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THE BINARY PULSAR PSR 1908+00 IN NGC 6760

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ABSTRACT

We present orbital parameters of the 3.6 ms binary pulsar 1908+00 in the globular cluster NGC 6760. The orbital period is 3.4 hr, and the mass function is $3 \times 10^{-6}\ M_\odot$, implying a minimum companion mass of 0.018 $M_\odot$. The companion is probably degenerate; and if it is hydrogen, it is close to overflowing its Roche lobe. The only other millisecond binary radio pulsar systems with orbital period <10 hr and mass function below $10^{-3}\ M_\odot$ are the eclipsing pulsars 1957+20 and 1744−24A, and the very low mass binary 0021−72J. These pulsars are ablating their companions and may be the progenitors of isolated millisecond pulsars. PSR 1908+00 shows no evidence for long-duration eclipses as are seen in 1744−24A, but short-duration eclipses as in 1957+20 are not excluded.

Subject headings: binaries: general — pulsars: individual (PSR 1908+00) — stars: neutron

1. INTRODUCTION

The pulsar was discovered during a pulse search of the globular cluster NGC 6760 (Anderson et al. 1990). Its rapid variation in apparent rotational frequency made it quickly evident that this would be an interesting binary system. Follow-up observations were conducted using the Arecibo 305 m radio telescope in the 1.4 GHz band and a bandwidth of 40 MHz. The choice of a relatively high observing frequency was made because of the large dispersion measure (DM = 201.5 cm^{-3} pc). The data were obtained using the Observatory's 128 × 2–lag correlator and an effective sampling interval of 506.625 μs. Both polarizations were summed together and the data recorded on magnetic tape for off-line analysis. Analysis was carried out on Cray Y-MP supercomputers at the Los Alamos National Laboratory and the San Diego Supercomputer Center.

Each time series was dedispersed and resampled to be uniformly spaced in the solar system barycenter frame. Both of these steps require shifting and interpolating time series. Interpolating a new time series from an existing one will introduce some noise, so the barycentering is combined with the dedispersion step to minimize this "interpolation noise."

The small orbital period causes the pulsar to be significantly accelerated during an integration, making the apparent frequency vary by order of one part in 10^5 over a typical 30 minute integration. Unfortunately, because the pulsar is faint ($\approx$1.5 mJy at 1.4 GHz) and at a declination where the antenna's gain is substantially reduced, shorter integrations are generally not practical. Therefore, in order to detect the pulsar, we resampled each time series to compensate for a linear but unknown acceleration. This is a satisfactory correction as long as the orbit can be reasonably approximated by a parabola during an observation (Middleditch & Córdova 1982; Johnston & Kulkarni 1991). Since, at this stage in the analysis, the orbital parameters are unknown, a range of trial accelerations is applied, and a pulsed signal is searched for in each trial. Each observation was searched at $\sim 10^3$ trial pulsar accelerations in order to obtain the current set of 56 independent observations of the pulsar on 16 days (Fig. 1). There are an additional $\sim 15^{\mathrm{d}}$ of observations with no detections, which is probably due to refractive scintillation (see discussion below); the detection limit is approximately a factor of 2 below the typical flux level in the detections.

The orbital period is 3.4 hr, and about one-third of an orbit was observable from Arecibo in a single $\sim$1 hr transit. An extensive series of observations was required to determine a unique set of orbital parameters. The line-of-sight component of the pulsar's orbital velocity can be obtained from the variations in the apparent pulsar period. The system is equivalent to a single-line spectroscopic binary, and the Keplerian parameters of the orbit are determined by a least-squares fit (Table 1 and Fig. 1).

2. RESULTS AND DISCUSSION

The 3.4 hr orbital period and pulsar semimajor axis $a_p \sin i$ of 37.5 ms places 1908+00 among the most compact binary pulsar systems. The eccentricity is consistent with 0 ($e < 0.01$), and the mass function $f_m = 2.8 \times 10^{-6}\ M_\odot$ implies a companion mass $M_C = 0.018/\sin i\ M_\odot$, where i is the unknown inclination of the orbit and the pulsar mass, M_p, is assumed to be 1.4 $M_\odot$ (Fig. 2).

