The Discovery of an Eccentric Millisecond Pulsar in the Galactic Plane

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Abstract. The evolution of binary systems is governed by their orbital properties and the stellar density of the local environment. Studies of neutron stars in binary star systems offer unique insights into both these issues. In an Arecibo survey of the Galactic disk, we have found PSR J1903+0327, a radio emitting neutron star (a "pulsar") with a 2.15 ms rotation period, in a 95-day orbit around a massive companion. Observations in the infra-red suggests that the companion may be a main-sequence star. Theories requiring an origin in the Galactic disk cannot account for the extraordinarily high orbital eccentricity observed (0.44) or a main-sequence companion of a pulsar that has spin properties suggesting a prolonged accretion history. The most likely formation mechanism is an exchange interaction in a globular star cluster. This requires that the binary was either ejected from its parent globular cluster as a result of a three-body interaction, or that that cluster was disrupted by repeated passages through the disk of the Milky Way.

Keywords: Pulsars, Millisecond pulsars, Globular clusters, Pulsar evolution, Binary pulsars
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INTRODUCTION

In the disk of the Galaxy, two classes of mechanism are currently thought operate to produce spun-up or "recycled" radio pulsars [1]. Recycled pulsars with spin periods of tens of milliseconds often orbit other neutron stars; these orbits are typically highly eccentric as a result of the second supernova explosion in the system. By contrast, "millisecond" pulsars (MSPs), with spin periods less than about 10 ms, typically have white-dwarf companions, and are found in orbits that have been circularized due to tidal effects during the recycling process. Indeed the most eccentric previously known highly recycled pulsar in the disk has an eccentricity of only 0.0008 [2]. This combination of short rotational period and circular orbit is considered vital evidence that points to accretion as a formation mechanism for MSPs. The pulsar we report here, PSR J1903+0327, appears to have been highly recycled, but has an orbital eccentricity of 0.44. This object poses severe problems to recycling theories for binary systems in the Galactic disk and most likely has a completely different origin.

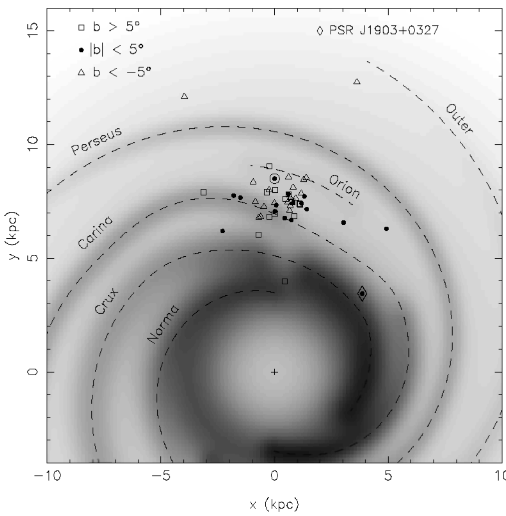

FIGURE 1. The positions of the known Galactic disk MSPs projected onto the Galactic disk. The position of PSR J1903+0327 is given by the diamond. Data taken from the ATNF Pulsar Catalogue [7].

DISCOVERY AND FOLLOW-UP OBSERVATIONS

The new pulsar was found in an ongoing survey of the Galactic Plane using the Arecibo L-band feed array receiver (ALFA) on the 305-m Arecibo radio telescope in Puerto Rico. The survey began in 2004 [3, 4] and collects data from the ALFA receiver for each of seven positions on the sky using digital spectrometers covering 100-MHz of bandwidth centered at 1400 MHz with 256 frequency channels and a time resolution of 64 μs. The high frequency resolution means that the dispersive smearing due to free electrons along the line of sight is minimized, and the corresponding high sampling rate ensures sensitivity to highly recycled pulsars.

The 2.15-ms pulsar PSR J1903+0327 was discovered in September 2006 as a highly significant signal (signal-to-noise ratio of 34) with dispersion measure (DM) of 297 pc cm^{-3} in data taken in October 2005 using a search pipeline based on the PRESTO suite of pulsar analysis software [5, 6].

