A HIGHLY ECCENTRIC 3.9 MILLISECOND BINARY PULSAR IN THE GLOBULAR CLUSTER NGC 6652

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ABSTRACT

We present the Robert C. Byrd Green Bank Telescope discovery of the highly eccentric binary millisecond pulsar PSR J1835-3259A in the Fermi Large Area Telescope-detected globular cluster NGC 6652. Timing over one orbit yields the pulse period 3.89 ms, orbital period 9.25 days, eccentricity ~0.95, and an unusually high companion mass of 0.74 $M_\odot$ assuming a 1.4 $M_\odot$ pulsar. We caution that the lack of data near periastron prevents a precise measurement of the eccentricity, and that further timing is necessary to constrain this and the other orbital parameters. From tidal considerations, we find that the companion must be a compact object. This system likely formed through an exchange in the dense cluster environment. Our initial timing results predict the measurements of at least two post-Keplerian parameters with long-term phase-connected timing: the rate of periastron advance $\dot{\omega}$ ~0.71 yr$^{-1}$, requiring 1 year of phase connection; and the Einstein delay $\gamma_{\text{GR}}$ ~10 ms, requiring 2–3 years of timing. For an orbital inclination $i > 50^\circ$, a measurement of $\sin i$ is also likely. PSR J1835-3259A thus provides an opportunity to measure the neutron star mass with high precision, to probe the cluster environment, and, depending on the nature of the companion, to investigate the limits of general relativity.

Key words: binaries: close – equation of state – globular clusters: individual (NGC 6652, NGC 6388) – gravitation – pulsars: individual (NGC 6652A)

1. INTRODUCTION

Globular clusters (GCs) are efficient producers of low-mass X-ray binaries (LMXBs) and their descendant millisecond pulsars (MSPs; Papitto et al. 2013 and references therein): orders of magnitude more MSPs and LMXBs exist, by mass, in clusters than in the Galactic field (Camilo & Rasio 2005). The dense GC environment heightens the probability of stellar interactions (parameterized by encounter rate $\gamma$; Verbunt & Freire 2014), increasing the likelihood of forming new binaries and of existing binaries gaining new companions. Systems that rarely (if ever) form through known binary evolutionary channels in the field can in principle form through such stellar interactions in GCs, for example: sub-ms pulsars, highly eccentric binaries, or unusual binary systems like MSP-main sequence (MS; Pallanca et al. 2010 and references therein), MSP-MSP, or MSP–black hole (MSP–BH) binaries (Ransom et al. 2008). Such systems would allow astrophysical studies that may not otherwise be possible, e.g., strong-field tests of gravity with MSP–MSP or MSP–BH binaries.

The Fermi Large Area Telescope (LAT) has found MSPs to be nearly ubiquitous $\gamma$-ray emitters; GeV emission from GCs (Abdo et al. 2010; Tam et al. 2011) may originate from the clusters’ MSP populations (e.g., Venter et al. 2009). The LAT-detected GCs included NGC 6388 and NGC 6652 (Abdo et al. 2010), neither of which contained any known MSPs, but whose $\gamma$-ray luminosities implied large MSP populations. NGC 6388 is particularly interesting due to its high encounter rate (e.g., Freire et al. 2008; Maxwell et al. 2012); NGC 6652 may also have a higher encounter rate than previously thought (Noyola & Gebhardt 2006). The presence of an MSP population is supported by the number of X-ray sources, including LMXBs, in both clusters (at least two in NGC 6652 and five in NGC 6388: Maxwell et al. 2012; Stacey et al. 2012). We searched these clusters for radio pulsars; here we report on the discovery and timing of a highly eccentric binary MSP in NGC 6652.

2. OBSERVATIONS AND PULSAR SEARCH ANALYSIS

We observed NGC 6388 and NGC 6652 (Table 1) with the National Radio Astronomy Observatory, Robert C. Byrd Green Bank Telescope (GBT) and the Green Bank Ultimate Pulsar Processing Instrument backend (DuPlain et al. 2008), at S band (2 GHz) in coherent search mode. The data were taken with 2048 spectroscopic channels and an effective bandwidth of 700 MHz (accounting for excised radio frequency interference), with coherent dedispersion at the clusters’ predicted dispersion measure (DM) values (Table 1). The observing log and minimum detectable flux densities $S_{\text{min}}$ for an assumed 10% duty cycle are given in Table 2.

