetic field and electron density.

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Supernova Remnants

The shock front in Supernova Remnants (SNRs) has long been expected to be the main site of particle acceleration up to energies of the order of 10^{15} eV, providing the energy required to maintain the pool of Galactic Cosmic Rays (Drury et al. 2001). Recent observations in the X-rays (XMM-Newton, Chandra) and in the TeV γ-rays (HESS) have provided the proof that electrons are accelerated in supernova remnants up to energies of about 100 TeV. However, a number of open questions still remain on the physics of particle acceleration. Radio observations at low frequency will reveal the missing part of the SNR nonthermal spectrum by providing their low energy synchrotron spectrum.

Relativistic electrons emit synchrotron radiation observable from radio up to X-rays, where the spectrum turns over. While X-ray data probe the highest energy of the accelerated particle distribution, radio observations probe the pool of relativistic electrons and offer direct constraints on the accelerated electron spectrum and magnetic field. Extending the radio observations of SNRs to low frequency is crucial to provide specific information on the physics of particle acceleration at shocks as detailed below.

In addition to a larger number of accelerated electrons ($S\nu \sim \nu^{\alpha}$, with $\alpha \sim -0.6$), there is in this low frequency radio window critical diagnostics available to distinguish between different acceleration models: test-particle versus nonlinear models. The test-particle model assumes that the number of accelerated particles is dynamically negligible while the nonlinear one takes into account the back reaction of accelerated ions on the structure and energetics of the shock.

Nonlinear models of particle acceleration predict a curvature in the synchrotron spectrum at low radio frequency (Ellison & Reynolds 1991) in contrast to the power-law synchrotron spectrum predicted by test-particle models. This signature has been suggested in only a few cases, due to the limited low frequency data (see Fig. 1 in Reynolds & Ellison 1992). With LOFAR, we will probe the spectrum of electrons down to energies as low as 0.7 GeV (for a magnetic field of 100 mG) and determine its synchrotron spectral index, providing new insights in the physics of particle acceleration in terms of models and magnetic field determination. LOFAR will not only allow the determination of a global spectral index, but also, in relatively bright SNRs, the mapping of the radio spectral index within the remnant (see Katz-Stone et al. 2000). This requires very reliable brightness maps at several wavelengths.

Using the considerably improved spatial resolution at low radio frequency will allow the mapping of the radio counterparts to the bright thin non thermal synchrotron filaments observed in X-rays at the shock and for which very high values of the magnetic field are invoked. There are a number of open questions on the properties of the magnetic field in SNRs (see Cassam-Chenaï et al. 2006) at the shock (amplified ?) and downstream in the remnant (advection versus damping ?). These open questions require high spatial resolution (< 1 arcsecond) to map the nonthermal synchrotron emission at these low energies and to constrain the magnetic field evolution in the remnant.

A number of SNRs are located in rich regions along the Galactic Plane: the radio emission can be strongly confused in these fields, in particular due to the contribution of thermal sources (see for example Helfand et al. 2006). Observing at lower frequency is important to limit the confusion by thermal sources. Together with a much improved sensitivity, this will allow the mapping of poorly known low surface brightness remnants, the discovery of new faint SNRs or those lying in confused regions. This is particularly important for remnants of core collapse supernova, which can be associated with a massive progenitor in an OB association or close to interstellar clouds. These remnants are potential sources of TeV emission through pion decay as suggested recently by HESS observations of RX J1713.7-3946 and as could be observed with GLAST in the near future. It is of prime interest to observe them at low frequency with LOFAR, with an improved spatial resolution and sensitivity.

Another important issue is related to the thermal internal absorption in SNRs with the objective of detecting the unshocked ejecta in young SNRs as done at 74 MHz for Cas A (Kassim et al. 1995). While the mass of shocked ejecta can be estimated from the X-ray spectra of highly ionized material, LOFAR provides an unique view to the cold invisible unshocked ejecta mass, complementary to optical/UV absorption toward background targets. This determination is essential for understanding the parameters of the supernova explosion, the dynamics and evolutionary stage of its remnant.

In conclusion, LOFAR is particularly well suited to observe SNRs and will provide unique insights in SNRs.

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Plerions and their Pulsars

In addition to the radio emission associated with the blast wave, which generally has a rim-brightened, shell-type morphology, many supernova remnants exhibit an interior, filled-center radio component with a flat, nonthermal spectral index and strong polarisation. These so-called {\em plerionic} components are thought to be due to the activity of a central pulsar born in the supernova explosion, which emits a relativistic wind of charged particles, principally electrons and positrons.

Power-law spectra characteristic of synchrotron emission from accelerated electrons (and positrons) are observed from the radio to the X-ray domain and beyond. Several such pulsar wind nebulae (PWNe) have also recently been detected in very high-energy (VHE) gamma-rays by the HESS telescopes (see e.g. Gallant 2006 for a review), where the emission mechanism is thought to be inverse Compton scattering by the same accelerated electrons. X-ray and VHE gamma-ray observations probe the electron spectrum at higher energies, which is thought to be the result of particle acceleration at the termination shock of the pulsar wind (Kennel & Coroniti 1984), perhaps by the Fermi mechanism (e.g. Achterberg et al. 2001).

The origin of the spectrum of lower-energy radio-emitting electrons in plerions is much more poorly understood. There are indications from the Crab Nebula radio wisps and infrared spectral morphology that acceleration of radio-emitting electrons is ongoing, rather than the result of injection earlier in the life of the system. A number of mechanisms have been proposed for the acceleration of these electrons (Gallant et al. 2002, Lyubarsky 2003). In the former case, observations at low radio frequencies are particularly interesting, as they could reveal a spectral feature at the lower end of the spectrum associated with the bulk Lorentz factor of the pulsar wind. There is a hint of such behaviour in available low-frequency data on the Crab Nebula (e.g. Baars et al. 1977). Sensitive and well-calibrated observations of plerions in the low-frequency domain, such as LOFAR will be able to perform, thus have the potential to substantially improve our understanding of pulsar winds.

Another aspect of plerions for which the capabilities of LOFAR will be particularly well suited will be the search for and study of their associated pulsars. Several plerions are not associated with detected pulsars, presumably because the main part of the radio beam of the embedded pulsars in those cases does not cross the line of sight. In other cases the pulsar has been detected at X-ray energies, but not in the radio domain. Nonetheless, deep searches in recent years for pulsed radio emission have revealed a number of weakly-emitting radio pulsars associated with young plerions (e.g. Camilo et al. 2002, 2006).

Most pulsars have relatively steep power-law spectra (e.g. Malofeev et al. 1994), so that they may more easily be detected at longer wavelengths. This fact, combined with the vast improvements in sensitivity and angular resolution brought by LOFAR, raises the possibility of detecting weak radio pulsars as point sources, and not only from a pulsed analysis of the signal. When performed with sufficiently large baselines and over long time spans, such observations would allow the measurement of the pulsar proper motion, unaffected by the systematic uncertainties which complicate the determination of this quantity from pulsar timing measurements. The proper motions of individual pulsars are crucial measurements for the evaluation of specific proposed associations of pulsars with supernova remnants.

For the same reason related to pulsar spectra, the sensitivity of LOFAR at low energies holds the potential for timing measurements of weak radio pulsars, provided the necessary analysis tools are developed. In particular, several of the pulsars recently discovered in young plerions have proven too weak to regularly follow, even with some of the leading radio instrumentation in this field.

The ability to perform regular radio timing of these objects at low frequencies would give new insights into the timing properties of such young pulsars. More importantly, the availability of radio timing data is an essential precondition for the discovery and study of pulsed gamma-ray emission from these pulsars. The upcoming instruments GLAST and HESS-2 in the relevant energy range should revolutionise this domain. This is but one example of the outstanding potential of LOFAR for the study of pulsars, which would deserve a much more detailed discussion than could be provided here.

In summary, LOFAR will yield previously unavailable avenues of investigation for our understanding of the phyics of plerions and their associated pulsars.

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Young stellar objects

Astrophysical context:

Two main stages of early PMS evolution of solar-type stars can be distinguished, divided in two subclasses (e.g., André 1996, André et al. 2000): protostars and T Tauri stars.

Protostars:

The earliest stage of evolution is that of a dynamically collapsing, rotating envelope, deeply embedded in a molecular core. Matter accumulates at the center to create a stellar embryo: initially, the mass of the future star is essentially contained in the envelope. This rapid accretion, "Class 0" phase lasts ~ 10^4 yrs. The accretion rate is high (M_dot ~ 10^{-6} M_sol/yr). Because the envelope temperature is cold (a few 10 K), Class 0 protostars are detected in the far-IR/submm range. Remarkably, Class 0 protostars are also VLA emitters, at the mJy level at 3.6 cm for d ~ 150 pc –this is even one of their distinctive characteristics. This emission is thought to be thermal and coming from the base of the bipolar molecular outflows associated with young stars, but in fact very little is known for lack of other radio constraints.

As accretion feeds the central object, its mass increases at the expense of the envelope. This is the so-called "Class I" stage. The envelope is warmer and is now detectable from the near-IR (or even optical) to the mm range. The accretion disk becomes visible, especially in absorption against scattered stellar light if it is oriented equator-on, as is illustated in Fig. 1 by the prototypical object HH30 in Orion. This phase lasts ~ 10^5 yrs.

From the radio point of view, Class 0 and Class I sources share about the same properties. One major difference, however, is that Class I sources are flaring X-ray sources (Feigelson & Montmerle 1999), while Class 0 sources are not detected (Montmerle et al., in preparation). This non-detection can be explained by the high extinction of the massive Class 0 envelope (Av up to 1000). The Class I protostars tend to be overluminous in X-rays with respect to the general X-ray vs. Radio (GHz) correlation seen in magnetically active stars (see above and Smith et al. 1999; Benz & Güdel 1994, Güdel 2002). In the LOFAR context, it is important to realize that Class 0 protostars have been first recognized via the radio (GHz) emission, detected with the VLA, at the base of molecular jets (e.g., André et al. 2000). This emission is widely interpreted as continuum thermal radiation associated with the "central engine" of the accretion-ejection mechanism, but its exact origin is still unclear. X-rays, for instance, cannot explain the gas ionization, unless their luminosity is much higher than typical of magnetic activity as in Class I protostars, in which case the question is transferred from the origin of the radio emission to the origin of the X-rays. As discussed below, LOFAR may contribute to solving this problem.

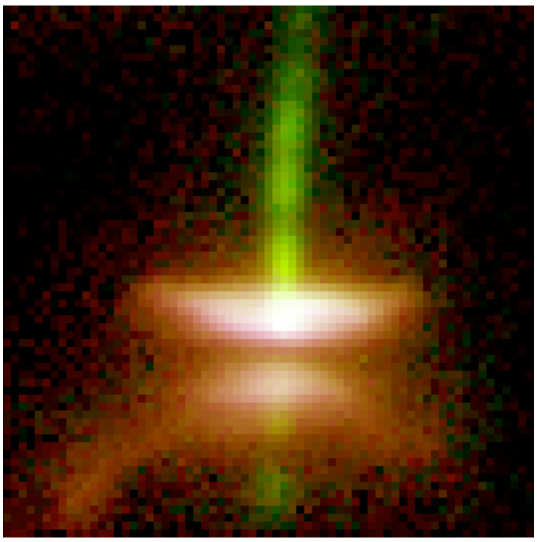


Fig. 1. *The HH30 object in Orion (HST observations by Burrows, 1995). The circumstellar disk is seen equator-on. Disk radius ~ 300 AU. The base of the jet is a radio source. The jet itself extends out to > 1000 AU.*

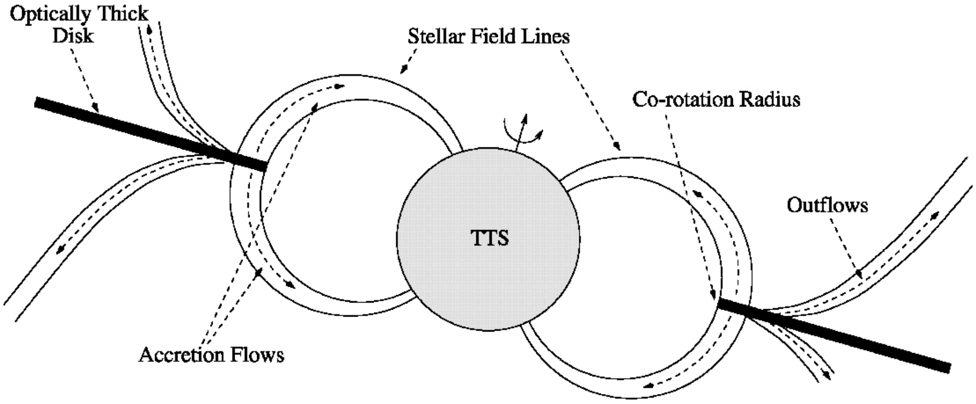


Fig. 2. *Schematic illustration of the "magnetospheric accretion" process, widely thought to take place in T Tauri stars, and probaly also in protostars (Stassun 2001).*

T Tauri stars:

At this stage the envelope has disappeared, but a circumstellar disk is still present. This disk is thought to feed the central star by "magnetospheric accretion", although the accretion rate is one to two orders of magnitude smaller than at the protostar stage. Fig. 2 gives a schematic representation of the process. Accreting T Taurti stars are called "classical" T Tauri stars in the optical: they are characterized by strong emission lines (in particular Hα), interpreted as the signature of the hot accreting gas. They are also called "Class II" T Tauri stars in the IR, because of the excess IR emission produced by their cold accretion disk.

