Precise mass measurements for the double neutron star system J1829+2456

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ABSTRACT
PSR J1829+2456 is a radio pulsar in a relativistic binary system with another neutron star. It has a rotational period of 41 ms and a mildly eccentric (\(e = 0.14\)) 28-hr orbit. We have continued its observations with the Arecibo radio telescope and have now measured the individual neutron star masses of this system. We find the pulsar and companion masses to be 1.295 ± 0.011 \(M_\odot\) and 1.310 ± 0.011 \(M_\odot\) (2\(\sigma\) − 95\% confidence, unless stated otherwise), respectively. We have also measured the proper motion for this system and used it to estimate its space velocity to be 46\(\pm\)72 \(\pm\)30 km s\(^{-1}\) with respect to the local standard of rest. Compared with the DNS population of measured masses, the relatively low values for companion mass, space velocity and orbital eccentricity in this system imply a similar binary evolution to that of other close double neutron star systems in which the (second-formed) companion is theorised to have been formed out of a low-kick, low mass-loss, symmetric supernova.

Key words: stars: binaries: general — stars: pulsars: general — methods: observational

1 INTRODUCTION
The observational study of neutron stars (NSs) in binary systems began with the discovery of the relativistic binary pulsar PSR B1913+16 by Hulse & Taylor (1975), who recognised its value for precise tests of the predictions of general relativity (GR) in the strong-field regime (Taylor & Weisberg 1989), as well as tests of alternative theories of gravity (e.g., Damour & Esposito-Farèse 1992; Damour & Esposito-Farèse 1993, 1996). Notable examples include the aforementioned PSR B1913+16, observations of which have shown agreement with GR predictions of orbital decay rate due to gravitational wave (GW) emission (Weisberg & Huang 2016); PSR B1534+12 (Stairs et al. 2002; Fonseca et al. 2014); the double pulsar (PSR J0737–3039A/B), which has given the most stringent test of GR in the strong-field regime (Kramer et al. 2006); PSR J0337+1715, a pulsar in a triple system that has provided the most constraining limits on violation of the strong equivalence principle (Archibald et al. 2018; Voisin et al. 2020); and PSR J1141–6545, whose white dwarf companion is observed to undergo relativistic frame-dragging whereby it drags the surrounding space-time during its rotation (Krishnan et al. 2020).

Observations of pulsars in binaries also allow us to probe binary formation and evolution. In particular, studies of double neutron star (DNS) systems can provide insight into the formation of the second-formed NS and ultimately the physics behind the second supernova, of which the DNS is a remnant (e.g., Tauris et al. 2017). The progenitor binary systems of most DNS systems contain stars of mass \(\gtrsim 8M_\odot\). The more massive star is first to end its main-sequence, the remnant of which is a fast spinning neutron star and a main sequence binary companion.

Amongst the known Galactic DNS population, it is becoming clear that there are two principal post–second supernova evolutionary channels, observationally distinguished by their companion masses, orbital eccentricities and space velocities. Systems with a high eccentricity, high companion...
mass and high peculiar space velocity ($v_{\text{LSR}}$) compared to the overall DNS population, such as PSRs B1534+12 and B1913+16, indicate that they are the result of a high mass-loss, asymmetric second–SN from a massive progenitor that led to a large natal kick from the system (e.g. Wex et al. 2000).

In contrast, systems with a low eccentricity (when compared to other DNSs), low companion mass and small $v_{\text{LSR}}$, such as PSRs J0737–3039 (Kramer et al. 2006; Ferdman et al. 2013), J1756–2251 (Ferdman et al. 2014), J1913+1102 (Ferdman et al. 2020) and J1946+2052 (Stovall et al. 2018) are theorized to have all undergone a different evolutionary track from the aforementioned binaries after the first supernova. As with most DNS systems, it is thought that the RLO of the companion star, as it evolves off the main sequence, results in a common envelope (CE) in which the first-formed NS is embedded. After inspiral of the NS due to dynamical friction and the ultimate ejection of the common envelope, a NS-helium (He) star binary is left behind (Tauris et al. 2017). Depending on the mass of the He-star and the orbital separation, the surface layers of the companion may be tidally stripped following Case BB RLO mass accretion to the NS, causing it to gain angular momentum and spin up to have a rotation period of tens of milliseconds (Tauris et al. 2015). If the He-star is massive enough, it also undergoes a supernova via a rapid electron capture to an iron or possibly an O–Ne–Mg core. The time scale for this capture is much faster than the timescales for non-radial hydrodynamical instabilities to occur (Nomoto 1984; Zha et al. 2019), leading to a low-kick symmetric supernova with very little mass left to eject, resulting in very little eccentricity increase (Tauris et al. 2017). A system that has undergone this process is expected to have a correspondingly low observed eccentricity and space velocity ($\lesssim 100 \text{ km s}^{-1}$).