With a period of 2.15-ms and so high a DM, PSR J1903+0327 is perfect example of the short period, high DM pulsar to which the PALFA survey is uniquely sensitive. This is the fifth fastest pulsar known in the Galactic disk [7]. Of the four known pulsars that are faster, PSR B1937+21 has the highest DM, 71 pc cm^{-3}; see Figure 1. Thus, PSR J1903+0327 has a DM/P ratio (an estimate of detection difficulty) $\sim$3 times higher than that of any pulsar found thus far in a blind survey.

Arecibo follow-up observations of PSR J1903+0327 were carried out on approximately 30 days between September 2006 and January 2007 with an identical observing set-up to that used for the survey. We also observed the pulsar with the Green Bank Telescope (GBT) in West Virginia at a center frequency of 1.95 GHz on approximately 60 days between December 2006 until April 2007. Each observation used the GBT Pulsar Spigot [8] with 768 frequency channels covering 600 MHz in usable bandwidth and sampled every 81.92 μs. We also observed the pulsar at 5 and 9 GHz using the Spigot with 1024 frequency channels covering 800 MHz of bandwidth and sampled every 81.92 μs. Integrated pulse profiles from these observations are shown in Figure 2.

To our surprise, the follow-up observations revealed the pulsar to be in a highly eccentric binary orbit (see Figure 2). A TEMPO-based analysis [10] of the arrival times produced the spin, astrometric, and binary parameters. Figure 3 shows that, although the spin parameters of PSR J1903+0327 are consistent with other known MSPs in the Galactic disk, a clear distinction can be seen when the known disk pulsars are plotted with rotation period against period derivative and eccentricity, shown in Figure 3.

Our measurement of the advance of periastron, if assumed to be due purely to General Relativity (as would be expected for a companion neutron star or white dwarf), allows a measurement of the total mass of the system of $M_{tot} = 2.5(2)\,M_{\odot}$. This is consistent with a neutron star, white dwarf or main sequence companion, assuming a $1.4\,M_{\odot}$ pulsar. Given the possibility that

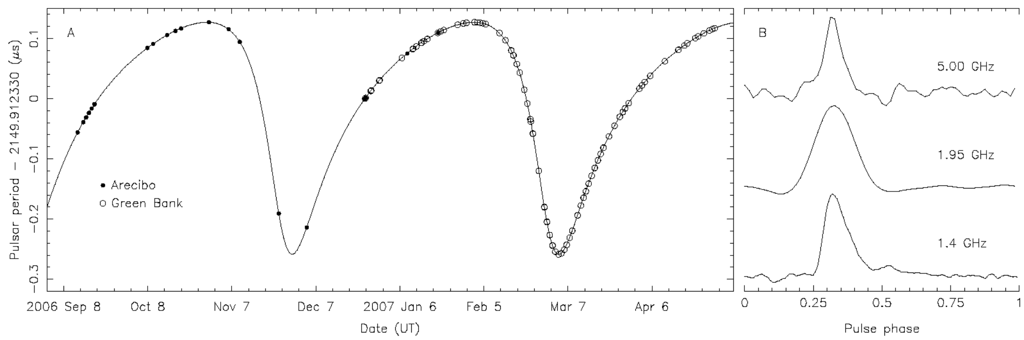

FIGURE 2. Left: orbital fit (line) to the barycentric periods and times (points) folded at the binary period of the system. The error bars are smaller than the points at this scale. Right: by fitting a Gaussian convolved with a one-sided exponential to the pulsar's profile, we measured a scattering time of $\tau_s = 0.126(1)$ ms at 1.4 GHz. The model described in [9] predicts $\tau_s = 0.66$ ms at this frequency, however this is well within the distribution of scattering time measurements of pulsars at similar DMs.

