The Arecibo 430-MHz Intermediate Galactic Latitude Survey: Discovery of Nine Radio Pulsars

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ABSTRACT

We have used the Arecibo Radio Telescope to search for millisecond pulsars in two intermediate Galactic latitude regions ($7° < |b| < 20°$) accessible to this telescope. For these latitudes the useful millisecond pulsar search volume achieved by Arecibo's 430-MHz beam is predicted to be maximal. Searching a total of 130 square degrees, we have discovered nine new pulsars and detected four previously known objects. We compare the results of this survey with those of other 430-MHz surveys carried out at Arecibo and of an intermediate latitude survey made at Parkes that included part of our search area; the latter independently found two of the nine pulsars we have discovered.

At least six of our discoveries are isolated pulsars with ages between 5 and 300 Myr; one of these, PSR J1819+1305, exhibits very marked and periodic nulling. We have also found a recycled pulsar, PSR J2016+1948. With a rotational period of 65 ms, this is a member of a binary system with a 635-day orbital period. We discuss some of the the properties of this system in detail, and indicate its potential to provide a test of the Strong Equivalence Principle. This pulsar and PSR J0407+16, a similar system now being timed at Arecibo, are by far the best systems known for such a test.

Subject headings: binaries: general — pulsars: general — pulsars: individual (PSR J2016+1948) pulsars: individual (PSR J1819+1305)

1. Introduction

Most of the pulsars found with the Arecibo radio telescope have been discovered in blind surveys. Since 1991, a series of 430-MHz surveys, which take advantage of the unparalleled gain of the 430-MHz line feed (19 K/Jy) have been carried out. The papers containing the results of most of these have already been published (Nice, Fruchter, & Taylor 1995, Camilo, Nice, & Taylor 1996, Camilo et al. 1996, Foster et al. 1995, Ray et al. 1996, Lommen et al. 2000). Those surveys, together with processing of data taken post-1997 (Lorimer et al. 2002, McLaughlin et al. 2003, Chandler 2002), have uncovered a total of 113 pulsars. Of these, 19 are recycled.

The optimal region for these surveys has always been considered to be the Galactic plane, despite the high sky temperatures involved. This was specifically the target region of the earliest surveys (Hulse & Taylor 1974, Hulse & Taylor 1975a, Hulse & Taylor 1975b). The pulsars normally found in this region of sky are slow rotators with relatively large Dispersion Measures (DM). They present a large dispersive smearing across each of the channels of the back-ends used to carry out the surveys. Such smearing makes the detection of millisecond pulsars (MSPs) with rotational periods less than a few times the timescale of the smearing a difficult proposition.

Dispersive smearing could in principle be eliminated by using narrower channels, but at some point a more fundamental problem is found, that of interstellar scattering. This is the broadening of any pulsed signal due to multi-path propagation, and can only be eliminated by observing at higher frequencies, where the pulsars are intrinsically fainter and the telescope beam smaller.

MSPs are therefore difficult or impossible to detect at 430 MHz for the high DMs usually found for the normal pulsar population near the Galactic plane. Looking along the Galactic plane, the distance at which a given DM is reached is much smaller than along lines-of-sight at higher latitudes, this means that the volume within which MSPs can be detected at 430 MHz is much smaller (both compared to normal pulsars, and per square degree, henceforth indicated as $\Box$) for the low Galactic latitudes. This applies, to a lesser extent, to the population of normal pulsars (see Fig. 1).

The high Galactic latitudes, with lines of sight containing significantly less plasma, can be considered a better place to look for MSPs from a point of view of their detectability. The survey by Wolszczan (1990) has demonstrated, by finding a millisecond pulsar orbited by the first known planets outside the solar system (PSR B1257+12) and a double neutron-star system (PSR B1534+12) that such studies are rewarding. This is confirmed by the large number of MSPs found in the Parkes 70-cm all-sky survey (Manchester et al. 1996, Lyne et

al. 1998).

The scale height for the MSP distribution is of the order of 0.65 kpc (Cordes & Chernoff 1997). A survey with good sensitivity can detect MSPs at larger distances, and therefore more objects will be detectable as we approach the plane of the Galaxy, because there will be more pulsars along the line of sight. At some Galactic latitude b, the number of MSPs will start to decrease as we approach the plane because of the large amounts of plasma along the line of sight.

This intuitive result, depicted schematically in Fig. 1, is also predicted by detailed simulations carried out by one of us (JN, with Shri Kulkarni) and by more recent simulations of the pulsar population of the Galaxy by Cordes and Chernoff (1997), who estimate the optimal latitude b to be about 20° at 430 MHz.

Motivated by our early simulations, we started a 430-MHz pilot survey of a small region of the Galaxy with $7° < |b| < 20°$ visible with the Arecibo radio telescope. Our aim was to test the expectation that many MSPs remain to be discovered in these intermediate Galactic latitudes. Some of the results of this Intermediate Latitude Survey (ILS) are presented in this work. The timing solutions for PSR J1756+18, PSR J2050+13 and PSR J2016+1947, and a detailed study of the latter pulsar will be presented elsewhere.

2. Search observations and their sensitivity

The ILS observations began in May 1989, and ended in September 1991. They used the 430-MHz Carriage House line feed. The data were acquired with the old Arecibo correlator, using 3-level quantization. The total bandwidth used was 10 MHz, the number of lags being 128. The sampling time used was 506.625 μs, each independent pointing containing 2^{17} such samples, for a total integration of 66.4 seconds. The total number of pointings processed was 6121, which represents a total observing time of 113 hours and a total survey area of about 130$^\square$. The pointing positions are indicated in Figure 2 (Galactic coordinates).

The data were processed at Caltech and the Los Alamos National Laboratories with the help of a Cray-YMP computer. The software used for the data reduction was the Caltech pulsar package PSRPACK, developed by Will Deich and one of us (JN). The multi-frequency data were dedispersed at a set of 163 trial DM values between 0 and 200 cm^{-3} pc. Each dedispersed time series was Fourier transformed, and the strongest periodic components were recorded. In order to increase sensitivity to signals with a small duty cycle, harmonically related components (at f, $2f$, ..., nf; with $n = 2$, 4, 8 and 16) were summed, and again the strongest peaks were recorded. The power spectrum was also searched for harmonics

up to $n = 4$ of frequency above Nyquist that might have been aliased back into the power spectrum, in an attempt to improve our sensitivity to millisecond pulsars.

The sensitivity of the ILS as a function of DM and period is displayed in Fig. 3 for a pulsar with a square pulse profile and a pulsewidth of 5%. For this figure, we took into account the observing system's equivalent flux density, integration time and observing bandwidth, dispersive smearing and the effect of the interstellar scattering as quantified by Cordes (2001).

The DM at which the sensitivity is degraded by half for a 5 ms pulsar is about $150 \, \mathrm{cm}^{-3}$ pc. If we find a pulsar with this DM in the direction of our survey for which the electron densities are larger ($l = 40°$ and $b = 7°$); then such a pulsar is at a distance of about 5 kpc, according to the Cordes and Lazio model of the electron distribution in the Galaxy (Cordes & Lazio 2002). The ILS can detect pulsars at these distances (e.g. PSR J1819+1305). For the direction where the electron densities are lower ($l = 70°$ and $b = -20°$), no pulsar should be found with such a large DM. The effect depends mainly on Galactic latitude (b). To summarize, for the higher Galactic latitudes the detectability of MSPs at 430 MHz is limited only by the sensitivity of the survey system, for the lower Galactic latitudes, it is also limited by pulse smearing.

