Discovery of 10 pulsars in an Arecibo drift-scan survey

D. R. Lorimer,1⋆ K. M. Xilouris,2 A. S. Fruchter,3 I. H. Stairs,4 F. Camilo,5 A. M. Vazquez,6 J. A. Eder,6 M. A. McLaughlin,1 M. S. E. Roberts,7 J. W. T. Hessels7 and S. M. Ransom8

1 University of Manchester, Jodrell Bank Observatory, Macclesfield, Cheshire, SK11 9DL
2 University of Virginia, Department of Astronomy, PO Box 3818, Charlottesville, VA 22903, USA
3 Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA
4 Department of Physics and Astronomy, University of British Columbia, 6224 Agricultural Road, Vancouver, BC V6T 1Z1, Canada
5 Columbia Astrophysics Laboratory, Columbia University, 550 West 120th Street, New York, NY 10027, USA
6 Arecibo Observatory, HC3 Box 53995, Arecibo, PR 00612, USA
7 Physics Department, McGill University, 3600 University Street, Montreal, QC H3A 2T8, Canada
8 National Radio Astronomy Observatory, 520 Edgemont Road, Charlottesville, VA 22903, USA

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ABSTRACT
We present the results of a 430-MHz survey for pulsars conducted during the upgrade to the 305-m Arecibo radio telescope. Our survey covered a total of 1147 deg² of sky using a drift-scan technique. We detected 33 pulsars, 10 of which were not known prior to the survey observations. The highlight of the new discoveries is PSR J0407+1607, which has a spin period of 25.7 ms, a characteristic age of 1.5 Gyr and is in a 1.8-yr orbit about a low-mass (>0.2 M⊙) companion. The long orbital period and small eccentricity (e = 0.0009) make the binary system an important new addition to the ensemble of binary pulsars suitable to test for violations of the strong equivalence principle. We also report on our initially unsuccessful attempts to detect optically the companion to J0407+1607, which imply that its absolute visual magnitude is >12.1. If, as expected on evolutionary grounds, the companion is an He white dwarf, our non-detection implies a cooling age of least 1 Gyr.

Key words: pulsars: general – pulsars: individual: J0407+1607.

1 INTRODUCTION

Recycled pulsars – neutron stars that are thought to have been spun up by the accretion of matter from a binary companion – are interesting objects to study. In addition to their application as excellent clocks for high-precision timing experiments (Davis et al. 1985), progress in our understanding of their origin and evolution continues to be made by large-area surveys of the radio sky.

Following the discovery by Wolszczan (1991) of two recycled pulsars at high Galactic latitudes, Johnston & Bailes (1991) demonstrated that the local observable population of these objects should be isotropic, and that low-frequency (~400 MHz) large-area surveys would be an excellent means of probing this population. This prediction was largely borne out by the discovery of ~50 recycled pulsars from a number of large-area surveys undertaken in this frequency range by many groups around the world (see, for example, Camilo 1995 for a review). More recently, sensitive surveys at higher radio frequencies (~1.4 GHz) continue to discover millisecond and recycled pulsars in large numbers at intermediate and low Galactic latitudes (Edwards et al. 2001; Faulkner et al. 2004) where interstellar propagation effects limit the Galactic volume surveyed at lower frequencies.

The 305-m Arecibo telescope has played a key role in low-frequency surveys. Between 1993 and 1998, the upgrade to the telescope meant that it was often parked at a fixed azimuth for extended periods. This provided a unique opportunity to survey the sky as it drifts through the stationary telescope beam at the sidereal rate. At 430 MHz, the sky coverage for a declination δ is 60 cos δ deg² d⁻¹. As a number of groups were interested in drift-scan surveys (Foster et al. 1995; Camilo et al. 1996a; Lommen et al. 2000; McLaughlin et al. 2002), the available sky was divided up into five zones and the zenith angle of the telescope was changed daily to cover each region uniformly.

