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Millisecond pulsars in the globular cluster 47 Tucanae

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ABSTRACT

Searches for pulsars in globular clusters during the past few years have discovered more than 30 pulsars in 13 clusters. About one-third of these are located in the globular cluster 47 Tucanae (NGC 104), and were discovered using the Parkes radio telescope in Australia at an observing frequency of 640 MHz (Manchester et al.). We have made further observations of 47 Tucanae at 640 and 436 MHz, with the aim of searching for previously undiscovered pulsars and performing timing measurements on the known ones. Here we report the discovery at 436 MHz of the pulsar 47 Tuc N, but find that 47 Tuc K, earlier reported by Manchester et al., is non-existent. We present timing solutions for the solitary pulsars 47 Tuc C and D. Both pulsars are found to have negative period derivatives which allow us to put a lower limit on the central density of the cluster. We give improved orbital solutions for the binary pulsars of 47 Tuc E and J, and show that 47 Tuc J is eclipsed by its companion for about a quarter of the orbital period. A preliminary orbital solution is obtained for the binary pulsar 47 Tuc I, which is probably also eclipsing. Finally, we discuss the origin and evolution of the 47 Tucanae pulsars.

Key words: pulsars: general – globular clusters: individual: 47 Tuc – radio continuum: stars.

1 INTRODUCTION

During recent years, globular clusters have become the subject of much interest as breeding grounds for millisecond pulsars. Under the standard evolutionary model, these pulsars are believed to be old neutron stars which have been spun up to extremely short rotation periods by the accretion of matter and the accompanying transfer of angular momentum from a companion star in a precursor X-ray binary phase (Alpar et al. 1982; Fabian et al. 1983). Since globular clusters contain a relative wealth of low-mass X-ray binary systems compared with the Galactic disc, they were predicted to host the resulting spun-up or 'recycled' pulsars (Hamilton, Helfand & Becker 1985); the high stellar densities in the cluster cores are expected to facilitate encounters in which a neutron star can capture an ordinary star to form an X-ray binary system (Fabian, Pringle & Rees 1975; Hills 1976). The first cluster pulsars to be discovered, in M28 (Lyne et al. 1987) and M4 (Lyne et al. 1988), supported this connection, and searches of globular clusters have now detected more than 30 pulsars amongst 13 clusters (see Lyne 1992, 1994 and Manchester 1993 for recent accounts). Whilst these pulsars cover a wide range of periods, many have periods in the millisecond range and all are believed to be either recycled or recently formed by accretion-induced collapse of a white dwarf, since none of the original pulsar content of these ancient star clusters is likely to have remained active to the present day. Bhattacharya & van den Heuvel (1991) provide a comprehensive review of the theory of the production of spun-up pulsars.

About a third of the known globular cluster pulsars are contained within the single cluster 47 Tucanae; being massive, dense and nearby, this cluster is a good candidate for the production and detection of spun-up pulsars. These pulsars were discovered as part of a survey of southern globular clusters for pulsars using the 64-m Parkes radio telescope in Australia, and were reported in Manchester et al. (1990, 1991). They have been previously referred to, using the usual naming convention, as PSR B0021−72C to PSR B0021−72M, but here we shall adopt the more compact nomenclature of 47 Tuc C to 47 Tuc M. The pulsars are weak, with many nominally below the detection limit of our receiver systems. Their detection was assisted by interstellar scintillation; diffractive and refractive effects of electron density irregularities in the interstellar medium can focus the observed pulsar signals on the Earth, producing occasional flux enhancements.

The detections of the 47 Tucanae pulsars reported in Manchester et al. (1991) were made at 640 MHz between 1989 July and 1991 February. More recent observations have been made at 436 MHz, and this paper reports the main results. Section 2 describes the 436-MHz observing system and the results of searches at this frequency for previously undiscovered pulsars in 47 Tucanae. Section 3 presents timing solutions and flux densities for two of the solitary pulsars, while Section 4 includes refined orbital solutions for two of the binary pulsars and reports a likely orbital solution for a further binary pulsar. In Section 5, we consider the origin and evolution of the 47 Tucanae pulsars.

2 PULSAR SURVEY OF 47 TUCANAE AT 436 MHz

Observations of 47 Tucanae at 436 MHz have been made since 1991 April with a receiver system which has a flux-density sensitivity at high Galactic latitude similar to that of the 640-MHz system. The two systems have equal bandwidths and, assuming a spectral index of -2 for millisecond pulsars, the lower frequency offers an increase in sensitivity by about a factor of 2.

