PLANETARY LOW-FREQUENCY RADIO ASTRONOMY WITH LARGE GROUND-BASED INSTRUMENTS

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ABSTRACT

Existing (UTR-2, GMRT, VLA, Nançay Decameter Array) and emerging (LOFAR) large low-frequency radio instruments start providing unprecedented capabilities in terms of sensitivity, angular resolution, polarization measurements, or all together, opening new perspectives for planetary studies, among which the detection and study of solar system planetary lightning, the fast radio imaging of Jupiter's magnetosphere, including synchrotron emission from radiation belts as well as decameter emission from high magnetic latitudes, and the search for radio emission from the plasma environment of exoplanets. Science objectives, recent results and ongoing programs are summarized here. RFI mitigation techniques now allow to work - to some extent - in the heavily polluted low-frequency radio environment of the Earth. Ionospheric propagation effects bring strong perturbations to both the amplitude and phase of received signals, especially near solar maximum. Feasibility of VLBI observations below 40 MHz is discussed.

INTRODUCTION

Planetary radio astronomy largely concerns plasma phenomena and thus low frequencies (typically ≤100 MHz). Here we briefly recall the main characteristics of some large ground-based instruments used for planetary LF Radioastronomy, and then we discuss planetary studies topics. The instrument list considered here (UTR-2, GMRT, VLA, Nançay Decameter Array, and LOFAR) is not exhaustive, but we included modest-size instruments whose modern receiving systems grant nevertheless with powerful capabilities. Planetary studies addressed include : Solar system planetary lightning, radio imaging of Jupiter’s radiation belts, fast radio imaging of Jupiter’s high latitude cyclotron emissions (including waveform capture and automated recognition methods for isolating and studying bursts with sub-millisecond durations), and search for radio emissions from the plasma environment of exoplanets. For each topic we discuss objectives, recent results, and ongoing programs. For the latter one, we also address RFI mitigation techniques, weak signal detection algorithms, new receivers and observation methods, and ionospheric effects. Present attemps of evaluating the feasibility of VLBI observations at frequencies below 40 MHz on a regular basis are mentioned.

Table 1. Characteristics of large ground-based instruments used for planetary LF Radioastronomy and exoplanet search

Instrument Name, Location, and References	Description	Frequency range (MHz)	Effective area (m^2)	Beam	Polarisation	Maximum effective sensitivity (Jy)
NDA (Nançay Decameter Array), France [1,14]	2×72 helix-spiral antennas (rectangular arrays)	10 - 100	~2 × 4000	~ 6° × 10°	2 circular → 4 Stokes	$\sim 10^2$
VLA (Very Large Array), New Mexico, USA [5,11]	Interferometer : 27 parabolas × 25m ∅ (Y-shape array)	74 (±0.75), 330, …	13250	≥ 0.4'	2 polar.	$10^{-1/-2}$
GMRT (Giant Meterwave Radio Telescope), Pune, India [21]	30 parabolas × 45m ∅ (core + Y-shape array)	50, 153, 233, …	~47000	0.25' - 1'	4 Stokes	$10^{-2/-3}$
UTR-2, Kharkov, Ukraine [2,12]	2040 dipoles (T-shape array)	7 - 35	~150000 (NS: 1800×60, EW: 900×60)	~30' × 10°	1 linear polar. (EW)	≤10
LOFAR (Low Frequency Array), The Netherlands [10,22,23]	Interferometer of phased arrays of dipoles (core + stations up to 400 km)	10 - 240	$\sim 10^6 \times (15/\nu)^2$	1.5" $\times(100/\nu)$ [ν in MHz]	4 Stokes	$\leq 10^{-3}$

INSTRUMENT CHARACTERISTICS

Table 1 lists the main characteristics of the instruments considered here. At these LF, all are phased arrays or interferometers. Phased arrays allow to derive absolute fluxes. Frequency ranges are covered fully (Nançay, UTR-2), in parts (LOFAR, using 4-MHz bands), or only as discrete narrow bands (VLA, GMRT). Beam sizes depend on the configuration of the array and sensitivity on integration time and channel bandwidth, so that only typical representative numbers are given. Details can be found in the papers cited in reference. By using modern digital receivers and real-time RFI-mitigation techniques, modest-size instruments as the Nançay Decameter array (NDA) nevertheless achieve powerful observation capabilities. LOFAR, which should start operations around 2007, will include such built-in RFI mitigation capabilities as well as ionospheric propagation effects, which will grant it with unprecedented capabilities.