3. Discoveries; pulsar timing

The ILS detected a total of 13 pulsars, or about one per $10^{\square}$. Of these, four were known before the start of our survey: PSR B1737+13, PSR B1842+14, PSR B2034+19 and PSR B2053+21. The remaining nine pulsars were previously unknown. Two of these were later discovered and timed independently at Parkes: PSR J1819+1305 and PSR J1837+1221 (Edwards et al. 2001). The pulse profiles for the 9 new pulsars are presented in Figure 4.

Within the search area, there were 2 known pulsars that we did not detect. One of them, PSR J1838+16 (Xilouris et al. 2000), like seven other pulsars found in the STScI/NAIC drift scan surveys and described in that paper, has a flux density between 0.5 and 1 mJy. It is possible that such a pulsar could have been missed because of interstellar scintillation. The other pulsar, PSR J2030+2228 (Rankin & Benson 1981), has a flux density at 400 MHz of about 5 mJy, i.e, we should expect for it a S/N of about 140. It is not clear why this object was not detected, possible causes are corruption of data with radio frequency interference (RFI) or nulling.

Confirmation and timing of the new pulsars was done using the 430-MHz Carriage House line feed, just as for the discovery observations. The re-observation attempts were made in

Characteristics of the five newly found pulsars with known phase-coherent timing solutions.

Pulsar	J1814+1130	J1819+1305	J1819+1305(a)	J1828+1359	J2017+2043	J2048+2255
Parameters:						
Measured						
Epoch (MJD)	51500	51650	51650	51500	51500	51500
Start (MJD)	51207	51209	-	50901	50901	50901
Finish (MJD)	52645	52645	-	52637	52645	52645
r.m.s. (μs)	237	348	-	513	110	127
N.TOAs	101	95	-	110	82	103
α (h:m:s)	18:14:42.742(2)	18:19:56.226(3)	18:19:56.22(4)	18:28:53.338(2)	20:17:28.938(2)	20:48:45.868(2)
δ (°:':")	11:30:43.95(5)	13:05:15.25(11)	13:05:14.2(7)	13:59:35.36(13)	20:43:31.90(3)	22:55:05:31(3)
l (°)	39.20	41.23	41.2	43.02	61.38	67.45
b (°)	13.31	12.82	12.8	11.25	−8.27	−12.94
Period (s)	0.751261115038(3)	1.060363543971(7)	1.06036354400(6)	0.741639520385(8)	0.537143086032(2)	0.2839009641977(10)
$\dot{P}$ (10^{-15})	1.66038(8)	0.3592(2)	0.373(9)	0.7286(2)	0.99555(5)	0.01516(2)
DM (cm^{-3} pc)	65	64.9	64.9	56	61.5	68.8
w_{50} (%)	1.3	6.3	5.9	1.7	0.9	2.2
S_{430} (mJy)	0.72	6.2	-	1.2	1.5	1.8
Derived						
τ_c (Myr)	7.2	45	45.0	16	8.5	300
B_0 (Gauss)	1.1×10^{12}	6.3×10^{11}	6.4×10^{11}	7.4×10^{11}	7.4×10^{11}	6.6×10^{10}
$\dot{E}$ (erg s^{-1})	1.5×10^{32}	1.2×10^{31}	1.24×10^{31}	7.1×10^{31}	2.5×10^{32}	2.6×10^{31}
Dist (kpc)	2.7	5.1	5.1	3.0	3.4	4.2
L_{430} (mJy kpc^2)	5	161	-	11	17	32

Table 1: Timing and derived parameters for five pulsars. The Right Ascension (α) and the declination (δ) are indicated in J2000 coordinates. (a) - as published in (Edwards et al. 2001) with the exception of the distance estimate. Their value for the pulse duty cycle at half height (w_{50}) was measured at a frequency of 1400 MHz. The flux density at 430 MHz (S_{430}) was calculated by averaging *all* the detections of the pulsars made after obtaining their timing solution (perfect pointing) and ignoring integrations with bad baselines. The resulting pulse profile is then compared with the the off-pulse r.m.s.; we assume the amplitude of the noise (in mJy) to be the expectation of the the radiometer equation for the total time added. The characteristic age, τ_c, is calculated using $\tau_c = P/(2\dot{P})$, the surface magnetic flux density B_0 is estimated using $B_0 = 3.19 \times 10^{19}\sqrt{P\dot{P}}$ and $\dot{E} = 4\pi^2 I \dot{P} P^{-3}$, where I is the moment of inertia of the neutron star (assumed to be 10^{45} g cm^2). The distances are estimated using using the latest electron model of the Galaxy (Cordes & Lazio 2002). The uncertainties of the timing parameters are twice the 1-σ uncertainties obtained with TEMPO.

December 1997, and six new pulsars were confirmed then: PSRs J1814+1130, J1819+1305, J1828+1359, J2016+1948, J2017+2043 and J2048+2255. None of the remaining seven candidates could be re-detected. The back-end used to confirm these six pulsars and then to time them was the Penn State Pulsar Machine (PSPM), a 128-channel filterbank. Each of the individual channels has a bandwidth of 60 kHz, the sampling time is 80 μs and the data are 4-bit sampled. In timing mode, the PSPM-folded, multi-channel pulse profiles were dedispersed using SIGPROC (Lorimer 2001). The topocentric times of arrival (TOAs) of the pulses at the telescope were estimated using another routine from the same package.

The discovery at Parkes of PSR J1837+1221, which coincides in position, period and DM with one of our unconfirmed candidates, led one of us (PCF) to re-observe the positions of the previous candidates. So far, two more pulsars have been confirmed: PSR J1756+18 and PSR J2050+13, again using the 430-MHz line feed and the PSPM. It is unclear why these objects were missed in 1997, but that might be because the telescope pointing had been affected by the telescope upgrade works. One of the pulsars (PSR J2050+13) is also exceedingly faint, being sometimes undetectable in 30-minute observations, it was found while scintillation was amplifying its flux density.

Of the six pulsars we have timed since 1997, one, PSR J2016+1948, is a member of a 635-day pulsar-white dwarf binary system; it still has no phase-connected timing solution. A consequence of this is that the $\dot{P}$ has not yet been conclusively measured. For some of the more recent measurements of this pulsar, we have also used the L-narrow receiver at a central frequency of 1410 MHz, and the Wide-band Arecibo Pulsar Processor correlator (WAPP) as a back-end with a total bandwidth of 100 MHz. The signal-to-noise ratio obtained is similar to that of the 430-MHz observations. The newly confirmed pulsars PSR J1756+18 and PSR J2050+13 also lack timing solutions, and they are now being timed at a frequency of 327 MHz. These three pulsars are listed in Table 2.

The remaining 5 pulsars timed since 1997 have phase-coherent timing solutions, which are presented in Table 1. These were obtained and refined using the TEMPO timing program [1]. Their timing parameters are typical of the "normal" pulsar population; the characteristic ages vary from 7 to 300 Myr. The residuals of the TOAs can be seen in Figure 5. For one of the two pulsars discovered independently at Parkes, PSR J1819+1305 (Edwards et al. 2001), the timing parameters obtained at the two sites can be compared for the same reference epoch (Table 1). The other pulsar that was also found at Parkes (PSR J1837+1221) has not been timed at Arecibo.

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[1]http://pulsar.princeton.edu/tempo/

3.1.   Understanding the survey results: Comparison with other surveys

A direct comparison can be made between the ILS and the 1400-MHz Swinburne Intermediate Latitude Survey (henceforth SILS), which was made using the Parkes 64-m radio telescope's multi-beam system (Edwards et al. 2001). The SILS target area was defined by $5° < |b| < 15°$ and $-100° < l < 50°$, so there is some overlap with the area covered by the ILS.

