The Masses of Two Binary Neutron Star Systems

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Abstract

The measurement or constraint of the masses of neutron stars and their binary companions tests theories of neutron star structure and of pulsar formation and evolution. We have measured the rate of the general relativistic advance of the longitude of periastron for the pulsar PSR B1802−07: \( \dot{\omega} = 0.060 \pm 0.009 \text{ yr}^{-1} \), which implies a total system mass, pulsar plus companion star, of \( M = 1.7 \pm 0.4 M_\odot \). We also present a much improved measurement of the rate of periastron advance for PSR B2303+46: \( \dot{\omega} = 0.0099 \pm 0.0002 \text{ yr}^{-1} \), implying \( M = 2.53 \pm 0.08 M_\odot \) for this system. We discuss the available constraints on distribution of mass between the pulsars and their companions, and we compare the pulsar masses with other determinations of neutron star masses.

Subject headings: pulsars — stars: binaries — stars: neutron — stars: individual (PSR B1802−07 — PSR B2303+46)

1 Introduction

Since the pioneering calculations of Oppenheimer and Volkoff (1939), physical models have predicted a limited range of neutron star masses. Nearly all modern equations of state for nuclear matter in bulk require \( 0.1 M_\odot \lesssim m_{\text{ns}} \lesssim 3 M_\odot \), assuming that general relativity is valid in the strong field regime (see reviews by Wheeler 1966, Hartle 1978, Baym & Pethick 1979, Shapiro & Teukolsky 1983; see also Bahcall, Lynn, & Selipsky 1990). Much tighter limits on the masses of radio and x-ray pulsars are suggested by the origin of these neutron stars in collapses of the degenerate cores of highly evolved massive stars. If collapse occurs when accretion of the stellar envelope onto the degenerate core increases the mass of the core to about the Chandrasekhar mass, \( m_c \approx 1.4 M_\odot \), then the gravitational mass (baryonic

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mass minus binding energy) of the resulting neutron star should be \( m_{\text{ns}} \lesssim 1.4M_\odot \). Detailed models generally produce neutron stars with \( m_{\text{ns}} \gtrsim 1.15M_\odot \), with typical values around \( 1.3M_\odot \) (Woosley 1987).

Spectroscopic observations of seven high-mass x-ray binary systems have allowed determination of the masses of their neutron star components to precisions of between 10 and 50\% (for reviews, see Joss & Rappaport 1976, Bahcall 1978, Nagase 1989). The discovery of the first radio pulsar in a relativistic binary orbit (Hulse & Taylor 1975) has permitted mass determinations of the neutron stars comprising the PSR B1913+16 system to better than 0.1\% precision (Taylor & Weisberg 1989; Taylor 1992). With more than twenty radio pulsars now known in binary systems, including four or five with neutron star companions, many more neutron star masses have become potentially measurable. In this Letter we present the latest results of two such measurements, for the binary pulsar systems PSR B1802+07 and PSR B2303+46. For each system we have measured the orbital period, eccentricity, and projected semi-major axis, as well as the rate of advance of the longitude of periastron. The results provide unambiguous measurements of the total masses of the two binary systems, as well as useful constraints on the individual component masses.

2 Observations

We have observed both PSR B1802+07 and PSR B2303+46 at the Very Large Array in Socorro, New Mexico, and at the 140 ft telescope of the National Radio Astronomy Observatory at Green Bank, West Virginia.

The pulsar PSR B1802+07 is in the globular cluster NGC 6539 (D’Amico et al. 1990). All observations of this pulsar at the Very Large Array were made using the Princeton Mark III pulsar timing system (Stinebring et al. 1992), on 19 days between March 1991 and September 1992, as part of a general study of binary and millisecond pulsars (Thorsett 1991). The VLA was used as a phased array, with a bandpass centered at 1665 MHz divided by a filter bank into fourteen adjacent 4 MHz channels in each circular polarization. Because of other filtering by VLA electronics, the effective total bandwidth was limited to 46 MHz. Detected signals in each channel were averaged synchronously with the pulsar period for intervals of 2–5 minutes, and the start time of each integration was recorded from a local clock traceable to the best atomic time scales by means of a Global Positioning System (GPS) receiver. In addition, 14 days of observations at the Green Bank 140 ft telescope were carried out, with equipment described below, between January and October 1992, at frequencies near 800 and 1330 MHz. Average pulse profiles were recorded at regular intervals at both sites, and subsequent processing included removal of differential time delays between channels (caused by dispersion in the ionized interstellar medium) and reduction of each
integrated profile to a single pulse time-of-arrival, using standard techniques (Taylor 1990).

