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ARECIBO PULSAR SURVEY USING ALFA. I. SURVEY STRATEGY AND FIRST DISCOVERIES

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ABSTRACT

We report results from the initial stage of a long-term pulsar survey of the Galactic plane using the Arecibo L-band Feed Array (ALFA), a seven-beam receiver operating at 1.4 GHz with 0.3 GHz bandwidth, and fast-dump digital spectrometers. The search targets low Galactic latitudes, $|b| \lesssim 5^\circ$, in the accessible longitude ranges $32^\circ \lesssim \ell \lesssim 77^\circ$ and $168^\circ \lesssim \ell \lesssim 214^\circ$. The instrumentation, data processing, initial survey observations, sensitivity, and database management are described. Data discussed here were collected over a 100 MHz passband centered on 1.42 GHz using a spectrometer that recorded 256 channels every 64 μs. Analysis of the data with their full time and frequency resolutions is ongoing. Here we report the results of a preliminary, low-resolution analysis for which the data were decimated to speed up the processing. We have detected 29 previously known pulsars and discovered 11 new ones. One of these, PSR J1928+1746, with a period of 69 ms and a relatively low characteristic age of 82 kyr, is a plausible candidate for association with the unidentified EGRET source 3EG J1928+1733. Another, PSR J1906+07, is a nonrecycled pulsar in a relativistic binary with an orbital period of 3.98 hr. In parallel with the periodicity analysis, we also search the data for isolated dispersed pulses. This technique has resulted in the discovery of PSR J0628+09, an extremely sporadic radio emitter with a spin period of 1.2 s. Simulations we have carried out indicate that ~1000 new pulsars will be found in our ALFA survey. In addition to providing a large sample for use in population analyses and for probing the magnetoionic interstellar medium, the survey maximizes the chances of finding rapidly spinning millisecond pulsars and pulsars in compact binary systems. Our search algorithms exploit the multiple data streams from ALFA to discriminate between radio frequency interference and celestial signals, including pulsars and possibly new classes of transient radio sources.

Subject headings: pulsars: general — pulsars: individual (PSR J0628+09, PSR J1906+07, PSR J1928+1746) — surveys

Online material: color figures

1. INTRODUCTION

Radio pulsars continue to provide unique opportunities for testing theories of gravity and probing states of matter that are otherwise inaccessible (Stairs 2003; Kramer et al. 2004). In large samples, they also allow detailed modeling of the magnetoionic components of the interstellar medium (e.g., Cordes & Lazio 2002; Han 2004) and the Galactic neutron star population (Lorimer et al. 1993; Arzoumanian et al. 2002).

For these reasons, we have initiated a large-scale pulsar survey that aims to discover rare objects especially suitable for their physical and astrophysical payoffs. Of particular importance are pulsars in short-period relativistic orbits, which serve as important tools for testing gravitational theories in the strong-field regime. Our survey parameters and data processing are also designed to find millisecond pulsars (MSPs). MSPs with ultrastable spin rates can be used as detectors of long-period ($\gtrsim$years) gravitational waves (e.g., Lommen & Backer 2001; Wyithe & Loeb 2003; Jenet et al. 2004), while submillisecond pulsars (if they exist) probe the equation of state of matter at densities significantly higher than in atomic nuclei. Long-period pulsars ($P \gtrsim 5$ s) and pulsars with high magnetic fields are also of interest with regard to understanding their connection, if any, with magnetars (Woods & Thompson 2006) and improving our understanding of the elusive pulsar radio emission mechanism. In addition, pulsars with especially large space velocities, as revealed through subsequent astrometry, will help constrain aspects of the formation of neutron stars in core-collapse supernovae (e.g., Lai et al. 2001). Finally, multiwavelength analyses of particular objects will provide further information on how neutron stars interact with the interstellar medium, on supernovae-pulsar statistics, and on the relationship between high-energy and radio emission from neutron stars.

The new survey is enabled by several innovations. First is ALFA,[14] a seven-beam feed and receiver system designed for large-scale surveys in the 1.2–1.5 GHz band. The 1.4 GHz

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[14] Arecibo L-band Feed Array information is available at http://alfa.naic.edu.

operating frequency of ALFA is particularly well suited for pulsar searching of the Galactic plane. Lower frequencies suffer the deleterious effects of pulse broadening from interstellar scattering, while pulsar flux densities typically are much reduced at higher frequencies. ALFA was constructed at the Australia Telescope National Facility (ATNF) and installed in 2004 April at the Gregorian focus of the Arecibo telescope. The ALFA front end is similar to the 13-beam system used on the Parkes telescope for surveys of pulsars and H I. The Parkes Multibeam (PMB) Pulsar Survey of the Galactic plane (Manchester et al. 2001; Morris et al. 2002; Kramer et al. 2003; Hobbs et al. 2004; Faulkner et al. 2004) has been extremely prolific, yielding over 700 new pulsars in the past 7 years. Our survey will complement the PMB survey in its sky coverage and will exploit the much greater sensitivity of the Arecibo telescope. However, because of the smaller size of the ALFA beams compared to the PMB system, many more pointings must be done in order to cover the same area of sky. In addition to providing better near-term localization of pulsars on the sky, the sensitivity of the telescope greatly decreases the time spent per pointing, which results in much better sensitivity to pulsars in compact binary systems without searching a large grid of acceleration values to combat binary motion.

Second, our initial and next-generation spectrometer systems have much finer resolution in both time and frequency than the spectrometer used with the PMB, increasing the detection volume of MSPs by an order of magnitude. This comes at the cost of an increase in data rate by 2 orders of magnitude ($\sim$0.3 TB hr^{-1}), requiring substantial computational and storage resources for analysis and archival, which are now available. For our own use in the early stages of the survey, as well as for long-term multi-wavelength studies, we archive both the raw data and data products from the data processing pipeline.

Large-scale pulsar surveys using the ALFA system have been organized through a Pulsar ALFA (PALFA) Consortium, of which the present authors and others are members. The planning and execution of PALFA surveys is a joint effort between NAIC and the Consortium to obtain legacy results for use by the broader astrophysical community. Similar consortia have been organized for other Galactic science and for surveys of extragalactic hydrogen.

The plan for the rest of this paper is as follows. Following a brief description of the ALFA system in § 2, in § 3 we describe the technical details and logistics of our survey, including sky coverage, data acquisition and processing, sensitivities, and archival of raw data and data products. In § 4 we report on initial results from preliminary survey observations that have so far resulted in the discovery of 11 new pulsars. Finally, in § 5 we outline our future plans and expectations for PALFA surveys.

2. THE ALFA SYSTEM

The ALFA feed horns are arranged in a close-packed hexagon surrounding a central horn at the Gregorian focus of the Arecibo telescope. Orthomode transducers provide dual, linearly polarized signals to cooled receivers. The beams from the seven feeds are elliptically shaped, with equivalent circular beam sizes (FWHM) of 3.′35. Beam centers of the outer six beams fall on an ellipse of size 11.′0 × 12.′8. Efficient coverage of the sky requires that we compensate for parallactic rotation of the beam pattern on the sky as the telescope azimuth changes. ALFA can be rotated relative to the telescope's azimuth arm to accomplish this. We note that, because the seven-beam pattern is elliptical, there are small offsets of the beams from their ideal positions as the feed is rotated.