The 436-MHz system was primarily designed for the Parkes southern-sky pulsar survey (see Bailes et al. 1994). The receiver is a cryogenically cooled system with a typical system temperature of 60 K on cold sky, giving an equivalent flux density of ~ 90 Jy. A total bandwidth of 32 MHz is used, with orthogonal linear polarizations being fed into two filter banks, each consisting of 256 filter channels of 0.125-MHz bandwidth, to facilitate off-line dedispersion. After detection and low-pass filtering, the two polarizations are summed. The resultant signals are high-pass filtered, integrated over 0.3 ms, sampled with one-bit precision and recorded on to Exabyte tape. Most of the observations of 47 Tucanae have been of ~ 45- or 90-min duration, although some longer observations of up to ~ 270 min have been made.

Computer searches for pulsars in the 436-MHz data have been carried out at Jodrell Bank using SUN Sparcstations, and on the Convex C220 computer of the Australia Telescope National Facility. Spectral analyses based on 2-, 4- and 8-Mpoint fast Fourier transforms (FFTs) were performed on dedispersed data sets from adjacent non-overlapping data segments. The shorter analyses allow us to benefit from the scintillation of the pulsar signals and to cope with the smearing of peaks in the spectra of binary pulsars caused by their changing Doppler shifts. Dispersion measures (DMs) in the range 23.4–25.4 cm^{-3} pc were searched, at intervals of 0.2 cm^{-3} pc, in order to cover the DM range of the previously detected cluster pulsars (Manchester et al. 1991). Transforms of up to 64 Mpoints were also performed for the longer data sequences at a single DM of 24.4 cm^{-3} pc. The known pulsars in 47 Tucanae are listed in Table 1, along with an indication of their binary status and the number of detections at 436 and 640 MHz.

As Table 1 shows, searches of 47 Tucanae at 436 MHz have discovered one further pulsar, 47 Tuc N, previously undetected at 640 MHz. In the spectral analyses, the pulsar shows itself most prominently in a spectral feature corresponding to a period of 1.527 ms. However, folding the data at twice this period reveals that this is a 3-ms pulsar with an interpulse of amplitude about 50 per cent of that of the main pulse. Detections over more than two years have shown the pulsar to be solitary and to have a DM of 24.5 ± 0.1 cm^{-3} pc. The lack of detections at 640 MHz suggests a very steep spectrum for this pulsar.

During the 436-MHz analyses, we realized that the periodicity of 47 Tuc K (Manchester et al. 1991) actually arises from the harmonic structure of 47 Tuc D. An 8σ spurious 'detection' close by in period compounded the mistake and led to the binary label.

Before the discovery of the 47 Tucanae pulsars listed in Table 1, the detection of two pulsars towards the cluster, denoted PSR B0021 − 72A and PSR B0021 − 72B, at a DM of 67 ± 2 cm^{-3} pc had already been announced (Ables et al. 1988). PSR B0021 − 72A was described by Ables et al. (1989) as a 4.479-ms pulsar in a 32-min binary orbit, while the details of PSR B0021 − 72B, another binary, have never been published. Manchester et al. (1990) argued that the quite different DM of 47 Tuc C (24.5 cm^{-3} pc) was consistent with the expected DM for the cluster, and this was, indeed, later confirmed as the nominal DM of the cluster with the discovery of the other pulsars reported by Manchester et al. (1991). Manchester et al. (1990) also reported that their searches at a frequency of 640 MHz had failed to detect PSR B0021 − 72A and PSR B0021 − 72B. Our receiver systems at 640 and 436 MHz offer improved sensitivity by at least a factor of 2 over the systems of Ables et al. (1989) at the same frequencies. We have now searched for these pulsars in a number of our observations at 436 MHz taken from five separate observing sessions. A total of ~ 50 data segments, each of ~ 10-min duration, were analysed for signals with periods and DMs around the nominal values for PSR B0021 − 72A. The published mean flux density at 430 MHz of 4 ± 2 mJy suggests that this pulsar should have been nominally detected at the 7σ level or better, around favourable orbital phases when the observed pulse duty cycle should be less than 25 per cent. No such signal was detected, suggesting an upper limit of ~ 2 mJy on the 436-MHz flux density. Information on PSR B0021 − 72B is scant, but Ables et al. (1988) reported the pulsar to be in a fairly wide binary orbit. Several 8-Mpoint spectral analyses, each corresponding to ~ 40 min of observing, were conducted in order to search for this pulsar, covering DMs in the range 65 to 69

Table 1. The pulsars of 47 Tucanae.

Pulsar	Period (ms)	Binary	Detections 436 MHz	Detections 640 MHz
47 Tuc C	5.756780	No	65	61
47 Tuc D	5.357573	No	47	24
47 Tuc E	3.536329	Yes	8	12
47 Tuc F	2.623579	No	23	7
47 Tuc G	4.040379	No	18	3
47 Tuc H	3.2103	Yes	0	5
47 Tuc I	3.484993	Yes	0	2
47 Tuc J	2.100633	Yes	10	9
47 Tuc L	4.3462	Probably	0	2
47 Tuc M	3.676644	No	2	2
47 Tuc N	3.053954	No	10	0

cm^{-3} pc in steps of 0.5 cm^{-3} pc. Again no signal in the appropriate period range was detected above the 7σ level, which corresponds to an upper limit of ~1 mJy on the 436-MHz flux density of this pulsar, assuming a 25 per cent duty cycle. It should be pointed out that at this value of DM, the strong scintillation experienced at the much lower nominal cluster DM, which has resulted in the discovery of many of the 47 Tucanae pulsars, is not expected because its frequency structure is much narrower than the receiver bandwidth.

