

## EIGHT NEW MILLISECOND PULSARS IN NGC 6440 AND NGC 6441

PAULO C. C. FREIRE,<sup>1</sup> SCOTT M. RANSOM,<sup>2</sup> STEVE BÉGIN,<sup>3,4</sup> INGRID H. STAIRS,<sup>3</sup>  
 JASON W. T. HESSELS,<sup>5</sup> LUCILLE H. FREY,<sup>6</sup> AND FERNANDO CAMILO<sup>7</sup>

*Received 2007 August 27; accepted 2007 November 9*

### ABSTRACT

Motivated by the recent discovery of 30 new millisecond pulsars in Terzan 5, made using the Green Bank Telescope’s S-band receiver and the Pulsar Spigot spectrometer, we have set out to use the same observing system in a systematic search for pulsars in other globular clusters. Here we report on the discovery of five new pulsars in NGC 6440 and three in NGC 6441; each cluster previously had one known pulsar. Using the most recent distance estimates to these clusters, we conclude that there are as many potentially observable pulsars in NGC 6440 and NGC 6441 as in Terzan 5. We present timing solutions for all of the pulsars in these globular clusters. Four of the new discoveries are in binary systems; one of them, PSR J1748–2021B (NGC 6440B), has a wide ( $P_b = 20.5$  days) and eccentric ( $e = 0.57$ ) orbit. This allowed a measurement of its rate of advance of periastron,  $\dot{\omega} = 0.00391(18)^\circ \text{ yr}^{-1}$ . If this is a purely relativistic effect, the total mass of this binary system is  $2.92 \pm 0.20 M_\odot$  ( $1 \sigma$ ) implying a median pulsar mass of  $2.74 \pm 0.21 M_\odot$ . There is a 1% probability that the inclination is low enough that pulsar mass is below  $2 M_\odot$ , and 0.10% probability that it is between 1.20 and  $1.44 M_\odot$ . If confirmed, this anomalously large mass would strongly constrain the equation of state for dense matter. The other highly eccentric binary, PSR J1750–37A, has  $e = 0.71$ , and  $\dot{\omega} = 0.0055(3)^\circ \text{ yr}^{-1}$ , implying a total system mass of  $1.97 \pm 0.15 M_\odot$  and, along with the mass function, maximum and median pulsar masses of 1.65 and  $1.26 M_\odot$ , respectively.

*Subject headings:* binaries: general — equation of state — globular clusters: individual (NGC 6440, NGC 6441) — pulsars: general — stars: neutron

### 1. INTRODUCTION

A recent survey of the globular cluster (GC) Terzan 5 with the S-band (1.7 to 2.6 GHz) receiver of the Green Bank Telescope (GBT) and the Pulsar Spigot spectrometer (Kaplan et al. 2005) has met with extraordinary success, finding 30 new millisecond pulsars (MSPs). The first 21 discoveries were announced in Ransom et al. (2005). More recently, nine more pulsars were discovered,<sup>8</sup> including PSR J1748–2446ad, the fastest spinning pulsar known (Hessels et al. 2006). These discoveries show that this observing system (henceforth GBT/S/PS) has an unprecedented sensitivity to MSPs outside the Arecibo sky, due in great part to the factor of 3 higher gain of the GBT as compared to the Parkes telescope. Perhaps even more importantly, the higher observing frequency ( $\sim 2$  GHz), large observing bandwidth (600 MHz), and relatively fine frequency resolution ( $\sim 0.78$  MHz) retain high sensitivity and time resolution for MSPs with large dispersion measures (DMs). The discovery of the 1.39 ms PSR J1748–2446ad at a DM of  $235.6 \text{ cm}^{-3} \text{ pc}$  dramatically demonstrates the sensitivity of the GBT/S/PS system to fast-spinning pulsars at high DMs. This success motivated us to

search for MSPs in other promising GCs with the GBT/S/PS system.

#### 1.1. Cluster Selection

In the high stellar density environments in the cores of GCs, binary systems with at least one main-sequence (MS) star are occasionally disrupted by the intrusion of a neutron star (NS). The most likely outcome is an “exchange encounter,” in which the lightest component of the previous binary is ejected and a NS-MS binary remains. The resulting NS-MS systems can become much more numerous than those formed from evolution of primordial binaries. With the evolution of the MS star, it can happen that matter will accrete onto the NS during a low-mass X-ray binary (LMXB) phase, particularly among the more compact systems. When the LMXB accretion stops, we are left with an MSP orbiting a white dwarf (WD) star.

Pooley et al. (2003) showed a strong correlation between the number of X-ray point sources in a GC (which are generally compact binaries) and the rate of stellar encounters within the half-mass radius, a parameter that they designate  $\Gamma$ . This correlation is stronger than for any other individual GC parameter and applies to active LMXBs as well (although with only a dozen systems in the Galactic GC system, the statistics are poorer).  $\Gamma$  might therefore be a good indicator of the present rate of MSP formation. Pooley et al. (2003) provide a simple way of calculating the stellar interaction rate at the core of any GC:

$$\Gamma_c \propto \rho_0^{1.5} r_c^2, \quad (1)$$

where  $\rho_0$  is the central mass density and  $r_c$  is the core radius. This parameter is perhaps more relevant than  $\Gamma$  for the formation of LMXBs because mass segregation constrains neutron stars to within a few core radii of the center of the GC.

<sup>1</sup> National Astronomy and Ionosphere Center, Arecibo Observatory, PR 00612; pfreire@naic.edu.

<sup>2</sup> National Radio Astronomy Observatory, Charlottesville, VA 22903.

<sup>3</sup> Department of Physics and Astronomy, University of British Columbia, Vancouver, BC V6T 1Z1, Canada.

<sup>4</sup> Département de physique, de génie physique et d’optique, Université Laval, Québec, QC G1K 7P4, Canada.

<sup>5</sup> Astronomical Institute “Anton Pannekoek,” University of Amsterdam, Kruislaan 403, 1098 SJ Amsterdam, Netherlands.

<sup>6</sup> Department of Astronomy, Case Western Reserve University, Cleveland, OH 44106.

<sup>7</sup> Columbia Astrophysics Laboratory, Columbia University, New York, NY 10027.

<sup>8</sup> See <http://www2.naic.edu/~pfreire/GCpsr.html>.

TABLE 1  
THE SIX GLOBULAR CLUSTERS WITH HIGHEST  $\Gamma_c$

Globular Cluster	$D^a$ (kpc)	$\rho_0^b$ [log ( $L_\odot$ pc $^{-3}$ )]	$\Gamma_c$ (%)	DM <sup>c</sup> (cm $^{-3}$ pc)	$\tau_{\text{scatt}, 2 \text{ GHz}}^d$ ( $\mu$ s)	$N_{\text{psr}}^e$	$\Delta T^f$ (hr)	DM Ref.
NGC 6388.....	10.0	5.34	9.5	318	1.4	0	2.2	
Terzan 5 .....	10.3	5.06	8.6	(234.3–245.6)	6	3 + <b>30</b>	8.0	(1)
NGC 6441 .....	11.7	5.25	8.0	(230.1–234.4)	2	1 + <b>3</b>	5.3	(2)
NGC 6440 .....	8.4	5.28	6.4	(219.4–227.0)	5	1 + <b>5</b>	8.4	(3)
NGC 6266 .....	6.9	5.14	5.1	(113.4–115.0)	4	6	7.0	(4)
Liller 1 .....	9.6	5.53	4.2	771	$\sim 3 \times 10^2$	0	6.2	

<sup>a</sup> Distance from the solar system from Harris (1996). These values have significant systematic uncertainties.

<sup>b</sup> Central density of GC; see last column of third table at <http://physwww.mcmaster.ca/~harris/mwgc.dat>.

<sup>c</sup> For GCs with known pulsars, we present the DM range for the known pulsars, with references in the last column, otherwise we predict the DM for the GC's estimated distance using the Cordes & Lazio (2002) model. These can be off by a factor of up to about 2.

<sup>d</sup> Extrapolated from other frequencies using  $\tau_{\text{scatt}, 2 \text{ GHz}} = \tau_{\text{scatt}}(F)/(F/2 \text{ GHz})^{4.4}$ . In the case of Terzan 5, the scattering was measured by Nice & Thorsett (1992) as 700  $\mu$ s at 685 MHz. Otherwise, we scale the scattering time at 1 GHz predicted by the Cordes & Lazio (2002) model for the DM in the previous column. These can be off by up to an order of magnitude.

<sup>e</sup> Number of previously known pulsars + **number of new pulsars**.

<sup>f</sup> Amount of time the GC is visible at the GBT per day.

REFERENCES.—(1) Ransom et al. 2005; (2) Possenti et al. 2006, this work; (3) Lyne et al. 1996, this work; (4) Possenti et al. 2003, Chandler 2003.

We calculated  $\Gamma_c$  for all Galactic GCs with the central luminosity densities and core radii given in Harris (1996),<sup>9</sup> assuming a constant conversion factor between central luminosity density and central mass density. The six best GCs are listed in Table 1, with their  $\Gamma_c$  presented as a percentage of the total  $\Gamma_c$  summed over all Galactic GCs. This table represents our initial survey expectations; we hypothesized that the percentages should be closely related to the fraction of the total GC MSP population contained in each GC.

For the first phase of the survey, we selected the GCs in Table 1 that had not been previously searched with the GBT/S/PS system: NGC 6388, NGC 6440, and NGC 6441. Liller 1 was searched at the same time as Terzan 5 by Ransom et al. (2005) and NGC 6626 has been searched by Jacoby et al. (2002). Despite the large predicted stellar interaction rates, only two pulsars were known in these GCs: PSR B1745–20A (NGC 6440A; Lyne et al. 1996) and PSR J1750–37A (NGC 6441A; Possenti et al. 2006). The spin periods and DMs of NGC 6440A and NGC 6441A are 288.6 and 111.6 ms and 220 and 234 cm $^{-3}$  pc, respectively. We assumed

that the lack of other known pulsars in these high-DM GCs was largely due to a bias of the earlier surveys against the detection of faster spinning MSPs. The high central frequency and improved time resolution of the GBT/S/PS system greatly diminish pulse broadening due to multipath propagation and dispersive smearing and would therefore alleviate the bias against the detection of other MSPs in these GCs.

## 1.2. Data Taking

From 2005 April 18 to August 21, we observed NGC 6388, NGC 6440, and NGC 6441 on three different occasions each, using the GBT's S-band receiver with the Pulsar Spigot. The longest integration times used for each GC are very close to their maximum track times indicated in Table 2.

