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# GIANT METREWAVE RADIO TELESCOPE DISCOVERY OF A MILLISECOND PULSAR IN A VERY ECCENTRIC BINARY SYSTEM

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## ABSTRACT

We report the discovery of the binary millisecond pulsar PSR J0514−4002A, which is the first known pulsar in the globular cluster NGC 1851 and the first pulsar discovered using the Giant Metrewave Radio Telescope. The pulsar has a rotational period of 4.99 ms, an orbital period of 18.8 days, and the most eccentric pulsar orbit yet measured ($e = 0.89$). The companion has a minimum mass of 0.9 $M_\odot$, and its nature is currently unclear. After accreting matter from a low-mass companion star that spun it up to a (few) millisecond spin period, the pulsar eventually exchanged the low-mass star for its more massive present companion. This is exactly the same process that could form a system containing a millisecond pulsar and a black hole; the discovery of NGC 1851A demonstrates that such systems might exist in the universe, provided that stellar mass black holes exist in globular clusters.

*Subject headings:* binaries: general — globular clusters: general — globular clusters: individual (NGC 1851) — pulsars: general — pulsars: individual (PSR J0514−4002A)

## 1. INTRODUCTION

Since 1987, several globular cluster (GC) surveys at Jodrell Bank, Arecibo, Parkes, and more recently the Green Bank telescope have found 79 pulsars in a total of 23 GCs.[5] These findings have confirmed that most of the binary millisecond pulsars (MSPs) in GCs have low-mass white dwarf (WD) companions and nearly circular orbits, as observed in the Galactic disk. This is an important confirmation of the evolutionary scenarios proposed by Alpar et al. (1982) for the formation of MSPs.

In GCs, exchange encounters, which only have a significant probability of occurring in dense stellar environments, occasionally exchange one of the components of a binary system with a typically more massive star. The exchanges may occur during encounters with either other binaries or isolated stars. In GCs such encounters can place isolated neutron stars into binaries with a main-sequence (MS) star that eventually evolves, "recycles" the neutron star, and finally forms a MSP-WD binary system. Such a process explains the anomalously large numbers of MSPs in GCs (by mass) when compared to the Galaxy. If the neutron star placed in orbit around a low-mass MS star is already a pulsar, we observe "irregular" eclipsing binary pulsars, such as PSR J0024−7204W in 47 Tucanae (Edmonds et al. 2002), PSR B1718−19 in NGC 6342 (Lyne et al. 1993), and PSR J1740−5340 in NGC 6397 (Ferraro et al. 2001), which are peculiar to GCs.

In this Letter we report and discuss the discovery of a unique binary MSP, PSR J0514−4002A (henceforth NGC 1851A) in the GC NGC 1851. We discovered this system in a new 327 MHz survey of GCs carried out using the Giant Metrewave Radio Telescope (GMRT), at Khodad near Pune, India.

## 2. THE GMRT SURVEY OBSERVATIONS AND THE DISCOVERY OF NGC 1851A

Our 327 MHz survey aims to find faint pulsars with steep radio spectra that would be missed by the high-frequency searches. It benefits from the large gain of the central array of the GMRT of 4.6 K $\mathrm{Jy}^{-1}$ when used in the phased array mode of the Array Combiner (Gupta et al. 2000; Prabu 1997).[6] This mode produces a beam on the sky with a diameter of about 3′. The number of spectral channels across the available 16 MHz band is 256, and the sampling interval used is 258 $\mu$s. Each observation consists of a pair of 72 minute scans containing $2^{24}$ samples. Between scans, the 14 antenna central array was rephased using a reference source.

We observed a set of 16 GCs in 2003 February. The data were written to tape and taken to McGill University, where we processed them using the BORG (a 104-processor Beowulf cluster dedicated to pulsar processing) running the PRESTO software package (Ransom 2001). One of the GCs observed was NGC 1851. Its distance ($D$) from the Sun is about 12.6 kpc (Cassisi, De Santis, & Piersimoni 2001), and its Galactic coordinates are $l = 244\overset{\circ}{.}51$, $b = -35\overset{\circ}{.}04$ (Harris 1996).[7] It is a relatively bright GC ($M_v = -8.33$) with a very condensed core [$c = \log (r_t/r_c) = 2.32$, where $r_t$ and $r_c$ are the tidal and core radii]. It is among the 10 clusters in the Galaxy with the highest central luminosity density ($\rho_0 \simeq 2 \times 10^5\ L_\odot\ \mathrm{pc}^{-3}$).

