LOFAR: A Powerful Tool for Pulsar Studies

B. W. Stappers\textsuperscript{1}, A. G. J. van Leeuwen\textsuperscript{2}, M. Kramer\textsuperscript{3}, D. Stinebring\textsuperscript{4}, J. Hessels\textsuperscript{5}

\textsuperscript{1} Stichting ASTRON, Postbus 2, 7990 AA Dwingeloo, The Netherlands
\textsuperscript{2} Department of Physics and Astronomy, University of British Columbia, 6224 Agricultural Road, Vancouver, BC V6T 1Z1, Canada.
\textsuperscript{3} University of Manchester, Jodrell Bank Observatory, Macclesfield, Cheshire SK11 9DL, UK.
\textsuperscript{4} Department of Physics and Astronomy, Oberlin College, Oberlin, OH 44074
\textsuperscript{5} Department of Physics, McGill University, Montreal, QC H3A 2T8, Canada.

Abstract. The LOW Frequency ARray, LOFAR, will have the sensitivity, bandwidth, frequency range and processing power to revolutionise low-frequency pulsar studies. We present results of simulations that indicate that a LOFAR survey will find approximately 1500 new pulsars. These new pulsars will give us a much better understanding of the low end of the luminosity function and thus allow for a much more precise estimate of the true total local pulsar population. The survey will also be very sensitive to the ultra-steep spectrum pulsars, RRATs, and the pulsed radio emission from objects like Geminga and AXPs. We will also show that by enabling us to observe single pulses from hundreds of pulsars, including many millisecond pulsars, LOFAR opens up new possibilities for the study of emission physics.

Table 1. LOFAR Sensitivity for Pulsar observations\textsuperscript{a}

| Frequency (MHz) | Sensitivity (mJy) | BeamSize |
|-----------------|-------------------|----------|
| 30              | 0.48              | 21'      |
| 75              | 0.33              | 8.3'     |
| 120             | 0.017             | 5.2'     |
| 200             | 0.015             | 3.1'     |

\textsuperscript{a} Integration times of 1 h, 2 polarisations, 32 MHz of bandwidth, 10% duty cycle and only using the LOFAR core.

1. Introduction

LOFAR will provide a low frequency radio telescope concentrated in the Netherlands with extensions into other European countries. It consists of a core, an extended array and a long baseline component which will have maximum baselines of 2 km, 100 km and \textasciitilde1000 km respectively. It will operate in the frequency range of 30 – 240 MHz which will be split into two bands, the low band (optimised for 30–80 MHz) and the high band (optimised for 115–240 MHz). Bandwidths of either 100 or 80 MHz will be digitised with 12-bit resolution and it will be possible to select a total of 32 MHz of bandwidth to be processed. There will be a total of 7700 low-band antennae and 7700 high-band tiles where each tile is made up of a grid of 16 antennae. The antennae and tiles will be divided up into a total of 77 stations. In the core there will be 32 stations and the remaining 45 will be arranged in a logarithmic spiral-like distribution outside of the core. All the antennae in a station will be combined to form a so-called station beam and it will be possible to exchange bandwidth for beams. For example one could decide to have 8 station beams (each with an independent look direction within the field of view of the antenna or tile) each of 4 MHz of bandwidth. This multibeaming capability allows for extremely wide fields of view to be monitored and/or it allows for multiple experiments to be carried out simultaneously. Estimates of the LOFAR sensitivity for pulsar observations using the core are given in Table 1 and more information about LOFAR in general can be found at www.lofar.org

