A MASSIVE NEUTRON STAR IN THE GLOBULAR CLUSTER M5

PAULO C. C. FREIRE,1 ALEX WOLSZCZAN,2 MAUREEN VAN DEN BERG,3 AND JASON W. T. HESSELS4

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ABSTRACT

We report the results of 19 years of Arecibo timing for two pulsars in the globular cluster NGC 5904 (M5), PSR B1516+02A (M5A) and PSR B1516+02B (M5B). This has resulted in the measurement of the proper motions of these pulsars and, by extension, that of the cluster itself. M5B is a 7.95 ms pulsar in a binary system with a >0.13 $M_\odot$ companion and an orbital period of 6.86 days. In deep $HST$ images, no optical counterpart is detected within $\sim2.5\sigma$ of the position of the pulsar, implying that the companion is either a white dwarf or a low-mass main-sequence star. The eccentricity of the orbit ($e = 0.14$) has allowed a measurement of the rate of advance of periastron: $\dot{\omega} = 0.0142^{+0.0007}_{-0.0007}$ yr$^{-1}$. We argue that it is very likely that this periastron advance is due to the effects of general relativity, the total mass of the binary system then being $2.29 \pm 0.17 M_\odot$. The small measured mass function implies, in a statistical sense, that a very large fraction of this total mass is contained in the pulsar: $M_p = 2.08 \pm 0.19 M_\odot$ (1 $\sigma$); there is a 5% probability that the mass of this object is $<1.72 M_\odot$ and a 0.77% probability that 1.2 $M_\odot \leq M_p \leq 1.44 M_\odot$. Confirmation of the median mass for this neutron star would exclude most "soft" equations of state for dense neutron matter. Millisecond pulsars (MSPs) appear to have a much wider mass distribution than is found in double neutron star systems; about half of these objects are significantly more massive than 1.44 $M_\odot$. A possible cause is the much longer episode of mass accretion necessary to recycle a MSP, which in some cases corresponds to a much larger mass transfer.

Subject headings: binaries: general — equation of state — pulsars: general — pulsars: individual (PSR B1516+02A, PSR B1516+02B) — stars: neutron

Online material: color figure

1. INTRODUCTION

Over the past 21 years, more than 130 pulsars have been discovered in globular clusters (GCs). Among the first discoveries were PSR B1516+02A and PSR B1516+02B (Wolszczan et al. 1989). Both are located in the GC NGC 5904. This cluster is also known as M5, and we refer to these pulsars below as M5A and M5B. M5A is an isolated millisecond pulsar (MSP) with a spin period of 5.55 ms. M5B is a 7.95 ms pulsar in a binary system with a low-mass companion (see § 5.2) and an orbital period of 6.86 days. At the time of its discovery, this was the MSP with the most eccentric orbit known ($e = 0.14$), this being $10^3$--$10^4$ times larger than that of MSP-white dwarf (WD) systems in the Galactic disk with similar orbital periods.

In the Galactic disk, 80% of all known MSPs are found to be in binary systems and, with the single exception of PSR J1903+0327 (D. Champion 2008, private communication), they are in low-eccentricity orbits with WD companions. In GCs, gravitational interactions with neighboring stars, or even exchange encounters, can produce binary systems with eccentric orbits (Rasio & Heggie 1995). These high eccentricities allow the measurement of post-Keplerian parameters such as the rate of advance of periastron ($\dot{\omega}$) or, in the future, the Einstein delay ($\gamma$) that are not normally measurable in MSP binaries in the Galactic disk. If these effects are relativistic, they allow estimates of the total binary and component masses.

When Anderson et al. (1997) published timing solutions for M5A and B, they used the eccentricity of M5B to detect its periastron advance. However, the large relative uncertainty of the measurement did not allow any astrophysically useful constraints on the total mass of the binary. In this paper we report the results of recent (2001 to 2008) 1.1--1.6 GHz (L-band) observations of M5. The first 2001 observations were part of an Arecibo search for pulsars in GCs, which found 11 new MSPs (Hessels et al. 2007). Three of these were found in M5, and subsequent observations of this GC were made chiefly with the aim of timing these new discoveries (I. H. Stairs et al. 2008, in preparation). M5A and B are in the same radio beam as the new pulsars and they are clearly detectable in the L-band data, permitting timing (see Figs. 1 and 2) of a quality much better than (M5A) or comparable to (M5B) that obtained at 430 MHz by Anderson et al. (1997). The whole data set now spans nearly 19 years and provides much improved timing parameters.

2. OBSERVATIONS, DATA REDUCTION, AND TIMING

M5A and B were observed with the Arecibo 305 m radio telescope from the time of their discovery in 1989 April until 1994 July using the 430 MHz Carriage House line feed. For this, a 10 MHz band centered at 430 MHz was used. The Arecibo correlator spectrometer made a three-level quantization of the signal and correlated this for a total of 128 lags. These data were then integrated for 506.58561 $\mu$s, and the orthogonal polarizations added in quadrature before being written to magnetic tape. The L-band observations began in 2001 June, using the "old" Gregorian L-Wide receiver ($T_{sys} = 40$ K at 1400 MHz). The "new" L-Wide receiver ($T_{sys} = 25$ K at 1400 MHz) has been used since it was installed in the Gregorian dome in 2003 February. The Wide-band Arecibo Pulsar Processors (WAPPs; Dow et al. 2000) make a three-level digitization of the voltages over a 100 MHz band for both (linear)
polarizations, autocorrelating these for a total of 256 lags. The data are then integrated for a total of 64 \( \mu \text{s} \) and the orthogonal polarizations added in quadrature and written to disk. At first, only one WAPP was available, and centered the observing band at 1170 MHz or 1425 MHz. From 2003, three more WAPPs have been available, and we now use three of them to observe simultaneously at 1170, 1425, or 1510 MHz. From 2003, three more WAPPs have been available, and centered the observing band at 1170 MHz or 1425 MHz, the cleanest bands within the wide frequency coverage of the new L-Wide receiver.

