A SEARCH FOR SUBMILLISECOND PULSARS

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ABSTRACT

We have conducted a search of 19 southern Galactic globular clusters for submillisecond pulsars at 660 MHz with the Parkes 64 m radio telescope. To minimize dispersion smearing we used the CPSR baseband recorder, which samples the 20 MHz observing band at the Nyquist rate. By possessing a complete description of the signal we could synthesize an optimal filter bank in software, and in the case of globular clusters of known dispersion measure, much of the dispersion could be removed using coherent techniques. This allowed for very high time resolution (25.6 μs in most cases), making our searches in general sensitive to submillisecond pulsars with flux densities greater than about 3 mJy at 50 cm. No new pulsars were discovered, placing important constraints on the proportion of pulsars with very short spin periods in these clusters.

Subject headings: globular clusters: general — pulsars: general — radio continuum: stars — techniques: miscellaneous

1. INTRODUCTION

With the discovery of the first "millisecond" pulsar, B1937+21 ($P = 1.56$ ms; Backer et al. 1982), it became clear that neutron stars can achieve very rapid rotation rates. This period is close to but still somewhat greater than the minimum rotation period for a neutron star, below which the star becomes unstable to mass shedding at the equator (see e.g., Cook, Shapiro, & Teukolsky 1994). Various equations of state have been proposed for nuclear matter, and owing to the differences in density under such equations, the limiting spin period of neutron stars depends on the choice of equation of state. The discovery of a pulsar with $P < 1$ ms would be of great value in eliminating potential equations of state. The distribution of periods of known pulsars cuts off quite sharply below about $P = 2$ ms; however, it is not clear whether this cut-off is intrinsic to the pulsar population (see Lorimer et al. 1996). Most previous pulsar surveys had a time resolution of ~ 300 μs for nearby pulsars, resulting in a strong decline in sensitivity for periods less than a few milliseconds, indicating that the short-period cut off may in fact be a selection effect. The only effective way to answer this question is to conduct surveys with sufficient time resolution to be well-sensitive to pulsars with $P < 1$ ms, and preferably with a flat sensitivity response to periods well below a millisecond in order to eliminate any bias toward longer pulse periods. For a traditional analog filter-bank system this would require a large number of channels with fast sampling and would involve considerable cost. An alternative is to record the raw receiver voltages at baseband and to perform all frequency decimation and detection in software for the best possible time and frequency resolution. Until recently this approach has been little used because of the formidable data storage and processing requirements; however, the rapid development that has occurred in these areas in the last decade means that the required hardware is now relatively affordable. We report here for the first time the use of baseband processing in a pulsar survey.

Historically approximately half of all millisecond pulsar discoveries were made in globular clusters, with most of the remainders found in large scale surveys of the Galaxy. Since the cores of most globular clusters are easily contained in a single telescope beam for low-to-intermediate observing frequencies, globular cluster searches are very efficient in their return of millisecond pulsars for observing campaigns of limited duration. Because of the large amounts of data to be processed from observations of high time and frequency resolution, globular clusters are a logical place to begin the search for submillisecond pulsars. We conducted several observations of each of 19 southern globular clusters with the CPSR baseband recording system (van Straten, Britton, & Bailes 2000) at the Parkes radio telescope. This paper describes the searches and their results.

