Eccentric Binary Millisecond Pulsars

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Abstract. In this paper we review recent discovery of millisecond pulsars (MSPs) in eccentric binary systems. Timing these MSPs we were able to estimate (and in one case precisely measure) their masses. These results suggest that, as a class, MSPs have a much wider range of masses (1.3 to \(>2M_\odot\)) than the normal and mildly recycled pulsars found in double neutron star (DNS) systems (1.25 < \(M_p\) < 1.44\(M_\odot\)). This is very likely to be due to the prolonged accretion episode that is thought to be required to form a MSP. The likely existence of massive MSPs makes them a powerful probe for understanding the behavior of matter at densities larger than that of the atomic nucleus; in particular, the precise measurement of the mass of PSR J1903+0327 (1.67 ± 0.01\(M_\odot\)) excludes several "soft" equations of state for dense matter.

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INTRODUCTION

In recent years, more than a dozen MSPs have been found in binary systems with eccentric orbits. These new and unexpected discoveries will allow precise measurements of the masses of several MSPs. The aim of this review is to convey the reasons why this is an exciting development.

In the first two sections, we will provide the context for this work. We describe how binary pulsars form; this will allow us to understand why they are found in two main distinct groups with different spin and orbital characteristics. We then describe briefly how we measure neutron star (NS) masses (and, in a few cases test general relativity, GR) with radio timing.

In the third section, we enter the core of the review, i.e., we describe the recent discovery of many MSPs in eccentric binaries. Most of these are located in globular clusters. We also review the properties of an intriguing new system, PSR J1903+0327, the first eccentric binary MSP in the galactic disk. We finally review what can be learned from these new binary systems.

We assume that the reader is familiar with the concept of NSs, and has an idea of what pulsar is: a NS with strongly anisotropic electromagnetic emission. For distant observers, this emission is modulated by the rotation of the object in a repeatable, clock-like fashion, much like the light “pulses” of a lighthouse. In what follows, we concern ourselves with radio pulsars only.

FORMATION OF BINARY PULSARS

Of a total of 1826 rotational-powered radio pulsars listed in the ATNF catalog, 141 are found in binary systems, which makes them relatively rare. Their formation is described in Lorimer (2008) and references therein. Fig. 1 is used there to summarize the two main channels for the formation of these systems.

At the top left, we start with a binary system with two main-sequence (MS) stars where at least one of the components has \(M_\ast > 8M_\odot\). Such stars are bound to end their lives as supernovae (SN) after only a few Myr of evolution (next below). This can disrupt the binary system, although the exact probabilities depend on the orbital parameters, the previous masses of the binary components and the magnitude and direction of the SN kick.

If the system survives the first SN, we observe a NS orbiting a MS star. There are at least four known examples of binaries at this particular evolutionary stage where the NS is observed as a radio pulsar. As the companion evolves, it eventually fills its Roche lobe. At this stage, transfer of matter from the companion to the NS creates an “X-ray binary”. The main consequence for the neutron star is spin-up: the accretion of matter from the companion transfers angular momentum from the orbit to the NS. This can make the NS reappear as a radio pulsar, in which case it is described as a "recycled" pulsar.

1 The Roche lobe is the region around a member of a binary system where matter can still be gravitationally bound to it.
2 X-ray emission is generated by the hot gas in the accretion disk around the NS, in the direct impact of matter with the surface of the NS and in some cases in thermonuclear deflagration of matter accumulated at its surface, giving X-ray binaries a rich observational phenomenology. High-energy emission (in X and gamma-rays) is also generated by the interaction of the pulsar wind with the companion’s wind.
The nature of these X-ray binaries and what happens during subsequent evolution is determined mainly by the mass of the companion.

1. If the companion’s initial mass is also above the $8M_\odot$ threshold, then it is also fated to explode as a SN and form a second NS. If the SN kick is correctly aligned, the two NSs remain bound, forming a DNS system. One of the NSs might then be detected as a recycled radio pulsar, as in the case of PSR B1913+16 [3], and the other might be detected as a young radio pulsar, as in the case of PSR J1906+0746 [4]. In one known case, PSR J0737−3039, both NSs are detectable as radio pulsars [5].

These systems always have eccentric orbits: the NSs behave like point masses, so no tidal circularization happens after the second SN. As we will see below, these two features make these systems especially useful in the study of gravitation.

2. If the companion’s mass initial mass is below the $8M_\odot$ threshold the companion will evolve much more slowly and eventually form a white dwarf (WD) star [6]. Because the companion is an extended object for up to several Gyr after the first SN, the orbit is very likely to be tidally circularized (unless the separation between components is large). No SN or other sudden events occur later on that can change this state of affairs. For that reason, the vast majority of pulsar - WD systems found in the disk of the Galaxy (and all those with orbital periods smaller than a few hundreds days) have nearly circular orbits.

The different accretion histories have other important implications, which matter directly to the work described here:

Spin Periods. If the companion is light and forms a WD its evolution timescale is of the order of several Gyr. The long accretion episodes made possible by this slow evolution result in NS spin frequencies of several hundred Hz, i.e, the NS becomes a “millisecond pulsar” (MSP). The first example of this class, PSR B1937+21,
was discovered in 1982 [7]. With a spin frequency of 642 Hz, this was until 2006 the fastest spinning pulsar known.

If the companion is massive and forms a NS its evolutionary timescale is of the order of a few Myr. Given the much shorter accretion episode, the resulting spin frequencies for the accreting NS are one order of magnitude smaller than for MSPs. For that reason, we designate them here as “centi-second pulsars” (CSPs).

Magnetic fields. One apparent consequence of accretion is a greatly diminished surface magnetic dipole. CSPs, and to a greater extent MSPs have magnetic dipoles 3 to 5 orders of magnitude smaller than those of normal pulsars. This results in a much smaller braking torque and a much longer lifespan (of the order of a Hubble time) as radio pulsars.