3 TIMING SOLUTIONS FOR 47 TUC C AND D

Extended timing observations of pulsars are important to determine precise values of pulsar parameters, such as their periods, period derivatives, positions, DMs and, if relevant, binary orbital parameters. The timing of globular cluster pulsars can also yield information about the host clusters as well as about the pulsars themselves (see Phinney 1992 for a review). While scintillation has brought its rewards in terms of the number of pulsars discovered in 47 Tucanae, the small numbers of detections of many of the pulsars at 640 MHz (Table 1), coupled with their very short periods and often binary motion, have made timing measurements difficult. However, at 436 MHz, where the mean flux densities are usually greater, and where scintillation effects are less extreme, detections are more frequent for some of the pulsars, and the use of this frequency has allowed us to obtain timing solutions for the pulsars 47 Tuc C and D.

Times of arrival were derived from detections at 436 MHz obtained between 1991 July and 1993 November, and from 640-MHz detections dating back to 1990 January. For each observation, the data were dedispersed and folded at the expected topocentric period of the pulsar. A limited search was then conducted in period and DM around the nominal values, and an integrated profile corresponding to the combination of values which yielded the highest signal-to-noise ratio was produced. Each profile was then convolved with an appropriate standard profile to provide a pulse arrival time. These arrival times were then converted to barycentric arrival times using the JPL DE200 ephemeris (Standish 1982) and analysed in the standard manner to give improved estimates of the pulsar position, period, period derivative and DM.

The timing solutions obtained for 47 Tuc C and D are detailed in Table 2. The pulsars are located 1.25 and 0.62 arcmin respectively from the centre of the cluster [RA(J2000) = $00^h24^m06^s$, Dec.(J2000) = 72°04′56″], which places them at 3 and 1.5 core radii in the plane of the sky, assuming a core radius for 47 Tucanae of ≈25 arcsec (Calzetti et al. 1993). The negative observed period derivatives of 47 Tuc C and D almost certainly do not represent a spinning up of the pulsars, but rather are the result of their accelerations in the gravitational field of the cluster (cf. PSR B2127+11A in M15, Wolszczan et al. 1989). These accelerations are towards us, so the pulsars are located on the far side of the cluster from the Earth. For a pulsar of period P, with a negative period derivative $\dot{P}$ resulting from an acceleration a_l along the line of sight,

$$\left|\frac{\dot{P}}{P}\right| < \left|\frac{a_l}{c}\right| \tag{1}$$

(Phinney 1992). Thus the measured period derivative can be used, through equation (1), to put a lower limit on $|a_l|$. When combined with the measured separation, R, of the pulsar from the cluster centre in the plane of the sky, and a suitable model for the mass distribution of the cluster, this can be used to put a lower limit on the central density of the cluster.

By considering the gravitational effect of the cluster on the pulsar, the acceleration can be written

$$a_l = \frac{GM}{R^2}\cos^2\theta\sin\theta, \tag{2}$$

where θ is the angle that the pulsar vector relative to the cluster centre makes with the plane of the sky, and M is the cluster mass contained inside the pulsar position. 47 Tucanae has a radial surface brightness distribution which has been fitted by a King model (Da Costa & Freeman 1985); see Spitzer (1987) for the details of what follows concerning King models. A King model cluster which has a large ratio of tidal radius to core radius is very close to a completely isothermal sphere. This is the case for 47 Tucanae for which this ratio ~100. Moreover, the inner regions of a globular cluster, with which we are concerned, are thought to be nearly isothermal. Now, the mass inside radius r, $M(r)$, for an isothermal sphere can be approximated by

$$M(r) = 8\pi\rho(0)\,\kappa^2 r, \tag{3}$$

where $\rho(0)$ is the central density of the cluster, and κ is the Jeans length at the cluster centre, the latter being approximately equal to $r_c/3$ for a King model cluster. Combining equations (2) and (3), and putting $r = R/\cos\theta$, we obtain

$$\rho(0) = \left|\frac{a_l R}{4\pi\kappa^2 G\sin 2\theta}\right|, \tag{4}$$

which takes its minimum value when $\sin 2\theta = 1$. Thus we can use the negative measured period derivative and radial position of a pulsar to put a lower limit on the central density of the cluster of

$$\rho_{\min}(0) = \left|\frac{a_l R}{4\pi\kappa^2 G}\right| = \left|\frac{9cR\dot{P}}{4\pi G r_c^2 P}\right|. \tag{5}$$