These disks are often called "protoplanetary disks", because there is increasing evidence that they are natural sites for planet formation (generally speaking). Their radii are typically Rd ~ 200-500 AU, compared with ~ 50 AU for the size of the solar system (inside the "Kuiper belt"), and of course 1 AU for the orbit of the Earth.

For yet unclear reasons (perhaps grain growth leading to planet formation), circumstellar disks disappear after 1 – 10 x 10^6 yrs. The "classical" T Tauri stars evolve into diskless, "weak-line" T Tauri stars, or Class III (no IR excess). The X-ray properties of Class II and Class III T Tauri stars are essentially similar, so that the presence of an accretion disk does not significantly influence the usual, solar-like activity (Feigelson & Montmerle 1999). In contrast, the radio properties are different: non-thermal VLA emission has been detected in many Class III sources, flaring on timescales ~ hrs as in X-rays, while the VLA emission of Class II sources is thermal. However, non-thermal emission likely exists but is absorbed by the surrounding ionized gas.

Therefore, apart from the diskless, Class III T Tauri stars, all YSOs exhibit thermal radio radiation in the VLA range. The origin of this emission is thought to be fully ionized material at the base of the outflows, but how this material is ionized is unclear, since T Tauri stars have late-type, cool photospheres. Their flux at 1 GHz is weaker than the flux of non-thermal radio emitting Class III sources, but as their spectrum varies from flat to a slope of 1 (more rarely 2), it must decrease less drastically at low frequencies. Such spectra are relatively well explained: in YSOs, slopes of 0.6 are expected from ionized winds at a constant speed, and between flat and 2 for collimated jets, as they come from inhomogeneous sources composed of both optically thick (slope 2 predicted from free-free emission) and thin media.

What can we do with LOFAR ?

Spatial resolution and sensitivity:

At a distance of 160 pc, typical of the nearest regions of low-mass (M < 2-3 Msol) star formation (Taurus, Ophiuchus, etc.), 1” = 160 AU. Thus LOFAR will not allow to probe the innermost regions of protoplanetary disks, but at its best resolution (0.5” when 400 km baselines become available, for the “high frequency” array), it can resolve extended structures like jets down to the size of the solar system. Thus, a first goal would be to observe and possibly map YSO jets (sizes ~ 100-1000 AU), as has been done with the VLA in a number of cases. With the best LOFAR resolution we could discriminate optically thick emitting zones from optically thin ones observed at higher frequencies. The proper motion of jets has been studied recently by Rodríguez et al. (2000). Also, sizes have been found to increase with decreasing frequencies, thus low-frequency mapping of jets may reveal new structures and interactions with the surrounding interstellar medium, perhaps reminiscent of the “smokelike” structures of extragalactic jets interacting with the intergalactic medium.

The non-thermal cm radio emission of T Tauri stars, inferred from rapid variability (rise or decay down to 2 hrs) and strong circular polarization, is compatible with optically thick gyro-synchrotron emission from a non-thermal, power-law energy distribution of electrons. Some have been resolved with VLBI. Their radio flux increases above 1 GHz and peaks at about 5, 8 or sometimes 15 GHz. The strongest expected flux at 300 MHz is of the order of 0.5 mJy, but it could not be detected with the VLA, and therefore remains unexplored; however, such a flux is within reach of the LOFAR sensitivity (0.4 mJy at 240 MHz in 1 hr and over 4 MHz).

In the VLA range, we see that YSOs show many analogies with other non-thermal radio stars such as RS CVn systems & Bp-Ap stars (André 1996; Güdel 2002). However, except for the Class III T Tauri stars, all YSOs are surrounded by circumstellar matter, which most models assume to be accreted along magnetic field lines: this is reminiscent of the solar wind being guided in planetary magnetospheres. This framework opens an entirely new field of investigation with LOFAR: the discovery of possible auroral-like phenomena in YSOs.

So far, all YSO models take into account only MHD plasma processes, whereas we know from planetary radio emissions that many non-MHD plasma processes are at work (see preceding sections). There is currently no theoretical calculation of radio emission in the m-dam range covered by LOFAR, so that observational predictions are risky. However a simple pilot study would immediately reveal new phenomena linked with magnetospheric accretion : make a LOFAR survey of individual Class II and Class III Tauri stars (a dozen each, for 1 hr, say) in the Taurus clouds (or a similar region in the southern hemisphere, like the Chamaeleon clouds), where the T Tauri stars are well separated spatially, and look for differences, qualitative and/or statistical. If positive, the experiment would open the way to testing the various models of magnetic accretion and outflow ejection, which X-rays alone cannot convincingly discriminate (Montmerle et al., in preparation).

In conjunction with VLA results, one could also investigate whether the radio/X-ray correlation found in the GHz range also stands at lower frequencies, and revisit the problem of the source of ionization at the base of protostellar jets.

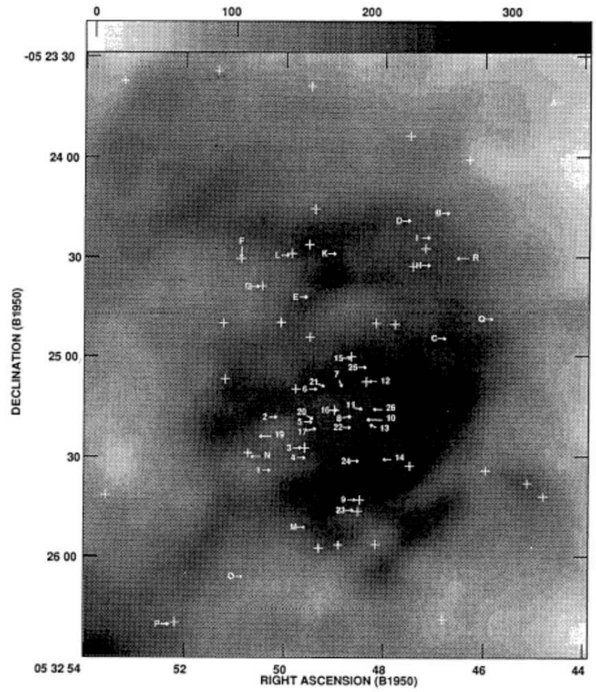
More massive young stars (OB stars) would also be interesting, because LOFAR would allow to probe the thermal emission of their ionized winds and velocity structure (in conjunction with the VLA at GHz frequencies).

Fig. 3 IR (left, VLT) and X-ray (right, Chandra) images of the Orion Nebula Cluster, 17' on a side, and with a comparable PSF (~ 0.2"). The Trapezium (massive stars exciting the nebula) can be clearly seen in both images, and there is an almost one-to-one correspondence between the IR and X-ray sources. The phased array properties of LOFAR at its maximum resolution could be used to map the same region, and obtain in one single observation the low-frequency radio properties of young stars in the range 0.1-20 Msun.

Large-scale surveys in phased array mode:

While the above observations concern individual stars, it may be much more efficient to use the property that stars form in clusters. While low-mass stars (up to M > 2 Msol) tend to form in loose clusters of 100x stars spread over a very large angular area when they are close (see the prototypical region of Taurus), regions of higher-mass star formation (up to M ~ 10-20 Msol or more) include thousands of low-mass stars in addition to the massive stars, concentrated in much smaller areas ("OB associations"). For instance, the Orion Nebula Cluster ("ONC"; d = 450 pc) contains ~ 2000 stars in ~1/4 sq. deg. The interest of observing such a cluster (as opposed to individual stars) is based on the X-ray emission observed in all the stars: low-mass star X-rays come from magnetic activity as above (e.g., Feigelson & Montmerle 1999), and high-mass star (spectral type > A) X-rays come from strong stellar winds, sometimes confined by extended magnetospheres (e.g., Babel & Montmerle 1997, Stelzer et al. 2005).

To illustrate the point, Fig. 3 shows side by side the IR (VLT-ISAAC) and X-ray (Chandra) images, 17' on a side and centered on the ONC. The X-ray image (Getman et al. 2005) has a PSF of ~ 0.2". Except for the lowest-mass stars (brown dwarfs) for which the X-ray detections are incomplete because of their intrinsic faintness, all the stars are detected. Given the X-ray/radio (cm) connection already mentioned above, it would be extremely interesting



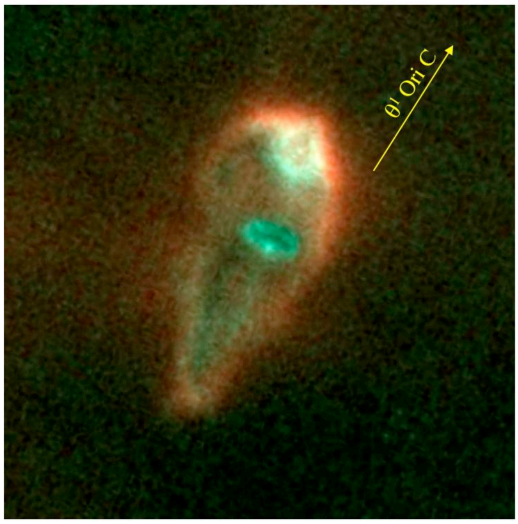


Fig. 4. Left: VLA image (1.4Ghz) of the Trapezium region (2' x 3') observed by Felli et al. (1993). Symbols indicate the sources detected at 5 and 15 GHz. About 1/3 are identified with optically visible stars, and a few are identified by ionized, photoevaporating disks such as the "teardrop-like" shells irradiated by the nearby high-mass star θ1 Ori C (right). The angular size of the ionized "tears" is ~ 2" (~ 1000 AU at 450 pc), and thus could be resolved by LOFAR.

to observe the region with LOFAR and use its phased array mode to obtain the low-frequency radio properties of all the stars in the field-of-view simultaneously. Because the large-scale features can be resolved out by the interferometer, point sources should be detectable over the HII region background. Note however that the observations would be most efficient at the highest spatial resolution (0.5", i.e., in the "high-frequency" part of LOFAR), since the stars would be essentially all resolved. Observations at lower frequency (during an earlier stage of LOFAR) would be valuable too, but confusion would plague the angularly closest sources.

For comparison with previous radio work, we also show in Fig. 4 a VLA image of much smaller area (2' x 3') around the Trapezium region (Felli et al. 1993), In this area, 43 radio sources are found, of which 18 are associated with optical objects. Most of these objects are stellar sources, but a few, initially associated with ionized globules, are now known to be associated with "teardrop-like" shells – protoplanetary disks photoevaporated and ionized by the Trapezium stars and shaped by their winds (see Throop & Bally 2005). These sources are particularly interesting, since, contrary to "standard" disks which are neutral, these disks are surrounded by ionized gas over large distances (100x pc) and may thus be resolved by LOFAR.

Conclusions

The study of Yong Stellar Objects with LOFAR, more precisely of their solar-like magnetic activity inspired from the X-rays, and of their associated extended structures (disks, jets, ionized shells) is potentially very rich. In particular, at least in the "high-frequency" mode with long baselines, because of their large sizes (up to ~ 1000 AU) these structures can be resolved as far as the most studied regions of star formation in the solar neighbourhood. Since young stars generally form in rich clusters of up to several thousand stars, barring confusion problems for the weakest, most spatially concentrated sources, hundreds of low- to intermediate-mass stars may be studied simultaneously, at least on paper.