Neither of the prominent electron density models of the Galaxy makes reliable predictions of the electron column density (normally expressed as the dispersion measure [DM]) to NGC 1851. The Taylor & Cordes (1993) model predicts a DM ∼ 28 pc $\mathrm{cm}^{-3}$ for $D > 3$ kpc, while the Cordes & Lazio (2002; NE2001) model predicts DM ∼ 45 pc $\mathrm{cm}^{-3}$ for $D > 7$ kpc. We therefore dedispersed the raw data at 500 trial DMs, from 20 to 70 pc $\mathrm{cm}^{-3}$ and spaced by 0.1 $\mathrm{cm}^{-3}$ pc, in order to minimize dispersive smearing and keep the total time resolution of our data between 0.5 and 1.5 ms. For each of these DM trials, a full Fourier domain–matched filter-based acceleration search (Ransom, Eikenberry, & Middleditch 2002) was carried out,

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[5] See http://www2.naic.edu/~pfreire/GCpsr.html and references therein.

[6] See http://www.rri.res.in/~dsp_ral/gac/gacmain.htm.

[7] See http://physwww.physics.mcmaster.ca/~harris/mwgc.dat for the updated version of the table of GC parameters presented in this Letter.

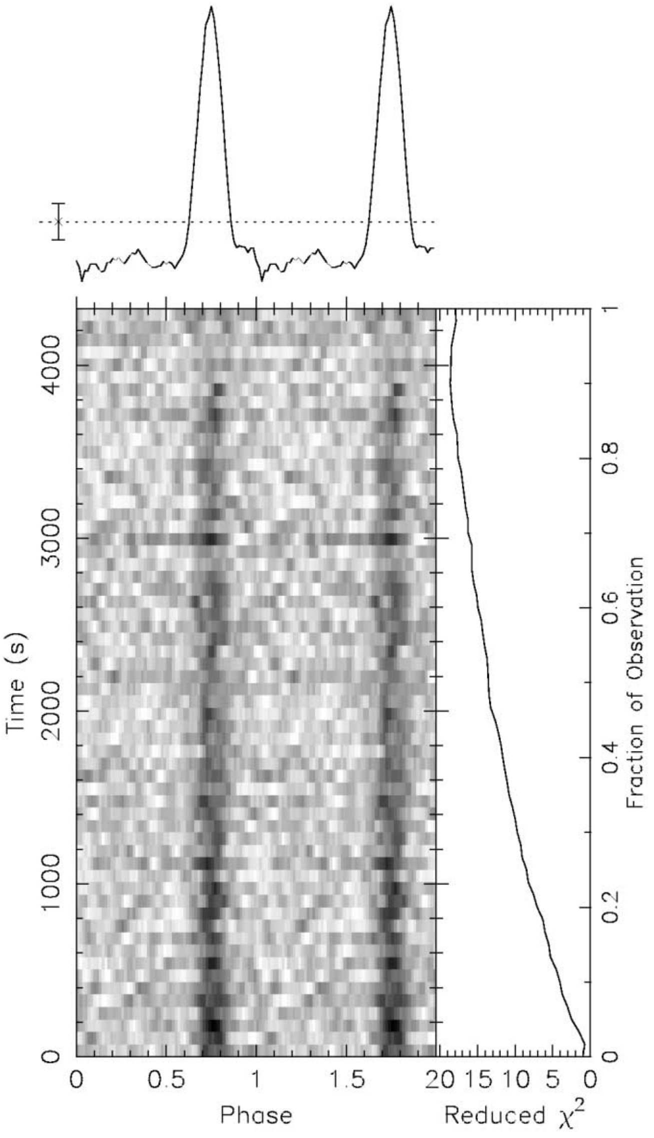

FIG. 1.—Discovery observation for NGC 1851A, in the GC NGC 1851. Pulsed emission is persistent throughout the scans. The pulse profile is rather narrow (*top*), corresponding to the time resolution of the system for this DM.

enabling the detection of binary systems with relatively short orbital periods. This is possible only because of the computing power of the BORG.