PSR B2303+46 was discovered by Dewey et al. (1985) and quickly identified as a member of a binary system with high orbital eccentricity (Stokes, Taylor, & Dewey 1985). At the VLA, we used the Mark III timing system on three days. The center frequency for these observations was 335 MHz, the channel bandwidth was 2 MHz, and total bandwidth was 20 MHz. At Green Bank, we made observations on 32 days between August 1989 and October 1992, using a digital Fourier transform spectrometer to divide a 40 MHz bandpass centered near 400 or 800 MHz into 512 frequency channels, which were detected, averaged, and reduced in a manner similar to the Mark III timing data. In addition to these new observations of PSR B2303+46, our analysis also included the pulse arrival times recorded on 58 days between 1985 and 1987, previously described by Taylor and Dewey (1988).

3 Analysis

The pulse times of arrival were analyzed using standard techniques (Taylor & Weisberg 1989, and references therein). The TEMPO pulsar timing software package was used to reduce the topocentric arrival times to the reference frame of the solar system barycenter, and then to fit a model of each pulsar’s spin, astrometric, and orbital elements to the data. The resulting parameters and their uncertainties are listed in Table 1. They include the celestial coordinates, the pulsar period and spin-down rate at a stated epoch, the dispersion measure, and the orbital period $P_b$, eccentricity $e$, projected semi-major axis $x \equiv a_1 \sin i/c$, time of periastron passage $T_0$, longitude of periastron $\omega$, and rate of advance of periastron $\dot{\omega}$. (Here $i$ is the angle between the line of sight toward the pulsar and the right-handed normal to the orbit, and $c$ is the speed of light.) Finally, an adjustable time offset was introduced in the multi-parameter fit to allow for differing instrumental delays at the two observatories. For both pulsars the five “Keplerian” orbital parameters have been measured with accuracies of 5 or more significant digits. The “post-Keplerian” parameter $\dot{\omega}$ is measured with less accuracy, approximately 15% for PSR B1802−07 and 2% for PSR B2303+46. The uncertainties quoted in Table 1 include both statistical effects and our best estimates of possible systematic errors, and are intended to be realistic 68% confidence limits.

The orbital period and semi-major axis of any binary pulsar system define the pulsar mass function,

$$f_1 \equiv \frac{(m_2 \sin i)^3}{(m_1 + m_2)^2} = \frac{x^3}{(P_b/2\pi)^2} \frac{1}{T_\odot} M_\odot,$$

where $m_1$ and $m_2$ are the pulsar and companion mass in solar units, $T_\odot \equiv GM_\odot/c^3 = 4.925490947 \times 10^{-6}$ s, and $G$ is the Newtonian constant of gravity. For PSRs B1807−02 and 2303+46 an additional mass constraint is provided by our measurement of $\dot{\omega}$. In both
of these binary systems we expect non-relativistic contributions to \( \dot{\omega} \), such as those caused by tidal or rotational distortions of the stars, to be completely negligible; consequently, the general relativistic expression for \( \dot{\omega} \) yields a solution for the total system mass,

\[
M \equiv m_1 + m_2 = \frac{1}{3\sqrt{3}} \left( \frac{P_b}{2\pi} \right)^{5/2} \left( 1 - e^2 \right)^{3/2} \left( \frac{1}{T_\odot} \right)^{3/2} \dot{\omega}^{3/2} \left( 1 - e^2 \right)^{3/2} \left( 1 - e^2 \right)^{3/2} \left( \frac{1}{T_\odot} \right)
\]

(2)

