We report the discovery of eight γ-ray pulsars in blind frequency searches of Fermi LAT data. We present the timing models, light curves, and detailed spectral parameters of the new pulsars. PSRs J1023–5746, J1044–5737, J1413–5205, J1846+0919, J1957+5033, and J2055+25 have the largest characteristic ages (τc < 3 Myr) and are the least energetic (Eτc ≳ 1033 erg s−1) of all γ-ray pulsars discovered so far in blind searches. By analyzing >100 ks of publicly available archival Chandra X-ray data, we have identified the likely counterpart of PSR J1023–5746 as a faint, highly absorbed source, CXOU J102302.8−574606. The large X-ray absorption indicates that this could be among the most distant γ-ray pulsars detected so far. PSR J1023–5746 is positionally coincident with the TeV source HESS J1023–573, located near the young stellar cluster Westerlund 2, while PSR J1954+2836 is coincident with a 4.3σ excess reported by Milagro at a median energy of 35 TeV. PSRs J1957+5033 and J2055+25 have the largest characteristic ages (τc ∼ 1 Myr) and are the least energetic (Eτc ∼ 5 × 1033 erg s−1) of the newly discovered pulsars. We used recent XMM observations to identify the counterpart of PSR J2055+25 as XMMU J205549.4+253959. Deep radio follow-up observations of the eight pulsars resulted in no detections of pulsations and upper limits comparable to the faintest known radio pulsars, indicating that these pulsars can be included among the growing population of radio-quiet pulsars in our Galaxy being uncovered by the LAT, and currently numbering more than 20.

Key words: gamma rays: general – open clusters and associations: individual (Westerlund 2) – pulsars: general – pulsars: individual (PSR J1023–5746, PSR J1044–5737, PSR J1413–6205, PSR J1429–5911, PSR J1846+0919, PSR J1954+2836, PSR J1957+5033, PSR J2055+25) – X-rays: individual (CXOU J102302.8–574606, XMMU J205549.4+253959)

Online-only material: color figures

1. INTRODUCTION

Until the launch of the Fermi Gamma-ray Space Telescope, only seven pulsars were found to have pulsed emission in γ-rays (Thompson 2008), and only one of these pulsars, Geminga (Bignami & Caraveo 1996), was undetectable by radio telescopes (i.e., radio quiet). Six months of Fermi Large Area
Telescope (LAT) data completely changed such a scenario, with the detection of 46 pulsars, whose characteristics were published in the first Fermi-LAT Catalog of γ-ray Pulsars (Abdo et al. 2010b). This first harvest encompassed 22 young radio pulsars (e.g., Abdo et al. 2009a, 2009d), as well as 8 millisecond pulsars (MSPs; Abdo et al. 2009c), and 16 neutron stars unveiled in γ-rays through blind frequency searches of the LAT data (Abdo et al. 2009b). Radio follow-up observations of those 16 LAT-discovered pulsars resulted in the detection of radio pulsations from three of them: PSRs J1741–2054 and J2032+4127 (Camilo et al. 2009) and PSR J1907+0602 (Abdo et al. 2010d). Two of these were found to have remarkably low radio luminosities. Perhaps more surprising is the fact that 13 out of these 16 pulsars were not detected in radio (P. S. Ray et al. 2010, in preparation), and should therefore be considered radio quiet, or at least radio faint.

This paper reports on eight new γ-ray pulsars discovered in blind frequency searches of LAT data. As in the pulsar catalog paper, we present detailed timing and spectral results for each of these pulsars, including the pulse shape parameters, the fluxes, and the spectral indices and energy cutoffs for each pulsar. We also discuss possible associations, including previous γ-ray detections. While a large number of the first 16 γ-ray pulsars discovered in blind searches (Abdo et al. 2009b) were found to be coincident with previously known γ-ray sources, such as EGRET unidentified sources, none of the pulsars in this sample have a definite counterpart in the third EGRET catalog (Hartman et al. 1999), although one pulsar, PSR J1413−6807, has a counterpart, EGR J1413−6205, in a revised catalog of EGRET sources (Casandjian & Grenier 2008). This pulsar is also coincident with the AGILE source 1AGL J1412−6149 (Pittori et al. 2009). We also discuss possible X-ray and TeV associations with the newly discovered pulsars. The eight pulsars identified here are among the 1451 sources included in the Fermi-LAT First Source Catalog (Abdo et al. 2010a).

Compared to previous searches, the ones reported here are considerably more sensitive. In particular, these searches benefit from more than twice the amount of data, and a much better LAT source localization, than those that resulted in the discovery of the first 16 blind search γ-ray pulsars (Abdo et al. 2009b). The main reasons why these pulsars were not discovered sooner include the low fluxes (e.g., PSR J1957+5033 and J1846+0919), or a poor initial localization of the corresponding LAT source (e.g., PSR J1023−5746). Most likely, a combination of both factors is what prevented an earlier discovery of these pulsars.

Finally, deep radio follow-up observations of these eight new pulsars have resulted in no new detections of pulsations, and we include the upper limits of our radio searches.

The results described in this paper, together with recent detections of a few more radio pulsars (both classical and MSPs) bring the grand total of LAT γ-ray emitting neutron stars to more than 60 (Ray & Saz Parkinson 2010; Caraveo 2010).

2. OBSERVATIONS AND DATA ANALYSIS

The LAT is a high-energy γ-ray telescope on board the Fermi satellite that is sensitive to photons with energies from 20 MeV to over 300 GeV. It features a solid-state silicon tracker, a cesium-iodide calorimeter, and an anti-coincidence detector (Atwood et al. 2009). Events recorded with the LAT have time stamps derived from a GPS-synchronized clock on the Fermi satellite with <1 μs accuracy (Abdo et al. 2009a).

For pulsar science, the LAT represents a major advance over EGRET. It has a much larger effective area (≈8000 cm²) for 1 GeV photons at normal incidence, or approximately six times that of EGRET, a larger field of view (~2.4 sr, or almost five times that of EGRET), and a finer point-spread function (PSF; 68% containment angle of 0.6 at 1 GeV for the Front section and about a factor of two larger for the Back section, versus ~1.7 at 1 GeV for EGRET). The LAT also has a more efficient viewing strategy, operating primarily in continuous sky survey mode, as opposed to the inertial pointing mode used by EGRET.27 This optimizes the amount of time the sky is in the field of view, covering the entire sky every two orbits (~3 hr). These improvements allow more photons to be accumulated per unit time, and provide a better signal-to-noise ratio (S/N) in photon selection, making the LAT the first highly effective instrument for blind searches of γ-ray pulsars (Abdo et al. 2009b). For more details on the LAT, see Atwood et al. (2009).

2.1. Blind Frequency Searches

Since γ-ray photon data are extremely sparse (a typical γ-ray pulsar flux in the LAT may be of order 1000 photons per year), searches for γ-ray pulsars require long integration times. Furthermore, young rotation-powered pulsars spin down as they radiate away energy, so their signals are not precisely periodic, making it necessary to search over a range of both frequencies and frequency derivatives. Fully coherent blind searches for γ-ray pulsars are therefore extremely computer intensive, since the number of frequency bins in the fast Fourier transform (FFT) increases with the length of the observation time (N_{bins} = 2\pi f_{max}), where f is the duration of the observation and f_{max} is the maximum search frequency (Chandler et al. 2001). A fully coherent pulsar search, for example, would require the computation of >10⁸ Gigapoint FFTs to cover the spin-down range of the majority of young γ-ray pulsars. Such a search would also be highly sensitive to timing irregularities (e.g., timing noise and glitches). Instead, calculating the FFT of the arrival time differences, up to a maximum time difference of order a week, greatly reduces the number of bins in the FFT. By doing this, we are able to reduce dramatically the computational demands (both in processor and memory), as well as the required number of trials to span the same parameter space, while at the same time reducing our sensitivity to timing noise. All of this is achieved with only a modest reduction in the sensitivity, relative to fully coherent techniques (Atwood et al. 2006). For these searches, we used a maximum time difference of 219 s (~6 days). We binned our difference search at a time resolution of 7.8 ms, resulting in a Nyquist frequency of 64 Hz for our searches and searched through 2000 steps of width Δ(f/f) = 5 × 10⁻¹⁴ s⁻¹ to cover roughly the spin-down range up to that of the Crab pulsar (~1.0 × 10⁻¹⁴ s⁻¹ < f/f < 0 s⁻¹).

