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# A SURVEY FOR MILLISECOND PULSARS

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## ABSTRACT

We have searched 960 square degrees of sky for radio pulsars, using the 305 m telescope at Arecibo, Puerto Rico. The 430 MHz survey reached a limiting sensitivity for slow pulsars of 0.7 mJy using a dual-polarization, 32 channel filter bank over 8 MHz of bandwidth. We have detected one new millisecond pulsar, 11 new slow pulsars, one previously known millisecond pulsar, and eight previously known slow pulsars. The new millisecond pulsar, PSR J2033+17, with a period of 5.9 ms, has been found to be in a binary system. The Keplerian circular orbital solution has a period of 56.2 days and a semimajor axis of 20.7 lt-s. One of the slow pulsars, PSR J2043+2740, is the second fastest pulsar that is not either recycled or associated with a supernova remnant. It is near the Cygnus Loop remnant, but timing measurements imply a pulsar characteristic age of 1.2 Myr, which makes an association unlikely.

*Subject headings:* binaries: close — pulsars: general — surveys

## 1. INTRODUCTION

The 305 m radio telescope at Arecibo, Puerto Rico, is undergoing a major upgrade. For much of the construction period, the telescope pointing capabilities have been severely restricted, and only low-frequency observations have been possible. To take advantage of this time, several research groups have been carrying out drift searches for radio pulsars at 430 MHz, with a goal of surveying the entire sky accessible to Arecibo with consistent sensitivity (e.g., Camilo et al. 1996; Foster et al. 1995a).

Understanding the formation and evolution of millisecond pulsars requires a large sample of pulsars from which statistical inferences can be drawn. Before 1990, there were only four millisecond pulsars known outside the globular cluster system. The Arecibo surveys, together with similar efforts at Jodrell Bank, Green Bank, and Parkes Observatory, were designed to substantially increase this number. There are now about 30 known pulsars with period $\lesssim 16$ ms.

The work described here includes the completion of the survey of Thorsett et al. (1993b [hereafter TDK], the THL survey), begun before the upgrade period, and an additional 600 square degrees covered during the upgrade (the UHL survey). The telescope is currently unavailable for all observations; however, we expect some additional time will be available for the UHL survey in late 1996.

In § 2 we describe the observations and data analysis. In § 3 we describe the characteristics of the 13 new pulsars, including an unusually fast nonrecycled pulsar (§ 3.1) and the binary millisecond pulsar PSR J2033+17 (§ 3.2). In § 4 we discuss the implications of this work and the future of large area searches along with prospects for more interesting measurements with continued timing of the new pulsars.

## 2. DATA COLLECTION AND ANALYSIS

The observations and analysis of these data were described in TDK and Ray et al. (1995). In summary, the 8 MHz bandpass at a center frequency of 430 MHz was received in two orthogonal circular polarizations, divided with a $2 \times 32 \times 0.25$ MHz filter bank into 32 channels, smoothed with a time constant of 330 $\mu$s, sampled, and digitized with 3 bit resolution every 180 $\mu$s (THL) or 250 $\mu$s (UHL). All of the data were taken in "drift mode," where the telescope is held at a fixed declination and hour angle and the sky is allowed to drift through the telescope beam. A particular point in the sky moves through the telescope beam in about 40 s.

Blocks of $2^{18}$ samples ($2^{17}$ samples), or 47.2 s (32.8 s), were analyzed in the THL (UHL) survey by dedispersing the signals at 75 trial dispersion measures (0–77 pc cm$^{-3}$ in all cases and up to 300 pc cm$^{-3}$ for many beams), and searching the Fourier transform of the data for significant peaks. To increase sensitivity to nonsinusoidal signals, harmonically related frequencies were combined for sets of 2, 3, 4, 8, and 16 harmonics. To avoid losing sensitivity to pulsars falling between data blocks, we overlap adjacent blocks by 50%.

The THL survey is the completion of the survey described by TDK and covered a rectangular region with $8^h < \alpha < 13^h$ and $19° < \delta < 26°$. This region was surveyed

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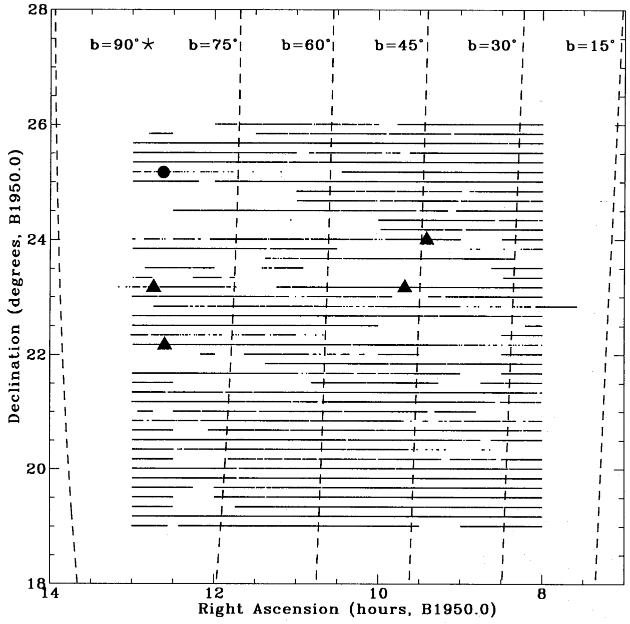