In principle, the measurement of one or more additional parameters involving \( m_1 \), \( m_2 \), and \( \sin i \) would allow an unambiguous solution for all three quantities. Potential candidates for additional observables include further relativistic effects (e.g., time dilation and gravitational redshift, orbital period derivative, and “Shapiro delay”); measurements of the interstellar scintillation timescale to yield the transverse orbital velocity of the pulsar, and hence the orbital inclination (Lyne 1984); and, for PSR B2303+46, the discovery of pulsations from its neutron star companion, whose orbital motion would provide an accurate value for the mass ratio. Unfortunately, for these two binary pulsars the prospects for any of these measurements appear remote. Expected values of the additional post-Keplerian parameters are well below present levels of detectability, even for observations extending over several decades (see Damour & Taylor 1992, Taylor 1992, for further details). Moreover, both pulsars are too faint for the necessary scintillation measurements to be feasible with current generation telescopes, and attempts to detect the companion of PSR B2303+46 as a radio pulsar have so far been unsuccessful.

We are left, therefore, with total mass determinations whose uncertainties are dominated by the uncertainties in \( \dot{\omega} \), plus firm constraints linking the values of \( m_1 \), \( m_2 \), and \( \sin i \) through the well-determined mass functions. The resulting measurements and limits are displayed for the two pulsars in Figures 1 and 2. In these illustrations the sloping straight lines flanked by dashed lines delimit 68% confidence regions for the total mass, \( M \equiv m_1 + m_2 \), of each system. The solid curves rising from left to right correspond to \( \sin i = 1 \), and the requirement \( |\sin i| \leq 1 \) excludes any mass combinations below these limits. Values of \( m_1 \) and \( m_2 \) anywhere within the unshaded regions are permitted by our data; however, in a probabilistic sense (for random orientations of the pulsar orbital planes) there is a 68% chance that \( \cos i > 0.68 \), and therefore that the correct component masses will be found below the dashed curves corresponding to \( \cos i = 0.68 \). At the bottom of Table [II] we list mass limits corresponding to the relevant corners of the 68% confidence regions in Figures 1 and 2. The results are fully consistent with our expectations that the companion of PSR B1802–07 is a white dwarf, while the companion of PSR B2303+46 is most likely another neutron star.
4 Discussion

The orbital period of PSR B1802−07 is similar to those of several other binary pulsars with low mass ($\lesssim 0.7 M_\odot$) companions, including PSRs B0021−72E, B0655+64, B1639+36B, B1831−00, and B1855+09. However, its orbital eccentricity is at least an order of magnitude larger than any of the others. This fact is almost certainly related to peculiarities in the evolution of this system. Rasio and Shapiro (1991) have described a model of its formation in which the neutron star collides (in the dense globular cluster environment of NGC 6539) with a $\sim 0.8 M_\odot$ giant. Hydrodynamical calculations showed that the giant’s envelope would be ejected within a few orbits, leaving a helium core in an eccentric orbit around the pulsar, together with a massive accretion disk. During a low-mass x-ray binary phase, the neutron star would accrete from this disk, and the orbital eccentricity would decrease. The disk is disrupted too soon for complete circularization of the orbit or for neutron-star spin-up to millisecond periods. This model is entirely consistent with our mass determinations. However, it is also possible that a more common evolutionary path produced a nearly circular orbit that was subsequently made more eccentric by one or more encounters with other cluster stars.

Our results for PSR B2303+46 are consistent with those of Taylor & Dewey (1988) and Lyne & Bailes (1990), and have considerably higher accuracy. There is every reason to believe that, as suggested previously, the companion of this pulsar is another neutron star. The companion mass is at least $1.15 M_\odot$, and if we assume a pulsar mass of at least $1.2 M_\odot$, then $m_2 < 1.33 M_\odot$. The average mass of the two neutron stars in this system is very well constrained: $m_{\text{ave}} = 1.27 \pm 0.04$. More sensitive searches for pulsed emission from the companion would probably be worthwhile.

In Figure 3 we display our new mass constraints for three neutron stars, together with mass measurements for 14 other neutron stars. All of these mass measurements are consistent with $m_{\text{ns}} = 1.35 \pm 0.27 M_\odot$, indicated by the vertical dashed lines in Figure 3. Indeed, all measurements except those for Her X-1 and Vela X-1 are consistent with a considerably narrower range, $1.35 \pm 0.10 M_\odot$. The weight of observational evidence appears to say that although the nuclear equation of state may permit stable neutron stars with masses down to $\sim 0.1 M_\odot$, nature prefers to form them in a narrow mass range just below the Chandrasekhar limit.

