Verbiest LPR12_010

Pulsar Timing with LOFAR

Semester : LOFAR_Cycle_C12

Abstract

We propose to monitor a sample of 45 millisecond pulsars (MSPs) and 40 slow pulsars with the HBA stations in the LOFAR core. The primary science drivers for this project are:

- to improve the sensitivity of pulsar timing arrays to gravitational waves (GWs) by monitoring variations in interstellar dispersion towards the MSPs in our sample;
- to investigate the nature of the turbulence in the interstellar medium (ISM), in particular to verify or refute currently preferred theoretical models;
- to measure or constrain possible small scales in the Galactic magnetic field strength for the first time;
- to measure pulsar spectral indices and spectral turnovers and to allow studies of time-variability of these;
- and to investigate mode and state changing as well as timing noise and glitches in both MSPs and slow pulsars.

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General Requirements

Observation settings:

Pipelines:

Pulsar Timing with LOFAR

The Pulsar Working Group & Transients Key Science Project

Update on LT10_004; a continuation of Long-Term Proposal LT05_003 (and LC9_041).

Summary

We propose to monitor a sample of 45 millisecond pulsars (MSPs) and 36 slow pulsars with the HBA stations in the LOFAR core. The primary science drivers for this project are:

- to improve the sensitivity of pulsar timing arrays (PTAs) to gravitational waves (GWs) by monitoring variations in interstellar dispersion towards the MSPs in our sample;
- to investigate the true nature of the turbulence in the ionised interstellar medium (IISM), in particular to verify or refute the currently preferred theoretical models;
- to measure or constrain possible small scales in the Galactic magnetic field (GMF) strength for the first time;
- to measure pulsar spectral indices and spectral turnovers and to allow studies of time-variability of these;
- and to investigate mode and state changing and timing noise in both MSPs and slow pulsars.

Below, we respond to the five items requested. For further details on the scientific motivation, organisation and planning, we refer to our original proposal from Cycle 10.

Assessment of the observations taken during the first year; and of any difficulty that arose

There were no major issues: nearly all observations were done in time and only few repeats were needed.

Assessment of whether the goals of the proposal will be achieved after one more year

Some of our science goals are by design on-going efforts that will technically not ever be fully completed, but mostly after the coming year we should be in a good position to re-evaluate our science goals, observing strategy and source list. A goal-by-goal discussion is given below.

DM corrections for PTAs: This is the main long-term goal which would be ongoing until GWs are detected and beyond, insofar as no other low-frequency telescope can be found to provide the measurements we achieve here. However, the sample size and observing cadence are being adjusted on an on-going basis. Specifically, presently about 15 MSPs in our sample are being tested both as part of this project and as part of the higher-frequency PTA observational campaigns, for suitability to be included in PTA efforts. If these are deemed unsuitable, they will be removed from our source list. This includes some black-widow pulsars that could be unstable and which are interesting sources in their own right, but which do not need ongoing monitoring at low frequencies but rather a set of irregularly spaced but lengthy observations. In summary, after the coming year, we will have sufficient data to make an informed decision on the inclusion or exclusion of all the MSPs presently in our sample. Those MSPs that are part of PTA efforts will need continuing monitoring beyond that time, but potentially with adjusted integration times.

IISM studies: Due to the lack of highly sensitive campaigns like our own, it is typically unpredictable which lines of sight probe particularly turbulent parts of the Galaxy and which lines of sight do not show any signatures of interest. By the end of the coming year, we will have sufficient data to make an informed decision on which lines of sight are of use for IISM studies and which lines of sight will be dropped. In order to get proper statistics on the number and amplitude of short-lived DM variations and lines-of-sight that show chromatic DMs, longer-term monitoring on a select number of sources will be required.

GMF studies: The recent paper by Sobey et al. shows that we have enough data to study the large-scale magnetic field of the Galaxy and Porayko et al. has shown that we now have the analysis methods to study shorter-lived variations in interstellar Faraday Rotation. This means that for most pulsars in our sample, a sufficient number of observations has already been obtained, but that for a smaller sample, which shows particular variability in the intervening medium, longer-term monitoring would be beneficial. Note that this sample by definition overlaps with the sources that require ongoing monitoring for the IISM studies.

Spectral indices and variations thereof: Sufficient data are available to determine the spectral indices and potential turnovers of all the pulsars in our observing list and this analysis is now held up solely by complexities in the calibration routines. To constrain or identify temporal variations in the spectral index of pulsars will require longer-term monitoring (beyond the coming year), but mostly this will be achieved based on the sample of sources that require ongoing monitoring for the other science goals.