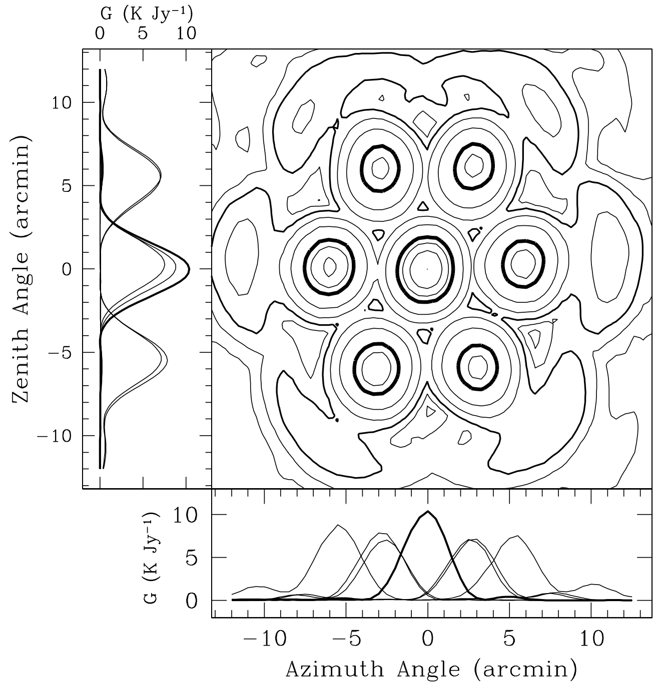

Fig. 1.—Contours of the telescope gain with the ALFA system averaged over its passband (1225–1525 MHz). Contours show the maximum gain for a given azimuth and zenith angle from any one of the seven beams and are the average of the two polarization channels. The gain values were measured on MJD 53,129 at low zenith angles using the extragalactic source 3C 286 and an assumed source flux density of 14.45 Jy for our measured band. Contour levels are at −1, −2, −3, −6, −9, −12, −15, and −19 dB from the central peak. The heavy contour is at the −3 dB level, and the next heaviest contour outside the six-beam pattern is −12 dB. Slices through the centers of the individual beam patterns of the seven feeds are also shown at constant azimuth and constant zenith angles. The equivalent circular beam width (FWHM), averaged over all beams, is 3.′35 at 1.42 GHz (Heiles 2004).

Figure 1 shows the measured gain contours for the feed systems. The on-axis gain is approximately 10.4 K Jy^{-1} at low zenith angles for the central beam, but is reduced to an average $\sim$8.2 K Jy^{-1} for the other six beams. The system temperature looking out of the Galactic plane is $\sim$24 K.[15] Receiver signals are transported via optical fiber to intermediate-frequency electronics and back-end spectrometers in the control building.

Currently, we are using four Wideband Arecibo Pulsar Processor (WAPP) systems (Dowd et al. 2000) to process 100 MHz passbands centered on 1.42 GHz for each ALFA beam. As used in our survey, the WAPPs compute 256 lags of the autocorrelation function for both three-level quantized polarization channels; correlation functions for the two channels are summed before recording to disk as 2 byte integers at 64 μs intervals.

Within 1 year, we anticipate using new spectrometers that will process the full 300 MHz bandwidth of the ALFA front-end system with 1024 spectral channels. The PALFA spectrometers will employ many-bit polyphase filters implemented on field-programmable gate array chips to provide the channelization. We expect that mitigation of radio frequency interference (RFI) will be more robust with the new spectrometer compared to the WAPP's three-level correlation approach. RFI shows a rich diversity in the overall ALFA band. For the initial portion of the survey using the WAPPs, we have therefore selected the cleanest

[15] Updated estimates of these system parameters and details on their azimuth and zenith angle dependences are available at http://alfa.naic.edu/performance.

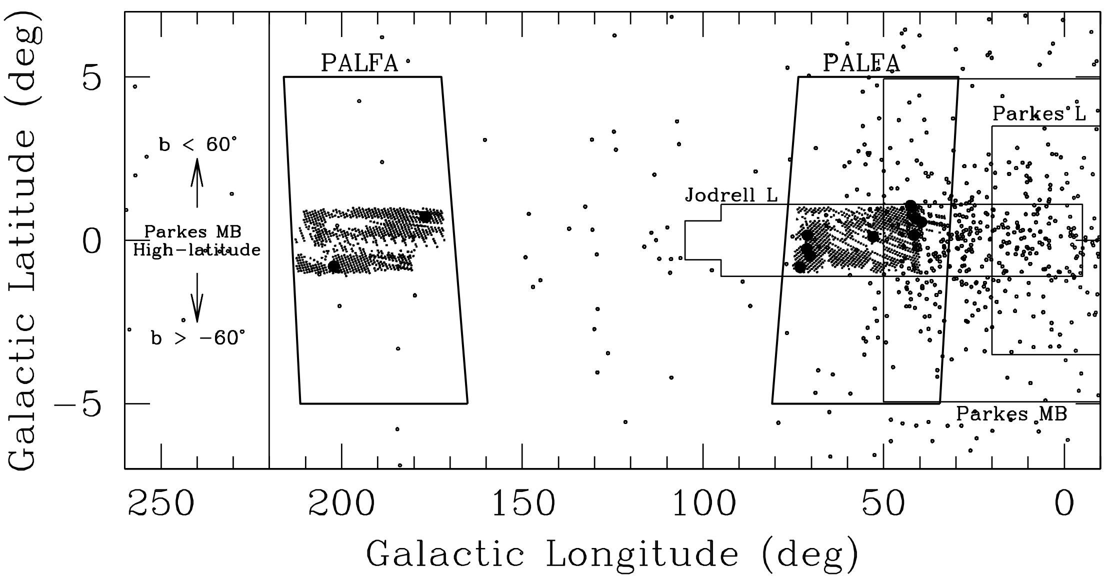

FIG. 2.—Regions of the Galactic plane to be surveyed with PALFA, taking into account declination limits of Arecibo and restricted to $|b| \leq 5°$. Hatched areas indicate regions covered so far in the precursor survey, and large filled circles represent newly discovered pulsars. Small dots designate known pulsars. We also show boundaries of several L-band surveys that have been made in or near these regions, including the PMB survey and single-pixel surveys with Parkes (Johnston et al. 1992) and Jodrell Bank (Clifton et al. 1992). The Swinburne Intermediate Latitude Survey (Edwards et al. 2001) covered the same longitude range as the PMB, but at latitudes $5° \leq |b| \leq 15°$. Arecibo surveys at 0.43 GHz have covered some of our proposed search areas, but to distances much smaller than we can reach, owing to the limiting effects of interstellar dispersion and scattering.