What is currently missing, however, is model predictions at the sub-GHz frequencies of LOFAR. It is likely that GHz images and spectra, such as given with the VLA, will be necessary to interpret the LOFAR data, the VLA giving clues about the emission processes (thermal vs. non-thermal…), and LOFAR giving access to the plasma absorption processes. Such a modelization can conceivably start from the properties of solar radio emission (magnetic activity) and HII regions (ionized structures). It is hoped that predictions will be available soon, but the sensitivity requirements are known: sub-mJy emission has to be detectable in a reasonable amount of time. If one takes single cluster survey observations, then in view of the number of sources expected longer exposures can be acceptable, with the corresponding increase in sensitivity: after all, if 0.4 mJy can be detected in 1 hr, in a week (12h/day, say, or ≈ 100h in all), then the sensitivity can reach ~ 0.04 mJy. So overall the prospects of YSO observations with LOFAR look certainly very promising.

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Solar science

Introduction to radio emission of the solar Corona

The solar corona is a hot ($T \approx 10^6 K$) fully ionized plasma. Its radio emissions can be both thermal and non thermal. Radio waves of frequency *f* can escape only if

$$f \geq f_p = \frac{1}{2\pi}\sqrt{\frac{n_e q^2}{\varepsilon_0 m_e}} = 9\sqrt{n_e}$$

where f_p is the local plasma frequency (MKS units). In the frequency range of LOFAR the plasma f_p is much larger than the gyromagnetic frequency

$$f_B = \frac{1}{2\pi}\frac{qB}{m_e} = 2.8\ 10^{10} B$$

(MKS units). It follows that most of non-thermal radio emissions occur at $f = f_p$ or $f = 2\,f_p$ through plasma emission. Gyro-synchrotron emission occurs also in some cases (such as for bursts associated with CMEs), also for $f > f_p$ since the lower part of their spectrum is suppressed by the Razin effect.

Given usual models for coronal electron density, the LOFAR frequency range corresponds roughly to the altitude range 0.2–1 Rs above the photosphere. Thus LOFAR is potentially interesting for imaging the solar corona in this altitude range. A key (and still unsolved) problem is that of producing fast non thermal electrons in the corona, particularly during flares. These electrons result in a variety of radio bursts and also in hard Xrays bursts at lower altitudes. We must note however that :

. According to existing spectral observations, the plasma frequency in the acceleration sites of these fast electrons lies usually in the range 0.5–1 GHz, which has never been imaged. Indeed dynamic spectra show often in this range simultaneous narrow bandwith ($\Delta f / f \leq 1$) radio emissions with positive and negative initial frequency drifts, which are interpreted as the signature of fast electron beams propagating respectively downward and upward from a common acceleration site. At lower frequencies (ie. higher altitudes) such fast drifting bursts always drift towards low frequencies, with the only exception of U-bursts, which are due to the bending by the magnetic field of electron streams initially propagating upward.

. It is difficult to relate precisely other energetic phenomena (such as Ha and hard X-rays brightening) observed at very low altitude with radio images of the corona at larger altitudes typical of LOFAR, because of complicated propagation effects.

What solar studies for LOFAR ?

Presently the Nançay Radioheliograph (NRH) produces images of the corona in the range 150 – 450 MHz, with resolution of ~ 1' of arc (depending on the frequency), and the Nobeyama Radioheliograph (NoRH) produces high resolution images at 17 and 34 GHz. It would be interesting to extend this frequency range, as will do the FASR project. Solar physicists put more emphasis on the decimetric range (1-2 GHz), but an extension toward low frequency may bring new insights in specific topics which are detailed below. Low frequency also means high altitudes in the corona, which may help to fill the gap between ground-based and spatial observations.

A) Dynamics of suprathermal particles and magnetic field topology

Radio observations are the diagnostic which is closest to the particles : radio waves directly result from the interaction of these particles with the medium, and originate from the site where particles are produced or exist. This makes a difference with other observations (EUV, soft XRays), more sensitive to the thermal properties of the medium. Hard XRays also produce a good diagnostic of energetic particles in flares, but they are emitted at very low altitudes, in the solar chromosphere.

Furthermore plasma emission at $f = f_p$ or $2 f_p$ gives exactly the electron density n_e in the emission region.

. during flares, electrons are accelerated (as previously said) in regions where ne is between 2.5 10^9 and 10^{10} cm-3, and they are subsequently guided along magnetic field lines. Drifting type III bursts are thus tracers of these lines and their degree of circular polarisation can be related (through theory) to the field itself. This is the only means of measuring B in the corona.

. electrons can also be accelerated to a few keV in the corona in the absence of flares. This results in long-lasting noise storms, both in meter and dam l range. The character of these storms changes at ~ 80 MHz (from type I to type III bursts). This change is probably related to the change in the magnetic topology, from closed to open, but it is still poorly studied and unserstood. Imaging at these frequencies with LOFAR would be helpful.

. "shock associated" fast drifting bursts are similar to fast drifting type III bursts, but they seem to originate from slow drifting type II bursts associated with shocks. They are typical of dam l range and have never been imaged.

B) Dynamics of CMEs, coronal shocks and associated type II bursts.

1) Radio imaging can reveal CMEs (Bastian et al., 2001 à préciser, Pick et al., 2005). Observations are possible on the disk, which is an advantage as compared to white light coronography since perspective effects are reduced or different :

. in the low corona (at high frequencies, up to 500 MHz,), they give insight on the initiation of CMEs.

. in the higher corona at lower frequencies, they give insight on the motion and evolution of CMEs.

The emision mechanism proposed in the reported cases is the gyrosynchrotron emission of fast electrons (up to 1 MeV). The spectrum over a wide frequency range (including fpeak) provides B and the maximum energy of electrons. The thermal emission ($\propto n_e^2$) should also be detectable (Bastian and Gary, 1997), and the spectrum over a wide frequency range (including both optically thin and thick cases) would give n_e. In both cases, a frequency coverage as wide as possible is desirable.

2) Type II bursts are slowly drifting bursts, observed below 150 MHz for most of them. Hence they have been poorly imaged. The velocities derived from their drift rate through a density model is about 10^3 km/sec. Hence they are usually ascribed to coronal shocks. They are always associated with flares and often (but not always) to (fast) CMEs. Their exact relationship with CMEs is still under discussion (White et al., 2006). Multifrequency imaging with LOFAR could give access to their trajectories and precise comparison with CMEs.

Solar radio imaging at low frequencies

The sun is a particular object, and we want to emphasize two specific aspects of interest for imaging it.

A) The theoretical resolution of LOFAR deduced from its size (~ 500 km) cannot be achieved for the sun.

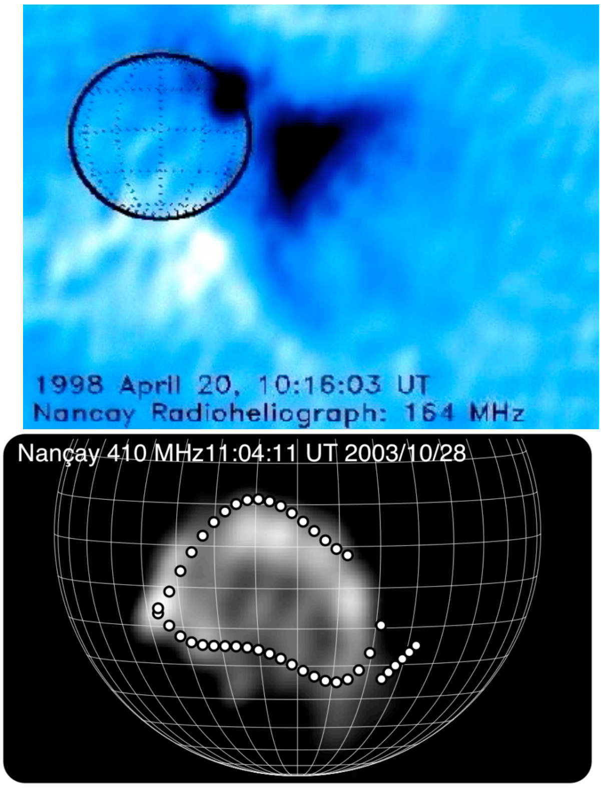

Figure 8: CME radio loops (Bastian et al, 2001)   and CME on the disk (Pick et al, 2005)

1) The solar corona and the solar wind are turbulent inhomogeneous plasmas and this affects affects the propagation of radio waves. Point sources (if any) should be broadened by irregular propagation.

. there are no reported sources < 40" of arc at 327 MHz. It should be pointed out that these results were obtained from observations with radiotelescopes with a potentially much lower spatial resolution (the VLA (Zlobec et al. (1992), and more recently from combination of NRH and GMRT (Mercier et al. (2006)). Solar sources are even larger at lower frequencies.

. using simples assumptions, Bastian (2004) deduces from solar wind measurements that:

- even for background (non solar) sources, the nominal resolution of LOFAR will be reached only at >90° from the Sun, because of scattering by inhomogenities in the solar wind,

- coronal point sources should have apparent sizes ~ 5-10' of arc at 100 MHz.

These predictions are in rough agreement with presently available observations.

2) The terrestrial ionsphere is denser and more perturbed during daytime, particularly in winter. The effects (apparent shifts and distorsion of images) are stronger at low elevations. Focussing effects were observed in Nançay at ~ 50 MHz (Mercier et al, 1989), that is the focal length of an ionospheric inhomogeneity is equal to its distance to the observer. The image is then totally destroyed.

Thus imaging the wide radio sun below 100 MHz will be a challenge. The practical spatial resolution for the sun will remain well below the LOFAR theoretical limit, and it is quite likely that below 150 or 100 MHz, the core of LOFAR alone, with a size of a few km (or possibly with the nearest remote stations), will be sufficient to reach this practical resolution. In particular, the use of far remote LOFAR stations in Nançay and other locations will be of no utility for improving the measurement of sizes or brightness temperatures of solar radio sources.

B) The sun can be a rapidly varying source, with time scales down to < 0.1 sec, which requires fast snapshot imaging. This should not be a problem for LOFAR. But the sun is also a wide source, especially when a CME occurs, and this requires short baselines. This constraint is strongest at the highest observing frequency, since the width of the radio sun increases less than λ (the scale height for n_e is << 1 Rs). Furthermore :

1) type III bursts and radio emission from CMEs at a given frequency can be produced at heights larger than expected from models for average electron density.

2) the quiet sun with angular width *w* has a complex visibility (FT of the brightness distribution) with a strong peak at the origin in uv plane, for spatial frequencies ≤ 1/*w*.

Hence most of the "energy" of the image is described by very low spatial frequencies, that is a relatively small number of baselines, which must be both large enough and accurately calibrated to produce an image with reliable large scale structures. From our experience of aperture synthesis images of the sun at 236 MHz with the NRH, it follows that correctly imaging the sun and CMEs requires baselines as short as 40 l (which corresponds to a maximum size of 1/40 radians (85' of arc) of the sun + CMEs), and that some redundancy is desirable. We thus conclude that properly imaging the quiet sun and CMEs at 240 MHz with LOFAR requires several baselines as short as 50 m, that is comparable to the size of the individual stations themselves. This raises the question of using sub-stations for getting such small baselines.

Tentative conclusion

Within the preceding conditions, LOFAR could usefully fill the gap between present ground and space solar radio observations (but with a spatial resolution well below the LOFAR nominal resolution) and bring significant advances in the above–mentionned subjects (and others …). We can tentatively propose a basis for a solar observational mode of LOFAR :

. only short baselines are needed (up to ~ 10 km ?), but with a dense uv coverage near the origin of the uv plane (sampling step < 40 λ) for proper quiet sun and CMEs (use of correlations between sub-stations ?)

. the time resolution should be better than 0.1 sec at 200 MHz,

. the instantaneous bandwith can be as large as ~ 100 kHz for most studies, since there are no radio emission lines,

. in a standard observational mode, several observing frequencies (at least 10) should be used, including ratios of 2 for studying fundamental/harmonic emissions.

Finally we must be aware that imaging the sun below 100 MHz could be difficult or even impossible for low elevations of the sun in winter.