In this paper, we report on an analysis of data in the regions surveyed by the ‘Space Telescope Science Institute and National Astronomy and Ionospheric Centre’ (STScI/NAIC) collaboration. A preliminary account of this work was given by Xilouris et al. (2000). In Section 2, we describe the survey observations and data analysis procedure. The results, follow-up timing and implications of the 10 new pulsars found in the survey, including the new binary pulsar J0407+1607, are detailed in Sections 3 and 4.

*E-mail: Duncan.Lorimer@manchester.ac.uk

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Table 1. Declination strips covered in the STScI/NAIC survey. For each strip we list the central zenith angle (ZA), gain (G), system temperature ($T_{\text{sys}}$) of the 430-MHz line feed, approximate limiting flux density ($S_{\text{min}}$), area of sky covered and the number of new and previously known pulsars detected (new+old).

<table>
<thead>
<tr>
<th>δ range (deg)</th>
<th>ZA (deg)</th>
<th>G (K Jy$^{-1}$)</th>
<th>$T_{\text{sys}}$ (K)</th>
<th>$S_{\text{min}}$ (mJy)</th>
<th>Area (deg$^2$)</th>
<th>Pulsars (new+old)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1–2</td>
<td>17</td>
<td>10.5</td>
<td>92</td>
<td>0.9</td>
<td>83</td>
<td>0+0</td>
</tr>
<tr>
<td>6–7</td>
<td>12</td>
<td>13.0</td>
<td>76</td>
<td>0.6</td>
<td>114</td>
<td>2+3</td>
</tr>
<tr>
<td>11–12</td>
<td>7</td>
<td>15.2</td>
<td>72</td>
<td>0.5</td>
<td>55</td>
<td>1+5</td>
</tr>
<tr>
<td>16–17</td>
<td>2</td>
<td>16.4</td>
<td>68</td>
<td>0.5</td>
<td>287</td>
<td>5+6</td>
</tr>
<tr>
<td>21–22</td>
<td>3</td>
<td>16.4</td>
<td>68</td>
<td>0.5</td>
<td>163</td>
<td>2+3</td>
</tr>
<tr>
<td>26–27</td>
<td>8</td>
<td>15.0</td>
<td>73</td>
<td>0.5</td>
<td>315</td>
<td>0+5</td>
</tr>
<tr>
<td>31–32</td>
<td>13</td>
<td>12.5</td>
<td>80</td>
<td>0.7</td>
<td>116</td>
<td>0+1</td>
</tr>
<tr>
<td>36–37</td>
<td>18</td>
<td>10.0</td>
<td>96</td>
<td>1.0</td>
<td>14</td>
<td>0+0</td>
</tr>
</tbody>
</table>

2 SURVEY OBSERVATIONS AND RESULTS

The survey observations were carried out between 1994 April and 1995 March using the 430-MHz carriage house line feed. While the nominal sensitivity of this receiver for observations close to the zenith is 16 K Jy$^{-1}$, these observations were made at a variety of zenith angles and during periods when the feed was slightly out of focus due to the maintenance work. As a result, the gain of the telescope varied considerably in the range 10–16 K Jy$^{-1}$. In drift-scan mode, a source passes through the 3 dB points of the primary beam (10 arcmin) in about 40 s. The declination ranges assigned to the STScI/NAIC collaboration, area coverage and approximate system parameters are summarized in Table 1. The sky coverage is shown in Fig. 1. An ASCII file containing the exact sky positions observed is available at http://www.blackwellpublishing.com/products/journals/suppmat/MNR/MNR9005/MNR9005sm.htm.

The incoming radio signals were sampled by the line feed as two orthogonal circular polarizations which, after amplification and down-conversion, were passed to a 32 × 250 kHz analogue filter-bank spectrometer, which sums the two polarization channels prior to detection with an RC time constant of 333 µs. The resulting total-power signals were sampled every 250 µs before being digitized with 3-bit precision and written to magnetic tape for off-line analysis.

