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THE MILLISECOND PULSARS IN NGC 6760

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ABSTRACT

We present the results of recent Arecibo and Green Bank observations of the globular cluster NGC 6760. Using Arecibo, a phase-coherent timing solution has been obtained for the previously known binary pulsar in this cluster, PSR J1911+0102A. We have also discovered a new millisecond pulsar in NGC 6760, PSR J1911+0101B, an isolated object with a rotational period of 5.38 ms and a dispersion measure DM = 196.7 cm^{-3} pc. Both pulsars are located within 1.3 core radii of the cluster center and have negative period derivatives. The resulting lower limits for the accelerations of the pulsars are within the range expected given a simple model of the cluster. A search for eclipses in the PSR J1911+0102A binary system using both telescopes yielded negative results. The corresponding limits on the extra gas column density at superior conjunction are consistent with the hypothesis that the observational properties of ultra–low-mass binary pulsars like PSR J1911+0102A are strongly affected by the inclination of the orbital plane of the system. Among globular cluster pulsar populations, that of NGC 6760 exhibits one of the largest known spreads in DM. This quantity seems to be roughly proportional to a cluster's central DM; this suggests that the observed spread is caused by a turbulent interstellar medium at spatial scales of 1 pc.

Subject headings: binaries: general — globular clusters: general — globular clusters: individual (NGC 6760) — pulsars: general — pulsars: individual (PSR B1908+00, PSR J1911+0101B)

1. INTRODUCTION

NGC 6760 lies toward the inner Galaxy, $l = 36\overset{\circ}{.}11, b = -3\overset{\circ}{.}92$ (Djorgovski & Meylan 1993). It is one of the metal-rich Galactic globular clusters (GCs) studied by Heitsch & Richtler (1999). Apart from its metallicity, it is a quite ordinary, moderately bright cluster (total absolute visual magnitude −7.86) and not especially condensed; $c \equiv \log(\theta_t/\theta_c) = 1.59$, where $\theta_c = 0\overset{\prime}{.}33$ is the angular core radius (Harris 1996)[7] and θ_t is the angular tidal radius. The estimated distance, taking into account differential reddening, is $D = 9.5$ kpc (Heitsch & Richtler 1999). Without taking that effect into account, one obtains a distance of 7.4 kpc, as in Harris (1996).

PSR B1908+00, now known as PSR J1911+0102A (hereafter PSR A), was discovered in a previous 1400 MHz Arecibo search of NGC 6760 (Deich et al. 1993). The pulsar is a member of a binary system, and its orbital parameters are remarkable in several respects. The orbital period was, at that time, one of the shortest known for a binary pulsar (3.38 hr), while the companion mass was the lowest known, only 0.02 $M_\odot$, assuming a pulsar mass of 1.4 $M_\odot$ and an orbital inclination angle $i = 60°$. Although the orbital parameters of PSR A closely resemble those of the original eclipsing pulsar, B1957+20 (Fruchter et al. 1988), no eclipses were observed in this new binary system, despite its shorter orbital period.

PSR A is now one of the 11 very low mass binary pulsars (VLMBPs) known in GCs. These binaries have mass functions smaller than 3×10^{-5} $M_\odot$; see Freire (2005) for a recent review of their properties. Analyzing the properties of the large VLMBP sample in 47 Tuc, Freire et al. (2003) noted that the occurrence of eclipses among these systems is strongly correlated with the mass function of the system. This can be understood if the range of secondary masses (m_c) in these systems is small, so that the differences in observed mass function (f) are mainly due to differences in inclination. For those systems with inclinations viewed close to edge-on ($i \sim 90°$), we detect eclipses; those with smaller inclinations have mass functions that are lower by a factor of $\sin^3 i$, and no eclipses are detected. To test this hypothesis, it is important to check that the "non-eclipsing" VLMBPs like PSR A do indeed lack eclipses. In § 2 we describe multifrequency observations with the Green Bank and Arecibo radio telescopes. In § 3 we describe the search for new pulsars in the Arecibo data and present the new pulsar discovery, PSR J1911+0101B (hereafter PSR B). We also present the timing solutions of both pulsars and describe how they were obtained. The properties of these timing solutions are discussed in § 4; these can be used to search for eclipses of PSR A near superior conjunction, to check the validity of the mass model of NGC 6760, and to probe the interstellar medium (ISM) along the line of sight. Finally, in § 5 we conclude with a summary of the main results and prospects for future observations.

2. OBSERVATIONS AND THEIR MOTIVATION

Observations were made with both the 100 m Robert C. Byrd Green Bank Telescope (GBT) and the 305 m Arecibo radio telescope. The GBT can observe in the important 500 and 800 MHz

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[7] For an updated list of the GC parameters presented in this article, and for the related bibliographical references, see http://physwww.mcmaster.ca/~harris/mwgc.dat.