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Radio emissions related to transient luminous events and gamma-ray flashes in the upper atmosphere of the Earth

Observations of Transient Luminous Events (TLEs) and Terrestrial Gamma ray Flashes (TGFs) have pointed out the existence of impulsive transfers of energy within the Earth's upper atmosphere. Among TLEs, sprites, jets and halos are attributed to mesospheric currents created by intense positive cloud-to-ground strokes, while elves are related to strong lightning EMP (Sentman et al., 1995; Lyons et al., 2003). Their duration is of the order of 1 to 300 milliseconds for sprites and hundreds of milliseconds for jets, much larger than the duration of single lightning emissions. There are a number of scenarios for explaining the mechanisms at the origin of sprites, but all involve the large cloud-to-ionosphere electrostatic field that develops following a discharge. For example, it has been suggested that the large cloud-to-ionosphere electrostatic field that develops following the largest positive cloud-to-ground lightning strokes is susceptible to breakdown by incident cosmic rays (in analogy to a Geiger-Muller tube), thereby producing runaway relativistic electrons that are responsible for the glow and secondary gamma ray emissions by bremsstrahlung processes (Roussel-Dupré and Gurevich, 1996). Alternately, Pasko et al. (1998) have suggested that sprites are associated with the spatially descending ionospheric currents that are generated in response to the large step-function electric field change from the underlying positive cloud-to-ground stroke. Immediately following a discharge, the ionosphere will respond to the new arrangement in cloud charge, but the response occurs at higher altitudes first (where the temporal relaxation, $\varepsilon_0/\Sigma(z)$, is fastest) and progressively descends in height over the course of milliseconds. In essence, the response is a descending current "plate" in the middle atmosphere. For very large underlying charge rearrangements (up to 300 C for positive cloud-to-ground strokes), the induced current response is so intense as to generate an associated Paschen glow that forms the sprite [Pasko et al, 1997, 1998].

TGFs detected in the Earth's atmosphere by the GRO (Gamma Ray Observatory) satellite [Fishman et al., 1994] and more recently by the satellite RHESSI (Smith et al., 2005) could be a manifestation of the runaway relativistic electrons. The spectrum measured by RHESSI reveals energies up to 30 MeV, in agreement with energies predicted by the runaway relativistic electron theory (Roussel Dupre, 2005). The analysis of the lower part of the TGF spectra suggest that there may exist two distinct sources with altitudes below 21 km and above 30 km. VLF ground based observations showed that the TGF parent lightning is characterized by weak charge moments indicating that the source is in or just above the thunderstorm (Cummer et al., 2005). Other measurements of very strong peak currents showed however that the lightning EMP could also be at the origin of TGFs (Inan et al., 2006).

Similar ground based observations related with TLEs have shown that Intense ELF (Extremely Low Frequency) radiation can be related to sprites. This may be due to their "slow discharge" nature leading to a spectral peak around 10-100 Hz followed by a steep decrease at higher frequencies (Farrell, 2000). But finer spatial and temporal sub-structure has also been observed for sprites (Gerken et al., 2002; Cummer et al., 2004), which could produce HF radio emission, difficult to detect due to propagation or directivity effects beaming the emission upwards. Also, the runaway electrons believed to be generated in the sprite/DC E-field process might also produce HF radio emission.

VHF broadband electromagnetic pulses, called TIPPs, were observed by the satellites ALEXIS [Holden et al., 1995] and Forté [Jacobson et al.,1999]. They are emissions in the range 20-300 MHz followed (10-100 microseconds later) by an echo on the ground. TIPPs are up to 10^4 times more powerful than ordinary lighting sferics [Desch et al., 2002], have a fixed-frequency duration of a few microseconds, and drift in the time-frequency plane over a total duration of tens to hundreds of microseconds (Jacobson et al., 1999). SIPPs are similar emissions observed from the ground at lower frequencies (between 3 and 30 MHz) probably after reflection by the ionosphere (Smith and Holden, 1996). TIPPs are related to narrow

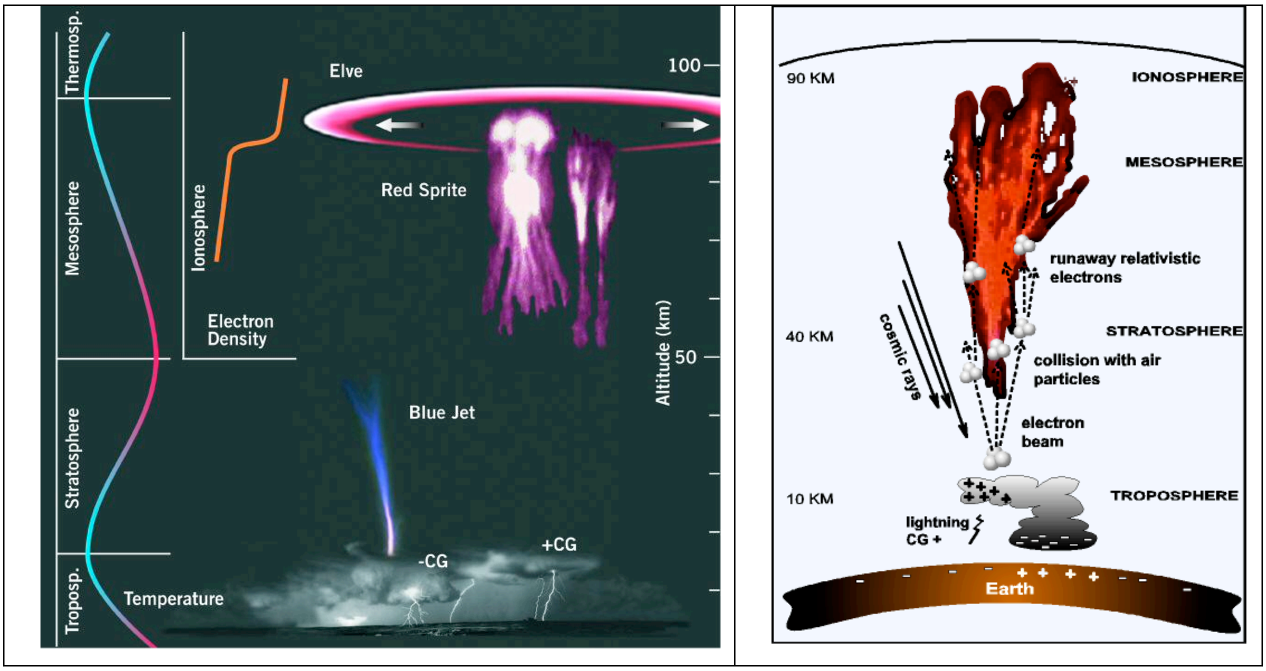

Figure 9: Sprites, jets, elves in the Earth's upper atmosphere (left) and representation of the processes implied in the runaway breakdown development.

positive bipolar pulses which are isolated discharges lasting few to tens of microseconds producing radio emission in the range 1-30 MHz (Tierney et al., 2005). A recent study has shown that energetic narrow bipolar events can be correlated with TGFs but this is not a general case (Stanley et al., 2006). Extensive air showers triggered by cosmic rays are invoked to show how narrow bipolar pulses might occur through runaway breakdown processes [Gurevich and Zybin, 2005].

To date, different observations show that the mechanisms are complex. TIPP/SIPP, TGFs and TLEs have never been observed simultaneously, but the large electrostatic fields that develop in sprite/gamma ray/radio emissions production make for possible causality. While on the one hand many of the details regarding the optical characteristics of sprites and elves are presumed known, fundamental issues regarding the association of TLEs, TGFs, lightning, associated radio emissions and the nature of the source of penetrating radiation itself remain a mystery.

LOFAR could provide important information in observing HF-VHF radio emissions related with TLEs and TGFs in complement with other planetary lightning observations (Zarka et al, 2004). LOFAR could provide new information in observing TIPPs/SIPPs over a large fraction of its frequency range (higher frequencies would correspond to reflection under the ionosphere at increasingly large angles and thus sources at increasing distances). LOFAR could also make new fundamental measurements regarding HF emission that could be correlated with ground based and spacecraft observations at various wavelengths (optical, X, Gamma) (Blanc et Lefeuvre, 2006). For example, National Lightning Detection Network could be used to identify potential sprite-producing lightning events and a determination of positive cloud-to-ground events, sprites, and TIPPs/SIPPs could be made. These processes may have a significant effect on the Earth's magnetosphere, in particular by modifying the source and loss terms of the radiation belts. Effects are also expected at the conjugate point of storm areas.

Sensitivity will probably not be an issue for measuring TIPPs/SIPPs with LOFAR , but very high temporal accuracy is required. It may be achieved through direct access to the waveform (instead of the spectrum) as recorded by LOFAR stations and virtual core during the occurrence of such events. In order to limit the volume of data to be transferred/stored, waveform information should be recorded at the various observing sites at the command of a trigger. An obvious trigger could be the detection of electromagnetic (e.g. optical) emission from the associated positive lightning discharge related to the sprite or TIPP/SIPP. High energy cosmic ray detection with LOFAR should have similar temporal requirements (Dallier et al., 2003).

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Planets

Planetary radioastronomy has a long tradition and a broad expertise in France, based on the Nançay Decameter Array, the Nançay Radio Telescope, and collaborations implying the intensive use of the Ukrainian (world's largest) Decameter Array UTR-2 [Lecacheux et al., 2004, and references therein]. These activities are still very active today. The planetary (and exoplanetary) objectives presently considered for LOFAR have been put forward by members of the French community, who take part in the reflections for an extended LOFAR [Vogt et al., 2006] and assume the leadership of the Planetary (and exoplanetary) Science Working Group of LOFAR's "Transients" Key Project [Braun et al., 2006].

The Low Frequency Array (LOFAR) could bring considerable advances in the field of planetary science [see Zarka, 2002, 2005, and references therein]. Planetary radio astronomy largely concerns plasma phenomena and thus low frequencies (LF - typically ≤100-200 MHz). We focus here on (i) the radio imaging of Jupiter's magnetosphere (Io torus and auroral regions) with arcsec and msec resolutions [Zarka, 2004, and references therein], (ii) the radio imaging of Jupiter's radiation belts at low frequencies with arcsec resolution [de Pater, 2004, and references therein], and (iii) the detection and study of solar system planetary lightning [Zarka et al., 2004, and references therein]. In the next section (XIII), we discuss the detection and monitoring of nonthermal radio emission from extrasolar planets' magnetospheres.

High latitude (auroral) magnetospheric emissions from Jupiter

An extended LOFAR offers the possibility to image with time resolution of a few milliseconds the sources of Jupiter's high latitude decametric radio emissions (≤40 MHz) which are due to the magnetosphere interaction with the solar wind and with the Galilean satellites, primarily Io (figures 10 & 11). Many spectral studies have been carried out from ground- and space-based instruments (figure 12), but imaging at low frequencies remains to be done. As explained in Zarka (2004), it will bring a wealth of fundamental information on Jupiter's high- latitude/mild energy (keV) electrons. If a resolution of 1" to 2" can be achieved at 30-40 MHz (requiring LOFAR baselines of up to 1000 km, i.e. remote stations in France, Germany, UK, etc.), then the observations could bring new information on the physics of the radio generation process (beaming angle of the radiation relative to the local magnetic field, as a function of frequency), on Jupiter's surface magnetic field (direct mapping of instantaneous cyclotron sources of highest frequency), on the Io-Jupiter electrodynamic interaction, as well as that with the other Galilean satellites (lead angles between the satellite flux tube and the radio emitting field line), and on the Io plasma torus (via measurements of Faraday rotation and diffraction fringes due to radio wave propagation through the torus). Fast imaging (at millisecond timescale) is made possible by the very high intensity of Jovian decametre bursts (up to several million Jansky as seen from the Earth), which could allow us to follow electron bunches and thus measure potential distributions along the Io flux tube [Hess et al. 2006]. Combined with observations at other wavelengths (radio, ultraviolet, infrared, X-ray) and addressing time variability, LOFAR's fast imaging capabilities should be of major interest for the study of Jupiter's magnetospheric structure and dynamics.