These observations take advantage of the relatively radio-frequency-interference (RFI)–clean band between 1650 and 2250 MHz. The Pulsar Spigot is built around the GBT correlation spectrometer and is available in a number of modes (Kaplan et al. 2005). For most observations, we used the Spigot in mode 2, in which two orthogonal polarizations with a total bandwidth of 800 MHz are digitized with three levels, autocorrelated with 1024 lags, and integrated for 81.92  $\mu$ s. The resulting autocorrelation

TABLE 2  
PARAMETERS FOR THREE GLOBULAR CLUSTERS

Parameter	NGC 6388	NGC 6440	NGC 6441
Right ascension of center, $\alpha$ .....	17 36 17.0	17 48 52.7	17 50 12.9
Declination of center, $\delta$ .....	–44 44 06	–20 21 37	–37 03 05
Galactic longitude, $l$ (deg).....	345.56	7.73	353.53
Galactic latitude, $b$ (deg).....	–6.74	3.80	–5.01
Cluster distance, $D$ (kpc).....	10.0	8.2 <sup>a</sup>	13.5 <sup>a</sup>
Angular core radius, $\theta_c$ (arcmin).....	0.12	0.13	0.11
Half-mass radius, $\theta_h$ (arcmin).....	0.67	0.58	0.64
Metallicity (log [Fe/H]).....	–0.60	–0.34	–0.53
$v_z(0)$ (km s $^{-1}$ ).....	19.13 <sup>b</sup>	13.01 <sup>b</sup>	19.5 <sup>+9.4</sup> <sub>–5.1</sub> <sup>c</sup>
$a_G^d$ (10 $^{-9}$ m s $^{-2}$ ).....	–0.46	–0.029	–0.46

NOTES.—Parameters as in Harris (1996), except where indicated. Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

<sup>a</sup> Valenti et al. (2007).

<sup>b</sup> Webbink (1985).

<sup>c</sup> Dubath et al. (1997).

<sup>d</sup> Calculated using the data above and the Kuijken & Gilmore (1989) model of the Galaxy.

<sup>9</sup> See <http://www.physics.mcmaster.ca/~harris/mwgc.dat> for an updated list of GC parameters.

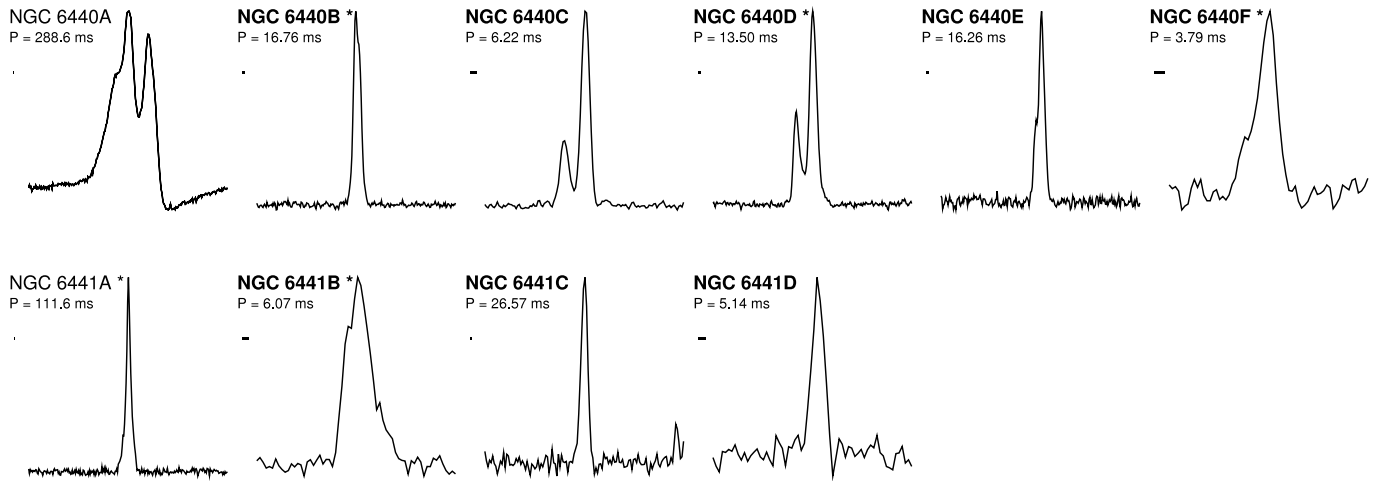


FIG. 1.—Average 1950 MHz pulse profiles for the 10 pulsars known in the GCs NGC 6440 and NGC 6441, obtained by adding all observations made with mode 2 of the Pulsar Spigot. These profiles cover one full rotation. The pulsars in binary systems have an asterisk after their names, and the newly discovered pulsars have their names in boldface. The horizontal width of the rectangles indicates the system's total time resolution in mode 2, including the effects of dispersive smearing, relative to each pulsar's spin period. The dip in power after the main pulse of NGC 6440A is likely a Spigot artifact.

functions are summed and then written to disk as 16-bit integers. After Fourier transforming the lags, we have 768 usable channels across the 600 MHz bandpass (0.78125 MHz channels). At a frequency of 2 GHz and a DM of  $220 \text{ cm}^{-3} \text{ pc}$ , the dispersive smearing across one channel is  $178 \mu\text{s}$ . Recently we have been using mode 14, this mode writes the  $81.92 \mu\text{s}$  integrations to disk as 8-bit integers, but does so with twice the frequency resolution, resulting in a dispersive smearing across one channel for a DM of  $220 \text{ cm}^{-3} \text{ pc}$  of  $89 \mu\text{s}$ .

In the cases of NGC 6440 and NGC 6441 the discovery of new pulsars lead us to observe these two GCs on a total of 37 and 24 extra occasions, respectively, from 2005 November 5 to 2007 March 28 (Spigot mode 2) and then from 2007 October 10 to November 1 (Spigot mode 14), with the latter data added only to the ephemeris of NGC 6440B (see § 3). The typical observing session devotes the first 2–3 hr on NGC 6440, then observes NGC 6441 for 2.5–4 hr, and then returns to NGC 6440 for 2–3 hr. The total usable observing times is about 90–100 hr for each pulsar in NGC 6440 and NGC 6441.

On two occasions we observed NGC 6440 and NGC 6441 at 820 MHz with a bandwidth of 50 MHz in order to determine the DMs of the pulsars more accurately and to search for pulsars with spectral indices that are too steep to be detected at 1950 MHz or that lie outside the area covered by the S-band beam. Because the telescope beam widths at these frequencies ( $6.5'$  at 1.95 GHz and  $15'$  at 820 MHz) are significantly larger than the half-mass radii of these GCs (see Table 2), we observed only single positions centered on the GCs.

## 2. SEARCH AND DISCOVERY OF NEW PULSARS

After masking the interference (in the manner described in detail in Hessels et al. 2007), the search data (taken in Spigot mode 2) were dedispersed in 48 subbands over the whole 600 MHz usable band at the “average” DMs for NGC 6440 ( $223 \text{ cm}^{-3} \text{ pc}$ ) and NGC 6441 ( $233 \text{ cm}^{-3} \text{ pc}$ ), with the effect of reducing the volume of data to be stored by a factor of  $\sim 20$ . For each subband set, we created  $\sim 40$  dedispersed time series covering a range of trial DMs  $\pm 10 \text{ cm}^{-3} \text{ pc}$  around the nominal GC DMs in steps of  $0.5 \text{ cm}^{-3} \text{ pc}$ . If a pulsar has a DM halfway between two trial DMs, that introduces an extra smearing of  $168 \mu\text{s}$ , resulting in

a total maximum smearing of  $245 \mu\text{s}$ . We also barycentered each time series using TEMPO.<sup>10</sup>

We Fourier-transformed each time series and searched them using a frequency-domain acceleration search technique (Ransom et al. 2002) that allows a fully coherent search in frequency/frequency-derivative space, as well as the incoherent addition of a number of harmonics (1, 2, 4, 8, or 16). The technique has an optimal sensitivity for pulsars in binary systems with an orbital period much longer than the observation time ( $P_{\text{orb}} \geq 10T_{\text{obs}}$ ). For this reason, the acceleration searches were performed on all the observations for the entire length of each observation, as well as on overlapping segments of various shorter durations (typically 27 and 82 minutes). A more detailed description of the search procedure is presented in Hessels et al. (2007).

We discovered eight new MSPs, all in S-band data, five of them in NGC 6440 and three in NGC 6441. Preliminary results on these objects were presented in Bégin (2006). Their pulse profiles, together with those of the previously known objects, are presented in Figure 1. These pulse profiles were obtained by adding *all* detections of the pulsars made in mode 2, carefully excluding all subintegrations in time or frequency that are corrupted by significant RFI.

We found no pulsars in NGC 6388, possibly due to dispersive smearing and/or interstellar scattering being substantially higher than the prediction given in Table 1. The search for pulsars in NGC 6388 was further hindered by the short time the GBT can observe the GC (2.2 hr; see Table 1). Furthermore, many of the pulsars in Terzan 5, NGC 6440, and NGC 6441 were found by searching follow-up timing observations, none of which were made for NGC 6388.

### 2.1. Flux Densities

The 1950 MHz flux densities ( $S_{1950}$ ) of all the pulsars in NGC 6440 and NGC 6441 and their pseudoluminosities at the same frequency ( $L_{1950} \equiv S_{1950} D^2$ ) are listed in Tables 3 (isolated pulsars) and 4 (binary pulsars). We determined these from the pulse profiles in Figure 1 by assuming that the off-pulse rms is

<sup>11</sup> The number of pulsars in Terzan 5 we use in this calculation is 30. This many were detected using the same search methods employed in the present survey.

TABLE 3  
PARAMETERS FOR THE ISOLATED PULSARS IN NGC 6440 AND NGC 6441

Parameter	PSR B1745–20A (NGC 6440A)	PSR J1748–2021C (NGC 6440C)	PSR J1748–2021E (NGC 6440E)	PSR J1750–3703C (NGC 6441C)	PSR J1750–3703D (NGC 6441D)
Observation and Data Reduction					
$S_{1950}^a$ (mJy).....	0.37	0.044	0.023	0.015	0.010
$L_{1950}^b$ (mJy kpc <sup>2</sup> ).....	25	3.0	1.5	2.7	1.8
Number of TOAs.....	107	161	61	82	68
Residual rms ( $\mu$ s).....	452	38	21	100	53
EFAC.....	1.72	3.37	1.02	1.17	1.25
Reference epoch (MJD).....	54,000	54,000	54,000	54,000	54,000
Timing					
$\alpha$ (J2000.0).....	17 48 52.689(2)	17 48 51.17320(15)	17 48 52.80040(14)	17 50 13.4541(7)	17 50 13.0969(4)
$\delta$ (J2000.0).....	–20 21 39.7(5)	–20 21 53.81(4)	–20 21 29.38(3)	–37 03 05.58(3)	–37 03 06.368(17)
$\nu$ (Hz).....	3.464969947246(19)	160.59270990836(6)	61.48547652886(2)	37.63830424257(6)	194.55492232569(15)
$\dot{\nu}$ (10 <sup>–15</sup> Hz s <sup>–1</sup> ).....	–4.7944(12)	1.543(4)	–1.1812(15)	1.411(4)	–18.652(9)
DM (cm <sup>–3</sup> pc).....	219.4(2)	226.95(6)	224.10(4)	230.67(2)	230.09(17)

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

<sup>a</sup> The uncertainties in these fluxes are of the order of 10%.