In this overlap area, both surveys detected PSR J1819+1305 and PSR J1837+1221. The SILS did not detect our two other discoveries in the common search area, PSR J1814+1130 and PSR J1828+1359. Although we are dealing with small number statistics, this result shows that the ILS has achieved a greater sensitivity to normal pulsars in the intermediate Galactic latitudes, as expected from Fig. 3.

The SILS detected a total of 170 pulsars (69 of which were new discoveries) in a search area 23 times larger than that of the ILS ($\sim 3000^{\square}$). This represents one detection per $\sim 17^{\square}$, which, as expected, is not as high as the detection density of the ILS. However, the SILS covered regions closer to the Galactic center and also at a slightly lower latitude range ($5° < |b| < 15°$), two factors that increased that survey's detection rate.

The number of normal pulsars detected by the Swinburne survey was not enhanced by the higher frequencies used. The pulsar with the highest DM detected by the SILS, PSR B1620$-$42, has a rotational period of 0.365 seconds and a DM of 295 cm^{-3} pc. Figure 3 shows that such a pulsar would not have been missed by the ILS because of pulse smearing. Therefore, for the sensitivity of the SILS, observing at 1400 MHz does not improve the detectability of slow pulsars for the Galactic latitudes sampled. This is acknowledged by Edwards et al. (2001), who find that the DM distribution of their slow pulsar discoveries is similar to that of their re-detected pulsars, which with almost no exception were found at lower frequencies. We can therefore conclude that, as expected, our survey is purely sensitivity-limited for this class of pulsars.

The situation changes for MSPs at similar DMs; where the SILS is still capable of making detections, unlike any 430-MHz survey (see Fig. 3). The SILS has detected twelve recycled objects, eight of them new (Edwards & Bailes 2001), with DMs between 26 and 117 cm^{-3} pc. Fig. 3 shows that our survey could in principle detect such objects. One consequence of this is that the fraction of recycled pulsars detected by the SILS (one in 14) is remarkably similar to ours (one in 13), even when our survey finds twice as many normal and recycled pulsars per square degree. Because of small number statistics, the recycled pulsar fractions would still be consistent had we found one more or one less recycled object.

A more recent Arecibo 430-MHz survey of the Galactic plane (Nice, Fruchter, & Taylor

1995) has covered a region of the sky twice as large ($260^{\Box}$, with $|b| < 8°$) with a sensitivity very similar to that of the ILS. It detected 61 pulsars, of which 4 are recycled. This represents more than twice the detection density of the ILS survey, which is due to the larger concentration of pulsars along the Galactic plane, yet the fraction of detections of recycled pulsars (one in 15) is remarkably similar to that of the ILS and the SILS. It is, however, true that the fraction of recycled objects does increase for the higher Galactic latitudes.

3.2.   Periodic nulling for PSR J1819+1305

PSR J1819+1305 is by far the most luminous pulsar discovered in this survey. Its pulse profile consists of three components; the relative intensities of these are observed to vary systematically from one 3-minute sub-integration to the next. Using single-pulse data obtained in December 2002, we found that the main cause of this variation is the strong intensity modulation of the first component of the pulse profile.

These single-pulse data also showed that there is further intensity modulation affecting the whole pulse profile, this can be seen in Fig. 6. Most of this is due to nulling, with emission absent for about 50% of the time. This nulling has the peculiarity of having a very marked periodicity at 53±3 rotations, which is both well defined, long and with a large nulling fraction compared to other pulsars known to exhibit periodic nulling (Rankin 1986).

The emission of this pulsar, by its combination of peculiar characteristics, deserves a more careful study. In particular, it will be interesting to determine its polarization characteristics, which might allow a good estimate of the angle between the magnetic and rotation axis and of the latter relative to the line of sight. This will be essential for a proper interpretation of the nulling, and might lead to new insights about the emission mechanism of pulsars.

3.3.   The PSR J2016+1948 binary system

Perhaps the most important result of this work is the discovery of the 65-ms pulsar PSR J2016+1948. This is a member of a binary system, together with a 0.29 $M_{\odot}$ white dwarf companion (assuming a pulsar mass of 1.35 $M_{\odot}$ and an inclination of 90°). The orbital period is 635 days. PSR J2016+1948 is the second most luminous pulsar discovered in the ILS, with $L_{430} = 35\,\text{mJy kpc}^2$.

For this binary system, we have not yet determined a phase-coherent timing solution for the whole data set. The position in the sky was determined with a set of 1400-MHz

pointings at the source's nominal position and half a beam width (one beam width is 3 arcmin at Arecibo) north, south, east and west of the nominal position. A position can be determined from the intensity of the pulsed signal of the detections, with an uncertainty that is a small fraction of the beam size. This procedure is known as "gridding" (Morris et al. 2002).

The remaining parameters for this pulsar were determined from the observed barycentric periods. Technically, this was achieved with TOA information: we have used TEMPO to fit for the orbital parameters and rotational period with a different time offset for each day's TOA set. Each of these sets gives an independent estimate of the barycentric rotation period for its day. The orbital model used was the ELL1 (Lange et al. 2001), which was specially designed for low-eccentricity systems like PSR J2016+1948, where no precise estimates of the longitude of periastron (and therefore, of the time of passage through periastron) can be made. We have used a bootstrap Monte Carlo method (Efron & Tibshirani 1993) to estimate the 1-σ orbital parameter uncertainties that appear in Table 2.

PSR J2016+1948 has the third longest orbital period known for this type of system; the longest are those of PSR B0820+02, for which $P_B = 1232$ days (Arzoumanian 1995) and PSR J0407+16 ($P_B = 669$ days, $\dot{P} < 10^{-18}$ and $e \sim 0.001$, Lorimer 2003, private communication). With a rotational period of 0.86 s, PSR B0820+02 has not been significantly recycled by interaction with the progenitor of the companion white dwarf. The much shorter rotational periods of PSR J2016+1948 (65 ms) and of PSR J0407+16 (25 ms), and the low upper limit for the period derivative of the latter pulsar are suggestive of extensive recycling.

The determination of the orbital eccentricities for these systems is important in its own right. The theories that describe the recycling of neutron stars into MSPs (Alpar et al 1982, Zahn 1977, Phinney 1992) predict the order of magnitude of the orbital eccentricity as a function of the orbital period. For $P_B = 600$–700 days, the eccentricity should be of the order of 10^{-3} (Phinney 1992). The values derived for the PSR J2016+1948 and PSR J0407+16 binary systems are in excellent agreement with that prediction.

4. PSR J2016+1948 as a gravitational laboratory

Pulsars have been used in several different ways for testing the fundamental properties of gravitation (Esposito-Farèse 1999, Bell 1999). One of the most fundamental and distinctive properties of general relativity (GR) is the strong equivalence principle (SEP). Like the weak equivalence principle (WEP), which led Einstein to elaborate GR, it requires the universality of free fall: acceleration of any object in an external gravitational field is independent of the

size or chemical composition of the object. However, SEP also requires the same accelerations under external fields for objects that have significantly different gravitational binding energies (Will 1993).

