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PSR B1802 − 07: a globular cluster pulsar in an eccentric binary system

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ABSTRACT

We report the discovery of the first binary radio pulsar to possess both a low-mass companion and a substantial orbital eccentricity. PSR B1802 − 07 is a 23-ms pulsar, located within the core of the globular cluster NGC 6539 and a member of a binary system with an orbital period of 2.6 d and eccentricity of 0.21. Timing observations reveal an advance in the longitude of periastron of $0\overset{\circ}{.}06 \pm 0\overset{\circ}{.}01$ yr^{-1}. If the periastron advance is due solely to relativistic effects, the total mass of the system is 1.65 ± 0.4 M$_\odot$, consistent with a neutron star of mass 1.4 M$_\odot$ and a white dwarf companion of mass 0.3 M$_\odot$. Most pulsar binary systems with low-mass companions have orbits which are extremely circular, due to tidal forces which they experience during the giant phase of their companion's evolution. The eccentricity of the system may have been induced by interactions with other stars of the globular cluster, or may result from incomplete circularization of an initially more eccentric orbit.

Key words: binaries: general – pulsars: individual: PSR B1802 − 07 – globular clusters: individual: NGC 6539.

1 INTRODUCTION

It is believed that the progenitors of millisecond pulsars are low-mass X-ray binary systems (LMXBs) (Alpar et al. 1982), in which a neutron star is spun up during the process of mass accretion from an evolving companion. Because LMXBs are more common relative to normal stars in globular clusters than in the galactic disc (Verbunt 1987), it was expected that a similar bias would be observed for millisecond pulsars. Such expectations were borne out by the discovery of millisecond pulsars, initially in M28 (Lyne et al. 1987), and subsequently in many other clusters. During the past few years, we have used the Parkes 64-m radio telescope for such searches and have discovered a total of 14 cluster pulsars, including 11 in the cluster 47 Tucanae (Manchester et al. 1990, 1991). The globular cluster NGC 6539 was one of the prime candidates for our search, because it is only 3 kpc from the Sun (Webbink 1985) and because a synthesis map of the field obtained at the VLA showed a point-like continuum radio source within the cluster (Fruchter & Goss 1990).

2 OBSERVATIONS AND RESULTS

The observing system used for clusters such as NGC 6539, where high dispersion measures were expected, was essentially the same as that used by Johnston et al. (1992) in the recent high-frequency Parkes survey of the galactic plane for pulsars. A dual-channel receiver operating at a central frequency of 1520 MHz and equipped with cooled FET amplifiers was used on the Parkes 64-m telescope. The equivalent system flux density was about 70 Jy on cold sky. The two orthogonal linear polarizations were each split into 64×5-MHz and 80×1-MHz spectral channels, detected and high-pass filtered, before corresponding polarization channels were summed. After appropriate integration, the filter outputs were sampled by a one-bit digitizing system at 1.2-ms intervals for the 5-MHz filters and 0.3-ms intervals for the 1-MHz filters, and recorded on magnetic tape. In off-line analysis, the data were dedispersed for 100 different dispersions in the range 0 to 1350 cm^{-3} pc and searched for periodic signals using 2, 4 and 8 million point transforms. Analyses of observations made on 1990 January 26 and

April 29, in the direction of NGC 6539, revealed the presence of a 23-ms pulsar. Subsequent observations demonstrated that this pulsar was in an eccentric 2.6-d orbit (D'Amico et al. 1990).

A total of 104 arrival-time measurements have been obtained for this pulsar over the past two years using the Parkes telescope and the 76-m Lovell Telescope at Jodrell Bank, which utilized a dual-channel receiver at 1.4 GHz and a $2\times32\times1$-MHz filterbank. The filter outputs were sampled, folded on-line synchronously with the apparent pulsar period and then dedispersed to form a mean pulse profile. Integration times were typically 18 min. Barycentric pulsar periods are plotted as a function of orbital phase in Fig. 1. The departure from a pure sinusoid shows clearly the eccentric nature of the binary system. There is no evidence of any variation in the mean pulsed flux density as a function of the orbital phase. In particular, there is no sign of any eclipse or attenuation of the pulsar signal at the orbital phase at which the companion is between the pulsar and the Earth.