100 MHz portion of the available spectrum, centered at a frequency of 1.42 GHz.

3. ALFA PULSAR SURVEYS

Previous surveys of the Galactic plane accessible with the Arecibo telescope have either been conducted at the lower radio frequency of 0.43 GHz (Hulse & Taylor 1975; Stokes et al. 1986; Nice et al. 1995) or with less sensitive systems at 1.4 GHz (Clifton et al. 1992; Manchester et al. 2001). Our new survey with the ALFA system promises to probe the pulsar population in the Arecibo sky significantly more deeply than the previous surveys.

3.1. *Sky Coverage*

Our long-term plan is to conduct comprehensive pulsar surveys of most of the sky accessible with the Arecibo telescope (declinations between $-1°$ and $+38°$) but with emphasis on the Galactic plane (e.g., $|b| \lesssim 5°$). The survey results discussed here are for the inner Galaxy ($40° \lesssim \ell \lesssim 75°$, $|b| \leq 1°$) and anticenter ($170° \lesssim \ell \lesssim 210°$, $|b| \leq 1°$) regions. Figure 2 shows the regions that have been and will be covered close to the Galactic plane. The PMB pulsar survey covered the region $260° \leq \ell \leq 50°$ and $|b| \leq 5°$; i.e., there is some area of overlap in the inner Galaxy. Later we will conduct a survey at intermediate latitudes up to $|b| \sim 20°$ to optimize the search for relativistic binary systems and MSPs.

Our strategy for sampling the sky employs two methods for maximizing the efficiency and sensitivity of the survey. As shown in Figure 3, three adjacent pointings of ALFA are required to tile the sky with gain equal to or greater than half the maximum gain. Rather than using this dense sampling scheme, we have so far adopted a sparse sampling scheme (Freire 2003) that makes only one out of three of these pointings. Monte Carlo simulations (Vlemmings & Cordes 2004; Faucher-Giguère & Kaspi 2004) indicate that sparse sampling should detect ~2/3 of the pulsars in the surveyed region. This scheme has the advantage that more solid angle is covered per unit time, although much of it at substantially less than half the full gain. The sparse sampling approach exploits the large sidelobes for the outer six beams, which are ~16% (−8 dB) of the peak gain centered ~5′ from the beam axis (see Fig. 1). The gains of these sidelobes are approximately 0.7 and 1.6 times the on-axis gains for the Green Bank Telescope and the Parkes 64 m telescope, respectively, and thus provide significant sensitivity.

Later on, we will make the two additional passes needed to achieve dense coverage. Despite the smaller numbers of new

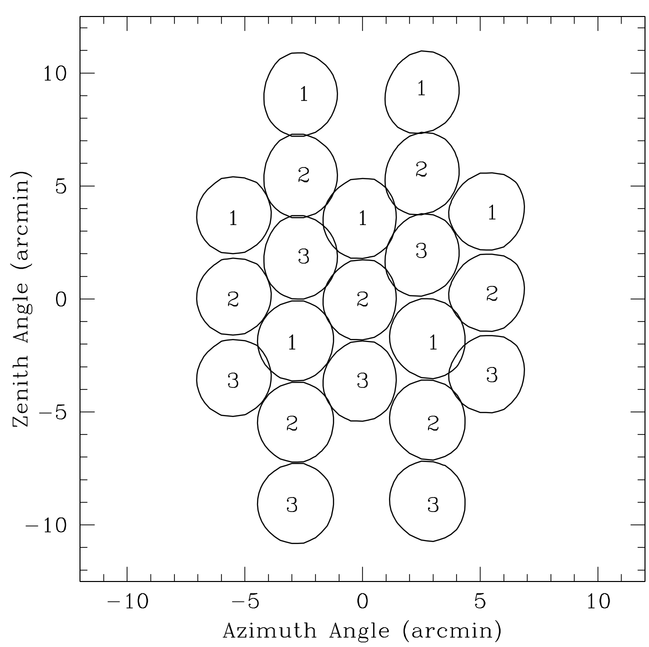

FIG. 3.—ALFA beam locations on the plane of the sky showing the half-power beam widths for three pointings derived from the data presented in Fig. 1. The pointings are labeled 1, 2, and 3 in a dense sampling grid that covers nearly all of the solid angle with at least half the gain of the relevant beam. Sparse sampling consists of making only one of these pointings. Note the ellipticity of the beams and their pattern for a given pointing.

pulsars expected in these subsequent passes, they will yield more pulsar discoveries than if we were to extend the sparse coverage to higher Galactic latitudes, where the pulsar density decreases rapidly.

We are also exploring a multiple-pass strategy, where a given sky position is observed two or more times. This approach is motivated by the fact that pulsar flux densities are highly variable (over and above the fundamental pulsation), sometimes by more than an order of magnitude, due to a number of intrinsic and extrinsic causes, including nulling and mode changes common to many pulsars, eclipses, and interstellar scintillation (both long-timescale refractive scintillation and fast, diffractive scintillation). RFI is also episodic. Our simulations suggest that pulsars can be missed in single-pass strategies, but that any improvement from multiple-pass approaches depends on the details and prevalence of flux modulations. We are in the process of comparing different strategies while also using simulations to fully optimize our usage of ALFA.

3.2. *Data Analysis*

To maximize the pulsar yield and overall science return from the PALFA survey, we are processing the data twice. During the observations, incoming data are transferred to the Arecibo Signal Processor,[16] a computer cluster that processes the data in quasi real time after reducing the time and frequency resolution to increase throughput. This "quick-look" analysis, described below, is primarily sensitive to pulsars with $P \gtrsim 30$ ms, which are expected to make up the bulk of all discoveries. We are currently developing an offline data analysis scheme that retains the full resolution of the data and will be sensitive to MSPs and pulsars in short-period binary systems, as well as to pulsars with large values of dispersion measure (DM). In addition to using a number of different pulsar search codes and algorithms, this latter analysis pipeline will also take advantage of the multiple beam data acquisition for RFI excision. Analysis of the raw data will be done on several computer clusters at the home institutions of members of the PALFA Consortium. Further details will be published elsewhere.

The quick-look pipeline uses freely available pulsar data analysis tools (Lorimer 2001) to unpack and transform the correlation functions from the WAPPs to spectra with 256 channels every 64 μs. The data are decimated in frequency and time by factors of 8 and 16, respectively, to allow quasi real-time processing. The resulting data sets with 32 frequency channels and 1024 μs time resolution are then corrected for the effects of interstellar dispersion by appropriately delaying low-frequency channels relative to the highest one. This process is carried out for 96 trial values of DM in the range 0–980 pc cm^{-3}. The step size in DM is approximately 2, 4, 8, 16, and 32 pc cm^{-3}, with changes in step size at approximately 62, 124, 253, and 506 pc cm^{-3}. Two different searches are then carried out on the resulting dedispersed time series, one for periodic signals and a second for isolated pulses.