Another very important effect of the much smaller torque is a much cleaner rotation: effects like “timing noise” and “glitches”, which make the rotational phase of most young pulsars unpredictable, is greatly diminished or even absent in CSPs and MSPs. This is fortunate, because the short spin periods allow very precise radio monitoring of the spin phase of these pulsars. This monitoring shows that some of the latter objects appear to be more stable than atomic clocks; this makes them extremely useful astrophysical tools (see below).

Masses. Another consequence of the different accretion histories has to do with mass transfer. Since the accretion episode necessary for the formation of a MSP is much longer than for CSPs, one can reasonably expect that the amounts of matter accreted by the former are much larger than by the latter. However, it is not clear whether this should introduce a systematic difference in mass between CSPs and MSPs. The recent results on MSP mass measurements (see below) shed some light on this matter.

**HOW TO MEASURE THE MASS OF A NEUTRON STAR**

As we described above, among radio pulsars recycled pulsars have the highest timing precision and the most stable rotation. Furthermore, a majority of them are found in binary systems, where such features can be more profitably employed.

After discovery of a binary pulsar, we can use Doppler variations in the spin period to measure the orbital velocity changes along the line-of-sight. The situation is analogous to that of spectroscopic binaries, where the changing Doppler shift continuously changes the wavelengths of the star’s spectral lines. Because we can only measure changes of velocity along the line of sight our knowledge of the binary parameters is incomplete.

**Keplerian Orbits**

In the case of a Keplerian orbit, the measured variations of the line-of-sight velocity can lead (after a least-squares fit to the observations) to a determination of five "Keplerian" parameters: the orbital period \( P \), the semimajor axis of the orbit \( a \) projected along the line of sight \( x \); for pulsars, this quantity is normally expressed in light seconds), the orbital eccentricity \( e \), the time of passage through periastron \( T_0 \) and the longitude of periastron \( \omega \). Three unknowns remain undetermined, the two component masses \( m_1, m_2 \) and the orbital inclination \( i \). For most spectroscopic binaries (and most binary pulsars) these quantities are simply not available.

However, there is an equation that links these three unknowns, the mass function:

\[
\frac{f}{G} = \frac{4\pi^2 x^3}{P^2} = \frac{(m_2 \sin i)^3}{(m_1 + m_2)^2},
\]

where \( G \) is Newton’s gravitational constant. This allows an estimate of one parameter (say, \( m_2 \)) from assumptions for the values of the other parameters \( (m_1, i) \).

Two more equations are needed to solve these 3 unknowns. No other equation can be obtained from the Keplerian parameters, and generally no more equations are readily available.

**Binary Pulsars**

The distinguishing feature of binary pulsars is that we can determine the range directly from the measured time of arrival (T.O.A.s) of the radio pulses. Such a measurement is impossible with spectroscopic binaries. This happens because the radio pulses (unlike spectral lines) repeat predictably at a single frequency in the star’s own reference frame (the neutron star’s spin frequency).

This is extremely important because it allows for an astounding gain in precision. As an example, when the orbit of PSR J2016+1947 was published [8], the orbit was estimated from variations in the Doppler shift of the spin frequency of the pulsar. The projected size of the orbit and the eccentricity determined from this method were \( x = (150.70 \pm 0.07) \) lt-s and \( e = 0.00128 \pm 0.00016 \)

After the correct rotation count was determined for all observations of this pulsar, the range of the pulsar relative to the center of mass of the binary could be measured directly, with a precision of a few km in each instance. As a result, we now obtain \( x = (150.7730407 \pm 0.0000009) \) lt-s and \( e = 0.001479863 \pm 0.00000016 \). This represents a gain in precision of about \( 10^3 \) and \( 10^4 \) respectively.

*This is the fundamental reason why binary pulsars are superior astrophysical tools.*
For most binary pulsars we are still unable to provide any extra equations to help solve the $m_1, m_2$ and $i$ system, despite the unmatched precision provided by the accurate ranging.

**Post-Keplerian Effects**

In a few cases, the precision provided by pulsar timing and the peculiarities of the system are such that small "post-Newtonian" deviations from a Keplerian orbit due to the effects of GR become detectable in the times of arrival of the pulses. These can be parametrized by five quantities, known as "Post-Keplerian (PK) parameters": the rate of advance of periastron ($\dot{\omega}$), the "Einstein delay" $\gamma$ (due to the larger than average gravitational redshift and special relativistic time dilation near periastron), the rate of orbital decay due to gravitational radiation $\dot{P}_b$ and two parameters that characterize the effect of the gravitational field of the companion on the propagation of the pulsar's radio signal (a.k.a. "Shapiro" delay): the "range" ($r$) and "shape" ($s$). If GR is the correct description of gravity, the PK parameters are given by:

$$\dot{\omega} = 3 \left( \frac{P_b}{2\pi} \right)^{-5/3} (T_\odot M)^{2/3} (1 - e^2)^{-1}$$

$$\gamma = e \left( \frac{P_b}{2\pi} \right)^{1/3} T_\odot^{2/3} m_c(m_p + 2m_c)$$

$$\dot{P}_b = -\frac{192\pi}{5} \left( \frac{P_b}{2\pi} \right)^{-5/3} f(e)T_\odot^{5/3} m_p m_c M^{-1/3}$$

$$r = T_\odot m_c$$

$$s = \sin i,$$

where $m_p$ and $m_c$ are the pulsar and companion masses, $M$ is the total mass, $T_\odot \equiv GM_\odot/c^5 = 4.925490947 \mu s$ and

$$f(e) = \left( 1 + \frac{73}{24} e^2 + \frac{37}{96} e^4 \right) (1 - e^2)^{-7/2}.$$  

The main thing to extract from these equations is that they depend on precisely measurable Keplerian parameters, but also on combinations of $m_p, m_c$ and $i$. Therefore, the measurement of two PK parameters provides, together with eq. 11, enough equations to solve for $m_p, m_c$ and $i$.