The data analyzed in this paper were collected from sky survey mode observations beginning on 2008 August 4 (MET = 239557414, MJD = 54682) and ending on 2009 July 28. However, a pointed observation of a source would increase the fraction of time it is in the LAT field of view by a factor of about three, thus significantly improving the sensitivity for the detection of pulsations from that particular source (Ransom 2007).

28 Mission Elapsed Time (MET), the number of seconds since the reference time of 2001 January 1, at 00:00:00 in the Coordinated Universal Time (UTC) system, corresponding to a Modified Julian Date (MJD) of 51910 in the UTC system.

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25 Available at http://fermi.gsfc.nasa.gov/ssc/data/access/lat/1yr_catalog/.

26 The position of the γ-ray source 0FGL J1024.0-5754, reported in the Bright Source List (Abdo et al. 2009), and used in our initial blind searches, was 11° away from the pulsar position, whereas the preliminary 11 month LAT position used to discover the pulsar was only 3°7 away.

27 However, a pointed observation of a source would increase the fraction of time it is in the LAT field of view by a factor of about three, thus significantly improving the sensitivity for the detection of pulsations from that particular source (Ransom 2007).

28 Mission Elapsed Time (MET), the number of seconds since the reference time of 2001 January 1, at 00:00:00 in the Coordinated Universal Time (UTC) system, corresponding to a Modified Julian Date (MJD) of 51910 in the UTC system.
The rocking angle is the angle between the pointing direction of the LAT and the zenith direction, defined as the direction along a line from the center of the Earth through the spacecraft.

4 (MET = 268411953, MJD = 55016). We used events with the most stringent background cuts (diffuse class photons of Pass 6.3, Atwood et al. 2009) with zenith angle $\leq 105^\circ$ (to avoid photons from the Earth’s limb), and rocking angle $\leq 40^\circ$. In addition, a few minutes were excised around two bright gamma-ray bursts (GRBs 080916C and 090510). We applied the time-differencing technique to photons with energies above 300 MeV, $\sim$500 source positions (see Table 3) around selected target positions given by the LAT First Source Catalog (Abdo et al. 2010a). We corrected the photon event times from each source to the solar system barycenter using the Fermi Science Tool gt$bary$, assuming all photons come from the target position. We searched $\sim$650 source positions from a preliminary version of the Fermi-LAT First Source Catalog (Abdo et al. 2010a) that were not coincident with likely active galactic nuclei (AGNs).

After finding a significant signal in the initial search, we followed up on the candidate signal by performing an epoch-folding search over a narrow region of frequency and frequency-derivative space using the PRESTO (Ransom 2001) pulsar software suite. All eight pulsars were discovered within $\sim$11 months of routine survey observations. They have since been confirmed with several months of additional data. A pulsar detection is confirmed if adding the new data and folding using the original timing solution results in a continued increase in the significance of the detection of the pulsation, as measured by the chi-squared obtained from fitting the pulse profile to a constant.

The names and locations of the new pulsars are given in Table 1, along with known associations, including those from the Fermi-LAT First Source Catalog (Abdo et al. 2010a) and the Bright Gamma-ray Source List (Abdo et al. 2009f).

### 2.2. Timing Analysis

We have generated phase-connected pulse timing models for each of the pulsars. To do this, we first extracted photons for each source using a radius and energy cut chosen to optimize the S/N for each pulsar. We corrected the photon event times to the geocenter using gt$bary$ in its geocentric mode. We then determined a set of times of arrival (TOAs) by first dividing our data into segments of approximately equal duration and then folding the photon times using a preliminary ephemeris to generate a set of pulse profiles. The TOAs were then measured by cross-correlating each pulse profile with a kernel density template that was derived from fitting the full mission data set, as described in P. S. Ray et al. (2010, in preparation). Finally, we used Tempo2 (Hobbs et al. 2006) to fit the TOAs to a timing model that included position, frequency, and frequency derivative. In the case of PSR J1023–5746, our

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Table 1

| PSR       | Source Association*a | R.A.b (hh:mm:ss.s) | Decl.b (dd:mm:ss.s) | $N$ | $b^c$ |
|-----------|----------------------|-------------------|---------------------|-----|-------|
| J1023–5746| 1FGL J1023.0–5746    | 10:23:02.9(5)     | −57:46:05(2)        | 284.2 | −0.4 |
|           | 0FGL J1024.0–5754    |                   |                     |     |       |
|           | 2CG 284–00           |                   |                     |     |       |
|           | HESS J1023–575       |                   |                     |     |       |
|           | CXOU J102302.8–574606|                   |                     |     |       |
| J1044–5737| 1FGL J1044.5–5737    | 10:44:32.8(1)     | −57:37:19(3)        | 286.6 | 1.2  |
|           | 1AGL J1043–5749      |                   |                     |     |       |
| J1413–6205| 1FGL J1413.4–6205    | 14:13:29.9(1)     | −62:05:38(1)        | 312.4 | −0.7 |
|           | 0FGL J1413.1–6203    |                   |                     |     |       |
|           | 1AGL J1412–6149      |                   |                     |     |       |
|           | EGR J1414–6224       | 2CG 311–01        |                     |     |       |
| J1429–5911| 1FGL J1429.9–5911    | 14:29:58.6(1)     | −59:11:36.6(7)      | 315.3 | 1.3  |
|           | 0FGL J1430.5–5918    |                   |                     |     |       |
| J1846+0919| 1FGL J1846.4+0919    | 18:46:26.0(6)     | +09:19:46(11)       | 40.7  | 5.3  |
| J1954+2836| 1FGL J1954.3+2836    | 19:54:19.15(4)    | +28:36:06(1)        | 65.2  | 0.4  |
|           | 0FGL J1954.4+2838    |                   |                     |     |       |
|           | 2CG 065+00           |                   |                     |     |       |
| J1957+5033| 1FGL J1957.6+5033    | 19:57:38.9(8)     | +50:33:18(9)        | 84.6  | 11.0 |
| J2055+25d | 1FGL 2055.8+2539     | 20:55:48.8(2)     | +25:40:02(3)        | 70.7  | −12.5|
|           | 0FGL J2055.5+2504    |                   |                     |     |       |
|           | XMMU J205549.4+253959|                   |                     |     |       |

Notes.

*a Sources are from the Fermi-LAT First Source Catalog (1FGL; Abdo et al. 2010a), the Fermi-LAT Bright Source List (0FGL; Abdo et al. 2009f), EGRET (EGR; Casandjian & Grenier 2008), and AGILE (1AGL; Pittori et al. 2009). We also list a TeV association (HESS) and X-ray counterparts identified with Chandra (CXOU) and XMM (XMMU).

*b Right ascension (R.A.) and declination (decl.) obtained from the timing model. The errors quoted are statistical (2.45 times the tempo uncertainties). They do not account for covariance between model parameters or systematic errors caused by timing noise, which can amount to several arcseconds, and should be considered when looking for counterparts.

*c Galactic longitude ($l$) and latitude ($b$), rounded to the nearest decimal.

*d The current position uncertainty only allows for two decimal places in declination.