In the first scan for NGC 1851, taken 2003 February 10, we detected a clear pulsed signal with a period of 4.991 ms (see Fig. 1). The signal was present at all frequency channels within the observing band, and the arrival times versus frequency are well described by a DM of 52.15(10) pc cm$^{-3}$. This value will help to refine electron density models of the Galaxy in the direction of NGC 1851. The observed pulsations had a width of ~0.8 ms, which is exactly the time resolution of the system after accounting for the dispersive smearing within each of the 62.5 kHz channels and the sampling interval. The intrinsic pulse is therefore essentially unresolved, implying that future observations with better time and frequency resolution will significantly improve the signal-to-noise ratio and timing precision. We confirmed this signal in NGC 1851 data taken on February 10, 11, and 20; the signal is not present in pointings made toward other clusters. This is therefore the first pulsar discovered in NGC 1851 and, incidentally, the first GMRT pulsar discovery. Highly significant changes of the barycentric pulsed period both within and between observations of the cluster immediately identified the pulsar as a member of a binary system. Further observations of NGC 1851 were made in 2003 December in order to determine the orbit of the pulsar, using the same observing system and parameters as for the original search. An early analysis of the orbital trajectory of the pulsar in the $P$-$\dot{P}$ diagram (Freire, Kramer, & Lyne 2001b) suggested that the orbit is not circular.

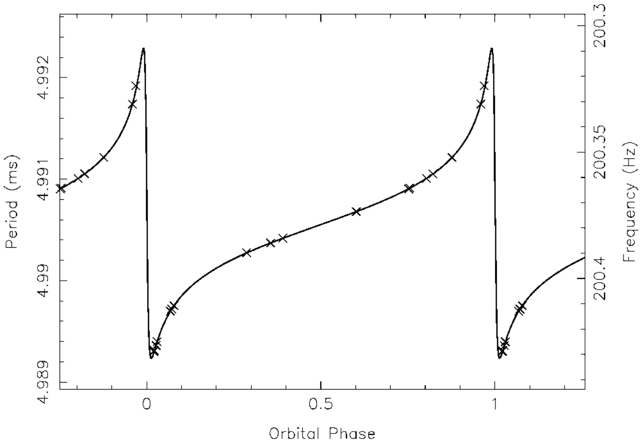

FIG. 2.—Measured rotational periods of NGC 1851A, as would be observed at the barycenter of the solar system, as a function of the pulsar's orbital phase. The solid lines indicate the prediction of the best-fit model.

Analysis of the rotational periods using TEMPO[8] proved most surprising: the best-fit model (see Fig. 2) indicates $e = 0.889(2)$, the most eccentric orbit of any known binary pulsar and several orders of magnitude more eccentric than the typical orbits of fast MSPs.[9] The orbital period $P_b$ is 18.7850(8) days, and the semimajor axis of the orbit projected along the line of sight ($x$) is 36.4(2) lt-s. This implies a minimum companion mass of 0.9 $M_{\odot}$, assuming a pulsar mass of 1.35 $M_{\odot}$ (for the median of expected inclinations, 60°, the companion mass is 1.1 $M_{\odot}$). The epoch of periastron $T_0$ is MJD = 52,984.46(2), the longitude of periastron $\omega$ is 82(1)°, and the barycentric rotational period $P$ is 4.990576(5) ms.

## 3. FLUX DENSITY AND POSITION

When the pulsar is obsesrved, the cross-correlations between the voltages of all active antennae (including those outside the central square, which are not directly used to search for pulsars) are also recorded. This allows for simultaneous high-resolution imaging of the cluster. We found a faint object at $\alpha = 05^{\rm h}14^{\rm m}06\overset{\rm s}{.}74 \pm 0\overset{\rm s}{.}06$, $\delta = -40°02'50\overset{''}{.}0 \pm 1\overset{''}{.}3$ (see Fig. 3), which is only $0\overset{'}{.}1$ from the center of the cluster ($\alpha = 05^{\rm h}14^{\rm m}06\overset{\rm s}{.}2$, $\delta = -40°02'50''$; Harris 1996). This places the source, as projected in the plane of the sky, just outside the cluster's ~$0\overset{'}{.}06$ core. Such a position is common among the pulsars with known positions within GCs, as is expected because of the effects of dynamical friction and mass segregation (Kulkarni & Anderson 1996; Freire et al. 2001a).

The flux density $S$ for this object is variable. For example, on the December 5 image, the source is not detectable (4 $\sigma$

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

[9] For this and the following quantities, the number in parentheses indicates the 1 $\sigma$ uncertainty, which we conservatively estimate to be 10 times the formal value computed by TEMPO based on the fact that there is still no phase-connected timing solution.