The measurement of additional PK parameters allows a test of the self-consistency of general relativity, or at least a verification that there are no classical contributions due to one of the components having a finite size. The most famous example of a GR test is that carried out with the first binary pulsar ever found, PSR B1913+16. The system has an eccentric ($e = 0.617$) and compact ($P_b = 7^{b}45^{m}$) orbit, which means that we can measure precisely the longitude of periastron ($\omega = 226.57518(4)$ on 1986 January 14) and how it changes with time ($\dot{\omega} = 4.226607(7) \times 10^{-12} \text{s}^{-1}$). The eccentricity causes a non-zero $\gamma$, which becomes measurable because of the fast precession: $\gamma = 0.004294(1)$. Assuming GR, i.e., assuming that eqs. 2 and 3 apply, we obtain for the CSP $m_p = 1.4408(3) M_\odot$ and for the younger unrecycled (and undetectable) NS $m_c = 1.3873(3) M_\odot$.

These masses allow us to predict the other three PK effects for PSR B1913+16 using eqs. 4 - 6, again assuming that GR applies. The compactness of this system and the long timing baseline allowed the measurement of one of these PK effects, the orbital decay due to the emission of gravitational waves: $\dot{P}_b = -2.4211(14) \times 10^{-12} \text{s}^{-1}$ [9]. This in perfect agreement with the prediction of eq. 4. Apart from testing the self-consistency of GR, this measurement demonstrated the existence of gravitational waves in the Universe. For this measurement the discoverers, Russel Hulse and Joseph Taylor earned the Nobel Prize in Physics in 1993.

A useful way of visualizing these consistency tests is by drawing a mass-mass diagram (Fig. 4) represents the constraints derived for PSR J1903+0327. In such a diagram, $m_p$ and $m_c$ are the two orthogonal axes. The measurement of each PK parameter limits the possibilities for $m_p$ and $m_c$ to a small band of the mass-mass diagram. In the case of DNS systems, where the components are point masses, all of these bands must meet at a single point, otherwise GR fails the test. That has not happened yet: Since the discovery of PSR B1913+16 similar tests have been made for other systems (for a review on this vast subject see [10]) and GR has passed all of them. A system discovered more recently, the "double pulsar" (PSR J0737–3039) [5], allows a total of four tests or GR from timing alone [11].

**Neutron Star Masses**

Both PSR B1913+16 and PSR J0737–3039A are "centi-second pulsars". All precise neutron star mass measurements made so far come from CSPs located in DNS systems. They range between 1.2489(7)$M_\odot$ for PSR J0737–3039B, a "normal" pulsar that was not recycled at all [11] and 1.4408(3)$M_\odot$ for PSR B1913+16 [9]. These values are very close to the Chandrasekhar mass ($\sim 1.4M_\odot$), the upper mass limit for white dwarfs, above which these objects become gravitationally unstable.

Is such a narrow distribution of masses also observed for MSPs? From our brief discussion on how they form,
MSPs could in principle be more massive, owing to the much longer accretion episode that formed them, but until recently no MSPs had their masses determined to less than 10% precision and no precise GR tests have been carried out in MSPs-WD systems.

This state of affairs is somewhat surprising, particularly considering that the timing precision for MSPs can be one or two orders of magnitude better than for CSPs. However, as we remarked in the section on the formation of binary pulsars, systems containing MSPs form with very small orbital eccentricities ($2 \times 10^{-3}$ to $10^{-7}$). As remarked above for PSR B1913+16, it is the eccentricity of the orbit that allows a measurement of $\dot{\omega}$ and $\gamma$, and it is the combination of these two parameters that generally provides the precise mass measurements for the NSs in DNS systems. For the circular orbits of MSP-WD binaries, no such measurements are possible.

So what about the other PK parameters? They don’t require an eccentric orbit to be measured, but $P_{b}$ is greatly amplified by a) a compact orbit, b) a large orbital eccentricity and c) a massive companion (eq. 4). The latter requirements mean that even for MSP-WD systems in compact orbits (where WD masses are of the order of 0.1-0.2 $M_{\odot}$ and the eccentricities are always very small) the orbital decay is is much smaller than in DNS systems. This makes its measurement quite difficult, despite the much better timing precision of MSPs. Nevertheless, orbital period decays due to GW emission have been measured and used to estimate MSP masses (e.g., [12]).

How about the Shapiro delay? This is a small timing effect (typically, of the order of a few $\mu$s in the T.O.A.s) which, being proportional to $m_{c}$, is significantly smaller in MSP-WD systems than in CSP-NS systems. However, the excellent timing precision of MSPs more than makes up for the smaller $m_{c}$. Nevertheless, this effect seldom provides a precise estimate for the pulsar mass in CSPs or MSPs.

This situation is somewhat frustrating: MSPs could in principle have higher masses than CSPs and normal pulsars, but despite their excellent timing precision, no precise mass measurements can be carried under normal circumstances. This results in a lack of GR tests made with MSP-WD systems, which is a great pity: the difference in binding energies between the components makes MSP-WD systems potentially very powerful in detecting violations of the strong equivalence principle (SEP) [10], the fundamental physical basis of GR.

This situation has started to change in recent years, as described below.

### Eccentric Binary Millisecond Pulsars in Globular Clusters

In globular clusters low-mass X-ray binaries are three orders of magnitude more common than in the Galactic disk. Given the unusual stellar density at the cores of globular clusters, it is likely the MS stars are captured by old NS lurking near the centers of these clusters. Evolution of such MS stars leads to accretion into the NS, i.e., large numbers of X-ray binaries [13]. These eventually become MSPs.