This system joins the emerging class of binary pulsars with very low mass companions ($M_C \lesssim 0.1\ M_\odot$) and short orbital periods ($P_b \lesssim 0^{\mathrm{d}}.5$; see Table 1 and Fig. 3): 1957+20 (Fruchter et al. 1988), 1744−24A (in the globular cluster Terzan 5; Lyne et al. 1990) and 0021−72J (in the cluster 47 Tuc; Manchester et al. 1991). The 1908+00 system is amazingly similar to 0021−72J.

Two of these four pulsars, PSR 1957+20 and PSR 1744−24A, are known to be eclipsing. Simple Roche lobe overflow does not suffice explain the duration of the observed eclipses in either pulsar, which is greater than would be expected if the eclipsing region were restricted to the diameter of the Roche lobe. The eclipsing material is instead attributed to "windy" mass loss arising from the ablation of the companions by the pulsar wind (e.g., Kluźniak et al. 1988; Phinney et al. 1988; van den Heuvel & van Paradijs 1988).

From analogy and theoretical reasoning (below), we expect 1908+00 to also be an eclipsing system. PSR 1908+00 shows no evidence for long-duration ($\gtrsim 0.15 P_b$) eclipses (see Fig. 1).

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TABLE 1

ORBITAL PARAMETERS FOR PSR 1908+00 AND OTHER MILLISECOND ECLIPSING PULSARS

Parameter	PSR 1908+00	PSR 0021−72J	PSR 1957+20	PSR 1744−24A
Period P (ms)	3.618524 (4)	2.1006	1.6074	11.56314839
Period derivative $\dot{P}$	$<1 \times 10^{-17}$	...	2×10^{-20}	1.9×10^{-20}
Orbital period P_b (days)	0.140996 (1)	0.120665	0.3819666	0.07564611
Projected semimajor axis $a_p \sin i$ (s)	0.0375 (20)	0.0405	0.08923	0.11966
Eccentricity e	$\lesssim 0.01$	0.0	0.000	0.0
Time of ascending node T_0 (JD)	2,447,154.404 (7)	2,448,124.3	2,447,244.58471	2,447,980.805347

NOTE.—Errors are 1 σ.

The eclipse duration limit is set by the typical integration time needed to detect the pulsar. With these limits we cannot rule out eclipses with short durations such as the $\sim 0.1 P_b$ eclipse in 1957+20.

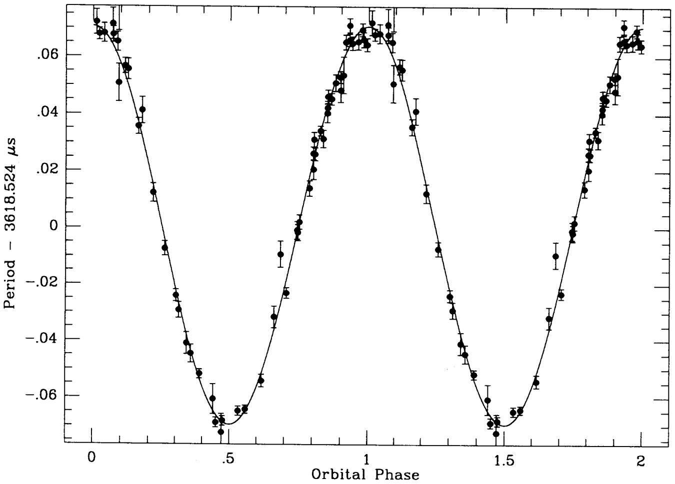

FIG. 1.—Barycentric period vs. orbital phase. The dots show the observed barycentric period of PSR 1908+00 as a function of orbital phase. The second half of the figure is a repeat of the first half for continuity. The solid line is the model for the orbit. Note that there are no preferred orbital phases at which the pulsar is not detected.