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work was supported in part by grants from the NSF to Princeton and Caltech, and S.E.T. is a Robert A. Millikan Research Fellow in Physics.
Table 1: Measured parameters of the two binary pulsar systems.\(^a\)

| Parameter                                | PSR B1802−07          | PSR B2303+46          |
|-------------------------------------------|------------------------|------------------------|
| Right ascension (J2000)                   | 18\(^{h}\)04\(^{m}\)49\(\prime\)896(2) | 23\(^{h}\)05\(^{m}\)55\(\prime\)842(17) |
| Declination (J2000)                       | −07\(^{\circ}\)35\(\prime\)24\(\prime\)65(11) | +47\(^{\circ}\)07\(\prime\)45\(\prime\)32(17) |
| Right ascension (B1950)                   | 18\(^{h}\)02\(^{m}\)07\(\prime\)213(2)   | 23\(^{h}\)03\(^{m}\)39\(\prime\)180(17)  |
| Declination (B1950)                       | −07\(^{\circ}\)35\(\prime\)39\(\prime\)57(11) | +46\(^{\circ}\)51\(\prime\)31\(\prime\)87(17) |
| Period (ms)                               | 23.10085521162(3)    | 1066.371071565(16)   |
| Period derivative ($10^{-19}$)             | 4.75(9)               | 5690.9(1.6)          |
| Epoch (MJD)                               | 48540.0               | 46107.0              |
| Dispersion measure (cm\(^{-3}\)pc)       | 186.38(3)             | 62.06(3)             |
| Orbital period, $P_b$ (s)                 | 226088.36(4)          | 1066136.648(15)      |
| Projected semi-major axis, $x$ (lt-s)     | 3.92047(4)            | 32.6878(3)           |
| Eccentricity, $e$                         | 0.211999(15)          | 0.658369(9)          |
| Longitude of periastron, $\omega$ (deg)   | 164.928(18)           | 35.0776(7)           |
| Time of periastron passage, $T_0$ (MJD)   | 49401.19075(12)       | 47452.560747(17)     |
| Advance of periastron, $\dot{\omega}$ (deg yr\(^{-1}\)) | 0.060(9)            | 0.0099(2)           |
| Total mass, $M$ ($M_\odot$)              | 1.7 ± 0.4             | 2.53 ± 0.08          |
| Pulsar mass, $m_1$ ($M_\odot$)            | 1.4$^{+0.4}_{-0.3}$   | 1.16 ± 0.28          |
| Companion mass, $m_2$ ($M_\odot$)         | 0.33$^{+0.13}_{-0.10}$| 1.37 ± 0.24          |

\(^a\)Figures in parentheses are uncertainties in the last digit quoted; all uncertainties are 1\(\sigma\) estimates, inclusive of possible systematic effects. J2000 coordinates are based on the DE200 ephemeris of the Jet Propulsion Laboratory, while B1950 coordinates refer to the Center for Astrophysics PEP740R ephemeris.
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Figure 1: The $m_1$-$m_2$ plane for PSR B1802−07. Hatched regions are excluded by limits on the total system mass, the requirement that $|\sin i| \leq 1$, or both. Dashed curve corresponds to $\cos i = 0.68$, and marks the upper boundary of a region with 68% probability of containing the correct masses, as described in the text.

Figure 2: The $m_1$-$m_2$ plane for PSR B2303+46. See caption for Figure 1.

Figure 3: Measured masses of 17 neutron stars. Objects in massive x-ray binaries are at the top, radio pulsars and their companions at bottom. The lower mass limits for PSRs B1802−07 and B2303+46 and upper mass limit for the companion of PSR B2303+46 assume $\cos i < 0.68$, and are probabilistic in nature (see text). Dashed vertical lines enclose a ±20% mass range around $1.35M_\odot$. References: PSRs B1802−07, B2303+46: this work; PSR B1855+09: Ryba and Taylor (1991); PSR B1534+12: Wolszczan (1991); PSR B1913+16: Taylor and Weisberg (1989); PSR B2127+11C: Anderson et al. (1992, preprint); 4U 1538-52: Reynolds, Bell, and Hilditch (1992); 4U 1700-37: Heap and Corcoran (1992); other x-ray pulsars: Nagase (1989).