The analysis for periodic, dispersed pulses follows most standard pulsar search schemes (see, e.g., Lorimer & Kramer 2004), and the software used for this analysis is based on code developed for an earlier survey (Lorimer et al. 2000). In essence, the procedure is to look for harmonically related signals in the amplitude spectrum (the magnitude of the Fourier transform) of each dedispersed time series. To increase sensitivity to signals

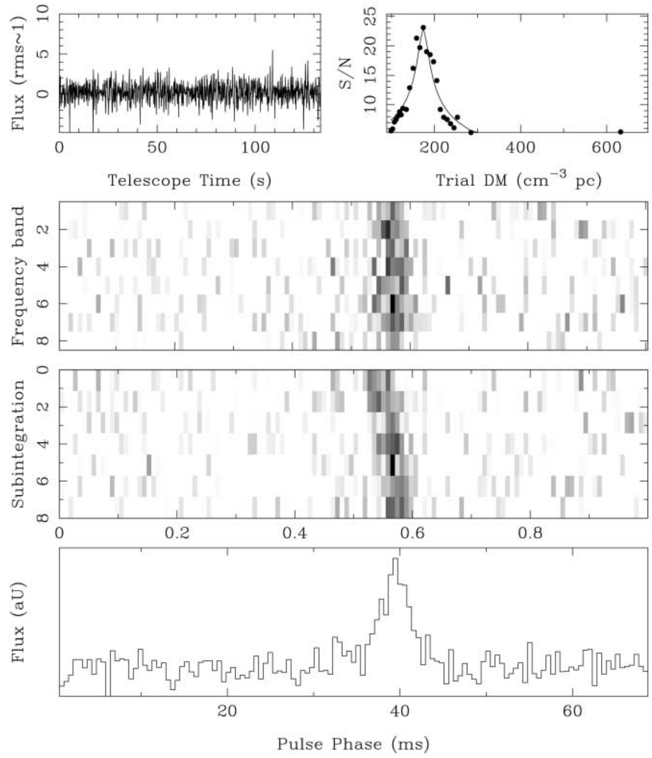

Fig. 4.—Sample periodicity search output from the quick-look analysis showing the discovery of the 69 ms pulsar PSR J1928+1746. *Top left*: A coarse version of the dedispersed time series used to assess basic data quality. *Top right*: S/N as a function of trial DM. The points show detections in the periodicity search, while the curve is the theoretically expected response given the system parameters and pulse width. *Middle panels*: Gray scales showing pulse intensity as a function of sky frequency (quantized into frequency bands) and observing time (quantized into subintegrations). *Bottom panel*: Folded pulse profile obtained by integrating over the whole passband.

with narrow duty cycles, which have many harmonics in the Fourier domain, the amplitude spectra are incoherently summed so that up to 2, 4, 8, and 16 harmonics are combined. A list of candidates with signal-to-noise ratios (S/Ns) above 8 is then formed, and the data are folded in the time domain to produce a set of diagnostic plots of the form shown in Figure 4. To simplify the viewing of the search output, a Web-based browsing system was developed for examination of candidate signals during an observing session. The most promising pulsar candidates are filed for future observation and follow-up.

In parallel with the periodicity analysis, we also search for isolated pulses in the 96 dedispersed time series based on code developed by Cordes & McLaughlin (2003). In brief, threshold tests are made on each dedispersed time series after smoothing it by different amounts to approximate matched-filter detection of pulses with different widths. In addition, we consider events defined by clusters of above-threshold samples in a "friends-of-friends" algorithm (Frederic 1995). For each pointing, diagnostic plots similar to those shown in Figure 5 are generated for inspection within the candidate browsing system. This example shows data for the 1.2 s pulsar PSR J0628+09, which we discovered in our single-pulse search through its bright individual pulses (see § 4.4). The three panels for each of the seven ALFA beams show, from left to right, the following: events above a threshold S/N > 5 versus time and DM channel, a scatter plot of DM channel versus S/N, and a histogram of the S/N. Events appear with the largest S/N in the DM channel that best matches the pulsar's DM; they also appear in neighboring DM channels

[16] Arecibo Signal Processor information is available at http://astron.berkeley.edu/~dbacker/asp.html.