If these scenarios are correct, there should be a correlation between NS mass and inferred SN kick velocity. This seems to be the case (Tauris et al. 2017); however the number of DNSs with good mass and proper motion measurements is still less than half of the known sample of 19 DNSs in the Galactic disk, which results in low-number statistics. It is therefore imperative not only that we discover, but also that we measure masses, proper motions and other parameters for, as many DNS systems as possible in order to expand on this relatively small population. This has additional benefits: recently, two DNSs with asymmetric NS masses have been discovered (Martinez et al. 2015; Ferdman et al. 2020), the latter system is expected to merge within 470 Myr. This suggests that such asymmetric DNSs mergers might be substantial, with a fraction of about 10% of the known population; however, we are still limited by the small population. Establishing more firmly the size of this population will be of particular importance for the interpretation of DNS mergers in LIGO/Virgo/Kagra data.

PSR J1829+2456 is a recycled pulsar with a rotational period of 41 ms, and is a member of a DNS system in a 28-h (1.18-d), mildly eccentric orbit ($e = 0.14$). It was initially discovered and timed by Champion et al. (2004) from data taken during a 1999 drift-scan survey using the 430-MHz Gregorian dome receiver system at the Arecibo radio telescope. At the time of its discovery, the dispersion measure (DM) was found to be $13.9 \text{ pc cm}^{-3}$, which implied a distance of $1.2 \pm 0.36 \text{ kpc}$ to the pulsar, estimated from the NE2001 Galactic ionized electron distribution model (Cordes & Lazio 2003). However, due to the existence of the Gould Belt, a dense region of gas and young stellar populations along the line of sight to PSR J1829+2456 (Gehrels et al. 2000; Grenier 2000), this distance has likely been overestimated. A more reliable estimated distance may come from using the YMW16 electron distribution model (Yao et al. 2017), which includes several local features such as those due to the Local Bubble, and adds a fourth spiral arm to the model of the Milky Way. The YMW16 models the distance of PSR J1829+2456 to be $0.91 \pm 0.18 \text{ kpc}$.

Soon after its discovery, the advance of periastron ($\dot{\omega}$) of PSR J1829+2456 was found to be $0.28 \pm 0.01^\circ \text{ yr}^{-1}$, leading to a total mass ($M_{\text{tot}}$) determination to be $2.6 \pm 0.1 M_\odot$. However, only limiting values of the pulsar and companion mass could be found, with $m_p < 1.38 M_\odot$ and $1.22 M_\odot < m_c < 1.38 M_\odot$ (Champion et al. 2004). Although these mass limits alone do not conclusively determine the companion to be a NS (as opposed to a massive white dwarf), the moderate eccentricity of the orbit in tandem with these mass limits, as well as the spin period of tens of milliseconds and a small $P$, which give a large characteristic age of 13 Gyr and a small surface magnetic field strength of $1.4 \times 10^9 \text{ G}$ (characteristics generally observed post-recycling), implied that the system is likely to be a DNS. Although the recycling of the first-formed pulsars in these systems likely circularized the orbits, as observed for high-mass X-ray binaries, DNS systems are expected to have higher eccentricities than NS–WD systems due to large, near-instant mass loss that occurs during the supernova that forms the second NS and its associated kick. By contrast, in NS–WD systems where the NS is recycled, the orbit retains the low eccentricity associated with their X-ray binary phase, since no second supernova disrupts the system (see e.g. Antoniadis et al. 2013; Wang et al. 2017).

The new observations for PSR J1829+2456 were predicted to allow us to significantly determine the system component masses as well as better constrain the proper motion. This would allow for tighter constraints on binary evolution models for DNS systems and determine this system’s evolutionary track in the context of the wider DNS population.

