A Renaissance in Low-Frequency Radio Pulsar and Fast Transient Science

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Abstract

Low-frequency, high-time-resolution radio studies have seen a renaissance in the last years not only because of the new generation of large radio telescopes but perhaps even more importantly because modern computing technology is facilitating high-resolution, wide-field observations. I will present ongoing pulsar and fast transient studies with LOFAR and the GBT at frequencies from 10−400 MHz. I will highlight the scientific successes of these studies, including the discovery of the first pulsar in a stellar triple system, as well as new insights into the magnetospheres of radio pulsars. These projects are pushing the envelope of big data in radio astronomy. For example, our LOFAR survey produces 40 Gb/s of data, and the > 1 Petabyte of data we have already acquired will take many millions of CPU core hours to reduce. These challenges are being successfully tackled, and are setting us on the path to make another big scientific leap with the Square Kilometer Array (SKA), where virtually all such data will have to be processed in real-time.

1 Introduction

Pulsar and fast transient surveys require the largest possible telescopes, and remain sensitivity limited. At the same time, a crucial way in which to push the envelope is by expanding the recorded bandwidth, field-of-view, and time/frequency resolution of the data. Though radio telescopes have not greatly increase in collecting area in the last decades, modern computing power continues to drive major advances in the field. The millisecond duration pulses produced by pulsars and other fast radio transients, see e.g. [1], are dispersed by their journey through the intervening ionized material, an effect that can only be well-compensated by high frequency resolution or more advanced, even more computationally expensive, processing.

Typical pulsar surveys now collect hundreds of Terabytes of data, and have even started moving into the multi-Petabyte regime. For the Square Kilometer Array (SKA), the data rates and computational needs explode because to make a big leap in collecting area requires moving from using large single-dishes (the traditional tool for radio pulsar surveys) to using a large interferometric array where many coherent array beams will need to be synthesized to recover an adequate field-of-view (while retaining sensitivity). Clearly, to take maximum advantage of the SKA will require real-time processing of many Tb/s of data. Fortunately ongoing and planned pulsar and fast transient surveys are charting a path towards this regime.

At the same time, a new generation of pulsar astronomers are returning to observing at low radio frequencies, i.e. 10−400 MHz. Low-frequencies can take advantage of the typically steep spectral indices of pulsars and the naturally larger field-of-view towards longer wavelengths. Here I will present the recent successes in the field, the challenges that are being overcome, and what can be expected on the road to the SKA. I will use low-frequency surveys with the Green Bank Telescope (GBT) and the Low-Frequency Array (LOFAR) to illustrate these points.

2 GBNCC: the Green Bank Northern Celestial Cap Survey

In the last few years, the GBT has demonstrated that it is a powerful low-frequency pulsar and fast transient search instrument. Operating in an almost interference-free band from 300−400 MHz, several surveys have been undertaken: i) a pilot survey of just the northern Galactic plane [2], ii) a drift-scan survey that made efficient use of the telescope while it was immobile and under repair [3,4] and, most recently, iii) the GBNCC survey, which will eventually survey the *entire* GBT-visible sky at 350 MHz [5]. Thus far, these surveys have combined to discover over 140 pulsars, including 16 millisecond pulsars, and close to a dozen sources detected first (and sometimes exclusively) through their individual, sporadic, bright pulses.

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A recent highlight is the discovery of millisecond pulsar J0337+1715 (Figure 1), the first pulsar to be hosted in a stellar triple system [6]. This system is an incredible playground for modeling exotic stellar evolution, and the interactions between the inner and outer orbit provide additional information compared with the normal Keplerian parameters, which together can be used to determine the component masses and orbital inclinations. Perhaps the most exciting aspect of the system is that it provides an unparalleled laboratory for testing the strong equivalence principle (SEP), which is a central tenet of the theory of general relativity. By looking for a deviation in how the inner pulsar and white dwarf 'fall' in the gravitational potential of the outer white dwarf, a violation of the SEP can be strongly constrained. Importantly, this can also be done in a regime where gravitational binding energy (of the neutron star) is non-negligible.

The GBNCC may also provide one of the best chances yet for detecting rare, but bright fast transients at low frequency. A full reprocessing of the current data set is in progress to find such signals. These can be found using similar techniques to those that identify the bright, individual pulses from sporadically pulsing pulsars (Figure 2).

