Pulsar Astrophysics the Next Fifty Years
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Pulsar science with data from the Large European Array for Pulsars

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Abstract. The Large European Array for Pulsars (LEAP) is a European Pulsar Timing Array project that combines the Lovell, Effelsberg, Nançay, Sardinia, and Westerbork radio telescopes into a single tied-array, and makes monthly observations of a set of millisecond pulsars (MSPs). The overview of our experiment is presented in Bassa *et al.* (2016). Baseband data are recorded at a central frequency of 1396 MHz and a bandwidth of 128 MHz at each telescope, and are correlated offline on a cluster at Jodrell Bank Observatory using a purpose-built correlator, detailed in Smits *et al.* (2017). LEAP offers a substantial increase in sensitivity over that of the individual telescopes, and can operate in timing and imaging modes (notably in observations of the galactic centre radio magnetar; Wucknitz 2015). To date, 4 years of observations have been reduced. Here, we report on the scientific projects which have made use of LEAP data.

Keywords. techniques: interferometric, (stars): pulsars: general, (stars:) pulsars: individual (J1713+0747, B1937+21), stars: rotation, (Galaxy:) globular clusters: individual (M28)

1. PSR B1937+21 Giant Pulses

Giant pulses (GPs) are a rare phenomenon (seen in only 14 pulsars) where occasional single pulses of flux densities orders of magnitude greater than the mean are emitted. We have searched for GPs in 3.1×10^7 rotations of PSR B1937+21 with LEAP, detecting 4265 GPs (Figure 1); the largest ever sample of GPs gathered for this pulsar. We have examined the distribution of polarisation fractions of GPs, finding no correlation between GP flux and fractional polarisation, and no correlation between polarisation fraction and pulse phase. We have measured the power law index of the flux distribution to be $\alpha = -3.8 \pm 0.2$, and have noted a low-flux turnover at ~ 4 Jy. We have measured modulation indices for the GPs, and found that they vary by ~ 0.5 towards the centre of the phase distributions, in contrast to the findings of Jenet *et al.* (2001) for the highly-stable regular emission. We compare the timing prospects of PSR B1937+21 using GPs and the average profile separately, and find no improvement when using the GPs for timing. This work is included in McKee (2017), with a paper in preparation.

2. M28 Pulsar Search

Globular clusters (GCs) are dense regions of stars, tightly bound to a gravitational centre. The high stellar density of GCs makes binary formation more likely, giving rise to large populations of binary pulsars and MSPs, and increases the probability of exotic binary systems forming (e.g. pulsar-black hole binaries). For this reason, GCs are attractive targets for pulsar searches (e.g. Hessels *et al.* 2007). The tied-array beam of LEAP is small (max. size: 50 mas), and therefore impractical for blind pulsar surveys,

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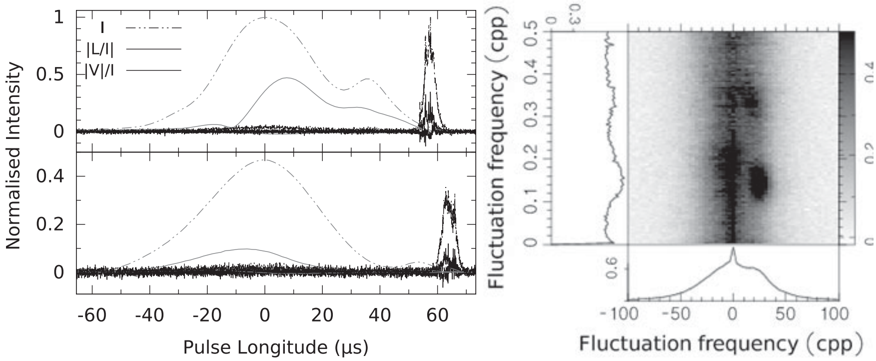

Figure 1. *Left:* PSR B1937+21 Stokes parameters vs. phase of the regular emission (grey) and GP emission (black), averaged over all our observations. The GP emission occurs at the edge of the regular emission regions, with a lag of 58 μs relative to the main pulse and 64 μs to the interpulse, and in both plots we see a small contribution from the regular emission is present in the GP data, indicating that regular emission occurs simultaneously with GP emission. *Right:* PSR J1713+0747 2D fluctuation spectrum, with horizontal and vertical integrations. Two maxima occur at 0.14 and 0.34 cpp, confirming phase-dependent modulation.

but the sensitivity of LEAP makes it well-suited to targeted searches. We are searching for pulsars in GC M28, by first phasing up on the bright MSP B1821−24A (M28A), and then adjusting the measured phase delays to reposition the virtual LEAP beam. As the angular size of M28 (1.56 arcmin) is much larger than our tied-array beam, we focus our search on currently-unclassified X-ray sources within the cluster, which may be associated with unknown MSPs. The ongoing search has produced re-detections of known pulsars within the GC, and will be the subject of an upcoming paper (Wang *et al.* in prep.).

3. PSR J1713+0747 Single Pulses

Single-pulse studies offer an opportunity to understand rotational variability of pulsars. These studies require bright pulsars and highly sensitive instruments, in order to discriminate single pulses from the background noise. We have performed a single-pulse study of PSR J1713+0747, using 197, 000 pulses from when the pulsar was brightly scintillating. Using these data, we confirm the detection of periodic intensity modulation, discovered by Edwards & Stappers (2003), which we demonstrate to be phase-dependent (Figure 1); the first detection of such behaviour in an MSP. The drifting sub-pulses are found to have two modes, with $P_2 = 6.9 \pm 0.1P$, and $P_3 = 2.9 \pm 0.1P$, where P is the spin period. We find that the fractional polarisation scales with flux density, with the brightest pulses being highly linearly-polarised. This work has been published in Liu *et al.* (2016).

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