## 2 OBSERVATIONS AND TIMING ANALYSIS

Initial observations of PSR J1829+2456 began in May 2003 (MJD 52785) with the Arecibo telescope, using the Penn State Pulsar Machine (PSPM) at a centre frequency of 430 MHz, and the Wideband Arcibo Pulsar Processor (WAPP) centred at 1400 MHz. Several observations were carried out using the Green Bank telescope (GBT) at 350 MHz in August 2006, only 10 pulse time-of-arrival (TOA) measurements could be salvaged due to overly pervasive radio frequency interference (RFI) in that data set. A full description of the data set and its analysis can be found in Champion et al. (2004).

The most recent observing campaigns for PSR J1829+2456 have been running since July 2017 (MJD 57950), and this work analyzes data taken until April 2020 (MJD 58948). All these observations were conducted at the Arecibo radio telescope roughly every 4 weeks using the Puerto Rico Ultimate Pulsar Processing Instrument (PUPPI) coherent de-dispersion backend. Two frequency
bands were used during these observations with centre frequencies of \(\sim 1400\) MHz and \(\sim 430\) MHz, over bandwidths of 800 MHz and 100 MHz, respectively. In the second year of PUPPI observations, we conducted a dense campaign of four epochs within one week in order to provide better orbital phase sampling.

A standard profile for each band was created in an iterative manner. We began by averaging all the folded data from a particular backend and using the resulting profile’s total intensity as the template. RFI excision was conducted on data from the correct frequency band by cross-referencing against this profile. This was done by fitting the current template to seven Gaussian curves to obtain a smooth standard profile, allowing for a clear distinction between on-pulse and off-pulse regions. Individual profiles were then rejected if their off-pulse RMS was a 95% outlier to the overall off-pulse RMS distribution. After RFI excision, a new profile was constructed in the same way as described above by averaging the newly RFI excised data.

The cleaned data were flux calibrated by comparing observations of the stably polarized quasar QSO B1442 (J1445+0958) as a continuum source at the closest available dates to the PSR J1829+2456 observations; the largest time difference we use was nine days. Data for this continuum source was provided by the NANOGrav collaboration. After flux calibration, the fully processed data were once again used to create a standard profile for the band, \(T_\nu\), where \(\nu\) is the centre frequency of the standard profile. The final standard profiles for both the 430 MHz and the L-band data are shown in Figure 1. All data manipulation was administered using the PSRVoid Python package\(^1\).

In all we calculated 609 new pulse times-of-arrival from the data set by determining a phase offset for each resulting data profile through cross-correlation with the standard profile for each observing band. This phase shift was then converted to a time offset using the rotation period at the specific epoch corresponding to the individual data profile (Taylor 1992). TOAs were created from time-averaged sub-integrations of about 15 minutes, corresponding to roughly 3 - 4 TOAs per receiver per observation.

The TOAs were then appended to the 153 existing TOAs from older observing campaigns for this pulsar. These were fit within the TEMPO2 pulsar timing software package (Hobbs et al. 2006; Edwards et al. 2006) using the JPL DE435 solar system ephemeris model (Folkner et al. 2016) and the TT(BIPM19) (Guinot 1988) clock correction in order to convert the observatory time-stamp given to each profile to the GPS time standard, and ultimately, to the Solar System barycentre (SSB) which is, to good approximation, an inertial reference frame. Where TT(BIPM19) could not be used (i.e. for the final two days of data), a TAI correction was made. TEMPO2 fits all TOAs to an existing model ephemeris via a weighted least-squares fit, and outputs a set of timing residuals, which are the differences between the observed TOAs and those predicted from the current model. In all, 762 TOAs were fit, spanning 16.9 years in total, at frequencies centred around 350 MHz, 430 MHz and 1400 MHz.

Residual errors were calculated from the uncertainty in the phase shift calculated in the cross-correlation process, as well as RMS additive noise in the time domain with extra error added in quadrature (EQUAD, or \(Q_i\) for each set of different observations, \(i\)), in order to account for unmodelled sources of white noise. This was done to bring the \(\chi^2\) closer to 1, resulting in more conservative, and realistic, parameter uncertainties. Optimal EQUAD values were determined using the “efac-equad” plugin for TEMPO2 and the new residual uncertainties for a particular observation were calculated by \(\sigma_{Li} = (\sigma_M^2 + Q_i^2)^{1/2}\) (see e.g. Arzoumanian et al. 2018, for a more detailed description of EQUADs). A breakdown of each observation campaign is shown in Table 1.

One full day of highly noisy data at MJD 58118 was omitted from our analysis. These data were obtained in the aftermath of Hurricane Maria and restoration work at Arecibo was ongoing; at this time, adverse effects to the data quality may have remained.