FIG. 1.—RFI-free sky coverage of the complete THL survey, including that reported by Thorsett et al. (1993b). The declination strips are in B1950.0 coordinates and are spaced by 10′. Note that the horizontal axis of the plot covers 105° while the vertical axis is only 10°. Newly discovered pulsars are marked with filled triangles and the previously known pulsar that was redetected is marked with a filled circle. The north Galactic pole is marked with a star.

in strips of constant B1950.0 declination. Further observations were made on 1993 May 25–June 8. The completed survey coverage is shown in Figure 1. The positions of the four new pulsars discovered in this survey are marked with filled triangles (including the two pulsars reported by TDK). The only previously known pulsar in the region was redetected and is denoted by a filled circle. The declination strips are separated by 10′ in declination and are lines of constant B1950.0 declination. The total sky coverage was $\sim 360$ square degrees.

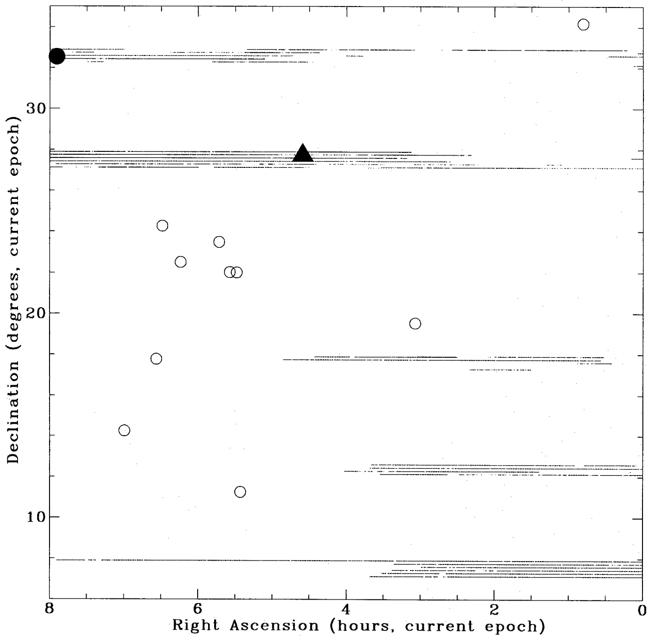

FIG. 2.—RFI-free sky coverage of the UHL survey between $00^{\rm h}$ and $08^{\rm h}$. New pulsars are marked with filled triangles, known pulsars that were rediscovered with filled circles, and known pulsars that have not been detected in this survey with open circles. Adjacent declination strips are separated by 9′.2.

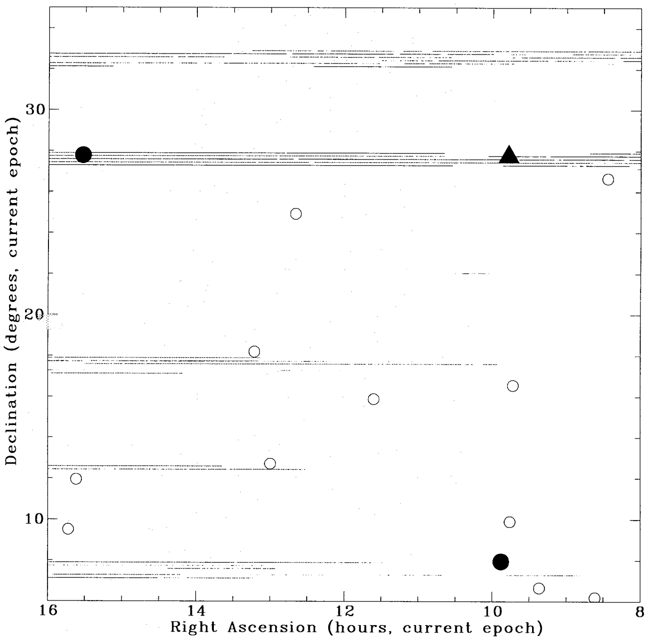

FIG. 3.—RFI-free sky coverage of the UHL survey between $08^{\rm h}$ and $16^{\rm h}$

The UHL survey took place during the Arecibo upgrade, with the telescope at a fixed azimuth and zenith angle, drifting in strips of current (1994.1–1994.9) declination. The entire sky has been divided into 1° declination strips and parceled out to several groups doing surveys during the upgrade. We report here on the 7°, 12°, 17°, 27°, and 32° declination strips. We have divided each strip into six tracks separated in declination by 9′.2 beginning at 7′ north of the stated declination lines. The half-power beam width of the telescope at 430 MHz is about 10′, so the declination strips

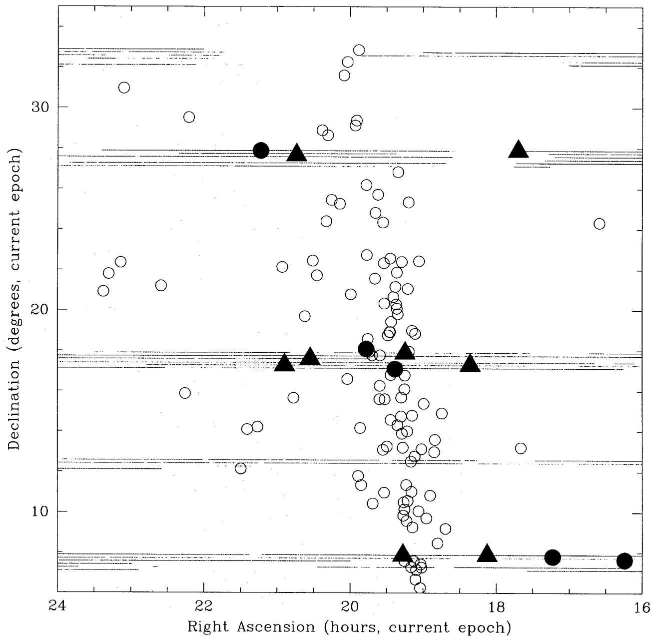

FIG. 4.—RFI-free sky coverage of the UHL survey between $16^{\rm h}$ and $24^{\rm h}$