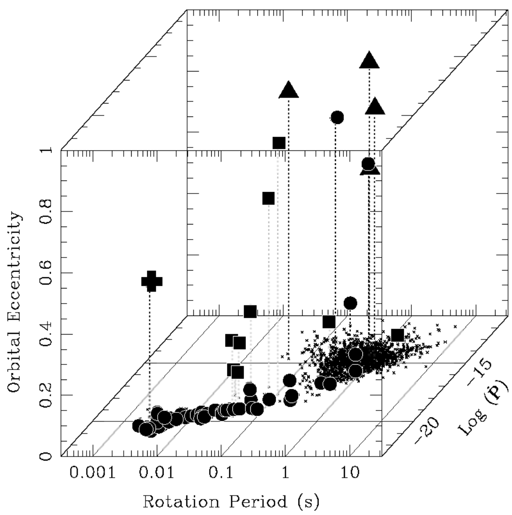

FIGURE 3. The disk population of pulsars plotted with rotational period against period derivative and eccentricity. Square points are double neutron star systems systems, triangles are pulsars with main-sequence or massive companions, circles are pulsars with white dwarf or sub-dwarf companions and the plus indicates the position of PSR J1903+0327. The bottom face of the cube is the traditional period, period derivative diagram. All points are projected onto this face as crosses. Isolated pulsars are crosses.

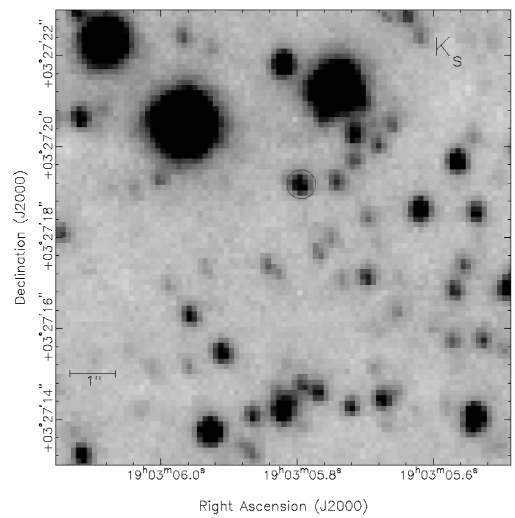

FIGURE 4. Near-infrared JHK observations with the Gemini North telescope of the field containing PSR J1903+0327. The star inside the 0.32" (95% confidence) error circle has $J = 19.2(2)$, $H = 18.4(2)$ and $K_S = 18.0(2)$. Based on the average stellar density in the field. there is a 2.6% probability of finding a star at the position of the pulsar by chance.

this is a double neutron star system, we searched for pulsations from the companion using the data taken at Arecibo. As well as searching each observation independently, individual observations were combined to increase sensitivity. The null results of this search set an upper limit on pulsed emission at 1.4 GHz of 20 μJy for a period of 2 ms and 9 μJy for a period of 200 ms.

The mass function measured for this system implies a minimum companion mass of $0.90\,M_\odot$, assuming a $1.4\,M_\odot$ pulsar, and could point to a main-sequence or giant companion. A one hour observation in near infra-red bands using the Gemini North telescope detected a star with J=19.2(2), H=18.4(2) and K_S=18.0(2) magnitudes within the 1-σ position error circle. Given the density of stars in this field there is a 2.6% probability of finding a star at that position without being associated. Using main-sequence star models [11] and estimating the reddening at the DM distance using red clump stars [12], we find a 10 Gyr main-sequence star of mass $0.9\,M_\odot$ has very similar J, H, K_S magnitudes to those of this counterpart.

THE ORIGIN OF PSR J1903+0327

What is the origin of this unique system with a short spin period and large orbital eccentricity? According to conventional evolutionary scenarios, the system should either have a short spin period and be in a circular orbit, or have a modest spin period and follow an eccentric orbit [13]. While several authors [14, 15] have explored ways to broaden the types of systems created in these scenarios, to our knowledge, in no case has an eccentric binary MSP system been simulated. Based on our current understanding it appears unlikely that PSR J1903+0327 formed through the evolution of a binary system in the disk of our Galaxy. If the companion is indeed a main-sequence star then it cannot have spun up the pulsar.

We now consider alternative possibilities for the formation of this remarkable object. One is that the MSP has not been recycled, but that its short rotational period, low magnetic field and high eccentricity were all properties imparted to it at birth. However, there are several strong arguments against a system with these properties resulting from the core-collapse of a massive star (the pathway through which most young, non-recycled, pulsars are formed). The initial period distribution of observed pulsars is completely inconsistent with the very rapid initial spin required here [16]. While it is possible that selection effects such as beaming or luminosity might bias these observational distributions, we note that pulsars with rapid periods are thought to have very broad beams, and that many nearby supernova remnants have been searched for central objects down to luminosities much lower than that of PSR J1903+0327 [17] and no similar objects have been found.