The data were processed in overlapping 33-s segments using a derivative of the software package developed for earlier Arecibo pulsar searches (Fruchter 1989; Nice 1992; Nice, Fruchter & Taylor 1995). In brief, the data were de-dispersed for 448 different assumed values of dispersion measure (DM) in the range 0–504 cm pc$^{-3}$. The resulting time series were then Fourier transformed so that the amplitude spectra could be searched for periodic signals buried in the noise. To increase sensitivity to signals with narrow duty cycles (i.e. many harmonics in the Fourier domain) the spectra were incoherently summed so that up to 2, 3, 4, 8 and 16 harmonics were combined. Signal-to-noise ratios (S/Ns) were computed from the amplitude of each point in the spectrum and the local root-mean-square deviation. The Fourier components of the 100 strongest events were then inverse transformed back into the time domain to compute the S/N of the resulting pulse profile. The profiles, periods, S/Ns and best DMs of each candidate were saved for visual inspection.

The sensitivity of the survey was dependent on the telescope’s zenith angle and hence varied for the different declination strips. In Table 1 we quote our theoretical minimum detectable flux density ($S_{\text{min}}$) to long-period pulsars with duty cycles of 4 per cent using the radiometer equation (see, for example, Lorimer & Kramer 2005).
The data analysis resulted in the detection of 33 pulsars in 1147 deg\(^2\) of sky. 10 of these pulsars were previously unknown prior to the survey observations. In Table 2, we list the S/\(N_s\) of the pulsars along with an estimate of the theoretical S/N based on the nominal survey parameters and accounting for position offsets from the centre of the (assumed Gaussian) telescope beam power pattern. In general, for S/\(N_s\) below 20, the observed and theoretical values are in reasonable agreement. For some of the bright pulsars (e.g. B0823+06), the detected S/\(N_s\) are much less than the theoretical values. We are unsure of the reasons for this, and, unfortunately, the raw data are no longer available. Given our short integration times, it is possible that the observations were affected by adverse scintillation and/or nulling.

Also included in Table 2 are six previously known pulsars that lie within 5 arcmin of the searched area but were not detected. Although one of these pulsars, J1909+0616, made the list of candidates with a S/\(N_s\) = 7.6, this was below the nominal survey threshold S/\(N_s\) of 9 and does therefore not count as an blind detection. Only two of the remaining five pulsars have theoretical S/\(N_s\) above this threshold. For PSR J1920+1110, we are unsure of its 430-MHz flux density, which has been extrapolated from the 1400-MHz value (Morris et al. 2002) assuming a spectral index of \(-1.6\). As this pulsar was not detected in more sensitive 430-MHz observations by Bhat et al. (2004), either the spectrum is flatter than assumed or the pulse is significantly affected by scattering at 430 MHz. The remaining pulsar which is nominally above our detection threshold, J1951+1123, has a period of 5.1 s and is known to null for several periods (Nice 1992). This is the most likely explanation for our non-detection.

In summary, given the uncertainties in pointing and unknown variations in received focus during these observations, this simple analysis of the detection statistics shows that our survey sensitivity is consistent with that reported by other groups (see, for example, Camilo et al. 1996a).

### 3 FOLLOW-UP OBSERVATIONS

Confirmation and follow-up observations of the new discoveries began at end of the Arecibo upgrade in 1998. These made use of the Penn State Pulsar Machine (PSPM; Cadwell 1997), a 128 \(\times\) 60 kHz channel analogue filterbank spectrometer which records either continuously sampled data ('search mode') or synchronously averaged pulse profiles at the predicted pulse period ('timing mode').

As in the original survey observations, we used the 430-MHz line-fed receiver for the bulk of our follow-up work. Following initial confirmation observations that verified the existence of each pulsar in search mode, we generated a preliminary ephemeris which was subsequently used to obtain timing-mode data. The basic observing and analysis procedures used were identical to those described by Lorimer, Camilo & Xilouris (2002).