Since 1987, 140 pulsars have been discovered in globular clusters (GCs) [4]. 3/4 of the total were discovered in the last ten years. As predicted, the vast majority of this pulsar population consists of MSPs, a situation that is very different than what is observed in the Galaxy.

As in the Galaxy, the X-ray binary phase produces to low-eccentricity orbits, but in GCs gravitational interactions with passing stars (or even exchange encounters) can, in a few cases, produce binary MSPs with highly eccentric orbits [14]. The first of the very eccentric ($e > 0.3$) binary MSPs to be discovered, PSR J0514-4002A, a 5-ms pulsar located in NGC 1851 has $e = 0.888$ [15]; more so than for any recycled pulsar in the Galaxy.

Such high eccentricities have already allowed the measurement of $\dot{\omega}$ for all the eccentric binary MSPs with well-known orbits (see Table 1). If the observed $\dot{\omega}$ is entirely due to the effects of GR (if, e.g., there are no classical contributions due to the finite size of the companion star), then this allows an estimate of the total mass of the binary $M$ (see eq. 2). These values are listed in Table 1.

As we have seen above, two equations (for the mass function $f$ and $\dot{\omega}$) are not enough to determine the three unknowns $m_{p}$, $m_{c}$ and $i$. In eccentric orbits, we can always measure $\gamma$ and obtain the third equation needed to solve the system. However, to be able to do so, we must wait for the orbit to precess: if there is no precession, the effect on the T.O.A.s parametrized by $\gamma$ can be absorbed by a small re-definition of the size of the orbit, $x$. The orbits of the eccentric MSPs are not as compact as those of the DNS systems for which we have measurements of $\gamma$; this means that the relativistic precession is much slower. The end result is that it takes many years of timing (more than has elapsed since the discovery of the eccentric binary MSPs in Table 1) to measure $\gamma$.

Therefore, the $m_{p}$-$m_{c}$-$i$ system cannot yet be solved for any of the eccentric binary MSPs in globular clusters. Despite this limitation, several important things can be learned from a measurement of $\dot{\omega}$ alone, as discussed below.

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4 For an updated list, see [http://www2.naic.edu/~pfreire/GCpsr.html](http://www2.naic.edu/~pfreire/GCpsr.html)
Early Results

The first measurement of $\dot{\phi}$ for a MSP was made in 2003 for PSR J0024$-$7204H, a 3.21-ms pulsar in the globular cluster 47 Tucanae [16]. The pulsar is in a mildly eccentric ($e = 0.07$) binary system with an orbital period of 2.35 days [17]. The measured periastron advance ($\dot{\phi} = 0.066 \pm 0.001 \text{yr}^{-1}$, [18]) implies, under the assumption of no classical contributions, $M = (1.61 \pm 0.04)M_\odot$.

As mentioned above, this measurement alone is not enough to determine $m_p$, $m_c$ and $i$. However, we can combine eq. (1) with $M$ (derived from $\dot{\phi}$) to determine a minimum companion mass from the condition $\sin i \leq 1$:

$$m_c > (fM^2)^{1/3}. \quad (8)$$

A maximum pulsar mass can then be derived from $m_p = M - m_c$; the idea is illustrated graphically in Fig. 2. In the case of PSR J0024$-$7204H, this implies $m_p < 1.52M_\odot$, i.e., the mass of this MSP cannot be much higher than the masses we find in DNS systems. The important point about this result (which was not even briefly mentioned in [18]) is that it shows that at least some NSs can be spun up to MSP periods with relatively small ($dm < 0.2M_\odot$) amounts of matter.

The discovery of PSR J1909$-$3744 [19] in a search of intermediate Galactic latitudes provided a similar result. This 2.9-ms pulsar is interesting because it has the narrowest pulse profile for any known pulsar ($\tau_{50} = 43\mu s$); as a result, it is one of the most precisely timed MSPs. Furthermore, the orbital inclination is close to $90^\circ$. This fortunate combination of characteristics allowed the most precise measurement of a Shapiro delay to date. The precise values for $r$ and $s$ (and $f$) provide unambiguous values for $m_c$, $i$ and $m_p = (1.438 \pm 0.024)M_\odot$ [20]. Again, this is consistent with the masses measured in DNS systems. Similar results have been obtained for other MSPs (see Table I).

At the start of 2005, it was known that at least some MSPs have masses similar to the NSs found in DNS systems. Spin-up to MSP periods can definitely be achieved with small amounts of matter.

Recent results

In 2005, [21] discovered 21 new MSPs in the globular cluster Terzan 5. Nine other MSPs have been found since, including the fastest-spinning pulsar known PSR J1748$-$2426ad, henceforth Ter 5 ad [22], making for a total of 33 pulsars in this cluster alone. A total of seventeen pulsars are members of binary systems; six of these have very eccentric ($e > 0.3$) orbits. This means that Terzan 5 alone contains half the known population of eccentric binary MSPs.

At the time of publication, only two eccentric binary pulsars Ter 5 I and J had phase-coherent timing solutions (i.e., an unambiguous pulse count for all detected pulses) with precise measurements of $\dot{\phi}$. Assuming the effect to be relativistic (a good assumption, because if the companion was extended the orbits of these two pulsars would circularize in about $10^5$ yr) the total system masses are $(2.17 \pm 0.02)M_\odot$ and $(2.20 \pm 0.04)M_\odot$. The upper mass limits derived for these two pulsars are very similar, $1.96M_\odot$.

In principle, this is consistent with the masses being within the range observed for the NSs in DNS systems. However, it is likely that the pulsar masses are significantly higher than $1.44M_\odot$. The small mass functions for these systems imply that the companions are likely to contribute little to the total binary mass.

