DISCOVERY OF TWO RELATIVISTIC NEUTRON STAR–WHITE DWARF BINARIES

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ABSTRACT

We have discovered two recycled pulsars in relativistic orbits as part of the first high-frequency survey of intermediate Galactic latitudes. PSR J1157–5112 is a 44 ms pulsar and the first recycled pulsar with an ultramassive ($M > 1.14 M_\odot$) white dwarf companion. Millisecond pulsar J1757–5322 is a relativistic circular-orbit system that will coalesce because of the emission of gravitational radiation in less than 9.5 Gyr. Of the ~40 known circular-orbit pulsars, J1757–5322 and J1157–5112 have the highest projected orbital velocities. There are now three local neutron star/white dwarf binaries that will coalesce in less than a Hubble time, implying a large coalescence rate for these objects in the local universe. Systems such as J1141–6545 are potential gamma-ray burst progenitors and dominate the coalescence rate, while lighter systems make excellent progenitors of millisecond pulsars with planetary or ultra–low mass companions.

Subject headings: binaries: close — gamma rays: bursts — planetary systems — pulsars: individual (J1157–5112, J1757–5322) — surveys: white dwarfs

1. INTRODUCTION

The first surveys of the Galactic plane at high frequencies for radio pulsars (Clifton & Lyne 1986; Johnston et al. 1992) uncovered a much younger and more distant population than the traditional 400 MHz surveys. High-frequency surveys are much less affected by the deleterious effects of scatter broadening and dispersion smearing, which make short-period pulsars impossible to detect at large dispersion measures. Unfortunately, the sampling rates employed in these early surveys limited their sensitivity to millisecond pulsars (MSPs; Johnston & Bailes 1991), and the spatial coverage was limited by the small beam of a radio telescope at high frequencies. No millisecond pulsars were discovered in these early high-frequency surveys. It was widely believed (Foster, Fairhead, & Backer 1991) that MSPs were steep-spectrum objects and that there was little point in searching for them at high frequencies. As the population of MSPs became larger, however, a series of spectral studies (Lorimer et al. 1995; Toscano et al. 1998) provided evidence that spectra of millisecond pulsars were not too dissimilar from those of normal pulsars. In a simulation of the Galactic millisecond pulsar population, Toscano et al. (1998) predicted that high-frequency surveys undertaken with the Parkes multibeam system (Staveley-Smith et al. 1996) should detect a large number of millisecond pulsars. Motivated by this study, we have conducted the first large-scale survey for millisecond pulsars at intermediate Galactic latitudes.

Our survey covered the region enclosed by $5^\circ < |b| < 15^\circ$ and $-100^\circ < l < 50^\circ$. Pointed observations of 265 s were made with the 64 m Parkes radio telescope using the 21 cm multibeam receiver. The receiver consists of 13 dual linear polarization feeds arranged in a sparse focal plane pattern, which allows full-sky coverage with beams overlapping at the half-power points. This increases the rate of sky coverage by a factor of 13 over a single-beam receiver and enabled us to conduct a large-scale survey in only 14 days of integration time. The system is sensitive to frequencies from 1230 to 1530 MHz, with an average total system noise temperature of 24 K. The back-end system was built at Jodrell Bank for the ongoing deep Galactic plane multibeam pulsar survey (Lyne et al. 2000). It includes 26 filter banks, each with 96 channels and total bandwidth of 288 MHz, centered at a sky frequency of 1374 MHz.

Filter bank outputs were summed in polarization pairs and one-bit digitized with an integration time of 125 $\mu$s. The large bandwidth, narrow channels, fast sampling, low system temperature, and multiple beams facilitated the discovery of a large number of pulsars, including millisecond pulsars, with greater time efficiency than any previous large survey. Data were recorded on magnetic tape for off-line processing on the Swinburne supercluster, a network of 64 Compaq Alpha workstations, using standard techniques (Manchester et al. 1996).

The survey is now complete. Full details of the survey will be provided in a subsequent paper (R. T. Edwards et al. 2001, in preparation). In all, we have discovered 58 new pulsars, of which one has a period of 44 ms and seven others have periods less than 20 ms. In this Letter we will discuss the two recycled pulsars for which we have phase-connected solutions, PSRs J1157–5112 and J1757–5322.