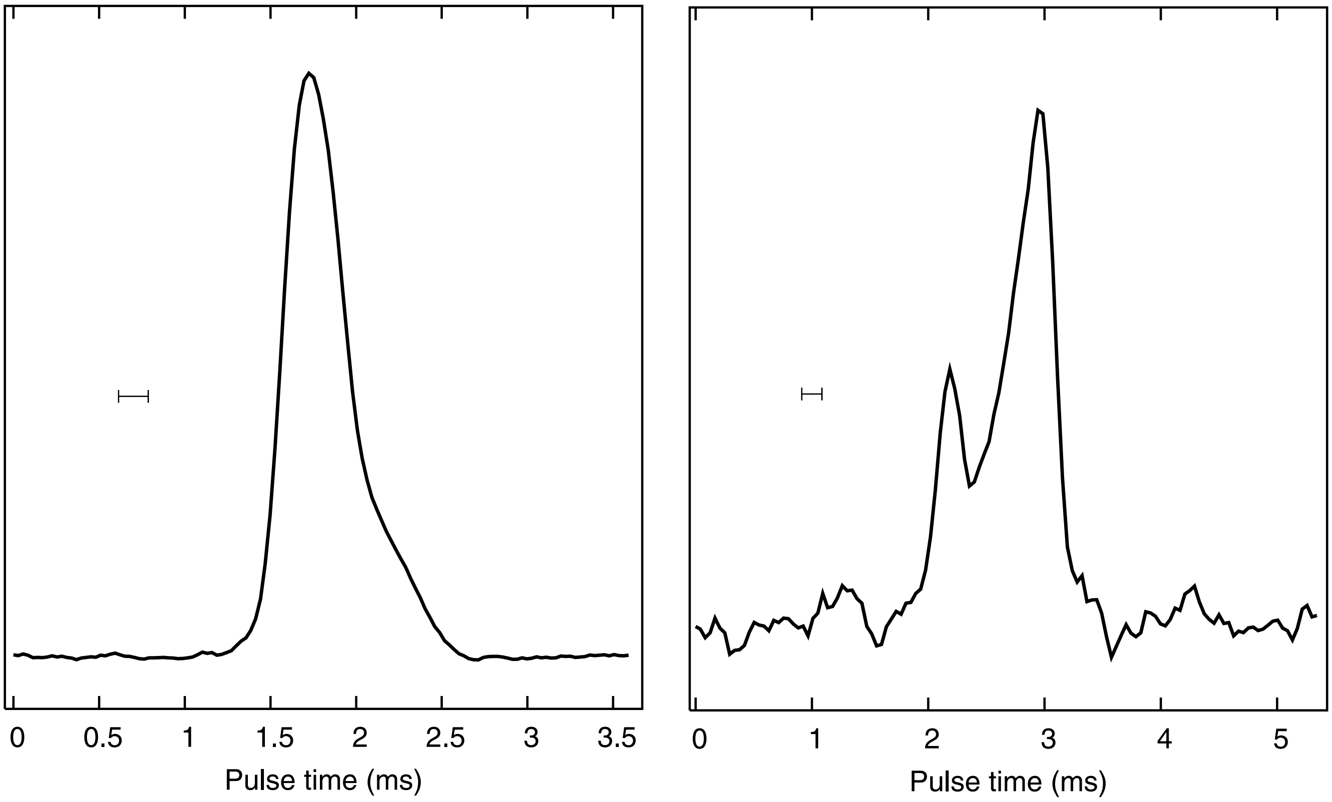

FIG. 1.—Full-cycle pulse profiles for the two known pulsars in NGC 6760. These were obtained by averaging all the Arecibo WAPP data from the bands centered at 1410 and 1510 MHz. The horizontal error bars indicate the instrumental time resolution at 1410 MHz. *Left*: PSR A. *Right*: PSR B.

bands and can track PSR A over a full orbit. Arecibo provides superior gain for observations near 1400 MHz.

