Binary Radio Pulsars
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New Binary and Millisecond Pulsars from Arecibo Drift-Scan Searches

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Abstract. We discuss four recycled pulsars found in Arecibo drift-scan searches. PSR J1944+0907 has a spin period of 5.2 ms and is isolated. The 5.8-ms pulsar J1453+19 may have a low-mass companion. The isolated 56-ms pulsar J0609+2130 is possibly the remnant of a disrupted double neutron star binary. The 41-ms pulsar J1829+2456 is in a relativistic orbit; its companion is most likely another neutron star.

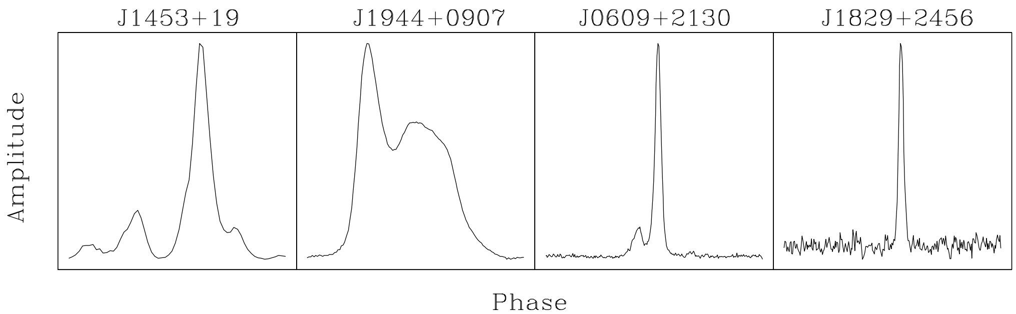

Figure 1. Integrated pulse profiles for the new pulsars. Each plot shows 360° of rotational phase.

1. Introduction

Recycled pulsars are believed to be formed when an old neutron star is spun up through the accretion of matter from a binary companion (Bisnovatyi-Kogan & Komberg 1974). For those companions massive enough to explode as a supernova, the binary lifetime is relatively short ($\sim 10^6 - 10^7$ yr) and the most likely outcome is the disruption of the binary. Those systems which survive the explosion are the double neutron star (DNS) binaries. For less massive companions, where the period of spin-up is longer ($\sim 10^8$ yr), the collapse leaves a white dwarf star in orbit around a rapidly spinning millisecond pulsar (MSP). Of the roughly 1700 known radio pulsars, only 100 are MSPs and less than 10 are in DNS systems. In order to understand the population of recycled pulsars in detail, a larger sample is required. Here we describe the implications for four recycled pulsars recently detected in Arecibo drift-scan searches.

2. Data Acquisition and Analysis

The data were taken with the Arecibo telescope at 430 MHz in drift-scan mode. A source drifts through the $10'$ beam in ~ 42 s. The incoming signals were passed to the Penn State Pulsar Machine (PSPM) which summed the two independent polarizations before 4-bit sampling the band into 128×60 kHz channels every $80\,\mu$s. The data were written directly to magnetic tape and later processed using COBRA, Jodrell Bank's 182-node Linux cluster. Processing consisted of dedispersion over a range of trial dispersion measures (DMs), Fourier transforms of length 2^{19}-pts and a single-pulse search. RFI mitigation was achieved by creating spectral masks based on consecutive 0-DM time series. For further details, see Lorimer et al. (2004). Analysis of data corresponding to roughly 1700 deg^2 of sky has resulted in the discovery of 12 new pulsars. We discuss here only the four these new pulsars that are recycled. In Figure 1, we show the pulse profiles of these pulsars.

We are carrying out regular Arecibo timing observations of all the new pulsars using the PSPM. Table 1 shows a phase-connected timing solution spanning 500 days for PSR J1944+0904. Solutions for J0609+2130 and J1829+2456 can be

Table 1. Observed and derived parameters for J1944+0907

Parameter	Value
Right ascension (h:m:s) (J2000)	19:44:09.321(4)
Declination (deg:m:s) (J2000)	09:07:23.25(1)
Spin period, P (ms)	5.185201903773(2)
Epoch of period (MJD)	52845.0
Timing data span (MJD)	52595–53093
Period derivative, $\dot{P}$ ($\times 10^{-20}$ s s^{-1})	1.65(5)
Dispersion measure, DM (cm^{-3} pc)	24.093(5)
Characteristic age, τ (Gyr)	5.0
Magnetic field strength, B (10^8 G)	3.0
Distance, d (kpc)	1.8

The numbers in parentheses represent uncertainties in the least significant digit. The characteristic age and magnetic field are calculated by the standard Manchester & Taylor (1977) formulae.

found in Lorimer et al. (2004) and Champion et al. (2004) respectively. We do not currently have a solution for PSR J1453+19.