The data were analyzed using PRESTO (Ransom et al. 2001). Time series were dedispersed at 1900 DMs from 0 to 691 cm$^{-3}$ pc for NGC 6652 and 5456 DMs between 0 and 800 cm$^{-3}$ pc for NGC 6388, and were searched for periodicities. We searched for accelerated signals over $z = \pm 200$ Fourier bins (see Ransom et al. 2001), corresponding to maximum line of sight accelerations between $\pm 300 - 3000$ cm s$^{-2}$ for a 5 ms pulsar.

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8 http://www.cv.nrao.edu/~sransom/presto/
3. DISCOVERY AND INITIAL TIMING ANALYSIS OF PSR J1835-3259A

We discovered PSR J1835-3259A (hereafter NGC 6652A) in the direction of NGC 6652 (DeCesar et al. 2011), with the fundamental frequency at an acceleration of 11.1 cm s\(^{-2}\) on 23 October 2010 (\(z = 9\)). Figure 1 shows the PRESTO discovery plot, and Table 2 contains estimates of the 2 GHz flux density \(S_2\). We discuss the unexpectedly low DM value of 63.35 cm\(^{-3}\) pc below (Section 4.1).

We fit the Doppler-shifted \(P\) and \(\dot{P}\) (Table 2) with a phase-incoherent orbital model Freire et al. (2001), using a routine by R. Lynch (2011, private communication) employing \texttt{mpfit}\(^{9}\), and found a very eccentric orbit (\(e > 0.7\)). Starting with this orbital model, we ran \texttt{tempo}\(^{10}\) iteratively on the pulse times of arrival (TOAs; Table 2) to converge on a family of timing solutions. We phase-connected the first five observations; we did not observe the pulsar at periastron, between observations 5 and 6, so we allowed the phase between these observations to remain arbitrary (i.e., we kept a JUMP between these observations’ sets of TOAs). Using the DD model (Damour & Deruelle 1985, 1986), we find \(e = 0.968\). “Faking” phase connection by removing the JUMP yields \(e = 0.950\); alternatively, including arbitrary phase JUMPs between all TOA sets yields \(e ≈ 0.8\), which we take to be the lowest possible \(e\) of this system.

The best-fit DD timing model parameters are in Table 3, with fit residuals in Figure 2. The systematics in the residuals are present in all our fits, including those with JUMPs between all observations; we attribute them to parameter, and therefore phase, uncertainties resulting from the lack of TOAs through periastron. We stress that the initial timing parameters in Table 3 belong to a family of solutions that the MSP’s timing solution requires further observations, especially through periastron passage. If further timing confirms the parameters, then NGC 6652A will be the most eccentric binary MSP known to date.

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9 http://cars9.uchicago.edu/software/python/mpfit.html
10 http://tempo.sourceforge.net/
4. DISCUSSION

We adopt timing parameters from the $e = 0.950$ model, pulsar mass $m_p = 1.4 M_\odot$, and cluster parameters from (Harris 1996, 2010 edition) for all calculations, unless otherwise stated.

4.1. Cluster Membership

The discrepancy between the discovery and predicted DMs (63.35 and 190 cm$^{-3}$pc, respectively) initially led us to question the MSP’s cluster association (DeCesar et al. 2011). However, the Cordes & Lazio model commonly has uncertainties of a factor 0.5–2, and sometimes larger. The measured DM is consistent with the low optical reddening $E_{B-V} = 0.10 \pm 0.02$ (Ortolani et al. 1994) and estimated X-ray absorption column $N_{\text{H}} \approx 5.5 \times 10^{20}$ cm$^{-2}$ (Predehl & Schmitt 1995) toward NGC 6652.

The high $e$ of NGC 6652A is much more probable in a GC than in the field due to the high probability of stellar encounters (Camilo & Rasio 2005), discussed further below. Additionally, given the beamwidth of the GBT at S-band (6/3), we estimate a $\approx 0.2\%$ chance of finding an unassociated MSP coincident with NGC 6652 (assuming an isotropic distribution of known galactic MSPs). We conclude that the MSP is almost certainly a cluster member.

4.2. Nature of the Companion

The minimum companion mass (orbital inclination $i = 90^\circ$) is $m_{c,\text{min}} \approx 0.74 M_\odot$ (Table 3). Comparing with the Australia Telescope National Facility Pulsar Catalog,$^{11}$ shows that the companion is unusually massive; it may be a MS or evolved star, or a compact object. Based on the cluster’s age ($11.7 \pm 1.6$ Gyr; Chaboyer et al. 2000), the MS turn-off mass is $\approx 0.8 M_\odot$ (Stacey et al. 2012). For $i < 70^\circ$, $m_c > 0.8 M_\odot$, limiting the range of inclinations for which an unevolved MS companion is possible (c.f. Freire et al. 2007).