2.1 Binary models

The nature of the system was characterised by parameterising a binary fit in terms of five Keplerian orbital elements: orbital period \((P_0)\); projection of the semi-major axis onto the line of sight \((x = a \sin i)\), where \(a\) is the semi-major axis of the pulsar’s orbit and \(i\) is the inclination; orbital eccentricity \((e)\); argument of periastron \((\omega)\); and epoch of periastron passage \((T_0)\). We also fit for any significant relativistic perturbations to these orbital elements – the so-called post-Keplerian orbital parameters. Two binary-timing models were used: the Damour-Deruelle (DD) theory-independent framework (Damour & Deruelle 1985, 1986), and the GR-modified DD

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\(^1\) https://github.com/HenrykHaniewicz/PSRVoid
Table 1. Summary of time-of-arrival data for PSR J1829+2456.

| Telescope | Instrument | Center Frequency (MHz) | Bandwidth (MHz) | Span (MJD) | #TOAs | Weighted $\chi^2$ | Weighted RMS (µs) | EQUAD |
|-----------|------------|------------------------|-----------------|------------|--------|-----------------|------------------|--------|
| Arecibo   | PSPM       | 434.0                  | 7.68            | 52785–53905 | 118    | 1.0044         | 18.0315          | 6.42   |
|           | PSPM       | 311.0                  | 7.68            | 53027–54746 | 4      | 2.1703         | 28.1169          | 0.00   |
|           | WAPP       | 1378.6                 | 100             | 54588–54835 | 10     | 1.0008         | 3.7705           | 3.38   |
|           | WAPP       | 319.6                  | 100             | 54647–54835 | 11     | 0.9289         | 9.6123           | 1.00   |
|           | PUPPI      | 1384.4                 | 800             | 57950–58948 | 479    | 1.0173         | 9.9827           | 6.58   |
|           | PUPPI      | 427.2                  | 16              | 52972–52973 | 10     | 0.5559         | 33.5703          | 0.00   |
| GBT GASP  |            |                        |                 |            |        |                 |                  |        |
| Overall   |            |                        |                 | 52785–58948 | 762    | 1.0678         | 10.086           |        |

†From the DDGR binary fit.

Table 2. Timing solution for PSR J1829+2456.

| Fit and data-set | DD | DDGR |
|------------------|----|------|
| Date span (yr)   | 32 | 16.9 |
| Date range (MJD) | 52785.3–58948.5 | 762 |
| Number of TOAs   | 32 | 762  |
| Solar System ephemeris | DE430 | TT(BIPM) |
| Clock correction procedure | TONB | TT(BIPM) |
| Reference timing epoch (MJD) | 55624.0 | 10.086 |
| RMS timing residual (µs) | 10.074 | 10.074 |

Observed quantities

Right ascension, $\alpha_{2000}$ | $18^h29^m34^s.66522(4)$ | $18^h29^m34^s.66526(4)$ |
Declination, $\delta_{2000}$ | $24^\circ 56' 18".13997(7)$ | $24^\circ 56' 18".13997(7)$ |
Rotation frequency, $\nu$ (s$^{-1}$) | $24.3844041401098(7)$ | $24.3844041401098(7)$ |
First derivative of rotation frequency, $\dot{\nu}$ (s$^{-2}$) | $-2.946(3) \times 10^{-17}$ | $-2.946(3) \times 10^{-17}$ |
Dispersion measure, DM (cm$^{-3}$ pc) | 13.7012(13) | 13.7012(13) |
Rate of dispersion measure, DM (cm$^{-3}$ pc yr$^{-1}$) | 0.00034(7) | 0.00034(7) |
Proper motion in right ascension, $\mu_\alpha$ (mas yr$^{-1}$) | $-5.41(6)$ | $-5.40(7)$ |
Proper motion in declination, $\mu_\delta$ (mas yr$^{-1}$) | $-7.70(9)$ | $-7.69(9)$ |
Binary period, $P_b$ (d) | 1.17602795267(18) | 1.17602795272(18) |
Orbital eccentricity, $e$ | $0.13914373(7)$ | $0.13914353(7)$ |
Projected semi-major axis of orbit, $a$ (AU) | $7.23678(4)$ | $7.23684(4)$ |
Longitude of periastron, $\omega$ (°) | 229.9361(5) | 229.9353(3) |
Epoch of periastron, $t_0$ (MJD) | 52848.5797774(13) | 52848.5797766(9) |
Advance of periastron, $w$ (° yr$^{-1}$) | $0.293193(18)$ | $-$ |
Einstein delay, $\gamma$ (s) | $0.00137(6)$ | $-$ |
Shapiro delay shape parameter, $s$ | $0.93(2)$ | $-$ |
Companion mass, $M_c$ ($M_\odot$) | $1.9(6)$ | $1.310(11)$ |
Total system mass, $M_{tot}$ ($M_\odot$) | $2.59(2)$ | $2.605(3)$ |