2.1. *GBT Observations*

The properties of eclipses in VLMBPs are highly frequency-dependent. As a rule, eclipses become more dramatic as the frequency decreases. For example, the eclipse lengths, $\triangle T$, of PSRs B1744−24A, B1957+20, and J2140−2310A scale inversely with frequency, ν, as $\triangle T \propto \nu^{\beta}$, where $\beta = -0.63 \pm 0.18$, -0.41 ± 0.09, and -0.45 ± 0.05, respectively (Nice et al. 1990; Fruchter et al. 1990; Ransom et al. 2004). Since eclipses observed at low frequencies are extended along the orbital plane, it is reasonable to suppose that they are extended off the orbital plane as well, so that, for lines of sight far from the plane (i.e., at low inclinations), eclipses might be detectable only at low frequencies. Further evidence that eclipses are more detectable at lower frequencies comes from PSRs J2051−0827 and J0023−7203J. The former shows no change in flux density and only small dispersive delays at 1400 MHz, while it is partially or completely eclipsed near 600 MHz (Stappers et al. 1996; Nice et al. 2005). The latter shows only small dispersive delays at 1400 MHz and occasional eclipses at 660 MHz, while eclipses occur regularly at 430 MHz (Freire et al. 2003). Given these properties, we made low-frequency observations of PSR A with the GBT at several frequencies between 575 and 1660 MHz (see also Nice et al. [2005], which includes results for other VLMBPs). Data were collected by the Spectral Processor, a Fourier transform spectrometer that allows a total bandwidth of 40 MHz. Spectra were folded online modulo the pulse period over intervals of 5 minutes. For these observations, we used two different modes: 512 channels across 40 MHz folded into 94 bin profiles (2002 July and some scans taken in 2002 October) and 1024 channels across 40 MHz folded into 70 bin profiles for the remaining data (taken in 2002 October). Off-line, the folded spectra were dedispersed, and pulse times of arrival (TOAs) were extracted using conventional techniques (see, e.g., Taylor 1992).

2.2. *Arecibo Observations*

Dispersion measure (DM) variations can be very effectively probed at higher frequencies using a telescope with a large gain and observing bandwidth. For this reason, and also to search for new pulsars and determine phase-connected timing solutions, we have been observing NGC 6760 with the Arecibo telescope since 2003 March. A total of 18 observations lasting as long as 4500 s were made using the new L-band wide receiver. This system provides unparalleled sensitivity from 1100 to 1730 MHz, where its equivalent flux density is only 2.5 Jy. For data acquisition, we used three of the four[8] Wideband Arecibo Pulsar Processors (WAPPs; Dowd et al. 2000), with each WAPP providing 512 channels covering 100 MHz spectral windows centered at 1170, 1410, and 1510 MHz, respectively. Some of the early observations used only one or two WAPPs. At the DM of PSR A, the dispersion smearing in each frequency channel ranges between 94 μs at 1510 MHz and 202 μs at 1170 MHz. The sampling time was 128 μs, so that the corresponding time resolution ranged between 160 and 240 μs. To extend the timing baselines, we also used data from a previous Arecibo survey, taken 2001

[8] The fourth WAPP was not used for these experiments because of the high levels of radio frequency interference in the remaining part of the band.

June 23–30, which targeted NGC 6760 using a different receiver and a single WAPP centered at 1525 MHz (Ransom et al. 2005; Hessels et al. 2003).

3. RESULTS

3.1. *Pulsar Search*

Assuming that the rms of the off-pulse samples is the noise level predicted by the radiometer equation for the sky temperature for the location of NGC 6760 at 1400 MHz (~4.6 K), we estimate that the flux density of PSR A at 1410 MHz is about 0.2 mJy. This value is substantially different from the estimate of Deich et al. (1993) of 1.5 mJy, but we believe it to be essentially correct. We estimate that the associated uncertainty of this value is about 30%. This pulsar is detected with an average signal-to-noise ratio (S/N) of about 200 in our 4500 s Arecibo observations. Motivated by the high sensitivity of the Arecibo observing system, we carried out a search for additional pulsars in NGC 6760 using the Borg, a 104 processor Beowulf cluster at McGill University, running the PRESTO software package (Ransom 2001) in a similar fashion to that described by Ransom et al. (2004). In brief, the accumulated correlation functions recorded by each WAPP were transformed into the equivalent spectral frequency channels and then dedispersed. We searched 41 trial DM values in the range 190–210 cm^{-3} pc in steps of 0.5 cm^{-3} pc. For each trial DM value, a full Fourier domain matched filter acceleration search was carried out (Ransom et al. 2002), enabling the detection of binary systems with relatively short orbital periods. The maximum detectable orbital acceleration as a function of spin period is

$$a_{\max} = \frac{Z_{\max} cP}{T_{\rm obs}^2}, \tag{1}$$

where $Z_{\max}$ is the maximum number of spectral bins that the fundamental harmonic can drift during the whole observation time $T_{\rm obs}$. In our searches, $Z_{\max} = 500$ and $T_{\rm obs} \sim 4500$ s. For a 1 ms pulsar, this represents an acceleration limit of 7.4 m s^{-2}. In order to detect highly accelerated binary pulsars, we have also searched short, overlapping sections of the observations. This search procedure was applied to a total of 10 observations.