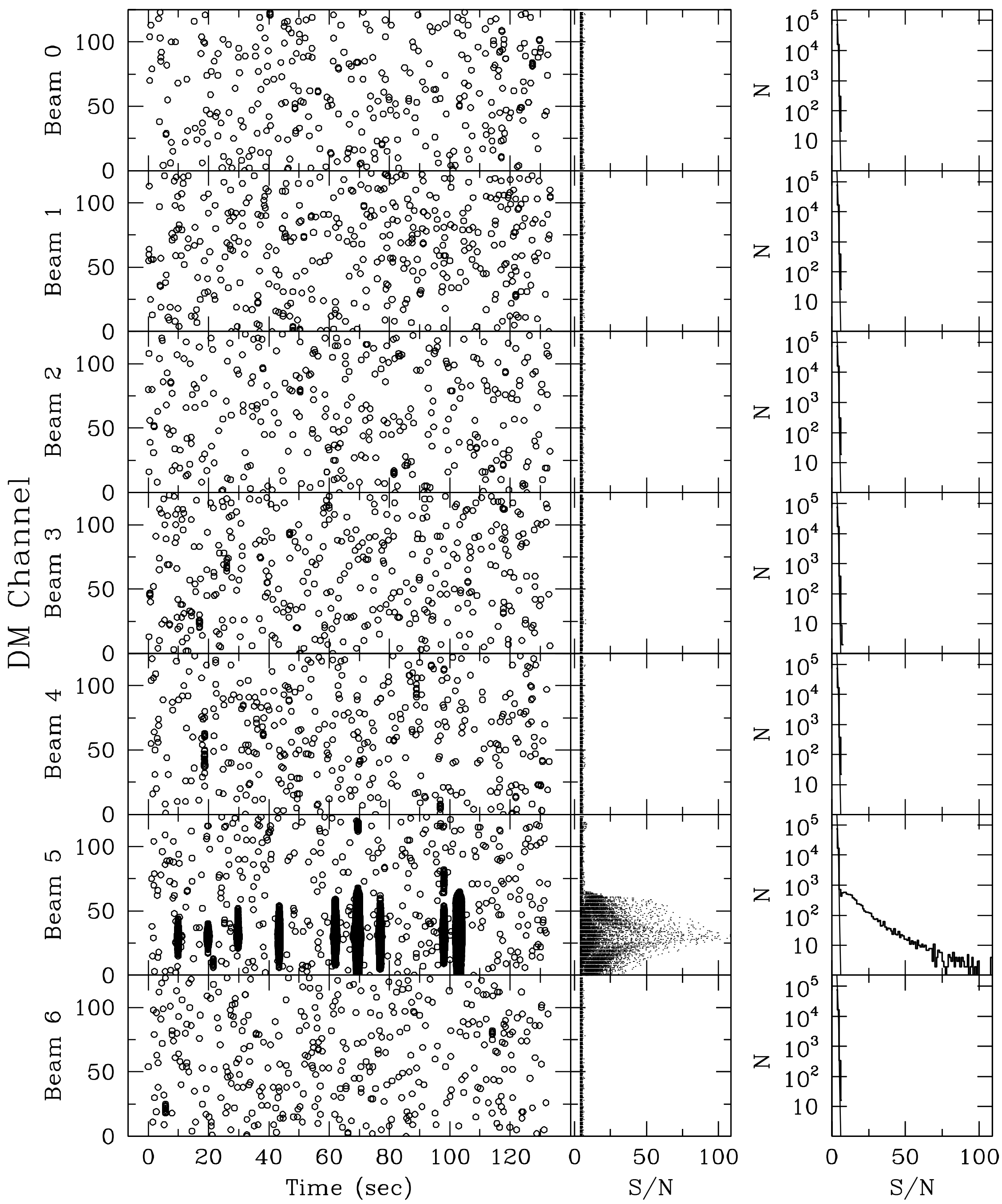

FIG. 5.—Single-pulse search output for a follow-up observation of the 1.2 s pulsar J0628+09. Each row shows data collected by one of the seven beams during the pointing. From left to right, the plots show the following: scatter plot of events with S/N > 5 vs. time and DM channel, scatter plot of DM channel and S/N for events, and the number of pulses vs. S/N. Individual pulses from J0628+09 are clearly seen in beam 5 only. The distribution of events vs. DM depends on the pulse shape and width (Cordes & McLaughlin 2003).

with a lower S/N that depends on the pulse width (Cordes & McLaughlin 2003).

3.3. *Database Management and Archiving*

PALFA survey results are archived in a MySQL[17] database system, which stores sky coverage and data quality information along with results from the data processing. This system is also designed to record the results from several different search codes that implement the processing system described above to allow comparison and optimization. The MySQL database includes an observational table with fields that characterize specific telescope pointings, the resulting raw data files, and ancillary information about the observations. Another table reports the results of the preliminary, quick-look data analysis, with fields that describe candidate signals and whether or not they correspond to known pulsars. There is another table that tracks the content and location of portable disk drives used to transport data from the observatory to processing sites. Additional tables report results from the data processing that uses the full data resolution, a list of refined pulsar candidates, and the status of confirming and other follow-up observations.

A data archive is under development at the Cornell Theory Center; it will include the original raw data, as well as analysis

[17] MySQL database system information is available at http://www.mysql.com.

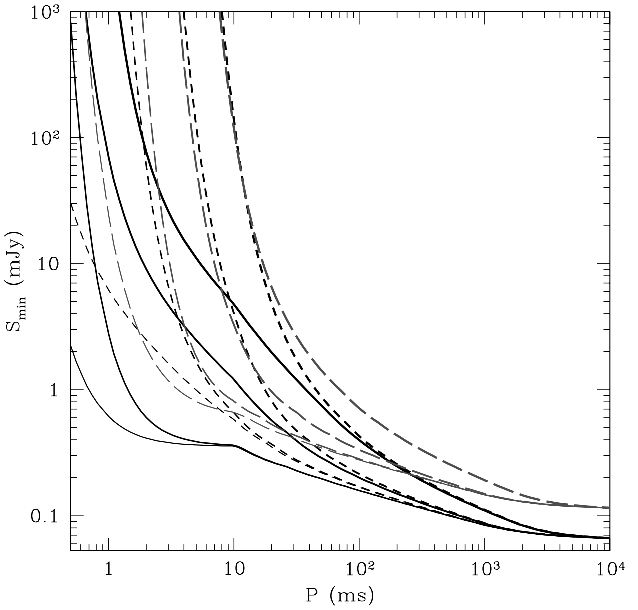

FIG. 6.—Theoretical minimum detectable flux density (S_{min}) vs. P for different values of DM. *Short-dashed lines*: Coarse-resolution PALFA data analyzed with the quick-look software that led to the discoveries reported in this paper. *Long-dashed lines*: The Parkes Multibeam Survey, which used 96 channels across 288 MHz and 250 μs sampling for scan durations of 2100 s. *Solid lines*: Full-resolution PALFA data. For each set of curves, DM values from the lowest to the highest curve are 1, 200, 500, and 1000 pc cm^{-3}. The break point at $P \sim 10$ ms for the solid curves occurs because we assume that the intrinsic pulse duty cycle scales as $P^{-1/2}$ with a maximum of 0.3, which occurs at this period. Above 10 ms, the number of harmonics contributing to detections increases from 1 to 16 (the maximum searched) as the duty cycle gets smaller. A threshold of 10 σ is used. [*See the electronic edition of the Journal for a color version of this figure.*]

products and database mining tools, accessible through a data gateway.[18]

3.4. *Search Sensitivity*

Data taken in our preliminary survey dwell on particular sky positions for 134 s for the inner Galaxy and 67 s for anticenter directions. The minimum detectable flux density S_{min} for PALFA with these parameters is a factor of 1.6 smaller than for the PMB survey, implying a maximum distance $D_{max} \propto S_{min}^{-1/2}$ about 1.3 times larger for long-period pulsars. The sampled volume on axis is accordingly about a factor of 2 larger for long-period pulsars. In our full-resolution analysis, the volume increase is even larger for small periods, owing to the smaller PALFA channel widths and the shorter sample interval. For $P \lesssim 10$ ms, the searched volume increase can be a factor of 10 or more.

Figure 6 shows idealized plots of S_{min} versus P for four values of DM (from 1 to 10^3 pc cm^{-3}), using postdetection dedispersion followed by a standard Fourier analysis with harmonic summing. The values of S_{min} include the effects of radiometer noise and pulse smearing from instrumental effects combined with dispersion and scattering in the interstellar medium using the "NE2001" electron density model (Cordes & Lazio 2002). Scattering has been calculated in the model for the particular direction $b = 0°$ and $\ell = 40°$. Directions at higher latitudes will show less scattering and better sensitivity for large values of DM. The results are also based on the assumption that pulse amplitudes are constant over the observation time that spans many pulse periods, which is obviously an idealization. Our calculations for the PMB survey do not include high-pass filtering in both hardware and software that degrades the sensitivity to long-period pulsars (see Manchester et al. 2001). No high-pass filtering is done in our analysis, either in hardware or in software. We emphasize that the curves in Figure 6 should be interpreted as *lower bounds* on the true values of S_{min}, because real-world effects such as RFI and receiver gain variations will raise the effective threshold of the survey. Our quick-look analysis described above, which analyzes data after decimation in time and frequency, has detection curves about 60% more sensitive than those for the PMB survey except for $P \lesssim 10$ ms, for which the large sampling time of the quick-look analysis significantly degrades the sensitivity.

[18] Cornell Theory Center data archive information is available at http://arecibo.tc.cornell.edu.