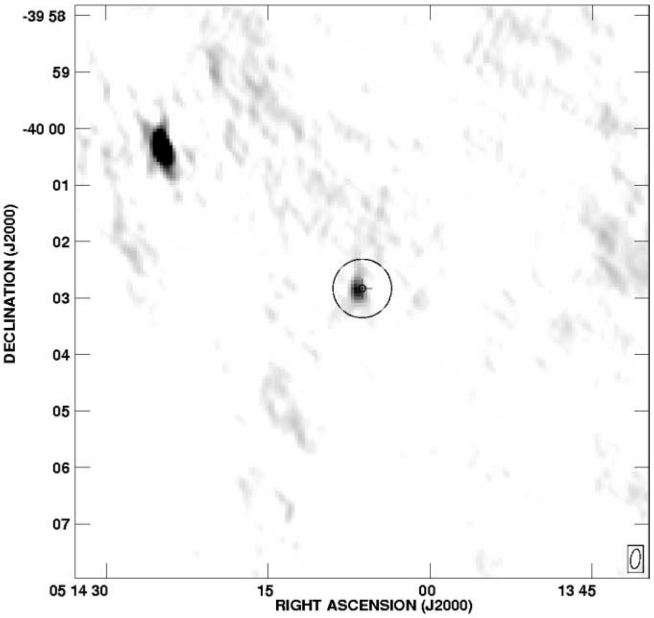

Fig. 3.—Radio image of NGC 1851 at 327 MHz, made by combining the data from four different epochs of observations in 2003 December. The pulsar is the faint source near the center of the cluster, which is indicated with a plus sign. The two circles indicate the core and half-mass radii (0′.06 and 0′.52, respectively). The brighter source to the northeast is not the pulsar; when the interferometer was pointed at it no pulsed emission was detected. The small ellipse in the bottom right corner indicates the dimensions of the synthesized beam of the interferometer, which includes *all* the active antennas. The diameter of the beam of the central square, used in the pulsar search, is about 3′.

limit of 2.4 mJy), while on December 6, 12, and 30 it is detectable with flux densities of 5.5 ± 0.5, 3.5 ± 0.5, and 4.2 ± 0.5 mJy, respectively. This correlates well with the relative intensities of the 4.99 ms pulsed signal for those days. The brighter source to the northeast, on the other hand, has a constant flux density (within 10%, which is the typical accuracy of the flux calibration scheme). There is therefore little doubt that the faint source near the center is NGC 1851A. The image in Figure 3 is a combination of these four epochs and gives a final estimate of the mean flux density at 325 MHz as 3.4 ± 0.4 mJy. The image shows no other sources of comparable flux density toward the cluster, indicating that we are not missing the detection of bright pulsars because of selection effects such as very short rotational or orbital periods. We also observed the cluster at 610 MHz on December 7 and 23, as well as January 1. We did not detect the pulsar in any of the individual epochs nor in a combined map made from all three observations at a 4 $\sigma$ level or better. From the rms noise of 0.1 mJy, we estimate the 610 MHz flux density to be less than 0.4 mJy. This implies a very steep spectrum, with $\alpha < -3.4$. This underlines the relevance of low-frequency surveys; it is unlikely that this pulsar could have been found at any other frequency.

## 4. FORMATION AND NATURE

All known eccentric ($e > 0.1$) binary pulsars in the disk of the Galaxy have relatively massive companions. This varied set of companions includes blue giants, other neutron stars, and heavy WDs. Blue giants live only a few megayears, which is probably not long enough to allow the sustained mass accretion required to spin up a pulsar companion to millisecond spin periods. This is in accordance with the observations; these pulsars have rotational periods of tens or hundreds of ms. The second supernova event is likely to make the orbit significantly eccentric, presuming that the binary survives. Since both stars are now compact, tidal circularization is henceforth impossible. The prolonged episode of stable mass accretion needed to spin up a neutron star to millisecond periods is only possible from evolved lower mass MS stars. Such large timescales allow effective tidal orbit circularization as well. This process likely created the MSP currently in NGC 1851A, although with a currently unknown low-mass WD companion.