2. Pulsar Survey:

Pulsars are steep spectrum objects whose pulsed flux density usually peaks in the 100-200 MHz range (e.g. Malofeev et al. 1994). As LOFAR will have unprecedented sensitivity in exactly this frequency range this makes it an excellent instrument for carrying out an all-sky pulsar survey. How many pulsars LOFAR will discover depends on the low end of the pulsar luminosity function. There are indications that the luminosity function turns over in the range 0.3-1 mJy kpc\textsuperscript{2} (Lyne et al. 1998) however it is likely that surveys have so far been incomplete already at the 10 mJy kpc\textsuperscript{2} level. LOFAR will be able to measure the low-end of the pulsar luminosity function significantly better than any previous survey allowing, for the first time, a much more precise estimate of the true total local pulsar population.
The apparent detection of a few neutron stars including Anomalous X-ray Pulsars and Magnetars only at frequencies near or below 100 MHz (e.g. Malofeev et al 2005, Kuzmin & Losovsky 1997, Malofeev & Malov 1997, Shitov & Pugachev 1997), the existence of pulsars like B0943+10, which have flux density spectra with a spectral index steeper than -3.0 [Deshpande & Radhakrishman 1994] and millisecond pulsars which have steep spectra which do not show a turn-over even at frequencies as low as 30 MHz (e.g. Navarro et al. 1995), suggest that a large number of pulsars is detectable only at low frequencies. Moreover, the radio beam of pulsars is known to broaden at low frequencies, increasing the illuminated sky and hence the detection probability at Earth. Indeed, the non-detection of Geminga at cm-radio wavelengths, a prominent rotation-powered pulsar visible at optical, X-ray and gamma-ray wavelengths, serves as a good example for a population of neutron stars that may be detectable only with LOFAR. With its sensitivity to these very different types of neutron stars, a LOFAR Galactic pulsar survey will be instrumental in providing a complete picture of neutron-star radio emission.

We have carried out sophisticated simulations using realistic population and scattering models to determine the optimum observing configuration, observing strategy and frequency for a pulsar survey with LOFAR (Figure 1 and van Leeuwen & Stappers 2006). If we extrapolate the known low-luminosity tail, we find that a LOFAR all-sky pulsar survey (the first survey of the Northern hemisphere in 10 years) will find around 1500 new pulsars, almost doubling the total number of pulsars known. The survey provides a complete local census of radio-emitting neutron stars, such as radio pulsars, AXPs and previous "radio-quiet" pulsars. Using the derived population properties (such as the pulsar period distribution) one can study the birth properties of neutron stars, core collapse physics, the velocities and spatial distribution of pulsars, and the physics of neutron stars in general. We note also that the long pointings possible, because of the wide field of view, in a LOFAR pulsar survey, makes it particularly sensitive to the recently discovered classes of infrequently emitting neutron stars like RRATs [McLaughlin et al. 2006] and pulsars that are on for 10% or less of the time [Kramer et al. 2006].

3. A survey for extragalactic pulsars.

Spiral and irregular galaxies will host young, bright, Crab-like pulsars, and due to its sensitivity, LOFAR can be the first telescope to find such pulsars besides those in the Magellanic Clouds. If observed face-on and located away from the Galactic disk, the scatter broadening to an external galaxy will be relatively low and thus a LOFAR survey will have excellent sensitivity for pulsars of all spin periods (van Leeuwen & Stappers 2006). For a relatively close galaxy like M33, LOFAR could detect all pulsars more luminous than 50Jy kpc². Our Galaxy hosts 10 pulsars which are brighter than that. There are at least 20 Galaxies for which LOFAR will have good sensitivity to their pulsar population. Complementary to this normal pulsar emission, some pulsars show ultra-bright 'giant pulses' that could be visible in even more remote galaxies (e.g. McLaughlin & Cordes 2003).

A survey for extragalactic pulsars would allow us to investigate if the bright end of the pulsar distribution in other galaxies differs from our galaxy, and how that ties into galaxy type and star formation history. Such pulsars can also help the understanding of the missing baryon problem, the history of massive star formation in these galaxies.
4. Pulsar emission physics

The sensitivity and frequency range of LOFAR open up the low-frequency window of pulsar emission to exciting new studies. It is precisely in the LOFAR frequency range where some of the most interesting changes in pulsar radio emission can be observed, including the very significant broadening of the pulse profile \cite{Cordes1978}, changes in the form of the pulse profile \cite{Kuzmin1998,Rankin1983}, a turn-over in the flux density spectrum, and it is also the frequency range where propagation effects in the pulsar magnetosphere may be expected to be largest \cite[e.g.][]{Cheng1979,Petrova2001}. Studying the latter, in particular with simultaneous multi-frequency observations of single pulses, will reveal interesting characteristics of the pulsar magnetosphere, such as particle densities and birefringence properties, that will ultimately lead to a better understanding of the workings of pulsars.