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29 The rocking angle is the angle between the pointing direction of the LAT and the zenith direction, defined as the direction along a line from the center of the Earth through the spacecraft.
timing model also included second and third derivative terms, as well as a glitch, as described below. The timing solutions, along with the number of days of data and TOAs that went into generating them, and the rms of the resulting model, are given in Table 2 (with the positions in Table 1). In the case of PSR J1413–6205, there is an apparent glitch at \( \sim MJD 54735 \). Periodicity searches of the data before the glitch indicate that the magnitude was \( \Delta f / f = 1.7 \times 10^{-6} \), fairly large, though not unusually so for young Vela-like pulsars (Dodson et al. 2002; Saz Parkinson 2009). However, the short span of data before the glitch prevented us from including the glitch in the timing model and thus the model for J1413–6205 in the table is constructed only from post-glitch data.

The case of PSR J1023–5746 is especially complicated. As is often the case in young pulsars (Hobbs et al. 2004), this pulsar suffers from large timing irregularities. In addition to experiencing a glitch of magnitude \( \Delta f / f \sim 3.6 \times 10^{-6} \) at \( \sim MJD 55041 \), this pulsar has a level of timing noise that required the use of higher order frequency derivative terms to model. Our model that fitted for position (whose results are presented in Table 2) required terms up to the third derivative of the frequency, to obtain featureless residuals to the fit and resulted in a position that is \( \sim 2'' \) from the \textit{Chandra} X-ray source CXOU J102302.8–574606. To test whether the proposed association with CXOU J102302.8–574606 was compatible with the timing measurements, we generated a different timing model, with the position fixed at that of the \textit{Chandra} source. This model required terms up to the fourth derivative of the frequency, but also resulted in a good fit with essentially featureless residuals. The high order polynomial terms required to model the timing noise are strongly covariant with the position, resulting in the statistical errors being a significant underestimate of the true error. The \textit{Tempo2} timing models used in this paper will be made available online at the \textit{Fermi} Science Support Center (FSSC) Web site.\textsuperscript{31} Figure 1 shows the distribution in frequency and frequency derivative of the new pulsars (shown with unfilled triangles), compared with the previously known \( \gamma \)-ray selected pulsars (shown as solid triangles) (Abdo et al. 2009b) and the total known pulsar population.

\textsuperscript{31} \url{http://fermi.gsfc.nasa.gov/ssc/data/access/lat/ephems/}

### Table 2

| PSR          | \( f \) (Hz) | \( -10^{-12} \) Hz s\(^{-1} \) | \( N_{\text{DAYS}} / N_{\text{TOAs}} \) | rms (ms) | \( \tau \) (kyr) | \( E \) (10\(^{34} \) erg s\(^{-1} \)) | \( B_5 \) (10\(^{12} \) G) | \( B_{\text{LC}} \) (kG) |
|--------------|-------------|-------------------------------|--------------------------------|----------|--------------|---------------------------------|----------------|------------|
| J1023–5746   | 4365        | 8.970827684(7)               | 30.8825(1)                      | 550/56   | 1.0          | 4.6                | 1095.5          | 6.6         |
| J1044–5737   | 2362        | 7.192749594(2)               | 2.8262(2)                       | 395/21   | 0.8          | 40.3               | 80.3            | 2.8         |
| J1413–6205\(^b\) | 5716        | 9.112389505(2)               | 2.2984(3)                       | 361/19   | 0.5          | 62.9               | 82.7            | 1.8         |
| J1429–5911   | 2750        | 8.632402182(2)               | 2.2728(2)                       | 395/21   | 0.8          | 60.2               | 77.5            | 1.9         |
| J1846–0919   | 1042        | 4.433578172(4)               | 0.1951(5)                       | 412/18   | 12.4         | 360.2              | 3.4             | 1.5         |
| J1954+2836   | 2953        | 10.786432929(3)              | 2.4622(4)                       | 383/22   | 0.9          | 69.5               | 104.8           | 1.4         |
| J1957+5033   | 449         | 2.668043530(2)               | 0.0504(3)                       | 415/20   | 10.6         | 837.7              | 0.5             | 1.6         |
| J2055+25     | 715         | 3.129291291(9)               | 0.0401(3)                       | 503/56   | 8.2          | 1226.9             | 0.5             | 1.2         |

**Notes.** The reference epoch for the timing solutions is MJD 54800, except for PSR J1023–5746 (MJD 54856) and PSR J2055+25 (MJD 54900).

\(^a\) PSR J1023–5746 requires second- and third-order frequency derivatives to model the timing noise: \( f = 7.1(2) \times 10^{-12} \) Hz s\(^{-2} \) and \( f = -1.09(4) \times 10^{-28} \) Hz s\(^{-3} \). Column 5 gives the span of days of data used to generate the timing model and the number of TOAs that were generated from such data. Column 6 gives the rms timing residual of the model. Columns 7 and 8 give the characteristic age and spin-down luminosity. Columns 9 and 10 give the magnetic field strength at the neutron star surface and at the light cylinder. The derived quantities in Columns 7–10 are obtained from the timing parameters of the pulsars and are rounded to the nearest significant digit.

\(^b\) All timing solutions are valid for the period MJD 54682–55016, except for that of PSR J1413–6205, which is only valid in the range MJD 54743–55016, due to a glitch which occurred around MJD 54718. Column 1 gives the pulsar name. Column 2 lists the number of photons obtained with the standard cuts used (\textit{diffuse} class, \( E > 300 \) MeV, \( R < 0.8 \)) over the 11 month observational period. Columns 3 and 4 list the frequency and frequency derivative.

### Table 3

| PSR          | Peak Multiplicity | \( \gamma \)-ray Peak Separation | Reference Phase | Off-peak Definition | ROI (°) |
|--------------|-------------------|---------------------------------|----------------|---------------------|--------|
| J1023–5746   | 2                 | 0.45 ± 0.01                    | 0.66           | 0.75–1.16           | 0.8    |
| J1044–5737   | 2                 | 0.35 ± 0.01                    | 0.62           | 0.66–1.16           | 0.8    |
| J1413–6205   | 2                 | 0.31 ± 0.02                    | 0.85           | 0.69–1.09           | 0.8    |
| J1429–5911   | 2                 | 0.46 ± 0.01                    | 0.86           | 0.84–1.13           | 0.8    |
| J1846–0919   | 1                 | 0.36                           | 0.36           | 0.50–1.09           | 0.8    |
| J1954+2836   | 2                 | 0.43 ± 0.01                    | 0.68           | 0.84–1.16           | 0.9    |
| J1957+5033   | 1                 | 0,04                           | 0.77           | 0.53–1.13           | 0.8    |
| J2055+25     | 1                 | 0.83                           | 0.50–1.16      | 0.8                 |

**Notes.** Light curve shape parameters of each pulsar, including the peak multiplicity, the phase separation between the two \( \gamma \)-ray peaks, the value of the phase at the reference epoch, barycentric MJD 54800 (UTC), and the off-peak region used in the spectral analyses. Column 6 lists the region of interest used to make the light curves, where we have selected only \textit{diffuse} class events.
The phases have been shifted so that the “first” peak lies approximately at $\phi = 0.25$. The name of each peak (i.e., “first” versus “second”) refers to their respective order of arrival relative to the off-peak emission. We caution, however, that for some pulsars (e.g., PSR J1954+2836) there may be no appreciable difference between the off-peak emission and the “bridge” emission between the two peaks, leading to some ambiguity in such designation. Consequently, there is also some ambiguity in our measurement of the corresponding peak separation. Five of the eight pulsars have a clear double peak structure, while three of them (PSR J1846+0919, PSR J1957+5033, and PSR J2055+25) are currently dominated by a single broad peak. For those pulsars showing a single peak, we tried folding the events at half or a third of the frequency (in case the original frequency found in our search was the second or third harmonic), but the various peaks obtained in this way were not statistically distinguishable.

The additional statistics accumulated from continued observations by the LAT are necessary to firmly establish whether the single broad peaks are real, or whether they can be resolved into narrow multiple peaks with small peak separations.

The pulse shape parameters, including peak multiplicity, $\gamma$-ray peak separation (computed by fitting the peaks with two Gaussians and taking the difference between the means), and off-peak definition, are given in Table 3.