No new accelerated pulsars were found. However, one new isolated 5.38 ms pulsar (PSR B) was found at a DM of 196.7 cm^{-3} pc as a result of this processing. It is detectable with an S/N of about 10 in an hour. This pulsar is about 8 times fainter than PSR A; i.e., its flux density at 1410 MHz is ~0.026 mJy, and its luminosity is about 2 mJy kpc^2. The pulse profiles for PSR A and PSR B can be seen in Figure 1. As expected, interstellar scattering is not detectable; the Cordes & Lazio NE2001 model (Cordes & Lazio 2002) predicts a scattering timescale of only 0.04 ms at 1400 MHz.

TABLE 1
Parameters for the NGC 6760 Pulsars

Pulsar	PSR J1911−0102A	PSR J1911−0101B
Observation and Data Reduction Parameters		
Period epoch (MJD)	53000	53000
Start time (MJD)	52083	52083
End time (MJD)	53243	53243
Number of TOAs	624	48
TOA rms (μs)	8.4	22
Timing Parameters		
α[a]	$19^{\rm h}11^{\rm m}11\overset{\rm s}{.}08957(4)$	$19^{\rm h}11^{\rm m}12\overset{\rm s}{.}5725(4)$
δ	$+01^\circ02'09\overset{''}{.}741(2)$	$+01^\circ01'50\overset{''}{.}44(2)$
P (ms)	3.618524251059(2)	5.384325706188(9)
$\dot{P}_{\rm obs}$ (10^{-21})	−6.58(2)	−2.0(3)
DM (cm^{-3} pc)	202.678(3)	196.69(2)
P_b[b] (days)	0.1409967943(6)	...
$T_{\rm asc}$ (MJD)	53000.0517850(8)	...
x (s)	0.037658(2)	...
e	<0.00013	...
Derived Parameters		
$\theta_\perp$ (arcmin)	0.42	0.12
a_{zC} (m s^{-2})	$<-2.6 \times 10^{-10}$	$<+1.6 \times 10^{-10}$
$\dot{P}_{\rm int}$	$<1.06 \times 10^{-20}$	$<3.35 \times 10^{-20}$
τ_c (Gyr)	>5.4	>2.5
B_0 (G)	$<2.0 \times 10^8$	$<4.3 \times 10^8$
f ($M_\odot$)	0.0000028842(4)	...
m_c[c] ($M_\odot$)	~0.02	...

[a] The uncertainties indicated for all parameters are 1 σ and are twice the formal values given by TEMPO.

[b] The orbital parameters are as follows: orbital period (P_b), time of passage through the ascending node ($T_{\rm asc}$), and semimajor axis of the orbit of the pulsar, projected along the line of sight, divided by the speed of light (x) and orbital eccentricity (e). Since the latter quantity is too small to be measured, we cannot estimate the longitude of the periastron relative to the ascending node (ω). All other parameters are as described in the text.

[c] To calculate the companion mass m_c, we assumed an inclination angle $i = 60^\circ$ and a canonical pulsar mass of 1.4 $M_\odot$.

3.2. *Pulsar Timing*

We have used our set of observations to obtain phase-coherent timing solutions for both of the pulsars now known in NGC 6760. After the pulse periods and DMs were established by the search analysis, we used the SIGPROC package[9] (Lorimer 2001) to dedisperse the data and PRESTO to fold the resulting time series and extract pulse TOAs. These TOAs were then analyzed with TEMPO.[10] We used the JPL's DE/LE 200 solar system ephemeris to subtract the effect of the motion of the telescope relative to the barycenter of the solar system. As is now standard practice for low-eccentricity binary systems like PSR A, the ELL1 binary model (Lange et al. 2001) was used in TEMPO in the fitting process. The resulting parameters are presented in Table 1. The TOA residuals are displayed in Figure 2; they show no obvious trends. This effort was greatly aided by the conspicuous lack of scintillation effects, as expected for pulsars with large DMs. Phase connection between 2001 and 2003 was confirmed using the GBT data collected in 2002. In particular, a well-known 1 s instrumental offset in the 2001 data, detected by other WAPP timing projects (Ransom et al. 2005), was confirmed and removed. Once phase connection was achieved, the GBT data were removed from subsequent analysis; because of their relatively low S/Ns and high measurement uncertainties, they added little to the timing solution. The number of rotations of PSR A and PSR B between the 2001 and 2003 observations is unambiguous.

4. DISCUSSION

4.1. *Search for Eclipses*

We found no evidence of eclipses of PSR A, as those would have been detected by either the absence of or the systematic

[9] See http://www.jb.man.ac.uk/~drl/sigproc.

[10] See http://pulsar.princeton.edu/tempo.