2. OBSERVATIONS AND ANALYSIS

In an observing run of 4 days from 2000 March 17–20 we conducted observations of 19 southern Galactic globular pulsars with the Parkes 64 m radio telescope. The signals from two orthogonal linear polarizations of the 50 cm receiver were mixed to baseband in a quadrature down-convertor and filtered to provide a 20 MHz band centered at a sky frequency of 660 MHz. The in-phase and quadrature components in each polarization were 2-bit–sampled at a sample rate of 20 M samples s^{-1} in accordance with the Nyquist theorem for complete description of the band-limited signal. Sampler thresholds were set at the beginning of the observation in accordance with the prescriptions of Jenet & Anderson 1998 and were held at these values for the duration of each observation. The resultant data stream had a bit rate of 160 Mbit s^{-1} and was written in segments of ~ 53.7 s (corresponding to 1 GB of data) to DLT 7000 tapes. The recording system consisted of four DLT 7000 drives, a large disk array, and a Sun Ultra 60 workstation and in conjunction with the down-conversion and sampling systems is known as the Caltech-Parkes-Swinburne Recorder (CPSR) (van Straten et al. 2000). A total of 55 observations of 30 minutes' duration each were recorded, resulting in a 1.8 TB data set.

The observations were processed on the 64-node Swinburne workstation cluster. Each observation could be processed by one of the schemes described below in about 12 hr using 2.5 MHz Compaq EV6 processors. Tapes were unloaded to a 1 TB RAID array to facilitate the reassembly of full 30 minute contiguous data streams from the 1 GB

files that were distributed across four or more tapes during recording. The statistics of samples in each file were examined and any files partially recorded before the sampler levels were correctly set were discarded.

In order to allow an efficient search in dispersion measure (DM), a filter bank was synthesized in software. The data were loaded in segments, and each polarization in each segment was transformed to the Fourier domain by means of an FFT. The spectrum was then divided into 512 equal sections and each section was transformed back to the time domain with an inverse FFT to produce a number of time samples in each of 512 frequency channels. The squared magnitude of each sample was taken, and samples were summed in polarization pairs. The resultant sample interval in each channel was 25.6 μs.

In the case of observations of clusters with previously known pulsars, we convolved each channel with a filter matched to the inverse of the response function of the interstellar dispersion at the estimated dispersion measure to the cluster (Hankins & Rickett 1975) by multiplication while the data was still in the Fourier domain. In this case, the length of the original FFT was important for it determined the effective resolution of the dedispersion filter to be applied. In addition, the cyclical nature of the convolution with the filter dictated that a certain number of samples (corresponding to approximately half the dispersive delay across each channel) must be discarded from either end of the resultant time series. To recover these samples the segments were overlapped, resulting in some inefficiency that could be minimized through the use of larger segments (transforms). Typically segments of 2^{15} samples were used, with a 64-point coherent dedispersion filter applied to each of the 512 channels.

The resultant data was similar in form to that recorded from orthodox analog filter banks, with the exception that each channel was recorded at half its Nyquist rate,[1] much faster than commonly practiced with analog filters. In addition, the use of coherent dedispersion in clusters with known pulsars meant that the dispersion smearing induced across each channel arose only from the difference between the true and assumed dispersion measure, and was generally expected to be much shorter than the sample interval. The dispersion smearing experienced by pulsars in clusters lacking a DM estimate is given approximately by DM/22.7 pc cm^{-3} in units of samples of 25.6 μs in duration, where 22.7 pc cm^{-3} is the so-called diagonal DM.

The synthesized filter-bank data for each observation were partially dedispersed with the "tree" algorithm of Taylor (1974) before being subject to a search process similar to that used for the intermediate latitude multibeam survey (Edwards et al. 2001). Data were dedispersed and summed into time series at a range of trial dispersion measures, either about a nominal cluster DM where such a value was available, or up to a maximum of 732 pc cm^{-3} in 1463 steps. The spacing of these steps was such that the pulse smearing induced in pulsars at DMs halfway between two trial values was comparable to the smearing across a single filter-bank channel. It was possible that the motion of a pulsar in its orbit about a close companion could have induced significant change in the observed pulse period over the course of the observation, and for this reason we incorporated an acceleration search. For each trial dispersion measure we computed several time series rebinned in such a way as to compensate for the effects of a range of values of acceleration. The method used was similar to that described by (Camilo et al. 2000). The resulting time series with trial pairs of values for dispersion measure and acceleration were then searched for periodicities, and a page of diagnostic information was produced for each potentially significant candidate.