Mode changing and timing noise: For this study the number of observations is critical and in that regard we expect that sufficient observations will be available after the coming year to allow a proper check of which pulsars can and cannot be used for a highly sensitive analysis at LOFAR frequencies. At that point it would become important to revise the source list and observing strategy for this science goal, also to enable simultaneous studies at higher frequencies.

Status of the data reduction, including an outline of missing tools and their status of development

The data reduction is proceeding well, with almost all tools in place and many results published or being prepared for publication (as described later). The only exception is the spectral-index investigation, which depends on reliable calibration methods that are still being worked on. A project-by-project overview follows.

DM corrections for PTAs: As promised one year ago, we are in the process of preparing a paper on the DM variations observed to date in all the MSPs in our sample. This paper will include between 30 and 40 of the MSPs that are being monitored, depending on how long the timing baseline is that we have on them. 26 of those are presently part of a PTA, but an additional $\sim$15 are presently being evaluated for potential inclusion in PTAs. The basic data analysis for this paper is essentially done and the more detailed interpretative analysis is presently on the way, implying we are well on track to publish (and thereby publicly release) these DM time series within the next 12 months, thereby allowing any PTA to use them in their work. Simultaneously we have continued to provide DM time series to help high-frequency timing efforts. In addition to the pulsars mentioned in our proposal last year, we have now provided LOFAR data and its derived products for six MSPs that are presently being timed at higher frequencies.

IISM studies: The basic data analysis for this project is in principle identical to that carried out by the pipeline for the previous project, so this analysis is also progressing well. In parallell with the MSP paper mentioned above, a similar strategy is now being undertaken for the slow pulsars, which are being analysed for inclusion in a paper that will be focussed on the properties of the IISM along these lines of sight, specifically testing the prevalence of small-scale variations, the slope of the turbulence spectrum and the overall measurement precision that is achievable with LOFAR. The data analysis for this is well on the way and this paper is expected to be finalised in short succession to the MSP paper mentioned above.

GMF studies: The RM measurements to most sources in our sample have been completed and published by Sobey et al. (2019), which also used these data to estimate the GMF's scale height. This work is being continued with improved calibration and ionospheric correction schemes; and an enlarged source sample. An further analysis looks for temporal variations in the Faraday Rotation to selected pulsars. The analysis pipeline for this investigation is finalised and is now being ran on selected sources where we hope to find variations; or alternatively from which we aim to place constraining bounds on the variability of the magnetic field.

Spectral indices and variations thereof: As mentioned above, the constraint in this regard is the reliability of present calibration schemes. Various groups are continuing work on this – largely also outside the scopes of our project. Data analysis is presently on hold as these calibration methods are being refined and updated.

Mode changing and timing noise: Since the total observing length is of key importance to the feasibility of this project, the processing in this case has so far focussed on some spot-checks of specific pulsars to verify feasibility without expecting to get a sufficient quantity of publishable outputs to warrant a publication. Several BSc theses have been completed on the moding investigations of PSR B0329+54 and presently an MSc student is finalising an analysis of the moding of PSR B1822$-$09. These results are now of sufficient quality that a PhD student will be assigned to this project within the next year. The tools for the analysis are all in place.

Any significant change of the personnel involved in the project

In the past year, PhD student Daniele Michilli graduated and left the project for CHIME. PhD student Chia Min Tan is about to defend his thesis and it is presently unclear if he will be able to continue work on this project. In addition to the people mentioned in our proposal, PhD student Nataliya Porayko has joined the work on the GMF and she too, will defend her thesis in a few months time.

A few new people have also joined the project. Specifically post-doc Ann-Sofie Bak Nielsen has joined the Bielefeld group and has started analysing the timing data of the black-widow pulsars in order to assess their usefulness for PTA inclusion. The group at the University of Manchester is presently looking for a PhD student

to take on the investigation of the mode changing and timing noise. Finally, MSc student Abubakr Ibrahim has recently finished his thesis at the University of Cape Town and will contribute to the IISM studies by analysing the DM time series of the slow pulsars. For this purpose, he has gained a half-year scholarship at the SKA office in South-Africa; and has applied for funding for a half-year research stay in Germany following that.