In order to determine accurate spin and astrometric parameters for each pulsar, we carried out a dedicated campaign of observations using the PSPM in timing mode. For each observation, the set of 128 folded pulse profiles (one profile per frequency channel) was appropriately delayed with respect to the centre observing frequency to account for the effects of interstellar dispersion. Standard software tools (Lorimer 2001) implemented this procedure to form a dispersed time-tagged integrated pulse profile for each observation. A pulse time of arrival (TOA) for each profile was then obtained by cross-correlating it in the Fourier domain with a high S/\(N_t\) template profile formed from the sum of many individual observations (Taylor 1992). The final template profiles are shown in Fig. 2.
The resulting high S/N ratio template was then used to obtain TOAs of higher precision, which were analysed with TEMPO in a further iteration to produce the final timing solution. Refined values of DM for each pulsar were obtained by forming four 1.92-MHz-wide sub-bands from each PSPM profile. The DM was derived from a fit to the PSPM in search mode. These data were then folded off-line to produce a set of pulse profiles and hence TOAs for a timing analysis. The advantage of this approach is that the data could be refolded later when the precision of the orbital parameters improved.

Despite this improved approach, small uncertainties in the assumed position resulted in significant covariances between the orbital parameters and position fits in TEMPO. Fortunately, as mentioned above, this pulsar was independently discovered by Roberts et al. (2004). Follow-up 1400-MHz Arecibo observations from that survey resulted in a positional determination which was used as a starting point for the final timing analysis. The final phase-coherent timing solution presented in Table 4 is the result of a simultaneous fit for spin, astrometric and binary parameters. The observed minus computed TOA residuals for this solution are featureless with a root-mean-square value of 16 μs. The DM was determined by including 1400-MHz observations of the pulsar with the Wide-band Arecibo Pulsar Processor (Dowd, Sisk & Hagen 2000) and, as for the other

### Table 3. Parameters for the nine isolated pulsars derived from the TEMPO timing analysis. Figures in parentheses are 1σ uncertainties in the least-significant digits as reported by TEMPO. The arrival times from which these ephemerides are derived are freely available on-line as part of the EPN data base (http://www.jb.man.ac.uk/~pulsar/Resources/epn).

<table>
<thead>
<tr>
<th>PSR</th>
<th>RA (J2000) (h:m:s)</th>
<th>Dec. (J2000) (°:′:″)</th>
<th>Period, (P) (s)</th>
<th>Epoch MJD</th>
<th>(P) (×10^{-15})</th>
<th>DM (cm^{-3} pc)</th>
<th>MJD range</th>
</tr>
</thead>
<tbody>
<tr>
<td>J0137+1654</td>
<td>01:37:23.88(1)</td>
<td>+16:54:42.1(4)</td>
<td>0.41476302650825(2)</td>
<td>52225</td>
<td>0.01233(3)</td>
<td>26.64(4)</td>
<td>5129–53119</td>
</tr>
<tr>
<td>J0329+1654</td>
<td>03:29:08.55(3)</td>
<td>+16:54:02(2)</td>
<td>0.893319660649(1)</td>
<td>52225</td>
<td>0.21525(6)</td>
<td>42.1(2)</td>
<td>5129–53119</td>
</tr>
<tr>
<td>J0609+2130</td>
<td>06:09:58.886(2)</td>
<td>+21:30:28.4(9)</td>
<td>0.05569801392951(2)</td>
<td>52758</td>
<td>0.000235(2)</td>
<td>38.73(2)</td>
<td>52295–53119</td>
</tr>
<tr>
<td>J1549+2113</td>
<td>15:49:40.94(5)</td>
<td>+21:13:26.9(1)</td>
<td>1.262471311613(5)</td>
<td>51738</td>
<td>0.8541(8)</td>
<td>24.8(2)</td>
<td>5175–52045</td>
</tr>
<tr>
<td>J1822+1120</td>
<td>18:22:14.60(1)</td>
<td>+11:20:56.2(2)</td>
<td>1.7870368054(2)</td>
<td>51602</td>
<td>2.346(4)</td>
<td>95.2(6)</td>
<td>51330–51873</td>
</tr>
<tr>
<td>J1838+1650</td>
<td>18:38:43.062(4)</td>
<td>+16:50:16.05(6)</td>
<td>1.90196739931(1)</td>
<td>51602</td>
<td>2.677(1)</td>
<td>33.9(2)</td>
<td>51330–51873</td>
</tr>
<tr>
<td>J1848+0604</td>
<td>18:48:54.62(7)</td>
<td>+06:04:46.8(3)</td>
<td>2.21860264699(3)</td>
<td>51602</td>
<td>3.736(6)</td>
<td>242.7(2)</td>
<td>51330–51873</td>
</tr>
<tr>
<td>J1905+0616</td>
<td>19:05:06.84(5)</td>
<td>+06:16:16(1)</td>
<td>0.989706231967(6)</td>
<td>51631</td>
<td>135.232(1)</td>
<td>256.05(1)</td>
<td>51330–51931</td>
</tr>
<tr>
<td>J2040+1657</td>
<td>20:40:17.865(3)</td>
<td>+16:57:30.46(7)</td>
<td>0.8656060225032(4)</td>
<td>51631</td>
<td>0.5949(6)</td>
<td>50.7(2)</td>
<td>51330–51873</td>
</tr>
</tbody>
</table>