Some MSP + low-mass WD systems in GCs, such as PSR B1802−07 ($P = 23.1$ ms, $P_b = 2.62$ days, $e = 0.212$; D'Amico et al. 1993), can become mildly eccentric because of interactions with other objects in the cluster (Rasio & Heggie 1995). This is almost certainly not the origin of the present NGC 1851A binary system since its eccentricity is probably too high to be explained by this mechanism and its companion too massive. We are therefore led to the conclusion that after recycling, NGC 1851A exchanged its former low-mass companion with a more massive object. This is the first system presenting clear evidence of such a process. A massive star (the pulsar's present companion) passed within a distance smaller than about 4 times the separation of the components of the previous binary system. The most likely outcome from such an event is the formation of an eccentric binary system containing the two more massive objects (Hut 1995). The low-mass component of the previous binary is ejected, causing the new binary system to recoil in the opposite direction. The probability for encounters is obviously larger for wider binaries, but the resulting recoil velocities are smaller. These events lead to relatively wide binaries (as observed for NGC 1851A) that are likely to remain near the center of the GCs. This is consistent with the projected position of NGC 1851A relative to the center of the cluster. If the original binary system is tightly bound, the resulting new binary system is also likely to be very tight. Such an encounter would produce a large recoil velocity and could make the resulting system escape the cluster or send it to the cluster's outer regions.

There are three previously known eccentric pulsar binaries with massive companions in GCs, but none of them presents such strong evidence of this kind of exchange encounter. The first is PSR B2127+11C (Anderson et al. 1990), a double neutron star in M15 ($P = 30.53$ ms, $e = 0.6813$, $P_b = 0.33$ days). This system is remarkably similar to the first known Galactic binary pulsar, PSR B1913+16 (Weisberg & Taylor 2003); therefore no mechanisms specific to GCs are needed to explain its formation. However, the fact that this pulsar is much more distant from the center of M15 than any of the other seven pulsars known in that cluster (Anderson 1992) hints at an exchange encounter with a powerful recoil from the ejected object. The second system is PSR J1750−37 (D'Amico et al. 2003). Its main characteristics ($P = 111.6$ ms, $e = 0.71$, $P_b = 17.3$ days) are very similar to another Galactic binary pulsar, PSR J1811−1736 (Lyne et al. 2000). An exchange encounter is, again, not the only possible formation mechanism but definitely a possibility. The third system is PSR J2140−2310B, in M30 (Ransom et al. 2004), which contains a 13 ms pulsar and $e > 0.5$. Its rotational period is about half of the smallest rotational period found for the eccentric Galactic systems. The formation of such an object is very likely to require an exchange encounter, but there is still a small probability that this is an MSP—a massive WD system that became eccentric through distant encounters with other stars, such as PSR B1802−07.

The nature of the companion of NGC 1851A is as yet unclear; it could be either a compact or an extended object. In

NGC 1851, a cluster with an age of ∼9 Gyr (Salaris & Weiss 2002), 1 $M_{\odot}$ stars are now leaving the main sequence. Because of the lengthy episode of MSP recycling that preceded its formation, the present NGC 1851A binary system is very likely to be a few gigayears younger than the cluster in which it lies. Mathieu, Meibom, & Dolan (2004) have determined that for the open cluster NGC 188 (with an age of 7 Gyr and a stellar population similar to that of GCs), binary systems containing MS stars with orbital periods larger than 15 days have not yet had time to circularize. Therefore, the observed eccentricity of the NGC 1851A system does not rule out the possibility of the companion being an extended object. In fact, partial and/or irregular "eclipses" from an extended object such as an MS star may explain the apparent flux variability from NGC 1851A.

## 5. CONCLUSION

We have discovered a remarkable 5 ms binary pulsar, the first to be found in the GC NGC 1851 and the first pulsar to be discovered with the GMRT. Its orbit is the most eccentric known for any system containing a pulsar, while its rotational period is much shorter than that of any other pulsar in an eccentric binary system. This indicates that after becoming an MSP by accreting matter from a low-mass companion star, this neutron star has almost certainly exchanged it for its present, significantly more massive companion. If black holes exist in GCs, an MSP–black hole binary could be formed in exactly the same way.

If the companion is a compact object, then two relativistic effects will be measurable, namely, the rate of advance of periastron and the Einstein delay. The measurement of both effects would lead to the determination of the masses of the two components of this system. A third relativistic effect, the orbital decay due to emission of gravitational waves, will be masked by the unpredictable acceleration of the binary in the gravitational field of the cluster, so no tests of general relativity are likely to be possible. If the companion is an MS star, we might measure the orbital precession caused by the quadrupole moment of the companion star and possibly a rotation of the orbital plane around the axis of rotation of the companion (Wex et al. 1998). In addition, variations in DM with orbital phase may be detectable (Johnston et al. 1996), particularly if the companion is an active star. For NGC 1851A none of these effects has been conclusively measured to date.

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