Derived quantities

Rotation period, $P$ (mas) | $41.0098235928589(18)$ | $41.0098235928588(18)$ |
First derivative of rotation period, $\dot{P}$ | $4.9550(6) \times 10^{-20}$ | $4.9550(6) \times 10^{-20}$ |
Galactic longitude, $l$ | $53iday424(1)$ | $53iday424(1)$ |
Galactic latitude, $b$ | $15d6120(1)$ | $15d6120(1)$ |
NE2001 DM-derived distance (kpc) | $1.20(36)$ | $0.91(18)$ |
YMW16 DM-derived distance (kpc) | $9.41(8)$ | $9.40(8)$ |
Total proper motion, $\mu_{tot}$ (mas yr$^{-1}$) | $40^P_{48}$ | $46^P_{30}$ |
Transverse velocity, $v_{trans}$ (km s$^{-1}$) | $40^P_{48}$ | $46^P_{30}$ |
Total peculiar velocity, $v_{pec}$ (km s$^{-1}$) | $13$ | $-$ |
Surface magnetic field strength, $B_s$ (10$^3$ G) | $1.44$ | $-$ |
Mass function, $f(M_c)$ | $0.294226(4)$ | $0.2942355(12)$ |
Inclination of orbit, $i$ (°) | $68^5_{4}$ | $74(4)^*$ |
Pulsar mass, $M_p$ ($M_\odot$) | $-$ | $1.295(11)$ |

PK parameters were measured using the Damour-Deruelle (DD) timing model (Damour & Deruelle 1985, 1986; Damour & Taylor 1992) in TEMPO2 whereas the quoted masses were calculated assuming GR as the correct theory of gravity (DDGR) (Damour & Deruelle 1985, 1986). Figures in parentheses represent the nominal 1σ (68%) uncertainties in the least-significant digits quoted.

Arbitrary jumps between telescopes were also fit for, which are not astrophysical and not shown here. Jumps were fit against Arecibo's PSPM backend at 327 MHz. Fitting against any other frequency / epoch / telescope gave consistent jumps.

*Calculated using the mass function and the component masses in the relation $f = (M_c \sin^2 i)/M_{tot}^2$. 

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model which considers general relativity as the correct theory of gravity (DDGR).

The DD model allows for individual post-Keplerian (PK) binary parameters to be measured theoretically independently. These may then be formulated under specific theories of gravity; in the case of GR (Damour & Deruelle 1985; Lorimer, D. R. and Kramer, M. 2005) we have:

\[
\omega = 3T_\odot^2 \left( \frac{P_b}{2\pi} \right)^{-5/3} \frac{(m_p + m_c)^{2/3}}{1 - e^2} \quad (1)
\]

\[
\gamma = T_\odot^{2/3} \frac{P_b}{2\pi} \frac{m_c(m_p + 2m_c)}{(m_p + m_c)^{4/3}} \quad (2)
\]

\[
P_b = \frac{192\pi^5}{5} \left( \frac{P_b}{2\pi} \right)^{-5/3} \frac{m_p m_c \left( 1 + \frac{1}{4} e^2 + \frac{7}{16} \gamma^2 \right)}{(m_p + m_c)^{1/3} (1 - e^2)^{7/2}} \quad (3)
\]

\[
r = T_\odot m_c \quad (4)
\]

\[
s = \sin i = T_\odot^{-1/3} \left( \frac{P_b}{2\pi} \right)^{-2/3} \frac{(m_p + m_c)^{2/3}}{mc} \quad (5)
\]

where \(\omega\) is periastron advance, \(\gamma\) is the Einstein delay parameter, \(P_b\) is the orbital decay, \(r\) and \(s\) are the Shapiro “range” and “shape” parameters, and \(T_\odot = GM_\odot/c^3 = 4.9254909476142675 \ldots \mu s\). Under GR then, two PK parameter measurements will allow us to solve for each component mass, and each additional PK parameter measurement provides a unique check for consistency, and therefore, a test of GR.