All theories of gravitation that describe gravity as a distortion of space-time; the so-called metric theories of gravitation (Will 1993), "predict" WEP by design. This is not the case for SEP, which is a feature peculiar to GR. If the assumption of SEP is wrong, as postulated in many alternative theories of gravitation, i.e., if

$$\frac{m_I}{m_G} - 1 \equiv \Delta = \eta \times \frac{U_G}{m_G\,c^2} \neq 0, \tag{1}$$

(where m_I and m_G are the inertial and gravitational masses of an object, η is the Nordtvedt parameter which measures deviations from SEP, U_G is the object's self-gravitational energy and c is the velocity of light) then the accelerations in the same external field of two objects will not be exactly equal because of the different gravitational binding energies.

This difference in acceleration causes a "polarization" of the binary, which is an increase in the eccentricity of the system along the direction of the external field known as the "Nordtvedt effect" (Nordtvedt 1968a).

Such an effect has not been found in the weak fields probed by solar system experiments, in particular the Lunar Laser Ranging (Nordtvedt 1968b). This experiment determined that, despite the differences in gravitational self-energy between the Earth and the Moon, these two objects fall at the same rate (to within one part in 10^{13}) in the gravitational field of the Sun (Williams, Newhall, & Dickey 1996). This implies that $\eta = -0.0007 \pm 0.0010$, which is entirely consistent with GR. However, Damour and Esposito-Farése (1992) have shown that, generally,

$$\eta = \eta_W + \eta_S(c_1 + c_2 + ...) + ... \tag{2}$$

where η_W and η_S are the weak and strong field components of the Nordtvedt parameter η and the c_i are the compactness of the bodies involved:

$$c_i = \frac{U_{G,i}}{M_i c^2}. \tag{3}$$

Is there a strong-field component of η? If so, GR is not the right description of gravitation. Such a test cannot be conducted in the solar system, where no strong fields are to be found.

A pulsar- white dwarf system, with the Galaxy generating the external field, provides the ideal laboratory to make such a measurement. Pulsars have very large gravitational binding energies of about -15% of the total mass (i.e., $c_1 \sim -0.15$, the exact number depends on the equation of state for cold matter at high densities and the mass of the pulsar). The white dwarf companion has, comparatively, a negligible gravitational binding energy, about 10^4 times smaller than that of the neutron star. If there is any strong-field component of the acceleration, it should be felt just by the pulsar, hence the difference in acceleration compared to the white dwarf and the associated Nordtvedt effect.

The figure-of-merit of a binary system for a Nordtvedt test is P_B^2/e (Arzoumanian 1995). However, Wex (1997) has shown that for an unambiguous interpretation of the low eccentricity of a binary system, the system's age has to be significantly larger than one Galactic orbit.

Among all the known binaries with previously published timing solutions, the P_B^2/e number is highest for the PSR B1800$-$27 system. The eccentricity of this system cannot be interpreted unambiguously because of the pulsar's age ($\tau_c = 300$ Myr) is of the order of a single Galactic orbit. Of all such binaries that pass the large τ_c criterion, PSR J1713+0747, with $\tau_c = 8.5$ Gyr (Camilo, Foster, & Wolszczan 1994), is the system for which P_B^2/e is largest: 6.14×10^7 days^2. For PSR J2016+1948 and PSR J0407+16, the P_B^2/e is $\sim 3 \times 10^8$ days^2 and $\sim 5 \times 10^8$ days^2, or factors of $\sim$4-5 and 7-8 times larger than for PSR J1713+0747.

Using all the binary systems that pass the large age criterion, a value of $|\Delta| < 0.004$ was obtained (Wex 1997). Assuming again that the pulsar's compactness is 0.15, this implies $\eta < 0.027$. The inclusion of PSR J2016+1948 and PSR J0407+16 in that ensemble of binary systems will significantly reduce the upper limits on $|\Delta|$ and η. An interesting aspect of these limits is that they will diminish with the mere addition of binary systems with high P_B^2/e to the ensemble being used (Wex 1997).

The upper limit of $|\Delta|$ has been used, together with the measurements of orbital decay for the PSR B1913+16 binary system, to impose fundamental constraints to any alternative theories of gravitation, in particular the tensor bi-scalar theories (Damour & Esposito-Farèse 1992, Esposito-Farèse 1999). These constraints will become significantly more stringent with the inclusion of systems like PSR J2016+1948 and PSR J0407+16. However, we must keep in mind that the determination of the equivalence of inertial and gravitational mass, particularly when very large self-gravitational energies are involved, is an important measurement in itself, with a significance wider than the tests it introduces to any particular gravitational theory. It will forever remain as a fundamental constraint to our understanding of gravitation.

5.   Conclusions

We have found nine new pulsars in a small Arecibo 430-MHz survey of the intermediate Galactic latitudes. We have timed six of these, with five now having phase-coherent timing solutions. These are old, normal pulsars; a population similar to that of the earlier Hulse-Taylor survey. As expected, there are no young pulsars among the sample that has been timed. We compare this survey with the SILS (Edwards et al. 2001) and conclude that we have reached greater sensitivity to this population of normal pulsars.

Two of the discoveries, PSR J1819+1305 and PSR J1837+1221, were independently found at Parkes by the SILS and then timed. We found that the former pulsar has strong variation of its integrated pulse profiles. This is partly due to nulling; the nulls exhibit a very strong periodicity at 53±3 rotations.

Because of small number statistics, it is impossible to obtain any firm conclusions, based on our survey alone, as to the number of recycled pulsars to be discovered at the intermediate Galactic latitudes at 430 MHz. We found a single pulsar that is likely to be recycled, PSR J2016+1948, out of a total of 13 detections, a proportion similar to what was obtained by 430-MHz surveys of the Galactic plane. However, a much larger 430-MHz ILS survey would certainly not find a larger fraction of recycled pulsars than the SILS at 1400 MHz (which is also one in 14). Therefore, our initial expectation, and also that of Cordes and Chernoff (1997), that for the latitudes near $|b| = 20°$ there are many recycled pulsars to be found (this being the main motivation of the present survey) cannot be confirmed by the ILS and SILS. This might imply that the scale height for recycled pulsars is larger than the value that was assumed in the previous calculations, 0.65 kpc.

PSR J2016+1947 has a rotational period of 64.9 ms and it forms a binary system with an ~0.3 $M_\odot$ white dwarf companion. This system has an orbital period of 635 days, with an orbital eccentricity of about 0.0012. The more precise determination of the orbital parameters of this binary will, together with the timing of another binary pulsar, PSR J0407+16, lead to much tighter constraints on any violation of the Strong Equivalence Principle.

the pulsars mentioned in this paper, freely available for use at the Arecibo Observatory; Duncan Lorimer, for comments and ideas that greatly improved the quality of this work and for making his pulsar processing software publicly available, and Chris Salter and Avinash Deshpande for comments that improved the quality of the manuscript. Avinash Deshpande also helped with the preliminary analysis of the PSR J1819+1305 data.

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Characteristics of three pulsars without coherent timing solutions.