Highest possible angular resolution imaging is required at lowest possible frequencies below 40 MHz. Some objectives are doable with moderate (100-300 km) baselines (e.g. Faraday probing of Io's plasma torus), but most of them will require higher resolution (say ≤4") and

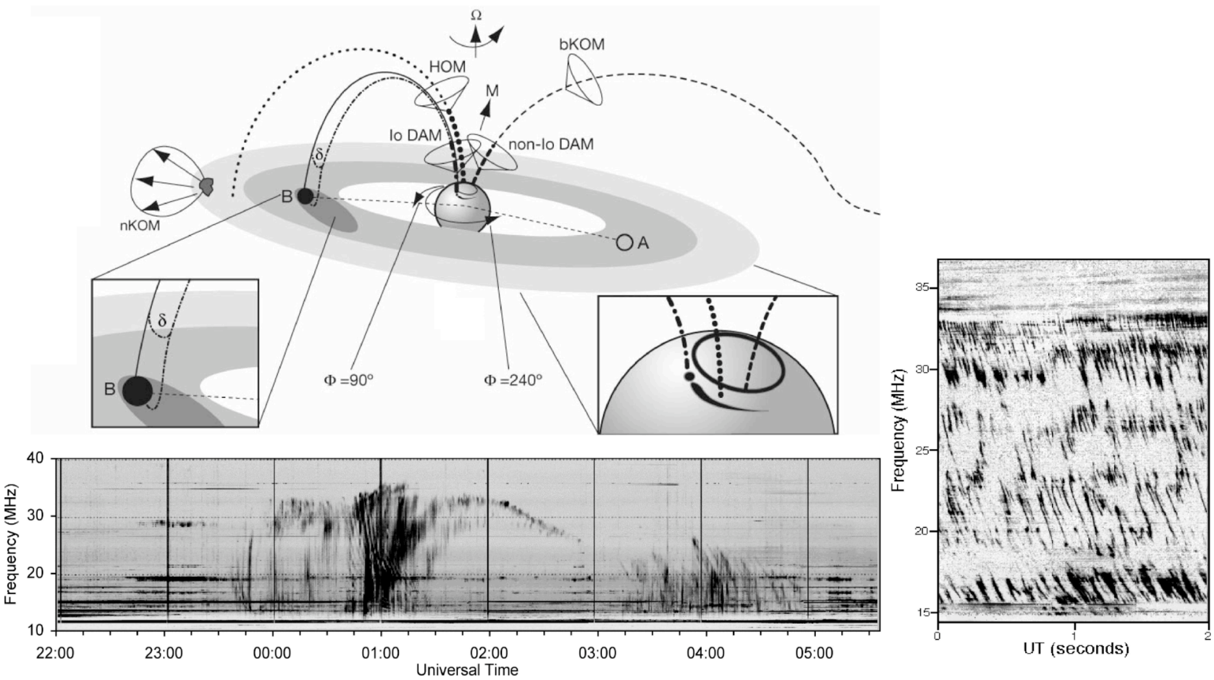

Figure 10: (Top left) Sketch of radio source locations in the Jovian magnetosphere. bKOM, HOM and DAM are auroral emissions generated near the local electron gyrofrequency fce and beamed in widely opened hollow cones aligned on magnetic field lines with various latitudes. These high-latitude emissions actually exist in both hemispheres. nKOM is emitted in Io's plasma torus. Left inset sketches the Io-Jupiter interaction through Alfvén waves, which results in strong radio emission (Io-DAM) detected when Io's phase is A or B. Right inset sketches the correspondance of radio sources with UV ones (main oval and Io's spots and trail). Only DAM emission is detectable from the ground. (Bottom left) Dynamic spectrum of a typical Io-DAM emission recorded on 1/1/1991 in Nançay, in right-hand circular polarization, with time resolution ~1 sec/spectrum. Horizontal lines are man-made interference, vertical lines are calibrations. (Bottom right) High resolution dynamic spectrum of Jovian short bursts recorded at Nançay using an Acousto-Optocal-Spectrograph, with resolution of 3 msec/spectrum.

thus extended baselines ≥500 km. Image or (u,v) cubes with 1 sec time resolution will be adapted to most objectives, except for short bursts due to electron bunches moving along Io's flux tube, for which series of images (or (u,v) maps) at millisecond time resolution are requested. Emission may be very intense, with bursts up to 10^{5}…^{6} Jy and dynamic range >20-30 dB. Full polarisation (4 Stokes parameters) is essential for identifying emission mode, for Faraday studies, etc.

Ability to do interferometry at ~700 km distance on a regular basis has been recently tested successfully (after early studies by [Dulk, 1970] and others) through VLBI-like observations of Jupiter between LOFAR-ITS and Nançay decametre array (see section XVII).

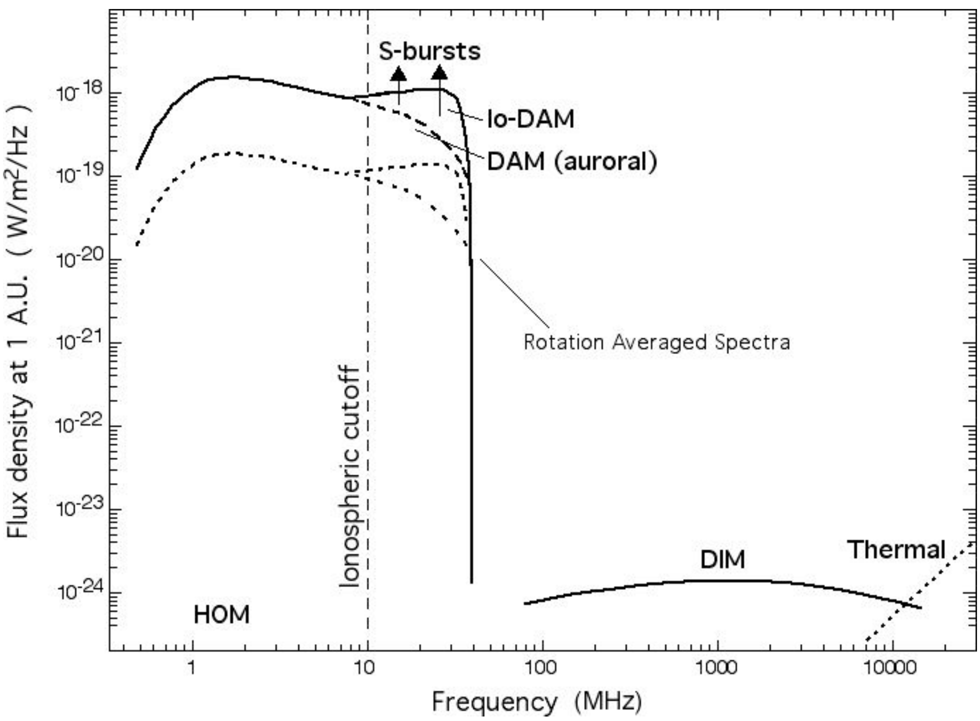

Figure 11: Spectra of Jovian radio components observable from the Earth's vicinity. « DIM' » represents the decimeter synchrotron emission from the radiation belts. DAM emission consists of the superposition of auroral-DAM (dashed), which extends down to the hecto-kilometer range, and Io-DAM (solid). Part of Io-DAM consists of impulsive bursts (S-bursts). The Earth's ionospheric cut-off lies on the average about 10 MHz. The sharp cut-off at 40 MHz corresponds to the maximum electron cyclotron frequency at the planetary surface. Dotted lines represent rotation-averaged spectra at times of intense activity (or equivalently typical averages over emission intervals). Solid/dashed lines represent peak intensities detected during active periods.

Jupiter's (and other planets) radiation belts

Jupiter's radiation belts power synchrotron emission over the meter-to-decimetre range. This radiation has already been imaged in the decimetre range by many ground-based instruments (figure 13), and historically has given the first information about Jupiter's quasi-dipolar magnetic field and energetic (MeV) electron populations in the inner magnetosphere [de Pater, 2004, and references therein]. High spatial resolution imaging below 300 MHz of the sources of such emission (and their time variability with planetary rotation and solar wind fluctuations) remains to be done. LOFAR will address this question over a large relative bandwidth, allowing us to study the origin, transport, scattering (by plasma waves, Coulomb scattering), and loss (through synchrotron emission or by interaction with dust) of high energy electrons in Jupiter's inner radiation belts.

No synchrotron emission has been detected from Saturn, due to the absorption of energetic particles by the rings [Van Allen and Grosskreutz, 1989]. A deep search for a weak radiation belt might be attempted. Bursts of energetic electrons were observed by the Mariner 10 mission in the magnetosphere of Mercury [Baker, 1986]. These might cause bursts of synchrotron emission (there was no radio instrument on Mariner 10 to confirm this).

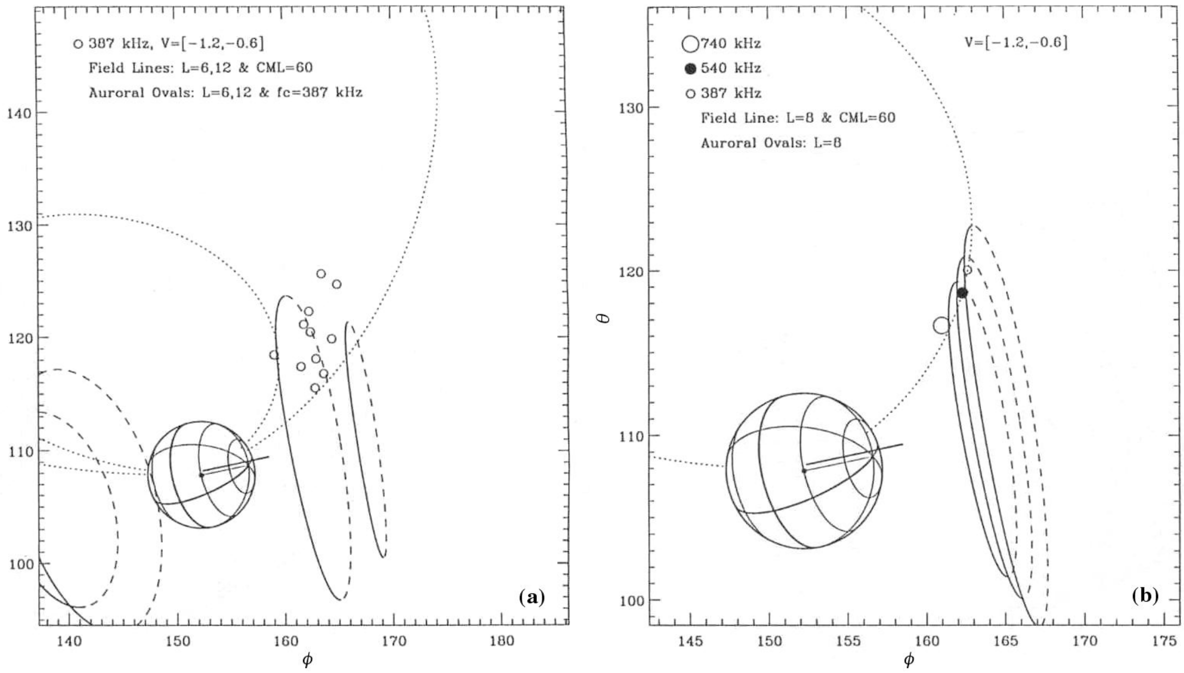

Figure 12 : Goniometric results from Ulysses near Jupiter on 1994/02/08, from 12 RJ (~106 km) from the planet. (a) The direction of the dominant hectometre RH circular source at 387 kHz measured during 12-sec intervals over a 35 minute-period is plotted as open dots in the frame of Ulysses radio antennas. Jupiter is represented with its rotation axis (lightface) and its magnetic axis (boldface) pointing to the North. Dotted lines are dipole magnetic field lines with apex at 6 and 12 RJ. Auroral ovals crossing these field lines at a local electron cyclotron frequency fce=387 kHz are solid/dashed lines (visible/hidden portion from Ulysses). (b) Average source directions over the same 35-min interval at 387, 540, and 740 kHz. The dotted dipolar field line with apex at 6 RJ crosses the 3 radio sources at the same point as the corresponding northern auroral ovals along which fce= 387, 540, and 740 kHz with increasing distance from the planet (solid/dashed). This measurement by Ladreiter et al. [1994] is the first direct proof that hectometre emission is produced at/near the local fce on the X mode (RH polarization from northern magnetic hemisphere). The geometry allows to deduce the 3D source location and radio beaming angle.

High angular resolution imaging will be required at selected frequencies between 50 and 240 MHz. The resolution offered by 100 km baselines is sufficient in LOFAR high-band, but extended baselines will be necessary ≤100 MHz. Image or (u,v) cubes with a few 10's of seconds time resolution are adapted. Intensity of emission is expected to be in the range 1-5 Jy. Full polarisation is needed (linear polarisation perpendicular to local B- eld expected).

