BINARY PULSARS

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There are now three radio frequency pulsars known to be in binary systems: PSRs 1913+16, 0820+02, and 0655+64. The first of these, discovered in 1974, moves in a tight, highly eccentric orbit with a period of approximately $7^h\ 45^m$. Its companion has not yet been identified with certainty, but must be a compact object of mass comparable to that of the pulsar. PSRs 0820+02 and 0655+64, recognized as binaries during the past fifteen months, have nearly circular orbits with periods of over three years and about one day, respectively. All three objects are of great interest for the opportunity they provide to measure the masses of neutron stars. In addition, the first has proven to be a useful probe of gravitational theories, and the study of all of them should yield important information concerning the evolution of binary systems and the formation of neutron stars.

Soon after the discovery of pulsars, it was recognized that finding one of these objects in a gravitationally bound orbit about another massive body would provide an important opportunity for measuring the mass of a neutron star, thereby providing invaluable information constraining the physics of matter at very high densities. However, it quickly became clear that most pulsars are not members of binary systems, because orbital motion would quickly make itself known through cyclic variations in the arrival times of the pulses. Since pulsar timing can be done with accuracies of order 100 μs, even very low-mass companions could be easily detected through their periodic displacements of the pulsar from the binary system barycenter. (The earth, for example, displaces the sun from the center of mass of the solar system by about 1500 μs. If the sun were a pulsar, a distant observer could in principle detect the presence of all of the planets through patient monitoring and analysis of the pulse arrival times.) The lack of such effects in the timing data of the first ~50 pulsars made it obvious that orbiting companions of stellar mass are quite rare.

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CLASSICAL ORBIT EFFECTS

Discovery of the pulsar PSR 1913+16 thus came as a surprise (Hulse and Taylor 1975), because variations in its pulsation period revealed almost immediately that it moves in an orbit of period $P_b \simeq 0.323$ days, large eccentricity ($e \simeq 0.617$), and mildly relativistic velocity ($|v|_{max} \simeq 10^{-3}$ c). The observed period variations yield a velocity curve exactly analogous to those obtainable for spectroscopic binary stars. The amplitude and shape of the curve may be used to calculate the values of five "Keplerian" orbit parameters, a suitable set of which are listed in part (a) of Table 1. The binary period (P_b) and projected semi-major axis (a_p sin i) then yield the pulsar mass function, which follows directly from Kepler's law:

$$f(m_p) = \frac{m_c^3 \sin^3 i}{(m_p + m_c)^2} = \frac{4\pi^2}{G}\,\frac{(a_p \sin i)^3}{P_b^2} = 0.1322\ M_\odot$$

(Here m_p and m_c are the masses of the pulsar and its companion, respectively, and G is the constant of gravitation; all other quantities are defined in Table 1.) The mass function does not directly yield the mass of either of the two orbiting objects, but it does provide a useful constraining relation. Figure 1 illustrates this constraint for PSR 1913+16, in the form of a family of curves giving the companion mass as a function of cos i (where i is the unknown angle of inclination between the plane of the orbit and the plane of the sky). Because any value of cos i is equally likely a priori, and because theory dictates that neutron star masses must lie in the range between a few tenths and ~2 solar masses, it is clear on the basis of the mass function alone that the companion of PSR 1913+16 has a mass not too different from that of the sun. Additional information is required in order to determine the pulsar and companion masses individually. One method for doing so is described in the last section of this paper.

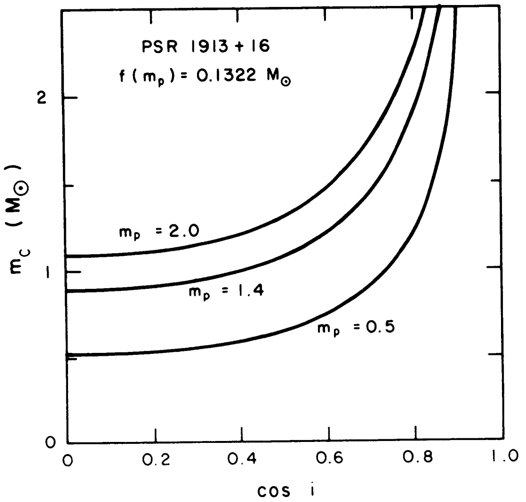


Fig. 1. Mass of the companion of PSR 1913+16, as a function of cos i, for each of three assumed pulsar masses