Globular clusters (GCs) are known to be excellent breeding grounds for MSPs, with formation rates per unit mass $\sim$100 times that in the disk [18, 19]. This increased production efficiency is due to interactions between neutron stars and other stars or binaries in the very high density cores of the clusters over their $\sim$10 Gyr lifetimes. These interactions can significantly alter binary orbits or exchange binary members, allowing isolated neutron stars to become binary MSPs or turning circular binary MSPs orbits into highly eccentric ones. Out of the $\sim$130 known GC pulsars [20], more than 10% of them are in highly eccentric ($e > 0.2$) orbits, implying that GCs produce *eccentric* binary pulsars at least 10^3 times more efficiently per unit mass than the disk. Furthermore, such interactions could explain a main-sequence companion to a recycled pulsar.

No GC is known near the position of PSR J1903+0327 [21], and we have used both the 2MASS catalog [22] and the *Spitzer* GLIMPSE survey data [23] to investigate if the pulsar may be associated with an unknown GC. Neither the 2MASS nor GLIMPSE infrared images of the field show any over-density of stars near the pulsar's position. Color-magnitude diagrams of stars in and outside a $35'$ radius around PSR J1903+0327 show no differences that can be attributed to the presence of a GC.

PSR J1903+0327 may have formed in a GC which was later disrupted, or escaped from an existing GC hundreds of Myrs ago such that they are no longer in the same part of the sky. Many GCs may have been completely disrupted via gravitational interactions with the disk and bulge over the course of many orbits in the Galactic potential, with their stars becoming part of the Galactic spheroid population (an approximately spherical distribution of older stars distributed in an extension of the central Galactic bulge, with a diameter of $\sim$10 kpc). Estimates suggest that over half the spheroid mass could have come from such disrupted GCs [24].

However, in the particular case of PSR J1903+0327, we are constrained by the relatively small characteristic age of the system, $\tau = 1.5(2)$ Gyr. Since a characteristic age is usually an upper limit on the true age of a radio pulsar [25], any model involving GC disruption requires a recycled pulsar to exchange its companion and acquire an eccentric orbit and its parent GC to then be totally disrupted in less than 1.5 Gyr. This is challenging, since disruption should require several orbits of a GC around the Milky Way, and each orbit is $\sim$ 0.5–1 Gyr.

Violent stellar interactions within GCs can sometimes boost neutron star systems to the outskirts of their clusters [26], or even eject them completely. Observationally, $\sim$5% of GC pulsars with accurate astrometric positions reside between $5-60$ core radii from the projected centers of their clusters [20]. Such separations are large for what should be dynamically relaxed and mass segregated neutron star systems [27], and indicate that interactions have ejected the pulsars to the halos of the clusters. Detailed simulations of neutron star interactions in GCs have recently shown that a large fraction of neutron star systems which have accreted mass (and therefore might be MSPs), are eventually ejected from their parent clusters within the current age of the clusters [28].

Further evidence for or against a GC origin of PSR J1903+0327 could come in the form of a proper motion measurement. If the GC hypothesis is correct then the space velocity of the pulsar would reflect not just its residual velocity after escaping the cluster, but also the velocity of the cluster itself. Clusters typically have high velocities ($\sim$200 km s^{-1}, [21]) while disk MSPs usually have lower velocities (70-100 km s^{-1}, [29]). A speed measurement might well provide evidence for or against the system originating in a GC. The timing noise in MSPs is sufficiently low that a measurement should be feasible after a few years of timing, or alternatively, could be provided by Very Long Baseline Interferometry astrometry.

Spectroscopic measurements to confirm the main-sequence companion are planned. Doppler shifts of spectral lines due to radial velocity changes in accordance with the orbital ephemeris of the pulsar would provide strong evidence of association. A measure of the metallicity of the companion could help constrain the origin of the system. If the companion has a very high metallicity it would argue very strongly against a GC origin.

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