For a non-compact companion, significant tides at periastron will circularize the orbit. The circularization, or dissipation, timescale $t_0$ for an eccentric binary system can be estimated as

$^{11}$ http://www.atnf.csiro.au/people/pulsar/psrcat/
Table 3

| Timing Parameter        | With Jump | Without Jump |
|-------------------------|-----------|--------------|
| R.A. \(J2000.0\)        | 18º 35' 44.856 | 18º 35' 44.856 |
| Decl. \(J2000.0\)       | -32º 59' 25.08 | -32º 59' 25.08 |
| Dispersion Measure \(\text{cm}^{-3} \text{pc}\) | 63.35 | 63.35 |
| Spin period, \(P\) (ms) | 3.888824(1) | 3.8888289774(4) |
| Spin period epoch (MJD) | 55488.931354 | 55488.931354 |
| Spindown rate \(\dot{P}\) \(\text{ms}^{-1}\) | 0 | 0 |
| Orbital period, \(P_o\) (days) | 9.2460(5) | 9.2459(5) |
| Projected semimajor axis, \(a\) (\(\text{cm}\)) | 19.6(3) | 19.09(5) |
| Eccentricity, \(e\) | 0.968(5) | 0.950(1) |
| Epoch of periastron passage, \(T_p\) (MJD) | 55477.061(5) | 55477.040(1) |
| Longitude of periastron, \(\omega\) (degrees) | 291.1(1) | 289.2(2) |
| Minimum companion mass, \(m_{\text{c, min}}\) | 0.765(14) | 0.736(3) |
| \((M_{\odot})\) | | |
| Fit \(\chi^2\) per degrees of freedom | 347.9/35 | 360.37/36 |

Notes.
- The solution uses the DD model (Damour & Deruelle 1985, 1986) and the TDB time system. The error on the last digit(s) of each parameter value is denoted in parentheses. The true solution is one in a family of solutions represented by the parameters listed here. The middle column gives the timing parameters obtained when allowing an arbitrary number of pulsar rotations between the fifth and sixth observations. The right column gives the parameters obtained with “forced” phase connection. The unique solution will be determined with further timing observations that include a periastron passage.
- The position was fixed at the cluster’s center.
- The DM was fixed to this best value from the discovery observation (2010 October 19).
- The spindown rate was fixed at zero; a phase-connected timing solution spanning ~one year will measure this parameter.

\[(\text{Socrates et al. 2012, and references therein})\]

\[t_D = \frac{m_c a_e s}{3k_1 \tau GM_{\odot} R^5} \]  

where \(a_e \equiv a \sin i (1 - e^2) \), \(\tau\) is the constant tidal lag time of the companion, \(k_1\) is the Love number, and \(R\) is the companion’s radius. For high \(e\), the tidal quality factor \(Q\) is related to \(\tau\) by Equation (23) of Socrates et al. (2012). We estimate \(k_1\) to be between 0.05 and 0.15 for both MS and white dwarf (WD) companions, based on calculations with Modules for Experiments in Stellar Astrophysics (MESA; Paxton et al. 2011; Brooker & Olle 1955). For \(Q = 10^6\), the circularization timescales are \(~\text{Myr}\) for an MS companion and \(~10^4\) Gyr for a WD companion. We conclude that the companion is a compact object, whose mass and nature will be constrained through further timing.

The merger timescale from gravitational-wave-driven inspiral depends on \(e\) as \(t_{\text{merge}} \propto (1 - e^2)^{7/2}\) (Peters 1964). For \(i = 90°\) \((m_{\text{c, min}} = 0.74 M_{\odot})\) and \(e = 0.95\), \(t_{\text{merge}} \approx 12\) Gyr; varying \(e\) yields a range of \(t_{\text{merge}} \sim 1\) Gyr \((e = 0.975)\) to \(>100\) Gyr \((e \lesssim 0.9)\). The system may therefore be disrupted (Section 4.4.2) before it has time to merge. In the event of a merger, when the system comes into contact, the outcome will depend on the exact nature of the binary. Stable mass transfer will be possible for \(q = m_c/m_p < 2/3\) \((i > 50°)\), forming an ultra-compact X-ray binary and possibly an isolated MSP. For larger inclinations, the mass transfer will be unstable; while a BH would form from accretion-induced collapse (AIC; Giacomazzo & Perna 2012, and references therein) if the system mass exceeds the maximum NS mass, it is unclear whether substantial mass would be ejected from the system during unstable mass transfer, preventing AIC (L. Bildsten 2015, private communication). An eventual merger of this system may result in a long-GRB-like, calcium-rich transient (e.g., King et al. 2007) if the companion is a massive WD, or a short GRB for a NS companion (e.g., Grindlay et al. 2006).