TABLE 1

New Pulsars Detected in This Survey

| Name | R.A.[a] (J2000.0) | decl.[a] (J2000.0) | Period[b] (s) | DM (pc cm$^{-3}$) | $d$[c] (kpc) | $S_{\rm est}$[g] (mJy) |
|---|---|---|---|---|---|---|
| J0435+27 ........ | 04 35 34 | 27:44 | 0.3262793 (9) | 53 (2) | 3.4 | 2 |
| J0927+23 ........ | 09 27 37 | 23:47 | 0.761886 (3) | 23 (2) | >2.5 | 1 |
| J0943+22[d] ....... | 09 43 25 | 22:56 | 0.532913 (12) | 25.1 | >2.4 | 5.5 |
| J0947+27 ........ | 09 47 22 | 27:42 | 0.85105 (2) | 29 (3) | >2.3 | 1 |
| J1238+21 ........ | 12 38 21 | 21:54 | 1.11836 (4) | 20 (2) | >1.8 | 2 |
| J1246+22[d] ....... | 12 46 38 | 22:53 | 0.473830 (4) | 17.9 | >1.8 | 29 |
| J1742+27[e] ....... | 17 42 02 | 27:53 | 1.360744 (8) | 36 (2) | 3.7 | 2 |
| J1807+07 ........ | 18 07 42 | 07:53 | 0.46430 (2) | 89 (9) | >7.7 | 1 |
| J1821+17 ........ | 18 21 31 | 17:17 | 1.3662 (2) | 79 (8) | >7.1 | 3 |
| J1915+07 ........ | 19 15 01 | 07:53 | 2.0588 (2) | 118 (10) | 3.7 | 2 |
| J1916+07 ........ | 19 16 54 | 07:53 | 0.54218 (4) | 305 (30) | 8.2 | 4 |
| J1933+07 ........ | 19 33 20 | 07:53 | 0.437446 (5) | 170 (20) | 8.9 | 1 |
| J2033+17 ........ | 20 33 21 | 17:36 | 0.0059490 | 25.2 | 1.4 | 3 |
| J2043+2740...... | 20 43 43.5 | 27:40:56 | 0.0961305 | 21.0 (1) | 1.1 | 15 |
| J2053+17[f]........ | 20 53 55 | 17:17 | 0.11926 | 25 (3) | 1.4 | 1 |

[a] The positions for all pulsars except for J2043+2740 are uncertain by ±5′ in each coordinate. Right ascension is in hours, minutes, seconds; declination is in degrees, arcminutes.

[b] The periods are barycentric periods and were all measured in 1993 or 1994.

[c] Distances are derived from the Galactic free electron model of Taylor & Cordes 1993.

[d] Previously reported by Thorsett et al. 1993b.

[e] This pulsar was independently discovered by Foster et al. 1995a.

[f] This strong candidate could not be confirmed because of the scheduling of the Arecibo upgrade project. It is included here for completeness, but should not be included in pulsar catalogs unless confirmed by other work.

[g] Rough flux density estimates; see text.

overlap slightly. The completed sky coverage, excluding that which was corrupted by radio frequency interference, is shown in Figures 2, 3, and 4.

## 3. PULSARS DISCOVERED

In a total of ∼960 square degrees reported by this paper and TDK, 14 new pulsars were discovered, whose parameters are summarized in Table 1 and profiles shown in Figures 5, 6, and 7. The parameter $S_{\rm est}$ is a *rough* estimate of the flux density of each pulsar at 430 MHz. It is intended to guide observers trying to detect these pulsars at other telescopes. There are several important uncertainties inherent in them including unknown position of the pulsar relative to the beam center, refractive and diffractive scintillation effects, unknown/uncalibrated sky background contribution to the system temperature, etc. During the survey, nine previously known pulsars, including the 4.57 ms pulsar PSR J1713+0747 (Foster, Wolszczan, & Camilo 1993), were also detected (see Table 2). The positions of the pulsars in Galactic coordinates are shown in Figure 8. Most of the new pulsars appear to be typical of the young pulsar population with two exceptions: PSR J2033+17, a 5.9 ms

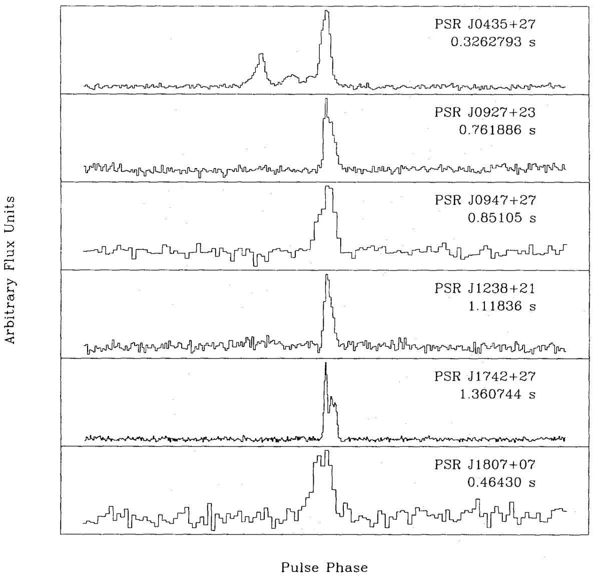

Fig. 5.—The profiles of six new pulsars reported in this paper. The vertical scale is arbitrary, and the highest point in the profile has been shifted to line up at phase 180°.