Short description of the intermediate scientific results and any publications achieved

In addition to the updates described above, within the last year three papers that were based directly on data from this project were published: Michilli et al. (MNRAS May 2018); Polzin et al. (MNRAS May 2018); and Sobey et al. (MNRAS April 2019). The first of these discussed IISM effects observed in PSR J2219+4754, the second one discussed eclipses in the black-widow system PSR J1810+1744 and the last one measured the rotation measures to the pulsars in our sample and used those to constrain the GMF. Two further papers that were published did not directly use data from this project, but were undertaken as part of this project or benefited indirectly from our data. These are Porayko et al. (March 2019), investigating the quality of TEC maps for ionospheric RM corrections – which is essential to our efforts to identify interstellar RM variations; and Donner et al. (April 2019), which investigates the DM variations in PSR J2219+4754 and their chromaticity. This last paper was fully based on single-station data taken in stand-alone mode, but built upon the work published last year by Michilli et al.

Three more papers are presently in an advanced stage of preparation. The first one of these is Nieder et al., which is to be submitted to ApJ on a timescale of weeks to months and discusses the gamma-ray detection and timing of PSR J0952−0607. For the analysis included in that paper DM corrections were essential. Due to the low brightness of this pulsar at LOFAR frequencies, meaningful DM estimates could only be derived from the core data which were derived from this project as well as an original DDT proposal following the pulsar's initial discovery. A second paper in an advanced stage of preparation is Donner et al., which reports on the MSP DM variations. As described above, the basic analysis is completed and work is ongoing on the scientific interpretation while the paper is being written. Submission to A&A on a timescale of months is realistic. Finally, Ibrahim et al. will report on the DM variations and overall IISM turbulence structure, in particular on the lines of sight to our slow pulsars. An initial analysis of this work has been undertaken already but this needs to be redone with some more refined analysis methods. We are already aware of the likely scientific outcomes and so the preparation of the paper has commenced. Due to contractual limitations, we aim to have this paper finalised within the coming half year.

In summary, with the exception of the spectral indices investigation, which is being held back by the development of improved calibration schemes; and the mode changing project, which has been investigated as part of undergraduate theses but which will be turned into a PhD thesis (or chapter thereof) in the coming few months, all of our projects have had relevant papers published in the recent past, or have papers in advanced stages of preparation. This clearly confirms that progress is as good as can be expected. We furthermore stress that this significant amount of progress is in large part due to the highly complementary data sets that have been gathered by this project and the "sister-project" LT10_014 (PI: Serylak). One prime reason is because even though in some instances the complementarity is straightforward, in many other cases it is only once the data are being analysed that it becomes clear which data set lends itself best for which aspect of the analysis (as neatly demonstrated by the Michilli et al. and Donner et al. papers).

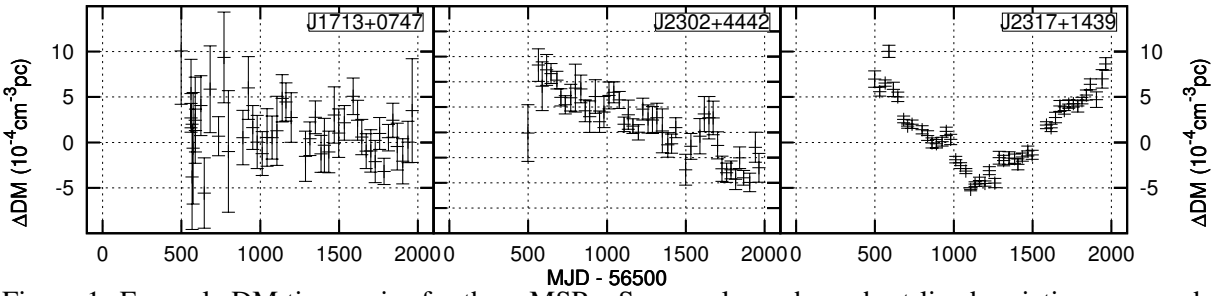

Figure 1: Example DM time series for three MSPs. Some pulsars show short-lived variations; some dramatic reversals; and some hardly show any changes yet. These data are being finalised for publication and public release.

Additional remarks

This is a progress report for project LT10_004.

Students involved

Student	Level	Applicant	Supervisor	Applicant	Expected completion date	Data required
Julian Donner	Doctor	Yes	Dr. Joris Verbiest	Yes	2020/10	Yes
Lucy Oswald	Doctor	Yes	Aris Karastergiou	Yes	2021/04	Yes
Nataliya Porayko	Doctor	Yes	Dr Aristeidis Noutsos	Yes	2019/05	Yes

No previous involved proposals

Targets:

Field	RA	Dec	Epoch	Time(Hours)	Comments