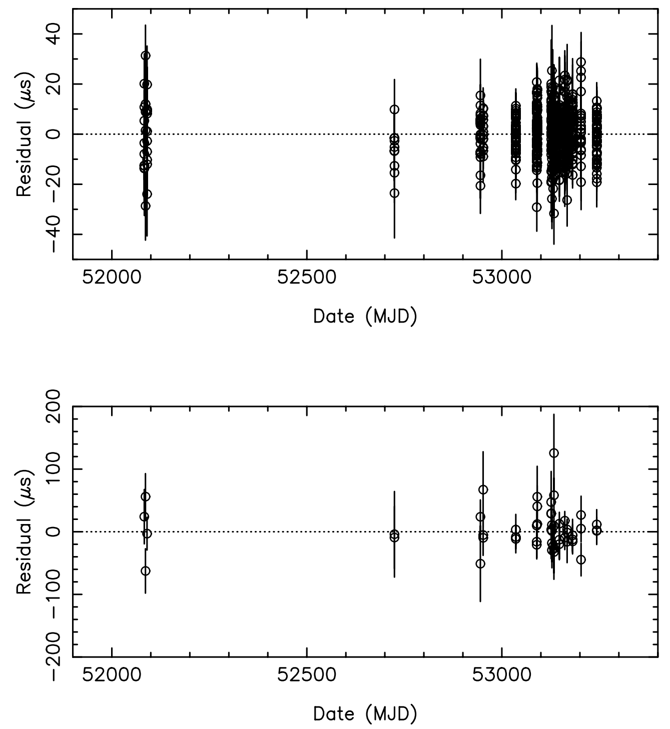

FIG. 2.—Post-fit Arecibo residuals for PSR A (*top*) and PSR B (*bottom*). Note the difference in vertical scale. The early Arecibo search data are at the left, near MJD = 52,000.

reduction in flux density around superior conjunction or, in the case of partial eclipses, systematic delays of the pulsed signal as it passed through the ionized eclipsing medium. Neither of these observational signatures were detected. The data are shown in Figure 3. Residual pulse arrival times are shown after subtracting the best available orbital model, presented in Table 1. The ascending node is at orbital phase $\phi = 0$, and superior conjunction and any eclipses should occur at $\phi = 0.25$.

Limits on the electron column density of ionized eclipsing material can be derived from limits on the TOA delays, $\triangle t$ at $\phi = 0.25$. We find $\triangle t \leq 200$ μs at 820 MHz (GBT) and $\triangle t \leq 5$ μs at 1120–1560 MHz (Arecibo), yielding upper limits of $\triangle\mathrm{DM} < 0.03$ cm^{-3} pc $= 10^{17}$ cm^{-2} and $\triangle\mathrm{DM} < 0.0017$ cm^{-3} pc $\sim 5\times10^{15}$ cm^{-2}, respectively. The latter limit is well under the observed dispersion delays in PSR J2051−0827 (Stappers et al. 1996, 2001) and PSR J0023−7203J (Freire et al. 2003), for which $\triangle\mathrm{DM} \sim 3\times10^{17}$ and $\sim 2\times10^{16}$ cm^{-2}, respectively.

Observations below 800 MHz could put more stringent limits on dispersive delays. However, we found the pulsar very difficult to detect at lower frequencies. It was only marginally detectable in 5 minute GBT observations at 575 MHz, as can be inferred by the large scatter in the timing residuals on MJD 52574 in Figure 3. (Because those residuals tend to cluster around zero, we are confident that the pulsar was, in fact, being detected.) The lack of eclipses provides for circumstantial evidence that the system's small mass function (lower than all of the eclipsing VLMBPs) is indeed due to a low inclination angle.

4.2. *Positions and Accelerations*

The best-fit right ascension (α) and declination (δ) of PSR A and PSR B indicate that these pulsars are very close to the center of the cluster. The projected angular distances from the center are indicated in Table 1 as $\theta_\perp$; these are equivalent to 1.25 and 0.35 core radii. In this respect, these pulsars are similar to the majority of the pulsars known in GCs.

The observed period derivatives ($\dot{P}_{\rm obs}$) of both pulsars are negative. As discussed in detail by Damour & Taylor (1991), the measured period derivative for a pulsar is a sum of several terms,

$$\left(\frac{\dot{P}}{P}\right)_{\rm obs} = \left(\frac{\dot{P}}{P}\right)_{\rm int} + \frac{\mu^2 D}{c} + \frac{a_z}{c}. \quad (2)$$

The first term on the right is the pulsar's intrinsic period derivative ($\dot{P}_{\rm int}$) divided by its rotational period (P); the second term is a fictitious centrifugal acceleration (known as the Shklovskii effect), where μ is the proper motion of the pulsar (expected to be close to the mean proper motion of the cluster); and the third term is the pulsar's line-of-sight acceleration. The first two terms on the right are essentially unknown (no proper motion has yet been measured for NGC 6760) but are always positive. Therefore, we know that the pulsar's line-of-sight acceleration relative to the solar system barycenter, a_z/c, must be smaller than $(\dot{P}/P)_{\rm obs}$.

