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Arecibo and the ALFA Pulsar Survey

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Abstract The recently started Arecibo L-band Feed Array (ALFA) pulsar survey aims to find ~ 1000 new pulsars. Due to its high time and frequency resolution the survey is especially sensitive to millisecond pulsars, which have the potential to test gravitational theories, detect gravitational waves and probe the neutron-star equation of state. Here we report the results of our preliminary analysis: in the first months we have discovered 21 new pulsars. One of these, PSR J1906+0746, is a young 144-ms pulsar in a highly relativistic 3.98-hr low-eccentricity orbit. The $2.61 \pm 0.02\ M_{\odot}$ system is expected to coalesce in ~ 300 Myr and contributes significantly to the computed cosmic inspiral rate of compact binary systems.

Key words: pulsars: general — pulsars: individual (PSR J1906+0746) — surveys

1 INTRODUCTION

Radio pulsars continue to provide unique opportunities for testing theories of gravity and probing states of matter otherwise inaccessible (Stairs 2003), and in large samples they allow detailed modeling of the Galactic neutron star population (Bhattacharya et al. 1992; Arzoumanian et al. 2002).

For these reasons, we have initiated a large-scale pulsar survey (Cordes et al. 2005, hereafter Paper I) that aims to discover pulsars in short-period relativistic orbits to test gravitational theories in the strong-field regime, and millisecond pulsars (MSPs) with ultrastable spin rates that can be used as detectors of long-period ($>$ years) gravitational waves (e.g. Lommen & Backer 2001). Furthermore, long-period ($P > 5$ s) and strongly magnetised pulsars may clarify the connection with magnetars, and the nature of the elusive radio emission mechanism. Additionally, determining the pulsar velocity distribution will help constrain aspects of the formation of neutron stars in core-collapse supernovae (e.g. Willems et al. 2004).

The new survey is enabled by several innovations. First is the Arecibo L-band Feed Array (ALFA), a seven-beam feed and receiver system designed for large-scale surveys in the 1.2–1.5 GHz band. The 1.4 GHz operating frequency of ALFA is particularly well suited for pulsar searching of the Galactic plane. Lower frequencies suffer the deleterious effects of pulse broadening from interstellar scattering and dispersion, while pulsar flux densities typically are much reduced at higher frequencies. The ALFA frontend is similar to the 13-beam system used for the extremely prolific Parkes multibeam (PMB) pulsar survey of the Galactic plane (Manchester et al. 2001). Our survey will complement the PMB survey in its sky coverage.

Second, our initial and next-generation spectrometer systems have much finer resolution in both time and frequency than the spectrometer used with the PMB, increasing the detection volume of MSPs by an

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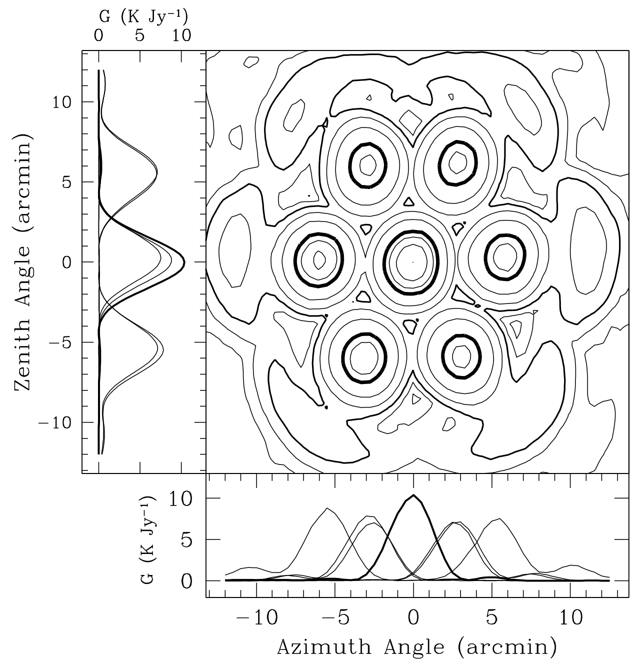

Fig. 1 Contours of the ALFA telescope gain. Levels are at –1, –2, –3, –6, –9, –12, –15 and –19 dB from the central peak. The equivalent circular beam width (FWHM), averaged over all beams, is 3.35 arcmin at 1.42 GHz. The on-axis gain is approximately 10.4 K Jy^{-1} for the central beam and ~ 8.2 K Jy^{-1} for the other six beams. The system temperature looking out of the Galactic plane is ~ 24 K. (Paper I; Heiles 2004).

order of magnitude. Additionally, the sensitivity of the Arecibo telescope allows for short pointings that simplify the detection of binary pulsars undergoing strong acceleration.