Through the DD method, values for \(\omega\), \(s\) and \(\gamma\) were measured to better than 10% significance. Figure 2 plots the pulsar mass against companion mass, with 95% Gaussian confidence mass constraints corresponding to each measured PK parameter under the assumption of GR.

When conducting the DDGR timing fit, which assumes GR as the correct theory of gravity in order to directly determine the companion and total system masses, we find \(m_c = 1.310 \pm 0.011 M_\odot\), low compared to the “canonical” median neutron star mass of 1.35 \(M_\odot\) (Thorsett & Chakrabarty 1999), and \(M_{\text{tot}} = 2.6052 \pm 0.0002 M_\odot\). In order to obtain the individual masses using DDGR, a contour grid was sampled over pulsar and companion mass with confidence levels being obtained by calculating the likelihood based on the \(\chi^2\) of the fit at each grid point. We find good agreement with the DD model mass constraints, as illustrated in Figure 2. Figure 3 shows the timing residuals from the DDGR model fit and Table 2 gives the resulting post-fit timing parameters from TEMPO2 using both the DD and DDGR models.

3 RESULTS AND DISCUSSION

Newly measured properties of PSR J1829+2456 have shown the system to be similar to several other DNS systems for which the component masses have been measured. Given the evolutionary relationship between the masses and the parameters discussed, it is likely that these systems all evolved in a similar way. Table 3 compares the known recycled DNS systems for which mass measurements have been made or bounded.

![Figure 2. Main window: Mass-mass diagram for PSR J1829+2456 showing the GR-derived mass constraints from each PK-parameter fit. The blue region is \(\omega\), the green region is \(r\) and the maroon region is \(s\), as reported by TEMPO2. The dashed line represents the \(s = 1\) constraint. Inset: The green contoured region represents the 95% confidence region for the pulsar and companion masses based on the DDGR model, which assumes general relativity for the timing fit.](image)

3.1 Component masses

We have precisely determined the pulsar and companion masses, assuming GR as the correct theory of gravity. The masses found were 1.295 \pm 0.011 \(M_\odot\), and 1.310 \pm 0.011 \(M_\odot\) for the companion. The system appears to have similar pulsar and companion masses to the DNS population (where precise mass measurements are known) and has a relatively low absolute companion mass although not as low as some notable outliers (see e.g. Martinez et al. 2015, but cf. Tauris & Janka (2019)).

3.2 Space velocities

As a result of the newly analysed campaign, the component proper motions for PSR J1829+2456 have been precisely determined. In order to compare this with other DNS systems, the three-dimensional space velocities for all binary systems containing pulsars with known individual proper motions were calculated. This involves a two-prior Monte Carlo approach to estimate both the distance (\(d\), using YMW16 estimates) and the tangential velocity (\(v_{\text{trans}}\)), each sampled from a Gaussian distribution with the 1 - \(\sigma\) width equal to their uncertainties. The error on \(v_{\text{trans}}\) was propagated through the error on \(d\) and the uncertainty in the proper motion. Since the radial velocity (\(v_r\)) is not possible to determine using pulsar timing, we have randomly sampled \(v_r\) from a distribution which is uniform in \(\cos i\), and calculated the total space velocity as follows (Tauris et al. 2017):

![Figure 3. Space velocity vectors for PSR J1829+2456 showing the DDGR-derived space component velocities from each PK-parameter fit. The blue region is \(v_r\), the green region is \(v_\theta\) and the maroon region is \(v_\phi\), as reported by TEMPO2. The dashed line represents the \(s = 1\) constraint. Inset: The green contoured region represents the 95% confidence region for the pulsar and companion masses based on the DDGR model, which assumes general relativity for the timing fit.](image)
Figure 3. Post-fit residuals in milliseconds, as a function of TOA in MJD, for PSR J1829+2456 determined by the DDGR timing model. Top: all available Times-of-Arrival. Bottom: the new observations in green (450 MHz) and gold (1400 MHz).