The most stringent lower limit on the central density of 47 Tucanae is derived from the timing results of 47 Tuc C. Assuming a heliocentric distance of 4.1 kpc for 47 Tucanae (Meylan 1988), equation (5) for 47 Tuc C yields a minimum central density of 8.0×10^4 $M_\odot$ pc^{-3}. Recent *Hubble Space Telescope* observations of the core of 47 Tucanae (Calzetti et al. 1993) have, however, established that the projected den-

Table 2. Timing parameters and flux densities for 47 Tuc C and D. Uncertainties in the last quoted digit are given in parentheses.

Pulsar	47 Tuc C	47 Tuc D
Pulse Period	5.75678001161(1) ms	5.35757328590(1) ms
Period Derivative	$-4.98(1) \times 10^{-20}$	$-0.28(2) \times 10^{-20}$
Epoch	47858.5	48040.7
Right Ascension (J2000)	00^h 23^m $50\overset{s}{.}343(2)$	00^h 24^m $13\overset{s}{.}877(3)$
Declination (J2000)	−72° 04′ 31″.46(1)	−72° 04′ 43″.82(1)
Dispersion Measure	24.61(1) cm^{-3}pc	24.70(1) cm^{-3}pc
436 MHz Flux Density	1.53(10) mJy	0.95(9) mJy
640 MHz Flux Density	1.54(17) mJy	0.55(7) mJy
Spectral Index	0.0(5)	−1.4(6)

sity profile departs from a single King model within the inner regions of the core, displaying a central cusp. Thus the central density should indeed be somewhat higher than this value. The quoted lower limit on the central density corresponds to a minimum averaged core density of 5.3×10^4 M$_\odot$ pc^{-3}.

The scintillation of the 47 Tucanae pulsars has made their nominal flux densities difficult to determine, particularly for those pulsars which are normally beyond our sensitivity. We have, however, collected enough flux density data on 47 Tuc C and D, at both 436 and 640 MHz, to calculate their mean flux densities at the two frequencies and their corresponding spectral indices. Both detections and non-detections were incorporated in these calculations, with non-detections being taken as half the detection threshold. The results have been included in Table 2. An unusual feature of these results is the flat spectrum of 47 Tuc C, whilst 47 Tuc D has the more typical spectral index for a pulsar of -1.4.

4 ORBITAL FITS FOR THE BINARY PULSARS 47 TUC E, I AND J

The small numbers of detections of the binary pulsars in 47 Tucanae have made it difficult to solve the parameters of their orbits. Preliminary orbital solutions for 47 Tuc E and J, based on early 640-MHz detections, were published by Manchester et al. (1991). These data have been augmented by periods obtained from more recent observations at 436 MHz.

The refined orbital solutions to the periods of 47 Tuc E and J are presented in Table 3. In this table, $a \sin i$ is the projected semimajor axis of the pulsar orbit, where i is the angle that the plane of the orbit makes with the plane of the sky. Information on the masses of the binary components can be derived from the mass function, given by

$$f(M_p, M_c, i) = \frac{4\pi^2}{G} \frac{a^3 \sin^3 i}{P_b^2} = \frac{M_c^3 \sin^3 i}{(M_p + M_c)^2}, \tag{6}$$

where M_p and M_c are the masses of the pulsar and the companion respectively, and P_b is the binary orbital period. Assuming a pulsar mass of 1.4 M$_\odot$ and an inclination angle of 90°, we obtain the minimum possible companion mass, M_{min}, quoted in Table 3. The true companion mass is then dependent on the inclination angle i according to

$$M_c \simeq \frac{M_{min}}{\sin i}, \tag{7}$$

provided that $M_c \ll M_p$. Plots of period against orbital phase for 47 Tuc E and J are shown in Figs 1(a) and (b). These plots were based on detections accumulated over about 3 yr of observations, and were obtained by folding at the fitted orbital period of the pulsar. A marked feature of the plot for 47 Tuc J is the complete absence of detections for about a quarter of the 2.9-h orbital period, in spite of an almost uniform density of observations. This gap is roughly centred on phase 0.25 when the pulsar is furthest from the Earth and behind the companion star, and is certainly due to the eclipse of the pulsar by material from its companion. It is not clear from the data in Fig. 1(b) whether the duration of the observed eclipse is frequency-dependent or whether eclipses in different orbits are of the same length. Whilst the latter is approximately the case for the original eclipsing pulsar PSR B1957+20 (Fruchter et al. 1990), the other eclipsing pulsars PSR B1744−24A (Lyne et al. 1990; Nice et al. 1990) and PSR B1718−19 (Lyne et al. 1993) show variable-length eclipses which sometimes last for a whole orbit and which are frequency-dependent.