### 2.3. Spectral Analysis

We have performed the same spectral analysis on the eight pulsars as was performed on the 46 pulsars presented in the First LAT Catalog of $\gamma$-ray Pulsars (Abdo et al. 2010b). The pulsed spectra were fitted with an exponentially cutoff power-law model of the form

\[
\frac{dN}{dE} = K E^{-\Gamma} \exp\left(-\frac{E}{C_{\text{cutoff}}}\right),
\]

where the three parameters are the photon index $\Gamma$, the cutoff energy $E_{\text{cutoff}}$, and a normalization factor $K$ (in units of photons $\text{cm}^{-2} \text{ MeV}^{-1}$), defined at an energy of 1 GeV. In order to extract the spectra down to 100 MeV, we must take into account all neighboring sources and the diffuse emission together with each pulsar. This was done using a 6 month source list that was generated in the same way as the Bright Source List, following the prescription described in Abdo et al. (2010b). We used all events in an ROI of $10^\circ$ around each pulsar, and included all sources up to $17^\circ$ into the model (sources outside the ROI can contribute at low energy). The spectral parameters for sources outside a $3^\circ$ radius of the pulsar were frozen, taken from the all-sky analysis, while those for the pulsar and sources within $3^\circ$ were left free for this analysis. In general, nearby $\gamma$-ray sources are modeled by a simple power law. In the case of PSR J1023–5746, however, the nearby sources include the $\gamma$-ray pulsar PSR J1028–5819 (Abdo et al. 2009e), as well as the bright pulsar-like LAT source 1FGL J1018.6–5856, both of which were modeled by a power law with an exponential cutoff. For the eight pulsars, an exponentially cutoff power-law spectral model was
significantly better than a simple power law. This can be seen by computing the test statistic $T_{\text{cutoff}} = 2 \Delta \log(\text{likelihood})$ of the model with a cutoff relative to one with no cutoff, as shown in Column 7 of Table 4, where the lowest value of $T_{\text{cutoff}}$ is $\sim 20$. Because the $\gamma$-ray sources we are fitting might contain a significant unpulsed component, we attempt to improve our fits to the pulsar spectrum by splitting the data into an on-peak and off-peak component, and performing the fit only to the on-peak events, while using the off-peak component to better estimate our background. Table 3 gives the definition of the off-peak phase intervals (the on-peak interval being the complement of the off-peak one), as determined by visual inspection of the light curves in all energy bands (the same method used in Abdo et al. (2010b)). We used the off-peak window to estimate the unpulsed emission. We re-fitted the on-peak emission to the exponentially cutoff power law, with the off-peak emission (scaled to the on-peak phase interval) added to the model and fixed to the off-peak result. The resulting spectral index and energy cutoff for the on-peak emission of each pulsar are those given in Columns 4 and 5 of Table 4. For more details on the spectral fitting, see Abdo et al. (2010b).

Three of the pulsars (J1023–5746, J1413–6205, and J2055+25) showed significant emission (TS $> 25$) in the off-peak component. The off-peak energy spectrum of PSR J1023–5746 shows no indication of a cutoff. Furthermore, the distribution of this emission does not follow the Galactic plane (as might be expected if this were due to an improperly modeled diffuse background) and peaks close to the pulsar position, all of which suggests that such emission may be due to a pulsar wind nebula (PWN). However, the other two pulsars, J1413–6205 and J2055+25, have an off-peak component that is best fit by a power law with exponential cutoff, with photon index of $\Gamma = 1 \pm 0.6$ and $\Gamma = 1 \pm 0.5$, and $E_{\text{cutoff}} = 1.8 \pm 1$ GeV and $E_{\text{cutoff}} = 0.65 \pm 0.26$ GeV, respectively. This could be an indication of magnetospheric origin, similar to what is seen in the case of PSR J1836+5925 (Abdo et al. 2010c). We caution, however, that these results are subject to some caveats. In the case of J1413–6205, the significance of the preference of the power law with a cutoff over a simple power law is marginal (a TS of 36 versus 26). The case of J2055+25, on the other hand, is highly sensitive to our definition of the off-peak phase interval. A reduction of the off-peak interval from 0.66 to 0.5 (i.e., a 25% reduction) reduced the TS from 99 to 52 (nearly 50%), which seems to suggest that we may be overestimating the “true” size of the off-peak interval. After obtaining the spectral parameters for each pulsar, we compute the corresponding photon and energy fluxes, and present the results in Columns 2 and 3 of Table 4. It is interesting to note that the oldest pulsars tend to have the hardest spectra and lowest cutoff energies. Earlier studies in Abdo et al. (2010b) showed a weak trend of spectral index with $E$, and a stronger trend is evident here, albeit with lower statistics.

3. THE NEW $\gamma$-RAY PULSARS

The new pulsars are drawn from similar populations as the first 16 pulsars discovered in blind searches. Five of the pulsars (J1023–5746, J1044–5737, J1413–6205, J1429–5911, and J1954+2836) are energetic ($E \geq 7 \times 10^{35}$ erg s$^{-1}$) and
likely that there is a one-to-one correspondence between those lower than those reported for the COS-B sources, it is un-

three new pulsars discovered by the LAT are a factor of about

may have even been partially detected by the COS-B detec-

B sources (3EG J1410–6147 (Hartman et al. 1999), even if PSR J1413–6205 falls slightly outside the EGRET 95% statistical error circle.

Given the complicated nature of this region, it is safe to assume that at least one, PSR J1028–5819 and the newly discovered PSR J1023–5746 up of various contributions which the LAT has now resolved for example, that the COS-B source 2CG 284-00 was made up of various contributions which the LAT has now resolved into at least three separate γ-ray sources, including the pulsars PSR J1028–5819 and the newly discovered PSR J1023–5746 (Abdo et al. 2009e). We should point out that the issue of source confusion is one faced by the LAT too, albeit at a different sensitivity level than EGRET. The problem is particularly severe in the Galactic plane, where there is a large component of diffuse emission. In the case of PSR J1023–5746, for example, this resulted in an initial LAT source location that was far removed (>10′) from the true position of the pulsar, making the early detection of pulsations from this source all the more challenging.

3.1. Source Associations

As shown in Table 1, five of the eight γ-ray pulsars are associated with sources found in the Fermi Bright Source List (Abdo et al. 2009f), while two of the pulsars were also reported as γ-ray sources by the AGILE team (Pittori et al. 2009). Only PSR J1413–6205 was clearly detected as a γ-ray source by EGRET (EGR J1414–6224; Casandjian & Grenier 2008) although it is very likely that another one, PSR J1023–5746, was at least partly responsible for the EGRET source 3EG J1027–5817 (Abdo et al. 2009e). Three pulsars (PSRs J1023–5746, J1413–6205, and J1954+2836) may have even been partially detected by the COS-B detector (2CG 284–00, 2CG 311–01, and 2CG 065+00, respectively; Swanenburg et al. 1981). Given the large error radii of the COS-B sources (~1°), however, and the fact that the fluxes of the three new pulsars discovered by the LAT are a factor of about 10 lower than those reported for the COS-B sources, it is unlikely that there is a one-to-one correspondence between those sources and the LAT pulsars. More likely, COS-B was detecting emission from a number of unresolved sources in the region (although it could also be that the COS-B sources included diffuse gamma-ray emission that was incorrectly modeled). It appears, for example, that the COS-B source 2CG 284-00 was made up of various contributions which the LAT has now resolved into at least three separate γ-ray sources, including the pulsars PSR J1028–5819 and the newly discovered PSR J1023–5746 (Abdo et al. 2009e).

Given the complicated nature of this region, it is safe to assume that at least part of the γ-ray emission from PSR J1413–6205 was captured as 3EG J1410–6147 (Hartman et al. 1999), even if PSR J1413–6205 falls slightly outside the EGRET 95% statistical error circle.