The argument is probabilistic, and it arises in part from assuming that there is no preferred orientation for the binary orbits. For randomly aligned orbits, it is much more likely that the orbital inclination is close to $90^\circ$ (edge-on orbits) than to $0^\circ$ (face-on orbits). The reason for this is that for face-on orbits only one possible orientation exists (orbital plane = plane of the sky), while for edge-on orbits there is an infinite number of possible orbital planes.
TABLE 1. MSP binaries. Notes: a) Binary systems are sorted according to the total estimated mass $M$. b) Methods are: $\dot{P}_b$ - relativistic orbital decay, $r, s$ - Shapiro delay “shape” and “range”, “Opt” - optically derived mass ratio, plus mass estimate based on spectrum of companion, $\dot{\omega}$ - precession of periastron. c) This pulsar is not technically a MSP, its spin period is longer than those found in most DNS systems. However, given the similarity of its orbital parameters to those of Terzan 5 I, we assume that it had a similar formation history. d) Because of its large companion mass and eccentricity, this system is thought to have formed in an exchange interaction [15].

| Name         | PSR       | GC          | $P$ (ms) | $P_b$ (days) | $e$ | $f/M_\odot$ | $M/M_\odot$ (a) | $M_c/M_\odot$ | $M_p/M_\odot$ | Method (b) | Ref. (c) |
|--------------|-----------|-------------|----------|--------------|-----|--------------|-----------------|----------------|---------------|-------------|----------|
|              |           |             |          |              |     |              |                 |                |               |             |          |
| MSP Mass Measurements | | | | | | | | | | | |
| J0751+1807   | -         | -           | 3.47877  | 0.26314      | 0.00000 | 0.009674 | -               | -              | 1.26$^{+14}_{-12}$ | $\dot{P}_b, s$ | [12]     |
| J1911−5958A | NGC 6752  | 3.26619     | 0.83711  | <0.00001      | 0.002688 | 1.58$^{+0.16}_{-0.10}$ | 0.18(2)   | 1.40$^{+0.16}_{-0.10}$ | Opt. | [28]     |
| J1909−3744   | -         | 2.94711     | 1.53345  | 0.00000       | 0.003122 | 1.67$^{+0.1}_{-0.2}$ | 0.2038(22) | 1.438(24)     | $r, s$ | [29]     |
| J0437−4715   | -         | 5.75745     | 5.74105  | 0.00002       | 0.001243 | 2.01(20) | 0.254(14) | 1.76(20)     | $r, s$ | [26]     |
| J1903+0327   | -         | 2.14991     | 95.1741  | 0.43668       | 0.139607 | 2.88(9) | 1.051(15) | 1.74(4)     | $\dot{\omega}, s$ | [27]     |
|              |           |             |          |              |     |              |                 |                |               |             |          |
| Binary systems with indeterminate orbital inclinations | | | | | | | | | | | |
| J0024−7204H  | 47 Tucanae | 3.21034     | 2.35770  | 0.07056       | 0.001967 | 1.61(4) | > 0.164   | < 1.52       | $\dot{\omega}$ | [18]     |
| J1824−2452C | M28       | 4.15828     | 8.87781  | 0.84704       | 0.006535 | 1.616(7) | > 0.260   | < 1.367      | $\dot{\omega}$ | [29]     |
| J1748−2446I | Terzan 5  | 9.57019     | 1.328    | 0.428        | 0.003658 | 2.17(2) | > 0.24    | < 1.96       | $\dot{\omega}$ | [21]     |
| J1748−2446J (c) | Terzan 5  | 80.3379    | 1.102    | 0.350        | 0.013066 | 2.20(4) | > 0.38    | < 1.96       | $\dot{\omega}$ | [21]     |
| B1516+02B   | M5        | 7.94694     | 6.85845  | 0.13784       | 0.000647 | 2.29(17) | > 0.13    | < 2.52       | $\dot{\omega}$ | [24]     |
| J0514−4002A (d) | NGC 1851 | 4.99058     | 18.7852  | 0.88798      | 0.145495 | 2.453(14) | > 0.96    | < 1.52       | $\dot{\omega}$ | [30]     |
| J1748−2021B | NGC 6440  | 16.76013    | 20.5500  | 0.37016      | 0.000227 | 2.91(25) | > 0.11    | < 3.3        | $\dot{\omega}$ | [25]     |
containing the line of sight. For a system with no known orbital inclination, the a priori probability of $i_1 < i < i_2$ is given by $\cos i_1 - \cos i_2$.

Taking this, $\omega$ and its uncertainty into account, we can calculate a probability distribution function (p.d.f.) for the mass of any MSP and for the mass of its companion. For Ter 5 I and J, we obtain median values for the masses above $1.7M_\odot$ in both cases. Combining the p.d.f.s for both pulsars, we obtain a 95% probability that at least one of the NSs has a mass over $1.68M_\odot$.

Two other results suggest the possibility of even more massive pulsars. PSR B1516+02B is a 7.9-ms binary MSP in a mildly eccentric ($e = 0.14$) orbit located in the globular cluster M5 [23]. After 19 years of Arecibo timing the $\omega$ for this system has been finally measured to good precision [24]. The total mass of the system is $(2.29 \pm 0.17)M_\odot$. This and the small Keplerian mass function for the companion imply $m_p = 2.08^{+0.18}_{-0.19}M_\odot$ (these are median and 1-$\sigma$ limits). There is a 0.7% probability that the pulsar has a mass similar to the NSs found in DNS systems, and there is a 95% probability of $m_p > 1.72M_\odot$ (see Fig.2).

As in the case of Terzan 5 I and J, we have to make the assumption that the precession of periapsis is relativistic. In the case of M5B, this is a relatively safe assumption: HST archival data shows no companion at the location of the pulsar. This implies that it is a small-sized star, either a WD or a main-sequence star with $m_c < 0.3M_\odot$. In either case, the contribution of the companion’s rotation to the observed $\omega$ is likely to be small [24].

