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Targeted millisecond pulsar surveys of *Fermi* γ-ray sources with LOFAR

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Abstract. We have used LOFAR to perform targeted millisecond pulsar surveys of *Fermi* γ-ray sources. Operating at a center frequency of 135 MHz, the surveys use a novel semi-coherent dedispersion approach where coherently dedispersed trials at coarsely separated dispersion measures are incoherently dedispersed at finer steps. Three millisecond pulsars have been discovered as part of these surveys. We describe the LOFAR surveys and the properties of the newly discovered pulsars.

Keywords. surveys – stars: neutron – pulsars: general – binaries: close

1. Introduction

The Large Area Telescope (LAT) on the *Fermi* γ-ray Space Telescope has given us an unprecedented view of the γ-ray sky. It has higher sensitivity and spatial resolution than previous γ-ray observatories, and as a result, over three thousand γ-ray point sources have been detected in the first 4 years of data (Acero *et al.* 2015). The majority of these sources are associated with different types of γ-ray emitting active galaxies, while a significant fraction (about 9%) are identified as pulsars, particularly energetic millisecond pulsars (MSPs). Radio pulsar surveys of unidentified *Fermi* γ-ray sources have been a very fruitful way for discovering new MSPs (see Ray *et al.* 2012 and references therein), and these surveys have been crucial in determining the nature of the presently unidentified population of γ-ray sources.

To date, targeted MSP surveys of unidentified *Fermi* γ-ray sources have performed at observing frequencies above 300 MHz (e.g. Cognard *et al.* 2011; Hessels *et al.* 2011; Keith *et al.* 2011; Ransom *et al.* 2011). Since the radio emission from pulsars generally exhibit steep spectra (Maron *et al.* 2000; Bates *et al.* 2013), these survey may potentially miss MSPs with very steep spectra. Here, we present the results of targeted surveys for MSPs towards *Fermi* γ-ray sources with LOFAR, using a semi-coherent dedispersion approach to limit the effects of dispersion.

2. Survey description

We used LOFAR to perform two targeted surveys for radio MSPs towards *Fermi* γ-ray sources. The first, a pilot survey, targeted 52 unassociated γ-ray sources from the 3FGL catalog by Acero *et al.* (2015), while the second survey used unpublished data to select 72 *Fermi* γ-ray sources with pulsar-like spectral and variability properties. All sources were located outside of the Galactic plane with $|b| > 10°$, visible to LOFAR (elevations $> 30°$) and well localized (95% confidence uncertainty region less than $10'$ in diameter). All sources were observed with the high-band antennas (HBAs) of 21 LOFAR core stations (van Haarlem *et al.* 2013), where the LOFAR beamformer was configured to form 7 tied-array beams, covering a $10'$ diameter field-of-view, each producing dual-polarization, complex, Nyquist sampled timeseries over 39 MHz of bandwidth centered at a frequency of 135 MHz. Integration times of 20 min were used in all cases, using single observations for the pilot survey, and two observations, separated by a few days, for the second survey. The two separated observations were aimed to improve the probability of detecting short period or eclipsing binary pulsar systems.

To limit smearing due to dispersion, we used a semi-coherent dedispersion approach, where the complex voltage data was first coherently dedispersed to 80 trial dispersion measures (DMs) at steps of 1 pc cm^{-3} from 0.5 to 79.5 pc cm^{-3} using the GPU accelerated `cdmt` software (Bassa *et al.* 2017a). For the pilot survey the resulting filterbanks had time and frequency resolution of 40.96 μs and 24.41 kHz, respectively, while the second survey reduced the resolution to 81.92 μs and 48.82 kHz to improve processing times, without significantly reducing sensitivity. A GPU accelerated brute force incoherent dedispersion algorithm (Barsdell *et al.* 2012) was used to dedisperse the filterbank files at steps of 0.002 pc cm^{-3} from -0.5 to 0.5 pc cm^{-3} around the coherent DM. All of the 40 000 dedispersed timeseries were searched for periodic signals using frequency domain acceleration searching, using a GPU accelerated algorithm implemented in `PRESTO` (Ransom 2001; Ransom *et al.* 2002). Standard sifting and folding tools from the `PRESTO` suite were used to assess pulsar candidates.

The survey sensitivity is estimated at about 2 mJy for millisecond spin periods (Pleunis *et al.* 2017). The semi-coherent dispersion method corrects for the smearing due to dispersion, and hence the survey sensitivity is ultimately limited by multi-path scattering. The Bhat *et al.* (2004) scattering relation predicts scattering to become dominant above DMs of 40 and 80 pc cm^{-3} for 1 and 10 ms spin periods, respectively (Pleunis *et al.* 2017). Since these surveys specifically target sources at high Galactic latitude, on average, the maximum DM is less than 50 pc cm^{-3}, and smearing due to scattering is not expected to be a dominant effect.