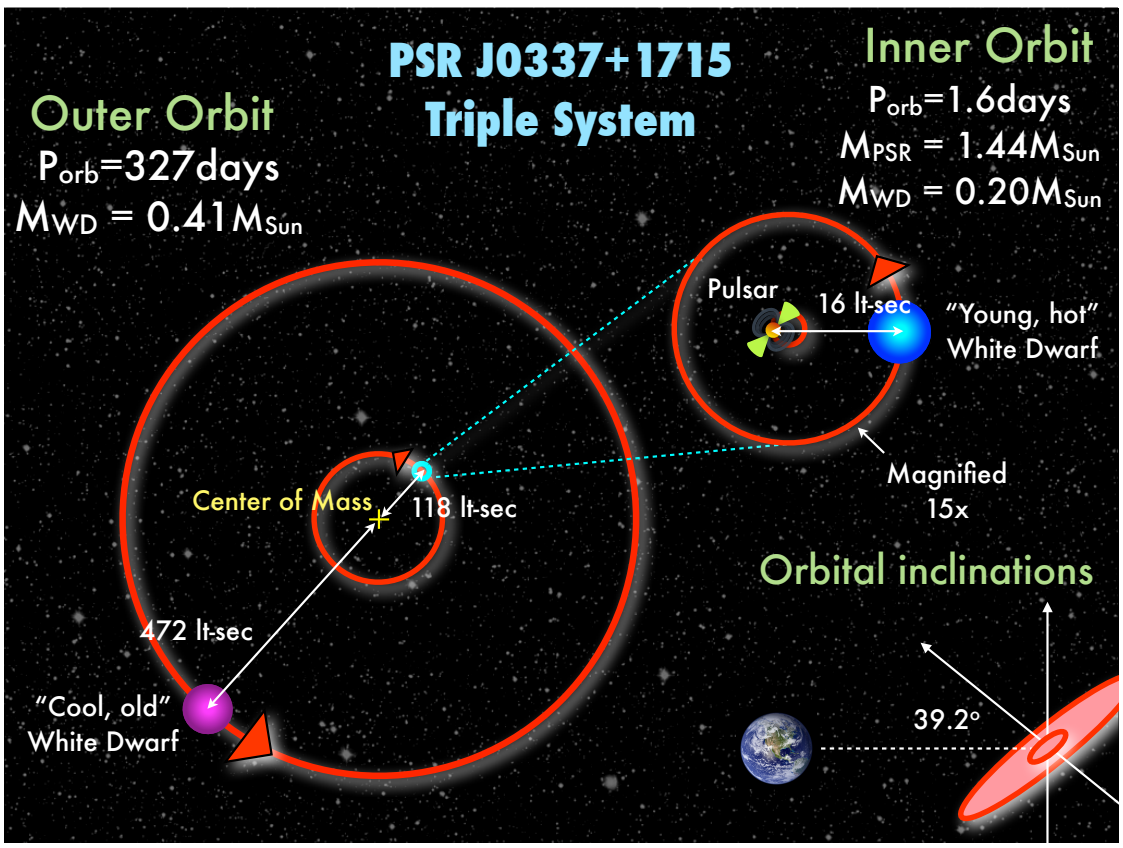

Figure 1: Artist's conception of the PSR J0337+1715 hierarchical triple system. Interaction between the inner and outer orbits provides additional signatures in the timing properties of the pulsar signal, which can be used to disentangle the orbital inclination and component masses.

3 LOTAAS: the LOFAR Tied-Array All-Sky Survey

LOFAR provides the opportunity to survey the sky at high-time-resolution and at yet lower frequencies compared with the GBT GBNCC survey [7,8]. The wide fractional bandwidth provided by LOFAR at the lowest observable frequencies from Earth (10−240 MHz) is also being exploited to learn novel new things about pulsar magnetospheres [9], and the propagation of the signal through the interstellar medium [10].

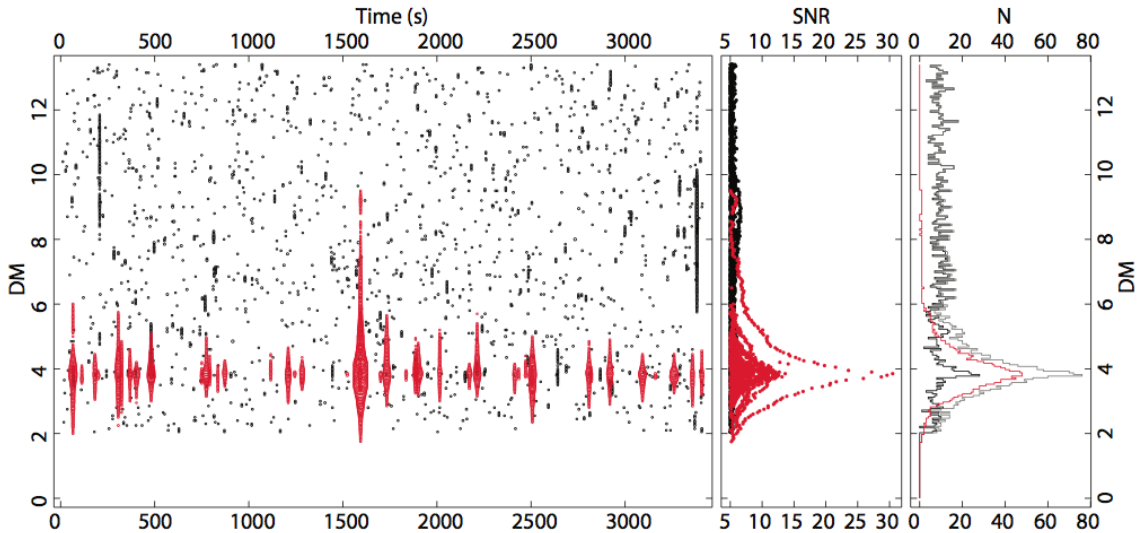

Figure 2: A recent, low-dispersion-measure pulsar discovered at 350-MHz with the GBT. These data are from a 1-hr LOFAR observation and show that the source produces sporadic but very bright individual pulses. This source is a prototype for the kind of nearby, intermittent source that the LOTAAS survey will find.