Parameters for the pulsar and the binary system derived from a fit to the arrival-time data are given in Table 1. The pulsar period is for the quoted epoch of periastron and the quoted errors are equal to the formal standard deviation obtained from the least-squares fit. Within the uncertainties, the position of the pulsar and that of the VLA source [α(B1950.0) = $18^{\rm h}02^{\rm m}07\overset{\rm s}{.}23\pm0\overset{\rm s}{.}01$, δ(B1950.0) = $-07°35'40\overset{''}{.}\pm0\overset{''}{.}1$] agree, as do the flux densities. The position is 15 arcsec, or about one-half the core radius, from the cluster centre (Fruchter & Goss 1990). At the optical distance for NGC 6539 of 3.1 kpc (Webbink 1985), the observed dispersion measure of 186 $\mathrm{cm^{-3}}$ pc corresponds to a mean electron density of 0.06 $\mathrm{cm^{-3}}$, consistent with the galactic distribution of interstellar electrons (Lyne, Manchester & Taylor 1985). This, together with the pulsar's sky position within the core of the cluster and the low probability of detecting a field pulsar of this type within the beam, makes the association of the pulsar with the cluster certain.

As indicated in Table 1, a significant rate of periastron advance, $\dot{\omega}$, has been measured. If this is entirely due to relativistic effects (Backer & Hellings 1986), it allows a determination of the total mass of the binary system:

$$m_{\rm p}+m_{\rm c}=\frac{P_{\rm b}^{5/2}}{2\pi G}\left[\frac{(1-e^2)c^2\dot{\omega}}{6\pi}\right]^{3/2}=1.65\pm0.4\,\mathrm{M_\odot}, \qquad (1)$$

where $P_{\rm b}$ is the orbital period, e the orbital eccentricity, c the speed of light, G the gravitational constant, and $m_{\rm p}$ and $m_{\rm c}$ are respectively the pulsar and the companion masses. The masses of the pulsar and its binary companion are also constrained by the mass function

$$M_{\rm f}=\frac{(m_{\rm c}\sin i)^3}{(m_{\rm p}+m_{\rm c})^2}=\frac{4\pi^2}{G}\frac{(a_{\rm p}\sin i)^3}{P_{\rm b}^2}=0.009\,453\,\mathrm{M_\odot}, \qquad (2)$$

Table 1. Observed and derived parameters of the PSR B1802 −07 system.

Pulsar period, P	$23.1008552021\pm0.0000000002$ ms
Pulsar period derivative, $\dot{P}$	$(4.70\pm0.04)\times10^{-19}$
Dispersion measure, DM	$186.38\pm0.01\,\mathrm{cm^{-3}\,pc}$
Right ascension (B1950.0)	$18^h02^m07\overset{s}{.}232\pm.001^s$
Declination (B1950.0)	$-07°35'40.0''\pm0.1''$
Projected semi-major axis, $a_p \sin i$	3.92059 ± 0.00005 light sec
Orbital period, P_b	2.616763 ± 0.0000005 days
Eccentricity, e	0.21206 ± 0.00002
Epoch of Periastron (MJD)	48299.53333 ± 0.00005
Longitude of periastron, ω	$164.74\pm0.01°$
Advance of periastron, $\dot{\omega}$	$0.06\pm0.01°\ \mathrm{yr^{-1}}$
Mean flux density, S_{1400}	0.5 ± 0.2 Jy
Pulsar Characteristic age, $\tau_c=P/2\dot{P}$	7.8×10^8 yr
Mass function, $f(m_p,m_c)$	$0.009543\ \mathrm{M_\odot}$
Total system mass, m_p+m_c	$1.65\pm0.4\ \mathrm{M_\odot}$