For all observations, the lags were Fourier transformed to generate power spectra. For the L-band observations, the power spectra were partially dedispersed at a dispersion measure (DM) of 29.5 cm\(^{-3}\) pc and stored as a set of 16 subbands on the disks of the Borg computer cluster at McGill University. At 1170 MHz, the partial dedispersion introduces an extra smearing of 18 and 1.6 \( \mu \text{s} \) for M5A and B, respectively. Adding these values in quadrature to the dispersive smearing per channel (60.9 and 59.7 \( \mu \text{s} \) respectively), we obtain a total dispersive smearing of 63.5 and 59.7 \( \mu \text{s} \) for M5A and B respectively, i.e., the subbanding introduces very little extra smearing. The 430 MHz power spectra and L-band subbands were dedispersed at the known DM of these pulsars and folded modulo their spin periods. All the L-band data reported in this paper were processed using the PRESTO pulsar software package.\(^6\)

We added the best 1170 MHz detections of both pulsars to derive “standard” pulse profiles, and these are displayed in Figure 1. A minimal set of Gaussian curves were fitted to these profiles to derive synthetic templates for each pulsar, and these were then cross-correlated with each observation’s pulse profile in the Fourier domain (Taylor 1992) to obtain topocentric times of arrival (TOAs). Adding all the 1170 MHz observations irrespective of their signal-to-noise ratio (S/N; this varies from day to day because of diffraction interstellar scintillation), we obtain a “global” pulse profile which has a lower S/N than the “standard” pulse profile. We calculated the average flux densities for both pulsars (see Table 1) from the off-pulse rms in their global profile, assuming a system equivalent flux density of 3.5 Jy, which is valid for 1170 MHz at the high zenith angles required to observe M5.

The TOAs were analyzed with TEMPO,\(^7\) using the DE 405 solar system ephemeris (Standish 1998) to model the motion of the Arecibo radio telescope relative to the solar system barycenter. The orbital parameters for M5B were modeled using the Damour & Deruelle orbital model (Damour & Deruelle 1985, 1986). For most of the early 430 MHz TOAs we have no reliable uncertainty estimates. Therefore, in order to achieve a reduced \( \chi^2 \) of 1 for both pulsars, we attributed a constant uncertainty to the 430 MHz TOAs that is similar to their unweighted rms. These times are listed in Table 1. With these TOAs, we obtain timing parameters that are virtually identical to those obtained by the previous analysis (Anderson et al. 1997). For the new L-band data, we find the TOA uncertainties to be underestimated in the case of M5A. Multiplying these by a factor of about 1.5, we achieve a reduced \( \chi^2 \) of 1 for its L-band TOAs. In the case of M5B, this factor is 1.05. These values are similar to those derived for other MSPs timed with the same software (Freire et al. 2008).

The resulting timing parameters and their \( 1 \sigma \) uncertainties are presented in Table 1. We estimate these uncertainties to be twice the \( 1 \sigma \) Monte Carlo bootstrap (Efron & Tibshirani 1993; Press et al. 1992) uncertainties. We discuss the validity of this choice for the particular case of the periastron advance of M5B in § 5. All the parameters that vary in time (\( \alpha, \beta, \nu, \text{and} \omega \)) are estimated for the arbitrary epoch, MJD = 54,000 (2006 September 22); \( T_0 \) was the first periastron passage to occur after that date. The post-fit timing residuals are essentially featureless at the present timing accuracy (see Fig. 2). The large gap without measurements between the early 430 MHz data and later L-band data is in part due to the Arecibo upgrade of the late 1990s. We included an arbitrary time step between these two data sets in the fit. We have tested the timing solution by introducing extra pulsar rotations between the two data sets, but these are always absorbed by this arbitrary time step, with no other changes in the fitted timing parameters.

The positions, periods, and period derivatives that we have obtained are consistent with those of Anderson et al. (1997). In

\(^6\) See http://www.cv.nrao.edu/~sansom/presto.

\(^7\) Available at: http://www.atnf.csiro.au/research/pulsar/tempo/.
what follows, we analyze solely the newly measured parameters: the proper motions and the rate of advance of periastron of M5B.

3. PROPER MOTIONS

In the reference frame of a GC, the rms of the velocities of its pulsars along the orthogonal axes perpendicular to the line of sight should be the same as the rms of their velocities along the line of sight. The stellar rms velocity along the line of sight at the center of M5 is 7.15 km s\(^{-1}\) (Webbink 1985); the rms of the pulsar velocities should be smaller, given the larger masses of the neutron stars (NSs). At the distance of M5, 7.5 kpc (Harris 1996\(^8\)), the stellar rms velocity represents a proper motion rms of only 0.2 mas yr\(^{-1}\). Given the present measurement precision, the estimated pulsar proper motions should be mutually consistent and reflect only the proper motion of the GC. The proper motion measurements in Table 1 are indeed \(\sim 1\)\(\sigma\) consistent with each other; from their weighted average we derive a proper motion for M5 of \(\mu_\alpha = 4.3 \pm 0.4\) mas yr\(^{-1}\) and \(\mu_\delta = -9.6 \pm 1.0\) mas yr\(^{-1}\).