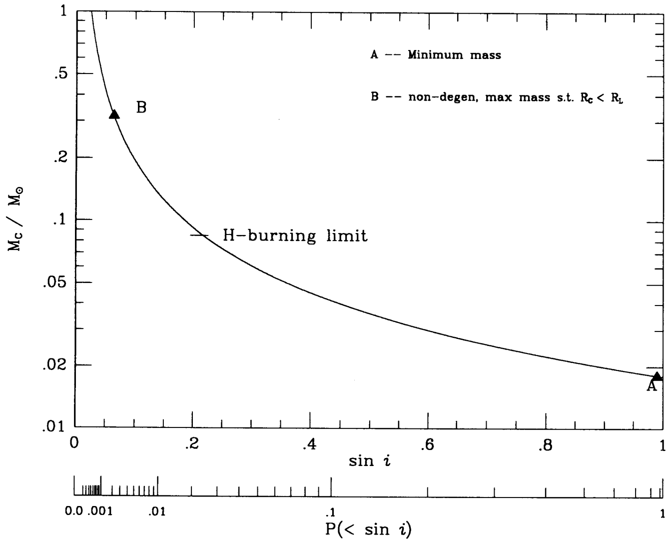

FIG. 2.—Companion mass as a function of inclination i. Filled triangle A marks the minimum mass of the companion, and filled triangle B marks the maximum mass for a nondegenerate companion to keep $R_C < R_L$.

The above conclusion applies to eclipses that occur essentially every orbit, as in 1957+20. In contrast, eclipses in 1744−24A occur irregularly but are of much longer duration (up to $0.5 P_b$; Lyne et al. 1990; Nice et al. 1990). We note that the observations in which PSR 1908+00 was not detected were clumped together: the pulsar would remain undetectable for several consecutive days and then be visible for a run of days at the next observing session 1–2 months later. This is consistent with refractive scintillation for an object at DM ≈ 200. The nondetections occurred at several orbital phases; there was no favored phase.

From the above discussion, it is clear that short-duration eclipses cannot be ruled out. We now investigate the conditions required for eclipses. Since nothing is known about the companion except its mass, we consider the following possible compositions: H-degenerate; He-degenerate; low-mass main-sequence; and "bloated" main-sequence stars. Eclipses can occur if there is mass loss from the companion, as will happen if the companion's radius R_C exceeds its Roche lobe radius R_L, or if a wind is driven from the surface. For R_L, we have

$$\frac{R_L}{a} = 0.46\left(\frac{M_C}{M_T}\right)^{1/3}, \quad \frac{M_C}{M_p} < 0.8\,, \qquad (1)$$

where a is the semimajor axis of the system and M_T is the total mass (Paczyński 1971).

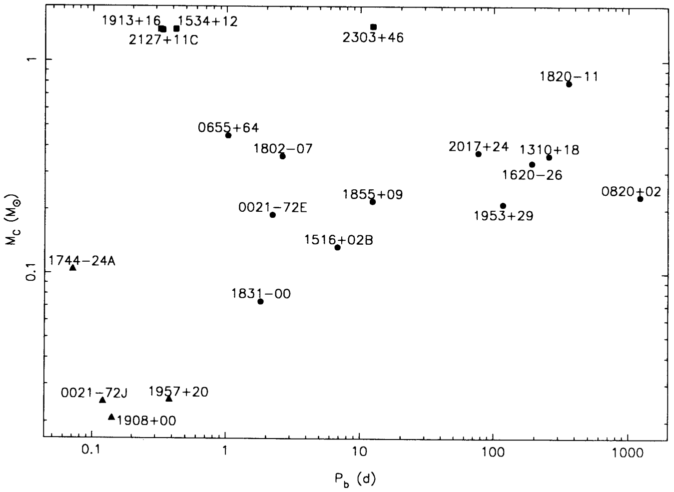

FIG. 3.—Orbital period vs. companion mass. The orbital period is plotted against companion mass for all binary pulsars with published mass functions. Triangles marks the new class of very low mass binary pulsars (VLMBP), circles denote the low-mass binary pulsars (LMBP), and squares denote the high-mass binary pulsars (HMBP). In the majority of systems, the individual masses are not known, in which case we assumed that the inclination is the median value (60°), giving a companion mass $M_C = 1.15\, M_{\rm min}$.

