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PULSARS: FROM NENUFAR TO SKA

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Abstract. NenuFAR is an official pathfinder of the future international radio telescope SKA. For both instruments, pulsars are part of the science case, and have a dedicated Key Programme. Many of the pulsar projects planned with SKA have a counterpart with NenuFAR. As expected from a pathfinder, lessons learned with NenuFAR will help with the SKA. We also present cases where having access to both the NenuFAR and SKA frequency bands will improve the results produced by both telescopes.

Keywords: low frequency radio astronomy, pulsars, NenuFAR, SKA

1 Introduction

Pulsars are rapidly rotating, highly magnetized neutron stars, which emit collimated beams of radiation across the electromagnetic spectrum. Most of the known pulsars have been discovered and studied in the radio band. According to the Australia Telescope National Facility (ATNF) Pulsar Catalog (Manchester et al. 2005)*, more than 3300 pulsars have been found to date. Since the original discovery (Hewish et al. 1968), countless radio telescopes have contributed to the study of radio pulsars, with each new telescope generation allowing new breakthroughs. This is still true today, and major advanced in the field of pulsar science is expected from the SKA and its pathfinders.

NenuFAR (New extension in Nançay upgrading LOFAR, see Zarka et al. 2020; Zarka et al. 2022)† is a newly built compact phased array (and interferometer) on the site of the Nançay Radio Observatory (France). The antenna's design and the receiver allow us to cover the band 10–85 MHz with a uniform gain. The core, of diameter 400 m, is formed of 1520 antennas arranged in hexagonal groups of 19 dual-polarization antennas called mini-arrays (MAs). Upon its completion in 2023, the core will consist of 1824 antennas (96 mini-arrays). NenuFAR is equipped with a real-time pulsar backend (Bondonneau et al. 2021). NenuFAR has started its early science operations in July 2019, and has obtained first results and discoveries, in particular for the study of radio pulsars (e.g. Bondonneau et al. 2021; Agar et al. 2021; Bilous et al. 2022; Bondonneau et al. 2022).

The Square Kilometre Array (SKA) (Dewdney 2015) will be the world's largest radio telescope, with eventually over a square kilometre of collecting area. It is currently under construction, with telescope sites in both South Africa and Australia. The telescope will be operated by the SKA Observatory, an intergovernmental organisation. South Africa will host the core of the high and mid frequency dishes, covering the frequency range 350–14000 MHz (with the possibility to later increase the upper frequency limit). Australia will host the low-frequency antennas, covering the frequency range 50–350 MHz. Early science observations are expected to start in the mid-2020s with a partial array. Development of the SKA builds upon the experience gained with precursors (radio telescopes built on one of the SKA sites) and pathfinders (radio telescopes built on the same

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*`https://www.atnf.csiro.au/people/pulsar/psrcat/`
†`https://nenufar.obs-nancay.fr/en/astronomer`

planet as the SKA, and with either related technology or common scientific studies). Among others, NenuFAR is officially labelled as SKA pathfinder.

Related to pulsars, the SKA Scientific Use Cases include "All sky pulsar surveys with SKA1-LOW and SKA1-MID", "Pulsar Timing with the SKA" and "Understanding the magnetospheres of pulsars using single pulses" (Wagg et al. 2021). These three science use cases have direct counterparts in the programme of the NenuFAR pulsar KP.

2 Synergy between low and high frequency pulsar observations

Despite the telescopes' location in different hemispheres, NenuFAR and the SKA (including both SKA1-LOW and SKA1-MID) do have have partial overlap in terms of observable sky. Nominally, the observable sky above NenuFAR ranges from declination between -23° and +90°. SKA1-LOW is located at a latitude of 26° south, and the specification is to be able to observe at elevation of 45° or higher[‡], leading to an observable declination range between -90° and +18°. Thus, the sky region with declinations $-23° < \delta < +18°$ will be accessible for joint observations. Some sky regions, however, can only be observed with either NenuFAR (regions at declination $\delta > +18°$) or the SKA (sky regions with for $\delta < -23°$). In addition, the minimum frequency of NenuFAR (10 MHz) is lower than that of SKA1-LOW (50 MHz).