For Saturn and Mercury's radiation belts and possible synchrotron emission, first observations should aim at detection only, and thus not require very high angular resolution. Lower frequencies than Jupiter's case should be observed (probably 10-30 MHz). In case of detection, then high resolution follow-up studies would be relevant.

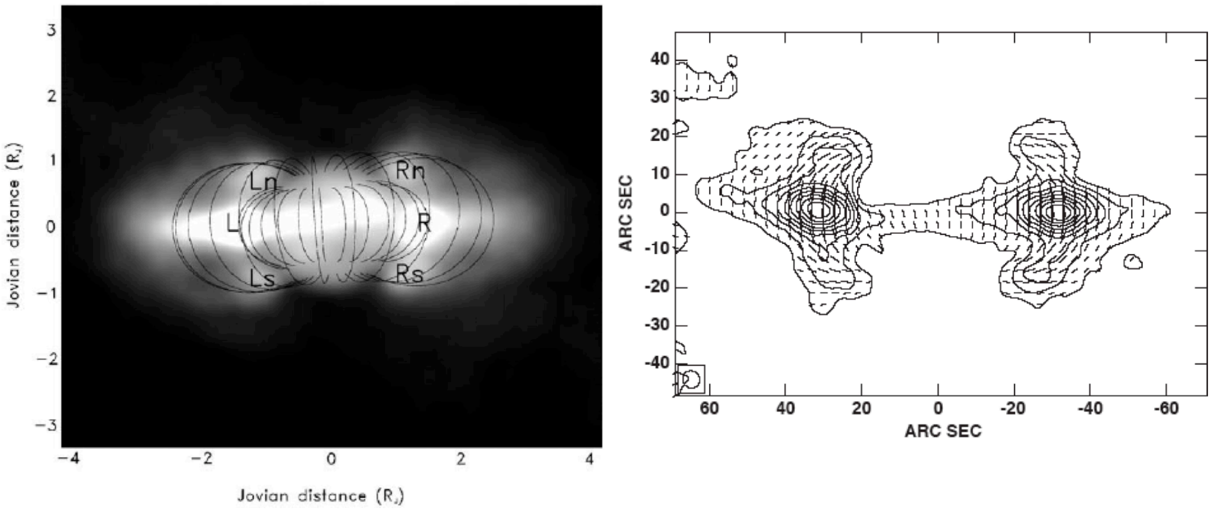

Figure 13: (Left) Radio image of Jupiter's decimetric emission at a wavelength of 20 cm, and a central meridian longitude of 312°, taken at the VLA in june 1994. The resolution is 0.3 RJ. The main radiation peaks are indicated by the letters L and R, and the high latitude emission peaks by Ln, Ls, Rn and Rs. Model magnetic field lines with apex at 1.5 and 2.5 RJ are superposed. Field lines are shown every 15°. (Right) Radio contour map of Jupiter's linearly polarized flux density at 15 GHz, averaged over the planet's rotation (the changing viewing aspect due to Jupiter's rotation was properly accounted for). Superposed are the electric vectors rotated by 90°, tracing out the planet's magnetic field as projected on the sky. The length of the vectors are proportional to the polarized flux density. Contours start at 4σ (1σ = 0.5 mJy/beam), and contour intervals are in steps of 3σ. The beam size (HPFW) is indicated in the lower left corner [from de Pater, 2004].

Solar system planetary lightning

Lightning is a transient, tortuous high-current electrostatic discharge resulting from macroscopic electric charge separation (by convection and gravitation combined), following small-scale particle electrification (via collisions and charge transfer). A large-scale electric field builds up, which may eventually lead to breakdown and ionise the intervening medium, causing a lightning stroke. A lightning discharge consists of many consecutive strokes and lasts typically 1-100 msec. It may have an important role in the atmospheric chemistry (production of non-equilibrium trace organic constituents, potentially important for biologicalprocesses). Electromagnetic signatures include optical, VLF and LF radio emissions.

Lightning on Saturn [Warwick et al., 1981] and Uranus [Zarka and Pedersen, 1986] have been discovered by the Voyager spacecraft (figure 14) and re-observed by Cassini. Their study has been proved to be possible using large ground-based instruments [Zarka et al. 2004, 2005], which may also be used to assess the existence of lightning in the thick atmosphere of Venus, in Martian dust clouds (dust devils), and on Neptune (marginal detection by Voyager). Tentative detections of Saturn's lightning have been carried out with decametres arrays in Ukraine and France, with a recent positive result [Konovalenko et al., 2006]. LOFAR will have powerful enough capabilities for systematic, long-term studies (figure 15).

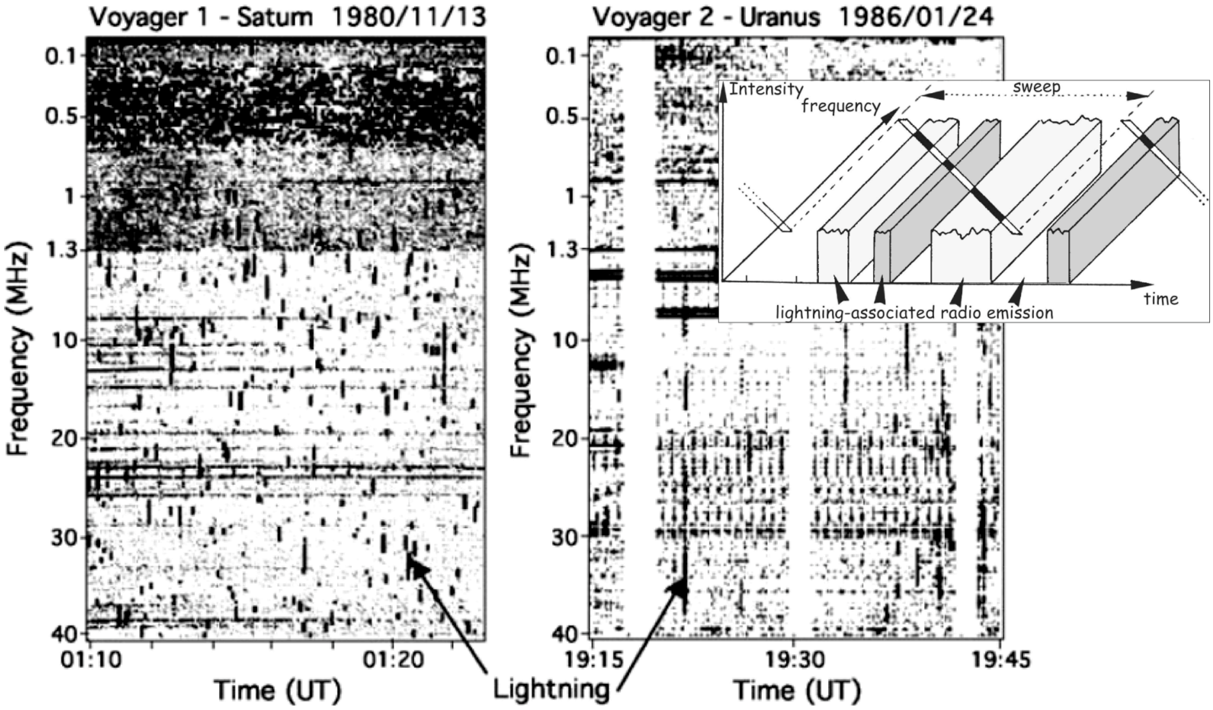

Figure 14: (Left) Dynamic spectrum of Saturn's lightning obtained during Voyager 1 fly-by ~1 hour after closest approach, from a range of 5 planetary radii (30000 km). The radio instrument onboard Voyager and Cassini are swept-frequency analyzers, thus detecting impulsive broadband phenomena as short streaks parallel to the frequency axis, randomly distributed over their whole spectrum (inset). (Right) Similar dynamic spectrum recorded ~1 hour after closest approach from Uranus. White areas are data gaps. Dark horizontal (and a few vertical) lines are spacecraft interference (in both panels).

Monitoring of planetary lightning (possibly in correlation with optical surveys) will allow the study of electrification processes (breakdown electric field build-up, which depends on atmospheric pressure, composition, electron density), atmospheric dynamics and cloud structure), of geographical and seasonal variations, and the comparison with the same processes on Earth.

High angular resolution imaging at 30-40 MHz and if possible at lower frequencies (down to 10 MHz) is required, because planetary diameters as seen from Earth are <1 arcmin. For the search of Martian discharges, frequencies of interest are in the whole LOFAR band (up to 240 MHz). Arcsec resolution (extended full array) is required to resolve the planetary disks, but lower resolution is enough at a first stage to confirm the planetary origin of the lightning bursts. Time resolution should be of the order of 1-100 msec (typical flash duration). Emission is intrinsically broadband. Expected fluxes are in the range 10 to 1000 Jy at Earth, depending on the target. Emissions are expected to be unpolarised (this can be checked through polarisation measurements). Lightning from exoplanets should be too weak to be detectable from the Earth.

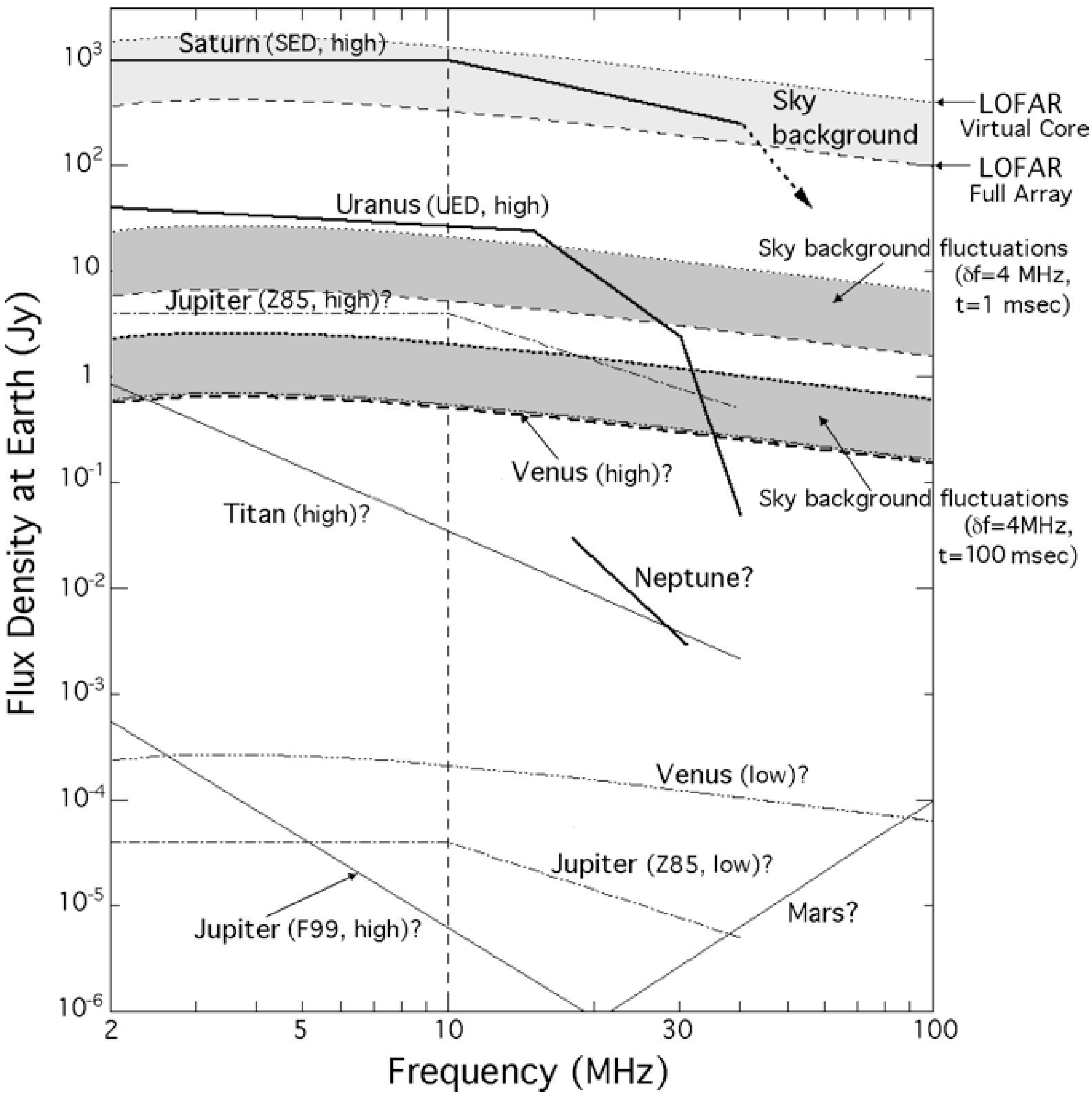

Figure 15 : Summary of planetary lightning spectra (observed or predicted) compared with expected LOFAR sensitivity. The light grey-shaded region is the sky background noise spectrum that will be detected by LOFAR, depending on the configuration used (virtual core only or full array). The darker grey-shaded regions characterize the noise background fluctuations that will define the sensitivity (1σ) of the observations with a bandwidth of 4 MHz and an integration time of 1 or 100 msec. Boldface planetary lightning spectra (for Saturn, Uranus, and Neptune) correspond to extrapolations of Voyager observations. Lightface lines represent upper limits or models of unobserved planetary lightning radio spectra. The range accessible to ground-based observation is at the right of the dashed line (ionospheric cutoff).