4. INITIAL RESULTS

For our preliminary survey observations carried out between 2004 August and October, we have used 17.1 hr of telescope time for 919 pointings in the Galactic anticenter and 32.2 hr for 865 pointings in the inner Galaxy, covering 15.8 and 14.8 deg^2 in each region, respectively. These numbers and their graphical presentation in Figure 7 were obtained using the MySQL database. Table 1 lists the 11 new pulsars that we have found so far. Table 2 lists the detection statistics of 29 previously known pulsars also seen in the quick-look analysis pipeline. Not included here is a detection of the 1.55 ms pulsar B1937+21, which was undetected due to the coarse time resolution of the quick-look pipeline. The pulsar was, however, easily detected when the raw data were folded at their full resolution. The high time-resolution data pipeline mentioned above will allow detection of any MSPs missed in the quick-look analysis.

4.1. *General Remarks*

Four of the pulsars discovered in the inner Galaxy (J2009+33, J2010+32, J2011+33, and J2018+34) are in the northernmost

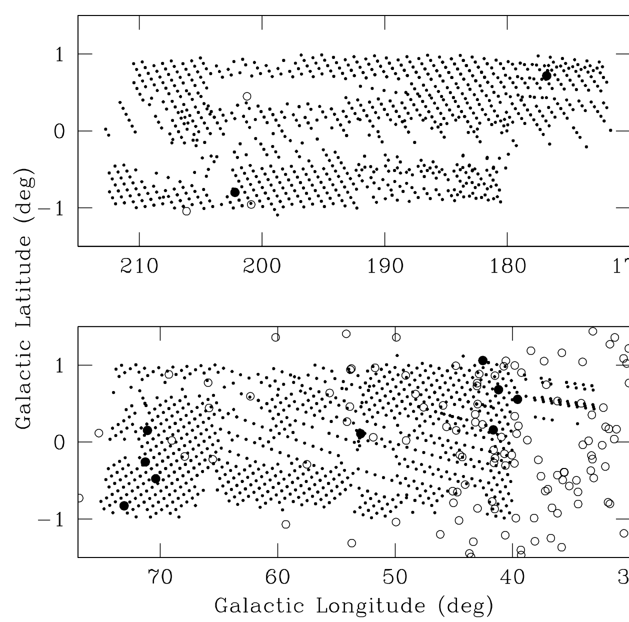

FIG. 7.—Regions of the Galactic plane surveyed with PALFA to date, showing the Galactic anticenter region (*top*) and inner Galactic plane (*bottom*). Dots denote the pointing centers of each seven-beam cluster, and filled circles show newly discovered pulsars, while the open circles designate previously known pulsars.

TABLE 1
PULSARS DISCOVERED IN THE PALFA PRECURSOR SURVEY

PSR	R.A. (J2000.0)	Decl. (J2000.0)	P (ms)	$\widehat{\mathrm{DM}}$ (pc cm^{-3})	⟨S/N⟩	SP?	Comments
J0540+32	05 40 38	+32 02 19	524	120	36	Y	Strong, sporadic single pulses
J0628+09	06 28 49	+09 09 59	1241	88	. . .	Y	Discovered as S/N = 40 single pulses
J1901+06	19 01 36	+06 09 36	832	162	14	Y	
J1904+07	19 04 09	+07 39 41	209	275	15	Y	Strong, sporadic
J1905+09	19 05 16	+09 01 22	218	452	14	N	
J1906+07	19 06 51	+07 49 01	144	217	11	N	Interpulse; original detection at 72 ms; binary with P_{orb} = 3.98 hr
J1928+1746	19 28 43	+17 46 23	69	174	19	N	First ALFA pulsar; flat spectrum
J2009+33	20 09 39	+33 25 58	1438	254	13	N	Sporadic
J2010+32	20 10 21	+32 30 22	1442	350	23	N	
J2011+33	20 11 47	+33 21 49	932	300	30	Y	Sporadic
J2018+34	20 18 54	+34 32 44	387	226	24	Y	

NOTES.—R.A. and Decl. are the right ascension and declination for the center of the beam where the pulsar was found. Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. Typical half-width uncertainty in pulsar position is one beam radius (about 1$'$.6) in both coordinates, except for PSR J1928+1746. The expression $\widehat{\mathrm{DM}}$ is the DM value at which the search algorithm identified the pulsar with maximum S/N, and ⟨S/N⟩ is the S/N of the averaged pulse shape. SP? denotes whether or not individual pulses from this pulsar were detected in the single-pulse search.

region detectable from Arecibo; all of these have DMs between 220 and 350 pc cm^{-3}. Some, if not all, of these objects are possibly associated with the Cygnus region, where a large number of supernovae will have produced many relatively young pulsars (e.g., Vlemmings et al. 2004 and references therein). Four additional objects (J1901+06, J1904+07, J1905+09, and J1906+07) are in the southernmost region visible from Arecibo, where the density of pulsars is known to be higher. This region was previously covered by the PMB survey, suggesting that our precursor survey indeed already surpasses the depth of the PMB survey when a

TABLE 2
PREVIOUSLY KNOWN PULSARS DETECTED IN THE PALFA PRECURSOR SURVEY

PSR	P (ms)	DM (pc cm^{-3})	$\widehat{\mathrm{DM}}$ (pc cm^{-3})	S_{1400} (mJy)	⟨S/N⟩	$\Delta\theta$ (arcmin)	SP?
J0631+1036	287	125	148	0.8	76	6.7	Y
J1855+0307	845	403	410	0.97	40	3.2	Y
B1859+07	644	253	282	0.9	42	2.3	Y
B1903+07	648	245	226	1.8	161	0.6	Y
B1904+06	267	473	508	1.7	82	2.4	Y
J1904+0800	263	439	424	0.36	17	2.0	N
J1905+0616	990	258	283	0.5	41	1.8	Y
J1906+0912	775	265	240	0.32	12	5.4	Y
J1907+0740	557	332	353	0.41	20	2.3	Y
J1907+0918	226	358	353	0.29	18	4.7	N
B1907+10	284	150	198	1.9	57	1.9	Y
J1908+0734	212	11	46	0.54	13	1.1	Y
J1908+0909	336	468	452	0.22	48	1.7	N
J1910+0714	2712	124	106	0.36	14	1.8	Y
B1913+10	404	242	240	1.3	30	4.4	Y
J1913+1000	837	422	452	0.53	26	1.7	Y
J1913+1011	35	179	170	0.50	10	2.7	N
B1914+13	282	237	219	1.2	150	1.8	Y
B1915+13	195	95	103	1.9	74	2.3	Y
B1916+14	1181	27	28	1.0	18	3.0	Y
B1919+14	618	92	74	0.7	41	0.5	Y
B1921+17	547	143	177	. . .	13	3.0	N
B1925+188	298	99	166	. . .	19	1.9	N
B1929+20	268	211	205	1.2	19	3.0	N
B1952+29	427	8	18	8.0	88	3.7	Y
J1957+2831	308	139	163	1.0	54	1.6	Y
B2000+32	697	142	184	1.2	43	2.2	Y
J2002+30	422	196	184	. . .	24	1.2	N
B2002+31	2111	235	197	1.8	88	3.3	Y

NOTES.— Pulsar parameters P, DM, and S_{1400} are from the ATNF pulsar database (Manchester et al. 2005). The expression $\widehat{\mathrm{DM}}$ is the DM value at which the search algorithm identified the pulsar, ⟨S/N⟩ = S/N of the averaged pulse shape, and $\Delta\theta$ is the angular distance from the nearest beam centroid in which the pulsar was detected. SP denotes whether or not individual pulses from this pulsar were detected in the single-pulse search.

conventional pulsar search analysis is done. Subsequent to our discovery, J1906+07 was identified in the acceleration search output of the PMB data (Lorimer et al. 2006).