Table 3. Binary orbital parameter values for 47 Tuc E, I and J. Uncertainties in the last quoted digit are given in parentheses.

Pulsar	47 Tuc E	47 Tuc I	47 Tuc J
Pulse Period (ms)	3.5363290(2)	3.484993(3)	2.1006334(1)
Orbital Period (days)	2.256844(3)	0.226(3)	0.120665
$a \sin i$ (l-s)	1.978(3)	0.039(2)	0.0402(2)
Eccentricity	< 0.003	0.0	0.0
MJD of Ascending Node	47861.149(1)	47861.511(1)	47149.69476
Mass Function ($M_\odot$)	0.00163	0.00000127	0.00000484
Companion Mass ($M_\odot$)	> 0.16	> 0.014	> 0.021

In Table 3, a preliminary orbital solution is also presented for the binary pulsar 47 Tuc I. This fit was arrived at from the 640-MHz data that contained the original discovery and confirmed the pulsar. This was possible due to the combination of a short orbital period and the fact that these two detections were just hours apart. The fit obtained from these detections is shown in Fig. 2.

The orbital solutions for 47 Tuc I and J yield very small values for the mass function and corresponding minimum companion mass. Since the a priori probability that $i < i_0$ is $1 - \cos i_0$, small inclinations are improbable, suggesting likely companion masses of only a few per cent of a solar mass. Furthermore, the fact that an eclipse is observed strongly suggests that the inclination angle is not small. If we take $i = 30°$ as the minimum reasonable inclination angle, then the maximum companion mass is only 0.042 M$_\odot$. This implies that the companion is not a main-sequence star, as the minimum mass of such stars is ~0.085 M$_\odot$ (Graboske & Grossman 1971). The same conclusion applies to 47 Tuc I.

The radius of a degenerate star companion is given by

$$R_c = 0.013(1+X)^{5/3} M_c^{-1/3}, \tag{8}$$

where both the radius and mass of the companion are expressed in solar units, and X is the hydrogen mass fraction (Paczyński 1967; Deich et al. 1993). For the 47 Tuc J system, the radius is $0.12\,(\sin i)^{1/3}$ for $X = 0.7$, and about 40 per cent of that for $X = 0$. Since the eclipse occupies at least 25 per cent of the orbital period, the radius of the eclipsing material must be about $\pi d/4$, where d is the separation of the two stars, or close to one solar radius. Therefore the eclipse cannot be due to the star alone; an extended atmosphere is required, implying mass loss from the system. The very low mass of the companion also implies that mass loss has occurred.

Two main processes could be responsible for mass loss in these systems: Roche-lobe overflow by the companion, or radiation-driven evaporation of the companion. For Roche-lobe overflow to occur, the companion radius, R_c, must exceed its Roche-lobe radius, R_l, given by

$$R_l = 0.46 d \left(\frac{M_c}{M_t}\right)^{1/3}, \tag{9}$$

where $M_t = M_c + M_p$ is the total mass of the system, and $M_c < 0.8\ M_p$ (Paczyński 1971). As Deich et al. (1993) have