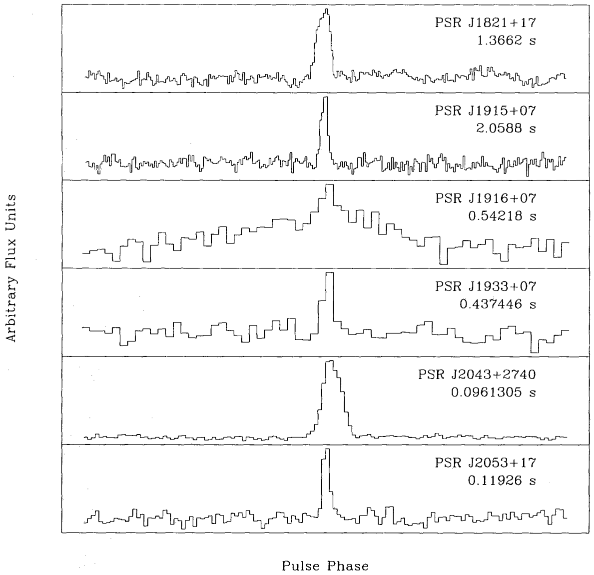

Fig. 6.—The profiles of another six new pulsars reported in this paper. The vertical scale is arbitrary, and the highest point in the profile has been shifted to line up at phase 180°.

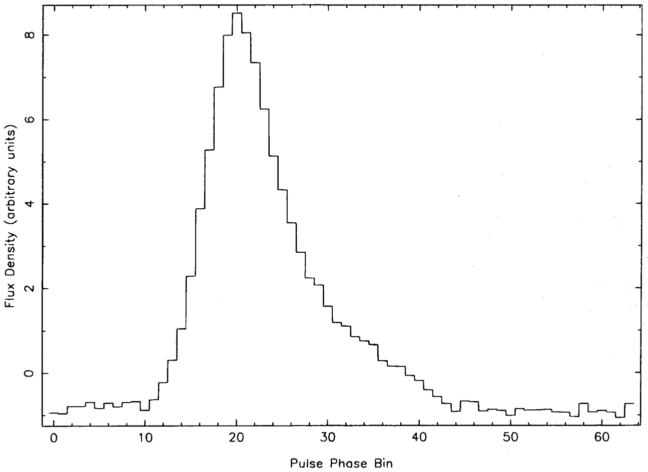

FIG. 7.—Pulse profile of PSR J2033+17. This profile was taken with the Arecibo 32 × 0.25 MHz filter bank at a center frequency of 430 MHz. The dispersive smearing across one channel of the filter bank is ~650 $\mu$s or 0.11 pulse periods.

pulsar in a binary system, and PSR J2043+2740, one of the fastest nonrecycled pulsars.

The detailed flux limit for these surveys is displayed in Ray et al. (1995); for slow pulsars it is ~0.7 mJy, increasing to 1–3 mJy for millisecond pulsars due to the effects of dispersion smearing and harmonic content beyond the Nyquist frequency of the sampling.

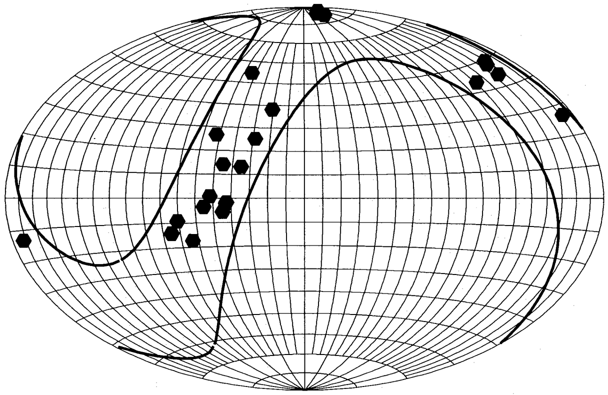

FIG. 8.—Map of the detected pulsars in Galactic coordinates. The center is the point $l = 0°$, $b = 0°$, and the solid lines outline the region of the sky accessible to the Arecibo telescope.

### 3.1. *PSR J2043+2740*

PSR J2043+2740 has a rotation period of 96.1 ms. With one exception, PSR B1830−08, every known pulsar with period shorter than this is either a "recycled" pulsar (characterized by a low magnetic field) or is a young pulsar for which an associated supernova remnant (in which the pulsar was formed) has been identified. PSR J2043+2740 is close to the Cygnus Loop supernova remnant, suggesting a possible association between the pulsar and the remnant. We have made a series of observations designed to better characterize the pulsar, allowing us to test this hypothesis.