The performance of much of the signal processing in software allows for a considerable degree of flexibility. We used several different sets of parameters as appropriate depending on whether the cluster had a known pulsar and also on the available computer time. The scheme denoted FD ("full DM search") searches the full range of dispersion measures from 0 to 732 pc cm^{-3} in 1463 steps with integrations of 1718 s. For clusters with known DM, the scheme known as FA ("full acceleration search") applied the coherent dedispersion kernels and searched a small specified range of dispersion measures in 201 accelerations evenly spaced in the range given by $|a| \leq 30$ m s^{-2}. Because of the large computational burden of the task, the FA search only processed 859 s of data, using 2^{25}-point transforms. Finally, to maintain sensitivity to accelerated millisecond pulsars in clusters with no DM estimate, we also performed a search denoted SA ("slow acceleration search"), which synthesized a filter bank of 256 channels and summed the resultant detected samples in groups of sixteen. The resultant sample rate was 204.8 μs with a diagonal DM of 90.8 pc cm^{-3}, and the full range of 0 to 2950 pc cm^{-3} was searched at 737 trial values. Again, only 859 s of data were processed, with 2^{22}-point transforms and 121 accelerations with $|a| \leq 30$ m s^{-2}.

A total of 10 clusters with previously known pulsars and nine without were searched, as indicated in Tables 1 and 2. The latter were selected from the catalog of Harris (1996) on the basis of proximity and luminosity. Since Fruchter & Goss (2000) observed several globular clusters in radio continuum and found unidentified steep spectrum emission in NGC 6544 and Liller 1 it was ensured that these clusters were included in the selection. The general strategy was to process clusters with an accurate DM estimate using the FA parameters and those without using the SA parameters. For the FA searches the dispersion measure range was generally

TABLE 1
OBSERVATIONS OF CLUSTERS WITH KNOWN PULSARS

Name	References	DM (pc cm^{-3})	N_{obs}	S_{max} (mJy)
47 Tucanae......	1–3	23.4–25.4	5	3
M4	4	61.9–63.9	3	
NGC 6342	5	74.9–76.9	2	1.3
NGC 6397	6	70.8–72.8	2	
NGC 6440	7	...	3	
Terzan 5	8, 9	237.0–242.1	3	5
NGC 6544	6	133.0–135.0	1	
NGC 6624	10	86.0–88.0	5	9 ± 2
M28..............	11	118.8–120.8	2	
NGC 6752	6	33.0–35.0	2	

REFERENCES.—(1) Manchester et al. 1990 (2) Manchester et al. 1991; (3) Camilio et al. 2000; (4) Lyne et al. 1988; (5) Lyne et al. 1993; D'Amico et al. 2001; (7) Manchester et al. 1989; (8) Lyne et al. 2000; (10) Biggs et al. 1994; (11) Lyne et al. 1987.

[1] The full Nyquist rate could be achieved through the use of complex-to-real inverse transforms; however, the time resolution was deemed sufficient as it stood.

Name	N_{obs}
NGC 2808	3
E3	3
NGC 3201	3
NGC 4372	4
NGC 4833	3
Ω Centaurus	4
Liller 1	3
M22	2
M30	2

selected in such a way as to include previously published values for pulsars in the cluster and to allow for ± 1 pc cm^{-3} of variation due to gas in the cluster environment. Since the published dispersion measure for PSR B1745$-$20 in NGC 6440 is significantly uncertain (Manchester et al. 1989), data from this cluster were processed with the SA parameters, as were those clusters lacking a previously known pulsar. Observations of all clusters were also processed with the FD parameters. For clusters also processed using FA, the FD search offers sensitivity outside the limited DM range of the FA search, while for those processed with SA the additional FD processing provides sensitivity to submillisecond pulsars. However, in both cases the FD search is insensitive to significantly accelerated pulsars.