Table 1. Parameters of PSR 1913+16

(a) Keplerian orbit parameters

Projected semimajor axis	$a_p \sin i$ (s)	2.3419 ± 0.0004
Orbital eccentricity	e	0.617138 ± 0.000008
Binary period	P_b (s)	27906.98157 ± 0.00006
Periastron longitude	ω (deg)	178.867 ± 0.002
Periastron passage time	T_0 (JD)	$2442321.433210 \pm 0.000002$

(b) Astrometric and pulsar "clock" parameters

Right ascension	$\alpha(1950)$	$19^h\ 13^m\ 12^s.469 \pm 0^s.014$
Declination	$\delta(1950)$	$16^\circ\ 01'\ 08''.15 \pm 0''.20$
Period	P (s)	0.0590299952695 ± 8
Derivative of P	$\dot{P}$ (ss^{-1})	$(8.636 \pm 0.010) \times 10^{-18}$
Second derivative of P	$\lvert \ddot{P} \rvert$ (ss^{-2})	$< 1.2 \times 10^{-28}$

(c) Relativistic orbit parameters

Periastron advance rate	$\dot{\omega}$ (deg yr^{-1})	4.226 ± 0.001
Time dilation	γ (s)	0.0044 ± 0.0003
Derivative of P_b	$\dot{P}_b$ (ss^{-1})	$(-2.1 \pm 0.4) \times 10^{-12}$
Orbital inclination	$\sin i$	< 0.96

Pulsar surveys undertaken during 1977-79 have increased the number of known pulsars to 328 (Manchester et al. 1978; Damashek, Taylor and Hulse 1978; Damashek, Backus and Taylor 1980). Timing measurements of approximately 200 recently discovered pulsars were begun in 1978 by three groups working independently and using the 210-foot antenna at Parkes, the 300-ft at Green Bank and the 250-ft Mark Ia at Jodrell Bank. The principal aim of these observations was to determine period derivatives and precise celestial coordinates of the pulsars, but each group was also alert for evidence of binary motions. Manchester et al. (1980) soon recognized that the period of one source, PSR 0820+02, had decreased, rather than increased, during most of 1977-78. In October 1978 the period began to increase again, and these authors concluded that PSR 0820+02 was a member of a long-period binary system. The period measurements of PSR 0820+02 made at Parkes, Jodrell Bank and Green Bank are summarized in Figure 2, and Table 2 lists the pulsar and orbital parameters deduced from the computed radial velocities.

The mass function of PSR 0820+02 is nearly 50 times smaller than that of PSR 1913+16, and, as indicated in Figure 3, suggests a companion with mass in the range of ~0.2 to ~0.5 $M_\odot$. Many questions

Table 2. Parameters of PSR 0655+64 and PSR 0820+02

	PSR 0655+64[a]	PSR 0820+02[b]
$\alpha(1950)$	$06^h\ 55^m\ 34^s.8 \pm 0^s.2$	$08^h\ 20^m\ 34^s.05 \pm 0^s.02$
$\delta(1950)$	$+64^\circ\ 18'\ 04'' \pm 5''$	$+02^\circ\ 08'\ 54''.3 \pm 0''.5$
P (s)	0.1956708852 ± 4	0.8648724 ± 2
$\dot{P}$ (ss^{-1})	$(1.48 \pm 0.02) \times 10^{-15}$	--
$a_p \sin i$ (s)	4.1243 ± 0.0004	152 ± 5
e	0.00033 ± 0.00018	0.05 ± 0.02
P_b	$88877.27 \pm .08$ s	1154 ± 30 days
ω (deg)	94 ± 30	34 ± 18
T_0 (JD)	2444323.15 ± 0.08	2444462 ± 90

[a] The position listed for PSR 0655+64 is derived from only five months of timing data, and is provisional. Possible mis-numbering of the pulses might render the position inaccurate by many times the quoted uncertainty, and would also change P and $\dot{P}$ somewhat.

[b] The position listed for PSR 0820+02 was measured by J.J. Condon (private communication) using the VLA at 1400 MHz. A timing position is not yet available.