M5 is one of the four GCs in the Galaxy for which optical proper motion measurements have not provided consistent (i.e., agreeing within the formal uncertainty estimates) results (Dinescu et al. 1999). Our M5 proper motion measurement is in marginal agreement with the values derived by Scholz et al. (1996; \(\mu_\alpha = 6.7 \pm 0.5\) mas yr\(^{-1}\) and \(\mu_\delta = -7.8 \pm 0.4\) mas yr\(^{-1}\)), but is in good agreement with the values derived from Hipparcos (Odenkirchen et al. 1997; \(\mu_\alpha = 3.3 \pm 1.0\) mas yr\(^{-1}\) and \(\mu_\delta = -10.1 \pm 1.0\) mas yr\(^{-1}\)).

4. SEARCH FOR THE OPTICAL COUNTERPART OF M5B

We have used the astrometric information on M5B to search for an optical counterpart in archival HST ACS/WFC data from programs GO 10120 and GO 10615. The GO-10120 images were taken on 2004 August 1 through the F435W, F625W, and F658N filters. Since the uncertainty in the absolute astrometry of HST data is 1"–2", we first tie the astrometry of the GO-10120 ACS images to the ICRS frame using UCAC2 stars (positional accuracy \(\leq 0.070\)" down to the magnitude limit of the UCAC2 catalog; Zacharias et al. 2004). Since UCAC2 standards in the small ACS field (3.4' \times 3.4') are scarce, we use ground-based imaging of M5 to derive secondary standards. We retrieved from the public archive of the 2.5 m Isaac Newton Telescope (INT) a 30 s Sloan-r Wide Field Camera image taken on 2004 June 8 and processed only the chip that contained the core of M5 (field of view \(\sim 23' \times 11'\)). Astrometric calibration of this image was achieved using 308 UCAC2 stars with positions corrected for proper motion to the epoch of the INT image. After fitting for shift, rotation angle, scale factor, and distortions, the final solution has rms residuals of 0.050" in right ascension and 0.047" in declination. We selected a set of 198 secondary standards from unsaturated and relatively isolated stars in the INT image. These were used in turn to compute an astrometric solution for the short (70 s) F435W distortion-corrected (using the MultiDrizzle software) exposure. The resulting fit for shift, rotation angle, and scale factor has rms residuals of 0.017" in right ascension and 0.014" in declination. We estimate the final 1\(\sigma\) accuracy of our ACS absolute astrometry as the quadratic sum of the errors in the UCAC2 astrometry, the UCAC2–INT tie and the INT–HST tie, i.e., 0.1" (or 2 ACS pixels).

The position of M5B at the epoch of the GO-10120 observations is shown in Figure 3. No optical sources are detected within the 2 \(\sigma\) error circle of the radio position (this only includes the uncertainty in the absolute astrometry, as the uncertainties in the radio position are negligible). The photometry shows the nearest sources—indicated as "1" and "2" at distances 2.7 and 3.0 \(\sigma\), respectively—to be main-sequence (MS) stars located \(\sim 1.3\) and

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\(8\) See http://www.physics.mcmaster.ca/resources/globular.html for an updated version of the table.
5. PERIASTRON ADVANCE OF M5B

We have determined a highly significant estimate for the rate of advance of periastron of M5B: \( \dot{\omega} = 0.0142(7) \) yr\(^{-1}\). The 1σ estimate provided directly by TEMPO is \( \dot{\omega} = 0.0142(3) \) yr\(^{-1}\). To verify that these values are realistic, we have 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 obtain the 1σ uncertainty as the half-width of the region where \( \chi^2(\dot{\omega}) - \chi^2(\dot{\omega}_{\text{min}}) < 1 \), \( \dot{\omega}_{\text{min}} \) being the value that minimizes \( \chi^2 \). The result is \( \dot{\omega} = 0.001422(43) \) yr\(^{-1}\) (Splaver et al. 2002). Estimating all parameters using a Monte Carlo bootstrap algorithm (§ 2), we obtain \( \dot{\omega} = 0.01422(36) \) yr\(^{-1}\). Furthermore, the lack of significant higher derivatives of the spin frequency (see Table 1) suggests that, with the present timing precision, we are unable to detect any of this pulsar’s timing noise which can contaminate the physical interpretation of its timing uncertainties. This is a necessary pre-condition for an accurate estimation of parameter uncertainties. We

\begin{table}
\centering
\caption{Parameters for Two Pulsars in NGC 5904}
\begin{tabular}{lcc}
\hline
Observation and Flux Parameters & PSR B1516+02A & PSR B1516+02B \\
\hline
\begin{tabular}{l}
Start of 430 MHz observations \\
End of 430 MHz observations \\
Number of TOAs at 430 MHz (\( \mu s \)) \\
Residual rms at 430 MHz (\( \mu s \)) \\
Start of L-band observations \\
End of L-band observations \\
Number of TOAs at L band \\
Uncertainty scale factor \( ^{\ast} \) \\
Residual rms at L band (\( \mu s \)) \\
Average flux density at 1170 MHz (mJy) \\
\end{tabular} & \begin{tabular}{c}
47635 \\
49432 \\
86 \\
49 \\
52087 \\
54497 \\
1278 \\
1.50 \\
9 \\
0.155 \\
\end{tabular} & \begin{tabular}{c}
82 \\
114 \\
162 \\
72 \\
0.027 \\
\end{tabular} \\
\hline
\end{tabular}
\end{table}