<sup>b</sup> In this and the next table, the distances used to calculate this parameter are those given in Table 2.

as predicted by the radiometer equation for the total observing time. In calculating the system’s equivalent flux density, we used a system temperature of 26 K toward NGC 6440 and 28 K toward NGC 6441, a gain of 1.95 K Jy<sup>–1</sup> for the GBT at S-band, and multiplied the result by 1.235 for the three-level efficiency factor of the correlator. These flux densities indicate that some of the new discoveries, particularly in NGC 6441, are as faint as the faintest

pulsars in Terzan 5, suggesting that we have achieved a sensitivity in our survey similar to that reported by Ransom et al. (2005).

We can compare the sizes of the pulsar populations in these clusters with that of Terzan 5 by comparing the distribution of their pseudoluminositities. The observing system and observing frequency are the same, the DMs of the pulsars are very similar, the scattering times are similarly small, the length of the integrations

TABLE 4  
PARAMETERS FOR THE BINARY PULSARS IN NGC 6440 AND NGC 6441

Parameter	PSR J1748–2021B (NGC 6440B)	PSR J1748–2021D (NGC 6440D)	PSR J1748–2021F (NGC 6440F)	PSR J1750–37A (NGC 6441A)	PSR J1750–3703B (NGC 6441B)
Observation and Data Reduction					
$S_{1950}$ (mJy).....	0.047	0.075	0.017	0.059	0.037
$L_{1950}$ (mJy kpc <sup>2</sup> ).....	3.2	5.0	1.1	10.8	6.7
Number of TOAs.....	1051	946	52	129	277
Residual rms ( $\mu$ s).....	46	42	36	86	116
EFAC.....	1.20	1.33	1.35	1.08	1.55
Reference epoch (MJD).....	54,000	54,000	54,000	54,000	54,000
Timing					
$\alpha$ (J2000.0).....	17 48 52.95290(8)	17 48 51.64665(7)	17 48 52.3339(3)	17 50 13.8016(5)	17 50 12.1770(4)
$\delta$ (J2000.0).....	–20 21 38.86(19)	–20 21 07.414(18)	–20 21 39.33(9)	–37 03 10.95(2)	–37 03 22.93(2)
$\nu$ (Hz).....	59.665418222544(17)	74.097014488305(13)	263.5998326931(2)	8.96050624775(3)	164.62146212170(16)
$\dot{\nu}$ (10 <sup>–15</sup> Hz s <sup>–1</sup> ).....	1.1717(6)	–3.2216(9)	0.733(13)	–0.4545(6)	–0.520(11)
DM (cm <sup>–3</sup> pc).....	220.922(11)	224.98(3)	220.43(8)	233.82(3)	234.391(9)
$P_b$ (days).....	20.5500072(6)	0.2860686769(4)	9.83396979(8)	17.3342759(7)	3.60511446(5)
$x$ (lt-s).....	4.466994(6)	0.397203(3)	9.497573(11)	24.39312(8)	2.865858(13)
$T_0$ (MJD).....	54005.480292(7)	54000.1053987(3)	54005.80617(6)	54003.127812(11)	54002.7705(11)
$e$ .....	0.5701606(15)	[0.0]	0.053108(3)	0.712431(2)	0.004046(9)
$\omega$ (deg).....	314.31935(13)	0	191.500(2)	131.3547(2)	323.07(11)
$\dot{\omega}$ (deg yr <sup>–1</sup> ).....	0.00391(18)	...	...	0.00548(30)	...
Derived					
$f$ ( $M_\odot$ ).....	0.0002266235(9)	0.000822203(16)	0.00951180(3)	0.0518649(5)	0.00194450(3)
$M$ ( $M_\odot$ ).....	2.92(20)	...	...	1.97(15)	...
$M_{p,\max}$ ( $M_\odot$ ).....	3.25	...	...	1.65	...
$M_{c,\min}$ ( $M_\odot$ ) <sup>a</sup> .....	0.11	0.12	0.30	0.53	0.17

<sup>a</sup> Calculated assuming a pulsar mass of 1.4  $M_\odot$ . Where a  $\dot{\omega}$  was measured, these limits include 99% of the total probability.

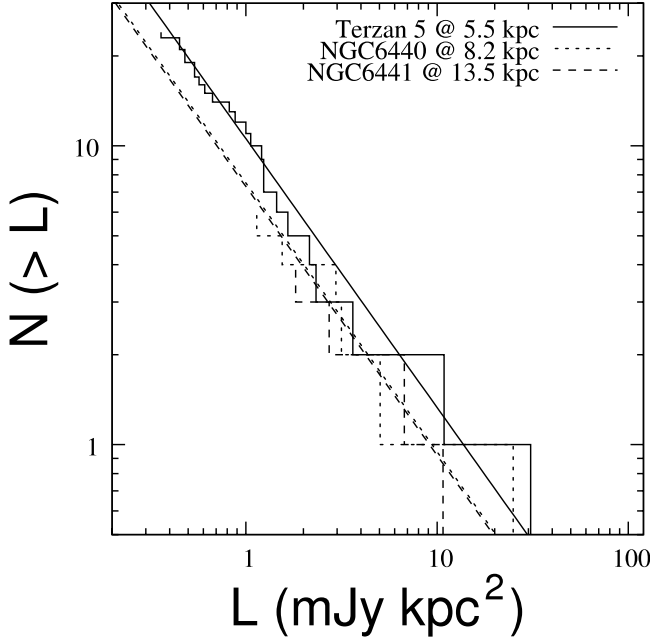


FIG. 2.—Cumulative distribution of pseudoluminosities at 1950 MHz for the pulsars in NGC 6440, NGC 6441, and Terzan 5. The pseudoluminosities are estimated assuming the most recent GC distance estimates (Ortolani et al. 2007; Valenti et al. 2007).

are similar (Table 1), and the search software is the same, making the search similarly sensitive to fast-spinning pulsars (§ 2.2). Furthermore, the software used to make the flux density measurements is similar (but not exactly the same as some refinements have recently been added to the program). All these factors make the flux densities directly comparable; the pseudoluminosities will then be directly comparable as well if the GC distances are accurate.

We have fitted a luminosity function of the type  $N(>L) = k_1 L^{-0.9}$  (derived by Hessels et al. [2007] as a best fit to the luminosities of 41 isolated pulsars in M5, M13, M15, M28, Terzan 5, 47 Tucanae, NGC 6440, and NGC 6441 above  $L_{1400} = 1.5 \text{ mJy kpc}^2$ ), where  $N(>L)$  is the number of pulsars above a pseudoluminosity of  $L$  and  $k_1$  is the number of pulsars brighter than  $1 \text{ mJy kpc}^2$ . If we assume the distances listed in Harris (1996; see Table 1), we obtain  $k_1 = 32.8, 7.9$ , and  $5.7$  for Terzan 5, NGC 6440, and NGC 6441, respectively. This would indicate that  $\Gamma_c$  does a poor job of predicting the number of MSPs in these GCs.

However, recent studies of these GCs have changed these distance estimates (see Table 2), sometimes drastically: in the case of Terzan 5, the most recent distance estimate is  $5.5 \text{ kpc}$  (Ortolani et al. 2007). It should be noted that these new distance estimates still have large systematic uncertainties (C. O. Heinke & S. Ortolani, private communication). These values affect our prediction for  $\Gamma_c$ : the total absolute visible luminosity of the core of the GC is proportional to  $D^2$ , but the volume of the core is proportional to  $D^3$ , and therefore  $\rho_0 \propto D^2/D^3 = D^{-1}$ . Inserting this result in equation (1), and keeping in mind that  $r_c$  is also proportional to  $D$ , we obtain  $\Gamma_c \propto D^{1/2}$ . With the revised distance estimates, we obtain revised  $\Gamma_c$  values of  $6.3\%$ ,  $6.3\%$ , and  $8.6\%$  for Terzan 5, NGC 6440, and NGC 6441, respectively.

When we use the new distance estimates to recalculate the pseudoluminosities of the pulsars in these three GCs (Fig. 2), we obtain  $k_1 = 10.6, 7.5$ , and  $7.3$  for Terzan 5, NGC 6440, and NGC 6441, respectively. Given the uncertainties in the distance estimates, this finding is consistent with all the clusters having

similarly sized pulsar populations and with  $\Gamma_c$  being a good predictor of the number of pulsars in a GC.

If the  $k_1$  numbers reflect the sizes of the pulsar populations, then assuming the Hessels et al. (2007) luminosity law, we should detect

$$N_{\text{PSR, NGC6440}} = N_{\text{PSR, Ter5}} (k_{1, \text{NGC6440}} / k_{1, \text{Ter5}}) (D_{\text{Ter5}}^2 / D_{\text{NGC6440}}^2)^{0.9} = 10.4 \quad (2)$$

pulsars in NGC 6440 and  $4.1$  pulsars for NGC 6441.<sup>11</sup> For NGC 6441, we detect as many pulsars as expected from the luminosity distribution, given its greater distance, but we do not detect faint ( $10\text{--}17 \mu\text{Jy}$ ) pulsars in NGC 6440. This could happen if some of them are in tight binary systems, which would make them more difficult to detect. In any case, the most likely reason we detect more pulsars in Terzan 5 is simply because that GC is closer to us.

To summarize, we can see from the discussion above that the distance to the GC does not have a major impact on the estimate of  $\Gamma_c$  ( $\Gamma_c \propto D^{1/2}$ ), but it has a fundamental impact in regard to estimating pulsar populations from the observed flux densities ( $k_1 \propto D^2 \times 0.9$ ). For Terzan 5, NGC 6440, and NGC 6441, the use of the latest distance estimates makes  $\Gamma_c$  a good predictor of the relative sizes of the pulsar populations.

## 2.2. Spin Period Distribution

Looking at the spin periods in Table 6 and comparing them with the spin periods of the pulsars in other GCs,<sup>12</sup> we notice a conspicuous absence of fast-spinning objects. Of the 33 known pulsars in Terzan 5 (a GC for which the discovery observations have very nearly the same time resolution as those in our survey), 15 have spin periods shorter than that of NGC 6440F, the fastest MSP we found, and 23 have spin periods shorter than that of NGC 6441D.

This could be a result of interstellar scattering being worse for NGC 6440 and NGC 6441 than it is for Terzan 5. Looking at Table 1, we can see that both NGC 6440 and NGC 6441 have predicted scattering times *lower* than those of Terzan 5. An inspection of the pulse profiles in Figure 1, particularly of the shorter period pulsars such as NGC 6440C and NGC 6441D, does not reveal the typical signature of interstellar scattering, an exponential decay of intensity after the main peak, as one would expect from the small scattering timescales in Table 1. The difference, if statistically significant, is likely to be real, not due to scattering or dispersive smearing.