3.2. Distance Estimates

In the absence of distance information from observations in other wavebands, for example, radio dispersion measures (DMs) or optical parallax determinations, it is still possible to discern a general idea of the distance to these blind search pulsars. The method hinges upon the observed correlation between intrinsic γ-ray luminosity \( L_\gamma \) above 100 MeV and pulsar spin-down energy loss rate \( \dot{E} \), as depicted in Figure 6 of Abdo et al. (2010b). The luminosity trend is calibrated from the observed >100 MeV fluxes using standard radio pulsar...
distance determination techniques and the presumption of a beam correction factor \( f_{\Delta} = 1 \) for the \( \gamma \)-ray emission cone for all pulsars (Watters et al. 2009).

The correlation is benchmarked at \( L_\gamma \sim 3.2 \times 10^{33}(E_{34})^{1/2} \) erg s\(^{-1}\) in Figure 6 of Abdo et al. (2010b), where \( E_{34} \) is \( E \) in units of \( 10^{34} \) erg s\(^{-1}\). Note that for \( E \lesssim 10^{34} \) erg s\(^{-1}\) there is a break in the observed trend to a stronger dependence on \( E \) (e.g., \( L_\gamma \sim E \); Abdo et al. 2010b). This is expected as pulsars cannot exceed 100% radiative efficiency. For the two pulsars that are below this transitional \( E \) (PSR J1957+5033 and PSR J2055+25), the efficiencies will be overestimated and thus the pseudo-distances given in Table 4 may be overestimates.

There is considerable scatter (by factors of 3–10) of inferred pulsar \( \gamma \)-ray luminosities about this linear relationship, possibly due to the inaccuracy of the \( f_{\Delta} = 1 \) assumption. An earlier version of this correlation was calculated for the EGRET pulsar database (Thompson et al. 1999). Physical origins for such a relationship are discussed in Zhang & Harding (2000), having first been identified by Harding (1981).

In this way, one obtains

\[
d_{ps} = 1.6 \frac{(E_{34})^{1/4}}{(f_{\Delta} G_{100-11}^{1/2})^{1/2}} \text{ kpc.} \tag{2}
\]

Here \( G_{100-11} \) is the observed energy flux \( G_{100} \), as listed in Table 4, in units of \( 10^{-11} \) erg cm\(^{-2}\) s\(^{-1}\). The significant scatter of inferred luminosities for radio-loud LAT pulsars about the correlation translates to uncertainties in pseudo-distances of the order of factors of 2–3. The resulting \( d_{ps} \) estimates for the new blind search pulsars are listed in Table 4, ranging from \( d_{ps} \sim 0.4 \) kpc for PSR J2055+2539 to \( d_{ps} \sim 1.8 \) kpc for the high \( E \) PSR J1023–5746. The relatively large pseudo-distance for PSR J1023–5746 is naturally expected due to interplay between its more-or-less typical \( G_{100} \) flux and its high \( E \). It is of considerable interest because of the possible association of this pulsar with the Westerlund 2 cluster, as discussed in Sections 4.2 and 4.3.

4. MULTIWAVELENGTH OBSERVATIONS

4.1. Radio

These pulsars were all discovered in \( \gamma \)-ray searches and thus are \( \gamma \)-ray selected pulsars, but targeted radio observations are required to determine if they are also radio quiet, or could have been discovered in radio surveys independently. The population statistics of radio-quiet versus radio-loud \( \gamma \)-ray pulsars have important implications for \( \gamma \)-ray emission models (e.g., Gonthier et al. 2004). The precise positions derived from the LAT timing of these pulsars allowed us to perform deep follow-up radio observations to search for pulsations from each of the new pulsars. We used the NRAO 100 m Green Bank Telescope (GBT), the Arecibo 305 m radio telescope, and the Parkes 64 m radio telescope for these observations. The log of observations is shown in Table 5 and the instrument parameters used in the sensitivity calculations are shown in...
of the beam half-width at half maximum. A computed flux limit where \( \theta \) is the offset from the pointing direction and HWHM is the beam half-width at half maximum. A computed flux limit of \( S \) at the beam center is thus corrected to \( S/f \) for target offset from the pointing direction. The resultant flux limits are compiled in Table 5. We compare these flux limits with the measured fluxes of the population of pulsars in the ATNF pulsar catalog (Manchester et al. 2005) in Figure 10. To make the fluxes comparable, we have scaled them all to the equivalent 1400 MHz flux density using a typical pulsar spectral index of 1.6. Using the scaled flux densities and the pseudo-distances given in Table 4, we can estimate the luminosity limits at 1.4 GHz. All eight pulsars have luminosity limits below \( L_{1.4} = 0.1 \) mJy kpc\(^2\). Prior to the detection of radio pulsations from three LAT blind search pulsars (Camilo et al. 2009; Abdo et al. 2010d), the least luminous young radio pulsar known was PSR J0205+6649 in SNR 3C 58 with \( L_{1.4} \approx 0.5 \) mJy kpc\(^2\) (Camilo et al. 2002).

Two of the new radio LAT pulsars, however, have luminosities an order of magnitude below this level. Thus, while the radio limits we present here are quite stringent by comparison with the overall known population of young pulsars, they are still far above the now least luminous pulsars known, and it is entirely possible that some of the new pulsars could be radio emitters at a level below our limits. It should also be noted that some of these pulsars, and in particular PSRs J1846+0919, J1957+5033, and J2055+25 located at high Galactic latitudes (|\( \beta \)| > 3\(^°\)), may be very nearby and have very low values of DM. As was seen in the case of PSR J1741--2054 (Camilo et al. 2009), the received flux from such a nearby pulsar can vary greatly due to interstellar scintillation. The best way to detect such pulsars in radio might involve multiple low-frequency observations. However, despite multiple low-frequency observations of these three pulsars, no radio detections were made (see Table 5).

The lack of even a single radio detection among these eight pulsars brings the total number of known radio-quiet pulsars to 22 (including Geminga), out of a total of 46 known young \( \gamma \)-ray pulsars, or \( \sim 50\% \). Such a high fraction may indicate that the size of the \( \gamma \)-ray beam is significantly larger than that of the radio beam, consistent with the predictions of fan-beam outer-magnetosphere models for \( \gamma \)-rays and narrow polar-cap models.
for radio beams. However, more detailed population studies will be required to quantify this effect.

4.2. X-ray

We searched archival X-ray observations for possible counterparts of the newly discovered LAT pulsars, but found the pre-existing X-ray coverage of these fields to be extremely sparse. PSR J1023–5746 is the only pulsar with any significant X-ray observations, due to its proximity to the Westerlund 2 cluster. It was observed on three different occasions (2003 August and 2006 September) by Chandra in the ACIS-S faint mode, with a total exposure of ~130 ks. In a new analysis of the Chandra data, we found a faint source at $\alpha_{2000} = 10^h 23^m 02^s 28$, $\delta_{2000} = \sim 57^\circ 46' 07'' 01$ with a 95% error radius of $\sim 2''$, consistent with our best timing position for the pulsar obtained from LAT data (see Figures 11 and 12). This source is one of 468 X-ray sources previously reported by Tsujimoto et al. (2007) in their survey of the massive star-forming region RCW 49. While Tsujimoto et al. (2007) identify it as CXOU J102302.84−574606.9, it is also referred to in the SIMBAD$^{35}$ astronomical database as CXOU J102302.8−574606, and we hereon adopt this designation.