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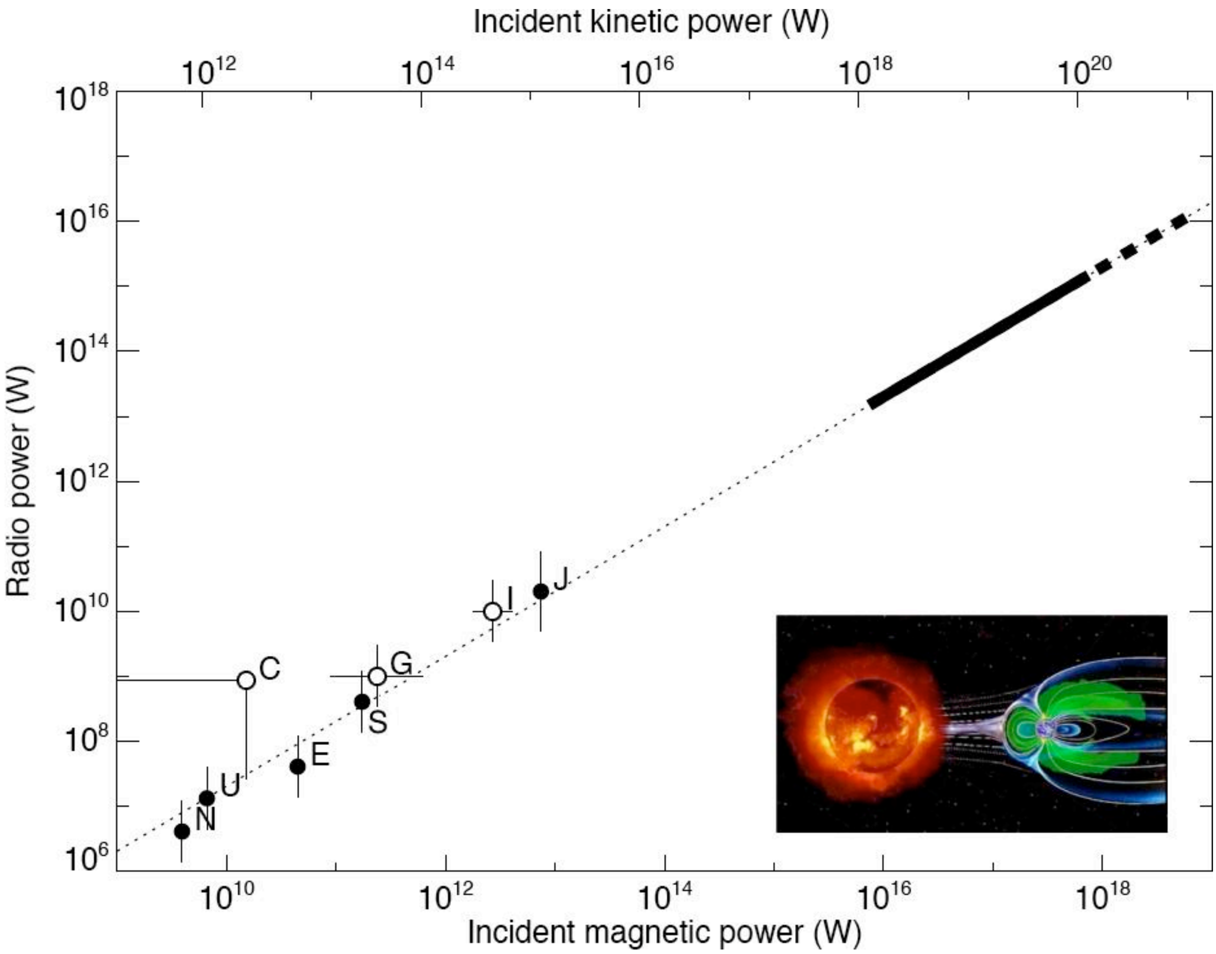

Figure 16: Scaling laws showing the proportionality (slope ~1) between output planetary radio powers and the solar wind power (kinetic - upper horizontal scale -, or magnetic - lower scale) incident on the magnetopause of the Earth (E), Jupiter (J), Saturn (S), Uranus (U) and Neptune (N) - sketched in the inset. Kinetic-to-radio efficiency is 10^{-5}, magnetic-to-radio efficiency is $\sim 2\times10^{-3}$. Open dots show the correlation between induced radio emissions from Io, Ganymede and an upper limit for Callisto, and dissipated magnetic power in the satellite-Jupiter interaction. The thick bar results from extrapolation to hot Jupiters of the solar wind-planet magnetospheric interaction (solid) and dipolar and unipolar star-planet interaction (dashed).

Exoplanets

The radio search for exoplanets is a very active and challenging field today, in which french researchers play an important role. Several theoretical/prediction papers have been published in the past few years, and many attempts to directly detect exoplanetary radio emissions are presently ongoing. LOFAR will certainly play a major role in the radio quest for exoplanetary signals, owing to its very high sensitivity. Observations are being prepared by the Planetary (and exoplanetary) Science Working Group of LOFAR's « Transients » Key Project [Braun et al., 2006], which has a french P.I.ship.

With Jupiter's decametric emissions being as intense as Solar ones, it is tempting to search for analogue non-thermal coherent emissions from the magnetosphere of exoplanets (Figures 16 & 17). However, due to the limitations imposed by the low frequency sky background fluctuations, man-made interference, and ionospheric fluctuations, only emissions at least 1000 times more intense than those of Jupiter have a chance of being detected at stellar distances (> several pc), even with LOFAR.

Theoretical studies have shown that the best candidates for intense radio emission are likely to be planets orbiting very close to their

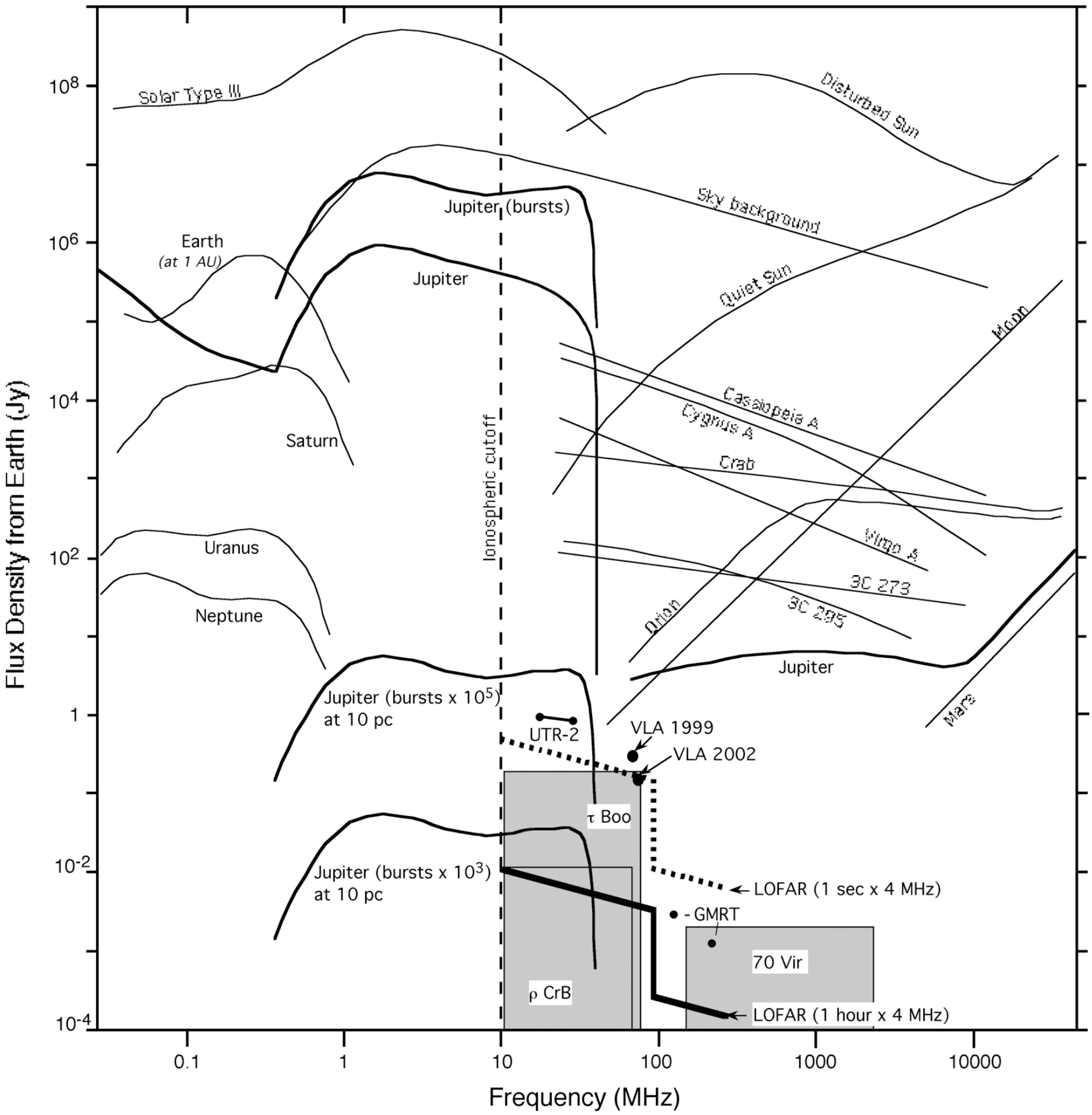

Figure 17 : Spectra of astronomical radiosources detected from the Earth's vicinity (1 Jansky = 1 Jy = 10-26 Wm-2Hz-1). Planetary spectra, corresponding to auroral radio emissions, are deduced from Voyager and Cassini measurements. Jupiter's average flux density is about 106 Jy, while peak flux densities reach or exceed 107 Jy during short-lived bursts. If all planetary emissions were normalized to the same observer distance of 1 AU, Jupiter's spectrum should be upscaled by ×20, Saturn's by ×100, Uranus' by ×400, and Neptune's by ×900, so that all are grouped within 2-3 orders of magnitude of each other. Jupiter's peak spectrum is reproduced with two different scalings to illustrate the possible radio spectrum of hot Jupiters. Shaded boxes are published predictions from a few candidate exoplanets. Sensitivities of UTR-2, VLA, GMRT and future LOFAR observations are indicated. The Earth's ionospheric cutoff is indicated at 10 MHz.

central star - the so-called « hot Jupiters » -, as well as planets orbiting strongly magnetized stars [Farrell et al., 1999 ; Zarka et al., 2001 ; Lazio et al., 2004 ; Cairns, 2004 ; Griessmeier et al., 2005 ;

Willes et al., 2005 ; Zarka, 2006]. Extensive predictions have been made concerning their detectability with LOFAR, and also suggestions about the optimal observing strategies to be adopted [Zarka et al., 1997 ; Farrell et al., 2004 ; Zarka, 2004 ; Ryabov et al., 2004]. The existence of star-planet plasma interaction is strongly suggested by the optical detection of a hot spot on the stars HD179949 and ν And [Shkolnik et al., 2005], supporting the possibility of intense radio emissions.

Direct radio detection of exoplanets could yield the first information about their magnetic fields (yielding constraints on scaling laws and internal structure models) and planetary rotation period, will allow comparative magnetospheric physics, and may possibly evolve towards a new type of discovery tool. In a more distant future, one may think of radio astrometric measurements of radio-exoplanets.