PLANETARY STUDIES : OBJECTIVES, RECENT RESULTS, ONGOING PROGRAMS

Solar system planetary lightning

The study of lightning on Saturn and perhaps Uranus has been proved to be possible using large ground-based instruments [30,35], which may also be used to assess the existence of lightning in Venus thick atmosphere, in Martian dust clouds, and on Neptune. Tentative detections of Saturn's lightning have been carried out with UTR-2 [32] and the NDA [36] with encouraging but yet non-conclusive results. But LOFAR will definitely have powerful enough capabilities to settle the matter [35]. Monitoring of planetary lightning will allow to study electrification processes, atmospheric dynamics, composition, geographical and seasonal variations, comparatively to the Earth's case.

Radio imaging of Jupiter's radiation belts

Jupiter radiation belts power synchrotron emission over the meter-to-decimeter range. This radiation is already imaged in the decimeter range by many ground-based instruments, and has given the first historical informations about Jupiter's quasi-dipolar magnetic field and energetic (MeV) electron populations in the inner magnetosphere. Imaging of its sources below 300 MHz (and their time variability) remains to be done. LOFAR, together with the VLA and GMRT, will address this question, allowing to study the origin, transport, scattering (by plasma waves), and loss (synchrotron or by interaction with dust) of high energy electrons in Jupiter's inner radiation belts [6 and references therein].

Fast radio imaging of Jupiter's high latitude cyclotron emissions

More original is the possibility offered by LOFAR to image at a few millisecond rate the sources of Jupiter's decametric radio emissions (≤40 MHz), due to the magnetosphere interaction with the solar wind and with the galilean satellites, primarily Io [27,30,34]. Many spectral studies have been carried out from ground- and space-based instruments, but imaging at LF remains to be done. As explained in [34], it will bring a wealth of fundamental information on Jupiter's high-latitude/mild energy (keV) electrons. If a resolution of 1-2" can be achieved at 30-40 MHz (requiring LOFAR stations at up to 1000 km distance – see below), then the observations could even bring new information on Jupiter's magnetic field, the Io-Jupiter electrodynamic interaction, and the plasma torus. Correlation with observations at other wavelengths (UV and IR) will be of major intererest. For Jupiter's high latitude emissions, fast imaging is made possible by the very high intensity of Jovian decameter bursts, up to several million Jansky as seen from the Earth. In parallel to future fast imaging, waveform capture and automated recognition methods have been implemented on existing LF instruments (NDA, UTR-2) for isolating and studying bursts with sub-millisecond durations [4]. Previous high resolution studies used semi-analog receivers as Acousto-Optical spectrographs [16], giving access to resolutions ~3 msec/spectrum, while more recent studies rely upon fully digital receivers with embarked real-time processing capabilities [17,24,25].

Radio emission from the plasma environment of exoplanets

With Jupiter's decametric emissions being as intense as Solar ones, it is tempting to search for analog non-thermal coherent emissions from the magnetosphere of exoplanets. However, due to the limitations imposed by the LF sky background fluctuations, man-made interference, and ionospheric fluctuations, only emissions at least 1000 times more intense than Jupiter's ones have a chance to be detectable at stellar distances (several pc), even with LOFAR [33]. Work on the subject has started less than 10 years ago. It consists of (i) theoretical estimates of the best candidates (found to be "hot jupiters", i.e. giant planets very close to their central star) [3,7,13,28,33], and (ii) observational searches using the VLA at 74 MHz [9,13], the GMRT at ~150 MHz [26], and UTR-2 below 32 MHz [18,19,32]. Extensive predictions have been made about their detectability with LOFAR, and optimal strategies of observation to be adopted [8,30]. Existence of star-planet plasma interaction is strongly suggested by detection of a hot spot on the star HD179949 in the visible [20], supporting the possibility of intense radio emissions [28].