This sensitivity for relativistic binaries is illustrated by our discovery of the latest binary system PSR J1906+0746 (Lorimer et al. 2006, hereafter Paper II). Since binaries like PSR J1906+0746 will coalesce due to gravitational wave emission well within a Hubble time, their merger rate (e.g. Phinney 1991; Kim et al. 2004) is of great interest to the gravitational wave detector community as potential sources for current interferometers such as LIGO (Abramovici et al. 1992).

Following a brief description of the ALFA survey setup in Section 2 we describe general survey results in Section 3 and our discovery of young, highly relativistic binary pulsar PSR J1906+0746 in Section 4. We conclude in Section 5, and outline our plans for the future.

2 THE ALFA PULSAR SURVEY

The ALFA system sits in the Gregorian focus of the Arecibo telescope and provides seven 3-arcmin $8-10$ K Jy^{-1} beams on the sky (Figure 1). Within a year, new polyphase-filter spectrometers will process the full 300 MHz bandwidth with 1024 spectral channels. Currently the four Wideband Arecibo Pulsar Processor (WAPP) systems (Dowd et al. 2000) record 256 channels every 64 μs, using the 100 MHz band around 1.42 GHz, as that band shows the least radio-frequency interference.

The data are processed twice: during the observations incoming data are transferred to the Arecibo Signal Processor (Demorest et al. 2004), a computer cluster that processes the data in quasi-realtime after reducing the time and frequency resolution to increase throughput. This analysis, described in detail in Paper I, is primarily sensitive to pulsars with $P \gtrsim 30$ ms, which are expected to make up the bulk of all discoveries. In the second processing step the data will be re-analysed on several computer clusters at the home institutions of members of the Pulsar ALFA (PALFA) Consortium. In this step full-resolution data and acceleration searches will be used, increasing sensitivity to MSPs and pulsars in short period binary systems as well as to pulsars with large values of dispersion measure (DM).

With our 134-s integration time, the minimum detectable flux density $S_{\rm min}$ for PALFA is a factor 1.6 smaller than for the PMB survey (Figure 2), implying a maximum distance $D_{\rm max} \propto S_{\rm min}^{-1/2}$ about 1.3 times larger for long-period pulsars. The sampled volume on axis is accordingly about a factor of two larger for long-period pulsars. In our full-resolution analysis, the volume increase is even larger for short periods, owing to the smaller PALFA channel widths and the shorter sample interval. For $P \lesssim 10$ ms, the searched volume increase can be a factor of 10 or more (Paper I).

3 GENERAL RESULTS

Between August 2004 and November 2005 we have used 75 hours of telescope time for 2516 pointings in the Galactic anti-center and 166 hours for 4838 pointings in the inner Galaxy, covering 43 deg^2 and 83 deg^2 in each region respectively (Figure 3). So far we have found 21 new pulsars in the first analysis. Seven of these are in the southernmost region visible from Arecibo. This region was previously covered by the PMB survey, suggesting that our survey indeed already surpasses the depth of the PMB survey in the first analysis. All previously known pulsars were detected in our pointings if they were within one beam radius of one of the ALFA beams. In addition, we detect some strong pulsars several beam radii from the nearest beam center.