Pulsar	J1756+18	J2016+1948	J2050+13
Parameters:			
Measured			
α (h:m:s)	17:56.0(3)	20:16:56.7(5)	20:50.0(3)
δ ($^{\circ}$:$'$:$''$)	18:19(5)	19:48:03(7)	13:01(5)
l ($^{\circ}$)	43.75	60.52	59.38
b ($^{\circ}$)	20.23	-8.68	-19.11
Period (s)	0.744	0.0649403887(4)	1.220
DM (cm^{-3} pc)	77	34	60
w_{50} (%)	2.1	2.1	~ 2-3
S_{430} (mJy)	~ 0.7	3.3	~ 0.4
P_B (days)	-	635.039(8)	-
x (s)	-	150.70(7)	-
e	-	0.00128(16)	-
ω ($^{\circ}$)	-	90(5)	-
T_{asc} (MJD)	-	51379.92(3)	-
Derived			
Dist (kpc)	5.3	3.9	3.7
S_{430} (mJy kpc^2)	~ 19	35	~ 5

Table 2: Parameters for three pulsars without phase-coherent timing solutions. See Table 1 for explanation of the parameters of the isolated pulsars. For PSR J2016+1948, α and δ are derived from gridding. This pulsar's rotational period and its orbital parameters (orbital period P_B, projection of the pulsar's orbital semi-major axis along the line of sight, in seconds, x, time of ascending node T_{asc}, eccentricity e and longitude of periastron ω) and their uncertainties are derived from a Monte-Carlo bootstrap calculation. T_{asc} is preferred to the time of passage through periastron because the orbit is nearly circular.
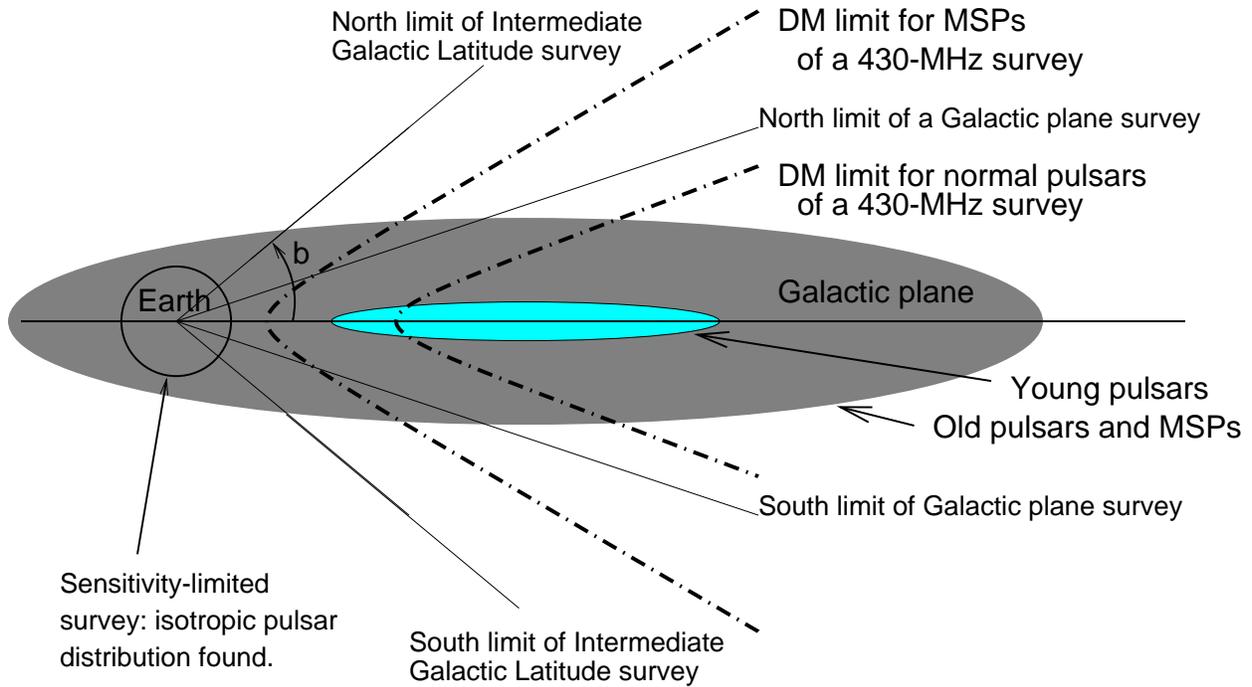
Fig. 1.— Schematic cross section of the Galaxy at the Galactic longitudes being probed, with some vertical exaggeration for clarity. Both the ILS and the Galactic surveys are probing essentially the same "normal" pulsar population; mainly old "normal" pulsars, with ages of tens to hundreds of Myr. The main difference between the two should be the higher fraction of recycled objects for the ILS survey. The telescope can see beyond the scale height of the pulsar population. The consequence of this is that the pulsars detected in ILS are, on average, less numerous and closer to the Earth than those found in the Galactic surveys. Because of the large concentrations of plasma near the Galactic plane, a survey at 430 MHz cannot detect young pulsars, as they lie beyond its DM limit. The Parkes Multi-Beam survey was designed to probe this region at 1400 MHz, discovering many young pulsars.
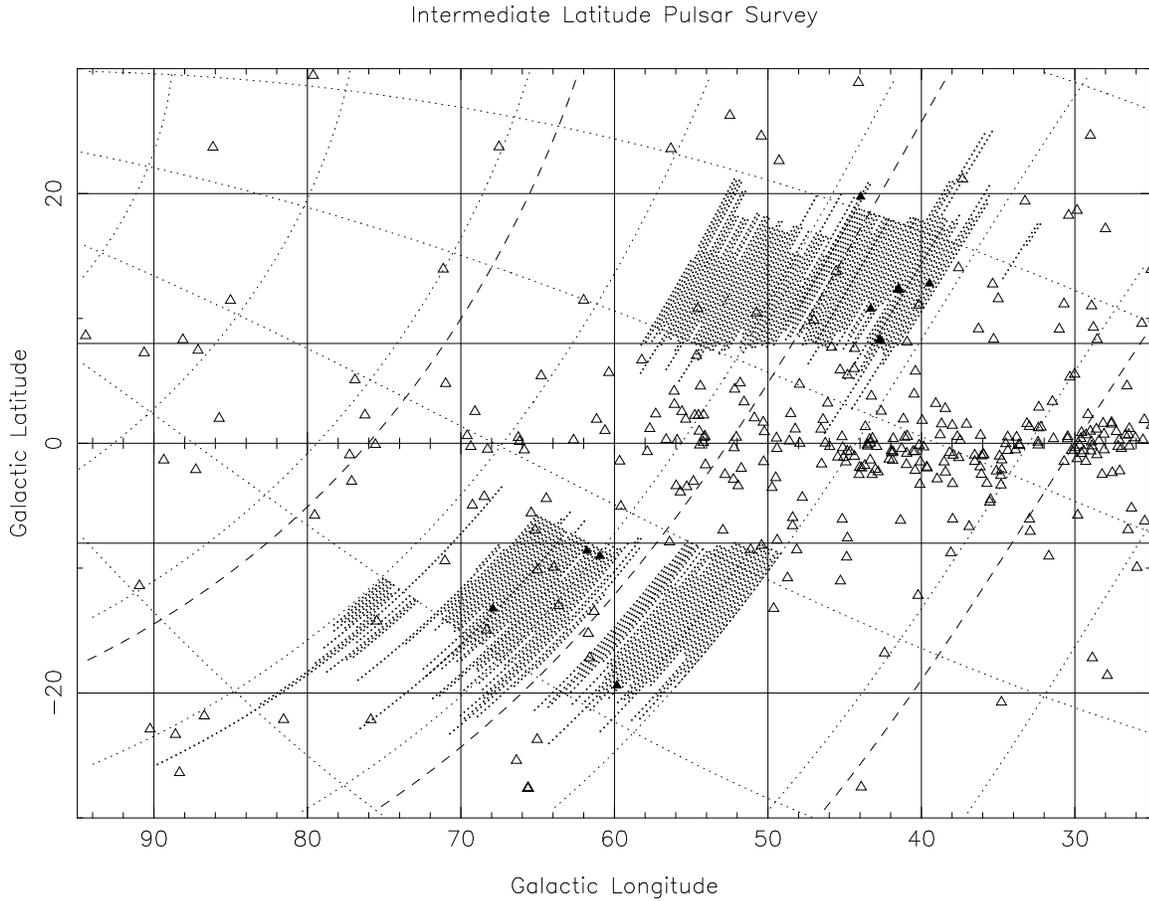
Fig. 2.— Pointings made during the Intermediate Latitude Survey, in Galactic coordinates. The unfilled triangles represent previously known pulsars, the filled triangles represent the new pulsars. Each pointing covers approximately the physical size of its representing dot at more than 50% of the sensitivity of the centre of the beam. The dashed lines represent the southern declination limit, the zenith declination and the northern declination limit of the Arecibo radio telescope. The database for known pulsars is the ATNF pulsar catalogue, which includes the pulsars found in the Parkes multi-beam surveys (http://www.atnf.csiro.au/research/pulsar/catalogue/).
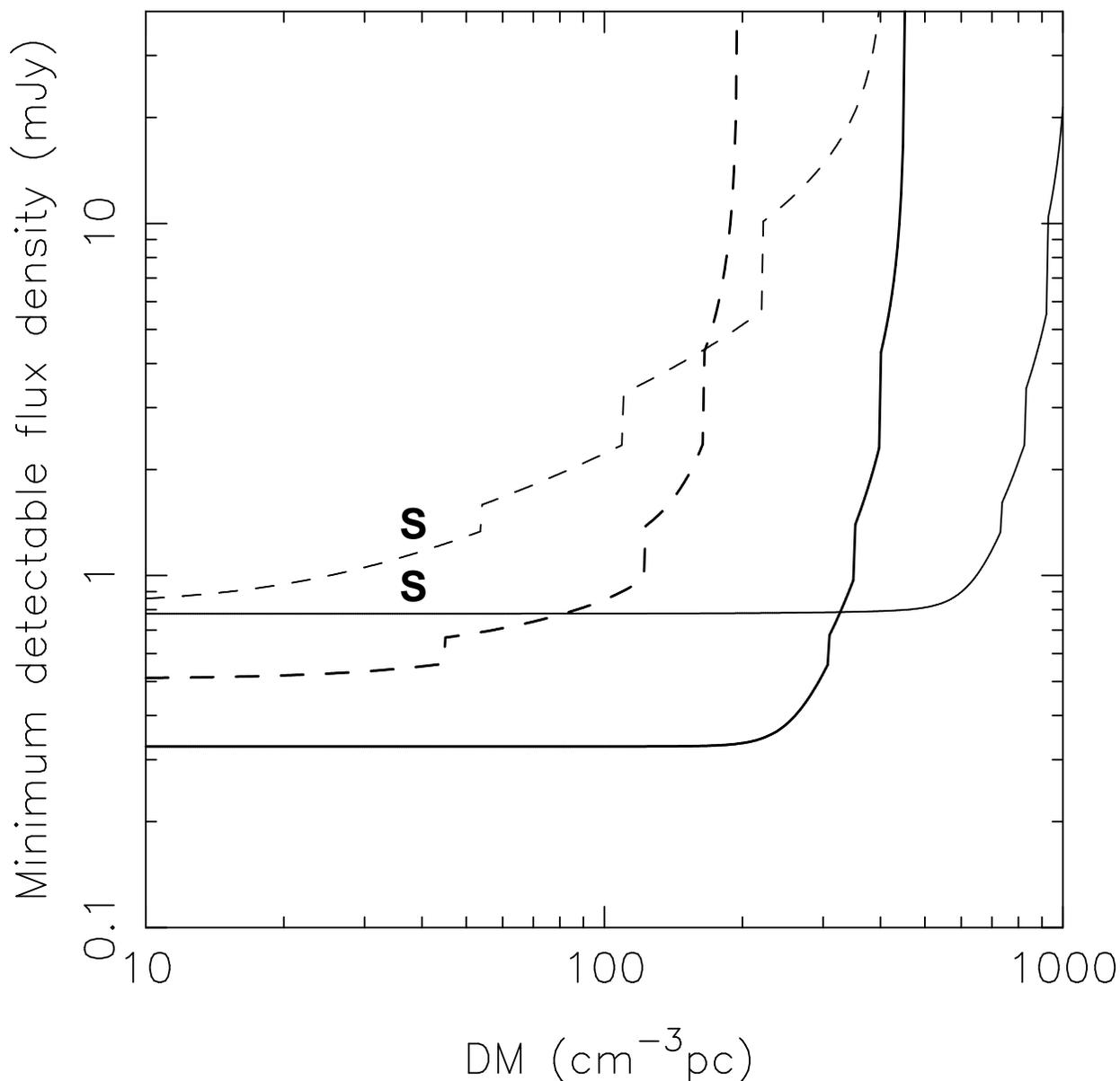
$$S_{min} \text{ for } S/N = 9.0$$