3. Two New Millisecond Pulsars

We discovered two MSPs in our searches. While we do not yet have a phase connection for J1453+19, we can certainly rule out a "regular" $0.3\,M_\odot$ white-dwarf companion. Further observations of the pulsar are underway. The isolated 5.8-ms pulsar J1944+0907 scintillates strongly at 430 MHz (see Fig. 2), with scintillation bandwidth and timescale of $\Delta\nu = 180$ kHz and $\Delta t = 101$ s. For its DM-derived (Cordes & Lazio 2002) distance of 1.8 kpc, this implies a transverse velocity of 114 km s^{-1}.

As shown in Table 2, including J1944+0907, and possibly J1453+19, there are now 14(15) isolated MSPs in the Galactic disk. We do not include isolated MSPs in globular clusters in this table as their formation processes may be quite different. How have these isolated MSPs in the disk formed? It is possible that they are formed through the accretion induced collapse of white dwarfs (Bailyn & Grindlay 1990) or through white dwarf mergers (Michel 1987). Another possibility is that the companions of these pulsars have been destroyed by ablation or tidal disruption (Bhattacharya & van den Heuvel 1991; Radhakrishnan & Shukre 1986). If this is the case, we might expect isolated MSPs to have higher velocities than binaries because closer binaries are more likely to suffer from these effects, and closer binaries are expected to have average higher velocities (Tauris & Bailes 1996). Measurements of isolated MSP velocities are therefore important for determining their origin. With DM-derived distances of 1.2 and 1.8 kpc for J1453+19 and J1944+0907, respectively, proper motion

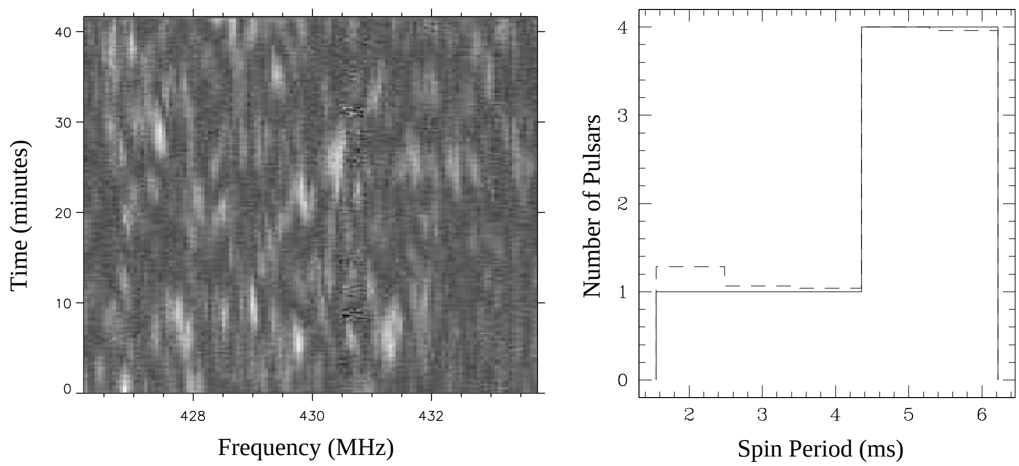

Figure 2. Left: Dynamic spectrum (i.e., on-pulse intensity versus time and frequency) for J1944+0907 at 430 MHz. The spectrum was formed with 10-s integrations and using the PSPM, with 128 frequency channels across the 7.68-MHz bandwidth. Right: Solid line shows the distribution of spin period for MSPs detected in Arecibo drift-scan searches. The dashed line shows the distribution corrected for sensitivity losses at short periods.

measurements may be possible with long-term timing. At our current level of precision, we should be able to confirm our scintillation speed measurement for J1944+0907 by the end of 2005.

In Table 2, we list transverse velocities for isolated MSPs inferred from timing proper motion or scintillation measurements (Toscano 1999; Gothoskar & Gupta 2000; Nicastro et al. 2001). The average velocity of isolated MSPS is roughly $70\,\mathrm{km\,s^{-1}}$, slightly lower than the average velocity of the binary millisecond pulsar population (e.g., Nicastro et al. 2001) and in contrast to what is expected if these isolated MSPs have ablated or tidally disrupted their companions. However, because the velocity determinations for MSPs depend on their largely uncertain distances, this conclusion is tentative.

In total, Arecibo drift-scan surveys have detected 11 pulsars (new and previously known) with periods less than 10 ms (Ray et al. 1995; Camilo et al. 1996; Ray et al. 1996; Lommen et al. 2000). In Figure 2, we show the distribution of spin periods along with a distribution corrected for the loss of sensitivity at short spin periods due to dispersion, scattering, and our finite sampling interval. If we naively assume that the actual distribution of spin periods is uniform and apply the analysis of Chakrabarty et al. (2003), we find that the minimum spin period of this distribution (at 95% confidence) is 1.2 ms. In their analysis of millisecond oscillations from X-ray bursters, Chakrabarty et al. found a minimum spin period of 1.3 ms. These limiting periods are much higher than those predicted by standard neutron star equations of state (e.g., Cook et al. 1994), suggesting that some other mechanism limits the minimum spin period. One possibility is

Table 2. Isolated millisecond pulsars. Distances are derived from Cordes & Lazio (2002). Scintillation-derived velocities are italicized.