All previously known pulsars were detected in our pointings if they were within one beam radius of one of the ALFA beams. In addition, we detect some strong pulsars several beam radii from the nearest beam center. A coarse analysis suggests that our detection rate is consistent with what we expect from the sparse-sampling strategy discussed earlier, based on simulations. A detailed analysis will be done as we continue the survey.

The single-pulse search analysis is notably successful in detecting six out of 11 of the new pulsars and 21 out of 29 of the known pulsars. These statistics are consistent with the fact that the known pulsars tend to be stronger than our new detections. The single-pulse analysis is valuable both for corroborating candidate detections from the periodicity analysis and, as we have shown in the case of J0628+09, for identifying pulsars that are missed in the periodicity search, owing to the intermittency of their pulses.

4.2. *PSR J1928+1746*

The first pulsar discovered in the ALFA survey, PSR J1928+1746, also has the shortest period among the pulsars discovered so far: $P = 68.7$ ms. While time for follow-up observations on this and the other pulsars discovered has so far been limited, we have made some multifrequency and timing observations of PSR J1928+1746. Using the TEMPO[19] software package to analyze 83 arrival times from PSR J1928+1746 spanning a 257 day baseline, we obtain the results presented in Table 3. The timing model implies that PSR J1928+1746 is a young isolated pulsar with a characteristic age $\tau_c = P/2\dot{P} = 82$ kyr, a surface magnetic field strength $B = 3.2 \times 10^{19} (P\dot{P})^{1/2}$ G $= 9.6 \times 10^{11}$ G (assuming a dipolar field), and a spin-down energy loss rate $\dot{E} = I\Omega\dot{\Omega} = 1.6 \times 10^{36} I_{45}$ ergs s^{-1} (where $\Omega = 2\pi P^{-1}$ and I_{45} is the moment of inertia in units of 10^{45} g cm^2).

Multifrequency observations from 1.1 to 9 GHz, shown in Figure 8, suggest that the radio spectrum is nearly flat, $S_\nu \propto \nu^{+0.2\pm0.3}$. The quoted error reflects empirical departures from the fit and thus includes any systematic calibration errors or random errors from scintillations. Estimates of the flux densities are coarse because we have simply scaled the S/Ns of the average pulse amplitudes and used typical values for the gain and system temperature. The flux densities at the higher two frequencies are likely to be influenced by modulations from interstellar scintillation (based on DM and the likely distance). High-frequency surveys are naturally biased toward the discovery of objects with flatter spectra than surveys at lower frequencies. In addition, young pulsars appear to have flatter spectra (Lorimer et al. 1995), so high-frequency surveys of the Galactic plane will be less biased against them. PSR J1928+1746 appears to be a prototype flat-spectrum object, of which we can expect to find more in our survey.

As shown in Figure 9, PSR J1928+1746 lies well within the localization map for the unidentified EGRET source 3EG J1928+1733. The EGRET source shows significant variability (Torres et al. 2001) that is indicative of a blazar, but has a photon index, $\Gamma = 2.23 \pm 0.32$, not inconsistent with those of known pulsars. If PSR J1928+1746 is the radio pulsar counterpart to 3EG J1928+1733, then the implied efficiency for conversion of spin-down energy into gamma rays is $\eta_\gamma \equiv L_\gamma/\dot{E} = 22\%\Omega_\gamma(d/6 \text{ kpc})^2$, where Ω_γ is the solid angle (in steradians) swept out by the pulsar's beam, and a photon index of -2 is assumed for the gamma-ray spectrum. While the nominal efficiency is higher than that of any of the confirmed gamma-ray pulsars (Thompson et al. 1999), we note that the above calculation is strongly dependent on the uncertain beaming fraction and on the DM-derived distance to PSR J1928+1746 of 6 kpc. In addition, the flux measurement used to calculate the efficiency from the 3EG catalog (Hartman et al. 1999) is the largest (and most significant) value, so the implied efficiency should be viewed as an upper bound. Two other young pulsars recently discovered within EGRET error boxes, J2021+3651 (Roberts et al. 2002) and J2229+6114 (Halpern et al. 2001), have similarly high inferred efficiencies. These pulsars will be excellent future targets for the *Gamma-Ray Large Area Space Telescope* (*GLAST*).

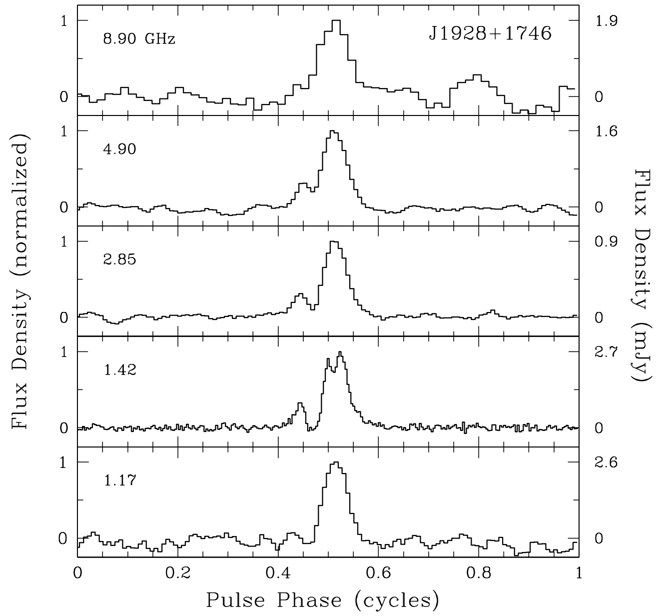

FIG. 8.—Pulse profiles for PSR J1928+1746 at five frequencies from 1.2 to 8.9 GHz obtained with integration times of 135, 4173, 804, 900, and 106 s, from low to high frequency. The flux density scale on the right-hand side is accurate to approximately 20%.

[19] TEMPO software package information is available at http://pulsar.princeton.edu/tempo.

