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FROM FERMI-LAT OBSERVATIONS TO THE BLIND PULSAR SURVEY SPAN512 WITH THE NANÇAY RADIO TELESCOPE

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Abstract. Since the discovery of the first pulsar in 1967, we know over 2500 pulsars today. Pulsars offer a broad range of studies: from the study of the properties of interstellar medium and of pulsar magnetospheres up to test of gravity in the strong-field regime and the characterisation of the cosmological Gravitation Wave Background. This explains why we keep searching for pulsars nowadays. Such focus was initiated at the Nançay Radio Telescope (NRT) with the observation of unidentified Fermi-LAT sources, which led to the quick discovery of three new millisecond pulsars. In 2012, a blind pulsar survey called SPAN512 (in reference to the large bandwidth of 512 MHz) was initiated and the NRT began to observe the low galactic latitude sky at 1.4 GHz. This survey is still in progress ($\approx$ 90% of the observations have been made) and, up to now, it has led to the discovery of three pulsars, two of them with millisecond spin periods.

Keywords: pulsar, radio telescope, survey, SPAN512

1 The Nançay Radio Telescope

The Nançay Radio Telescope (NRT), inaugurated in 1965, is a transit telescope with a 4'(Right ascension α) $\times$ 22' (Declination δ) power beam and is equivalent to a 94-m diameter parabolic dish. With such configuration, a source with a declination $\delta > -39°$ can be observed for at least one hour per day when it passes through the meridian. The telescope was initially designed for the observation of galaxies, comets and star envelopes at 1.4 GHz, which corresponds to the frequency of the emission line of the neutral Hydrogen. An intensive program of pulsar observations is in progress since 2004. The NRT produces high quality data for pulsar timing array (PTA, hereafter) projects whose aim consists in detecting the Gravitational Wave signature of the population of massive binary black holes (Desvignes et al. 2016). The Nançay Ultimate Pulsar Processing Instrument, which started to operate in late 2011, is a baseband recording system using a digitizer made of FPGA board developed by the CASPER group (ROACH, Reconfigurable Open Architecture Computing Hardware*) and a computing machine made of Central Processing Units (CPUs) and Graphics Processing Units (GPUs). Here the analog-to-digital converters firstly sample and digitise (in 8-bit) the signal over a 512 MHz band at the Nyquist rate with dual polarisations. A polyphase filter bank channelises the band into 128 channels, each of 4 MHz width. The channels are then packetised into four sub-bands and sent to four GPU clusters for real-time coherent dedispersion (timing mode). The modularity of the aforementioned system easily allows us to divide the bandwidth into 1024 channels in search mode (survey mode, Desvignes et al. 2013). The raw data are then decimated in time to produce dynamic spectra written into 4-bit PSRFITS format (Hotan et al. 2004).

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The signal received from a pulsar is dispersed by free electrons and ionised material encountered along the line of sight. To correct for this physical phenomenon, a delay proportional to the so-called dispersion measure (DM) and to the inverse square law frequency, is applied to each frequency channel. In survey mode, data are analysed with pulsar searching software like PRESTO (Ransom et al. 2002) and Radio Frequency Interference (RFI) caused by human activities is removed by identifying strong narrow-band signals. At this stage in the analysis, the times of each data acquisition are corrected for the delay between the observatory and the solar system barycentre. Then, the time series produced are Fourier transformed using a fast Fourier transform followed by a harmonic summing routine. A search in acceleration is also performed to look for pulsars in binary system which may be accelerated by a companion star. The output is a list of candidates whose informations like potential periods (P), accelerations, signal-to-noise ratio (S/N), coherent power, number of summed harmonics, etc. are recorded. Candidates with S/N above 6 are folded. As pulsars are generally very weak sources, the addition of many pulses in phase is necessary to increase the S/N and make them detectable. The strategy adopted for pulsar surveys consists in dedispersing data exploring the whole range of dispersion measure (from 0 up to 1800 pc.cm^{-3}) and fold candidates with the best signal-to-noise ratio. Such procedure was applied in 2011, pointing at the position of a dozen of unidentified Fermi-LAT sources. This led to the fast discovery of three new millisecond pulsars: PSR J2043+1711 (Guillemot et al. 2012), PSR J2302+4442 and PSR J2017+0603 (Cognard et al. 2011).