An even more massive NS might be located in the globular cluster NGC 6440. PSR J1748–2021B is a 16.7-ms pulsar with an eccentric ($e = 0.57$) and wide ($P_b = 20.55$ days) orbit with a low-mass companion. The relatively good precision of its timing and the high eccentricity provide a good measurement of $\omega$ [25]. Again, assuming that there are no classical effects on the orbit, the total mass of the binary is $(2.92 \pm 0.20)M_\odot$. Together with the small mass function measured for this system, this implies an extraordinary mass for this pulsar, $(2.74 \pm 0.20)M_\odot$, with a mere 1% probability of $m_p < 2.0M_\odot$. Until the appropriate optical studies are carried out, this result is not as secure as in the case of M5B.

**MSP Mass Distribution**

The timing results for these MSPs do not prove that there are neutron stars with masses significantly in excess of $1.44M_\odot$. It is still possible (but highly unlikely) that there are classical contributions to the observed $\omega$ for most of them. They are, however, highly suggestive: plotting the p.d.f.s and taking them at face value, we see that the mass distribution for MSPs is much broader than that observed for CSPs and normal NSs in DNS systems (see Fig.3). About half of the eccentric MSPs in globular clusters seem to have large ($> 1.6M_\odot$) masses.

It appears therefore that, although some MSPs were spun up with relatively modest amounts of matter, that was not the case for all MSPs. The reasons for this somewhat surprising result are not known at present.

In the Galaxy, the situation appeared to be different until 2008, with PSR J0751+1807 and PSR J1909−3744 indicating relatively low masses and other MSPs yielding inconclusive results. The situation has now changed for Galactic MSPs as well with the mass measurement of PSR J0437−4715 [26] and in particular the discovery of PSR J1903+0327 [27].

**PSR J1903+0327**

PSR J1903+0327 was a the first MSP found in the ongoing ALFA pulsar survey [31]. It is a 2.15-ms pulsar in a 95-day orbit with a $\sim 1M_\odot$ main-sequence star companion. That is very unusual, but even more unusual is the orbital eccentricity of the system: $e = 0.44$. The standard evolutionary scenarios briefly described at the start of this review cannot explain the formation of such a system; this is one of the reasons why this MSP is so interesting. As in the case of the isolated MSPs in the
FIGURE 4. $\cos i$-$m_c$ and $m_p$-$m_c$ diagrams for PSR J1903+0327. The contour levels enclose 99.7%, 95.44% and 68.3% of all probability. The light contour levels are derived from a $\chi^2$ map calculated from $r$ and $s$ only; the heavy contour levels are calculated assuming that the observed $\dot{\omega}$ is relativistic. Top and Right: projected 1-D p.d.f.s for $\cos i$, $m_p$ and $m_c$. The pulsar and companion p.d.f.s are much narrower when we take the $\dot{\omega}$ into account, but entirely within the regions predicted using $r$ and $s$ alone. Orange lines: regions of the diagrams consistent with the PK parameters and their 1-$\sigma$ uncertainties estimated by TEMPO2.

Galactic disk the formation of this system is still not well understood [27]. As an example, it is possible that PSR J1903+0327 formed in the same way as the isolated MSPs, i.e., by somehow eliminating its mass donor, which was much closer to the pulsar than its present MS star companion. The latter object has been there from the start, formerly as the outer element of a hierarchical triple; it has never interacted significantly with the MSP.

The other reason why this binary MSP is so interesting is that its unusual characteristics mean that 3 PK parameters can be measured precisely. The eccentricity allows a precise measurement of $\dot{\omega}$ and the large companion mass ($m_c \sim 1M_\odot$) allows a measurement of $r$ and $s$. Combining $\dot{\omega}$ and $s$ as measured at the end of 2007 [27] obtained $m_p = (1.74 \pm 0.04)M_\odot$: with the ever-present qualifier that we are assuming $\dot{\omega}$ to be relativistic. At this time only a small fraction of the orbit had been measured at high timing precision (2.2 GHz) with Arecibo, and $r$ could not be measured precisely.

To measure $\dot{\omega}$ and $s$ more precisely and verify whether $\dot{\omega}$ is relativistic, we have started a dense timing campaign with Arecibo. The idea is to measure $r$ precisely and see if it is consistent with the companion mass we derive from $\dot{\omega}$ and $s$.

When the first 2.2-GHz orbit was completed with Arecibo, the pulsar mass estimate decreased to $(1.67 \pm 0.01)M_\odot$, but it has been stable at that level the last 18 months. The companion mass derived from the latest values of $\dot{\omega}$ and $s$ is $(1.028 \pm 0.004)M_\odot$. The latest value measured for $r$ is $(1.03 \pm 0.04)M_\odot$. This agreement apparently confirms the assumption that $\dot{\omega}$ is relativistic. However, because of the lower precision in the measurement of $r$, it is impossible to exclude small contributions to $\dot{\omega}$. At the moment, if we calculate the p.d.f. for the mass of PSR J1903+0327 based on $r$ and $s$ alone (i.e., assuming nothing about $\dot{\omega}$), we obtain $m_p = (1.67 \pm 0.11)M_\odot$ and a 98.4% probability that the mass is above $1.44M_\odot$ (see Fig. 4). The precision of $r$ is still improving significantly with continued timing.

The mass value derived for PSR J1903+0327 from $\dot{\omega}$ and $s$ is the most precise MSP mass ever measured. The likely contribution from other effects to $\dot{\omega}$ is now being evaluated, but it is clear by now that is is likely to be small. After more than 30 years of searching, this is the first precisely measured NS mass larger than that of PSR B1913+16 and the first that is incompatible (and significantly above) the Chandrasekhar mass. This pulsar proves that accretion can significantly increase the mass
STUDIES OF SUPER-DENSE MATTER

Why is a precise measurement of MSP masses so important? First, because of accretion, they can be more massive than NSs in DNS systems. If they are, then they test our models of how matter behaves at the center of NSs.