2. PSR J1157–5112: ULTRAMASSIVE COMPANION

PSR J1157–5112 is a 44 ms pulsar in a 3.5 day circular orbit, discovered in an observation made on 1999 January 19. Its parameters, derived from pulse time of arrival (TOA) analysis, are listed in Table 1. The pulsar’s relatively short pulse period, small spin-down rate, and circular orbit indicate recycling in a binary from an evolved companion (van den Heuvel 1984). If the companion formed a neutron star after recycling the pulsar, we would expect an eccentric orbit due to the sudden mass loss associated with the neutron star’s production. The circularity of the orbit implies that the companion is a white dwarf. Since observed neutron star masses are consistent with a Gaussian distribution with a standard deviation of just 0.04 $M_\odot$ around the mean of 1.35 $M_\odot$ (Thorsett & Chakrabarty 1999), a conservative lower limit on the mass of the companion white dwarf can be obtained by assuming a 1.27 $M_\odot$ pulsar and an edge-on orbit. This means that $M_{WD} > 1.14 M_\odot$, indicating an “ultramassive” ONeMg degenerate, and could easily be near the Chandrasekhar limit if the orbit is near the median inclination angle of binaries. By similar reasoning, if the white dwarf mass is less than 1.35 $M_\odot$, the pulsar mass is at most 1.75 $M_\odot$.

A number of ultramassive white dwarf systems are now known. The largest sample are those that have been discovered...
in recent X-ray and extreme-ultraviolet observations (Bergeron, Saffer, & Liebert 1992; Vennes et al. 1997), the masses of which are estimated from model-dependent spectroscopic measurements. The companion to PSR J1157−5112 is the first ultramassive white dwarf to have a firm lower mass limit that relies only on the narrow band of observed neutron star masses and Newtonian physics. Stellar mergers have been suggested for the formation of ultramassive white dwarfs; however, it is clear from the maintenance of a binary association that this is not the case with the companion of PSR J1157−5112, which must have resulted from largely standard stellar evolution.

PSR J1157−5112 is the latest example of a pulsar system that possesses a very massive white dwarf companion. Recent optical observations of the eccentric binary pulsar B2303+46 have indicated that a faint object consistent with a white dwarf is coincident with the position of the pulsar (van Kerkwijk & Kulkarni 1999). If this proves to be a genuine association, the periastron advance and mass function limit the companion mass to greater than 1.2 $M_\odot$. The newly discovered pulsar binary J1141−6545 (Kaspi et al. 2000), with a minimum companion mass of 0.95 $M_\odot$, is probably also a white dwarf (Kaspi et al. 2000; Tauris & Sennels 2000). The orbits of these systems are highly eccentric, and thus it is believed that the neutron stars were born after their white dwarf companions. Since the pulsar in the PSR J1157−5112 binary is recycled, it is the first example of an ultramassive white dwarf that was formed after the neutron star.

The high mass ratio between any possible progenitor to the white dwarf and the pulsar must have resulted in a phase of unstable mass transfer. The system probably passed through a common-envelope phase when the white dwarf progenitor was on the asymptotic giant branch (AGB), as suggested by van den Heuvel (1994) for the PSR J2145−0750 system. Recent models (Ritossa, García-Berro, & Iben 1999) indicate that main-sequence stars as massive as 11 $M_\odot$ can avoid core collapse on the AGB to produce ultramassive white dwarfs ($M_{\text{wd}} = 1.37 M_\odot$ in the above case). Given that envelope loss in the common-envelope phase reduces the resultant remnant mass from a donor star of given mass (Iben & Tutukov 1993), we expect that the progenitor to the white dwarf companion of PSR J1157−5112 weighed in excess of 10 $M_\odot$. This would mean that the companion’s radius (Ritossa, García-Berro, & Iben 1996, 1999; García-Berro, Ritossa, & Iben 1997; Iben, Ritossa, & García-Berro 1997) was less than 800 $R_\odot$ at the time of Roche lobe overflow. The orbital energy lost during spiral-in to the current orbit was insufficient to expel the envelope of the companion, without an additional energy source such as an accreting neutron star. Future proper-motion measurements will help constrain models for its evolution. For an 11 $M_\odot$ companion with a pre-CE Roche lobe radius greater than 500 $R_\odot$ (requiring that at most $\frac{1}{3}$ of the envelope ejection energy come from nonorbital sources), the kick velocity of the pulsar birth event must have been less than 120 km s$^{-1}$ for the system to have remained bound. On the other hand, if the system was much closer at the time of explosion much greater kicks could be accommodated and we might expect the system to have a very large runaway velocity (Bailes 1989).

Along with J1757−5322 (below), J1157−5112 brings the total number of intermediate-mass binary pulsars (those with white dwarf companions heavier than 0.6 $M_\odot$; Arzoumanian, Cordes, & Wasserman 1999; Tauris & Savonjie 1999; Camilo et al. 1996) to seven. The companion of PSR J1157−5112 is by far the most massive of the class. That the neutron star survived what seems to have been a common-envelope phase with a massive AGB star strongly supports the case against black hole formation via hypercritical accretion (Armitage & Livio 2000).