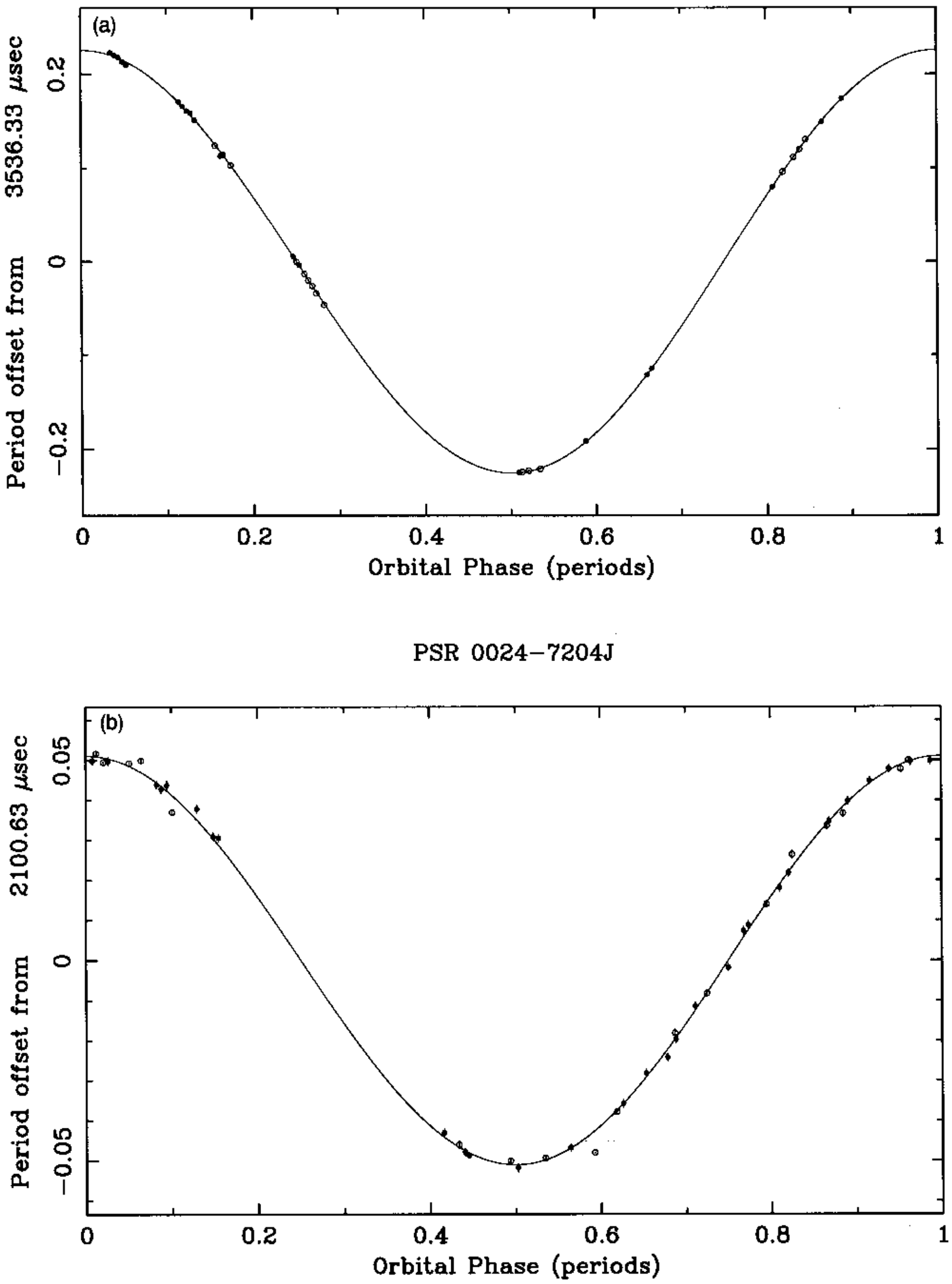

Figure 1. Pulse period plotted against orbital phase for the binary pulsars (a) 47 Tuc E and (b) 47 Tuc J. Observations at 640 MHz are indicated by filled symbols and those at 436 MHz by open symbols.

shown, the companion radius is comparable to the Roche-lobe radius for degenerate hydrogen companions of this low mass, so Roche-lobe overflow is possible.

Mass loss from the companions of 47 Tuc I and J could be in the form of an evaporative wind resulting from irradiation of the companion by the pulsar (Ruderman, Shaham & Tavani 1989). Assuming the isotropic emission of the pulsar's spin-down luminosity, the irradiating energy density at the companion is given by

$$F_{\mathrm{p}}(d)=\frac{I\Omega\dot{\Omega}}{4\pi d^2}=\frac{I\pi\dot{P}}{a^2P^3}, \qquad (10)$$

where I is the pulsar's moment of inertia, and Ω is its angular speed of rotation. Assuming values of $\dot{P}$ for both pulsars which correspond to the typical surface magnetic field strength for a millisecond pulsar of 3×10^8 G and an average inclination angle of 60°, the values of $F_{\mathrm{p}}(d)$ obtained for 47 Tuc I and J are 1.3×10^{11} and 2.1×10^{12} erg s^{-1} cm^{-2}, respectively. The efficiency with which such a flux produces mass loss is uncertain, with estimates covering several orders of magnitude, and so it is difficult to assess how effectively these pulsars could be evaporating their companions. However, we note that the energy densities for 47 Tuc I and J straddle the value calculated for the system of PSR