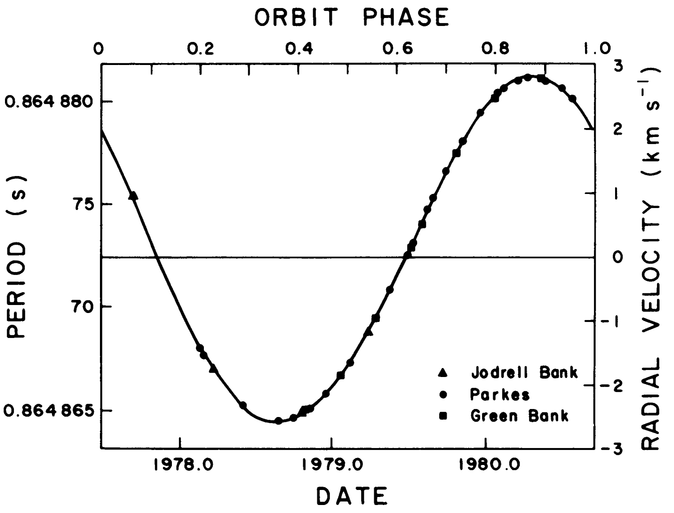
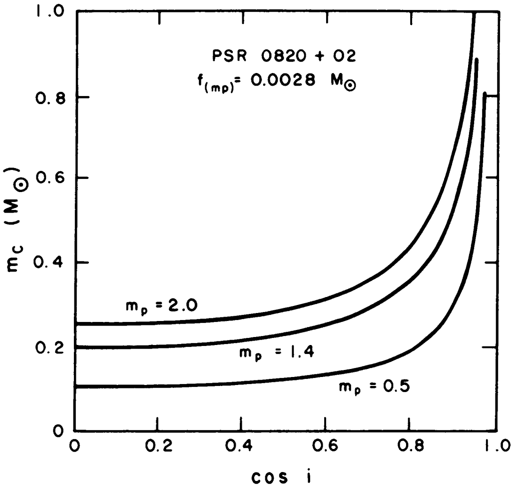


Figure 2. Period measurements of PSR 0820+02 during 1977-80

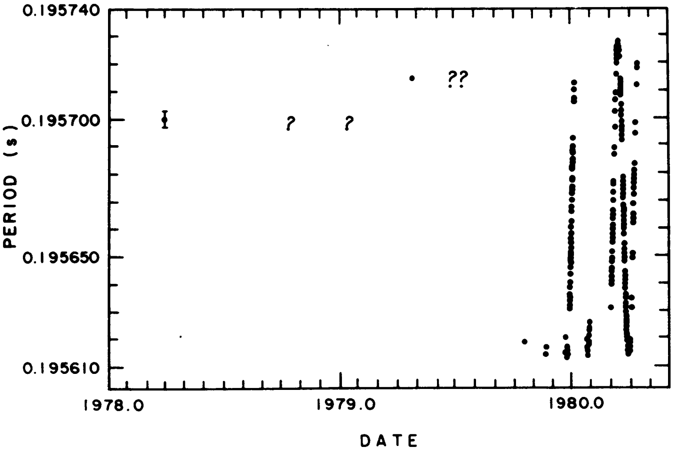
remain to be answered concerning the details of this binary system and its evolution, such as: why is the orbit so large and so nearly circular? And how did it remain bound as the two stars evolved? Blandford and DeCampli (1981) will discuss these and other problems in the next paper.

Figure 3. Mass of the companion of PSR 0820+02 as a function of cos i for each of three assumed pulsar masses



The third binary pulsar, PSR 0655+64, was difficult to recognize as such--the reason being, as it turned out, that its orbital period is so close to one day. As shown in Figure 4, the first few timing measurements of this source made in 1978-79 were inconsistent and perplexing. By late 1979, it was clear that the pulsation period was variable by an amount at least as large as $\Delta P/P$ = 1/2000, but the pattern of variations was still anything but clear. More frequent observations were begun in December, and soon revealed that the period changes were periodic, repeating with a cycle just longer than one day (Damashek, Backus and Taylor 1980). Because these observations were being made with the NRAO 300-ft telescope--a transit instrument with very limited tracking capability--five weeks of almost daily observations were required to sample all orbital phases. The resulting

Figure 4. Period measurements of PSR 0655+64, as a function of date. Question marks represent times when the pulsar was not seen.