#### 3.1.1. *Observations*

The search data provide very limited position information (~10′ precision), so we made a high-precision measurement with the Very Large Array (VLA). Two 5 minute "snapshot" observations were made at 1.66 GHz with the B array on 1994 July 15 and 16. Two bright sources are evident in the synthesized map from the July 15 data. One is apparently a double or slightly extended source with position (accurate to about 1″) $20^{\mathrm{h}}43^{\mathrm{m}}50\overset{\mathrm{s}}{.}1$ $+27°40'45''$ (J2000.0) and a flux of 120 mJy at 1.66 GHz. We identify this source with the cataloged radio source 87GB 204141.8+272952. The other prominent source in the field was at the position $20^{\mathrm{h}}43^{\mathrm{m}}43\overset{\mathrm{s}}{.}50$ $+27°40'56.3''$ (J2000.0) with a 1.66 GHz flux of 7 mJy. In the next day's observation, the bright source was still present, but the other source was not seen. We identify the second source with the pulsar; the nondetection the second day being consistent with pulsar scintillation. We note that the absolute fluxes are not carefully calibrated and are uncertain by about 50%.

We have performed extended timing observations to measure the spin-down rate of this pulsar, from which its characteristic age and magnetic field strength can be inferred. Observations were made at Arecibo and Green Bank, West Virginia. Arecibo observations were made between 1994 May 23 and 1994 August 1. The Arecibo observations were made with the same 32 channel filter bank used for the survey, and the data were folded into profiles off-line at the observed period found using a Fourier transform.

Observations at Green Bank used two telescopes. Telescope 85-3 (26 m aperture) was used to make almost daily

TABLE 2

PREVIOUSLY KNOWN PULSARS DETECTED IN THIS SURVEY[a]

| Name | R.A. (J2000.0) | decl. (J2000.0) | Period (s) | DM (pc cm$^{-3}$) | $S_{400}$ (mJy) | W50 (ms) |
|---|---|---|---|---|---|---|
| B0751+32........ | 07:54:40.6 | +32:31:58 | 1.44234 | 39.4 | 6 | 10 |
| B0950+08........ | 09:53:09.3 | +07:55:36 | 0.25306 | 3.0 | 400 | 11 |
| B1237+25........ | 12:39:40.5 | +24:53:49 | 1.38244 | 9.3 | 110 | 5 |
| B1530+27........ | 15:32:10.0 | +27:45:47 | 1.12483 | 14.6 | 12 | 26 |
| B1612+07........ | 16:14:41.0 | +07:37:31 | 1.20680 | 21.3 | 10 | 12 |
| B1921+17........ | 19:23:21 | +17:06 | 0.54721 | 135 | 2 | 25 |
| B1944+17........ | 19:46:53.0 | +18:05:41 | 0.44062 | 16.3 | 35 | 18 |
| B2110+27........ | 21:13:04.3 | +27:54:00 | 1.20285 | 24.7 | 14 | 13 |
| J1713+0747...... | 17:13:49.5 | +07:47:38 | 0.00457 | 16.0 | 36 | 0.25 |

[a] Parameters are from Taylor, Manchester, & Lyne 1993.

observations from 1994 July 16 to 1994 December 2. Two linear polarizations at 610 MHz were detected in 16 1 MHz filter channels. The signals were sampled and folded at the predicted topocentric pulse period with a Princeton Mark III pulsar timing system (Stinebring et al. 1992). Typically eight scans, each with an integration time of 280 s, were collected each day.

The 140 foot (43 m) telescope at Green Bank was used to make observations at approximately 2 month intervals between 1994 July and 1995 November. At each epoch, observations were made at 575, 800, and occasionally 1400 MHz on one or more days. At each frequency, the Spectral Processor, a Fourier transform spectrometer, synthesized 512 channels across a 40 MHz passband. The spectra were folded at the topocentric pulse period into profiles with 128 bins. Typically three scans of 2–3 minutes duration were collected each day.

Data from each observatory were time-tagged to a local clock, traceable to UT. Profiles from individual spectral channels were combined into a single, dedispersed profile by summing them after shifting them in time to compensate for interstellar dispersion. These profiles were cross-correlated with a standard template to measure the topocentric pulse time of arrival. A total of 815 times of arrival were measured. They were analyzed with the standard program TEMPO (Taylor & Weisberg 1989), yielding the astrometric and rotation parameters in Table 3. In addition to the parameters shown, arbitrary offsets were fit between data taken with the three different instrumental systems we used.

The measured period derivative, $1.27(1) \times 10^{-15}$, is unusually low for a pulsar with such a short period. Combining this with the pulse period, we infer the pulsar's magnetic field to be $3 \times 10^{11}$ G, and its characteristic age to be $1.21 \times 10^{6}$ yr. Residual pulse arrival times after subtracting the best-fit timing model are shown in Figure 9. Clearly the model does not fully describe the data; excess timing noise is observed. This timing noise can bias parameters inferred from the timing model; to compensate for this, we "whitened" the residuals by fitting for several additional frequency derivatives when calculating the parameters presented in Table 3. Such noise is a common feature of young pulsars and is thought to be weakly correlated with period derivative (Cordes & Helfand 1980; Arzoumanian et al. 1994). The observed activity parameter (Cordes 1993) is $A = -0.5$, somewhat greater than the $A = -1.5$ predicted from the pulsar period and period derivative; however, there is a great deal of scatter about this empirical relation.