Fig. 3.— Minimum detectable flux density of the present survey (with S/N = 9.0) for two pulsar periods, 5 ms (dashed line) and 365 ms (solid line) as a function of DM, assuming a duty cycle of 5% and interstellar scattering as detailed in Cordes (2001). The lighter curves, indicated with an "S", represent the minimum flux density at 430 MHz of the weakest pulsars with the same periods detectable by the Swinburne survey (Edwards et al. 2001), assuming a relatively flat spectral index of −1.2 (a more negative spectral index would cause an even greater discrepancy in sensitivities between the two surveys). The steps seen at high DMs are due to the harmonics of the pulsar's fundamental frequency (due to each pulsar's peculiar pulse profile, in this case a square wave) becoming undetectable, for having a higher frequency than the time resolution of the experiment at the given DM.

PSR J1814+1130

PSR J1819+1305

PSR J1828+1359

PSR J2016+1948

PSR J2017+2043

PSR J2048+2255

PSR J1756+18

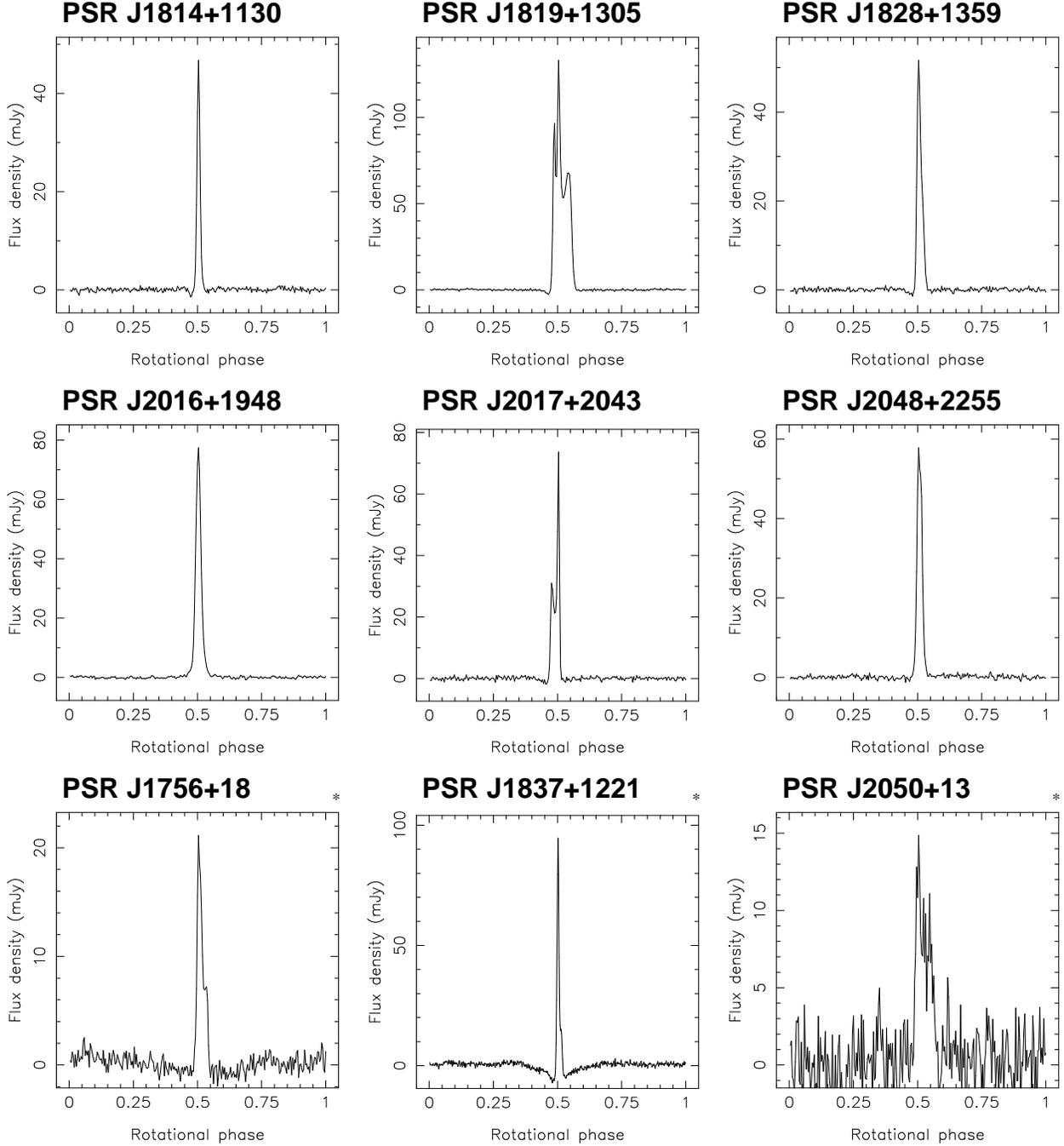**PSR J1837+1221**

PSR J2050+13

Fig. 4.— Pulse profiles at 430 MHz for the nine pulsars discovered in this survey, obtained by averaging the best detections. For the six pulsars we have timed, these are also the templates used in deriving the TOAs. The dips before and after