A two-sided Kolmogorov-Smirnov (2K-S) test (Press et al. 1992) gives an  $87\%$  probability that the spin period distributions of NGC 6440 and NGC 6441 are those of a common population. Comparing these two with Terzan 5, we obtain, respectively,  $1.1\%$  and  $1.8\%$  probabilities for the same hypothesis. Comparing these two with the pulsar population in 47 Tucanae, we obtain probabilities of  $0.13\%$  and  $0.27\%$ , respectively.

This phenomenon is not restricted to NGC 6440 and NGC 6441. In a recent  $1.4 \text{ GHz}$  GC pulsar survey made with the Arecibo telescope, Hessels et al. (2007) searched for pulsars in M15. Despite being even more sensitive to short-period pulsars than the Terzan 5 survey, they found none. The spin period distribution of the M15 pulsars detected by Hessels et al. (2007) is

<sup>11</sup> The number of pulsars in Terzan 5 we use in this calculation is 30. This many were detected using the same search methods employed in the present survey.

<sup>12</sup> See <http://www.naic.edu/~pfreire/GCpsr.html>.

indistinguishable from those of NGC 6440 and NGC 6441 (2K-S probabilities of 62% and 65%), but different from that of Terzan 5 (2K-S probability of 2.6%).

### 2.3. Dispersion Measure Distribution

The DMs of the known pulsars in NGC 6440 range from 219.4 to 226.9  $\text{cm}^{-3}$  pc, a span of 7.5  $\text{cm}^{-3}$  pc. In Terzan 5 the known pulsars have DMs between 234.3 to 243.5  $\text{cm}^{-3}$  pc, a span of 9.2  $\text{cm}^{-3}$  pc (Ransom et al. 2005). However, two of the pulsars in Terzan 5 (A and D) have anomalously high DMs. Each of these pulsars is spatially more distant from the center of the GC than the other pulsars. All the other pulsars have DMs between 234.32 and 239.82  $\text{cm}^{-3}$  pc. If we randomly choose six pulsars in Terzan 5, there is a 66% probability that the set will include none of the two outliers. In that case, the maximum DM span will be 5.5  $\text{cm}^{-3}$  pc, lower than but comparable to what we observe in NGC 6440.

This is consistent with the idea that the variations in DM between pulsars are generally due to differences in the Galactic electron column density.<sup>13</sup> Since both NGC 6440 and Terzan 5 are at similar DMs and have their pulsars spread over roughly similar areas of the sky, the differences in DM between the pulsars should be similar. The spread in DMs seems to be linearly correlated with the absolute DM of the GC (Freire et al. 2005), an idea that is supported by the observed spread of DMs in NGC 6440.

For NGC 6441, where only four pulsars are known, the DMs range between 230.09 and 234.39  $\text{cm}^{-3}$  pc. The slightly more compact distribution of the smaller number of pulsars is likely to produce a smaller range of DMs than observed in NGC 6440.

## 3. TIMING

Diffraction scintillation causes a modulation of the intensity of the pulsed signal in time and frequency. “Scintles” are the regions of the dynamic spectrum where the signal is amplified relative to average. The high DMs of these pulsars imply that the scintles have narrow bandwidths (of the order of  $\sim 20$  and  $\sim 60$  kHz at 1.95 GHz for NGC 6440 and NGC 6441; Cordes & Lazio 2002) and are therefore averaged out over our wide observing band. This means that the flux densities of the pulsars are very steady, resulting in the very high detection rate we achieved during our timing campaign: even the faintest new MSPs are always detectable. These detections were cross-correlated with a synthetic profile, obtained from fitting a minimal set of Gaussian curves to the summed profiles presented in Figure 1. This cross-correlation is done in the Fourier domain, as described in Taylor (1992), and from it we derive pulse times of arrival (TOAs). For the faint, isolated pulsars we calculated about 1 TOA per observation, but for the binary systems, such as NGC 6440B and particularly NGC 6440D, a significantly larger number were calculated in order to retain orbital phase information.

These TOAs were fitted to a pulsar model containing spin (its frequency  $\nu$  and its first derivative  $\dot{\nu}$ ) and astrometric (right ascension  $\alpha$  and declination  $\delta$ ) parameters, plus the DM using TEMPO. The parameters obtained from these fits are presented in Tables 3 and 4. To account for the motion of the telescope relative to the barycenter of the solar system, we used the DE405 solar system ephemeris.<sup>14</sup> The DMs are calculated by comparing pulse TOAs at 820 and 1950 MHz, but they assume that there is no sig-

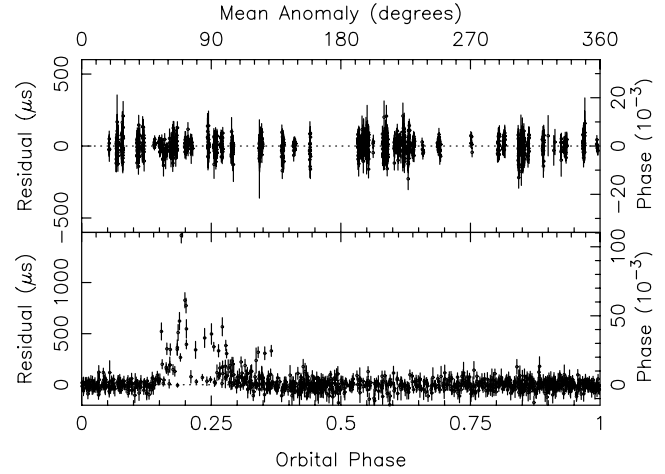


FIG. 3.—Time of arrival residuals as a function of orbital phase for NGC 6440B (top) and NGC 6440D (bottom).

nificant longitudinal evolution of the pulse profile with frequency. For the binary pulsars, the orbital parameters (orbital period  $P_b$ ; semimajor axis of the pulsar’s orbit  $a$  projected along the line of sight in light seconds,  $x \equiv a \sin i/c$ ; eccentricity  $e$ ; longitude of periastron  $\omega$ ; time of passage through periastron  $T_0$ ; and in two cases the rate of advance of periastron  $\dot{\omega}$ ) were also fitted (see Table 4) using the Damour & Deruelle orbital model (Damour & Deruelle 1985, 1986). The reference epoch for all solutions is MJD = 54,000 (2006 September 9). The timing solution of NGC 6440B is the only one that includes the “mode 14” data taken in 2007 October; all the others include only mode 2 data, which end in 2007 March 28.

The three-level sampling of the Spigot introduces systematics on the profiles that are not well understood. Following standard pulsar timing practice in such cases, we compensate for this by increasing the uncertainties on the TOAs by the small factor indicated in Tables 3 and 4 as “EFAC,” such that the reduced  $\chi^2 = 1$ . In all cases except that of NGC 6440C, these factors are small, indicating that the timing models in Tables 3 and 4 do a good job of predicting the rotational phases of the pulsars, i.e., there are no unmodeled trends in the TOA residuals (for two examples, see Fig. 3). For this reason, we believe that the  $1\sigma$  uncertainty estimates returned by TEMPO are essentially accurate, so they are reported directly in Tables 3 and 4. In § 4.3 we test the validity of this hypothesis for the measurement of the  $\dot{\omega}$  of NGC 6440B.

The large EFAC of NGC 6440C indicates the presence of unmodeled effects in its TOA residuals. The cause of these is unknown at present and will be investigated elsewhere.

### 3.1. Positions

In Table 5 we calculate the angular offsets of the pulsar positions listed in Tables 3 and 4 relative to the centers of their respective GCs listed in Table 2. These are displayed graphically in the top panels of Figures 4 and 5. The projected distances of the pulsars from the center of the GC ( $r_\perp$ ) were calculated using the most recent GC distance estimates listed in Table 2. There is nothing unusual about the spatial distribution of the pulsars in these GCs. As in 47 Tucanae and most other GCs, all pulsars are located within the half-mass radius of the GC (Camilo & Rasio 2005)—in the present cases at less than  $0.6'$  (or 4.5 core radii) from the center. This is not an observational bias: the S-band telescope beam still has  $>50\%$  sensitivity  $3'$  from the center of the GC. Furthermore, the 820 MHz observations do not reveal any extra pulsars within  $\sim 8'$  from the center of the GC. The congregation

<sup>13</sup> The exception is 47 Tucanae (Freire et al. 2001b) where the DM differences between pulsars are predominantly due to gas intrinsic to the GC.

<sup>14</sup> See E. M. Standish 1998, JPL Planetary and Lunar Ephemerides, available from <http://ssd.jpl.nasa.gov/iau-comm4/de405iom/de405iom.pdf>.

TABLE 5  
PULSAR OFFSETS FROM THE CENTERS OF NGC 6440 AND NGC 6441

PULSAR	$\theta_{\alpha}^{\text{a,b}}$	$\theta_{\delta}^{\text{a}}$	$\theta_{\perp}$		$r_{\perp}$ (pc)
	(arcmin)	(arcmin)	(arcmin)	( $\theta_c$ )	
NGC 6440					
A.....	−0.0017	−0.0447	0.04	0.34	0.11
B.....	0.0601	−0.0307	0.07	0.52	0.16
C.....	−0.3571	−0.2801	0.45	3.49	1.08
D.....	−0.2472	0.4930	0.55	4.24	1.32
E.....	0.0240	0.1269	0.13	0.99	0.31
F.....	−0.0858	−0.0389	0.09	0.72	0.22
NGC 6441					
A.....	0.1797	−0.0993	0.21	1.87	0.81
B.....	−0.1432	−0.2989	0.33	3.01	1.30
C.....	0.1111	−0.0096	0.11	1.01	0.44
D.....	0.0395	−0.0229	0.05	0.41	0.18

<sup>a</sup> The uncertainty of these parameters is much smaller than the uncertainty of the position of the center of the GC (they were computed assuming that the center is *exactly* where indicated in Table 2). This precision is, however, necessary to calculate the angular distances between the pulsars.

<sup>b</sup> Note that  $\theta_{\alpha} = d\alpha \cos \delta$ , where  $d\alpha$  is the difference of the right ascension of the pulsar and the center of the GC.

of pulsars at the center is a real phenomenon, due to mass segregation in the GC.