LIMITATIONS : RADIO FREQUENCY INTERFERENCE AND IONOSPHERE

For detection of weak emissions such as from radio-exoplanets in a polluted radio frequency environment, as it is the case al LF, powerful RFI mitigation techniques have to be implemented [18]. Specific observation procedures taking advantage of the multi-beam capabilities of antenna arrays have been used [32], and specific algorithms created for the detection of weak signals [19,29,32]. In parallel, ongoing progress on digital receivers and built-in RFI mitigation methods improve our capacity to work in a polluted RF environment [24,25]. Extensive analysis of observations of candidate radio-exoplanets (hot jupiters) performed at UTR-2 between 1999 and 2002 have shown that RFI may be efficiently reduced/eliminated by post-processing [19,29,32], but that the ionospheric fluctuations near solar maximum activity are a major perturbation, generating ghost emissions by scintillation of remote radio sources through the ionosphere. It is thus crucial to perform such observations requiring very high sensitivity at solar minimum (the next one is in 2006-2007, thus prior to LOFAR start of operations).

TOWARDS LOW FREQUENCY VLBI …

Finally, reaching ~1" angular resolution at 30-40 MHz would defnitely have a major interest for planetary studies. As explained above, this requires LOFAR stations at up to 1000 km distance from the core, operating in (near real-time) VLBI mode. Tests are presently performed in Ukraine [14] and between NDA and the first LOFAR initial test station (ITS – see Fig. 1) [15] in order to assess the possibility to work in interferometric mode on a regular basis at ~1000 km distance. If successful, these studies would provide a strong argument in favour of LOFAR extension stations in the surrounding European countries.

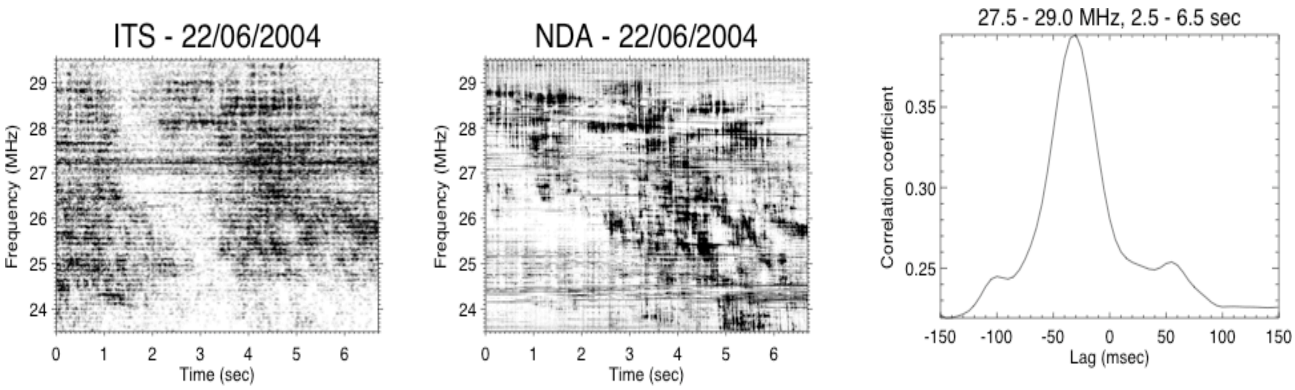

Fig. 1. Simultaneous observation of Jupiter's bursts at LOFAR/ITS and NDA, and temporal cross-correlation.

CONCLUSION

LF ground-based radioastronomy offers promising possibilities for planetary studies in our solar system as well as for the search for radio-exoplanets. The latter is definitely a major goal of future LF radioastronomy, from the ground as well as from space-based interferometers, and hopefully from a Moon-based LOFAR-like instrument in a not too distant future [31].

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