The TOAs obtained for each pulsar were transformed to equivalent arrival times at the solar system barycentre and fit to a simple spin-down model using the TEMPO\(^1\) software package. After several iterations, an initial ephemeris was obtained, which was then used to form an improved template profile from the sum of each pulse profile appropriately phase-aligned according to the timing model. The resulting high S/N ratio template was then used to obtain TOAs of higher precision, which were analysed with TEMPO in a further iteration to produce the final timing solution. Refined values of DM for each pulsar were obtained by forming four 1.92-MHz-wide sub-bands from each PSPM profile. The DM was derived from a fit to the TOAs from each sub-band keeping the spin and astrometric parameters fixed at the final timing solution values. For nine of the new pulsars, the TOAs were adequately fit using an isolated pulsar spin-down model and the resulting parameters from each fit are presented in Table 3.

In the time since the original survey observations and follow-up, five of the new pulsars have been independently discovered in other surveys. The binary pulsar J0407+1607, discussed below, was detected during a survey of gamma-ray error boxes at Parkes (Roberts et al. 2004). PSRs J0609+2130 (Lorimer et al. 2004) and J1549+2113 (Foster et al. 1995; Lewandowski et al. 2004) were discovered in contemporary 430-MHz Arecibo drift-scan surveys. Finally, PSRs J1848+0604 (Faulkner, private communication) and J1905+0616 (Morris et al. 2002) were detected by the Parkes Multi-beam Survey. PSRs J1549+2113 and J1848+0604 have no previously published timing solution and are presented for the first time in Table 3. For PSR J0609+2130, we have added an additional year of PSPM TOAs to those already published by Lorimer et al. (2004). The longer time baseline of the resulting ephemeris presented in Table 3 has significantly improved the precision of the derived parameters (Morris et al. 2002). For PSR J1905+0616, we have included Jodrell Bank TOAs collected at 1412 MHz by Morris et al. (2002) in our final timing analysis. This has resulted in an improvement on the ephemeris published by Morris et al.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right ascension (J2000) (h:m:s)</td>
<td>04:07:54.939(3)</td>
</tr>
<tr>
<td>Declination (J2000) (°:′:″)</td>
<td>16:07:16.4(2)</td>
</tr>
<tr>
<td>Spin period, (P) (ms)</td>
<td>25.70173919463(2)</td>
</tr>
<tr>
<td>Period derivative, (P) (×10^{-20})</td>
<td>7.9(3)</td>
</tr>
<tr>
<td>Epoch of period (MJD)</td>
<td>52799</td>
</tr>
<tr>
<td>Dispersion measure, (DM) (cm^{-3} pc)</td>
<td>35.65(2)</td>
</tr>
<tr>
<td>Projected semimajor axis, (a) (s)</td>
<td>106.45026(2)</td>
</tr>
<tr>
<td>Orbital period, (P_o) (d)</td>
<td>669.0704(1)</td>
</tr>
<tr>
<td>Orbital eccentricity, (e)</td>
<td>0.0009368(6)</td>
</tr>
<tr>
<td>Longitude of periastron, (\omega) (deg)</td>
<td>291.74(2)</td>
</tr>
<tr>
<td>Epoch of periastron, (T_o) (MJD)</td>
<td>52774.69(3)</td>
</tr>
</tbody>
</table>

\(^1\) See http://pulsar.princeton.edu/tempo.
pulsars, keeping all other model parameters constant in the TEMPO fit.