the pulse profiles are caused by the fact that the PSPM is a 4-bit machine that subtracts the radio intensity signal from a running average, this significantly reduces the amount of data to be acquired.
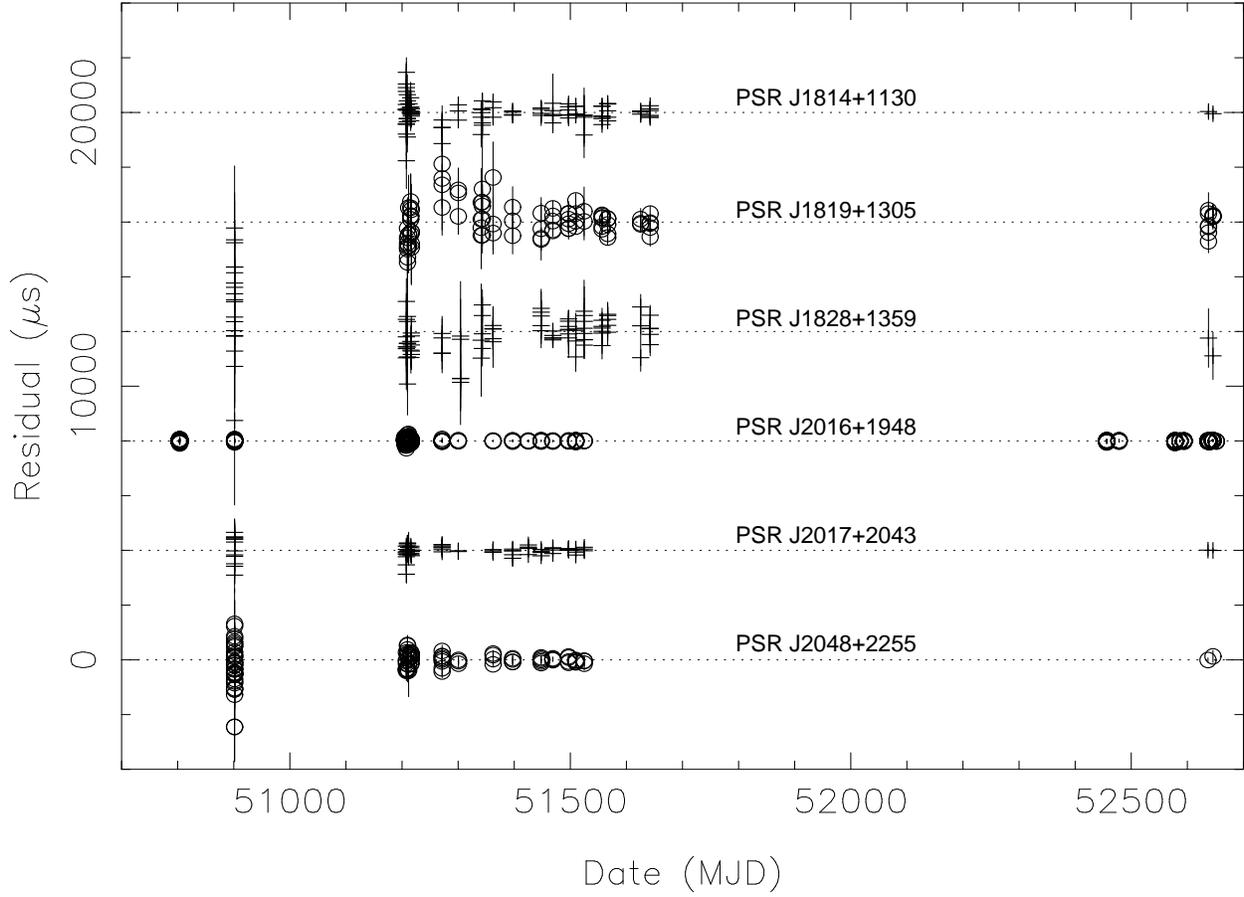
Fig. 5.— Difference between the measured times of arrival and the prediction of the timing models for six of the newly discovered pulsars. These are displayed with offsets of 20, 16, 12, 8, 4 and 0 ms for clarity. There are no rotation ambiguities between the late 1990s data and the 2002/2003 data, the pre-fit phase error for the latter data was typically less than 2%. For PSR J2016+1948 only the time coverage is indicated.
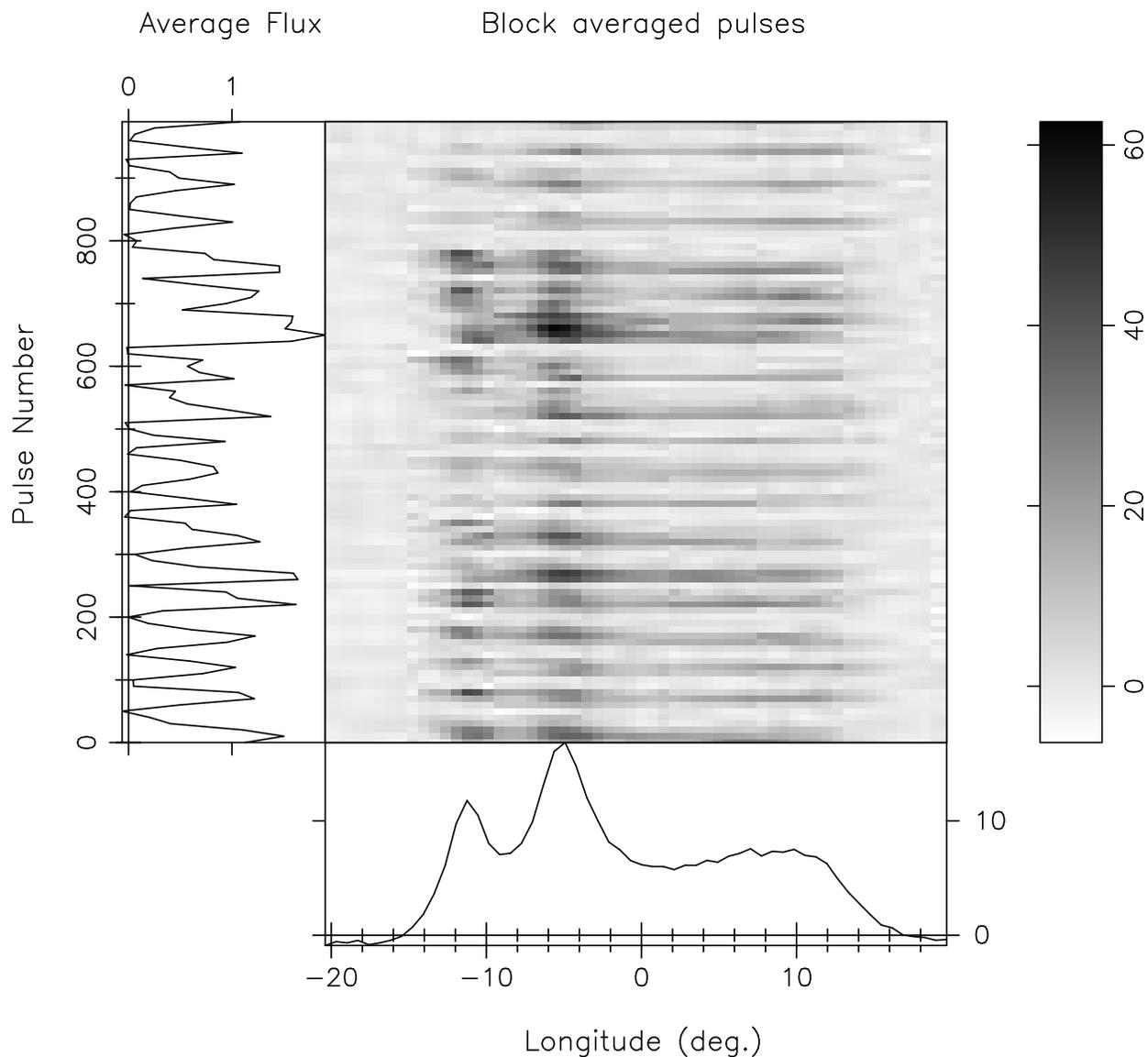
Fig. 6.— A 17.2-minute observation of PSR J1819+1305 at 430 MHz. The data, obtained in December 29 2002, were dedispersed at 64.9 cm^{-3}pc and folded according to the ephemeris in Table 1. The grayscale plot represents the pulsar's intensity as a function of rotational longitude (horizontal axis, only a small portion of the whole cycle is visible) and of pulse number (vertical axis). In the lower plot, we present the integrated pulse profile. In the vertical plot on the left, we present the pulse intensity as a function of pulse number. There the periodic nature of the nulling becomes apparent.