TABLE 3

PARAMETERS OF PSR J2043+2740 AS OF MJD 50052

| Parameter | Value |
|---|---|
| Interferometric Parameters | |
| Right ascension (J2000.0) | $20^{h}43^{m}43.5\ (2)^{s}$ |
| Declination (J2000.0) | $+27°40'56\ (2)''$ |
| Flux at 1.66 GHz (mJy) | 7 (3) |
| Timing Parameters | |
| Right ascension (J2000.0) | $20^{h}43^{m}43.5\ (1)^{s}$ |
| Declination (J2000.0) | $+27°40'54\ (1)''$ |
| Period (s) | 0.09613056295 (5) |
| Period epoch (MJD) | 49773.0 |
| Period derivative | $1.27(1) \times 10^{-15}$ |
| Dispersion measure (pc cm$^{-3}$) | 21.0 (1) |
| Derived Parameters | |
| Characteristic age (yr) | $1.20(1) \times 10^{6}$ |
| Surface magnetic field (G) | $3.5 \times 10^{11}$ |
| Spin-down luminosity (ergs s$^{-1}$) | $5.6 \times 10^{34}$ |
| Distance (kpc) | 1.1 |

3.1.2. *Is PSR J2043+2740 Associated with the Cygnus Loop?*

Three parameters can be used to judge an association between the pulsar PSR J2043+27 and the Cygnus Loop

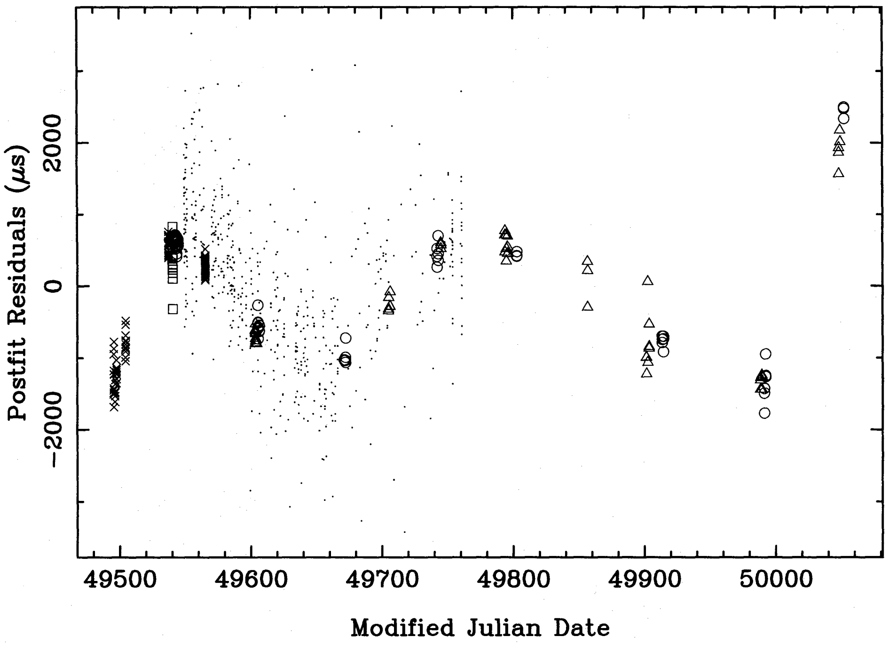

FIG. 9.—Post-fit timing residuals for PSR J2043+2740. The various symbols represent the observing frequency: crosses for 430 MHz, circles for 575 MHz, triangles for 800 MHz, squares for 1400 MHz, and dots for 610 MHz.

supernova remnant: distance, sky position, and age. The pulsar distance, estimated from its dispersion measure of 21 pc cm$^{-3}$, is 1.1 kpc, with an uncertainty of about 50% (Taylor & Cordes 1993). This is consistent with the remnant distance of $600^{+600}_{-300}$ (Shull & Hippelein 1991), which is derived from a kinematic and proper motion study of the remnant.

The pulsar lies approximately 1° outside the boundary of the Cygnus Loop. The pulsar velocity inferred by assuming that the pulsar was born in the supernova that created the Cygnus loop depends on the poorly known remnant age and distance, but could be as high as 1500 km s$^{-1}$. This is quite a bit higher than the 450 km s$^{-1}$ mean birth velocity of pulsars (Lyne & Lorimer 1994), although it is comparable to velocities inferred from several other currently proposed pulsar-SNR associations (Gorham et al. 1996 and references therein). If the supernova origin was not in the geometric center of the remnant, but rather in the "southern breakout" region of the remnant, the required velocity would be reduced by a factor of 2.

The pulsar characteristic age of $1.21 \times 10^6$ yr is 2 orders of magnitude larger than the $\sim 2 \times 10^4$ yr estimated age of the Cygnus Loop remnant (Ku et al. 1984). The ages could be reconciled if the pulsar were born with a period not much shorter than its current period.

Because an association with the Cygnus Loop requires the pulsar to have both a rather high birth velocity and a true age very different from the characteristic age, we conclude that PSR J2043+2710 was probably not formed in the supernova that produced the Cygnus Loop remnant. This conclusion could be strengthened with a proper motion measurement. An alternative explanation for the pulsar's short period (and low magnetic field) is that it has undergone a short episode of mass accretion from a companion that has since been lost. Many such pulsars must be produced from systems similar to the progenitors of the five known double neutron star binaries, that instead become unbound during the second supernova. However, the period of J2043+2740 is much shorter than the limiting spin-up period of a neutron star with a field of $3 \times 10^{11}$ G.