To obtain an estimate of the transverse speed of J0407+1607, we performed a scintillation analysis on an observation at 430 MHz using the Arecibo Observatory Fourier Transform Machine (AOFTM), a fast-dump digital spectrometer which provides 1024 frequency channels across a 10-MHz bandwidth (see, for example, McLaughlin et al. 2002). Performing a standard autocorrelation analysis on the pulsed intensity as a function of time and radio frequency (for details of this technique, see Lorimer & Kramer 2005) we find the characteristic time-scale and bandwidth of scintillation to be 843 ± 6 s and 190 ± 2 kHz, respectively. Adopting the expressions given by Cordes & Rickett (1998) for a uniform scattering medium, and taking a distance of 1.3 ± 0.2 kpc derived from the DM and the Cordes & Lazio (2002) electron density model, we estimate the transverse speed of PSR J0407+1607 to be 35 ± 5 km s\(^{-1}\). Although this result is model-dependent, it implies a transverse speed which lies at the low end of the distribution known for millisecond pulsars (Nice & Taylor 1995). In future, it should be possible to measure the Proper Motion of this pulsar directly by extending the existing baseline of timing observations. The predicted proper motion at this distance is 6.1 mas yr\(^{-1}\). Through simulations with TEMPO, we estimate that a direct proper motion measurement of this magnitude through timing techniques will be possible within 3 yr. The effect of proper motion on the observed semimajor axis should also be measurable on a similar time-scale, allowing us to place constraints on the orbital inclination angle in future.

The PSPM and AOFTM data do not provide any information about the polarization properties of PSR J0407+1607. To investigate this, in 2002 March, we observed the pulsar for 78 m at 430 MHz using the Princeton Mark IV data recording system (Stairs et al. 2000) in narrow-band (5 MHz) mode. The Mark IV data were coherently de-dispersed off-line and the data were calibrated using observations with a noise diode of known flux density and polarization. The total intensity, linear and circularly polarized pulse profiles are shown in Fig. 3. Relative to the total intensity, we find that both the linear polarization and modulus of the circularly polarized component have an average value of 13 per cent, typical of other millisecond pulsars (Xilouris et al. 1998; Stairs, Thorsett & Camilo 1999). Also shown in Fig. 3 is the position angle of the linear polarization (dotted) as a function of pulse phase. A determination of the emission geometry of this pulsar is therefore non-trivial.

4 DISCUSSION

Various observed and derived parameters of the new pulsars are summarized in Table 5 where we also include estimates of each pulsar’s 430-MHz flux density. These were derived from the PSPM profiles using identical procedures to those described by Lorimer et al. (2002).

4.1 General remarks

In common with results from other Arecibo drift-scan surveys (Foster et al. 1995; Camilo et al. 1996a; Lommen et al. 2000; McLaughlin et al. 2002), the new pulsars are relatively faint, nearby objects. Their inclusion in future population syntheses should provide valuable constraints on the low end of the radio pulsar luminosity function. In 1147 deg\(^2\) of sky searched, we detected five recycled pulsars: J0407+1607, J0609+2130, B1534+12, B1913+16 and B1937+21. Of the two new discoveries, the binary pulsar J0407+1607 is discussed below, while the isolated pulsar J0609+2130 has already been discussed in detail by Lorimer et al. (2004). We simply note here that our detection rate of one recycled pulsar per ∼230 deg\(^2\) is consistent with that of other Arecibo surveys (see Camilo 1995).

The youngest pulsar in our sample, with a characteristic age of 116 kyr is PSR J1905+0616. As noted and discussed by Kramer et al. (2003), this object lies within the bounds of the EGRET source 3EG J1903-0550. An association is unlikely simply due to the large density of pulsars in this region and hence the high probability of a chance alignment. In addition, as noted by Kramer et al., the
spin-down energy loss of J1905+0616 is not large enough to be a likely source of the gamma-ray emission seen.