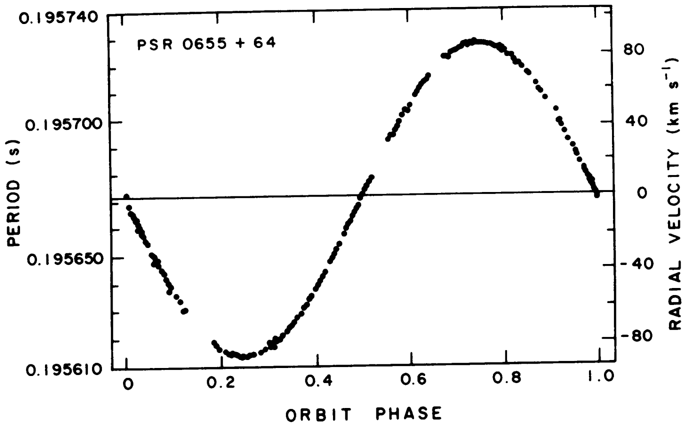


Figure 5. Period and radial velocity of PSR 0655+64 as a function of orbital phase

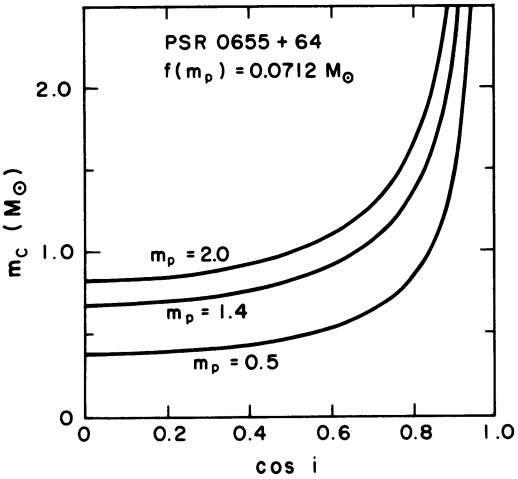


Figure 6. Mass of the companion of PSR 0655+64 as a function of cos i for each of three assumed pulsar masses

velocity curve, shown in Figure 5, showed that PSR 0655+64 moves in a nearly circular orbit of period approximately 24^h41^m and mass fuction $f(m_p) = 0.0712\ M_\odot$. More detailed pulsar and orbital parameters are listed in Table 2. As shown in Figure 6, the mass function implies a probable mass of the companion star in the range ~0.5 to ~2 $M_\odot$.

Unambiguous determination of the masses of PSR 0655+64 and PSR 0820+02 requires more data than that contained in their velocity curves. It is interesting to note that both pulsars are well above the galactic plane (b = 25° and 21°, respectively) and have rather small dispersion measures (24 and 9 cm^{-3} pc), indicating distances < 1 kpc. Thus, unless the companions are neutron stars (which seems unlikely in both cases, for evolutionary reasons), optical detection of the companions may prove to be possible. Such work would, needless to say, be very important. Although high confidence-level timing positions are not yet available for either of these pulsars, they should become available soon. Another important measurement for PSR 0655+64 would be the accurate determination of dispersion measure as a function of orbit phase, which might reveal the presence of an atmosphere or stellar wind around the companion.

RELATIVISTIC EFFECTS

Effects beyond the first order in (v/c) will probably not be observable for PSRs 0655+64 and 0820+02, because of their moderate orbital velocities and very small eccentricities. However, relativistic effects can easily be observed in timing observations of PSR 1913+16, and much additional information can be obtained from their study (Taylor et al. 1976; Taylor, Fowler and McCulloch 1979). The largest such effect, by far, is the secular advance of the longitude of periastron of the orbit. As shown in part (c) of Table 1, this angle is observed to increase by about 4.2 degrees per year. If, as appears to be the case, the rotation is entirely the result of the expected general relativistic effect, then the rate establishes the total mass of the system at $m_p + m_c = 2.826 \pm 0.001\ M_\odot$.

The next largest relativistic effect is the time dilation arising from second order or "transverse" Doppler shift and gravitational redshift. Because of the large orbital eccentricity, each of these effects gives rise to an observable periodically varying delay of the pulse arrival times. A single measurable parameter, listed as γ in Table 1, quantifies them both, and it can easily be shown (Blandford and Teukolsky 1976) that γ depends on a different combination of the two masses than does $\dot{\omega}$. Thus measurement of γ, together with $\dot{\omega}$, permits the direct calculation of $m_p = 1.43 \pm 0.07$ and $m_c = 1.40 \pm 0.07\ M_\odot$. The mass function then requires that $\sin i = 0.73 \pm 0.04$, or $i = 47° \pm 3°$.