The line-of-sight acceleration term has a contribution from the acceleration of NGC 6760 itself in the gravitational field of the Galaxy relative to the solar system barycenter. This can be estimated using a mass model for the Galaxy: $a_{zG} = -2.78 \times 10^{-10}$ m s^{-2} for $D = 9.5$ kpc (Paczyński 1990). Subtracting this term from $(\dot{P}/P)_{\rm obs}$, we obtain upper limits for the line-of-sight component of the gravitational field of NGC 6760 at the locations of the pulsars; this is indicated in Table 1 as a_{zC}. The fact that this quantity is negative for PSR A implies that it is on the far side of NGC 6760.

To check whether these values are reasonable, we implemented a simple cluster mass model (see the Appendix for details) to calculate the acceleration along the line of sight as a function of the pulsar's projected distance from the center of the cluster ($r_\perp \equiv D\theta_\perp$), the cluster's core radius ($r_c = \theta_c D$), and the rms of spectroscopic stellar velocities at $\theta_\perp = 0$, $\sigma_z(0)$. For NGC 6760, $\sigma_z(0) = 5.77$ km s^{-1} (Webbink 1985). The minimum acceleration of PSR A can be comfortably accounted for by this model, which predicts maximum line-of-sight accelerations of 1.14 and 1.75×10^{-9} m s^{-2} at the locations of PSR A and PSR B, respectively. If we assume that the pulsars cannot have an acceleration larger than this value, then from equation (2) we can derive upper limits for the intrinsic period derivatives. From these, we can derive lower limits for the characteristic ages (τ_c) and upper limits for the magnetic flux densities at the magnetic poles (B_0); all these limits are presented in Table 1. Both pulsars are quite old, and the magnetic flux densities at their poles must be relatively small. Such strong constraints can only be placed because of the small accelerations predicted by the NGC 6760 mass model. For most of the allowed range of $\dot{P}_{\rm int}$ for PSR B, the pulsar has a negative acceleration, indicating that it is more likely on the far side of the cluster.

4.3. *DM Spread*

The spread of DMs in NGC 6760 (196.68–202.68 cm^{-3} pc) is remarkably large, about the same as that in Terzan 5 (Lyne et al. 2000; Ransom 2001). The origin of the DM spread is an interesting question. For the pulsars in 47 Tuc, Freire et al. (2001) showed that the DM variation in that GC is mostly due to the cluster gas itself. For M15, with a higher central DM, the DM variation between pulsars has been attributed to subarcminute-scale irregularities in the Galactic electron column density as a