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TABLE 2

ADDITIONAL PARAMETERS FOR PSR 1908+00 AND OTHER MILLISECOND ECLIPSING PULSARS

Parameter	PSR 1908+00	PSR 0021−72J	PSR 1957+20	PSR 1744−24A
Right ascension	$19^{\mathrm{h}}10^{\mathrm{m}}23^{\mathrm{s}}.6$	$00^{\mathrm{h}}24^{\mathrm{m}}06^{\mathrm{s}}.0$	$19^{\mathrm{h}}59^{\mathrm{m}}22^{\mathrm{s}}.6$	$17^{\mathrm{h}}48^{\mathrm{m}}03^{\mathrm{s}}.6$
Declination	$00^\circ04'55''.65$	$-72^\circ04'52''.73$	$+20^\circ47'56''.49$	$-24^\circ46'49''.40$
Dispersion measure DM ($\mathrm{cm^{-3}\ pc}$)	201.5 (5)	24.5	29.128	242.153
Intrinsic period derivative $\dot{P}_{\mathrm{intr}}$	2×10^{-20} [a]	4×10^{-20} [c]	2×10^{-20}	1×10^{-20} [a]
Surface magnetic field B (G)	3×10^{8} [a]	3×10^{8} [a]	1.8×10^{8}	3×10^{8} [a]
Mass function f_m ($M_\odot$)	2.84×10^{-6}	4.9×10^{-6}	5.2×10^{-6}	3.2×10^{-4}
Minimum companion mass $M_{C,\mathrm{min}}$ ($M_\odot$)	0.018[b]	0.021[b]	0.022[b]	0.089[b]
Median values ($i = 60°$):				
Companion mass $M_{C,\mathrm{med}}$ ($M_\odot$)	0.021[b]	0.025[b]	0.025[b]	0.10[b]
Semimajor axis a (cm)	8.9×10^{10}	8.6×10^{10}	1.7×10^{11}	5.7×10^{10}
Companion radius R_C ($R_\odot$)	$0.12 \sin^{1/3} i$ [c]	$0.11 \sin^{1/3} i$ [c]	$0.11 \sin^{1/3} i$ [c]	$0.09 \sin^{-1} i$ [d]
Roche lobe radius R_L ($R_\odot$)	$0.14 \sin^{-1/3} i$	$0.15 \sin^{-1/3} i$	$0.28 \sin^{-1/3} i$	$0.15 \sin^{-1/3} i$
R_C/R_L	$0.90 \sin^{2/3} i$ [c]	$0.86 \sin^{2/3} i$	$0.39 \sin^{2/3} i$	$0.82 \sin^{4/3} i$
Pulsar flux at companion $F_p(a)$ ($\mathrm{ergs\ s^{-1}\ cm^{-2}}$)	2.4×10^{11}	2.6×10^{12}	7.4×10^{11}	8.8×10^{9}

[a] Assumed $B = 3 \times 10^8$.
[b] Assumed $M_p = 1.4\, M_\odot$.
[c] Assumed $X = 0.7$ degenerate companion.
[d] Assumed main-sequence companion.

If the companion is degenerate, then (Savonije 1983)

$$\frac{R_C}{R_\odot} = 0.013(1 + X)^{5/3}\left(\frac{M_C}{M_\odot}\right)^{-1/3}, \tag{2}$$

where X is the hydrogen mass fraction. For $X = 0.7$, $R_C = 0.12(\sin i)^{1/3}\, R_\odot$. If $X = 0$, as might be the case if the companion's core has been exposed by ablation of the envelope, $R_C = 0.05(\sin i)^{1/3}\, R_\odot$; a helium companion like this has been inferred for the 11 minute binary system in NGC 6624 (Stella, Priedhorsky, & White 1987). The companion could also be a low-mass main-sequence star, for which

$$\frac{R_C}{R_\odot} = \frac{M_C}{M_\odot} \tag{3}$$

(Savonije 1983). This is unlikely since the minimum mass for a hydrogen-burning star is 0.085 $M_\odot$ (Graboske & Miller 1971), implying $\sin i \leq 0.22$, which has probability 0.025.

Use of equation (3) is questionable for companions which have presumably undergone substantial mass loss and are illuminated by the pulsar. We consider as an alternative the mass-radius relation for the "bloated star" sequence (Podsiadlowski 1991; Frank, King, & Lasota 1992) and *assume* it can be extended to the lowest main-sequence masses:

$$\frac{R_C}{R_\odot} = 1.28\left(\frac{M_C}{M_\odot}\right)^{2/5}. \tag{4}$$

We note that Roche lobe overflow is expected to take place. However, the probability of obtaining such small inclinations is small.