Because of the frequent loss of data stored on DLT tapes, some observations were not processed to the full extent of the scheme above. In particular, only three of the four observations of NGC 4833 were processed in SA mode, and only four of the five observations of NGC 6624 and neither of the two observations of NGC 6752 were processed in FD mode. At the start of processing, no pulsars were known in NGC 6752, so it was searched using the SA parameters. With the announcement of the discovery of a pulsar in this cluster (D'Amico et al. 2001) it was decided to reprocess the data using the FA parameters and the published dispersion measure; however, only one observation was successfully retrieved from tape and processed in this manner.

3. RESULTS AND DISCUSSION

3.1. Detections

Off-line processing yielded detections of six pulsars, all of which were previously known, including PSR B1744$-$24A in Terzan 5 with a line-of-sight acceleration of 29 m s^{-2}. The pulsars are listed in Table 3 along with their pulse periods and the signal-to-noise ratio of detections. Variations in flux density due to scintillation (and in the case of

TABLE 3

DETECTIONS

Name	Cluster	P (ms)	DM (pc cm^{-3})	S/Ns
B0021$-$72D	47 Tucanae	5.35	24.7	34.3, 11.3
B0021$-$72E	47 Tucanae	3.54	24.2	15.4
B1620$-$26	M4	11.1	62.9	23.7, 22.8, 20.5
B1744$-$24A	Terzan 5	11.6	242	11.0
B1820$-$30A	NGC 6624	5.44	86.8	15.3
B1821$-$24	M28	3.05	120	10.4, 18.1

PSR B1744$-$24A, eclipses) are the expected cause of variations in detectability and signal-to-noise ratio from one observation to the next.

One promising pulsar candidate was observed in 47 Tucanae in an observation centered at MJD 51621.25740, with a topocentric period of 3.756394 ms, a dispersion measure of 24.3 pc cm^{-3}, and an acceleration of 7.2 m s^{-2}. The signal-to-noise ratio of this candidate was 9.7, placing it at the threshold of credibility, and in the absence of any other detections of similar periodicities we are hesitant to label the signal a " pulsar." All other periodicities were consistent with random chance (owing to the complexity of the search space) or persistent terrestrial interference.

3.2. Sensitivity

The sensitivity of pulsar observations is a function of the radiometer noise and the observed duty cycle. After Dewey et al. (1985), the minimum detectable mean flux density is

$$S_{min} = \frac{\alpha \beta T_{sys}}{G \sqrt{N_{pol} B t_{obs}}} \sqrt{\frac{\delta}{1-\delta}}, \quad (1)$$

where α is a dimensionless loss factor, β is the threshold signal-to-noise ratio, T_{sys} is the system temperature, G is the telescope gain, N_{pol} is the number of polarizations, B is the observing bandwidth, t is the integration time, and δ is the effective duty cycle. The observed pulses are broadened somewhat relative to those actually emitted by the pulsar owing to factors such as multipath propagation (scatter-broadening), dispersion smearing in filter-bank channels, and the finite duration of the sampling interval. These effects should be added in quadrature with the intrinsic pulse width to yield the effective pulse width. All pulsar systems incorporate a degree of sensitivity loss modeled with α, the major factor in the past being the use of 1-bit sampling, which contributes $(\pi/2)^{1/2} \simeq 1.25$ to this value. Most surveys in the past have assumed an extra 15% loss due to other factors, giving $\alpha = 1.5$. Since the present survey samples with 2 bits of precision, we begin with a value of 1.15 (see Jenet & Anderson 1998) and adding 15% for other losses, arrive at an assumed value of $\alpha = 1.3$. From the appearance of spurious signals in this search and based on the distribution of true pulsar signal-to-noise ratios in previous work (Edwards et al. 2001), we use a value of $\beta = 10$ as the minimum signal-to-noise ratio for a pulsar candidate of firm credibility. The effective system temperature is mainly the result of contributions from thermal noise in the receiver and from Galactic synchrotron radiation. The receiver used in this work contributes approximately 60 K to the system temperature, while the Galactic contribution is a strong function of Galactic latitude, contributing ~ 10 K at high Galactic latitudes and ~ 100 K at the Galactic plane. Pulsar signals are superimposed on this noise with a gain from the 64 m collecting dish of $G \simeq 0.6$ K Jy^{-1}.