TABLE 3
OBSERVED AND DERIVED PARAMETERS FOR PSR J1928+1746

Parameter	Value
R.A. (J2000.0)	$19^h28^m42^s.48$ (4)
Decl. (J2000.0)	17°46′27″ (1)
Spin period, P (ms)	68.728784754 (1)
Period derivative, $\dot{P}$	1.3209 (5) $\times 10^{-14}$
Epoch (MJD)	53448.0
Dispersion measure, DM (pc cm^{-3})	176.9 (4)
Flux density at 1400 MHz, S_{1400} (mJy)	0.25
Surface magnetic field, B (Gauss)	9.6×10^{11}
Characteristic age, τ_c (kyr)	82
Spin-down luminosity, $\dot{E}$ (ergs s^{-1})	1.6×10^{36}
DM Distance (NE2001), D (kpc)	~6
Radio luminosity at 1400 MHz, $S_{1400}D^2$ (mJy kpc^2)	~9

NOTES.—Since the timing data collected so far span only 257 days, the phase-connected timing solution should be viewed as preliminary. The figures in parentheses give the uncertainties in the least-significant digits quoted. To be conservative, these are calculated by multiplying the nominal 1 σ TEMPO standard deviations by an ad hoc factor of 10. The DM distance is calculated using the NE2001 electron density model for the Galaxy (Cordes & Lazio 2002).

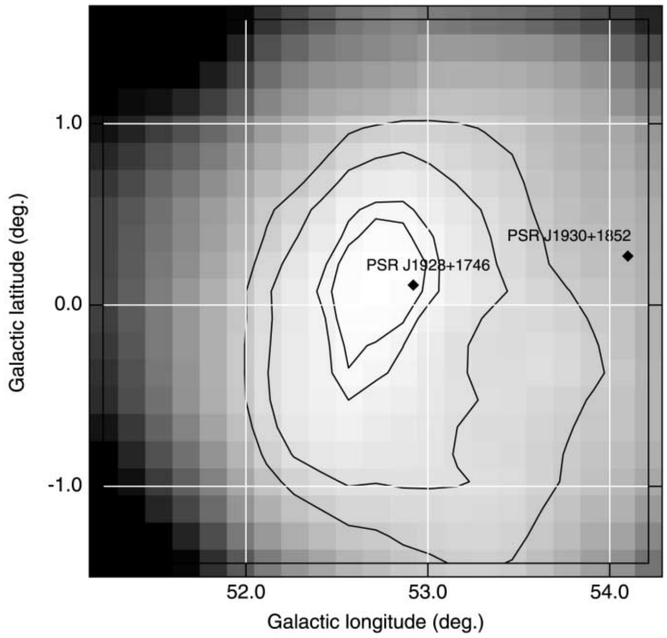

FIG. 9.—EGRET localization test statistic of the high-energy gamma-ray source 3EG J1928+1733 (Hartman et al. 1999). Contours delimit probability regions, from innermost to outermost, of 50%, 68%, 95%, and 99% for the location of the gamma-ray emission. In addition to PSR J1928+1746, which lies close to the center, we also show the next nearest pulsar, J1930+1852, previously advanced (Camilo et al. 2002) as a possible counterpart to 3EG J1928+1733, even though it lies outside the 99% contour. [*See the electronic edition of the Journal for a color version of this figure.*]

4.3. *PSR J1906+07*

PSR J1906+07 was initially attributed a spin period half of its actual value, owing to the presence of its interpulse. Very recently, this object has been found to be a binary pulsar by comparing the parameters in Table 1 with entries in the PMB database and by making new observations at Jodrell Bank. The orbital period is 3.98 hr, the eccentricity is 0.085, and its projected orbital semimajor axis is $a_1 \sin i = 1.42$ lt-s, yielding a mass function of 0.11 $M_\odot$. Discovery of the binary nature of this source and a discussion of its properties may be found in Lorimer et al. (2006).

The discovery of PSR J1906+07 underscores the power and great potential of PALFA surveys for finding binary pulsars. The large sensitivity of the Arecibo telescope allows us to use integration times short enough so that many binaries will be detected without recourse to acceleration searches, as has been necessary with the PMB survey. Acceleration searches lead to a greater number of statistical trials that, in turn, require a higher detection threshold to minimize the number of "false-alarm" detections.

4.4. *PSR J0628+09*

Many pulsars show large modulations of the pulsed flux density. In some cases, it is easier to detect single pulses than the periodicity in a Fourier analysis (Nice 1999; McLaughlin & Cordes 2003). In our quick-look analysis, most of the known pulsars and three of the pulsars discovered in the periodicity search (J0540+32, J1904+07, and J2011+33) appear strongly in the single-pulse search and less so for three other pulsars. Some single pulses of PSR J1904+07 are detected with $S/N \sim 36$, more than twice that found by the periodicity search. PSR J0628+09 was discovered *only* by the detection of its very sporadic single pulses, some of which have peak $S/N \sim 100$. The discovery data set had only three large pulses in a 67 s scan, too few to allow the pulsar's detection in the periodicity search. A periodicity of 2.48 s was determined from the arrival times of those pulses. Subsequent observations with a greater number of strong pulses and an above-threshold detection in the periodicity analysis have allowed us to determine the true period of 1.24 s.

The discovery of PSR J0628+09 clearly demonstrates the importance of single-pulse searches. As shown in Figure 5, these searches are enabled by the simultaneous measurements in multiple beams, which allow discrimination between RFI and celestial events. Extrapolating from the present sample to the whole survey, we can expect to find a significant number of pulsars through their single pulses and not through their periodicity. The analysis also may detect radio transients from nonpulsar objects, a plausible outcome given the recent discovery of a transient radio source in the direction of the Galactic center (Hyman et al. 2005) and a number of other transient radio sources found in a single-pulse analysis of the PMB survey (McLaughlin et al. 2006).

5. FUTURE PLANS AND EXPECTATIONS

We have described the initial stages of a large-scale survey for pulsars using ALFA, the seven-beam system at the Arecibo Observatory that operates at 1.4 GHz. Our discovery of 11 pulsars from precursor observations—using a preliminary data acquisition system that sampled only one-third of the available bandwidth followed by a quick-look analysis—is extremely encouraging. A new spectrometer that uses the full bandwidth will become available within the next year. The full data processing pipeline, now under development, will have excellent sensitivity to MSPs and is expected to yield further pulsar discoveries in our existing data. This pipeline will include masking of RFI in the frequency-time plane prior to dedispersion, a new matched-filtering search algorithm for events that have a broader range of frequency-time signatures than those encountered for pulsars, and compensation for acceleration in binary systems.

In the near future, we expect to begin regular timing programs on several telescopes to obtain precise determinations of the spin and astrometric parameters of these pulsars and others that will be discovered. The full survey will take more than 5 years, depending largely on the allocation of telescope time. Numerical models of the pulsar population, calibrated by results from the PMB survey and incorporating measured characteristics of the ALFA system, suggest that as many as 1000 new pulsars will be discovered.

The raw data from the search, as well as the data products from the search analysis, will be archived and made available to the broader community via a Web-based portal. Initially, the database system will enable our own mining of the data for new pulsars and perhaps other astrophysical signals. Later, we expect the system to provide opportunities for multiwavelength searches, such as identification of radio counterparts to X-ray sources or to candidate gamma-ray pulsars seen in data from *GLAST*.

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