### 3.2. Period Derivatives

In the third column of Table 6, we list the observed period derivatives ( $\dot{P}_{\text{obs}}$ ). Four effects can contribute to  $\dot{P}_{\text{obs}}$  (Phinney 1993):

$$(\dot{P}/P)_{\text{obs}} = (\dot{P}/P)_{\text{int}} + (1/c)(a_G + a_{\text{GC}} + a_{\text{PM}}), \quad (3)$$

where  $\dot{P}_{\text{int}}$  is the pulsar's intrinsic period derivative,  $a_{\text{GC}}$  is the line-of-sight component of the acceleration of the pulsar caused by the gravitational field of the GC,  $a_G$  is the difference of the accelerations of the GC and of the solar system in the gravitational field of the Galaxy, projected along the line of sight,  $a_{\text{PM}} = \mu^2 D$  (Shklovskii 1970) is the centrifugal acceleration due to the transverse motion of the pulsar  $\mu$ , and  $D$  is the GC's distance from the Earth, listed in Table 2. The pulsar proper motions  $\mu$  are not yet directly measurable, and there are no optical measurements of the proper motions of the two GCs; so, like  $\dot{P}_{\text{int}}$ ,  $a_{\text{PM}}$  is not known but is always positive.

In the fourth column of Table 6, we list the observational upper limits for the pulsar acceleration,  $a_{p,\text{max}}$ , obtained by rearranging all the known terms of equation (3) to the right side of the equation:

$$a_{p,\text{max}} \equiv a_{\text{GC}} + c(\dot{P}/P)_{\text{int}} + \mu^2 D = c(\dot{P}/P)_{\text{obs}} - a_G. \quad (4)$$

We calculated  $a_G$  using a mass model of the Galaxy (Kuijken & Gilmore 1989), the estimated distance to the GCs, and their Galactic coordinates given in Table 2. Since we have no estimates of the proper motion of the GCs, we assume from now on that  $\mu^2 D = 0$ . In all GCs for which this term is measured, it is small relative to the intrinsic period derivatives and even smaller compared to the accelerations induced by the GC.

In the fifth column of Table 6 we list the theoretical maximum value of  $a_{\text{GC}}$  for each pulsar's line of sight,  $a_{\text{GC,max}}$ . This is calculated using an analytical mass model for the centers of GCs de-

scribed in the appendix of Freire et al. (2005), using the core radius and central velocity dispersion listed in Table 2. Both  $a_{p,\text{max}}$  for the individual pulsars and  $a_{\text{GC,max}}$  for all lines of sight close to the center of the GC are displayed in the bottom halves of Figures 4 and 5.

Using equation (4), we can calculate upper (and in the cases of NGC 6440A and D, lower) limits for  $\dot{P}_{\text{int}}$  assuming the extreme possible accelerations  $\pm a_{\text{GC,max}}$ . These limits are displayed in the sixth and seventh columns of Table 6. From these  $\dot{P}_{\text{int}}$  limits, we can calculate upper and lower limits for the magnetic field at the surface [estimated using  $B_0 = 3.2 \times 10^{19} (P\dot{P}_{\text{int}})^{1/2}$  G] and lower and upper limits for the characteristic age of these pulsars (estimated using  $\tau_c = P/2\dot{P}_{\text{int}}$ ), these are displayed in the final columns of Table 6. No pulsar in either GC has  $a_{p,\text{max}} < -a_{\text{GC,max}}$ , which means that the present GC mass models can predict line-of-sight accelerations large enough to explain the observed negative period derivatives (and plausibly maintain that the pulsars are not spinning up).

#### 3.2.1. NGC 6440A

As previously found by Lyne et al. (1996), PSR B1745–20A has a characteristic age  $\sim 10^3$  times smaller than the age of the GC and  $B_0 \sim 3 \times 10^{11}$  G, a value that is more typical of what one finds in the general Galactic population. For these two reasons, there have been some doubts about the association of this pulsar with NGC 6440. The discovery of five new MSPs in NGC 6440 at DMs similar to that of PSR B1745–20A confirms its association with NGC 6440. Furthermore, PSR B1745–20A is closer to the center of the GC ( $\theta_{\perp} = 0.04'$ ) than any of the new MSPs.

This association of a “young” pulsar with a GC is not unique to NGC 6440. The first known examples were PSR B1718–19, in NGC 6342 (Lyne et al. 1993) and PSR B1820–30B in NGC 6624 (Biggs et al. 1994). The possible origins of these objects, and in particular NGC 6440A, are discussed in detail in Lyne et al. (1996). Either neutron star formation continues to happen in GCs—through electron capture supernovae (ECSs), which can form when an accreting WD star reaches the Chandrasekhar limit or when a WD binary coalesces—or some form of mild recycling happened, in which the pulsar was not spun up to very short spin periods and not much of its magnetic field was buried. The ECS scenario is particularly appealing as this type of supernova also produces small kicks, which nicely solves the problem of neutron star retention in GCs (Ivanova et al. 2007).

#### 3.2.2. NGC 6440D

Unlike in the case of NGC 6440A, the upper limit for  $\tau_c$  and the lower limit for  $B$  does not imply that this pulsar is younger or has a stronger magnetic field than the other MSPs. It is possible that the other “slow MSPs” (with  $13 < P < 27$  ms) have similar ages and magnetic fields as those of NGC 6440D; their intrinsic  $\dot{P}$ -values might simply be masked by the GC accelerations. The apparently special limits for NGC 6440D might have more to do with its large distance from the center of the GC: the range of possible GC accelerations  $a_{\text{GC,max}}$  is the smallest for all pulsar positions in NGC 6440 and NGC 6441; this leads to tighter limits on  $\dot{P}_{\text{int}}$ . If NGC 6440D is a typical slow MSP, then the magnetic fields of these objects are 1 order of magnitude larger than those observed in 47 Tucanae (Freire et al. 2001a); this would cause the observed difference in spin periods between GCs discussed in § 2.2.

## 4. BINARY SYSTEMS

Before this survey only one binary pulsar was known in these two GCs, NGC 6441A (Possenti et al. 2006). We have discovered

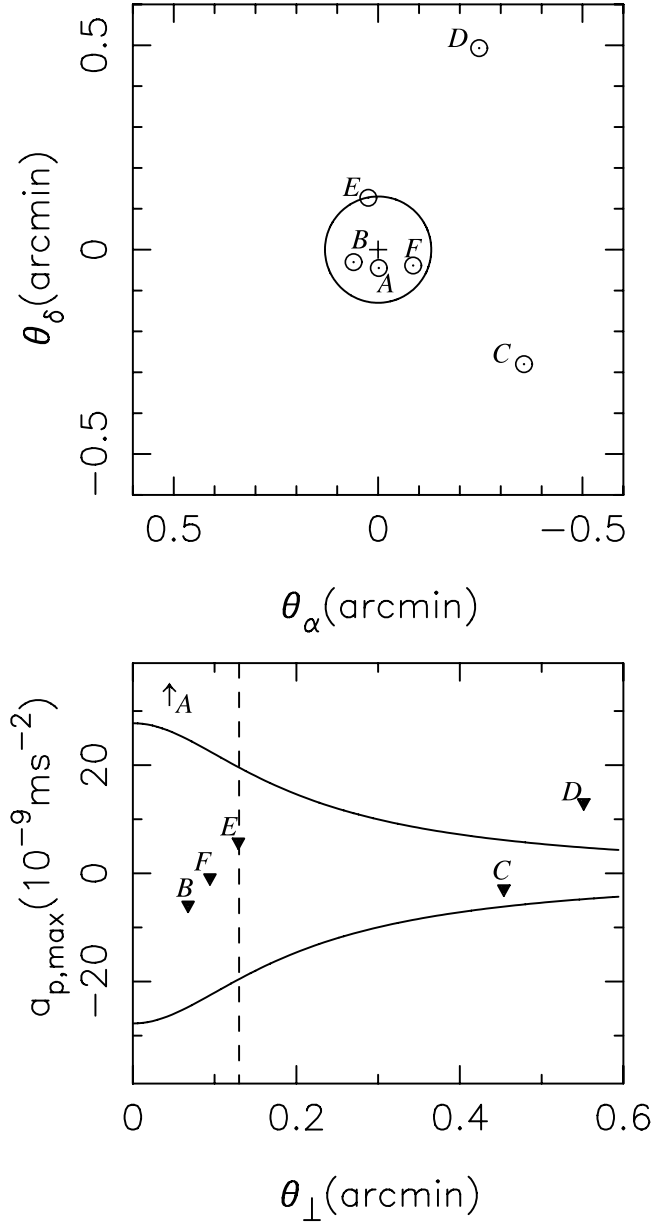


FIG. 4.—*Top*: Positions of the six known pulsars in NGC 6440, plotted as west-east ( $\theta_\alpha$ ) and south-north ( $\theta_\delta$ ) offsets from the center of the GC (see also Table 5). The angular core radius ( $\theta_c = 0.13'$ ) is represented by a circle. *Bottom*: Upper limits for the accelerations of the MSPs (triangles). These are compared with the maximum acceleration that can be caused by the GC, as a function of  $\theta_\perp$  (solid curves). The angular core radius is indicated by the vertical dashed line. Pulsar NGC 6440A, and to a much lesser extent NGC 6440D are significantly above the maximum GC acceleration, indicating that its large positive  $\dot{P}$  is caused by its intrinsic slowdown.

four new binary systems, three in NGC 6440 (B, D, and F) and one in NGC 6441 (B). These binaries make up half of the total observed pulsar population in these GCs. This ratio is similar to that of Terzan 5, but significantly lower than what we find in 47 Tucanae and M62; in the latter GC all the six known pulsars are in binary systems.