The sensitivity as a function of period for the searches described here is plotted in Figures 1 and 2. The values are for a cold sky of around 10 K; for clusters near the Galactic plane sensitivity drops by around a factor of 2.3. Our analysis includes the effects of the finite sample interval and dispersion smearing in filter channels but does not attempt to model scatter-broadening due to its dependence on the composition of the intervening interstellar medium. From the work of Ramachandran et al. 1997 we expect most pulsars in the clusters searched to experience of the order of
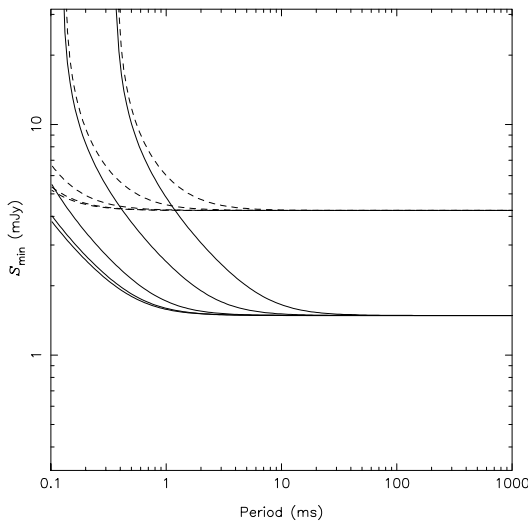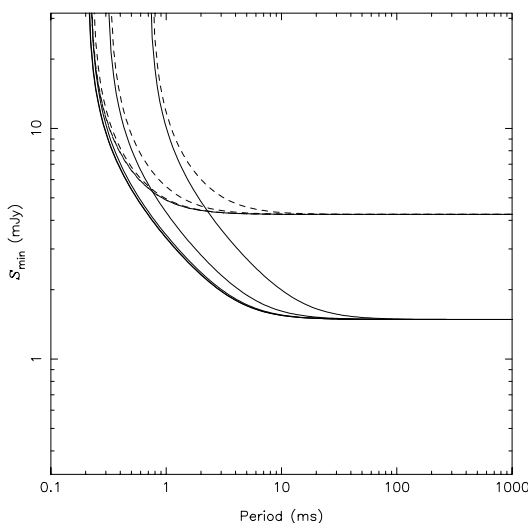
FIG. 1.—Minimum detectable mean flux density as a function of pulse period for FA search parameters. Solid and dashed lines represent pulsars with 5% and 30% intrinsic duty cycles, respectively. For each pulse width curves for dispersion measures of 0, 10, 30, 100, and 300 pc cm⁻³ are shown (*left to right*).

one sample of scattering (to 50% intensity, based on a DM of 80 pc cm⁻³); however, the spread about this value is likely to be large. It should also be noted that sensitivity is strongly dependent on the intrinsic pulse width, a factor that has been somewhat neglected in the past. Since the majority of recycled pulsars have pulse duty cycles between 5% and 30% (see e.g., Kramer et al. 1998), we show in the figures sample curves for these values, resulting in a baseline sensitivity of 1.3–4 mJy. Figure 1 applies to observations of 859 s in duration with 512 channels and 25.6 μs sampling, such as the FA search. The curves for FD would be of the same shape but with a slight downward shift (by a factor of

FIG. 2.—Minimum detectable mean flux density as a function of pulse period for SA search parameters. Solid and dashed lines represent pulsars with 5% and 30% intrinsic duty cycles, respectively. For each pulse width curves for dispersion measures of 0, 10, 30, 100, and 300 pc cm⁻³ are shown (*left to right*), although the first three are in general so close as to be difficult to distinguish (cf. Fig. 1).