4 THE YOUNG, RELATIVISTIC BINARY PULSAR J1906+0746

4.1 Discovery and Follow-Up Observations

PSR J1906+0746 was discovered with a signal-to-noise ratio S/N $\sim$ 11 in data taken on 2004 September 27. The pulsar was 2$'$.5 (1.47 beam radii) from the center of the beam, where the antenna gain is ∼5 times smaller than at its center. PSR J1906+0746 also lies in the region of sky covered by the PMB. Examination of the search output of the 35-minute PMB observation of this position showed a 144-ms periodicity with S/N $\sim$ 7, below the nominal S/N threshold of 8–9. While PSR J1906+0746 appears with S/N $\sim$ 25 in the

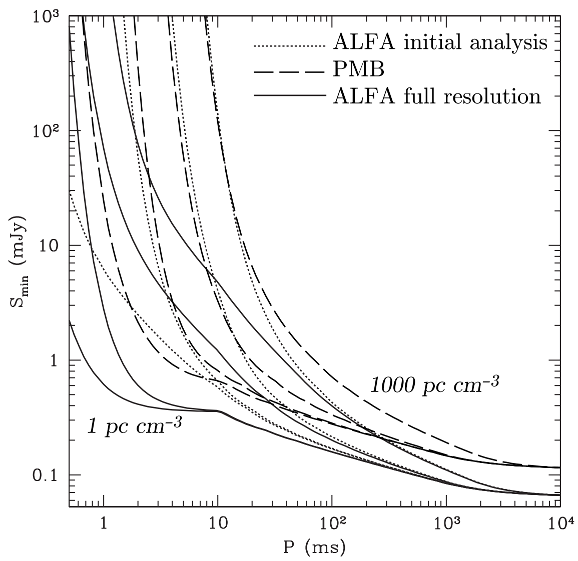

Fig. 2 Theoretical minimum detectable flux density ($S_{\rm min}$) vs. P for different DMs. Real-world effects such as RFI and receiver gain variations will raise the effective threshold of the survey over these lower bounds. Per survey, DM values from the lowest to the highest curve are 1, 200, 500 and 1000 pc cm^{-3}. We assume the intrinsic pulse duty cycle scales as $P^{-1/2}$ with a maximum of 0.3 at 10 ms, hence the breakpoint at that period (Paper I).

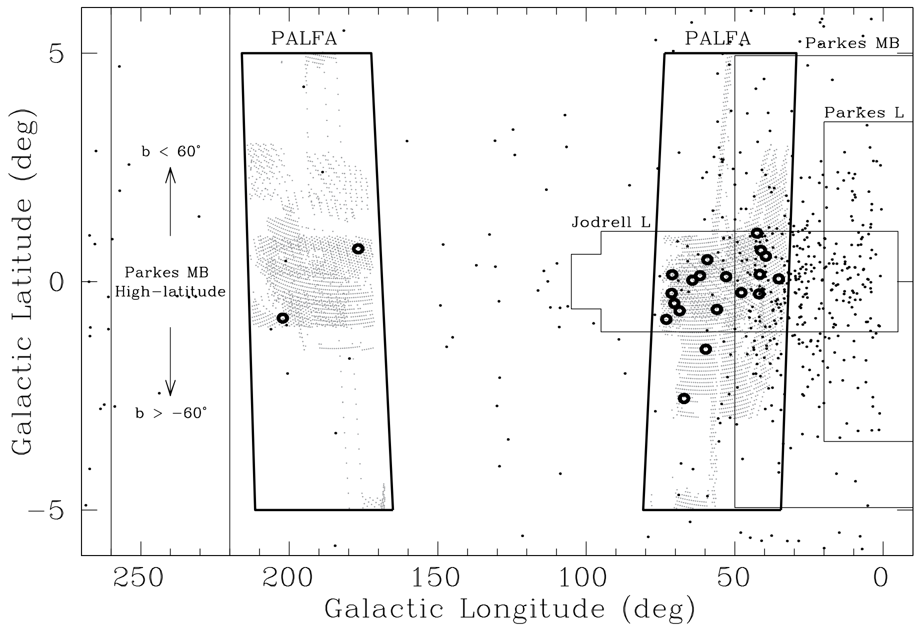

Fig. 3 ALFA surveys regions. Gray dots indicate pointings so far, small black dots designate known pulsars and large circles represent newly discovered pulsars. We also show boundaries of similar L-band surveys: the PMB, Parkes (Johnston et al. 1992), Jodrell Bank (Clifton et al. 1992) and Swinburne PMB High-latitude (Edwards et al. 2001) surveys.

PMB “stack-and-slide” algorithm output (Faulkner et al. 2004), it was not selected as a candidate in the PMB because of significant amounts of radio-frequency interference close to 144 ms.