2 The SPAN512 survey conducted with the Nançay Radio Telescope

Motivated by the aim to discover exotic pulsar systems and, more specifically, millisecond pulsars (MSPs, hereafter), whose spin stability might be very suitable for PTA programs, the pulsar survey SPAN512 (Desvignes et al. 2013) has been conducted at Nançay since 2012. This survey inspects the sky at L-band at intermediate galactic latitudes ($3.5^\circ < |b| < 5^\circ$) away from the inner Galaxy ($74^\circ < l < 150^\circ$). Figure 1 shows the extent of the survey on the sky. The large bandwidth of 512 MHz and the fine time resolution of 64 μs allow this survey to be sensitive to very faint and distant MSPs. Moreover, the long integration time of 18 minutes increases the likelihood of detecting transient pulsars (Rotating Radio Transients, intermittent pulsars... See Lyne 2009 and Keane & McLaughlin 2011 for reviews) and the total observing time predicts the detection of at least one Fast Radio Burst (Thornton et al. 2013; Petroff et al. 2016). A total of 50 Terabytes of data have been produced from the 6 034 sky pointings which amount to 1740 hours of observing time. All the data were processed at the IN2P3 supercomputer in Lyon[†]. The processing consisted in applying the steps described in Section 1 to analyse survey data. The acceleration search is sensitive to object with an orbital period roughly ten times longer than the observing time. To search for very short orbital period objects, we split the observations into two parts and analyse them separately, making the acceleration search more efficient. After the processing, 750 000 candidates were produced. We then needed to select the most promising ones, to be reobserved and possibly confirm. This selection task may be very laborious and human eye inspection makes it very subjective. One approach was to use a Neural Network algorithm, such as the one developed by Zhu et al. 2014. This Neural Network estimates the probability of a candidate to be a pulsar using Image Pattern Recognition and allows the astronomer to inspect fewer candidates. After inspection, a list of around 60 candidates have been prioritised for re-observation.

3 Results: Discovery of three new pulsars

Soon after the beginning of the observations in 2012, the SPAN512 survey revealed two new pulsars: PSR J2048+49 (P $\approx$ 0.56 s and DM $\approx$ 221 pc.cm^{-3}) and PSR J2205+60 (P $\approx$ 2.4 ms and DM $\approx$ 157 pc.cm^{-3}). The pulse profile of J2205+60 is very thin. This characteristic, together with the expected stability of an MSP could make PSR J2205+60 one of the pulsars used to search for Gravitational Waves through Pulsar Timing Arrays (Desvignes et al, in prep). Recently, using the (Zhu et al. 2014) Neural Network, we have discovered a new 2.08-ms pulsar, PSR J2055+38 (see Fig. 2). From November 2015 up to now, 27 observations of this pulsar have been recorded at 1.4 GHz and a timing analysis is in progress. The position and the period derivative are not yet very well known and more data need to be collected to improve the timing solution. However, the current data allowed us to obtain a phase-connected solution and to assert that the new pulsar discovered is in a Black Widow (BW) system (see Freire 2005 and Roberts 2013 for reviews) where the pulsar is ablating its

[†] `http://cc.in2p3.fr/`

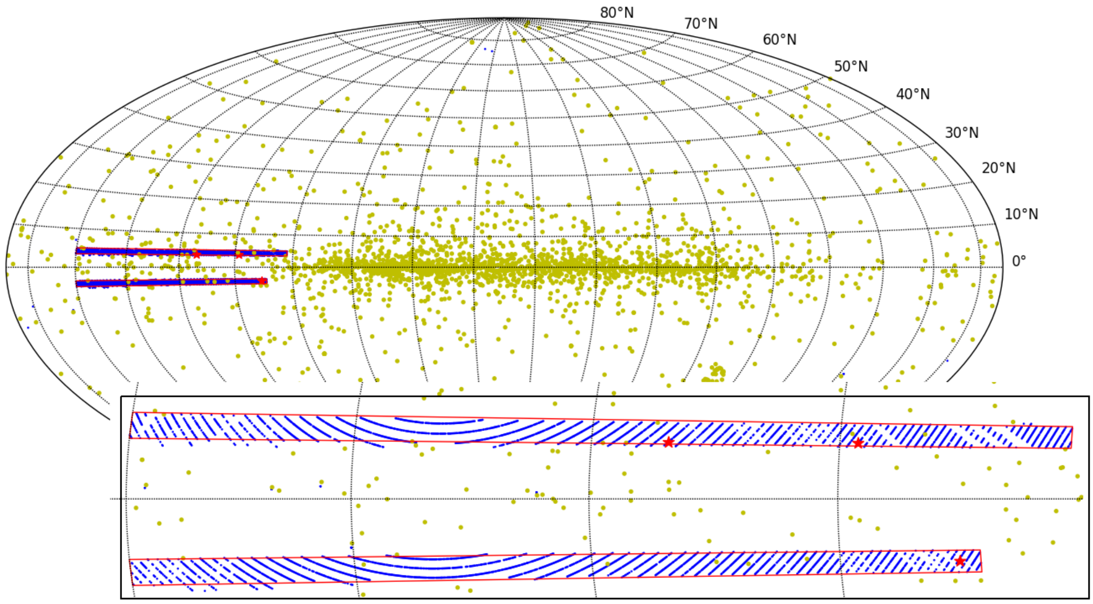

Fig. 1. Pulsar survey SPAN512 coverage is shown in the red squares. The blue points represent beams already pointed in the sky. In green, this is the distribution of the already known pulsars. The red stars are the pulsars discovered with the SPAN512 survey.

companion and the mass lost by the companion creates clouds of ionized material. Almost every BW system exhibits more or less variable eclipses in their radio signal. At 1.4 GHz, PSR J2055+38 is no exception, as it found to be eclipsing for around 10% of its orbit around the orbital phase $\phi \approx 0.25$ (see Fig. 2).