Notes. Results of the unbinned maximum likelihood spectral fits for the new γ-ray pulsars (see Section 2.3). Columns 2 and 3 list the on-peak (defined as the complement of the off-peak region defined in Column 5 of Table 3) photon flux $F_{100}$ and on-peak energy flux $G_{100}$, respectively. The fits used an exponentially cutoff power-law model (see Equation (1)) with photon index $\Gamma$ and cutoff energy $E_{\text{cut}}$ given in Columns 4 and 5. The systematic uncertainties on $F_{100}$, $G_{100}$, and $\Gamma$ due to uncertainties in the Galactic diffuse emission model have been added in quadrature with the statistical errors. Uncertainties in the instrument response induce additional biases of $\delta F_{100} = (\pm 30\%, -10\%)$, $\delta G_{100} = (\pm 20\%, -10\%)$, $\delta \Gamma = (\pm 0.3, -0.1)$, and $\delta E_{\text{cut}} = (\pm 20\%, -10\%)$. The test statistic (TS) for the source significance is provided in Column 6. The significance of an exponential cutoff (as compared to a simple power-law) is indicated by $TS_{\text{cut}}$ in Column 7, where a value $> 10$ indicates that the exponentially cutoff model is significantly preferred in every case. Column 8 gives a pseudo-distance estimate, $d_{\text{ps}}$, calculated using Equation (2), described in Section 3.2.

### Table 4

| PSR        | Photon Flux ($F_{100}$) | Energy Flux ($G_{100}$) | $\Gamma$ | $E_{\text{cut}}$ (GeV) | TS | $TS_{\text{cut}}$ | $d_{\text{ps}}$ (kpc) |
|------------|-------------------------|-------------------------|----------|------------------------|----|-------------------|-------------------|
| J1023−5746 | 41.5 ± 0.5              | 26.9 ± 1.8              | 1.58 ± 0.13 | 1.8 ± 0.3          | 868 | 88                | 1.8               |
| J1044−5737 | 14.3 ± 1.7              | 10.3 ± 0.65             | 1.60 ± 0.12 | 2.5 ± 0.5           | 799 | 69.7              | 1.5               |
| J1413−6205 | 12.9 ± 2.2              | 12.9 ± 1.0              | 1.32 ± 0.16 | 2.6 ± 0.6           | 461 | 64.9              | 1.3               |
| J1429−5911 | 16.2 ± 2.4              | 9.26 ± 0.81             | 1.93 ± 0.14 | 3.3 ± 1.0           | 318 | 20.8              | 1.6               |
| J1846+0919 | 4.1 ± 0.77              | 3.58 ± 0.35             | 1.60 ± 0.19 | 4.1 ± 1.5           | 363 | 19.8              | 1.1               |
| J1954+2836 | 11.9 ± 1.6              | 9.75 ± 0.68             | 1.55 ± 0.14 | 2.9 ± 0.7           | 595 | 54.3              | 1.6               |
| J1957+5033 | 3.3 ± 0.52              | 2.27 ± 0.20             | 1.12 ± 0.28 | 0.9 ± 0.2           | 395 | 39.3              | 0.9               |
| J2055+25   | 11.1 ± 1.1              | 11.5 ± 0.70             | 0.71 ± 0.19 | 1.0 ± 0.2           | 779 | 127               | 0.4               |

### Table 5

| Target | Obs Code | Date      | $t_{\text{obs}}$ (s) | DM Max (pc cm$^{-3}$) | R.A. (J2000) | Decl. (J2000) | Offset (arcmin) | $T_{\text{sky}}$ (K) | $S_{\text{min}}$ (μJy) |
|--------|----------|-----------|----------------------|-----------------------|--------------|--------------|-----------------|---------------------|---------------------|
| J1023−5746 | Parkes-ABF | 2009 Apr 14 | 16200 2000 | 10:23:10.6 | 57:44:20 | 2.0 | 6.0 | 31 |
| J1023−5746 | Parkes-10cm | 2009 Nov 26 | 11500 1500 | 10:23:02.3 | 57:46:09 | 0.1 | 0.9 | 22 |
| J1044−5737 | Parkes-BPSR | 2009 Aug 2 | 16200 2000 | 10:44:33.3 | 57:37:15 | 0.1 | 4.2 | 21 |
| J1413−6205 | Parkes-BPSR | 2009 Aug 2 | 16200 2000 | 14:13:14.2 | 62:04:34 | 2.1 | 8.1 | 25 |
| J1429−5911 | Parkes-BPSR | 2009 Aug 3 | 16200 2000 | 14:30:02.2 | 59:11:20 | 0.5 | 6.5 | 22 |
| J1846+0919 | AO-Lwide | 2009 Aug 7 | 3600 2000 | 18:46:26.8 | 09:19:42 | 0.2 | 3.8 | 4 |
| GBT-350 | 2010 Mar 4 | 1800 130 | 18:46:25.8 | 09:19:40 | 0.0 | 140.6 | 272 |
| GBT-350 | 2010 May 26 | 3600 130 | 18:46:25.8 | 09:19:40 | 0.0 | 140.6 | 209 |
| J1954+2836 | AO-Lwide | 2009 Aug 4 | 1200 1310 | 19:54:18.9 | 28:36:10 | 0.1 | 3.2 | 7 |
| J1957+5033 | AO-Lwide | 2009 Oct 14 | 2700 1310 | 19:54:19.2 | 28:36:06 | 0.0 | 3.2 | 4 |
| J1957+5033 | GBT-820 | 2009 Sep 21 | 4000 1100 | 19:57:32.1 | 50:36:33 | 3.4 | 6.9 | 25 |
| J1957+5033 | GBT-350 | 2010 Mar 4 | 3000 150 | 19:57:38.7 | 50:33:14 | 0.0 | 62.9 | 225 |
| J2055+25 | AO-327 | 2009 May 15 | 1800 2500 | 20:55:34.8 | 25:40:23 | 3.2 | 62.2 | 85 |
| J2055+25 | AO-Lwide | 2009 May 15 | 1800 2500 | 20:55:34.8 | 25:40:23 | 3.2 | 1.4 | 106 |

Notes.

a Maximum value of dispersion measure (DM) searched.

b Telescope pointing direction (not necessarily source position).

b Offset between telescope pointing direction and pulsar position.

d Sky temperature estimated by scaling 408 MHz (Haslam et al. 1981) all-sky map to observing frequency using spectral index of $-2.6$.

f Flux limits are at the observing frequency, not scaled to an equivalent 1.4 GHz flux.

$^{34}$ Obsids 3501, 6410, and 6411.

$^{35}$ http://simbad.u-strasbg.fr/simbad/
contours correspond to the significance (5

The LAT data are consistent with a point by the HESS collaboration from the extended TeV source HESS J1023–575

Figure 11. Fermi-LAT image of a 1 deg$^2$ region of the sky around PSR J1023–5746. The smoothed counts map was generated using all diffuse class events above 100 MeV between 2008 August 4 and 2009 July 4 (∼21.2 Ms live time). The color scale is in counts per square arcmine. The overlaid green contours correspond to the significance (5σ, 6.25σ, 7.5σ, and 8.75σ) reported by the HESS collaboration from the extended TeV source HESS J1023–575 (Aharonian et al. 2007). The LAT data are consistent with a point source. The white circle represents the position (and 95% error circle) of the LAT source location based on 11 months of data and was the position used in the blind search that resulted in the discovery of pulsations. The large black rectangle is the area explored in the Chandra X-ray observations shown in Figure 12, and the smaller black box within it, represents the 1 arcmin$^2$ region around the X-ray counterpart of PSR J1023–5746, CXOU J102302.8–574606, also shown in Figure 12 at a larger scale.

(A color version of this figure is available in the online journal.)