$1/\sqrt{2}$ or ~ 0.15 decades). The maximum DM range searched in the FA search was only ± 2.5 pc cm⁻³, and the dispersion smearing in each channel even at the edges of the range is very small owing to the earlier coherent removal of a nominal cluster DM. Hence the zero-DM curves in Figure 1 are the most appropriate for clusters with known pulsars. For the SA search the curves in Figure 2 should be used. Note that the sampling interval of this search configuration (204.8 μs) is comparable to previous searches, and the degradation of sensitivity at high dispersion measures is improved because of the small channel bandwidth (and hence the large diagonal DM of 90.8 pc cm⁻³). Nevertheless, it is apparent from Figure 2 that the available sensitivity declines rapidly as periods go below 10 ms. On comparison of Figures 1 and 2 the superiority of high time resolution processing over traditional survey configurations (analogous to SA) for the detection of millisecond and submillisecond pulsars is clear.

However, it must be noted that while the present work had good sensitivity to submillisecond pulsars, its sensitivity to slower pulsars was comparable to or poorer than previous surveys. The four published 50 cm flux densities we have found in the literature for previously known pulsars in these clusters are presented in Table 1. These flux values are compatible with our detections and nondetections. PSR B1718−19 (in NGC 6342) lies well below the flux limit and was not detected. The (rather uncertain) reported value for PSR B0021−72C in 47 Tucanae, also undetected, lies slightly above to the predicted minimum given its duty cycle of $\sim 15\%$; however, we expect that the reported deep scintillation of pulsars in 47 Tucanae is the cause of this result as well as the strong detection of B0021−72D, reported to be weaker than B0021−72C (Manchester et al. 1991). The remaining undetected pulsars were mainly discovered in work that was either of greater intrinsic sensitivity, or that exploited scintillation-induced flux variability by conducting numerous observations of the clusters at different epochs.

3.3. *Acceleration Effects*

The preceding analysis neglects the effects of acceleration due to orbital motion. The differential Doppler shift induced over the course of the observation can result in the smearing of power across several bins of the fluctuation spectrum. Since the shift moves frequency components a by multiplicative factor (at/c), the loss of sensitivity is greatest at higher harmonics. The acceleration spacing of the FA search is ~ 0.3 m s⁻², implying a worst-case differential shift factor of 0.15 m s⁻² × 859 s/c $\simeq 4.30 \times 10^{-7}$ for a pulsar with an acceleration midway between two trial values. Since each bin of the fluctuation spectrum represents 1/859 s $\simeq 1.16 \times 10^{-3}$ Hz, the 2500 Hz fundamental of a putative 0.4 ms submillisecond pulsar would experience at most ~ 1 bin of acceleration smearing, with higher harmonics experiencing proportionately more smearing but representing a smaller fraction of the total power of the pulsar.