\begin{table}
\centering
\caption{Ephemerides}
\begin{tabular}{lcc}
\hline
Reference epoch (MJD) & 54000 & 54000 \\
R.A., \( \alpha \) (J2000) & \( 15^h18^m33.32307(6) \) & \( 15^h18^m31.4625(8) \) \\
Decl., \( \delta \) (J2000) & \( +02^h05^m27.435(3) \) & \( +02^h05^m30.3(3) \) \\
Proper motion in \( \alpha \), \( \mu_{\alpha} \) (mas yr\(^{-1}\), J2000) & 4.6(4) & 3.4(1.2) \\
Proper motion in \( \delta \), \( \mu_{\delta} \) (mas yr\(^{-1}\), J2000) & \( -8.9(1.0) \) & \( -11.8(2.8) \) \\
Spin frequency, \( \nu \) (Hz) & 180.063624055103(3) & 125.83458757935(6) \\
Time derivative of \( \nu \), \( \dot{\nu} \) \( (10^{-15} \text{ Hz s}^{-1}) \) & \( -1.33874(4) \) & \( 0.05233(15) \) \\
Dispersion Measure, DM (psec cm\(^{-3}\)) & 30.0545(10) & 29.46(3) \\
Orbital period, \( P_o \) (days) & \ldots & \ldots \\
Projected size or orbit, \( x \) (l-rate) & \ldots & 3.04857(2) \\
Orbital eccentricity, \( e \) & \ldots & 0.137845(10) \\
Time of passage through periastron, \( T_0 \) (MJD) & \ldots & 54004.02042(15) \\
Longitude of periastron, \( \omega \) (deg) & \ldots & 359.898(8) \\
Rate of advance of periastron, \( \dot{\omega} \) (deg yr\(^{-1}\)) & \ldots & 0.0142(7) \\
Second time derivative of \( \nu \), \( \ddot{\nu} \) \( (10^{-27} \text{ Hz s}^{-2}) \) & \( [-0.6 \pm 0.5]^{1} \) & \( [4.4 \pm 5.4] \) \\
Time derivative of \( x \), \( \dot{x} \) \( (10^{-12} \text{ l-rate s}^{-1}) \) & \ldots & \( [-0.12 \pm 0.09] \) \\
Time derivative of \( P_o \), \( \dot{P}_o \) \( (10^{-12}) \) & \ldots & \( [15 \pm 31] \) \\
\hline
\end{tabular}
\end{table}

\begin{table}
\centering
\caption{Derived parameters}
\begin{tabular}{lcc}
\hline
Spin period, \( P \) (ms) & 5.55359254401089(11) & 7.946940656275(4) \\
Time derivative of \( P \), \( \dot{P} \) \( (10^{-21} \text{ s s}^{-1}) \) & 41.2899(13) & \ldots \\
Mass function, \( f(M_{\text{p}}) \) & \ldots & \ldots \\
Total system mass, \( M_p \) (\( M_\odot \)) & \ldots & 0.000646723(13) \\
Maximum pulsar mass, \( M_{\text{p max}} \) (\( M_\odot \)) & \ldots & 2.52 \\
Minimum companion mass, \( M_{\text{min}} \) (\( M_\odot \)) & \ldots & 0.13 \\
\hline
\end{tabular}
\end{table}

\end{document}
therefore believe that the 1σ TEMPO uncertainty estimates are essentially accurate. We choose, however, to be more conservative by making our 1σ uncertainties twice as large as the values suggested by the Monte Carlo method (see Table 1). This caution is due to our use of two different data sets with a large time gap between them.

This time gap is common to many Arecibo timing data sets, such as that of PSR J0751+1807. Nice et al. (2005) claimed a mass of 2.1 \( M_\odot \) for that pulsar. This claim has recently been retracted, the latest estimate for the pulsar mass now being 1.26\( ^{+0.14}_{-0.12} \)\( M_\odot \) (1σ; Nice 2008\(^{9}\) ). The problem with the earlier estimate was not related to the gap, as the new estimate is based on essentially the same data. Its cause was the use of a necessarily imperfect ephemeris when folding the very earliest data. This resulted in orbital-dependent smearing of the pulse profiles that led to an error in the calculation of the orbital phase for the earliest data and an overestimate of the orbital period decay. Because those data were folded online, this problem could only be solved by ignoring the earliest TOAs. Our 430 MHz data contained the signals of more than one pulsar, so we had to record them to tape. This allowed us to refold them iteratively after the timing solution had been obtained (Anderson et al. 1997). After updating the timing solution to 2008, we have also refolded all our L-band data; therefore none of the pulse profiles used in this work are smeared due to imprecise folding.