The high degree of acceleration detected in the PMB observation immediately implied that PSR J1906+0746 is a short-period binary system. Follow-up observations with the Jodrell Bank, Arecibo, Green Bank and Parkes telescopes refined the orbital and spin parameters and the position (Table 1): PSR J1906+0746 is a young object with a characteristic age of 112 kyr and a strong magnetic field ($B = 3.2 \times 10^{19}$). The pulsar is characterized by a narrow main pulse and significant interpulse feature with high linear polarization at 1.4 GHz (Figure 5; Paper II).

4.2 Nature of Companion

From the orbital parameters of PSR J1906+0746, we infer a Keplerian mass function $f(m_\mathrm{p}, m_\mathrm{c}) = (m_\mathrm{c} \sin i)^3/(m_\mathrm{p} + m_\mathrm{c})^2 = 0.11\, M_\odot$. Here m_p is the pulsar mass, m_c is the companion mass and i is the

Table 1 Observed and Derived Parameters of PSR J1906+0746 (Paper II)

Parameter	Value	Parameter	Value
Right ascension (J2000)	$19^\mathrm{h}06^\mathrm{m}48.^\mathrm{s}673(6)$	Projected semi-major axis, x (lt s)	1.420198(2)
Declination (J2000)	$07^\circ 46' 28.6(3)''$	Periastron advance rate, $\dot\omega$ ($^\circ$ yr^{-1})	7.57(3)
Spin period, P (ms)	144.071929982(3)	Dispersion measure, DM (cm^{-3} pc)	217.780(2)
Spin period derivative, $\dot P$	$2.0280(2) \times 10^{-14}$	Rotation measure, RM (rad m^{-2})	+150(10)
Epoch (MJD)	53590	Characteristic age, τ_c (kyr)	112
Orbital period, P_b (days)	0.165993045(8)	Total system mass, M ($M_\odot$)	2.61(2)
Orbital eccentricity, e	0.085303(2)	Spin-down power, $\dot E$ (erg s^{-1})	2.7×10^{35}
Spectral index, α	–1.3(2)	Inferred distance, d (kpc)	~ 5.4
Mass function, f ($M_\odot$)	0.1116222(6)	Coalescence time, τ_g (Myr)	~ 300
Magnetic field, B (Gauss)	1.7×10^{12}	Flux density at 1.4 GHz, S (mJy)	0.55(15)

angle between the orbital plane and the plane of the sky. Our measurement of the orbital periastron advance $\dot{\omega} = 7.57 \pm 0.03\,^\circ$ yr^{-1}, is, after the double pulsar system (Burgay et al. 2003), the second largest observed so far. Interpreting this large value within the framework of general relativity implies that the total system mass $M = m_\mathrm{p}+m_\mathrm{c} = 2.61\pm0.02\,M_\odot$ (Paper II). Measured masses of the neutron stars in double neutron star binary systems range from 1.25 $M_\odot$ (Lyne et al. 2004) to 1.44 $M_\odot$ (Weisberg & Taylor 2003), so it is likely that the mass of PSR J1906+0746 is within these limits. If so, then $1.17\,M_\odot < m_\mathrm{c} < 1.36\,M_\odot$, implying the companion is either a massive white dwarf or another neutron star. For the case of a white dwarf companion, the implication (Dewey & Cordes 1987; Tauris & Sennels 2000) would be that PSR J1906+0746 formed from a binary system of near unity mass ratio in which both stars were below the critical core-collapse supernova mass limit $M_\mathrm{crit} \sim 8M_\odot$. Following a phase in which the accretion of matter from the evolved and more massive primary star onto the initially less massive secondary pushed its mass above M_crit, the secondary underwent a supernova explosion to form the currently observable pulsar.

In the alternative case of a neutron star companion, the small inferred characteristic age and large magnetic field of PSR J1906+0746 suggest that PSR J1906+0746 is the young second-born neutron star, while the companion is a longer-lived recycled pulsar, spun up to a period of a few tens of ms during the accretion phase. We have searched for radio pulsations of this companion but have found none down to a 1.4-GHz luminosity limit of $\sim$ 0.1 mJy kpc^2; only 0.5% of all currently known pulsars (Manchester et al. 2005) have a luminosity below this value.