Operating from 119−151 MHz, the LOFAR Tied-Array All-Sky Survey (LOTAAS) is complementary but also different to the GBNCC in several ways. LOTAAS combines the innermost 12 LOFAR high-band antenna (HBA) stations in order to form 219 coherent and 3 incoherent array beams (Figure 3). This provides a large 9 sq. deg./30 sq. deg. (coherent/incoherent) field-of-view per pointing - over 30 times the field-of-view covered by the GBNCC pointings. This large field-of-view allows us to dwell for 1-hr per pointing, a factor of 30 times longer than the 2-minute dwell times of the GBNCC survey.

Though it only achieves twice the cumulative sensitivity of the GBNCC survey, LOTAAS will be a powerful survey for finding very nearby, low-dispersion-measure pulsars as well as sources that are highly intermittent (Figure 2). Thus far, 225 pointings have been observed, resulting in 900 TB of archived data. In other words, besides pushing the envelope into new scientific parameter space, LOTAAS is also pushing the envelope in terms of the data rates and computing power required to find pulsars and fast transients. The raw data rate of the observations is 40 Gb/s (25 times that of GBNCC), but the challenges do not end there. To properly search each 1-hr pointing for interesting astrophysical signals requires 2.5 hrs/beam/24-core computing node. In other words, to keep up with the processing real time would require a 13,000-core cluster. For the SKA, the computational task will be an order-of-magnitude larger, and the limitations of storing many Petabytes of data quickly push one towards real-time processing, likely using GPU-based or other high-performance strategies.

4 Acknowledgements

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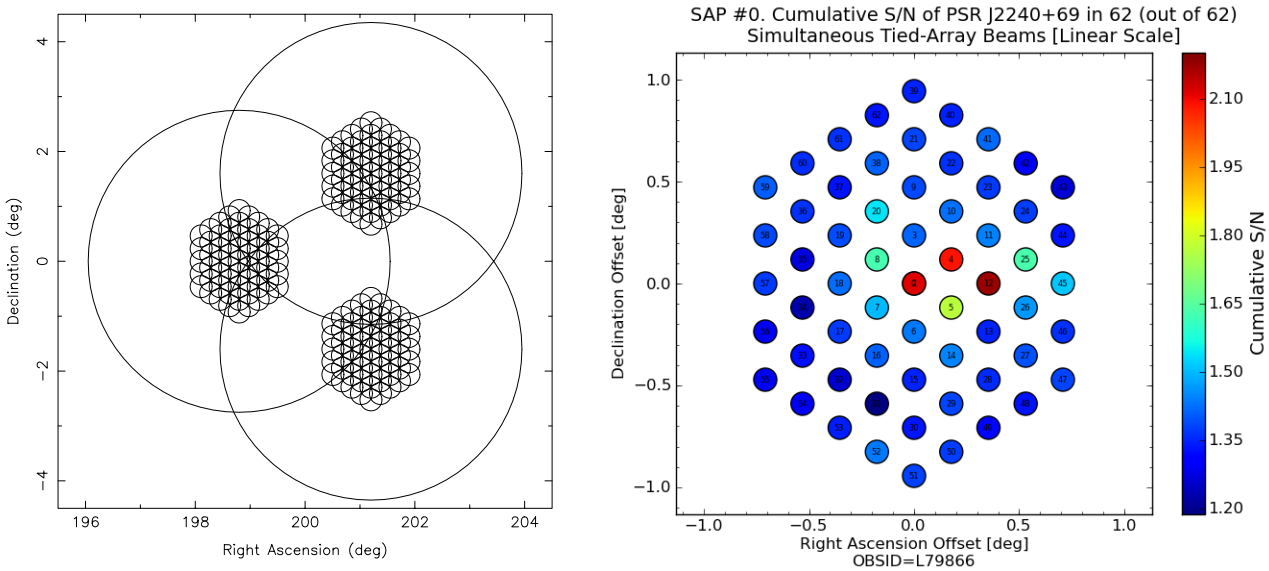

Figure 3: *Left:* Diagram showing the footprint of a single LOTAAS survey pointing. The small circles are 'tied-array' beams formed by coherently summing 12 HBA sub-stations. The larger circles indicate the simultaneous incoherent fields-of-view (which provide larger field-of-view, but at lower sensitivity). *Right:* A pulsar detection as it appears in the multiple tied-array beams of the LOTAAS survey. The color scale shows the signal-to-noise in the various beams. In this way, the source is well localized *and* can be more easily differentiated from radio frequency interference.

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