5.1. Is \( \dot{\omega} \) Relativistic?

The possible contributions to \( \dot{\omega} \) in a system containing a pulsar and an extended star have been studied in detail by Lai et al. (1995). In their analysis of the binary pulsar PSR J0045−7319, they concluded that the only likely contribution to \( \dot{\omega} \) in such systems is from rotational deformation of the companion. If we assume that PSR J0045−7319 has a mass of 1.4 \( M_\odot \), the companion mass is 8.8 \( M_\odot \), and the companion radius is \( R_c \sim 6.4 \ R_\odot \) (Bell et al. 1995), the orbital separation \( a \sim 126 \ R_\odot \). Using these values, they reached the conclusion that the contribution to \( \dot{\omega} \) from tidal deformations, which are proportional to \( (R_c/a)^3 \sim 1.32 \times 10^{-4} \), is not significant in that system. For MSB, again assuming a pulsar mass of 1.4 \( M_\odot \), with a MS companion of maximum mass 0.3 \( M_\odot \) (see § 4) and radius \( R_c = 0.3 r_{0.3} R_\odot \) (where \( r_{0.3} \sim 1 \)), then the orbital inclination \( i \) is \( \sim 24^\circ \), \( a \sim 18 \ R_\odot \), and \( (R_c/a)^3 \sim 4.5 \times 10^{-6} r_{0.3}^2 \). This is 30 times smaller than for PSR J0045−7319, becoming even less significant for smaller MS companion masses and correspondingly higher inclinations.

Using equations (68) and (79) of Wex (1998), we can estimate the contribution to \( \dot{\omega} \) due to rotational deformation:

\[
\dot{\omega}_{\text{rot}} = n \frac{k R_c^2 \Omega^2}{a^2 (1-e^2)^2} \left( 1 - \frac{3}{2} \sin^2 \theta + \cot i \sin \theta \cos \theta \cos \Phi_0 \right),
\]

where \( n \) is the orbital angular frequency (\( 2\pi/P_b = 1.06 \times 10^{-5} \) rad s\(^{-1} \)), \( k \) is the gyration radius (for a homogeneous sphere this is 0.63, while for any centrally condensed objects this will always be smaller; it is about 0.2 for a completely convective star), \( \Omega \) is the rotation rate relative to break-up, \( \theta \) is the angle between the rotational and orbital angular momenta (if the companion is nondegenerate, these tend to be aligned, so \( \theta = 0 \)), 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).

For the situation discussed above (a 1.4 \( M_\odot \) pulsar with the latest possible MS companion, \( R_c = 0.3 r_{0.3} R_\odot \)), we have \( R_c/a = 16.55 \times 10^{-3} r_{0.3} \). We can also calculate the break-up angular velocity:

\[
\Omega_{\text{max}} = \sqrt{\frac{G M_c/R_c^3}{1 + \frac{1}{3} \sqrt{\frac{G M_c}{r_{0.3} R_c} r_{0.3}^{-3/2}}}} \text{ rad s}^{-1}.
\]

If the companion’s rotation is tidally locked to its orbit around the pulsar, then \( \Omega = n/\Omega_{\text{max}} = 5.06 \times 10^{-6} r_{0.3}^{-1/2} \). Therefore, \( \dot{\omega}_{\text{rot}} = 2.65 \times 10^{-15} r_{0.3} \text{ rad s}^{-1} = 4.79 \times 10^{-6} r_{0.3}^{-3/2} \text{ yr}^{-1} \) (or 3 times this if the companion were to be a homogeneous sphere). This is \( \sim 3 \times 10^3 \) times smaller than the value we determined (§ 5). If the companion were to be significantly distended for its mass (i.e., if \( r_{0.3} > 1 \)), as is the case for the companion of PSR J1740−5340 (Ferraro et al. 2001), then \( \dot{\omega}_{\text{rot}} \) could be significant. This scenario can be excluded, since no optical counterpart is readily detectable within \( \sim 2.5 \sigma \) of the pulsar (see § 4).

If the companion were to be a WD, then it could be more massive than 0.3 \( M_\odot \) and still evade optical detection. Irrespective of its mass, the contribution to \( \dot{\omega} \) from tidal deformation of a WD is negligible, but that is not necessarily the case for the contribution from rotational deformation. As an example, we recalculate \( \dot{\omega}_{\text{rot}} \) for a 0.3 \( M_\odot \) WD. For WDs, we have \( k = 0.45 \) (Livio & Pringle 1998), more than twice as large as for fully convective stars. For WDs \( r_{0.3} \) is of the order of 0.1, i.e., the \( (R_c/a)^2 \) term in equation (1) would be \( \sim 10^2 \) times smaller than discussed for \( r_{0.3} \sim 1 \). However, a WD companion is not likely to be tidally locked. If it were spinning fast, then \( \Omega \sim 1 \). While there is no special a priori reason why this should be true, it is a possibility that cannot be excluded. This would mean that \( \Omega^2 \) could be \( \sim 4 \times 10^4 \) times larger than discussed above, with \( \dot{\omega}_{\text{rot}} \) similar to the observed \( \dot{\omega} \). This is particularly so for the larger sized WDs (those

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\(^9\) See also http://www.ms2007.org/talks/nice.pdf.
with the lowest masses). Following Splaver et al. (2002), we note first that if the companion is not tidally locked, the angular momenta of the orbit and companion spin will probably not be aligned ($\theta \neq 0$). In this case, the spin of the companion will induce a precession of the orbital plane. This will cause a change in $i$, affecting the projected semimajor axis of the orbit, which will vary with a rate $\dot{x}$. Rewriting equation (81) of Wex (1998), we can relate $\dot{\omega}_{\text{rot}}$ to $\dot{x}$:

$$\dot{\omega}_{\text{rot}} = -\frac{\dot{x}}{x} \left[ \frac{1}{\sin \theta} \frac{1 - (3/2) \sin^2 \theta}{\sin \theta \cos \theta \sin \phi_0 + \cot \phi_0} \right].$$

This equation has the advantage that it does not depend on the mass (or the nature) of the companion. Thus, our observed $2 \sigma$ upper limit of $|\dot{x}/x| < 9.6 \times 10^{-14}$ s$^{-1}$ implies $|\dot{\omega}_{\text{rot}}| < (1.7 \times 10^{-5})$ yr$^{-1}$ times a geometric factor. In 80% of cases this geometric factor will be smaller than 10, and the upper limit for $\dot{\omega}_{\text{rot}}$ is similar to the present measurement uncertainty for $\dot{\omega}$.