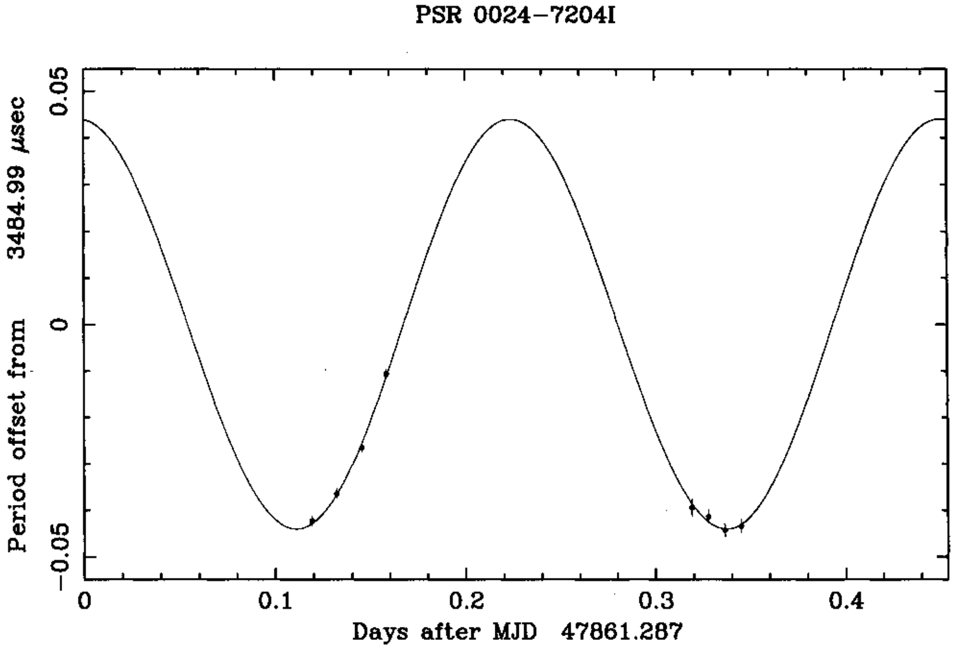

Figure 2. Pulse period plotted against time for the binary pulsar 47 Tuc I.

B1957+20 (5.3×10^{11} erg s^{-1} cm^{-2}) and are much greater than that calculated for the system containing PSR B1744−24A (4.2×10^{9} erg s^{-1} cm^{-2}).

5 THE ORIGIN AND EVOLUTION OF THE 47 TUCANAE PULSARS

In this section, we consider the possible origin and evolutionary history of the 47 Tucanae pulsars within the framework of the standard model of millisecond pulsar evolution mentioned in Section 1. While acknowledging that alternative models have been proposed in which the millisecond pulsars in globular clusters were born spinning rapidly (Chen, Middleditch & Ruderman 1993), either through the accretion-induced collapse of white dwarf stars in cataclysmic variables (Michel 1987; Bailyn & Grindlay 1990) or by some other means, these are not considered here. We shall first of all briefly review the main features of the standard model of millisecond pulsar production. Again, see Bhattacharya & van den Heuvel (1991) and references therein for a more detailed account.

In the crowded central regions of globular clusters, a single neutron star may capture a main-sequence or giant companion, either by two-body tidal capture or through an exchange encounter with a binary in which the neutron star replaces one of the binary components. Depending on the initial orbital period after capture, the resulting system may evolve into a 'wide' or a 'close' binary system containing a spun-up radio pulsar. For systems with initial orbital periods greater than about 12 h, nuclear-driven expansion of the companion will eventually cause it to overflow its Roche lobe, forming an X-ray source and spinning up the neutron star. The orbit expands due to the mass transfer, so that at the end of the nuclear burning we are left with a millisecond pulsar in a wide binary orbit. If, on the other hand, the initial orbital period is less than 12 h, gravitational radiation and magnetic braking are significant and cause the orbit to decay, resulting in Roche-lobe contact and mass transfer. This process may stop at an orbital period of about 3 h, when the donor star becomes fully convective and magnetic braking ceases. In this case, the result is a millisecond pulsar in a tight orbit with a companion of mass about 0.3 $M_{\odot}$. The companion mass may then be further reduced by ablation by the pulsar, in some cases completely evaporating the companion to leave a solitary millisecond pulsar.

A summary of what can be deduced about the origins of the binary pulsars in 47 Tucanae follows.

(i) *47 Tuc E.* The companion to this pulsar probably evolved through a red giant phase. However, the orbit of his pulsar cannot have undergone significant expansion during mass transfer; consequently the initial orbital period after capture was probably little more than half a day.

(ii) *47 Tuc H.* A unique orbital solution has not yet been achieved for this pulsar. Significant period variations were observed over intervals of an hour, suggesting that the orbital period is ~ few days. The system is probably similar to that of 47 Tuc E.

(iii) *47 Tuc I.* The short orbital period for this system suggests that the neutron star was captured by a main-sequence star and that the evolution was driven by orbital decay, although the orbital period lies above the 3-h threshold at which mass transfer should stop. This suggests that the standard model for the subday orbital period systems may require modification, perhaps taking into account the irradiation of the donor star during the X-ray phase (see Podsiadlowski 1991; Tavani 1992; Frank, King & Lasota 1993).

(iv) *47 Tuc J.* As for 47 Tuc I, the capture was probably by a main-sequence star. The orbital period is just below the 3-h boundary which marks the end of the X-ray phase of evolution in the standard model.

(v) *47 Tuc L.* No Doppler acceleration is apparent in the ~ 40-min duration of the discovery observation of this pulsar. Thus, if the pulsar is binary, it is not likely to be in a very close orbit.