4.3. Post-Keplerian (PK) Parameters and Mass Constraints

Finding \(m_c\) and \(m_p\) requires measurements of at least two PK parameters (we employ the general relativistic formalism of Damour & Taylor 1992). Our preliminary timing solution predicts that the rate of change of the longitude of periastron passage \(\omega\) (i.e., the orbital precession rate) is \(\dot{\omega} > 0.07\) yr\(^{-1}\), the Einstein delay \(\gamma_{\text{GR}} > 10\) ms, and \(\dot{P}_o > 6 \times 10^{-12}\) s\(^{-1}\). Because of the high \(e\), we will measure \(\omega\) with high precision: from simulations assuming the \(e = 0.95\) orbital model parameters, we find that we will measure \(\dot{\omega}\) with \(>100\)σ significance after one year of timing, yielding the total system mass \((\dot{\omega} \propto M_{\text{tot}}^{2/3})\), where \(M_{\text{tot}} = m_p + m_c\) and constraints on \(m_p\) and \(m_c\). Knowledge of the pulsar position (requiring 1 year of timing or an interferometric detection) would yield a measurement of \(\dot{\omega}\) with one month of phase-connected timing. Our simulations also show that \(\gamma_{\text{GR}}\) will be measured with 10% uncertainty with 2.5 years of phase connection.

We may also measure one Shapiro delay parameter, \(s = \sin i\). For \(i > 50°\), the timing residuals from \(s\) are significantly larger than the \(\approx 20\) μs uncertainties in the pulse TOAs we used to build the timing model. Statistically, it is most likely that the MSP companion is a WD, requiring \(i > 40°\) for \(m_c < 1.4 M_{\odot}\). Even a marginal detection of Shapiro delay will yield a precise \(s\) because \(\dot{\omega}\) and \(s\) are nearly orthogonal in the mass–mass diagram (Lynch et al. 2012). With these two PK measurements, we would precisely measure \(m_p\) and \(m_c\). We note that the very precise mass of PSR J1807-2500B (NGC 6544B) was measured in this way (Lynch et al. 2012).

4.4. System Origin

The vast majority of field MSP binaries have circular orbits (see Champion et al. 2008) from dissipation during the mass-transfer phase (Phinney 1992); known eccentric systems in the field are either double NSs (with eccentricity coming from a second supernova (SN) kick; e.g., Brandt & Podsiadlowski 1995), disrupted triples (Champion et al. 2008), or possibly NS–He WD binaries with circumbinary disks (Antoniadis 2014 and references therein). In contrast, a number of the MSP binaries in GCs are substantially eccentric (e.g., Freire et al. 2008; Lynch et al. 2012), with a likely origin in dynamical encounters (e.g., Verbunt & Freire 2014). The highest-\(e\) binary MSP currently known, PSR J0514-4002A (NGC 1851A; Freire et al. 2007), has \(e = 0.888\) and an unusually massive \((m_c > 0.96 M_{\odot})\) companion, similar to NGC 6652A. We here consider the plausibility of several

\[12\] Also see http://www.naic.edu/~pfreire/GCpsr.html.
mechanisms through which NGC 6652A could have gained its high \( e \).

### 4.4.1. Possible Formation Mechanisms

There are several ways to form a high-eccentricity system like NGC 6652A. An initially circular orbit may gain eccentricity from three-body encounters with other stars in the GC (Rasio & Heggie 1995). For a double neutron star, the eccentricity could have been imparted on the system by the SN kick of a massive companion (Brandt & Podsiadlowski 1995 and references therein). The system could also have formed through an exchange encounter, in which the original companion was ejected from the system and the third body became the new companion (e.g., Verbunt & Freire 2014). In this case, the new companion can be any type of compact object.

The SN kick is ruled out by observational evidence that all known radio pulsars with NS companions have spin periods of 20–100 ms (Tauris 2011), suggesting that MSPs cannot be fully recycled by short-lived, massive companions. The first scenario is plausible, as using Equation (5) of Rasio & Heggie (1995), we find that \( \approx 11.8 \) Gyr (comparable to the GC age) of non-exchange three-body interactions would be needed for a binary in an initially circular orbit to gain \( e = 0.95 \). However, the exchange encounter scenario seems most natural, and we discuss this mechanism in more detail below.

Other scenarios for the origin of the binary’s eccentricity include a physical collision between a MSP and a giant star (e.g., Freire et al. 2007), or a triple system in which the outermost companion is pumping the eccentricity of the inner binary (e.g., B1620-26; Thorsett et al. 1999). These mechanisms cannot be excluded a priori, but are outside the scope of this letter.