Pulsar	P (ms)	DM (pc cm^{-3})	D (kpc)	V_t (km s^{-1})
J0030+0451	4.87	4.33	0.3	$<$ *15*
J0711−6830	5.49	18.4	0.9	87
J1024−0719	5.16	6.49	0.4	124
J1453+19	5.79	14.2	1.2	
J1629−6902	6.00	29.5	1.0	
J1709+2313	4.63	26	1.4	89
J1721−2457	3.50	47.8	1.3	
J1730−2304	8.12	9.61	0.5	*56*
J1744−1134	4.08	3.14	0.4	36
J1843−1113	1.85	59.96	2.0	
J1905+0400	3.78	25.7	1.3	
B1937+21	1.56	71.0	3.6	79
J1944+0907	5.19	24.1	1.8	*114*
J2124−3358	4.93	4.62	0.3	53
J2322+2057	4.81	13.4	0.8	80

that gravitational radiation can carry away angular momentum from accreting neutron stars (Wagoner 1984; Bildsten 1998).

4. New Recycled Pulsars

In Lorimer et al. (2004), we proposed that J0609+2130 is a disrupted double neutron star binary. Simulations (e.g., Portegies Zwart & Yungelson 1998) show that, given standard evolutionary scenarios and kick velocities, we expect roughly 10 disrupted systems to every DNS. Therefore, why do we not observe more pulsars like J0609+2130? One reason may be that the standard assumptions used in simulations about evolutionary scenarios and kick velocities are incorrect. Measuring proper motions of recycled pulsars may provide insights into their evolutionary histories. We expect to measure or constrain the proper motion of PSR J0609+2130 through our on-going timing observations.

The 41-ms pulsar J1829+2456 is in a relativistic 28-hr orbit of eccentricity 0.13 (Champion et al. 2004). From the measurement of periastron advance, we find the total mass of the system to be 2.4 $M_\odot$ and constrain the minimum companion mass to be 1.2 $M_\odot$. This constraint, along with the similarity of the spin parameters to those of the double neutron star binaries, makes the companion likely to be another neutron star. We have searched our data for a companion radio pulsar by correcting the time series for the known pulsar orbit but thus far have detected no companion signals. A sensitive optical search to rule out a massive white dwarf companion is planned. If J1829+2456 is indeed a DNS, it will be the eighth such system known. With the large number of systems now known, it is finally possible to look for trends in system properties which may shed light on the evolution of these objects. For instance, we show in Figure 3 a possible correlation between eccentricity and spin period.

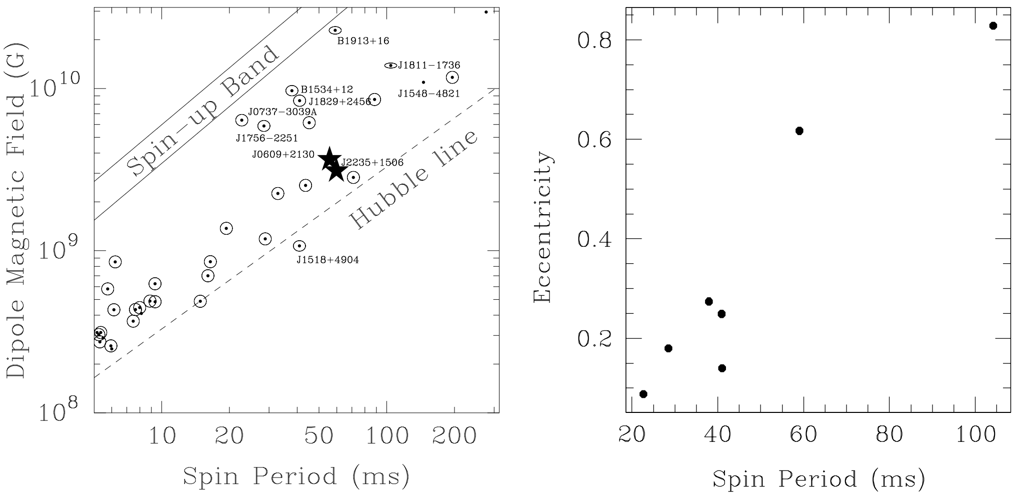

Figure 3. Left: Part of the $B-P$ diagram highlighting the unique positions (starred symbols) of the solitary pulsars J0609+2130 and J2235+1506 (Camilo, Nice & Taylor 1993). Pulsars with surrounding ellipses are members of binary systems. Known DNS binary systems, including likely new DNS systems J1756–2251 and J1829+2456, are labeled. The "Hubble line" is the locus of points of constant characteristic age equal to a Hubble time (assumed to be 15 Gyr). The spin-up band is the end point of spin-up by accretion for the model of Arzoumanian, Cordes & Wasserman (1999). Right: Eccentricity plotted against spin period for the double neutron star binaries (again including J1756-2251 and J1829+2456.) Perhaps this is because high eccentricity systems with compact orbits (and hence small post-accretion spin periods) will quickly inspiral and become undetectable while high eccentricity systems with wider orbits (and larger post-accretion spin periods) will inspiral more slowly and remain detectable for longer.

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