### 3. PSR J1757−5322: COALESCING BINARY

PSR J1757−5322 is an 8.9 ms pulsar that was discovered in an observation made on 1999 May 8, at an epoch where the orbital acceleration experienced by the pulsar (~7.5 km s$^{-2}$ in the line of sight) resulted in noticeable period evolution in the 265 s integration. Subsequent observations revealed the pulsar to be in a nearly circular 11 hr orbit with a companion of at

| Parameter | J1157−5114 | J1756−5322 |
|-----------|------------|------------|
| Right ascension, $\alpha$ (J2000.0) | $11^\circ57^\prime08^\prime.166(1)$ | $17^\circ57^\prime15^\prime.1618(4)$ |
| Declination, $\delta$ (J2000.0) | $-51^\circ12^\prime56^\prime.14(3)$ | $-53^\circ22^\prime26^\prime.38(1)$ |
| Pulse period, $P$ (ms) | 43.5892270628(12) | 8.869961227275(4) |
| $P$ epoch (MJD) | $51,400.000000$ | $51,570.000000$ |
| Period derivative, $P$ | $14.6(16)$ | $2.78(15)$ |
| Dispersion measure (pc cm$^{-6}$) | $39.67(3)$ | $30.79(4)$ |
| Orbit period, $P_{\text{orb}}$ (days) | $3.50738639(3)$ | $0.4533112382(7)$ |
| Projected semimajor axis, $a$ (lt-s) | $14.28634(3)$ | $2.086526(5)$ |
| Epoch of ascending node, $T_{\text{asc}}$ (MJD) | $51,216.4442642(14)$ | $51,394.1080692(3)$ |
| $e \cos \omega'$ | $-0.000322(4)$ | $-1.0(40) \times 10^{-6}$ |
| $e \sin \omega'$ | $0.000240(4)$ | $4.3(45) \times 10^{-6}$ |

**Derived Parameters**

| Parameter | J1157−5114 | J1756−5322 |
|-----------|------------|------------|
| Longitude of periastron, $\omega$ (deg) | $306.7(6)$ | $347(58)$ |
| Orbital eccentricity, $e$ | $4.02(4) \times 10^{-6}$ | $4.4(45) \times 10^{-6}$ |
| Companion mass, $M_{\text{wd}}$ ($M_\odot$) | $>1.14$ | $>0.55$ |
| Characteristic age, $\tau$ (Gyr) | $4.70$ | $5.04$ |
| Surface magnetic field, $B_{\text{surf}}$ ($\times 10^6$ G) | $25.55$ | $5.02$ |

**Note:** Values in parentheses apply to the final digit of the value and represent twice the formal uncertainties produced by TEMPO after scaling TOA uncertainties to achieve a reduced $\chi^2$ of unity.

* We used the ELL1 binary timing model of TEMPO (N. Wex 1998, unpublished). To avoid the large covariance between the time of periastron ($T_2$) and $\omega$ for $e \ll 1$, the time of ascending node ($T_{\text{asc}}$) and the Laplace parameters $e \cos \omega$ and $e \sin \omega$ are used instead.
least $0.55 \, M_\odot$. A phase coherent timing solution has been obtained, the parameters of which are listed in Table 1. From similar reasoning to that invoked above for J1157−5112, we expect that the companion is a white dwarf. Its parameters are compatible with the common-envelope model discussed above for the intermediate-mass binary pulsars.

The J1757−5322 system is highly relativistic, having the highest orbital velocity of all circular-orbit binaries (followed by J1157−5112). The near circularity of the orbit reduces the measurability of relativistic effects; however, some effects could be measurable in the coming decades with long timing baselines. Specifically, assuming an inclination angle $i = 60^\circ$ (the median value for randomly oriented orbits), general relativity predicts that the periastron of J1757−5322 is advancing at a rate of $\sim 1^{\circ.2} \, yr^{-1}$, that its orbital period is decreasing by $1.8 \, \mu s \, yr^{-1}$, that the pulsar’s spin axis is precessing an entire turn every 1700 yr, and that the system will coalesce in at most 9.5 Gyr because of the emission of gravitational waves. The Shapiro delays due to spacetime curvature around the companion (for $i = 60^\circ$) are 29 and 13 $\mu s$ peak-to-peak, respectively, for PSR J1157−5112 and PSR J1757−5322 and may be considerably longer if the systems are nearly edge-on to the line of sight.

After about 7.6 Gyr the orbital period of J1757−5322 will have decreased to one-third its current value, resulting in 4 times the orbital acceleration. Such a system, if observed in our survey, would have experienced significant signal-to-noise ratio loss, limiting the chance of detection. However, such a system will live for only $\sim 400$ Myr, as compared with $\sim 8$ Gyr for the preceding less accelerated post-CE evolution phase in which J1757−5322 was detected. Such highly accelerated systems are thus likely to be around 1 order of magnitude lower in detectable population.