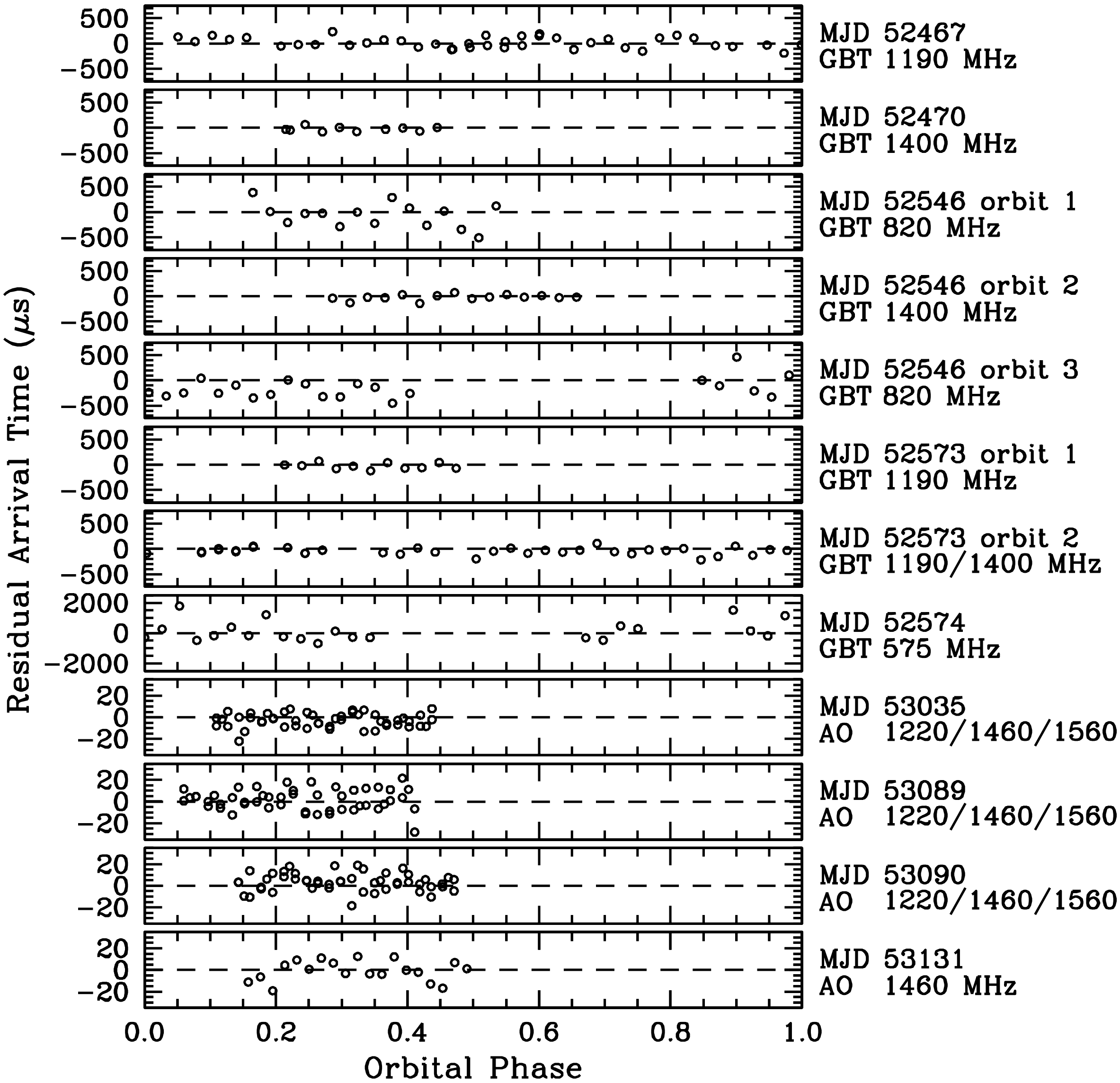

Fig. 3.—Residual pulse arrival times of PSR A, measured at the GBT and Arecibo over 12 orbits on nine separate days. Observing frequencies and telescope used are indicated in the figure. A partial eclipse would be indicated by arrival time delays, or complete lack of signal, at orbital phase 0.25. All observations on the indicated days are shown in the figure; there are no instances of missing signals. Gaps in some orbits indicate times at which data were not collected, rather than an intrinsic fading of the pulsed signal. At Arecibo the partial coverage is caused by the limited field of view of the telescope. There are other observations made at Arecibo that are not displayed because they do not cover the relevant orbital phase.

function of sky position (Anderson 1993). For both Terzan 5 and NGC 6760, the spreads of pulsar DMs are much larger still, despite the large differences in the nature of the clusters. This indicates that the spread of DMs in Terzan 5 is probably not due to the presence of gas in the cluster but instead to a cause common to both clusters. For high electron column densities, one would generally expect that variations of the DM with sky position at these subarcminute scales will play a larger role. The observed correlation between DM and ΔDM is approximately linear (see Fig. 4), indicating that it will be very difficult to detect the plasma content of GCs at high DMs. This result is also important for GC pulsar searches, since it provides a guideline for the range of trial DMs required to be sensitive to pulsars in a given cluster.

If the plasma irregularities in space were completely random, we would expect a random walk–like dependence of ΔDM versus DM; i.e., the spread in the DM would be proportional to the square root of the DM. However, this is not consistent with the observations, which indicate instead a linear relation of DM variance and DM. According to Backer et al. (1993 and references therein), this implies that the ISM is turbulent in nature at the spatial scales being probed by pulsar separations in GCs, about 1 pc.

5. CONCLUSIONS AND PROSPECTS

In a comprehensive study of PSR J1911+0102A, we have failed to detect any eclipses, but we have determined this pulsar's timing solution. This, together with the low mass function of the system, adds weight to the hypothesis that the observational properties of VLMBPs are mainly determined by the inclination of the system. Timing studies at Arecibo show the pulsar to be located near the center but on the far side of NGC 6760 and to have a large characteristic age and small magnetic field. These data further constrain the occurrence of partial eclipses. A second isolated 5.38 ms pulsar, PSR J1911+0101B, was discovered in these data. It too is located near the center of the