For these two reasons, having access to both NenuFAR and the SKA can benefit science cases. In the following, we will detail a few examples where pulsar science using both NenuFAR and the SKA is more than the sum of its parts.

2.1 *Pulsar searches*

NenuFAR is currently undertaking a blind search of the northern sky (above 39° of declination). This blind survey is organised in 7692 pointings of 30 minutes, with a bandwidth of 37.5 MHz around a central frequency of 58 MHz. More details on the blind survey can be found in Brionne et al. (2022a) and Brionne et al. (2022b). At the same time, one of the sciences cases of the SKA is to perform all sky pulsar surveys with SKA1-LOW and SKA1-MID.

Obviously, the increased sky coverage available to the combination of NenuFAR and the SKA will lead to a larger number of discoveries. In addition, searches for new pulsars at low and high frequencies are complementary in the sense that they probe different populations. The widely used ATNF catalogue is biased toward higher frequency observations, and may not well represent the pulsar population than can be observed at frequencies below 1 GHz. Indeed, despite the use of standard techniques, LOTAAS discovered a unusually high number of slow pulsars, including a pulsar 23.5 seconds (the pulsars with the lowest know spin frequency at that time, Tan et al. 2018). The difference in pulsar populations is clearly confirmed by the statistical comparison of the distribution of pulse periods of pulsars in the ATNF catalogue with those redetected and discovered with the LOTAAS survey. The probability that the spin periods of the LOTAAS discoveries, are drawn from the (selection bias corrected) known pulsar population is less than 1% (Sanidas et al. 2019; van der Wateren et al. 2022). For this reason, we expect the pulsar surveys performed with NenuFAR (such as the blind survey described in Brionne et al. 2022a) and the SKA to yield different, yet complementary results.

2.2 *Pulsar emission physics*

Following the radius-to-frequency-mapping (see e.g. Ruderman & Sutherland 1975; Cordes 1978), low-frequency radio emission traces the high altitudes in a pulsar's magnetosphere. As a consequence, a detailed wide-band study of a pulsar's radio emission allows us to map a large volume-fraction of a pulsar's magnetosphere: the low frequencies carry information on the outer part of the magnetosphere, and the high-frequency observations inform us about the inner magnetosphere.

Similarly, the precise measurement of the spectral turnover will allow us to gain a better understanding of the radio emission mechanism of pulsars. Indeed, the spectra of most pulsars are well described by a single spectral index (Sieber 1973; Maron et al. 2000; Jankowski et al. 2018) for frequencies >200 MHz. At frequencies below 200 MHz, the spectral index flattens and most non-recycled pulsars show a turnover between 50 and 100 MHz (e.g., Sieber 1973; Kuzmin et al. 1978; Izvekova et al. 1981; Bilous et al. 2016; Jankowski et al. 2018; Bilous

[‡]Observations at lower elevation will be possible, but will have reduced sensitivity and polarisation fidelity.

et al. 2020; Bondonneau et al. 2020). The physical cause for this turnover is still unknown (see, e.g. Bilous et al. 2020, Sect. 5). Studying this turnover requires both observations above and below the turnover frequency; the former can be provided by LOFAR, GMRT or SKA1-MID, whereas the latter can be provided by NenuFAR and SKA1-LOW. The low minimum frequency of NenuFAR will especially valuable for pulsars which have their spectral turnover a frequencies lower than ~ 70 MHz.

2.3 *Gravitational waves*

Pulsar Timing Arrays (PTAs, e.g. the IPTA, Hobbs et al. 2010) aim to detect low frequency gravitational waves using high precision pulsar timing, typically at L- and S -band. Pulsar timing is part of the SKA science case.

However, the expected signal of gravitational waves is of extremely small amplitude and competes with the effects generated by fluctuations of the column-integrated electron content (dispersion measure, DM) in the ionised interstellar medium and in the solar wind. The latter can be particularly critical, as it can induce correlated signals between pairs of pulsars in the same way as the gravitational wave background ((Tiburzi et al. 2016).

One promising way to remove this foreground signature is to obtain high-precision measurements of the DM along various lines of sight with a high cadence, combined with a good model of the solar wind (Tiburzi et al. 2021; Chalumeau et al. 2022). For a given DM value, the dispersive delay increases with decreasing observing frequency ($\Delta t \propto \nu^{-2}$). As a consequence, low frequency observations are the best way to determine precise DM values.