These deep searches suggest that the companion to PSR J1906+0746 is either: (a) a white dwarf; (b) a faint radio pulsar with a luminosity below 0.1 mJy kpc^2; or (c) a pulsar whose radio beam does not intersect our line of sight. Option (a) will be hard to test, as the ~ 1 Myr old white dwarf will have cooled and dimmed. Option (b) is unlikely to be better testable in the near future (Paper II).

4.3 System Age and Implications for the Compact-Binary Merger Rate

PSR J1906+0746 has the smallest characteristic age ($\tau_\mathrm{c} = 112$ kyr) of any binary pulsar currently known, but we have not found any associated supernova remnant (Paper II).

A simple estimate of the birth rate can be made by considering the cumulative distribution of characteristic ages. Figure 4 shows this distribution for a sub-sample of 150 pulsars detected in the PMB which have inferred magnetic field strengths within 1 dB of PSR J1906+0746 (i.e. $|\log(B) - \log(B_{1906})| < 0.1$). This sample shows a linear trend at small ages with a slope of 45 Myr^{-1}. Since the PMB has only detected one J1906+0746-like pulsar in this sample, the inferred birthrate of *similar pulsars potentially observable in the PMB* is $45/150 = 0.3$ Myr^{-1}. Scaling this rate to the whole Galaxy (Paper II) we estimate the birth

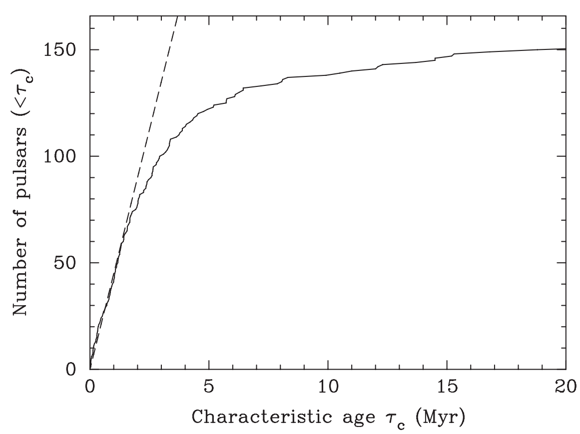

Fig. 4 Cumulative distribution of characteristic ages for pulsars detected in the PMB with similar surface magnetic fields to PSR J1906+0746. The heavy solid line shows the expected trend corresponding to a birthrate of potentially observable objects of 45 Myr^{-1} (see text). Luminosity decay and decreasing beaming fractions make older pulsars harder to detect (Paper II).

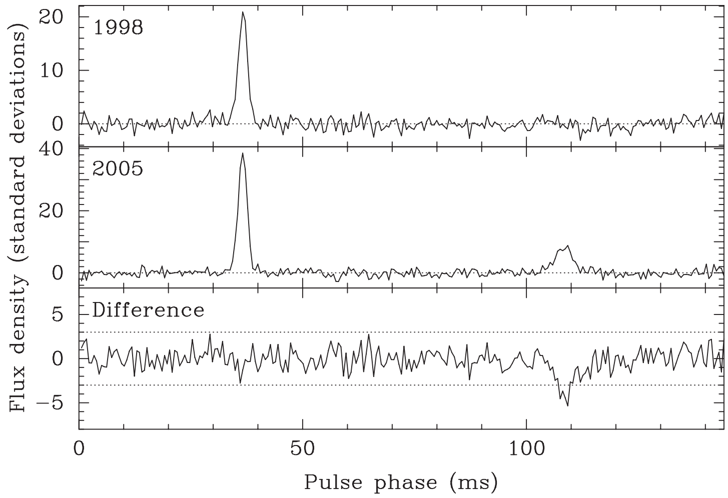

Fig. 5 Pulse profiles, integrated for 35 minutes at 1.374 GHz for PMB 1998 data (top) and PMB 2005 data (middle). The lower panel shows the difference profile after scaling both profiles to the area of the main pulse. The dashed horizontal lines show ± 3 standard deviations computed from the off-pulse noise region (Paper II).

rate of PSR J1906+0746-like objects to be $\sim 60 \times (0.2/f)$ Myr^{-1}, where f is the unknown fraction of 4π sr covered by the radio beam. For a steady-state population this equals the merger rate, and it is similar to that derived recently by (Kalogera et al. 2004) for double neutron star binaries.