Thus, the very short period must be due to the pulsar either being born with the low magnetic field of $3 \times 10^{11}$ G or being a mildly recycled pulsar that has had its magnetic field reduced through a short episode of accretion from a companion which has been lost.

### 3.2. *PSR J2033+17*

The millisecond pulsar PSR J2033+17 was discovered in data taken on 1994 July 17, confirmed 1994 August 18, and reobserved on 1994 September 9 and 1994 October 19. These data were sufficient to establish that the pulsar is in a binary system (see the first four points in Fig. 10), but did not strongly constrain the orbital period.

Consequently, we performed observations of the pulsar from 1994 November 2–6 using the Arecibo 128 × 78.125 kHz autocorrelator, which has been used extensively for millisecond pulsar timing (Prince et al. 1991, for example). For each data set, the observation was subdivided into short intervals, and average pulse profiles were computed by folding the data modulo the best period determined from a Fourier transform of the day's data. Topocentric arrival times were computed for each profile by cross correlating with a high signal-to-noise template. These daily sets of TOAs were fitted using TEMPO to determine a barycentric period for the pulsar each day. These periods were fitted to a circular orbit model, which describes the data well (with a limit on the eccentricity of $e \lesssim 0.05$). The observed barycentric periods and best-fit model are shown in Figure 10. The best-fit orbital model parameters are presented in Table 4.

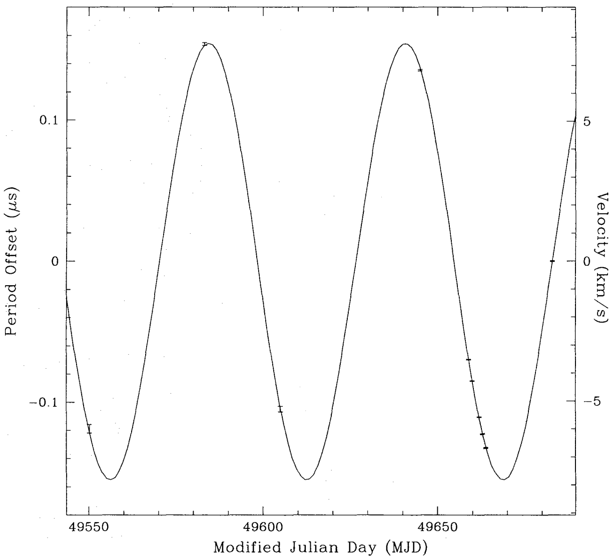

FIG. 10.—Observed barycentric period offsets relative to 5.9489582 ms for PSR J2033+17, and the best-fit circular orbit model. The errors on the first two points are considerably larger than the later points due to short integration times (30 s and 10 minutes). The projected orbital velocity is shown on the right axis.

## 4. DISCUSSION

### 4.1. *Newly Discovered Pulsars*

In over 900 square degrees of sky, these surveys (with TDK) detected 21 young pulsars (13 new), and two millisecond binary pulsars (one new). In another survey (Ray et al. 1995), one (previously known) millisecond pulsar was detected in about 225 square degrees surveyed at the same sensitivity. The combined surveys imply a surface density of

TABLE 4

PARAMETERS OF PSR J2033+17[a]

| Parameter | Value |
|---|---|
| Right ascension (J2000.0) (in hours, minutes, seconds) | 20 33 21 (20) |
| Declination (J2000.0) (in degrees, arcminutes) | 17 36 (5) |
| Galactic longitude ($l$) (in degrees) | 60.9 |
| Galactic latitude ($b$) (in degrees) | −13.1 |
| Dispersion measure (pc cm$^{-3}$) | 25.2 (3) |
| Pulse period (s) | 0.0059489575 (2) |
| Orbital period (d) | 56.2 (1) |
| Semimajor axis (lt-s) | 20.07 (8) |
| Epoch of ascending node (MJD) | 49584.32 (12) |
| Eccentricity | <0.05 |
| Mass function ($M_\odot$) | 0.00275 (3) |
| Minimum companion mass ($M_\odot$) | 0.2 |
| Companion mass at $i = 60°$ ($M_\odot$) | 0.22 |
| Inferred Distance (kpc) | 1.4 |

[a] As of 1994 November.

millisecond pulsars above 1 mJy of 1 per 375 square degrees for an observing frequency of 430 MHz. This is somewhat, but not significantly, lower than the rate found in the Pennsylvania State–NRL and Princeton surveys with identical observational hardware (Foster, Wolszczan, & Cadwell 1995b; Camilo, Nice, & Taylor 1993)

Using a recent model of the Galactic free-electron distribution (Taylor & Cordes 1993), the distances to the new pulsars can be estimated. These distance estimates are shown in Table 1. Seven are lower limits, since the integral along the line of sight of the free-electron density model never reaches the measured DM for the pulsar. The model underpredicts the maximum DM in the direction of these pulsars by up to 25% (also noted by Camilo & Nice 1995). These pulsars will be useful for making the next generation of free-electron distribution models and provide information about the thickness of the electron layer in our Galaxy.