The very low companion masses ($\lesssim 0.02$ $M_\odot$) observed in systems such as 47 Tuc I and J are quite mysterious. Millisecond pulsars have extremely long lifetimes, and the existence of two millisecond pulsars with such low-mass companions implies that the current state of these binaries is long-lived. Evaporation models suggest that the time-scale for evaporation scales as the companion mass M^{-1} for non-degenerate stars, but as M^3 for degenerate ones (van den Heuvel & van Paradijs 1988). If evaporation or ablation is responsible for the very low masses, then lifetime arguments suggest that they must now be non-degenerate. It seems unlikely that these pulsars will ever completely annihilate their companions.

The single pulsars 47 Tuc C, D, F, G, M and N may have originated from wide binary systems and lost their companions through ionization, or from close orbits, having achieved their isolation through the evaporation of their companions. A third possibility is that a solitary pulsar could have resulted from a catastrophic encounter between a neutron star and a main-sequence star in which the latter was completely disrupted, resulting in the formation of a massive accretion disc around the neutron star (Krolik 1984). An objection to this mechanism is that if an active pulsar is produced at all, it is expected to have experienced only a brief spin-up episode; accretion from the massive disc is expected to occur at a super-Eddington rate, quickly resulting in the expulsion of the disc by radiation pressure (Verbunt et al. 1987). This is inconsistent with the short periods of the 47 Tucanae pulsars and, indeed, it has been suggested (e.g. Tavani 1992) that this route could be responsible for the long-period solitary pulsars detected in some globular clusters.

Rappaport, Putney & Verbunt (1989) and Romani (1990) have shown that, for 47 Tucanae, ionization is unlikely to disrupt binaries with orbital periods less than ~1000 d in a reasonable fraction of a Hubble time. The observed sample of orbital periods shows a bias towards periods of a few days or less, well below the minimum value for ionization. Therefore, unless the central density is very much greater than the measured upper limit, it seems unlikely that many of the solitary pulsars derive from the ionization of very wide orbit binaries. It is therefore likely that most of the solitary pulsars lost their companions through ablation or Roche-lobe overflow in close binary systems. We also note that the circularity of the binary orbits of the 47 Tucanae pulsars is consistent with the rather low level of interaction expected between such short-period systems and other bodies (Rappaport et al. 1989).

It is notable that the rotation periods of the 47 Tucanae pulsars are all very short. Several pulsars with longer periods have been detected in globular clusters (see Manchester 1993 for a review). The pulsars with periods > 100 ms are solitary and located in very dense clusters, at least twice as dense as 47 Tucanae: PSR B1745−20 (289 ms) in NGC 6440, PSR B1820−30B (379 ms) in NGC 6624, and PSR B2127+11A (111 ms) in M15. This may be linked to the significance of the two-body tidal capture in these clusters. Two-body tidal captures are expected to occur preferentially in the denser globular clusters (Verbunt & Hut 1987), and this enables the slow class of pulsar to be circumstantially identified with the products of these encounters. Indeed, at least one-third of close two-body encounters involving a main-sequence star are expected to result in the destruction of the ordinary star (Verbunt 1989) which, as described earlier, may lead to suitable progenitors for the slow class. The two-body tidal capture rate, R, in a globular cluster scales as

$$R \sim \frac{\rho_c^2 r_c^3}{v_{\rm rms}} \tag{11}$$

(Verbunt & Hut 1987), where ρ_c is the core density, r_c is the core radius, and $v_{\rm rms}$ is the rms speed of stars in the core. The lack of these pulsars amongst the 47 Tucanae pulsars is consistent with their origin in two-body encounters. Using cluster parameters published by Webbink (1985), the tidal capture rate for 47 Tucanae is ~14 per cent of the total rate for the clusters containing members of the slow class, which together contain the same number of known pulsars as 47 Tucanae. The evolution phase of a cluster and the amount of time spent at its present core density may also be factors relating to the number of tidal capture products it contains; M15 and NGC 6624 are post-core collapse clusters (Djorgovski & King 1986) and may have spent most of their recent histories at even higher core densities. There is mounting evidence, including *Hubble Space Telescope* results (Calzetti et al. 1993), that 47 Tucanae is currently going through a phase of dynamical evolution, interpreted as core collapse and, as such, may have spent a significant fraction of its lifetime at lower core densities. Thus 47 Tucanae may, for much of its past, have been more closely related to the lower density clusters, implying that exchange interactions are the dominant formation mechanism for the progenitor systems of millisecond pulsars in this cluster.

The subday orbital period binary pulsars in M15 (Anderson et al. 1990), Terzan 5 (Lyne et al. 1990) and NGC 6342 (Lyne et al. 1993) are located well outside the cores of their respective clusters and were probably ejected from the inner regions of the clusters by recoil velocities imparted during their formation in exchange encounters (Phinney & Sigurdsson 1991; Wijers & Paczyński 1993). As more positions are obtained for the pulsars of 47 Tucanae, we would expect some to be located in regions remote from the cluster core.

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