To summarize, $\dot{\omega}_{\text{rot}}$ can only be significant if the companion is degenerate, rotating near breakup velocity, and with its rotational angular momentum nearly aligned with the orbital angular momentum, making $\dot{x}$ undetectable. Otherwise, $\dot{\omega}$ is relativistic.

### 5.2. Binary, Pulsar, and Companion Masses

When $\dot{\omega}$ is solely due to the effects of general relativity, we can measure the total mass of a binary system:

$$M = \left( \frac{P_0}{2\pi} \right)^{5/2} \left[ \frac{1 - \gamma^2 \omega_0^2}{3} \right]^{3/2} \left( \frac{1}{T_0} \right),$$

where $T_0 \equiv GM_*/c^3 = 4.9254909474\mu$s. For M5B, we obtain $M = 2.29 \pm 0.17 M_\odot$. For the nominal value of $\omega$ and a median $i$ of 60°, the mass of the companion is 0.173 $M_\odot$, and the mass of the pulsar is 2.11 $M_\odot$. This is well above all NS masses that have been precisely measured to date.

We calculated a two-dimensional probability distribution function (pdf) for the mass of the pulsar and the mass of the companion, assuming that the pdf for $\omega$ is a Gaussian with the half-width equal to the $1 \sigma$ uncertainty listed in Table 1 and an a priori constant probability for cos $i$. The two-dimensional pdf is then projected in both dimensions, resulting in one-dimensional pdfs for the mass of the pulsar and the mass of the companion. These are displayed graphically in Figure 4. The pulsar definitely has a mass smaller than 2.52 $M_\odot$, and the companion has a mass larger than 0.13 $M_\odot$. The median and $1 \sigma$ limits for the pulsar and companion mass are 2.08\(^{+0.18}_{-0.15}\) and 0.172\(^{+0.107}_{-0.052}\) $M_\odot$, respectively. There is a 99%, 95%, and 90% probability that the pulsar is more massive than 1.38, 1.72, and 1.82 $M_\odot$, respectively. There is a 0.77% probability that $i$ is low enough to make the NS mass fall within the range of the components of double neutron star (DNS) systems, from 1.20 $M_\odot$ measured for the companion of PSR J1737$-$2235 (Faulkner et al. 2005) to 1.44 $M_\odot$ measured for PSR B1913+16 (Weisberg & Taylor 2003). For M5B, assuming its nominal value of $\omega$, these mass limits would imply that 7.9° $< i < 10.2°$.

### 6. Statistical Evaluation of Mass Measurements

M5B has the second largest mass estimate among all known NSs after PSR J1748$-$2021B (NGC 6440B). Because of indeterminate orbital inclinations, all mass estimates based solely on $\dot{\omega}$ are probabilistic statements: one more PK parameter is necessary to have an unambiguous determination of $i$ and $M_\text{p}$. No such parameters have yet been measured for M5B, NGC 6440B, or any other eccentric MSP binaries in GCs; in some cases this is due to their low timing precision (like M5B, which is faint and has a broad pulse profile), and in others to their small timing baselines (like NGC 6440B). Nevertheless, unambiguous upper limits for the pulsar masses and lower limits for the companion masses can always be obtained from a measurement of a relativistic $\dot{\omega}$ alone (see Table 2). Furthermore, in systems where the mass function is very small and the total binary mass is very large (as for M5B and NGC 6440B) there is a much greater probability that most of the mass of the binary belongs to the pulsar itself, as described in § 5.2.

### 6.1. Evidence for High Average Neutron Star Masses

An interesting feature of the eccentric binary MSPs in GCs is that as the binary mass increases, the mass function $f$ does not increase (see Table 2). The exception is NGC 1851A, a system thought to have resulted from an exchange interaction (Freire et al. 2004). If these binaries were to have $M_\text{p} < 1.44 M_\odot$, then the increase in total mass would be due to higher companion masses, resulting in a general trend to higher mass functions. This is generally not the case.

If we assume that all these GC MSPs have “normal” masses (between 1.2 and 1.44 $M_\odot$), we can then calculate the orbital inclinations of these binaries from their total masses and mass functions. These are displayed graphically in Figure 5. Of the five massive GC systems, four seem to have small orbital inclinations (i.e., with cos $i > 0.8$), the exception being NGC 1851A. A priori, one would expect only one out of five systems to have such a small $i$. We have used a Kolmogorov-Smirnov test to compare the cos $i$ values corresponding to the nominal $\omega$ values and $M_\text{p} = 1.44 M_\odot$ (only possible to calculate for the five massive binaries) with a fake set of 100 randomly oriented binary systems (i.e., with a uniform distribution of cos $i$). We obtain a 0.46% probability that the observed distribution is extracted from this set with random orbital orientations. If we use instead $M_\text{p} = 1.2 M_\odot$, we can calculate cos $i$ for all the eccentric GC binaries. The probability that the resulting distribution of cos $i$ is selected from the set with random orientations is 7.7 $\times 10^{-5}$.