#### 4.1. NGC 6440F and NGC 6441B

These two binaries, with orbital periods of 9.8 and 3.6 days and minimum companion masses of  $0.30$  and  $0.17 M_\odot$ , respectively (assuming pulsar masses of  $1.4 M_\odot$ ), might be the only

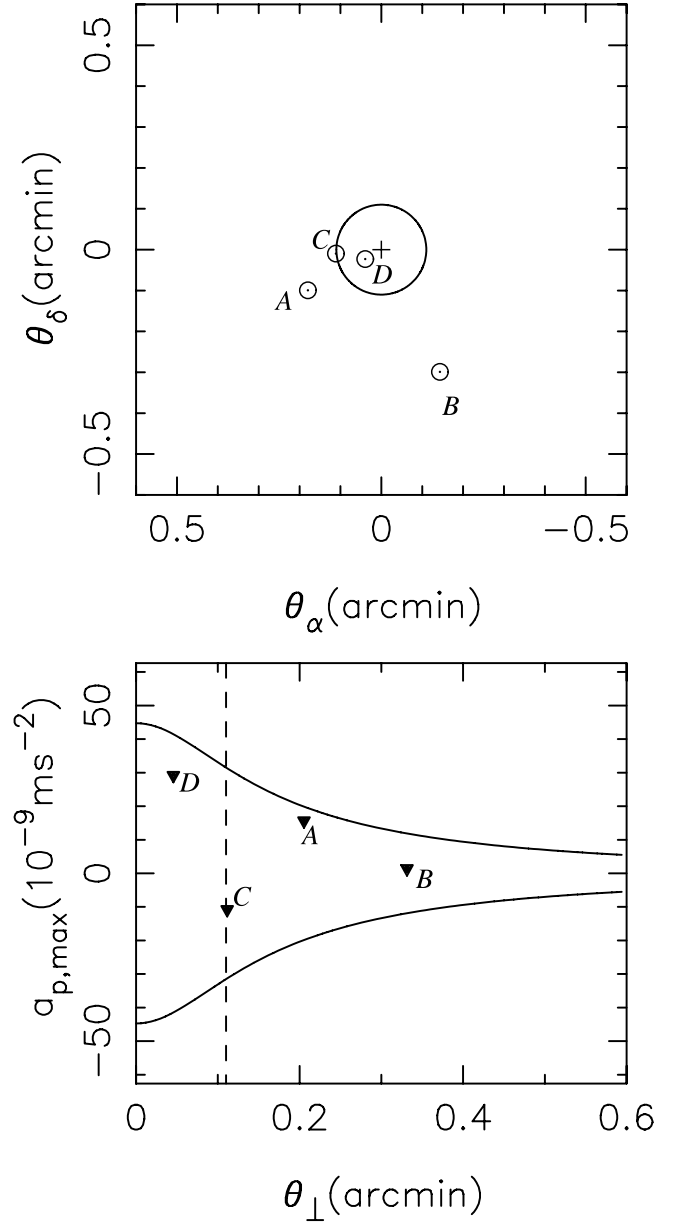


FIG. 5.—*Top*: Same as top panel of Fig. 4 for the four MSPs in NGC 6441. The angular core radius ( $\theta_c = 0.11'$ ) is represented by a circle. *Bottom*: Upper limits on the accelerations of the MSPs in NGC 6441 (triangles) and theoretical maximum acceleration as a function of  $\theta_\perp$  (solid curves).

“normal” MSP-WD binaries among the new pulsars. Their spin periods (3.79 and 6.07 ms) are at the lower end of the spin period distribution found in NGC 6440 and NGC 6441, but they are typical of what is found among similar MSP-WD binaries in other GCs and in the Galactic disk. Their eccentricities (0.0531 and 0.00404) are small compared to the highly eccentric NGC 6440B and NGC 6441A, but they are nevertheless much larger than what is found in binary systems with similar orbital periods in the Galactic disk. This is a common occurrence in GCs and is probably due to perturbations caused by close flybys of other stars in these GCs (Heggie & Rasio 1996).

#### 4.2. NGC 6440D—Eclipsing Binary

The binary system NGC 6440D has an orbit with nonmeasurable eccentricity and a period of 6.9 hr. It is an eclipsing system



TABLE 6  
LIMITS FOR DERIVED PARAMETERS OF THE NGC 6440 AND NGC 6441 PULSARS

Pulsar	$P$ (ms)	$\dot{P}_{\text{obs}}$ ( $10^{-18}$ )	$a_{p,\text{max}}$ ( $10^{-9}$ m s $^{-2}$ )	$a_{\text{GC,max}}$	$\dot{P}_{\text{int,max}}$ ( $10^{-18}$ )	$\dot{P}_{\text{int,min}}$	$B_{\text{max}}$ ( $10^9$ G)	$B_{\text{min}}$	$\tau_{c,\text{max}}$ (Gyr)	$\tau_{c,\text{min}}$
NGC 6440										
A.....	288.6027917197(16)	399.33(10)	414.8	26.30	424.7	374.0	353.2	331.4	0.012	0.011
B.....	16.760127219257(5)	-0.32913(16)	-5.86	24.72	1.05	(0.0)	4.24	(0.0)	(+ $\infty$ )	0.25
C.....	6.226932720487(2)	-0.05984(16)	-2.85	6.15	0.07	(0.0)	0.66	(0.0)	(+ $\infty$ )	1.45
D.....	13.495820403909(2)	0.58678(16)	13.06	4.77	0.80	0.37	3.32	2.26	0.57	0.27
E.....	16.264003411125(5)	0.3124(4)	5.79	19.62	1.38	(0.0)	4.78	(0.0)	(+ $\infty$ )	0.19
F.....	3.793629114949(3)	-0.01055(18)	-0.81	22.53	0.27	(0.0)	1.03	(0.0)	(+ $\infty$ )	0.22
NGC 6441										
A.....	111.6008373133(4)	5.661(8)	15.67	19.88	13.2	(0.0)	38.8	(0.0)	(+ $\infty$ )	0.13
B.....	6.074542086503(6)	0.0192(4)	1.41	11.88	0.27	(0.0)	1.29	(0.0)	(+ $\infty$ )	0.36
C.....	26.56867837497(4)	-0.996(3)	-10.77	31.30	1.82	(0.0)	7.01	(0.0)	(+ $\infty$ )	0.23
D.....	5.139936774902(4)	0.4928(2)	29.20	41.46	1.21	(0.0)	2.52	(0.0)	(+ $\infty$ )	0.067

with eclipses that usually last for about 10% of the orbital cycle. Its minimum companion mass is  $0.12 M_{\odot}$ , calculated assuming a pulsar mass of  $1.4 M_{\odot}$ . Freire (2005) called attention to the fact that eclipsing binary pulsars have a bimodal distribution of mass functions: those with  $f > 10^{-4} M_{\odot}$  were designated as eclipsing low-mass binary pulsars (ELMBPs), while those with  $f < 3 \times 10^{-5} M_{\odot}$  were designated as very low mass binary pulsars (VLMBPs). The VLMBPs are more commonly known as “black widow” pulsars. NGC 6440D is clearly a ELMBP. Unlike black widows, these objects only occur in GCs, suggesting that they form through exchange interactions when a radio pulsar acquires a MS companion.

Sometimes NGC 6440D is detectable during superior conjunction. This indicates that the orbital inclination is certainly less than  $90^\circ$ ; otherwise the companion itself would cause an eclipse. It also implies that the concentration of the material producing the eclipse is highly variable with time. Nevertheless, the cloud of material seems to generally lead the companion in orbital phase (see Fig. 3), i.e., ingress occurs at a much larger distance from superior conjunction than egress. Before, after, and sometimes through the eclipse we detect  $\sim 0.5$  ms delays in the times of arrival (see Fig. 3). These are probably due to an increase in the electron column density near the companion of up to  $\sim 0.5 \text{ cm}^{-3} \text{ pc}$  (or about  $1.5 \times 10^{18} \text{ cm}^{-2}$ ), which is of the same order of magnitude as what has been found in similar binary systems, e.g., M30A (Ransom et al. 2004).

If the system is nearly edge on, with pulsar and companion masses of  $1.4$  and  $0.124 M_{\odot}$ , the separation between the stellar components is  $1.47 \times 10^{11} \text{ cm}$  ( $2.1 R_{\odot}$ ). On some occasions the eclipse extends up to  $\sim 30^\circ$  from superior conjunction (normally before the companion), which implies the detection of material at  $\sim 1.0 R_{\odot}$  from the center of the companion. The size of the Roche lobe of the companion is  $0.42 R_{\odot}$ ; therefore, it is clear that we are detecting the presence of material that is not bound to the companion at ingress. We almost never detect unbound material at egress.

This is different from what one observes in ELMBPs such as 47 Tuc W (Camilo et al. 2000) Terzan 5 P and ad (Ransom et al. 2005; Hessels et al. 2006), PSR J1740–5340 in NGC 6397 (D’Amico et al. 2001), or M28 H (Bégin 2006; S. Bégin et al. 2008, in preparation), which display long-duration irregular eclipses likely related to excessive unbound ionized material from the companion over much of the orbit. Three of these ELMBP

companions have been identified at optical wavelengths (47 Tuc W: Edmonds et al. 2002; PSR B1718–19 in NGC 6349: Kerkwijk et al. 2000; and PSR J1740–5340 in NGC 6397: Ferraro et al. 2001), and in all cases the observed companion is a low-mass, nondegenerate star. None of the ELMBPs with shorter eclipses, such as M30 A and Terzan 5 A (Lyne et al. 1990) and M62 B (Possenti et al. 2003) have been optically detected. The situation is similar at X-rays: only the systems with large eclipses have been detected (e.g., 47 Tuc W; see Bogdanov et al. 2005). In these systems the hard X-ray emission is generated by the collision of MSP and stellar winds. None of the ELMBPs with shorter eclipses have been definitively detected at X-ray wavelengths. If NGC 6440D is similar to these ELMBPs, it seems less likely that it will be detected at either optical or X-ray wavelengths.

When an exchange encounter forms a ELMBP, the ejection of the previous companion to the pulsar imparts a kick to the binary, making it fly away from the central regions of the GC in an eccentric orbit. It is probably for that reason that two ELMBPs (PSR B1718–19 and PSR J1740–5340) are found at large distances from the centers of their parent GCs (Freire 2005). NGC 6440D follows this trend: of all the pulsars in NGC 6440 and NGC 6441, it is farthest from the center of its GC as projected on the plane of the sky.

#### 4.3. NGC 6440B: Eccentric Binary with a Supermassive Neutron Star?

NGC 6440B and NGC 6441A (§ 4.4) are part of a diverse class of binary pulsars in GCs with eccentric orbits that includes mostly recent discoveries such as M30 B (Ransom et al. 2004) NGC 1851A (Freire et al. 2004, 2007), six systems in Terzan 5 (I, J, Q, U, X, and Z; Ransom et al. 2005; I. H. Stairs et al. 2008, in preparation), and M28 C and D (Bégin 2006; S. Bégin et al. 2008, in preparation). With the exception of M15C (Jacoby et al. 2006), which is very similar to some DNSs seen in the Galaxy, they have no Galactic analogs. All of these systems were likely formed through stellar exchange encounters.