The companion of J1757−5322 will fill its shrinking Roche lobe when it has an orbital period of $\sim 50$ s. The range of potential outcomes of this is diverse and interesting. Models suggest that, after a period of mass transfer, the white dwarf will tidally disrupt and form an accretion disk around the pulsar in just a few seconds if the companion mass is greater than about $0.7 \, M_\odot$ (van den Heuvel & Bonsembi 1984). The rapid mass transfer will result in an enormous release of energy, potentially in the form of a gamma-ray burst. However, it is not clear whether or not the accretion luminosity would be self-limiting because of the outward radiation pressure inhibiting mass transfer (Fryer et al. 1999). If there is no remnant of the white dwarf, we might expect a solitary millisecond pulsar with a very rapid rotation rate (van den Heuvel & Bonsembi 1984) (possibly like PSR B1937+21) and bigger than average mass. Alternatively, it may be that the mass of the pulsar is driven over the critical limit for neutron stars and becomes a black hole. If the disk surrounding the neutron star is not completely destroyed, the formation of a planetary system around a millisecond pulsar is not unreasonable, similar to PSR B1257+12. On the other hand, if just $5\%$ of the mass of the white dwarf is retained intact, a short-period eclipsing pulsar system such as PSR J2051−0827 may result. The measurement of the proper motion of the system is therefore vital in addressing these issues. A large velocity would provide a good match to the planet pulsar PSR B1257+12. A very small velocity is probably less conclusive.

The observed rate of gamma-ray bursts in the local universe (Phinney 1991) is now broadly compatible with the expected coalescence rate of pulsar–white dwarf binary systems. There are now three such systems known that will coalesce in the lifetime of the universe. PSR J0751+1807 will coalesce in $\sim 7$ Gyr. It is only 2 kpc away but has a light $0.15 \, M_\odot$ companion that upon reaching its critical Roche lobe will undergo stable mass transfer to its much heavier pulsar companion, resulting in an ultracompact X-ray binary (Ergma, Lundgren, & Cordes 1977). PSR J1141−6545, as mentioned above, has a white dwarf companion of at least $0.95 \, M_\odot$ in an eccentric orbit that will coalesce in only $\sim 1.3$ Gyr and is $\sim 3.2$ kpc distant. It is a prime candidate for rapid mass transfer after the onset of Roche lobe overflow and a potential gamma-ray burst progenitor because of its high mass. The alarming thing about this pulsar is its youth. Its characteristic age is just 1 Myr, and it may not pulse for much more than 10 Myr because of magnetic dipole breaking pushing it past the rotation limit for the emission of radio pulses. If we take the standard pulsar beaming fraction of $\sim 5$ and the short lifetime of the binary in an observable state ($\sim 10$ Myr) compared with the coalescence time (1.3 Gyr), the extrapolated Galactic coalescence rate for such objects is enormous! We could reasonably expect there to be $5 \times 1300/10 = 850$ dead white dwarf neutron star binaries within a few kpc of the Sun that will coalesce in less than a Hubble time. The total Galactic pulsar population would then be 1–2 orders of magnitude greater than this, and the coalescence rate near $10^{-5} \, yr^{-1}$ per galaxy, similar to that expected of double neutron star binaries, another candidate for gamma-ray bursts (Phinney 1991; Narayan, Paczyński, & Piran 1992).

The contribution of PSR J1757−5322 to the inferred death rate of white dwarf–neutron star binaries is much smaller. With the relative proximity (2 kpc) but enormous characteristic age (5 Gyr) of PSR J1757−5322, we might expect $\sim 250$ similar coalescing systems in the Galaxy, with a coalescence rate of $5 \times 10^{-3} \, yr^{-1}$ if we assume an evenly distributed disk population 15 kpc in radius. Hence, there should be $\sim 500$ systems in the Galaxy that have already coalesced, compatible with the observed population of Galactic disk pulsars with planetary or evaporating white dwarf remnant companions (three within 1.5 kpc).

The white dwarf companions of PSR J1157−5112 and PSR J1757−5322 are possibly observable with 10 m class telescopes or the Hubble Space Telescope (HST). PSR B0655+64 ($M_{WD} > 0.64 \, M_\odot$) has a timing age of 3.6 Gyr and a 22d R-magnitude companion (Kulkarni 1986) at a distance of about 500 pc. The pulsars described here are probably 2–4 times as distant and of comparable timing ages, so we might expect their companions to have $R$ magnitudes of 24–26. Detections of the companions to PSR J1757−5322 and PSR J1157−5112 will provide invaluable information about the cooling times of massive white dwarfs as the pulsars give independent estimates of their ages.

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