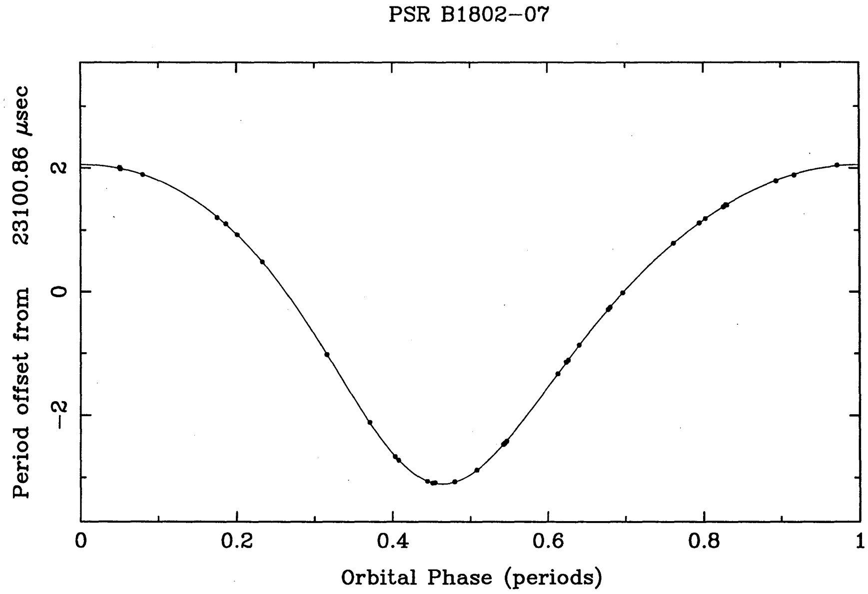

Figure 1. The barycentric pulse period as a function of time. The solid curve is the model given in Table 1.

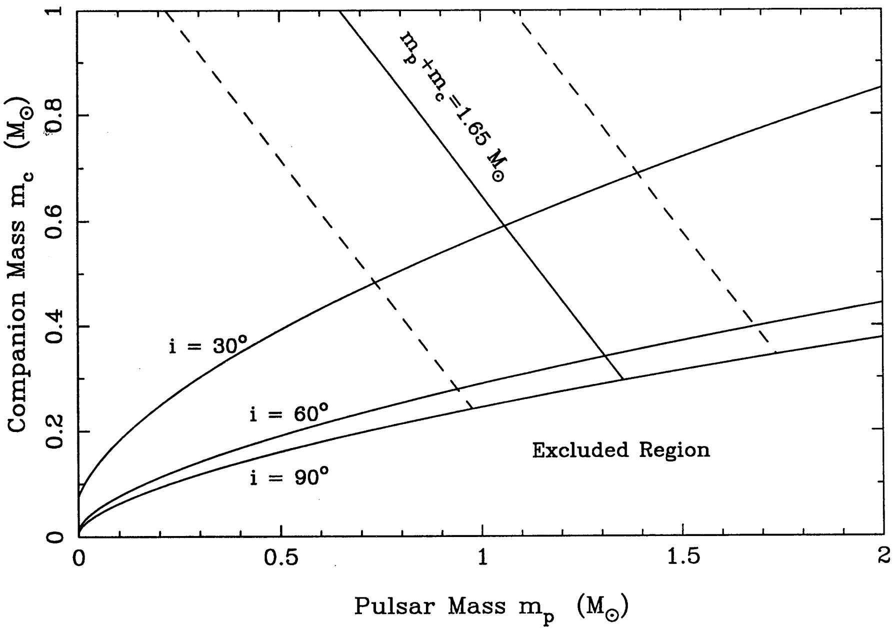

Figure 2. Observational constraints on the masses of the pulsar and the companion star placed by measurements of the mass function and the rate of periastron advance. The dashed lines correspond to the range of uncertainty in the total mass of the system.

where a_p is the semimajor axis of the pulsar and i the angle of inclination of the orbit to the plane of the sky. Fig. 2 illustrates the combined constraints on the two masses. The a priori probability that the inclination angle i is less than some angle i_0 is $1-\cos i_0$. Therefore the most probable value of the companion mass is ~ 0.3 $M_\odot$, which corresponds to inclination angles greater than about 45°, except that angles near 90° are excluded by the absence of observable eclipses. The corresponding pulsar mass is ~ 1.4 $M_\odot$, similar to previous measurements of neutron star masses (Taylor & Weisberg 1982; Lyne & Bailes 1990; Prince et al. 1991; Ryba & Taylor 1991; Wolszczan 1991). A system consisting of two neutron stars is extremely unlikely because it would require a very small inclination angle and comparatively light neutron stars with masses $\lesssim 1.0$ $M_\odot$.

A low-mass companion may suffer tidal distortion which may contribute to the observed advance of periastron. Such a contribution will have the same sign as the relativistic term and hence reduce the derived sum of masses. For a main-sequence companion, the classical contribution would be many times that observed, but for a white dwarf it is unlikely to be significant (Schiff 1958). We assume for the discussion below that the binary system consists of a ~ 1.4-$M_\odot$ neutron star and a low-mass (~ 0.3 $M_\odot$) white dwarf companion.