Some immediate objectives for this exciting area include : the (possibly first ?) direct extrasolar planet detection (planet-star distinction via polarization and periodicity) and follow-up studies ; derivation of the planetary rotation period ; magnetic field measurement, implying constraints on scaling laws and internal structure models; comparative magnetospheric physics ; the development of radio-exoplanet search tools.

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Technical Inputs

High angular resolution

Reaching ~1" angular resolution at 30-40 MHz would definitely have a major interest for many studies, including planetary ones. This requires LOFAR stations at up to 1000 km distance from the core, operating in (near real-time) VLBI mode. But this requires that ionospheric propagation does not destroy the phase coherency of LF waves recorded in remote stations via random, decorrelated phase fluctuations and jumps. Following early low-frequency VLBI experiments [e.g. Brown et al., 1968 ; Block et al., 1970 ; Dulk, 1970 ; Lynch et al., 1972 ; Hartas et al., 1983 ; Phillips et al., 1988] new observations have been performed in 2005 between the Nançay Decameter Array (NDA) and LOFAR's Initial Test Station (ITS), with a procedure very close to the future VLBI observations that will be carried out between remote stations and LOFAR's core. The two sites were separated by ~700 km, and waveform recording was done in baseband (direct digitization of the 0-40 MHz band at 80 Msamples/second with 12 bit resolution). The radiosource used was Jupiter, at a time when intense impulsive radio bursts were emitted in the 20-25 MHz range, i.e. an intense point-like source. Several seconds were recorded simultaneously. Processing included beamforming (analog at NDA, digital at ITS), synchronization of data (via cross-correlation of emission fine structures in dynamic spectra), digital filtering, and cross-correlation of filtered waveforms within various time-frequency windows.

High correlation coefficients (>0.5) were obtained for intense bursts and windows of 2.5 to 25 msec × 150 kHz (figure 18). A variable delay associated to Earth rotation and ionospheric fluctuations (and perhaps instrument drift) was measured over a few seconds of observation (figure 19). The work demonstrated the feasibility of phase interferometry at ~700 km distance at ~22 MHz (~60000 λ), confirming earlier studies, and proving that phase shifts and variations introduced by ionospheric propagation do not destroy phase coherency between NDA and ITS over 10's to 100's msec. It was the first time that VLBI-type observations were performed over a broad relative bandwidth with baseband digitization, digital filtering, and direct correlation over the 12- or 14- bit signals. Publications associated to this work are [Nigl et al., 2006a,b]. The above results support the european extension of LOFAR to baselines of several 100s km, and in particular LOFAR station in France, among which one station in Nançay.

In addition, we propose to implement at least one « super-station » LOFAR in France (and perhaps in other European countries). A standard LOFAR station consists of 96 antennas (in the low-band) or groups of antennas (in high-band) connected to a back-end with 96 inputs, which ensures digitization, processing and transfer of the recorded data. We define a « super-station » as a standard LOFAR station where we can choose to switch the back-end from the standard antennas to larger groups of antennas. For example, we can have 96 subgroups of 8 or 16 low-band dipoles to connect to the back-end instead of the 96 individual dipoles. Analog beamforming is performed within each subgroup in order to have the same number of inputs to the back-end and the same output data rate. The antennas thus synthesized will have a smaller field of view but a 8 to 16 times larger sensitivity. The super-station can thus be used as a standard LOFAR station (when connected to standard antennas) of as a super-station with high sensitivity (almost comparable to that of LOFAR's virtual core) in specific observing modes. In the latter case, which could for example be used when the ionosphere is

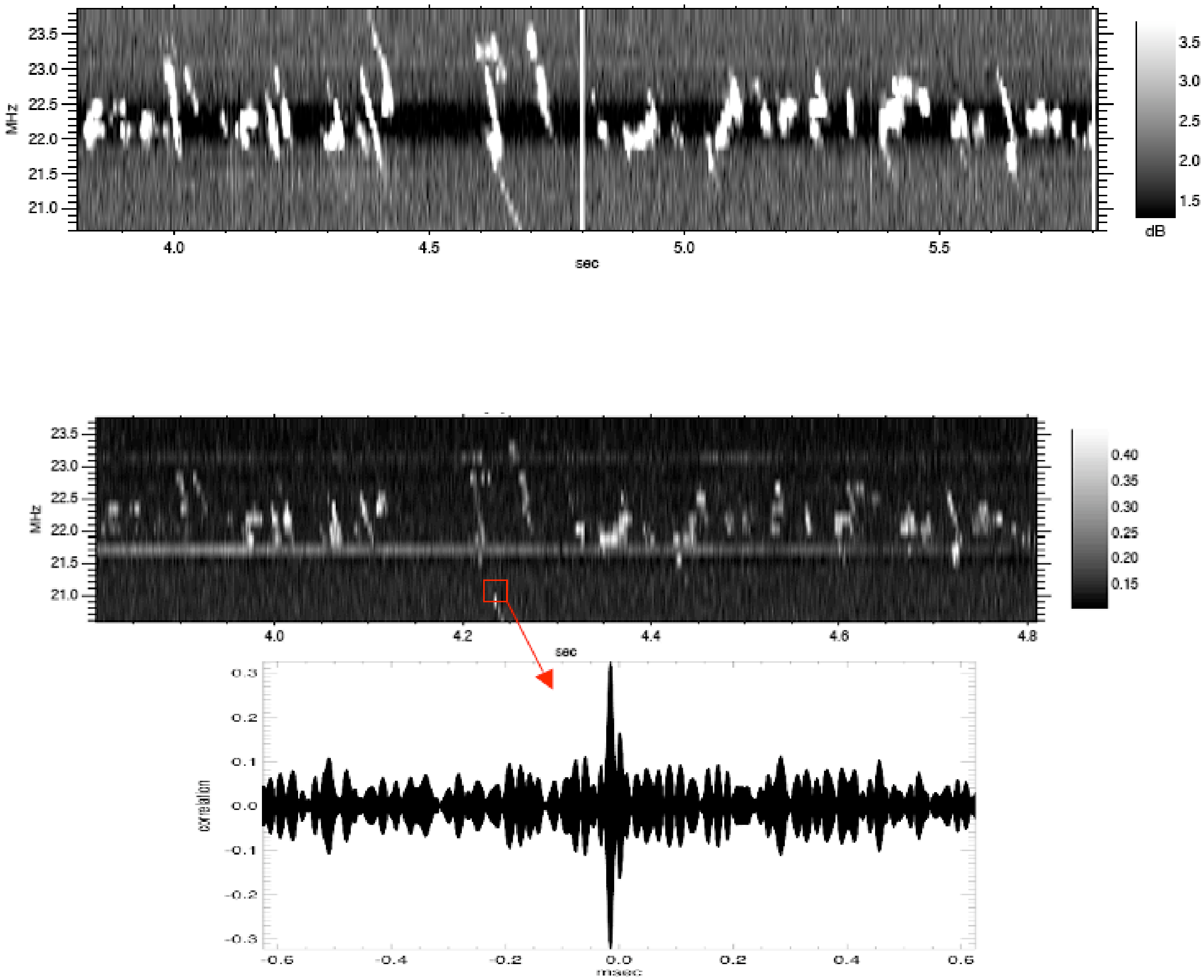

Figure 18: (Top) Dynamic spectrum of Jovian radio bursts recordet at NDA (a backgroung has been subtracted and the dynamic range saturated to see better the Jovian bursts, whose level is in dB above the background). (Middle) Cross-correlation coefficients NDA-ITS computed aver 2.5 msec × 150 kHz samples. (Bottom) Zoom on a particular sample , for which the cross-correlation coefficient is displayed as a function of NDA-ITS time delay.

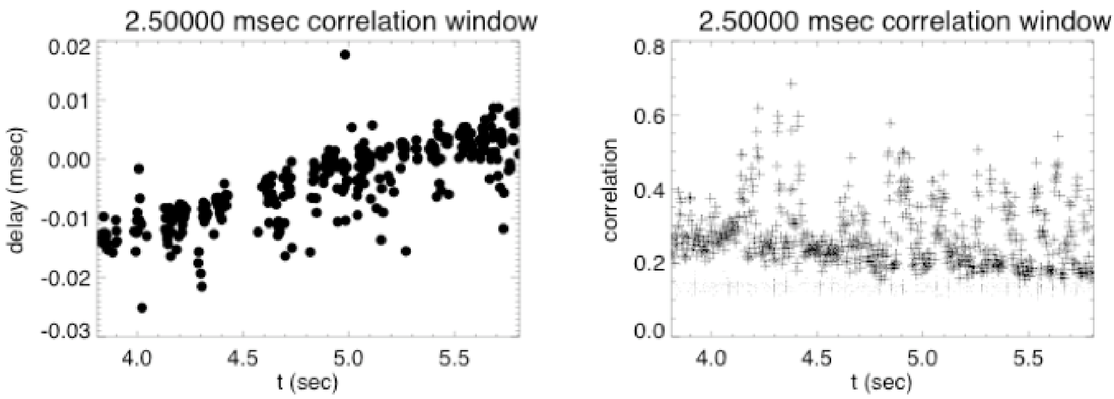

Figure 19: (Right) Variations of the cross-correlation coefficient versus the time for 2.5 msec× 150 kHz samples. Maximum values for each time interval is emphasized (+). (Left) Time delay versus time for every column of figure 18 (middle). The delay measured for the sample with maximum correlation in each column is retained. A ~20 μsec variation is observed during the 2 sec of the observation, which must be attributed to the variation of light travel time difference from the source to each radiotelescope plus possible additional differential delay introduced by propagation through the ionosphere, and instrumental drift.

too much disturbed for phase interferometry, correlation post-detection can be done between the super-station and the virtual core, ensuring a better immunity to interference and allowing to confirm the detection of very weak sources. One interest is that the cost of low-band antennas is weak compared to the total cost of a LOFAR station.

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Lofar-Moon

The spectral domain below ~10 MHz is not aaccessible to ground-bsed radiotelescopes because the terrestrial ionosphere reflects towards space radiation with frequency lower than the peak ionospheric plasma frequency, typically 10 MHz. Radio observations at lower frequencies are performed by instruments onboard satellites of spacecraft, generally using electrical monopole or dipole antennas as sensors. Such antennas, short compared to the radio wavelength (λ) at low frequencies, have a low effective area, of the order of A~λ2/8 m2. The sensitivity of space-borne low-frequency radio experiments is thus very poor. The main limitation to sensitivity comes from the galactic radio background (more precisely its statistical fluctuations), which equivalent temperature is ~104 to 106 K in the range 30 - 1 MHz [Dulk et al., 2001]. Embarked radio experiments also have a very poor angular resolution (no better than a few 10's°), except interferometric measurements (which require flight in formation), or goniopolarimetric measurements (implying the correlation of signals received by several antennas on a spinning or 3-axes stabilized spacecraft). Finally, low-frequency spacecraft measurements are polluted by various radiations of terrestrial (lightning discharges, artificial emitters, auroral kilometric radiation ≤800 kHz) and solar (radio bursts) origin.

The Moon presents several attractive characteristics for installing a low frequency radio interferometer : its ionosphere is very tenuous, especially during the night (cutoff frequency ≤200-500 kHz – also at 200 kHz, the sky background is ~2 orders of magnitude less than at 1 MHz [Manning and Dulk, 2001]) ; the Moon is also an efficient shield against radio emissions from the Earth (on the far side) or the Sun (during the night) ; it is a stable base to install the antennas making the interferometer, whose baselines must be known accurately. Although the true interest of such a Moon-based low-frequency array for astronomical observations (planetary and exoplanetary radio emissions, cosmological background or signature of reionization, interplanetary/interstellar propagation, etc.) appears only with an effective area corresponding to at least a few tens of dipolar antennas, proposals of small prototypes are already on their way to space agencies. They will allow to address the technical questions to be solved before successful operation (antenna positioning, communication/data flow, energy source …) and to characterize the radioelectrical environment due to the lunar wake in the solar wind.

The experience gathered from LOFAR development and operation will obviously be crucial for lunar-based radio observations, as a number of common problems are addressed : digitizing many antennas, transporting large data streams, recombining the signals in real time, etc. It is thus equally crucial to take an active part to LOFAR in order to be on the track for the future LOFAR-on-the-Moon projects.

Several workshops have already taken place in Europe (and in the USA) with active French participation (e.g. Exoplanets and Solar System Science at Low Radio Frequencies, DGLR International Symposium "To Moon and beyond", Bremen, Germany, 15-16/09/2005, published on CD-Rom – see also www.beyondmoon.de).

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