4.2 PSR J0407+1607 and 3EG J0407+1610

PSR J0407+1607 is coincident with the unidentified EGRET source 3EG J0407+1610 (Hartman et al. 1999), a relatively weak gamma-ray source with mean flux $F = 2.4 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$ above 100 MeV (assuming a photon spectral index of $-2$). While the variability index (see McLaughlin et al. 1996, for a definition) is only 0.19, and consistent with other EGRET sources known to be associated with pulsars, our $P$ measurement of J0407+1607 implies a rate of loss of spin-down energy $\dot{E} = 1.9 \times 10^{32}$ erg s$^{-1}$. This can be used to test the validity of an association with 3EG J0407+1610 by calculating the required efficiency $\eta$ of conversion of the pulsar’s spin-down luminosity into gamma rays. At the DM-derived distance of 1.3 kpc, and assuming a gamma-ray beaming fraction of $1/4\pi$ sr, we find an incompatible value of $\eta = (F \cdot D^2/E) \sim 20$. A much smaller distance and/or beaming fraction would be required so that $\eta \lesssim 1$. We therefore conclude that PSR J0407+1607 is most likely not the source of the gamma rays from 3EG J0407+1610.

4.3 PSR J0407+1607 and strong equivalence principle violations

The orbital parameters of the J0407+1607 binary system are consistent with standard models of binary evolution (see, for example, Phinney & Kulkarni 1994) in which the radio pulsar has been spun up by the accretion of matter while its companion star was in a red giant phase. Indeed, the observed orbital eccentricity is in excellent agreement with the prediction from the Phinney (1992) relationship between eccentricity $e$ and orbital period $P_{\text{o}}$.

Millisecond pulsar–white dwarf binaries such as PSR J0407+1607 make excellent probes of the strong equivalence principle (SEP). The SEP states that free fall of a body is completely independent of its gravitational self-energy. If the SEP is violated, then the ratio of inertial mass to gravitational mass of a falling body differs from unity by an amount $\Delta$. As originally proposed by Damour & Schäfer (1991), and by analogue with Nordvedt’s earlier tests of the SEP in the Earth–Moon system (Nordvedt 1968a,b), a violation of the SEP for a pulsar–white dwarf binary would mean that both objects ‘fall’ in the local Galactic gravitational field at a different rate. As a result, a violation would cause a polarization of the orbital plane toward and parallel to the centre of the Galaxy.

Following the earlier work of Damour & Schäfer, Wex (1997, 2000) derived limits on $\Delta$ from an ensemble of binary pulsar–white dwarf systems. As the figure of merit for this calculation is $P_o/e^2$, long-period circular orbit binaries such as J0407+1607 are particularly important members of the ensemble used in the test. Recently, a robust Bayesian analysis by Stairs et al. (2005), which uses all known binary pulsars relevant for this test including J0407+1607, has found a limit on SEP violations of $\Delta < 5.5 \times 10^{-3}$ (Stairs et al. 2005). This new limit is comparable to the weak-field limits found in the Earth–Moon system (Nordtvedt 1968a,b).

4.4 The companion to PSR J0407+1607

The observed mass function of PSR J0407+1607 is $2.89 \times 10^{-3}$ $M_\odot$. Assuming a mass for the pulsar in the range 1.3–1.6 $M_\odot$, the implied companion mass is 0.2 $M_\odot$, where $i$ is the unknown inclination angle between the plane of the orbit and the plane of the sky. From extensive studies of other millisecond pulsar binaries with similar orbital characteristics to J0407+1607 (for a recent review, see van Kerkwijk et al. 2005) it is most likely that the companion to J0407+1607 is a low-mass white dwarf. An inspection of archival Palomar data in the digitized sky survey archive reveals no optical counterpart down to the plate limit (approximately 19th magnitude), with the closest object in the field being 8 arcsec ($50 \sigma$) offset from the radio position given in Table 4.