To examine the true sensitivity loss we processed real data from an FA search, to which we had added simulated signals from nonaccelerated pulsars of various pulse widths and periods. We used a trial acceleration spacing of 0.05 m s⁻² in the range $|a| < 6$ m s⁻² to examine the loss of signal-to-noise ratio when trial accelerations do not match the true acceleration of the pulsar (in this case zero). The results are shown in Figure 3. Even in the worst case, a 0.4
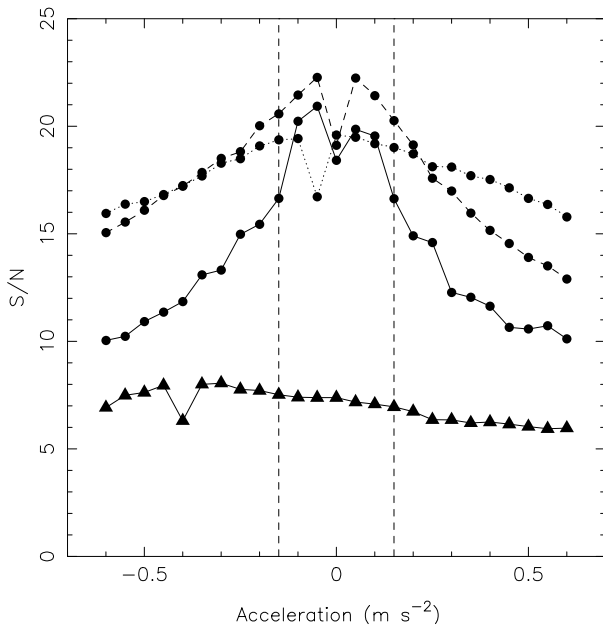
FIG. 3.—Spectral signal signal-to-noise ratio as a function of trial acceleration for simulated pulsar signals. Circles and triangles represent values resulting from Gaussian profiles with FWHM values of 5% and 30%, respectively, and are joined by solid, dashed, and dotted lines for pulse periods of ∼0.43, 0.89, and 1.84 ms. All signals were simulated with zero acceleration and equal mean flux density. Vertical dashed lines are placed at ± 0.15 m s^{-2} to represent displacements from zero by half the spacing used in the FA search.

ms signal with a pulse width of 5% FWHM (that is, at the extreme lower end of observed MSP pulse widths), some 80% of sensitivity was retained at the outer edges of the range of acceleration offsets experienced in the FA search. It is clear that the impact of acceleration on sensitivity of the FA search was small for $P \gtrsim 0.4$ ms. In addition, owing to scintillation it is expected that a real pulsar would experience less signal-to-noise loss than is indicated by these results. For the SA search a more modest acceleration spacing of 0.5 m s^{-2} was chosen because the long sample interval employed itself severely limits sensitivity to submillisecond pulsars. In this case, any pulsar or harmonic with a period greater than 0.6 ms would experience less than one bin of acceleration-induced spectral smearing.

Of course, all of the above only applies to pulsars with accelerations that remain essentially constant throughout the observation and lie within the range of $|a| < 30$ m s^{-2} searched. The former requirement is likely to be satisfied for the vast majority of systems; the loss of signal-to-noise ratio under a constant acceleration approximation is likely to be significant only for systems with orbital periods less than a few hours (see Johnston & Kulkarni 1991). Nevertheless, such exotic and interesting systems do exist and it is important that general surveys maintain sensitivity to them, either through repeated observation (to exploit favorable orbital phases of nearly constant acceleration) or by the use of more involved techniques (e.g., Ransom 2000).

Of those systems exhibiting constant acceleration, sensitivity in this work may still have been compromised if the acceleration exceeded ± 30 m s^{-2}. This range is typical of previous pulsar searches and is likely to encompass the majority of pulsar systems; however, there are several known exceptions. The eclipsing binary of Terzan 5 (Lyne et

al. 1990) experiences line-of-sight accelerations greater than this for approximately 30% of its orbit, with a maximum value of 33.2 m s^{-2}. The eccentric double neutron star systems B2127+11C (in M15), B1534+12, and B1913+16 also experience strong accelerations, exceeding 30 m s^{-2} in the line of sight for 20%–50% of the orbit. Such systems have relatively long pulse periods ($P \gtrsim 30$ ms) and so would be detected in the present work at accelerations up to around 40 m s^{-2}. However, the acceleration in these systems exceeds even this value for a significant proportion of the time, reaching a peak in excess of 100 m s^{-2} for the highly eccentric systems B2127+11C and B1913+16. Eccentric systems with much shorter orbital periods are expected to evolve from pulsars typical of the presently known double neutron star population via the loss of orbital energy in the form of gravitational radiation. The detectability of such pulsars in this and previous globular cluster searches would be severely affected by acceleration smearing. The primary aim of this work was to detect or place limits on the existence of (sub)millisecond pulsars (which are not expected to have neutron-star companions), and the computational load associated with high-resolution baseband processing limited the feasibility of searching a broad acceleration range. However, we note that future surveys with good basic sensitivity would be well served by searching a range of at least ± 100 m s^{-2}, perhaps at a reduced sample rate of ∼1 ms and with correspondingly fewer trial dispersion measures and accelerations.