The orbital eccentricity of NGC 6440B has allowed a highly significant measurement of the rate of advance of periastron:  $\dot{\omega} = 0.00391(18)^\circ \text{ yr}^{-1}$ . As mentioned above, this is a  $1 \sigma$  uncertainty derived by TEMPO. To check if this uncertainty value is realistic, we estimated  $\dot{\omega}$  and its associated uncertainty using two other methods. First, all the timing parameters of NGC 6440B were estimated using a Monte Carlo bootstrap algorithm (Efron & Tibshirani 1993;

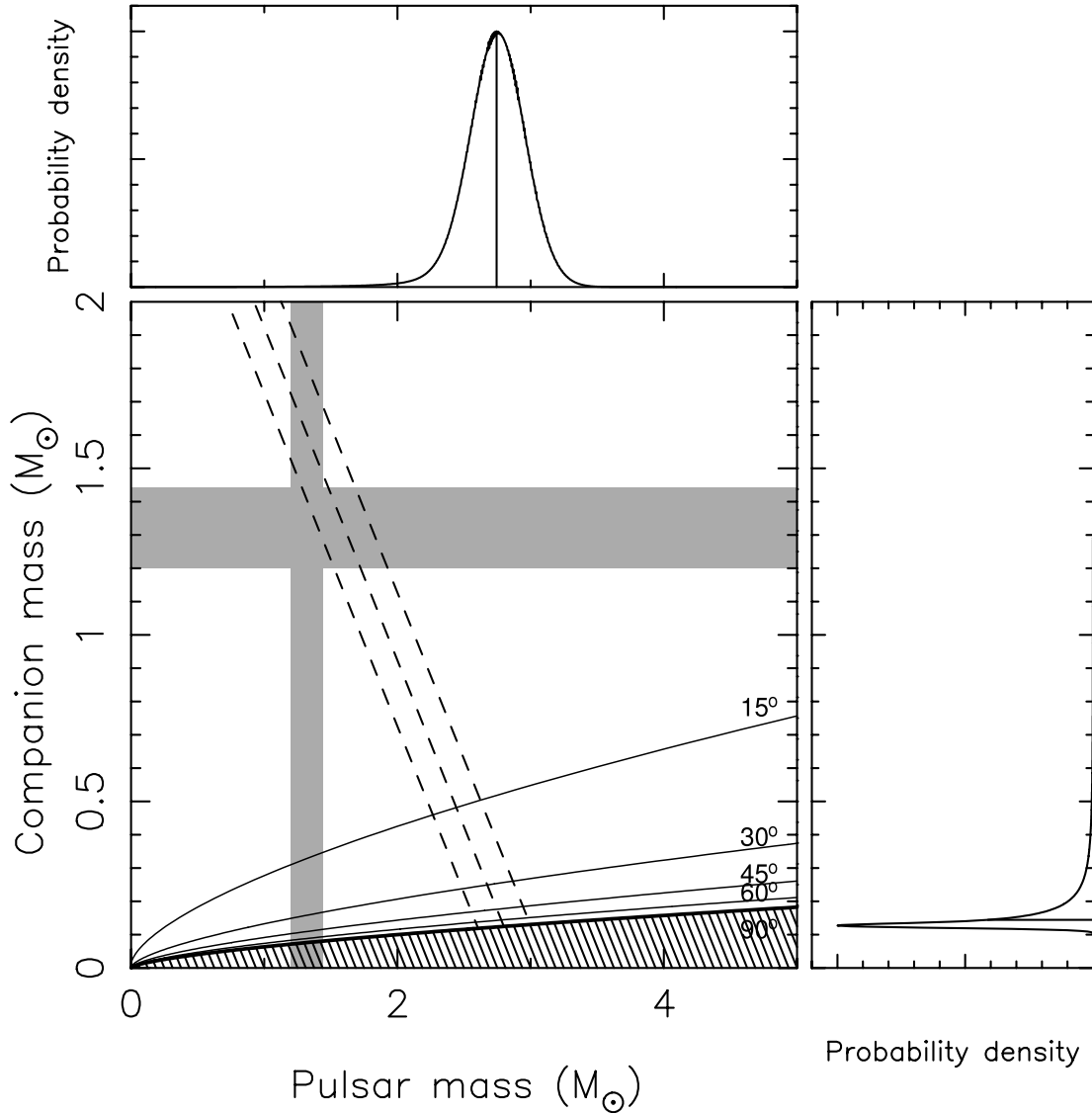


FIG. 6.—Graphical display of the constraints on the masses of NGC 6440B and its companion. In the main display, the hatched region is excluded by knowledge of the mass function and by  $\sin i \leq 1$ . The slanting straight lines correspond to a total system mass that causes a general-relativistic  $\dot{\omega}$  equal or within  $1\sigma$  (dashed lines) of the measured value. The five solid curves indicate constant orbital inclinations. The gray bars indicate the range of precisely measured neutron star masses. We also display the probability density function for the mass of the pulsar (top) and the mass of the companion (right), and mark the respective medians with vertical (horizontal) lines.

Press et al. 1992) with a total of 1024 fake TOA data sets that are consistent with the real data set. From this we obtain  $\dot{\omega} = 0.00391(16)^{\circ} \text{ yr}^{-1}$ . In the second estimate we kept  $\dot{\omega}$  fixed and fitted all the remaining timing parameters, recording the resulting  $\chi^2$ . Doing this for a range of values of  $\dot{\omega}$ , we can estimate the  $1\sigma$  uncertainty as the half-width of the region where  $\chi^2(\dot{\omega}) - \chi^2(\dot{\omega}_{\min}) < 1$ , and  $\dot{\omega}_{\min}$  is the value that minimizes  $\chi^2$  (Splaver et al. 2002). The result of this estimate is  $\dot{\omega} = 0.00391(18)^{\circ} \text{ yr}^{-1}$ . Both these estimates indicate that, at least for the  $\dot{\omega}$  of NGC 6440B, the  $1\sigma$  TEMPO uncertainty is reliable.

The orbital coverage of the timing data is excellent (see Fig. 3): the orbit was well sampled at the end of 2005, at the start of 2007, and again during 2007 October. For this reason,  $\dot{\omega}$  is not strongly correlated to any timing parameter: its largest correlation is with  $P_b$  (96%), which is normal for this particular parameter.

#### 4.3.1. Mass Estimate from Periastron Advance

Assuming that  $\dot{\omega}$  is fully relativistic (an important assumption, as we see below) implies a total system mass of  $2.92 \pm 0.20 M_{\odot}$ . This binary system is located, at least in projection, close to the

center of the GC, where the massive objects should predominantly occur. In Figure 6 we present the mass constraints on the components graphically. We assume that the probability density function (PDF) for  $\dot{\omega}$ ,  $p(\dot{\omega})$ , is a Gaussian, with half-width similar to the  $1\sigma$  uncertainty given by TEMPO. We also assume a constant probability density for  $\cos i$ , where  $i$  is the orbital inclination ( $90^{\circ}$  for an edge-on orbit). From these constraints, we calculate a two-dimensional PDF for the mass of the pulsar and the mass of the companion. This is then projected in both dimensions, resulting in final PDFs for the mass of the pulsar and the mass of the companion.

The total mass of this system suggests that it is a double neutron star (DNS) binary. However, the probability that the pulsar lies within the range of neutron star masses that have been precisely measured to date—from  $\sim 1.20 M_{\odot}$  for the companion of PSR J1756–2251 (Faulkner et al. 2005) to  $1.44 M_{\odot}$  for PSR B1913+16 (Weisberg & Taylor 2003) indicated in Figures 6 and 7 (gray bars)—is only 0.10%. This eventuality would require very low orbital inclinations, between  $\sim 4^{\circ}$  and  $\sim 5^{\circ}$ . In this inclination range, it is also possible that the pulsar has a blue straggler

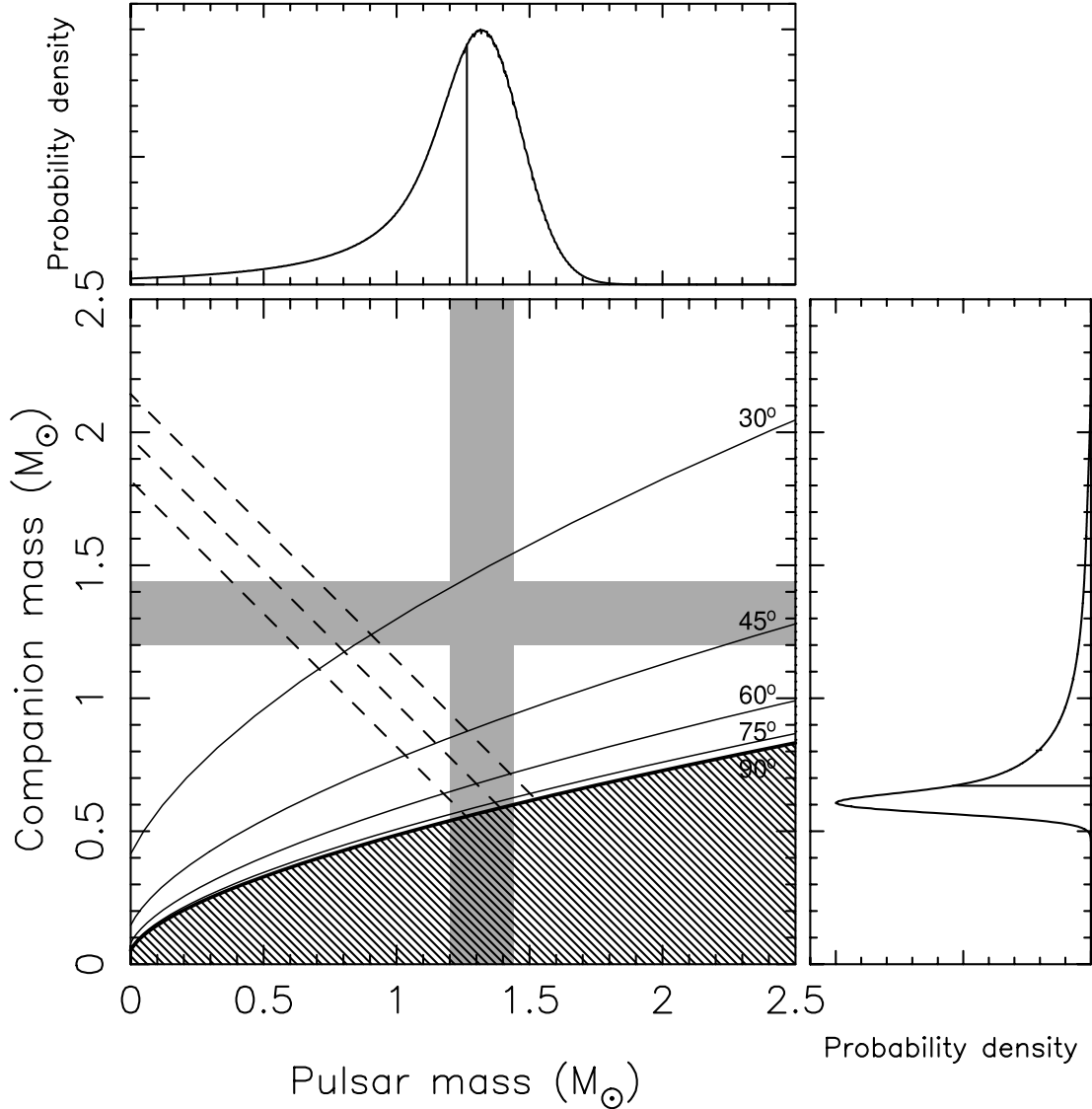


FIG. 7.—Display as in Fig. 6, this time for the NGC 6441A binary system.

companion, a possibility that can be investigated using optical/IR imaging.

Before this study the most massive neutron star known was PSR B1516+02B in the GC M5 ( $1.96^{+0.09}_{-0.12} M_{\odot}$ ; Freire et al. 2008). If NGC 6440B had a similar mass, then the companion could be a  $\sim 0.9 M_{\odot}$  white dwarf, or a blue straggler of similar mass. However, we note that there is only a 0.97% probability that the mass of the pulsar is below  $2.0 M_{\odot}$ .