Given their small size ($R \sim 10 \text{km}$) and large mass ($M \sim 1.4M_\odot$), NSs contain some of the densest matter in the Universe: the core can have densities of several times $10^{14} \text{g cm}^{-3}$. They are therefore unique astrophysical laboratories for testing theories of nuclear matter under high pressures and densities well in excess of that of the atomic nucleus.

Because matter at such densities are not readily available on Earth, its microscopic composition and the relation between macroscopic quantities like pressure and density (the equation of state, or EOS) are essentially unknown. As Fig. 5 shows, there are large variations in predicted radii and maximum masses for different candidate EOSs. These reflect basic uncertainties about the microscopic behavior and composition of matter at and above nuclear density. Some EOSs, such as GS1, assume that large percentages of matter are in exotic states (hyperons, deconfined quark matter), any of which produces a decrease in the nucleonic (protonic and neutronic) degeneracy pressure at any given density, since a larger variety of particles are present. This means that matter is relatively more compressible; this results in smaller maximum stellar masses. Other EOSs, such as MSO, assume a larger fraction of nucleons and have higher pressures for any given density. This means that they predict matter to be relatively incompressible and result in larger neutron star mass limits.

As we can see in Fig. 5, the mass measured for PSR J1903+0327 is higher than the maximum possible mass predicted by some EOS models still being considered in the literature. Such models are excluded by the PSR J1903+0327 mass measurement.

The mass measurement for PSR J1903+0327, being the largest known with certainty, also sets a quantitative upper limit to its central density, which then cannot be exceeded in any neutron star of lower mass. As successively more massive neutron stars are observed, the limiting central density gets smaller. Approximately, the limit is $\rho_{\text{max}} \leq 36 \rho_s (M_\odot/M_{\text{max}})^2$ where $\rho_s = 2/7 \times 10^{14} \text{ g cm}^{-3}$ is the nuclear saturation density. A large enough observed mass ($2M_\odot$) could rule out the appearance of exotic phases in neutron stars, such as deconfined quarks [3]: these are indicated by the SQM lines in Fig. 5.

PROSPECTS

In Terzan 5, we now have measurements of $\omega$ for a total of seven binary systems. Two more such measurements have been obtained for two new eccentric binary pulsars in M28, PSR J1824–2452C and D [29]. The increased number of mass p.d.f.s will assist the statistical studies of the MSP mass distribution.

For the eccentric binary MSP with the shortest orbital period, Ter 51, $\gamma$ is now becoming detectable. This will yield a precise MSP mass measurement for a second system (after PSR J1903+0327) where we expect the pulsar to be massive. Whether such a high mass will be confirmed or not remains to be seen.

Meanwhile, HST time has already been allocated for the study of the environs of these candidate supermassive pulsars. The detection (or not) of their companions will be important to address the issue of whether the observed $\omega$ is purely relativistic or not. In the case of M5B, the non-detection of the companion in archival images seems to indicate that this is indeed the case, but that is not as clear in the case of NGC 6440B.

For the latter binary, our simulations indicate that it will take about 15 years to determine $\gamma$ with any useful precision and determine the mass of the pulsar unambiguously, but the potential rewards are immense, particularly for the study of the EOS: a mass well in excess of $2M_\odot$ would exclude most of the EOSs now being proposed. We expect that advances in instrumentation, with resultant improvements in timing precision, will lead to significant results well before that.

The prospects for the study of PSR J1903+0327 are very bright, particularly at optical wavelengths (no pun intended here!). Measurements of the spectral line widths of the companion might address once and for all the issue of whether the companion is rotating fast or not and whether it can contribute to the observed advance of periastron. If not, then we can consider that the combination of 3 PK parameters ($\omega, r, s$) provides one test of GR. Measurements of the spectral line shifts will also determine the mass ratio precisely, providing one extra constraint in the system, i.e., one extra test of GR.

Finally, new searches are likely to find several more eccentric binary MSPs, particularly in GCs.

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FIGURE 5. Mass-Radius relation for neutron stars. Each black curve represents a family of neutron stars masses and radii according to a given equation of state. The region bounded by the Schwarzschild condition $R < \frac{2GM}{c^2}$ is excluded by general relativity, and that bounded by $R < \frac{3GM}{c^2}$ (labeled “causality”) is excluded by requiring the speed of sound inside the star to be smaller than the speed of light. The mass-shedding limit for the fastest spinning radio pulsar (PSR J1748$-$2446ad, with spin frequency 716 Hz) is labeled “rotation”; points in the green region below this line are not allowed for that particular pulsar. Stricter constraints may arise from X-ray sources like XTE J1739$-$285 (dashed curves calculated under different neutron star models) if their spin frequencies are confirmed to be higher than that of PSR J748$-$2446ad, potentially excluding some equations of state (such as GM3) which lie almost entirely below the rotation curve. A recent, precise millisecond pulsar (MSP) mass measurement (for PSR J1903+0327) excludes the “softest” EOSs (red horizontal line). Adapted from [32].
REFERENCES