Such low inclinations might be less unlikely were there a tendency for pulsars to emit in a plane perpendicular to their orbit. During accretion, orbital angular momentum is transferred to the NS, making its rotation axis nearly perpendicular to its orbital plane. If the angle between the magnetic and rotational axes of pulsars ($\alpha$) is small, the magnetic axis will describe a narrow cone nearly perpendicular to the orbital plane. However, no such tendency for small $\alpha$ has been described in the literature. If a pulsar has a small $\alpha$, its beam will probably illuminate a smaller fraction of the sky, particularly if it is narrow. This can only make the low-$\alpha$ objects less likely to be detected. Furthermore, no such tendency toward low orbital inclinations is seen among the two lighter binary MSPs in GCs, nor among the systems with estimated orbital inclinations: NGC 6752A has $i > 70°$ (Bassa et al. 2006), PSR J1909$-$3744 has $i = 86.6\(^{+1}_{-2}\)$ (Jacoby et al. 2005; Hotan et al. 2006), PSR J0437$-$4715 has $i \sim 43°$ (Verbiest et al. 2008), and the massive binary PSR J1903+0327 has $i \sim 79°$ (D. Champion 2008, private communication).
If the low mass functions of the massive binaries are not a result of systematically low orbital inclinations, they can only be due to systematically small companion masses. This implies that in the majority of these systems the pulsar masses are significantly larger than in the lighter binaries.

### 6.2. Implications for the Equation of State of Dense Matter

Because there is no physically plausible reason to assume that most massive binaries have a small \( i \), we now assume that the probability density of \( \cos i \) is constant. We use this to calculate the mass pdfs from \( \omega \) as described in § 5.2 for all the pulsars in Figure 5. The pdfs are displayed graphically in Figure 6. If the probability that \( 1.2 M_\odot < M_p < 1.44 M_\odot \) is small (as is the case for Terzan 5 I and J, M5B, and NGC 6440B), it is a direct indication that the required orbital inclination ranges are very narrow (as shown in Fig. 5) and therefore unlikely under the present assumption. For M5B, this probability is only 0.77%, while for NGC 6440B it is even smaller, only 0.10%. Multiplying such probabilities for all the massive MSPs in GCs, we obtain a composite probability of \( 5.3 \times 10^{-9} \) that all have masses between 1.2 and 1.44 \( M_\odot \). It is therefore very likely that some of these NSs are significantly more massive.

As discussed above in § 5.2, for M5B there is a 95% probability that the pulsar is more massive than 1.72 \( M_\odot \). This would exclude a third of the equations of state considered in Lattimer & Prakash (2007). However, in this respect NGC 6440B should be far more constraining; there are 99% and 95% probabilities that the mass of that pulsar is \( >2.01 \) and \( 2.36 M_\odot \), respectively. We consider the M5B result to be more secure; the nondetection of its \( \dot{\omega} \) (§ 5.1).

There are two MSPs listed in Table 2 for which large masses have already been determined, PSR J0437−4715 and PSR J1903+0327. The latter in particular has the potential for a precise, unambiguous measurement of a large pulsar mass in the very near future. At the moment, it has not been confirmed whether its \( \omega \)
| Name                  | PSR        | GC          | P (ms) | P_b (days) | e    | f/M_⊙ | M/M_⊙a | M_r/M_⊙ | M_p/M_⊙ | Methodb | Reference |
|-----------------------|------------|-------------|--------|------------|------|-------|--------|---------|---------|---------|-----------|
| J0751+1807            |            |             |        |            |      |       |        |         |         |         |           |
| J1911-5958A           | NGC 6752   |             | 3.26619| 0.83711    | <0.00001| 0.002688| 1.58±0.16| 0.18(2) | 1.40±0.10| Opt.     | 2         |
| J1909+3744            |            |             | 2.94711| 1.53345    | 0.00000| 0.003122| 1.67±0.3 | 0.2038(22)| 1.47±0.8 | r,s      | 3         |
| J0437-4715            |            |             | 5.75745| 5.74105    | 0.00002| 0.001243| 2.01(20)| 0.254(14) | 1.76(20) | r,s      | 4         |
| J1903+0327            |            |             | 2.14991| 95.1741    | 0.43668| 0.139607| 2.88(9) | 1.07(2)  | 1.81(9)  |          |           |

Selected MSP Mass Measurements

| Name                  | PSR        | GC          | P (ms) | P_b (days) | e    | f/M_⊙ | M/M_⊙a | M_r/M_⊙ | M_p/M_⊙ | Methodb | Reference |
|-----------------------|------------|-------------|--------|------------|------|-------|--------|---------|---------|---------|-----------|
| J0024-7204H           | 47 Tucanae |             | 3.21034| 2.35770    | 0.07056| 0.001927| 1.61(4) | >0.164  | <1.52   |          | 6         |
| J1824-2452C           | M28        |             | 4.15828| 8.07781    | 0.84704| 0.006553| 1.616(7)| >0.260  | <1.367  |          | 7         |
| J1748-2446I           | Terzan 5   |             | 9.57019| 1.328      | 0.428  | 0.003658| 2.17(2) | >0.24   | <1.96   |          | 8         |
| J1748-2446J           | Terzan 5   |             | 80.3379| 1.102      | 0.350  | 0.013066| 2.20(4) | >0.38   | <1.96   |          | 8         |
| B1516+02B             | M5         |             | 7.94694| 6.85845    | 0.13784| 0.000647| 2.29(17)| >0.13   | <2.52   |          | § 5.2     |
| J0514+0002A           | NGC 1851   |             | 4.99058| 18.7852    | 0.88798| 0.145495| 2.453(14)| >0.96   | <1.52   |          | § 9       |
| J1748-2021B           | NGC 6440   |             | 16.76013| 20.5500    | 0.57016| 0.000227| 2.91(25)| >0.11   | <3.3    |          | § 10      |

a Binary systems are sorted according to the total estimated mass M.