Having now specified the relevant orbital parameters and the component masses, we can calculate the expected rate of orbital period decay from the loss of energy through gravitational radiation. The relevant expression in general relativity, valid in the appropriate slow motion, weak field approximation, was derived by Peters and Matthews (1963). Expressed as a rate of change of orbital period, and after insertion of the measured orbital parameters, their result yields the prediction $\dot{P}_b = (-2.38 \pm 0.02) \times 10^{-12}\ s\ s^{-1}$. The excellent agreement with the measured value of $(-2.1 \pm 0.4) \times 10^{-12}$ quoted in Table 1 is strong evidence that the dominant damping mechanism is, in fact, gravitational radiation, in the amount predicted by general relativity. The accumulating shift in orbital phase, relative to that for an orbit with constant period, is illustrated in Figure 7. The curve drawn through the measurements corresponds to the predicted value of $\dot{P}_b$.

Our model for analyzing the timing measurements of PSR 1913+16 (Blandford and Teukolsky 1976; Epstein 1977) is obviously an idealized one. For example, it treats both the pulsar and its orbiting com-

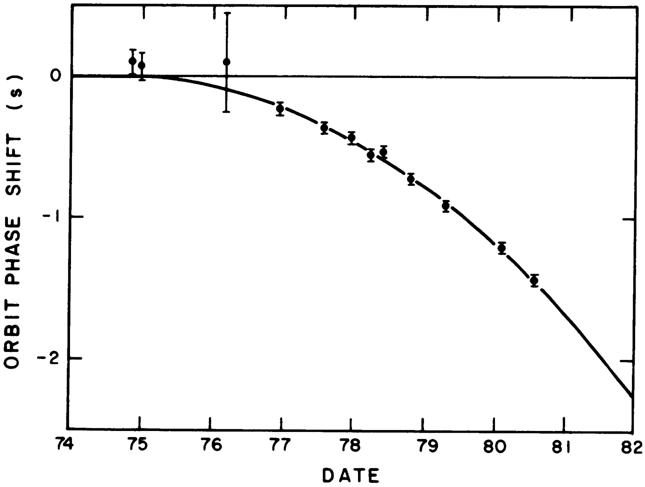


Figure 7. Observed accumulation of excess orbital phase, relative to a hypothetical orbit of constant period. The predicted change due to gravitational radiation is shown by the parabolic curve.

panion as point masses, and ignores such possible effects as tidal bulges and viscous dissipation of orbital energy. However, it is heartening to note that the model contains more observables than free parameters, and the overall self-consistency of the solution lends further confidence in the results. It is possible, though I believe very unlikely, that the self-consistency is partly fortuitous--and that we have obtained some of the right answers for the wrong reasons.

There are at least two more relativistic effects which may in time be measurable in the PSR 1913+16 system, and which would provide even stronger evidence for the validity of our model: a combination of time retardation and third order terms in the orbital velocity (Epstein 1977), and geodetic precession of the pulsar spin axis (e.g., Hari-Dass and Radhakrishnan 1975). The first of these provides a direct, though difficult, method of measuring the orbital inclination sin i, and the second may permit one to map the pulsar radiation beam in latitude as well as longitude. Unfortunately, my colleagues and I no longer believe that we have measured these effects with useful accuracy (McCulloch, Taylor and Weisberg 1979; Taylor, Fowler and McCulloch 1979). Allowance for possible small systematic errors in the measured pulse arrival times increases the uncertainty in the direct measurement of sin i, especially on the low side; Table 1 lists our remaining rather rigid upper limit, sin i < 0.96. Attempts are being made to reduce the uncertainties and to provide a definitive measurement of sin i. Circular polarization measurements have shown that most, if not all, of the reported secular change in pulse shape (taken as evidence of spin precession) are an artifact of weak circular polarization. The best statement we can now make is that the pulse shape has not changed by a measurable amount in several years. This fact suggests that the pulsar spin axis is aligned nearly perpendicular to the orbital plane.

I will finish with an interesting statement about the pulsar emission mechanism, based on the apparent near coincidence of the equatorial plane and orbit plane of PSR 1913+16, and the conclusion that the orbit plane is inclined by about 47° to the plane of the sky. If pulsars emit directionally because of relativistic beaming at the light cylinder, the radiation must be concentrated within ∿ ±10° of the equatorial plane--and in that case, PSR 1913+16 should be invisible to us. On the other hand, polar-cap emission models can easily radiate at an angle of 47° to their equator, if the magnetic axis is pointed in that general direction.

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