We find no optical source within 5" (upper limit $m_V \sim 21$) in the NOMAD optical catalog. CXOU J102302.8–574606 has a typical PWN-like power-law spectrum with a photon index of 1.2 ± 0.2 and an $N_H$ of (1.5 ± 0.4) × 10$^{22}$ cm$^{-2}$, resulting in an unabsorbed flux of 1.2 ± 0.3 × 10$^{-13}$ erg cm$^{-2}$ s$^{-1}$ (for a total of ~600 counts). No other simple spectral model was statistically suitable. The off-axis PSF of the Chandra ACIS camera is a complicated function of energy, and given that this source is ∼8' from the center of the field of view we cannot make any claims about the spatial extension of the counterpart. The $N_H$ value is comparable to the Galactic one (∼1.3 × 10$^{22}$ cm$^{-2}$) implying a fairly large distance (possibly greater than 10 kpc). The distance to the Westerlund 2 cluster has been a matter of debate, with estimates as low as 2.8 kpc (Ascenso et al. 2007), or as high as 8.0 ± 1.4 kpc (Rauw et al. 2007). The most recent estimate, based on an analysis of the CO emission and 21 cm absorption along the line of sight to the cluster places it at a distance of 6.0 ± 1.0 kpc (Dame 2007). We note that the pseudo-distance that we have estimated for PSR J1023–5746 (given in Table 4) is 1.8 kpc. A rough estimate of the average transverse velocity of the pulsar from its birth site to its current location over its lifetime is given by $\frac{\Delta \theta}{\Delta t} = \frac{(\theta_d)(d_{1.8})}{(t_{4.6})}9.0 \times 10^2$ km s$^{-1}$, where $\theta_d$ is the angular separation between the pulsar and its birth site, in units of 8 arcmin, $d_{1.8}$ is the distance to the pulsar, in units of 1.8 kpc, and $t_{4.6}$ is the age of the pulsar, in units of 4.6 kyr. This would be among the highest transverse velocities measured for any pulsar (e.g., Hobbs et al. 2004). Accordingly, the association seems improbable unless (1) the pulsar was born far from the cluster core (e.g., from a runaway progenitor), (2) the cluster and pulsar distance are lower than our pseudo-distance estimate of 1.8 kpc, or (3) the true pulsar age is substantially greater than its characteristic age. An on-axis Chandra observation might be able to resolve the expected bow shock structure of the apparent PWN and test this association.

Shortly after identifying these eight LAT sources as pulsars, we obtained short (∼5 ks) Swift-XRT observations in PC mode of seven of them (J1044–5737, J1413–6205, J1429–5911, ...

Table 6

| Obs Code | Telescope | Gain (K Jy$^{-1}$) | Freq (MHz) | $\Delta f$ (MHz) | $\beta^a$ | $n_p$ | HWHM (arcmin) | $T_{rec}$ (K) |
|----------|-----------|-------------------|------------|----------------|-----------|------|--------------|-------------|
| GBT-350  | GBT       | 2.0               | 350        | 100            | 1.05      | 2    | 18.5         | 46          |
| GBT-820  | GBT       | 2.0               | 820        | 200            | 1.05      | 2    | 7.9          | 29          |
| GBT-820BCPM | GBT    | 2.0               | 820        | 48             | 1.05      | 2    | 7.9          | 29          |
| GBT-S    | GBT       | 1.9               | 2000       | 700$^b$        | 1.05      | 2    | 3.1          | 22          |
| AO-327   | Arecibo   | 11                | 327        | 50             | 1.12      | 2    | 6.3          | 116         |
| AO-430   | Arecibo   | 11                | 430        | 40             | 1.12      | 2    | 4.8          | 84          |
| AO-Lwide | Arecibo   | 10                | 1510       | 300            | 1.12      | 2    | 1.5          | 27          |
| AO-ALFA  | Arecibo   | 10                | 1400       | 100            | 1.12      | 2    | 1.5          | 30          |
| Parkes-MB288 | Parkes | 0.735             | 1374       | 288            | 1.25      | 2    | 7.0          | 25          |
| Parkes-10cm | Parkes | 0.66              | 3078       | 864            | 1.25      | 2    | 3.3          | 30          |
| Parkes-AFB | Parkes  | 0.735             | 1374       | 256            | 1.25      | 2    | 7.0          | 25          |
| Parkes-BPSR | Parkes | 0.735             | 1352       | 340            | 1.05      | 2    | 7.0          | 25          |
| Nançay-L | Nançay    | 1.4               | 1334       | 128            | 1.05      | 2    | 4 × 22       | 35          |

Notes.

$^a$ Instrument-dependent sensitivity degradation factor (usually 1 < $\beta$ < 1.5). If no value, assume $\beta = 1.25$.

$^b$ The instrument records 800 MHz of bandwidth, but to account for a notch filter for RFI and the lower sensitivity near the band edges, we use an effective bandwidth of 700 MHz for the sensitivity calculations.

In Table 6, we list the observations with the following details:

- **Obs Code**: Identification code for each observation.
- **Telescope**: Name of the telescope used.
- **Gain (K Jy$^{-1}$)**: Instrument-dependent sensitivity degradation factor (usually between 1 < $\beta$ < 1.5). If no value, assume $\beta = 1.25$.
- **Freq (MHz)**: Frequency used for the observation.
- **$\Delta f$ (MHz)**: Bandwidth of the observation.
- **$\beta^a$**: Instrument-dependent sensitivity degradation factor, assuming $\beta = 1.25$.
- **$n_p$**: Number of photons detected.
- **HWHM (arcmin)**: Half-power width of the beam.
- **$T_{rec}$ (K)**: Recombination temperature.

The table includes data from various telescopes, including the GBT, Arecibo, Parkes, and Nançay, among others. Each entry represents a different observation mode and sensitivity, allowing for a comprehensive analysis of the pulsar data.
Figure 12. Chandra ACIS-S (0.1–10 keV) X-ray image of the Westerlund 2 cluster region using ~130 ks of data taken in 2003 August and 2006 September. The color scale is in counts per square arcsecond. The small box on the right represents a 1 arcmin² region around the source CXOU J102302.8–574606, which we have identified as the X-ray counterpart of PSR J1023–5746. Note that the source is ~8′ away from the core of the cluster. Inset—zoomed-in image of the 1 arcmin² region around CXOU J102302.8–574606. The white ellipse represents the 95% confidence error ellipse of the position of PSR J1023–5746, based on the timing, as listed in Table 1. The errors are statistical only. Although the X-ray source appears to be extended, indicating the possible presence of a PWN, a full extended source analysis is dependent on a more complete understanding of the PSF of the instrument at such a large off-axis location.

J1846+0919, J1954+2836, J1957+5033, and J2055+25). In the first six cases, no likely X-ray counterparts were found within the LAT error circle. In the case of J2055+25, a 6.3 ks observation revealed two sources relatively close to the pulsar location (~1′ away), but inconsistent with the current best position derived from the timing and likely associated with bright field stars (sources (b) and (d) in Figure 13). The upper limit on the flux for a putative X-ray counterpart in any of these five Swift-XRT observations is ~1.5–2 × 10^{-13} erg cm^{-2} s^{-1}, under the hypothesis of a power-law spectrum with a photon index of 2 and N_H of 10^{21} cm^{-2}.

On 2009 October 26, the XMM-Newton satellite observed the field of PSR J2055+25 using the three European Photon Imaging Cameras (EPICs) MOS1, MOS2, and pn instruments. For MOS1 and pn cameras thin filters were used while for MOS2 the medium filter was used. All three instruments obtained data in full frame mode which resulted in a time resolution of 2.6 s for the MOS1, MOS2 cameras and 73.4 ms for the pn camera. The data from each instrument were analyzed utilizing the XMM-Newton Science Analysis System (SAS) software version 9.0.0. The calibration data utilized by SAS were the latest available at the time of data reduction. We filtered the event data for bad events, retaining only those events from the MOS cameras with predefined patterns 0–12, and also excluded times of high background.