Combining the above equations yields

$$\frac{R_C}{R_L} = \begin{cases} 0.90 \sin^{2/3} i & \text{degenerate, } X = 0.7 \\ 0.36 \sin^{2/3} i & \text{degenerate, } X = 0.0 \\ 0.13 \sin^{-2/3} i & \text{main sequence, } 0 < \sin i < 0.22 \\ 1.9 \sin^{-1/5} i & \text{bloated main sequence, } 0 < \sin i < 0.22\,. \end{cases} \tag{5}$$

From equation (5) we see that Roche lobe overflow is possible but not probable. A degenerate hydrogen companion will not overflow the Roche lobe; however, the companion would be closer to filling it than the companions to either PSR 1957+20 or PSR 1744−24A, assuming similar inclinations for the systems (see Table 2). An ordinary nondegenerate companion to PSR 1908+00 will overflow its Roche lobe for $\sin i \lesssim 0.047$, but $P(\sin i < 0.047) = 0.001$, a rather unlikely situation. Finally, if the bloated main sequence holds at low masses, the companion would certainly overflow its Roche lobe; yet this requires the low-probability inclination $\sin i \lesssim 0.22$.

An alternative source of eclipsing material is a wind driven from the companion. Following van den Heuvel & van Paradijs (1990), we use a simple model and assume the pulsar radiates its spindown luminosity L_p isotropically, and that a fraction f of the flux irradiating the companion is converted to a wind emerging at the companion's escape velocity v_e. The irradiating flux at the companion is $F_p(a) = I\Omega\dot{\Omega}/4\pi a^2$, where I is the pulsar moment of inertia and $\Omega = 2\pi/P$. The rate of mass loss $\dot{M}_C$ is then given by

$$\tfrac{1}{2}\dot{M}_C v_e^2 = f F_p(a)(4\pi R_C^2)\,, \tag{6}$$

leading to

$$\dot{M}_C = f(4\pi^2 I/GM_C)(\dot{P}/P^3)(R_C^3/a^2)\,. \tag{7}$$

From equation (1), $a \propto R_L$, and thus $\dot{M} \propto R_C^3/R_L^2$ is maximized as R_C approaches R_L.

The value of most of the quantities on the right-hand side of equation (7) is uncertain; only P is well known for this group of pulsars. The estimates for f span several orders of magnitude, from 10^{-4} to 10^{-1} (Phinney et al. 1988; Kluźniak et al. 1988; Emmering & London 1990; Rasio, Shapiro, & Teukolsky 1991; Ruderman, Shaham, & Tavani 1989a; Ruderman et al. 1989b). The companion radius depends on both its unknown mass and composition. The intrinsic period derivative $\dot{P}_{\mathrm{intr}}$ is well known only for PSR 1957+20.[5]

We now also assume that all spun-up pulsars with millisecond periods have the same magnetic field as the millisecond disk pulsars (about 3×10^8 G; Kulkarni 1992). Under these assumptions, $F_p(a)$ is computed for PSR 1908+00 and the two eclipsing millisecond pulsars (Table 2). For PSR 1908+00,

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[5] For PSR 1744−24A, $\dot{P} = -1.5 \times 10^{-20}$. However, Nice & Thorsett (1992) argue that the measured $\dot{P}$ is the combination of the intrinsic $\dot{P}$ plus comparable or greater contributions from the acceleration of the system in the galactic and globular cluster gravitational potentials. This renders the observed $\dot{P}/P^3$ useless as a measure of spindown luminosity.

$F_p(a)$ is (1) within a factor of 3 of the irradiating flux at the companion to PSR 1957+20; and (2) an order of magnitude greater than that for PSR 1744−24 or any of the ordinary low-mass binary pulsars. We conclude that mass loss from the companion is likely, which may be manifested in eclipses shorter than can be seen with the current orbital phase resolution. If $f \gtrsim 0.01$, it will be sufficient to evaporate the companions of either of PSR 1908+00 or PSR 1957+20 in less than 3×10^7 yr. An orbital decay on this time scale, cause unknown, has been seen in the 1957+20 system. However, it would be still surprising if PSR 1908+00 were to spiral in or evaporate on such a time scale, since it would imply a large birthrate in this low-density cluster (Webbink 1985).

3. FUTURE WORK

Having obtained the Keplerian orbital elements, we are now in a position to fold the time series synchronously with orbital phase. The observations will be divided into segments of duration $\sim 0.02P_b$, and folded profiles at each phase will be co-added in a search for (*a*) systematically reduced emission when the companion is at inferior conjunction; and (*b*) dispersion variations as a function of orbital phase. It is important to determine if any eclipsing is occurring, and this reanalysis is intended to more carefully detect eclipse signs. We will also attempt to phase-connect the observations to improve the parameters, in particular to obtain $\dot{P}$ and $\dot{P}_b$.

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