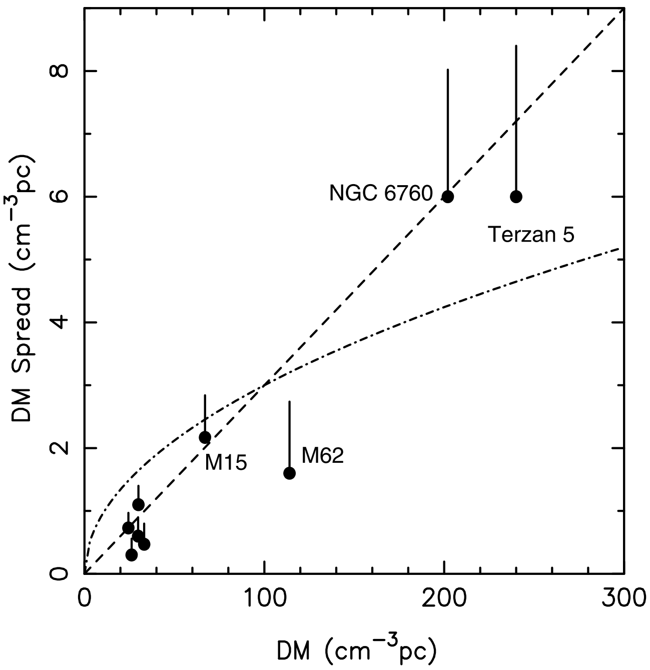

FIG. 4.—Observed DM spread for the pulsars in GCs as a function of DM. These observed values are always lower limits; new pulsar discoveries in each GC can only increase the spread in the future. This is symbolically indicated by the vertical line segments (their length is arbitrary but proportional to the DM of the cluster). For meaningful DM spread estimates, only GCs with three or more known pulsars were included, with the exception of NGC 6760; for this object, the measured DM spread is already quite significant, despite the fact that only two pulsars are known. The dashed line indicates than no known cluster has shown a DM spread significantly larger than 3% of its DM. The dot-dashed line indicates the best fit for a DM spread proportional to DM$^{0.5}$; this is clearly a much poorer fit.

cluster and probably on its far side. The large difference in DM between the pulsars suggests that the ISM is turbulent on spatial scales similar to their separation, about 1 pc.

By providing precise positions for the pulsars, the timing solutions make it possible to identify these pulsars at optical/near-infrared and X-ray wavelengths. Continued timing will make it possible to measure the proper motion of NGC 6760, to search for expected orbital variability of PSR A (as observed for other VLMBPs; see references in Freire 2005), to monitor possible DM variability, and to check for the presence of distant stellar or planetary companions to either PSR A or PSR B.

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APPENDIX

CLUSTER MODEL

We implemented a very simple analytical model of NGC 6760 based on the empirical density law for dense star clusters derived by King (1962). For a star cluster with an angular tidal radius that is significantly larger than the core radius, the surface mass density near the center is given by

$$f(r_\perp) = \frac{f_0}{1 + (r_\perp/r_c)^2}, \tag{A1}$$

where f_0 is the central surface mass density. The corresponding spatial density is

$$\rho(r) = \frac{\rho_0}{[1 + (r/r_c)^2]^{3/2}}, \tag{A2}$$

where r is the linear distance to the center of the cluster, defined as $r^2 = z^2 + r_\perp^2$, where z is the distance of any point to the plane of the sky passing through the center of the cluster, and $\rho_0 = f_0/2r_c$ is the central density. Equations (A1) and (A2) correspond to the limits of equations (14) and (27) of King (1962) for infinite tidal radii and do not apply to core-collapsed clusters. We can integrate equation (A2) radially to obtain the mass inside a given radius r,

$$M(r) = \int_0^r \rho(r')4\pi r'^2\,dr' = 4\pi\rho_0 r_c^3\left[\sinh^{-1}\left(\frac{r}{r_c}\right) - \frac{r}{r_c\sqrt{1 + (r/r_c)^2}}\right], \tag{A3}$$

where $\sinh^{-1}x$ can also be expressed as $\ln[x + (1 + x^2)^{1/2}]$. Therefore, equation (A3) diverges logarithmically for infinite radii, but it is a good approximation near the center of the cluster.

The acceleration at r, $a(r)$, can be obtained by multiplying $M(r)$ by $-G/r^2$. From Spitzer (1987) we find that $\rho_0 = 9\sigma_z^2(0)/(4\pi G r_c^2)$. This allows us to present $a(r)$ as a function of well-known observables,

$$a(r) = \frac{9\sigma_z^2(0)}{D\theta_c}\frac{1}{x^2}\left(\frac{x}{\sqrt{1+x^2}} - \sinh^{-1}x\right), \tag{A4}$$

where $x \equiv r/r_c$. The line-of-sight component $a_z(r)$ can be obtained by multiplying $a(r)$ by z/r. For each of the pulsar line-of-sight distances to the center of the cluster, $r_\perp$, we calculate $a_z(r)$ for a variety of values of z, recording the maximum values found.

Integrating equation (A4) from the center of the cluster until a given location r, one obtains the gravitational potential relative to the center of the cluster,

$$\begin{aligned} V - V_0 &= -\int_0^r a(r')\,dr' \\ &= -9\sigma_z^2(0)\int_0^x \frac{1}{x'^2}\left[\frac{x'}{\sqrt{1+x'^2}} - \ln\left(x' + \sqrt{1+x'^2}\right)\right]dx' \\ &= 9\sigma_z^2(0)\left[1 - \frac{\ln\left(x + \sqrt{1+x^2}\right)}{x}\right], \end{aligned} \tag{A5}$$

where $x' \equiv r'/r_c$.

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