#### 4.4.2. Dynamical Formation Through an Exchange Encounter

We consider a dynamical encounter resulting in a companion exchange, using FEWBODY (Fregeau et al. 2004) to simulate a particular scenario. As a progenitor system, we take the current most common MSP binary in GCs: an MSP in a circular two-day orbit with a low-mass companion. We chose \( m_c = 0.2 \, M_\odot \), which follows from a binary period of two days using the period–core mass relation from Tauris & Savonije (1999) for Pop II stars. We simulated 5000 encounters between this binary and a third body, drawing the incoming velocities from a Maxwellian distribution\(^\text{13}\) using \( \sigma = 10 \, \text{km s}^{-1} \) distributed between 0 and \( 30 \, a \) (where \( a \) is the binary’s semimajor axis). For the third body we assume a WD with \( 0.7 \, M_\odot \).

Approximately 70% of the encounters result in an exchange, with the low-mass companion ejected and an eccentric binary remaining. The new binary has a range of eccentricities strongly biased toward high values, with 66% of the new systems having \( e > 0.8 \), but energies comparable to that of the progenitor. The orbit has expanded due to the factor of 3.1 increase in \( m_c \), leading to a factor of 3.1\(^{1/2} \) increase in \( P_b \).

Therefore, systems with \( e \approx 1 \) and \( P \approx 10 \) days are naturally formed through this mechanism. If no exchange happened, then the binary remains close to the two-day initial period, albeit with enhanced eccentricity.

We estimate the frequency of encounters between a particular NGC 6652A-like binary and a single star in NGC 6652 using the single-binary encounter rate \( \gamma \) from Verbunt & Freire (2014), normalized to \( M_4 \), and find \( \gamma_{6652} \approx 6.7 \gamma_{M4} \). A NGC 6652A-like binary in M4 would

\(^{13}\) While the velocity profile of NGC 6652 has not been measured directly, we estimate a velocity dispersion \( \sigma \) of about 10–15 km s\(^{-1} \), scaling from GCs with similar physical core radii (NGC 6388, 6093, and 6441); comparable values are obtained by McLaughlin & van der Marel (2005).
encounter single stars at a rate $\xi_{1+2} \sim (\rho_{c,M4}/L_\odot)\sigma_{1+2}^\gamma_{M4}$, where $\rho_c$ is the GC core density and $\sigma_{1+2}$ is the gravitationally focused single-binary cross-section (Equation (A2), Leigh & Sills 2011). In M4, this encounter rate is $\xi_{1+2,M4} \sim 0.17 \text{yr}^{-1}$; in NGC 6652, $\xi_{1+2,6652} \sim 1 \text{Gyr}^{-1}$. We note that the core radius of 1''15 measured by Noyola & Gebhardt (2006) is much smaller than that from (Harris 1996, 2010 edition), yielding $\gamma_{6652} \approx 38^M_4$ and $\xi_{1+2,6652} \sim 6 \text{Gyr}^{-1}$. The companion exchange scenario is therefore quite plausible. The position of NGC 6652A in the cluster may give additional clues to its formation (see Phinney & Sigurdsson 1991).

5. CONCLUSIONS

We discovered one new MSP, NGC 6652A. Although NGC 6388 and NGC 6652 are expected to host substantial MSP populations, cluster MSPs are extremely faint—detecting them requires long integration times and the largest telescopes in the world. We did not find more MSPs in these GCs simply because we are sensitivity limited. NGC 6652A is an intriguing source for southern-hemisphere Square Kilometer Array (SKA) precursors and eventually the SKA Mid-Frequency Aperture Array.14

Our timing analysis over 1.2 orbits of NGC 6652A shows that the MSP is in an extremely eccentric binary system with an unusually massive compact companion. The system quite plausibly formed through an exchange encounter in the dense cluster environment. We cannot exclude all other formation mechanisms a priori; determining the nature of the companion will help discriminate between scenarios. Similarly, a precise position will help determine whether the binary is dynamically relaxed (and hence close to the core as expected from mass segregation) or has been kicked out of the core by a recent encounter.

With a phase-connected timing solution over $\geq 1 \text{yr}$, we will uniquely determine the MSP’s timing parameters and measure its position and $\omega$ to high precision. After $\approx 2.5 \text{yr}$ of timing, we expect to measure $\gamma_{GR}$, allowing measurements of $m_p$ and $m_c$ and clarifying the companion’s nature. If $i > 50^\circ$, we may also measure $\sin i$. New timing observations are underway, and will be reported in a subsequent paper.

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14 https://www.skatelescope.org/mfaa