The median pulsar mass is  $2.74 M_{\odot}$ , with the lower and upper  $1 \sigma$  limits at  $2.52$  and  $2.95 M_{\odot}$ , and the  $2 \sigma$  limits at  $2.23$  and  $3.15 M_{\odot}$ . The pulsar has a 99% probability of being less massive than  $3.24 M_{\odot}$ . For the companion, the median of the distribution is at  $0.142 M_{\odot}$ , with the lower and upper  $1 \sigma$  limits at  $0.124$  and  $0.228 M_{\odot}$ , and the  $2 \sigma$  limits at  $0.113$  and  $0.571 M_{\odot}$ , implying that it could be a low-mass WD or an unevolved MS star. If this high pulsar mass is confirmed, it would be by far the largest neutron star mass ever measured. That would have profound consequences for the study of the equation of state of dense matter, since almost no models predict neutron stars more massive than  $2.5 M_{\odot}$  (Lattimer & Prakash 2007).

If NGC 6440B really has a mass of  $\sim 2.7 M_{\odot}$ , it would imply that the end products of the coalescence of DNS systems might

themselves be stable as supermassive neutron stars. The total masses of the known DNS systems range from  $2.57 M_{\odot}$  (Faulkner et al. 2005) to  $2.83 M_{\odot}$  (Weisberg & Taylor 2003). Such coalescence products might be observable after coalescence, either through gravitational wave emission (Andersson 2003), cooling through neutrino emission (direct URCA process; Page & Applegate 1992), or even high-energy blackbody emission.

It is possible that NGC 6440B itself formed this way. M15 C, the only DNS known in the GC system (Jacoby et al. 2006), is expected to coalesce in about  $3 \times 10^8$  yr ( $\sim 3\%$  of the age of M15). If the products of DNS coalescence are as likely to be detected as radio pulsars as their progenitors, then we should detect  $\sim 30$  of them in the whole GC system. It is possible that some isolated MSPs in GCs and the Galactic disk formed this way. The massive isolated MSPs in GCs can later acquire a companion through exchange encounters, forming a system like NGC 6440B, where we can measure their large masses.

#### 4.3.2. Is the Periastron Advance Relativistic?

The previous discussion rests on the assumption that the observed  $\dot{\omega}$  is fully relativistic. If there was an extra contribution to  $\dot{\omega}$  from tidal or rotational deformation of the companion,

then no reliable estimates can be made of the total mass of the system.

Lai et al. (1995), in their analysis of the binary pulsar PSR J0045–7319, concluded that the only likely contribution to  $\dot{\omega}$  in that system is from rotational deformation of the companion. NGC 6440B has a shorter orbital period than PSR J0045–7319 (20.5 vs. 51 days), but it also has a much smaller companion mass ( $\sim 0.12 M_{\odot}$  at  $i = 90^{\circ}$  to  $\sim 1.5 M_{\odot}$  at  $i \sim 4^{\circ}$ – $5^{\circ}$ ) versus  $\sim 9 M_{\odot}$  for the companion of PSR J0045–7319 (Bell et al. 1995). Main-sequence stars of such masses have radii of  $R \sim 0.18$ – $1.5$  and  $\sim 4.5 R_{\odot}$ , respectively (Lang 1991). This implies that even if the companion of NGC 6440B were extended, the contribution to  $\dot{\omega}$  from its tidal deformation [the latter proportional to  $(R/a)^3$ , where  $a$  is the separation between components] would always be smaller for NGC 6440B than it is for PSR J0045–7319.

The only possible exception to this would be if the companion of NGC 6440B were a  $\sim 0.9 M_{\odot}$  star undergoing a pre-giant or giant phase. Given the mass function of the system, that would require a very low orbital inclination. A giant star of that mass would have a radius of up to 1 AU (Lang 1991) and would not fit in the space between the pulsar and companion at any orbital phase. If it were in a pre-giant phase, its atmosphere would be very extended and have significant mass loss, leading to variations in the DM with orbital phase. The resulting tides should not only have circularized the orbit, but they should also have directly observable effects on the timing: unmodeled effects in the rotation of the pulsar and random variations of the orbit's period and apparent size (Nice et al. 2000). For PSR J0045–7319, there is strong orbital decay due to tidal effects (Kumar & Quataert 1998).

For NGC 6440B, we obtain  $\dot{P}_b = (-0.0 \pm 1.4) \times 10^{-9}$  and  $\dot{x} = (-0.21 \pm 0.14) \times 10^{-12}$ . The pulsar times very well, with an EFAC similar to those of the isolated MSPs in the GC (see Table 4); no unmodeled systematic trends are visible in the TOA residuals (Fig. 3). Fitting for the halves of the orbit “in front” and “behind” the companion, we see no DM variations larger than our detection limit of  $0.07 \text{ cm}^{-3} \text{ pc}$ . The possibility of an unusually extended companion to NGC 6440B and of a significant tidal contribution to  $\dot{\omega}$  can be safely excluded.

The contribution from rotational deformation, henceforth designated as  $\dot{\omega}_{\text{rot}}$ , could be significant if the companion (degenerate or not) were spinning rapidly. The rotational deformation will also induce a change in the projected semimajor axis of the orbit  $\dot{x}$ . Splaver et al. (2002), based on the results of Lai et al. (1995) and Wex (1998), relate  $\dot{\omega}_{\text{rot}}$  to  $\dot{x}$ :

$$\dot{\omega}_{\text{rot}} = (\dot{x}/x) \left[ \tan i \frac{1 - (3/2)\sin^2\theta}{\sin\theta \cos\theta \sin\Phi_0} + \cot\Phi_0 \right], \quad (5)$$

where  $i$  is the orbital inclination of the binary,  $\theta$  is the angle between the angular momentum vector of the secondary and the angular momentum vector of the orbit; and  $\Phi_0$  is the longitude of the ascending node in a reference frame defined by the total angular momentum vector (see Fig. 9 of Wex 1998).

Thus, our observed upper limit of  $|\dot{x}/x| < 8 \times 10^{-14}$  implies  $|\dot{\omega}_{\text{rot}}| < (1.5 \times 10^{-4})^{\circ} \text{ yr}^{-1}$  times a geometric factor. In 80% of cases this geometric factor will be smaller than 10. Therefore,  $\dot{\omega}_{\text{rot}}$  will in most cases be of the same order of magnitude as the present measurement uncertainty for  $\dot{\omega}$ . Certain special combinations of  $i$ ,  $\theta$ , and  $\Phi_0$  will make the geometric factor large, but, again, this would only occur if the companion were rotating fast.

To summarize, the contribution to the  $\dot{\omega}$  of this system from the tidal deformation of the companion is negligible. Furthermore, observational limits on  $\dot{x}$  indicate that  $\dot{\omega}_{\text{rot}}$  is also likely to be negligible and the observed  $\dot{\omega}$  due to the effects of general relativity.

#### 4.4. NGC 6441A: Eccentric Binary with a Massive Companion

NGC 6441A was the only pulsar previously known in NGC 6441 (Possenti et al. 2006), although its phase-connected timing solution has never been published. Its orbital period is 17.3 days, and its orbit is highly eccentric ( $e = 0.71$ ), allowing a measurement of the advance of periastron for this system,  $\dot{\omega} = 0.00548(30)^{\circ} \text{ yr}^{-1}$ . Assuming, again, that this effect is fully due to general relativity, we obtain a total mass of  $1.97 \pm 0.15 M_{\odot}$ , consistent with the estimate made by Possenti et al. (2006):  $2.15 \pm 0.06 M_{\odot}$ . Using the methods applied in the case of NGC 6440B, we calculated PDFs for the mass of this pulsar and its companion for our measurement of the total mass of the binary; these are displayed graphically in Figure 7. There is a 99% probability that the companion is more massive than  $0.53 M_{\odot}$  and that the pulsar is less massive than  $1.65 M_{\odot}$ . The medians for the pulsar and companion masses are  $1.26$  and  $0.67 M_{\odot}$ , respectively, and there is a 45.6% probability that the pulsar mass is within the  $1.20$ – $1.44 M_{\odot}$  mass range. The nature of the companion is unknown, but no observational hints of tidal effects ( $\dot{x}$ ,  $\dot{P}_b$ , DM variations) are present, suggesting it is a compact object.

## 5. CONCLUSION AND PROSPECTS

We have discovered eight new pulsars in the GCs NGC 6440 and NGC 6441. Their pseudoluminositivities indicate that there may be as many pulsars in these GCs as in Terzan 5, but fewer pulsars are observed in the former because of their larger distances. The pulsar population in these GCs seems to have distinctly lower spin frequencies. To some extent, this is due to the presence of apparently young objects like NGC 6440A. At least in the case of NGC 6440A and D, and possibly in the case of the other slow MSPs, the larger spin periods could be related to many of them having higher magnetic fields than the MSPs in other GCs.

Four of the new pulsars are in binary systems. NGC 6440D is an eclipsing binary, with a companion star with a mass of about  $0.12 M_{\odot}$  or larger. NGC 6440B is a 16.7 ms pulsar in a 20.5 day orbit with an orbital eccentricity of 0.57. A measurement of the rate of advance of periastron for this system suggests that this binary hosts the most massive neutron star to date:  $2.74 \pm 0.21 M_{\odot}$ , with only a 1% probability that the inclination is low enough that pulsar mass is below  $2 M_{\odot}$ . This result depends on the (likely) possibility that the observed periastron advance is fully relativistic. Such a large mass would introduce the strongest constraints to date on the equation of state; it also suggests that the products of the coalescence of double neutron stars might be stable neutron stars. The rate of advance of periastron was also measured for NGC 6441A, indicating a significantly less massive pulsar ( $M_p < 1.65 M_{\odot}$ ).

The pulsars in NGC 6440 will be monitored carefully over the next few years. In the case of NGC 6440C, the new data will allow a detailed investigation of the origin of its timing irregularities. In the case of NGC 6440B, the continued monitoring will lead to an improvement in the precision of  $\dot{\omega}$ . Simulations indicate that the Einstein delay ( $\gamma$ ) may become measurable with about 15 yr of data; this would provide unambiguous mass

measurements and determine the nature of the companion. Deep optical studies of NGC 6440 might be extremely valuable in determining the nature of the companion of NGC 6440B.

The National Radio Astronomy Observatory is a facility of the National Science Foundation (NSF) operated under cooper-

ative agreement by Associated Universities, Inc. I. H. S. held an NSERC University Faculty Award while most of this work was performed, and pulsar research at the University of British Columbia is supported by a Discovery Grant. J. W. T. H. holds an NSERC postdoctoral fellowship and CSA supplement. L. H. F.'s work for this paper was sponsored by the Research Experience for Undergraduates program of the NSF.

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