Bondonneau et al. (2021) have demonstrated that NenuFAR is capable of delivering DM measurements with an unprecedented precision (of the order of 10^{-5} pc cm^{-3}) for pulsar B1133+16; a comparable precision was recently also obtained for the millisecond pulsar J2145-0750, which is used in the PTAs (Figure 1).

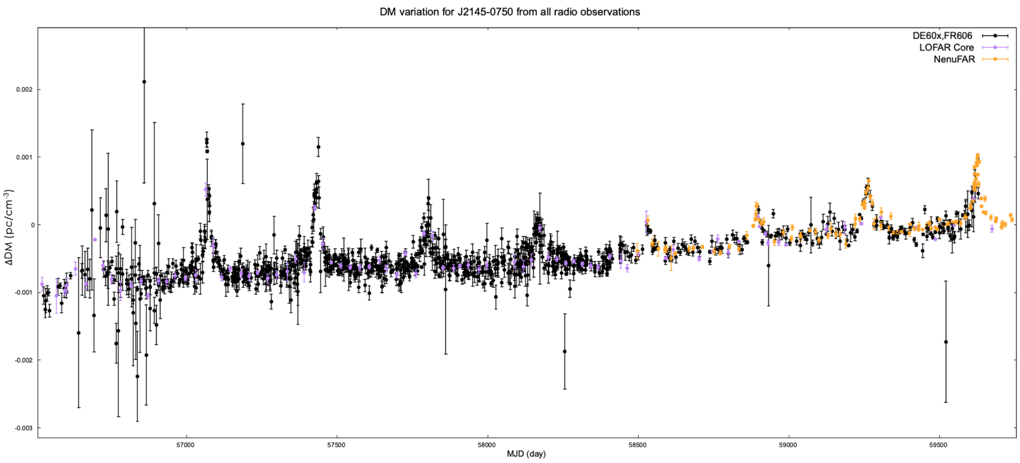

Fig. 1. DM time series for the millisecond pulsar J2145-0750, based on LOFAR and NenuFAR observations.

Such high precision DM timeseries can then be used to correct variations of the dispersive delays in higher-frequency observations from PTAs (Donner et al. 2020). This, however, must be done with care: Cordes et al. (2016) discuss how scattering can lead to frequency-dependent DM, and this effect was indeed observed with LOFAR singlestation data (Donner et al. 2019). Luckily, Donner et al. (2019) found that the long-term DM trends were consistent across the different frequency bands. Moreover, Donner et al. (2020) did not find any evidence for a frequency-dependent DM when analyzing 36 millisecond pulsars in the 110-190 MHz frequency band, so we expect the impact of this effect to be limited.

With this, NenuFAR will provide high-cadence DM time series for a few millisecond pulsars that are routinely observed within the PTA collaborations. The contributions of the interstellar medium and the solar wind will be disentangled following Tiburzi et al. (2021). With this, NenuFAR will contribute to improved models of the solar wind; such models are required, as the existing ones do not yet satisfy the requirements for high precision pulsar timing (Tiburzi et al. 2019, 2021).

High-precision DM measurements as described above are required for all PTA pulsars. Depending the pulsar's declination, either SKA1-LOW or NenuFAR (or, in some cases, both) will be able to provide the required observations.

3 Conclusions

With its high sensitivity at low frequencies, NenuFAR is also a milestone on the route to the Square Kilometer Array (SKA), hence its pathfinder label. It will help refine the SKA science goals, particularly those concerning the emission mechanism and propagation effects in the context of highly dispersed and scattered signals. As such, it will contribute to maintaining a useful bridge of pulsar studies over the coming decade and support the community of pulsar astronomers focusing on emission processes, populations, and ISM characterization. For both instruments, pulsars are part of the science case, and have a dedicated Key Programme. Many of the pulsar projects planned with SKA have a counterpart with NenuFAR, which offers to possibility for pilot studies. When the SKA will become operational, joint studies between the SKA and NenuFAR will be performed in the two hemispheres in complementary frequency ranges, providing the potential for additional discoveries. We have shown that having access to the low frequency information provided by NenuFAR and the high frequency information provided by the SKA will improve the scientific return of both instruments.

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