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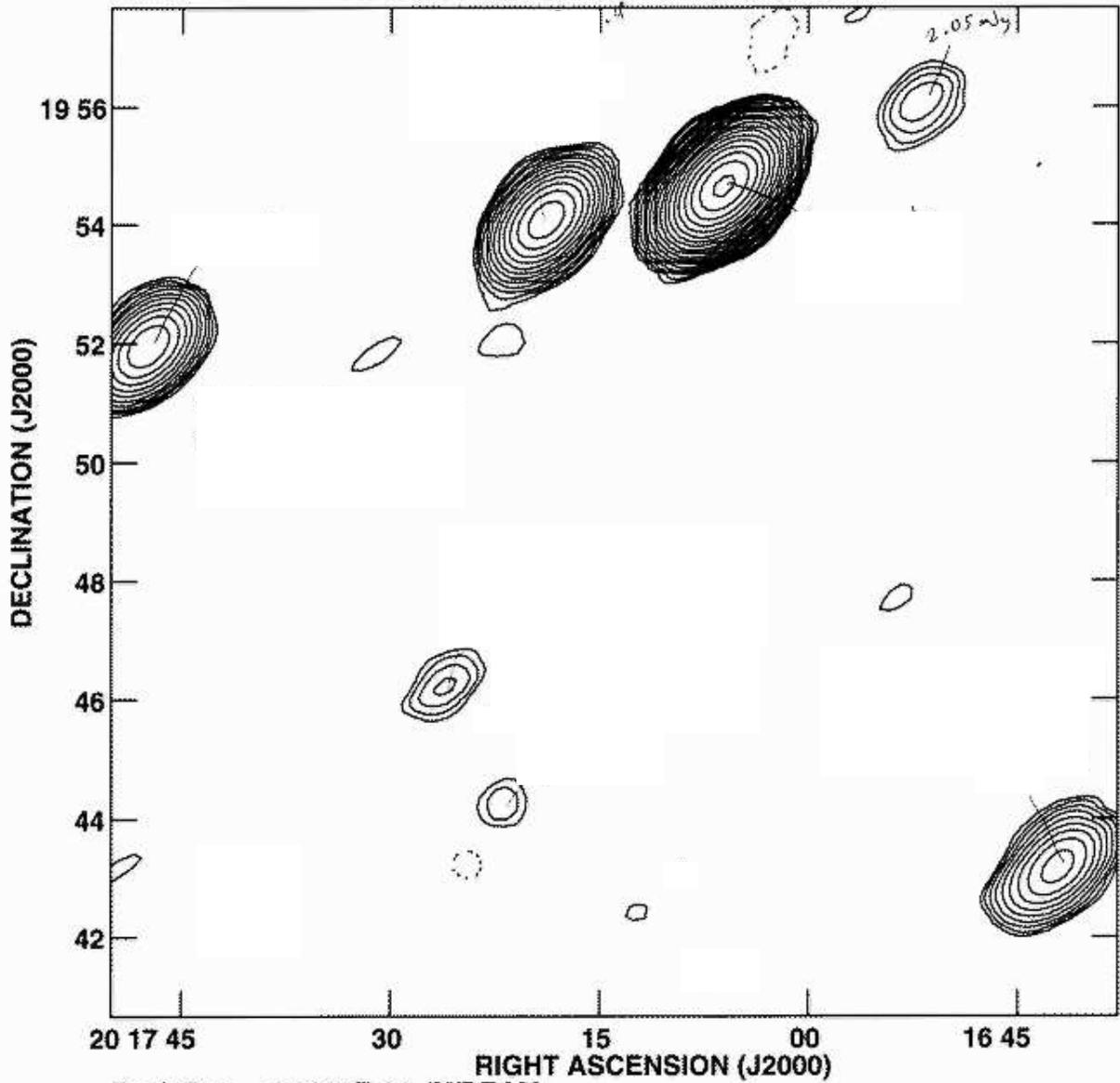
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128.0, 181.0, 256.0, 362.0, 512.0)