To search for a fainter optical counterpart, the field surrounding PSR J0407+1607 was observed in 2003 October with the 2.3-m Bok telescope at Kitt Peak using the Steward Observatory imaging camera in combination with the Harris B and V filters. Four 27-min $B$ and four 20-m $V$ images were obtained under non-ideal seeing ($\sim$1.5 arcsec) conditions. All images were bias-subtracted and flat-fielded using the IRAF package. For photometry calibration, we selected all stars in a $3 \times 3$ arcmin$^2$ box around the pulsar location from the USNO-B1.0 Catalog.$^4$

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Table 5. Observed and derived parameters for the 10 pulsars discovered in the survey. For each pulsar, we list the Galactic longitude ($l$) and latitude ($b$), the flux density at 430 MHz ($S_{430}$), the pulse width measured at 50 and 10 per cent of the peak intensity (respectively $W_{50}$ and $W_{10}$), the equivalent width of a top-hat pulse having the same area and peak intensity of the profile ($W_{\text{eq}}$), the distance derived from the DM assuming the Cordes & Lazio (2002) electron density model ($D$), as well as the base-10 logarithms of the 430-MHz luminosity ($L_{430}$), the characteristic age ($\tau = P/(2\dot{P})$), the surface dipole magnetic field [$B = 3.2 \times 10^{29}(P/P^2)^{1/2}$G] and the rate of loss of spin-down energy ($\dot{E} = 3.95 \times 10^{31}/P^2$ ergs$^{-1}$).

<table>
<thead>
<tr>
<th>PSR</th>
<th>$l$</th>
<th>$b$</th>
<th>$S_{430}$</th>
<th>$W_{50}$</th>
<th>$W_{10}$</th>
<th>$W_{\text{eq}}$</th>
<th>$D$</th>
<th>$\log_{10} L_{430}$</th>
<th>$\log_{10} \tau$</th>
<th>$\log_{10} B$</th>
<th>$\log_{10} \dot{E}$</th>
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<tr>
<td>J0137+1654</td>
<td>138.3</td>
<td>-44.6</td>
<td>1.4</td>
<td>14</td>
<td>62</td>
<td>20</td>
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<td>0.3</td>
<td>8.73</td>
<td>10.9</td>
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<td>0.6</td>
<td>17</td>
<td>37</td>
<td>23</td>
<td>1.8</td>
<td>0.3</td>
<td>7.82</td>
<td>11.6</td>
<td>31.1</td>
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<td>-25.8</td>
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<td>5.3</td>
<td>6.6</td>
<td>4.8</td>
<td>1.3</td>
<td>1.3</td>
<td>9.71</td>
<td>9.16</td>
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<td>0.8</td>
<td>1.6</td>
<td>7.4</td>
<td>2.4</td>
<td>1.2</td>
<td>0.06</td>
<td>9.57</td>
<td>9.56</td>
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<td>7</td>
<td>22</td>
<td>15</td>
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<td>7.37</td>
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<td>59</td>
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<tr>
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<td>46</td>
<td>73</td>
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<td>24</td>
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<td>5.06</td>
<td>13.1</td>
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<td>0.7</td>
<td>7.36</td>
<td>11.9</td>
<td>31.6</td>
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</table>

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$^2$ See http://www-gsss.stsci.edu/DSS.
$^3$ See http://iraf.noao.edu.
The detection limit was determined to be magnitude 21 in $B$. This is in good agreement with the 20.9 magnitude of the star identified as 1061−0042921 in the USNO-B1.0 catalogue detected at the noise level in our images. Four 20-m exposures were aligned and added to produce the final $V$ image. We used the published visual magnitude of the nearby stars SA 94−171 and GD 71 (Landolt 1992) to determine the relationship between instrumental and aperture magnitudes. From this procedure, we estimate a limiting apparent visual magnitude for detection of 23.

At the nominal distance of $1.3 \pm 0.2$ kpc, our upper limit corresponds to an absolute visual magnitude of at least $12.1$. Assuming the companion to be an He white dwarf, we can use the cooling curves computed by Hansen & Phinney (1998) to place a lower limit on the age of the white dwarf companion. From an inspection of fig. 13 in their paper, our current non-detection constrains the cooling age to be $\geq 1$ Gyr, compatible with the 1.5 Gyr characteristic age of J0407+1607. More stringent constraints should be available soon following deeper observations of this system now underway with the Palomar telescope, which will be described elsewhere.

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