The current estimate of pulsar birth velocities is very large ($\sim 450$ km s$^{-1}$). However, the average velocity of observed older ($\gtrsim 10^7$ yr) pulsars is considerably lower ($\sim 100$ km s$^{-1}$) (Lyne & Lorimer 1994) because fast, old pulsars have moved far from the Galactic plane, where they are difficult to detect. Current, sensitive high-latitude surveys may start to reveal this population; indeed some of the pulsars discovered in this survey at large distances from the Galactic plane may be members of this "fleeing" pulsar population.

Inspection of the pulse profiles in Figures 5 and 6 reveals several things. At the current signal-to-noise level, 11 of the 13 pulsars appear to have single component profiles, as do the majority of the pulsar population. Two of the pulsars display clear multiple component profiles. PSR J1742+27 shows a triple profile with a total extent of $\lesssim 10°$ of pulse longitude. PSR J0435+27 has a rather unusual profile that shows at least three and possibly four components with a total separation of about 45° of longitude. The profile is rather similar to PSR B1541+09, which also shows a rather wide multicomponent profile, and Rankin (1990) classifies it as a triple. PSR J0435+27 deserves further study to establish its classification and to see if it exhibits drifting subpulses or mode changing as seen in several triples by Hankins & Wolszczan (1987).

### 4.2. *The Millisecond Pulsar J2033+17*

A pulsar with an orbit whose Keplerian parameters are determined from Doppler shifts in the pulse period is akin to a single-line spectroscopic binary in which the orbit is determined by measuring Doppler shifts of spectral lines in one of the members. For PSR J2033+17, the mass function is

$$f(m_1, m_2, i) = \frac{(m_2 \sin i)^3}{(m_1 + m_2)^2} = \frac{4\pi^2 (a_1 \sin i)^3}{P_b^2 G} = 0.00275(3)\ M_\odot\ , \qquad (1)$$

where $m_1$ is the pulsar mass, $m_2$ the companion mass, $a_1$ the semimajor axis of the pulsar's orbit, $P_b$ the orbital period, sin $i$ is the orbital inclination, and $G$ is Newton's gravitational constant. If we assume that $m_1 = 1.4\ M_\odot$ (Thorsett et al. 1993a), then the minimum companion mass for an edge-on orbit is 0.2 $M_\odot$, and the most probable companion mass ($i = 60°$) is 0.22 $M_\odot$. A direct measurement of the pulsar and companion masses is of interest, but difficult in the case of a circular orbit because neither the relativistic precession of periastron nor the relativistic time dilation and transverse Doppler shift can be measured. Mass determination by measurement of the Shapiro time delay as the pulsar passes behind its companion (Ryba & Taylor 1991) may be possible if the orbital plane proves to be nearly edge-on.

In systems where mass transfer comes from a low-mass ($\lesssim 2 M_\odot$) star filling its Roche lobe, there should be a relation between the remnant white dwarf mass and the orbital period (Refsdal & Weigert 1971; Phinney & Kulkarni 1994):

$$P_b \simeq 1.3 (m_c / 0.16\ M_\odot)^7 \text{ day}\ , \qquad (2)$$

yielding a mass of $\sim 0.27\ M_\odot$. The predicted companion mass for PSR J2033+17 from a more accurate model (Phinney & Kulkarni 1994) is 0.295 $M_\odot$, implying an inclination of 43°. There is considerable uncertainty in the prediction due to the unknown metallicity of the white dwarf progenitor, but it provides an indication of a likely mass for the white dwarf companion of PSR J2033+17.

Only an upper limit on the orbital eccentricity is currently available. Phinney (1992) has applied the fluctuation dissipation theorem to the randomly induced multipole moments in a convective red giant star, and predicted a relation between the orbital period of such a system and its eccentricity. For PSR J2033+17, the predicted value is between $4 \times 10^{-5}$ and $4 \times 10^{-4}$ with a most likely value of $2 \times 10^{-4}$. An eccentricity of this magnitude could be measured with a few months of precision timing data.

Camilo (1995) noted that no millisecond pulsars with low-mass companions in circular orbits had an orbital period between 12 and 67 days. The 56.2 day orbital period of PSR J2033+17 falls within this putative gap.

## 5. CONCLUSION

We will continue to monitor PSR J2033+17, whenever time is available at Arecibo and at the Green Bank 140 foot telescope, to accurately determine the binary and astrometric parameters and to measure the rotational stability of the pulsar to evaluate its suitability for setting limits on the stochastic gravitational radiation background (e.g., Thorsett & Dewey 1996). At a distance of 1.4 kpc, and out of the crowded Galactic plane, the cooling white dwarf companion of the pulsar may be optically detectable. Only a few such white dwarf companions have been detected, but the determination of the cooling ages of the white dwarfs has important implications for estimating the initial periods of millisecond pulsars (van Kerkwijk & Kulkarni 1995; Lundgren et al. 1996; Camilo, Thorsett, & Kulkarni 1994).

The survey during the Arecibo upgrade is incomplete and will continue if possible during the telescope recommissioning in late 1996. At the current rate, we expect the discovery of about two more recycled pulsars as well as a dozen or so young pulsars in the 20% of the Arecibo accessible sky allocated to this project. The completed survey will be useful for population studies when combined with the rest of the Arecibo surveys, the Parkes southern sky survey and the Jodrell Bank northern sky survey. Their consistent flux limits, and minimal selection effects due to short periods, will allow the recycled pulsar population to be characterized far better than previously possible. They will also help constrain the local population of low-luminosity young pulsars which is important for estimating the pulsar birth rate.

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