The orbital eccentricity of 0.085 for PSR J1906+0746 is remarkably similar to that of PSR J0737−3039 (Burgay et al. 2003), but smaller than observed for other double neutron star systems. For PSR J0737−3039 this could be a selection effect as low-eccentricity systems take longer to coalesce (Chaurasia & Bailes 2005). Only with the detection of further young systems like PSR J1906+0746 will we be able to conclude whether the low eccentricity is a necessary feature of young systems and how this constrains supernova kicks and pulsar formation.

4.4 Pulse Profile Evolution

Pulsars observed in four other relativistic binaries (PSR B1913+16: Weisberg & Taylor 2003; PSR B1534+12: Stairs et al. 2004; PSR J1141−6545: Hotan et al. 2005; PSR J0737−3039B: Burgay et al. 2005) show mean pulse profile variations with time. The simplest explanation for this effect is geodetic precession. The profile variations occur as the precessing pulsar beam changes its orientation with respect to our line of sight.

Figure 5 shows a first comparison between the integrated profiles at 1400 MHz from the 1998 PMB detection and a recent Parkes observation at the same frequency using the same observing system. We have scaled each profile to the area of the main pulse and formed the "difference profile" by subtracting the 2005 profile from the 1998 one. In the absence of any profile evolution, the difference profile should be free from systematic trends and have a standard deviation consistent with the quadratic sum of the off-pulse noise present in the two input profiles. We observe a significant departure from random noise around the interpulse region which is not detectable in the 1998 observation (Paper II). Further observations with better S/N, flux calibration and polarimetric capability are required to confirm and quantify these changes.

4.5 Prospects

Future radio timing and polarimetric observations of PSR J1906+0746 should allow the study of several relativistic effects. The very narrow pulse shape observed means that our current Arecibo TOAs have an uncertainty of $\sim 5\mu$s in a 5-min integration. Simulations based on this level of precision show that we expect to measure the gravitational redshift and time dilation parameter, γ, within the coming year and, within a few years, measure the rate of orbital decay, $\dot{P}_b$. Such measurements would determine the orbital inclination and masses of the stars so that the system could possibly be used for further tests of general relativity. Assuming reasonable ranges for the pulsar mass, the orbital inclination angle is likely to be in the range $42° < i < 51°$. For this range of inclinations, a measurement of the Shapiro delay is less likely at the present level of precision. The distance to PSR J1906+0746 is currently estimated using the Cordes & Lazio (2002) electron density model. As for PSR B1913+16, kinematic contributions to $\dot{P}_b$, which depend on the assumed location in the Galaxy and hence the distance, are likely to be a limiting factor for high-precision tests of general relativity with this system. We are currently attempting to obtain independent distance constraints via the detection of neutral hydrogen absorption and emission.

Comparing pulse profiles taken in 1998 and 2005, we have found some evidence for long-term evolution of the pulse profile. Given that the expected geodetic precession period is only ~ 200 yr, the observed variations could be the first manifestations of this effect. Future observations with high time resolution and polarimetric capabilities should provide more quantitative insights.

5 CONCLUSIONS AND FUTURE WORK

We have described the initial stages of a large-scale survey for pulsars using ALFA, the seven-beam system at the Arecibo Observatory that operates at 1.4 GHz. Our discovery of 21 new pulsars, including a young 144-ms pulsar in a highly relativistic 3.98-hr orbit about a $> 0.9\ M_\odot$ companion, using a preliminary data acquisition system and analysis is very encouraging.

The full ALFA survey will take more than five years, depending largely on allocation of telescope time. Numerical models of the pulsar population, calibrated by results from the PMB survey and incorporating measured characteristics of the ALFA system, suggest that as many as 1000 new pulsars will be discovered with the new spectrometer and the full-resolution analysis. That substantial increase of the number of known pulsars will not only improve our understanding of the galactic neutron star population, but also promises to contain individual systems that probe new regions of physics.

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