4 Conclusions and perspectives

A blind pulsar survey SPAN512 is being conducted with the NRT to scan the intermediate Galactic latitudes. Although this survey is not finished, it allowed us to discover three new pulsars, two of them having millisecond spin periods. We need to collect more data to study one of the pulsars discovered, PSR J2055+38, an eclipsing BW pulsar. Even if most of BW pulsars are not suitable for PTAs due to their chaotic nature, the study of the variations of the intra-binary ionised material can help us to have better insights about the formation process of millisecond pulsars and about the pulsar surroundings. Even if there is no source in Fermi-LAT catalogs near the position of PSR J2055+38, most of BW pulsars have a γ-ray counterpart. Hence, we hope to be able to detect γ-ray pulsations from this pulsar using the radio timing ephemeris.

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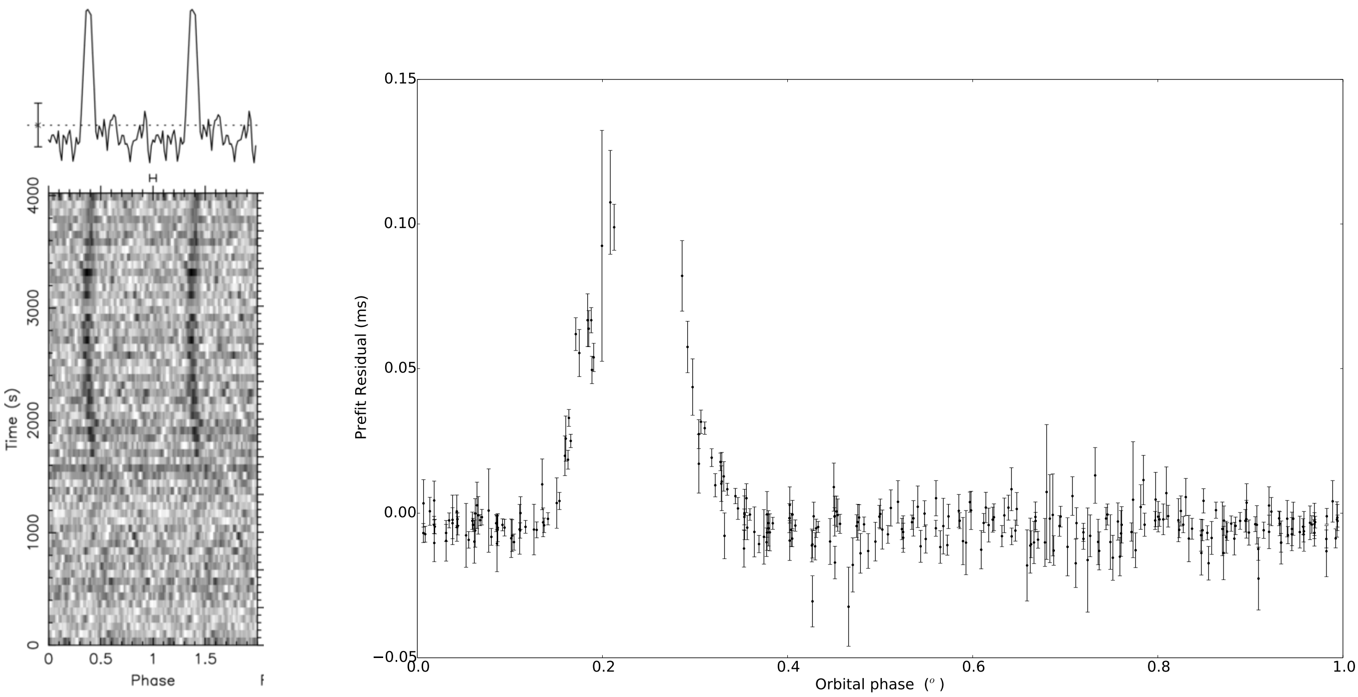

Fig. 2. Left: Profile of PSR J2055+38. We can notice the presence of eclipse during the observation. **Right:** Timing residuals for PSR J2055+38, eclipses occur at the orbital phase $\phi \approx 0.25$.

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