In Figure 13, we show the combined image from the MOS1, MOS2, and pn cameras on XMM, resulting from an effective exposure of 19.0 ks after filtering. XMMU J205550.8+254048 and XMMU J205547.2+253906 (the “tadpole”) are apparent in the Swift-XRT image but owing to the higher effective area of XMM a number of fainter sources were also detected in the image including a faint source virtually coincident with the pulsar position: XMMU J205549.4+253959. The region is crowded so in order to minimize contamination from other X-ray sources we form a spectrum by extracting events in a 29 arcsec circular region around the X-ray position centroid and also extract a background spectrum from a region that appears to be free of X-ray sources on the same CCD. For a circular region 29 arcsec in radius around a point source the MOS1 PSF encircles roughly 85% of the photons at 1.5 keV. We can extract 97 photons from the source region and thus can form only an approximate spectrum for XMMU J205549.4+253959. Fitting an absorbed power law to this spectrum, we obtain an approximate flux of ~2.4 × 10^{-14} erg cm^{-2} s^{-1} in the 0.5–10 keV energy band with a power-law index of Γ ~ 2.1.

4.3. TeV

Four of the eight new pulsars are in the Northern Hemisphere and four are in the Southern Hemisphere. Only the Milagro TeV observatory, an all-sky survey instrument, has observed the four northern hemisphere pulsars. Milagro has reported a 4.3σ excess from the location of PSR J1954+2836, with a measured flux at 35 TeV of 37.1 ± 8.6 × 10^{-17} TeV^{-1} s^{-1} cm^{-2} (Abdo et al. 2009g). The remaining three pulsars in the Milagro field of view show no sign of TeV emission, though this is perhaps
not surprising given that they have spin-down luminosities that are 30–200 times lower than PSR J1954+2836.

Of the Southern Hemisphere pulsars, three have no reported TeV observations. The remaining one, PSR J1023–5746 is coincident with the TeV source HESS J1023–575 (see Figure 11). The HESS collaboration reported the detection of TeV emission from a source with an extension of 1.5 ± 0.5 × 10^{-3}°, or less than 1.5% of the spin-down luminosity of this pulsar, making the energetics of such an association plausible (e.g., Camilo et al. 2009). Recently, a jet and arc of molecular gas toward this source has been reported which suggests the possible occurrence of an anisotropic supernova explosion (Fukui et al. 2009). The discovery of the very young and energetic pulsar PSR J1023–5746 suggests that it likely plays an important role in the TeV emission from HESS J1023–575. Given the long list of known TeV PWNe (currently the most numerous class of TeV sources) and the significant number of these associated with bright γ-ray pulsars, such a scenario seems at least plausible, if not probable.

The first five months of LAT data led to the discovery of the first 16 pulsars found from blind searches of γ-ray data (Abdo et al. 2009b). Here, we report the discovery of an additional eight γ-ray selected pulsars by performing blind frequency searches on 11 months of Fermi-LAT data. These new pulsars are largely drawn from the same population as the previous 16 (see Figure 5). Deep radio follow-up observations of these newly discovered pulsars suggest that they are all either radio quiet, or extremely radio faint.

Figure 13. XMM-Newton (0.2–12 keV) X-ray image of the region around PSR J2055+25, using ~26 ks of data taken in 2009 October. The color scale is in counts per square arcsecond. The green ellipse represents the current best location derived from pulsar timing, given in Table 1. North is to the top and east to the left. Four sources, labeled by letters, can be clearly identified in the image: (a) XMMU J205548.0+254115, (b) XMMU J205550.8+254048, (c) XMMU J205549.4+253959, and (d) XMMU J205547.2+253906, the “tadpole.” The best timing position of the pulsar is virtually coincident with that of XMMU J205549.4+253959. XMMU J205550.8+254048 and XMMU J205547.2+253906 are apparent in a short Swift-XRT image, but the source coincident with the pulsar, XMMU J205549.4+253959, is not detected by the XRT.

(A color version of this figure is available in the online journal.)

References:

Abdo et al. 2009a and 2010a

http://tevcat.uchicago.edu/

5. CONCLUSION

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REFERENCES

Abdo, A. A., et al. 2009a, Astropart. Phys., 32, 193
Abdo, A. A., et al. 2009b, Science, 325, 840
Abdo, A. A., et al. 2009c, Science, 325, 848
Abdo, A. A., et al. 2009d, ApJ, 700, 1059
Abdo, A. A., et al. 2009e, ApJ, 695, L72
Abdo, A. A., et al. 2009f, ApJS, 183, 46
Abdo, A. A., et al. 2009g, ApJ, 700, L127
Abdo, A. A., et al. 2010a, ApJS, 188, 405
Abdo, A. A., et al. 2010b, ApJS, 187, 460
Abdo, A. A., et al. 2010c, ApJ, 712, 1209
Abdo, A. A., et al. 2010d, ApJ, 711, 64
Aharonian, F., et al. 2007, A&A, 467, 1075
Ascenso, J., Alves, J., Beletsky, Y., & Lago, M. T. V. T. 2007, A&A, 466, 137
Atwood, W. B., Ziegler, M., Johnson, R. P., & Baughman, B. M. 2006, ApJ, 652, L49
Atwood, W. B., et al. 2009, ApJ, 697, 1071
Bignami, G. F., & Caraveo, P. A. 1996, ARA&A, 34, 331
Camilo, F., et al. 2002, ApJ, 571, L41
Camilo, F., et al. 2009, ApJ, 705, 1
Caraveo, P. A. 2010, arXiv:1009.2183
Casandjian, J.-M., & Grenier, I. A. 2008, A&A, 489, 849
Chandler, A. M., Koh, D. T., Lamb, R. C., Macomb, D. J., Mattox, J. R., Prince, T. A., & Ray, P. S. 2001, ApJ, 556, 59
Dame, T. M. 2007, ApJ, 665, L163
Dodson, R. G., McCulloch, P. M., & Lewis, D. R. 2002, ApJ, 564, L85
Fukui, Y., et al. 2009, PASJ, 61, L23
Gonthier, P. L., Van Guilder, R., & Harding, A. K. 2004, ApJ, 604, 775
Harding, A. K. 1981, ApJ, 245, 267
Hartman, R. C., et al. 1999, ApJS, 123, 79
Haslam, C. G. T., Klein, U., Salter, C. J., Stoffel, H., Wilson, W. E., Cleary, M. N., Cooke, D. J., & Thomasson, P. 1981, A&A, 100, 209
Hobbs, G., Lyne, A. G., Kramer, M., Martin, C. E., & Jordan, C. 2004, MNRAS, 353, 1311
Hobbs, G. B., Edwards, R. T., & Manchester, R. N. 2006, MNRAS, 369, 655
Lorimer, D. R., & Kramer, M. (ed.) 2004, Handbook of Pulsar Astronomy (Cambridge: Cambridge Univ. Press)
Manchester, R. N., Hobbs, G. B., Teoh, A., & Hobbs, M. 2005, AJ, 129, 1993
Pittori, C., et al. 2009, A&A, 506, 1563
Ransom, S. M. 2001, PhD thesis, Harvard Univ.
Ransom, S. M. 2007, in AIP Conf. Ser. 921, The First GLAST Symposium, ed. S. Ritz, P. Michelson, & C. A. Meegan (Melville, NY: AIP), 54
Rauw, G., Manfroid, J., Gosset, E., Nazé, Y., Sana, H., De Becker, M., Foellmi, C., & Moffat, A. F. J. 2007, A&A, 463, 981
Ray, P. S., & Saz Parkinson, P. M. 2010, arXiv:1007.2183
Saz Parkinson, P. M. 2009, in AIP Conf. Ser. 1112, Science with the New Generation of High Energy Gamma-ray Experiments: Proc. of the 6th Ed.: Bridging the Gap between GeV and TeV, ed. D. Bastieri & R. Rando (Melville, NY: AIP), 79
Swanenburg, B. N., et al. 1981, ApJ, 243, L69
Thompson, D. J. 2008, Rep. Prog. Phys., 71, 116901
Thompson, D. J., et al. 1999, ApJ, 516, 297
Tsujimoto, M., et al. 2007, ApJ, 665, 719
Watters, K. P., Romani, R. W., Weltevrede, P., & Johnston, S. 2009, ApJ, 695, 1289
Zhang, B., & Harding, A. K. 2000, ApJ, 532, 1150