3. Pulsar discoveries

The LOFAR surveys described here resulted in the discovery of three new radio MSPs. Their pulse profiles are shown in Figure 1. The first, PSR J1552+5437, was found in the pilot survey observation of γ-ray source 3FGL J1553.1+5437, and is an isolated pulsar with a 2.43 ms spin period at a DM of 22.90 pc cm^{-3}. Folding of the 7 yr of *Fermi* LAT γ-ray photons yields a phase coherent timing ephemeris, and a γ-ray pulse profile that appears to be aligned with that in the radio. Non-detections of the pulsar at 820 MHz

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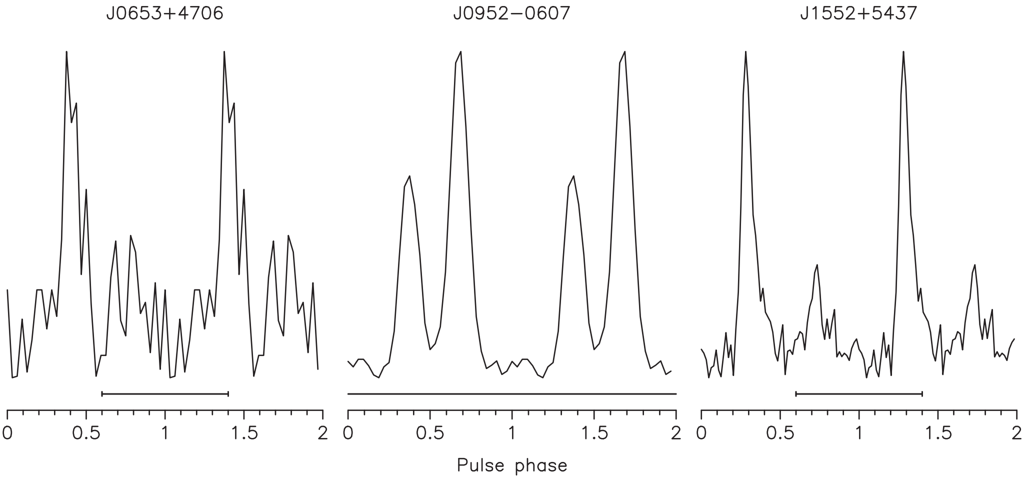

Figure 1. Pulse profiles taken from the discovery observations. Two pulse periods are shown. The horizontal error bar denotes the dispersive smearing in the absence of coherent dedispersion.

and 1.5 GHz indicate PSR J1552+5437 has a steep radio spectrum, for $S_\nu \propto \nu^\alpha$ with $\alpha < -2.8(0.4)$. This discovery has been published by Pleunis *et al.* (2017).

PSR J0952−0607 was the second LOFAR MSP discovery. With a spin period of 1.41 ms and DM = 22.41 pc cm^{-3}, it is the second fastest spinning pulsar known. Its spin frequency of $\nu = 707$ Hz is 9 Hz slower than the fastest MSP discovered, Terzan 5ad ($\nu = 716$ Hz; Hessels *et al.* 2006). The pulsar is in a 6.42 hr binary system with an optically detected *black widow* companion. Remarkably, even at the low observing frequencies of LOFAR, no radio eclipses are seen. Like PSR J1552+5437, J0952−0607 also has a steep radio spectrum, with $\alpha \sim -3$, being detectable at 150 MHz with LOFAR and 350 MHz with the GBT. This discovery has been published by Bassa *et al.* (2017b). Analysis of the *Fermi* γ-ray data is ongoing.

The third MSP discovered by LOFAR is PSR J0653+4706. It has a 4.75 ms spin period and a DM of 25.54 pc cm^{-3}. The pulsar is a member of a 5.84 d binary system with a $M_c \gtrsim 0.21\,M_\odot$ companion. PSR J0653+4706 is also visible with the GBT at 820 MHz and at 1.5 GHz with the Lovell telescope (under favorable scintillation), indicating the radio spectrum of PSR J0653+4706 is not as steep as the other two LOFAR discoveries. Its location on the sky may make it a suitable addition to pulsar timing arrays.

4. Discussion

The discovery of these three radio MSPs, being the first discovered with digital aperture arrays through their pulsations, shows the promise of pulsar surveys at low frequencies with LOFAR, the MWA, LWA and SKA1-Low. The crucial ingredient in their discovery is the use of coherent dedispersion to remove dispersive smearing.

The steep radio spectra of PSRs J0952−0607 and J1552+5437 add to the emergent picture in which the fastest spinning pulsars have the steepest spectra. Recent studies with LOFAR (Kondratiev *et al.* 2016) and the GMRT (Frail *et al.* 2016) show that the majority of MSPs with spin frequencies larger than $\nu > 300$ Hz ($P < 3.33$ ms) have spectra steeper than $\alpha < -2.5$. Furthermore, Kuniyoshi *et al.* (2015) and Frail *et al.* (2016) found that MSPs seen in γ-rays tend to have steep radio spectra. These systems typically have aligned radio and γ-ray profiles (Espinoza *et al.* 2013; Johnson *et al.* 2014), as seems the case for PSR J1552+5437 (Pleunis *et al.* 2017). It is suggestive that these

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tendencies are pointing to a commonality, possibly related to the small light cylinder of fast spinning MSPs, forcing the co-location of γ-ray and steep spectrum radio emission.

After presenting these results at the IAU337 symposium there was some discussion on whether the tendency that the fastest spinning MSPs have the steepest radio spectra is an observational bias in their discovery or an intrinsic property of these pulsars. As an argument in favor of a discovery bias, Terzan 5ad, the fastest spinning MSP ($\nu = 716$), was mentioned as it was discovered and timed at S-band (Hessels *et al.* 2006; Prager *et al.* 2017). Arguments against the steep spectra being a bias in discovery revolved around the inherent difficulty, due to scattering and dispersion, of discovering fast spinning MSPs at low versus high observing frequencies. As part of this discussion, Scott Ransom was willing to bet that the tendency is due to observational bias. Scott's bet was taken on by Joeri van Leeuwen, where the loser shall make the winner a bottle of steeped liquor (such as a citrus-infused gin or bacon-steeped vodka), if the majority of the tendency is confirmed as being an intrisic MSP property or an observational within 5 years of the IAU337 symposium.

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