3.4. The Population of Submillisecond Pulsars

It is clear from inspection of Figure 1 and the preceding analysis that our FA search, unlike most searches in the past, had a relatively flat sensitivity function for all periods greater than ∼0.4 ms. The FD search also provided similar characteristics for nearby (DM $\lesssim 50$ pc cm^{-3}) unaccelerated pulsars. We are therefore in a stable position to analyze the period distribution of the detected population relatively free of concerns regarding selection effects. Unfortunately the system used was only sensitive enough to detect a few pulsars, making any assertions somewhat perilous given small number statistics. However, it is clear even from this sample that the majority of recycled pulsars do have pulse periods of a few milliseconds or more. All six pulsars detected lay in the two octaves from 3–12 ms, while no pulsars were detected in the preceding three octave interval, 0.375–3 ms over which we had comparable sensitivity.

No new pulsars were discovered in NGC 6544, Liller 1, or Terzan 5 despite the presence of steep-spectrum emission as reported by Fruchter & Goss (2000). It is probable that several pulsars in each cluster are responsible for the emission, with each individual pulsar having a flux density below our detection limit. An exception might be the "N" source of Terzan 5 (Fruchter & Goss 2000), which was unresolved at a resolution of 2″.9 (cf. the cluster core radius of 11″; Harris 1996). From the published spectral index and 20 cm flux, we infer a 50 cm flux density of 9 mJy. The sky temperature in this region is ∼300 K at 70 cm (Haslam et al. 1982), implying a temperature of ∼100 K at 50 cm (Lawson et al. 1987). The sensitivity limits are thus 160/70 $\simeq$ 2.3 times greater than indicated in Figure 1; however, even so, a very broad profile and/or very short spin period would be required for the pulsar to have remained undetected at 9 mJy. It is possible that the source is a pulsar and was undetected due to scatter broadening. Up to a milli-

second of scattering could be induced by the intervening interstellar medium without having hampered the detection of the presently known pulsars, with pulse periods of 11.6 and 8.4 ms (Lyne et al. 2000). Such scattering would be catastrophic for the detection of very fast pulsars and could explain the lack of detection of the "N" source in this work. Observations made at higher radio frequency could answer this question since the time scale of scatter-broadening scales as v^{-4}. However, the lower flux density of pulsars at high frequency necessitates the use of a large bandwidth, beyond the present capabilities of baseband recording and processing systems. Analog filter banks generally do not have sufficiently narrow channels to detect very fast pulsars at high dispersion measures such as that of Terzan 5. Indeed, the probable nondetection at 20 cm of the "N" source as a pulsar by Lyne et al. (2000) must be taken with the caveat that the system used induced ~ 200 μs of dispersion smearing, rendering it relatively insensitive to very fast pulsars. Another alternative is that the "N" source is in a binary so close (or with such a massive companion) that its line-of-sight acceleration often exceeds the bounds of our search, or that its velocity evolution is significantly nonlinear on the timescale of our observations.

To strongly constrain the shape of the lower end of the millisecond pulsar period distribution, observations are needed that are not only equally sensitive all pulsars slower than ~ 0.5 ms, but that are also sufficiently sensitive to detect a large number of pulsars. The work described here has shown that present technology is sufficient to achieve the former requirement through baseband processing technology; however, it falls short in basic sensitivity. We expect that future projects with cold, high-frequency receivers and larger (Nyquist-sampled) bands will achieve the necessary sensitivity and mitigation of scattering to finally resolve this issue.

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