1. Manchester, R. N., Hobbs, G. B., Teoh, A., & Hobbs, M. 2005, AJ, 129, 1993
2. Lorimer, D. R. 2008, Living Reviews in Relativity, 2008-8
3. Halser, R. A., & Taylor, J. H. 1975, ApJ, Lett., 195, L51
4. Lorimer, D. R., et al. 2006, ApJ, 640, 428
5. A. G. Lyne, M. Burgay, A. Possenti, R. N. Manchester, F. Camilo, M. A. McLaughlin, D. R. Lorimer, N. D’Amico, B. C. Joshi, J. Reynolds, P. C. C. Freire 2004, Science, 303, 1153
6. Alpar, M. A., Cheng, A. F., Ruderman, M. A., & Shaham, J. 1982, Nature, 300, 728
7. Backer, D. C., Kulkarni, S. R., Heiles, C., Davis, M. M., & Goss, W. M. 1982, Nature, 300, 615
8. Navarro, J., Anderson, S. B., & Freire, P. C. 2003, ApJ, 594, 943
9. Weisberg, J. M. & Taylor, J. H. 2003, in Radio Pulsars, ed. M. Bailes, D. J. Nice, & S.E. Thorsett, (San Francisco: Astronomical Society of the Pacific), 93
10. Stairs, I. H. 2003, Living Reviews in Relativity, 2003-5
11. Kramer, M.; Stairs, I. H.; Manchester, R. N.; McLaughlin, M. A.; Lyne, A. G.; Ferdman, R. D.; Burgay, M.; Lorimer, D. R.; Possenti, A.; D’Amico, N.; Sarkissian, J. M.; Hobbs, G. B.; Reynolds, J. E.; Freire, P. C. C.; Camilo, F. 2006, Science, 314, 97
12. Nice, D. J., Stairs, I. H., & Kasian, L. E. 2008, 40 Years of Pulsars: Millisecond Pulsars, Magnetars and More, 983, 453
13. Clark, G. W. 1975, ApJ, Lett., 199, L143
14. Rasio, F. R. & Heggie, D. C. 1995, ApJ, 445, L133
15. Freire, P. C., Gupta, Y., Ransom, S. M., & Ishwara-Chandra, C. H. 2004, ApJlett, 606, L53
16. Manchester, R. N., Lyne, A. G., Robinson, C., Bailes, M., & D’Amico, N. 1991, Nature, 352, 219
17. Camilo, F., Lorimer, D. R., Freire, P., Lyne, A. G., & Manchester, R. N. 2000, ApJ, 535, 975
18. Freire, P. C., Camilo, F., Kramer, M., Lorimer, D. R., Lyne, A. G., Manchester, R. N., & D’Amico, N. 2003, MNRAS, 340, 1359
19. Jacoby, B. A., Bailes, M., van Kerkwijk, M. H., Ord, S., Hotan, A., Kulkarni, S. R., & Anderson, S. B. 2003, ApJ, Lett., 599, L99
20. Jacoby, B. A., Hotan, A., Bailes, M., Ord, S., & Kulkarni, S. R. 2005, ApJlett, 629, L113
21. Ransom, S. M., Hessels, J. W. T., Stairs, I. H., Freire, P. C. C., Camilo, F., Kaspi, V. M., & Kaplan, D. L. 2005, Science, 307, 892
22. Hessels, J. W. T., Ransom, S. M., Stairs, I. H., Freire, P. C. C., Kaspi, V. M., & Camilo, F. 2006, Science, 311, 1901
23. Anderson, S. B., Wolszczan, A., Kulkarni, S. R., & Prince, T. A. 1997, ApJ, 482, 870
24. Freire, P. C. C., Wolszczan, A., van den Berg, M., & Hessels, J. W. T. 2008, ApJ, 679, 1433
25. Freire, P. C. C., Ransom, S. M., Bégan, S., Stairs, I. H., Hessels, J. W. T., Frey, L. H., & Camilo, F. 2008, ApJ, 675, 670
26. Verbist, J. P. W.; Bailes, M.; van Straten, W.; Hobbs, G. B.; Edwards, R. T.; Manchester, R. N.; Bhat, N. D. R.; Sarkissian, J. M.; Jacoby, B. A.; Kulkarni, S. R. 2008, ApJ, 679, 675
27. D. J. Champion, S. M. Ransom, P. Lazarus, F. Camilo, C. Bassa, V. M. Kaspi, D. J. Nice, P. C. C. Freire, I. H. Stairs, J. van Leeuwen, B. W. Stappers, J. M. Cordes, J. W. T. Hessels, D. R. Lorimer, Z. Arzoumanian, D. C. Backer, N. D. Ramesh Bhat, S. Chatterjee, I. Cognard, J. S. Deneva, C.-A. Faucher-Giguère, B. M. Gaensler, J. Han, F. A. Jenet, L. Kasian, V. I. Kondratiev, M. Kramer, J. Lazio, M. A. McLaughlin, A. Venkataraman & W. Vlemmings 2008, Science, 320, 1309
28. Bassa, C. G., van Kerkwijk, M. H., Koester, D., & Verbunt, F. 2006, A&A, 456, 295
29. Bégan, S., Ransom, S. M., Freire, P. C. C., Stairs, I. H., Hessels, J. W. T., Katz 2009, ApJ. in preparation
30. Freire, P. C. C., Ransom, S. M., & Gupta, Y. 2007, ApJ, 662, 1177
31. Cordes, J. M.; Freire, P. C. C.; Lorimer, D. R.; Camilo, F.; Champion, D. J.; Nice, D. J.; Ramachandran, R.; Hessels, J. W. T.; Vlemmings, W.; van Leeuwen, J.; Ransom, S. M.; Bhat, N. D. R.; Arzoumanian, Z.; McLaughlin, M. A.; Kaspi, V. M.; Kasian, L.; Deneva, J. S.; Reid, B.; Chatterjee, S.; Han, J. L.; Backer, D. C.; Stairs, I. H.; Deshpande, A. A.; Faucher-Giguère, C.-A. 2006, ApJ, 637, 446
32. Lattimer, J. M., & Prakash, M. 2007, Physics Reports, 442, 109
33. Lattimer, J. M., & Prakash, M. 2005, Physical Review Letters, 94, 111101