Our calculations show that in the LOFAR high band single pulses can potentially be detected with reasonable signal to noise from up to one-third of pulsars while in the low band it is about one-quarter of pulsars. This is a very large increase on what has previously been possible, and when combined with LOFAR’s ability to track sources, allows for the rich study of the emission physics of radio pulsars. Furthermore LOFAR will also be able to detect single pulses from millisecond pulsars (MSPs), something which has so far been done for less than a handful of sources \cite[e.g.][]{Edwards2003}, and will allow us for the first time to compare the mode changing, nulling and drifting subpulse properties of MSPs with their younger, higher magnetic field, slower spinning brethren.

5. Interstellar medium studies

Pulsars are excellent probes of the ionized component of the interstellar medium through scintillation \cite{Rickett2001}, dispersion measure, and Faraday rotation.
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6. Other possibilities

LOFAR will be very useful for monitoring and timing. While it will not perform high precision timing, at the top of the high-band sufficiently accurate timing will be possible to enable, for example, frequent observations of a large sample of glitching pulsars. This would allow for the better parameterisation of glitches and the possibility of triggering rapidly after a glitch to allow follow-up at other wavelengths. Similarly timing of a large number of pulsars will also be valuable for follow up with GLAST where accurate ephemerides are required to fold the long data sets. With regular monitoring it will also be possible to study and potentially catch transitions in the "more off than on" pulsars. The radio-sky monitor will also find new transient pulsar sources, such as RRATs, and allow rapid follow-up and via the transient buffer board a look back in time at the event itself.

7. Conclusions

LOFAR will reopen, with wider bandwidths, large frequency range and unprecedented sensitivity, the low-frequency window for pulsar emission studies. The wide fields of view and sensitivity will also allow for an efficient and sensitive survey of the whole Northern sky enabling the discovery of hundreds of new pulsars including a number of exotic objects and systems. A survey of local group galaxies will also likely detect the first truly extragalactic pulsars. Pulsars observed with LOFAR will provide excellent probes of the interstellar, and potentially intergalactic, medium and will be especially useful for gaining a better understanding of the local interstellar medium. Furthermore the exciting possibilities of multibeam and radio-sky monitoring open up new avenues of pulsar and radio emitting neutron star research.

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scintillation studies have been revolutionized in the last five years by the discovery of faint halos of scattered light extending outward 10–50 times the width of the core of the scattered image [Stinebring et al. 2001]. This, in turn, gives a wide-angle view of the scattering medium with milliarcsecond resolution, and the illuminated patch scans rapidly across the scattering material because of the high pulsar space velocity. LOFAR will be an outstanding instrument with which to study this phenomenon, particularly for strong, nearby pulsars. The dynamic nature of these phenomena also fits well with LOFAR’s excellent monitoring capabilities. In a sense, this scintillation imaging will allow us to monitor the range of interstellar conditions encountered along a particular sight line. This monitoring will not be particularly time consuming, but it will add greatly to the more static view of the ISM afforded through other techniques.

LOFAR will make important contributions to traditional dispersion measure, rotation measure, and scattering measure determinations. By almost doubling the number of known pulsars, the proposed survey will add a dense grid of new sight lines through the Galaxy to those that already exist. The dispersion and scattering measures of this new sample will improve our global model of the distribution of the ionized ISM and its degree of clumpiness. The new rotation measures will place important constraints on the overall magnetic field structure of the Milky Way, which is still not well characterized. At LOFAR frequencies it is possible to also measure the very small rotation measures of the nearby population of pulsars providing an unprecedented tool for studying the local magnetic field structure.