b Methods are: (P_b) relativistic orbital decay; (r,s) Shapiro delay “shape” and “range”; (Opt) optically derived mass ratio, plus mass estimate based on spectrum of companion; (ω) precession of periastron.

This pulsar is not technically a MSP; its spin period is longer than those found in most DNS systems. However, given the similarity of its orbital parameters to those of Terzan 5 I, we assume that it had a similar formation history.

Because of its large companion mass and eccentricity, this system is thought to have formed in an exchange interaction (Freire et al. 2004).

References.—(1) Nice et al. 2008 (total and companion masses not provided); (2) Bassa et al. 2006; (3) Hotan et al. 2006; (4) Verbiest et al. 2008; (5) D. Champion 2008, private communication; (6) Freire et al. 2003; (7) Bégin et al. 2008; (8) Ransom et al. 2005; (9) Freire et al. 2007; (10) Freire et al. 2008.
is relativistic or not, although it is likely to be so. These results strengthen the case for the existence of massive NSs.

7. FORMATION OF MASSIVE NEUTRON STARS

The MSP mass estimates in Table 2 and the mass pdfs in Figure 6, especially those of M5B and NGC 6440B, suggest that the distribution of MSP masses could span a factor of 2, a situation that is completely different from that found for the components of DNSs. NGC 1851A and the MSPs in the “light” ($M < 2 M_\odot$) binaries have masses smaller than 1.5 $M_\odot$, i.e., they are not significantly more massive than mildly recycled NSs, despite having spin frequencies of hundreds of Hz. In particular, the case of M28C demonstrated that if all NSs start with $M_p > 1.2 M_\odot$, then some MSPs can be recycled by accreting $<0.15 M_\odot$ from their companions. At the other end of the distribution, NGC 6440B could be twice as massive.

It could be that MSPs were born with this wide range of masses. Hydrodynamical core-collapse simulations (Timmes et al. 1996; Belczynski et al. 2008) indicate that stars below $\sim 18 M_\odot$ form $\sim 1.20–1.35 M_\odot$ NSs (such as 47 Tuc H, M28C, and NGC 1851A), while stars with masses between 18 and $20 M_\odot$ form 1.8 $M_\odot$ NSs (similar to PSR J0437$-$4715, PSR J1903+0327, Terzan 5 I, J, and M5B). Above $20 M_\odot$, stars experience partial fallback of material immediately after the supernova that can significantly increase the mass of the stellar remnant, making it either a supermassive NS (like NGC 6440B) or a black hole.

This possibility raises the question of why such massive NSs, while representing about half of the MSPs in Table 2, have not been found among the nine known DNS systems. Most of the secondary NSs in DNS systems have masses between 1.2 and 1.3 $M_\odot$, and recently van den Heuvel (2007) suggested that these were formed by electron capture (EC) supernovae. The nine primary NSs in DNS systems were still likely formed in normal (iron core collapse) supernovae. The predicted percentage of massive NSs is quite small, and with only nine known DNS we are unlikely to see any massive NSs as the primary (Belczynski et al. 2008), a situation that is very different from what is derived for the MSPs.

If the extra mass of some MSPs were instead acquired during the long accretion episodes that recycled them, we can explain naturally why we only see massive NSs as MSPs (not just in GCs, but also in the Galaxy; e.g., Verbist et al. 2008; D. Champion 2008, private communication) but not in DNS systems.

8. CONCLUSION

We have measured the positions and proper motions of M5A and B. This has allowed a detailed search for the companion of M5B. However, no object was detected within $2.5 \sigma$ of the position of M5B to a magnitude limit of 26–26.5, indicating that its companion is either a low-mass MS star or a WD. We have measured the rate of advance of periastron for this binary system, concluding that it is very likely due solely to the effects of general relativity. In this case, the total mass of the binary is $2.29 \pm 0.17 M_\odot$, similar to the total masses of Terzan 5 I and J. Like those pulsars and NGC 6440B, the relatively low mass function for M5B indicates that most of the system mass is likely to be in the pulsar, which we estimate to be $2.08 \pm 0.19 M_\odot$ (1 $\sigma$). There is a 95% probability that the mass of this pulsar is above $1.72 M_\odot$.

If confirmed, this would exclude about a third of the equations of state that are now accepted as possible descriptions of the bulk properties of superdense matter.

Together with other recent results, the large mass derived for M5B suggests that MSPs have a very broad mass distribution; half of these objects seem to be significantly more massive than 1.44 $M_\odot$. It is likely that all NSs began with the a narrow mass...
range like that found in DNS. They then accreted different amounts of matter (in some cases as much as their starting mass) during their evolution to the MSP phase.

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