Except for the significant eccentricity, the observed parameters of this binary system are fully consistent with those of a binary radio pulsar which has been recycled in a low-mass binary system (Bhattacharya & van den Heuvel 1991). Tidal forces result in almost complete circularization of the orbit during the accretion phase. In the alternative formation process, accretion-induced collapse (AIC) of a white dwarf (Michel 1987; Bailyn & Grindlay 1990), a significant eccentricity (~ 0.1) is likely to be introduced on formation, but, in a close system such as this, the orbit would probably be circularized soon after the collapse event by tidal forces. The orbits of all other pulsars with low-mass companions are nearly circular, which suggests that the eccentricity of the system is probably related to its cluster membership.

This system could have formed as the result of the exchange of a previously single neutron star with one of the members of a primordial binary system in the core of the cluster. Because of the recently recognized large number of such binaries, and their large cross-section, such captures are quite probable within clusters such as NGC 6539 (Hut, Murphy & Verbunt 1991). The resulting binary system typically has a very large eccentricity. Subsequent tidal interactions will reduce both the eccentricity and the size of the orbit, but it is possible that a significant eccentricity will be left at the conclusion of the accretion phase. The relatively long rotational period of PSR B1802 – 07 (for a recycled pulsar) suggests that the accretion phase was comparatively short, enhancing the likelihood of a significant eccentricity being left.

Another possibility is that interactions with stars in the dense core of the cluster may be responsible for the observed eccentricity, as has been suggested to explain the small eccentricity (~ 0.02) of PSR B1620 – 26 in the cluster M4 (McKenna & Lyne 1988). A succession of weak interactions gradually builds up the eccentricity on a time-scale given by

$$\tau = 7\times 10^9\ \mathrm{yr}\left(\frac{10^5\ \mathrm{pc}^{-3}}{n}\right)\left(\frac{0.01\ \mathrm{au}}{a}\right)\left(\frac{\mathrm{M}_\odot}{m_1+m_2}\right)\left(\frac{\mathrm{M}_\odot}{m_3}\right)$$
$$\times\left(\frac{m_1+m_2+m_3}{\mathrm{M}_\odot}\right)^{1/2}\left(\frac{e}{0.001}\right)^{1/3}\left(\frac{v_{\mathrm{th}}}{10\ \mathrm{km\ s}^{-1}}\right), \qquad (3)$$

where e and a are the binary eccentricity and separation respectively, m_1 and m_2 are the binary component masses, and collisions are with cluster stars of mass m_3, number density n and thermal velocity $v_{\mathrm{th}} = (3kT/\mathrm{M}_\odot)^{1/2}$ (Hut & Paczyński 1984; Rappaport, Putney & Verbunt 1989). If we substitute parameters for the PSR B1802 − 07/NGC 6539 system, we obtain a time-scale of ~ 30 Gyr.

This time is very long and, in particular, much longer than the characteristic age of PSR B1802 − 07, 780 Myr (Table 1). The characteristic age of a pulsar is usually considered to be a good upper limit to its actual age (Manchester & Taylor 1977). It is possible that PSR B1802 − 07 is accelerated in the cluster gravitational field in a way similar to PSR B2127 + 11A (Wolszczan et al. 1989) in M15, so as to increase its apparent period derivative. The line-of-sight acceleration required to give the observed derivative is $c\dot{P}_{\rm obs}/P = 6 \times 10^{-7}$ cm s^{-2}, while the maximum possible acceleration (Phinney 1993) is calculated to be $\sigma^2/R_\perp = 3.5 \times 10^{-7}$ cm s^{-2}, where σ is the velocity dispersion and $R_\perp$ the projected perpendicular distance from the cluster centre. While this suggests that the pulsar can only be about twice as old as it appears, we note that uncertainties in the cluster parameters may increase the cluster acceleration by more than a factor of 2, perhaps making the actual pulsar age nearer to that of the cluster, so that it is not impossible for the observed eccentricity to have been induced by weak interactions within the cluster core. We cannot, of course, rule out the possibility that the eccentricity was generated by a single more violent encounter in the past gigayear or so. Although this seems unlikely, when one considers that this is the only one of the 20 or so known cluster binary pulsars with a low-mass companion to exhibit a substantial eccentricity, it may not be unreasonable.

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