Figure 4. The YMW16–derived space velocities, taken with respect to the Local Standard of Rest (LSR), of all DNSs with known masses and component proper motions. The gold point represents PSR J1829+2456. Errors in $v_{\text{LSR}}$ and $m_c$ are the 2\sigma confidence level values.

$$v_{\text{tot}}(d,i) = \sqrt{v_t^2 + v_{\text{trans}}^2}$$

$$= \sqrt{v_t^2 (\cot^2 i + 1)}$$

$$= 4.74d\sqrt{\cot^2 i + 1}\sqrt{\mu_0^2 + \mu_0^2 \cos^2 \delta}$$

where the declination $\delta$ is measured in radians. This was iterated 10000 times over the sampling parameters $d$ and $i$ and the result was converted to the Local Standard of Rest from SSB using the method given by McMillan (2017). We arrive at a value for the velocity of PSR J1829+2456 of $46^{+72}_{-30}$ km s$^{-1}$, assuming YMW16. We have also performed this calculation for all DNSs with measured proper motions; these are reported in Table 3. Although population sizes are relatively small, calculations suggest two different velocity environments with an overall upward trend with companion mass among DNSs. The two red points in Figure 4 represent PSRs B1534+12 and B1913+16. These pulsar binaries are thought to have formed in an asymmetric SN given their estimated kick velocities (Tauris et al. 2017). This hints at a distinct population divide to several other DNS systems such as J1756–2251 and J0737–3039 (both in blue). At its estimated median LSR velocity, PSR J1829+2456 appears to be in the latter group, following the currently observed upward trend with respect to $m_c$. The uncertainties in its velocity are still somewhat too large to draw definitive conclusions.

We now calculate the kinematic contributions for $P$ and $P_0$. These are given by the second derivative of the line-of-sight distance from the pulsar to the Earth, or the first derivative of the Doppler factor. Using calculations in (Stovall et al. 2019), we obtain three main contributions: $8.01 \times 10^{-21}$ for the Shklovskii effect (Shklovskii 1970), $-1.23 \times 10^{-21}$ for the difference in rotational accelerations between the Solar System and the pulsar, projected along the direction between the two, and $-1.09 \times 10^{-21}$ for the difference in vertical accelerations between the Solar System and the pulsar, projected along this same direction. The total acceleration is then $5.69 \times 10^{-21}$.

The resulting kinematic $P_0$ is too small to be measured: if we fit for $P_0$, we obtain $-5.2 \times 10^{-14}$, so the uncertainty is still too large for the precision of our measurement. Subtracting the kinematic contributions from $P$, we find an intrinsic $P$ of $4.38 \pm 0.8 \times 10^{-20}$, and values for the pulsar characteristics as described in Table 2.

### 3.3 Orbital parameter co-variance

The mass measurements due to GR, as derived from constant PK parameter inputs, have greater precision than the DD-derived masses implying that the uncertainties for the PK parameters as given by TEMPO2 are an underestimate.
It has been shown that, for sufficiently wide orbits, the derivative of the projected semi-major axis can be highly co-variant with $\gamma$, which itself is co-variant with the current value for $x$ as well as the proper motion (Ridolfi et al. 2019, equations 25 and 43 respectively). We calculate the maximum and minimum values for $\gamma$ to be $1.5$ ms and $1.3$ ms respectively. This constitutes an uncertainty in $\gamma$ four times larger than measured in TEMPO2 which more than accounts for the discrepancy between the GR-derived mass contours and the $\gamma$ region (see Figure 2).

The contribution of the Einstein delay to $\dot{x}$ is several orders of magnitude greater than the expected GR-derived uncertainty for $\dot{x}$ implying that a non-negligible residual contribution due to $\dot{x}$ has been “absorbed” into our measurement for $\gamma$. Fitting $\gamma$ and $\dot{x}$ together in the DD model and accounting for the absorption discrepancy, gives an uncertainty in $\gamma$ of ±0.3 ms. Currently only about 85% of the orbit has been directly observed and increasing this coverage is likely to remove such co-variances.

### 3.4 Eccentricities

A more precise value for the orbital eccentricity has also been measured and compared against the population. Much like the space velocities, there is a clear increase in eccentricity with respect to the companion mass (Figure 5), with many currently known DNS binaries having low eccentricities. Low eccentricity implies a low mass-loss event and many of the lowly eccentric pulsars with above median companion masses have, or are predicted to have, smaller kick-velocities. This suggests a symmetric, low mass-loss SN, since the companion is similar in mass to the pulsar. These findings also agree with the theory that a larger resulting DNS eccentricity corresponds to those systems which also have undergone a large natal kick. as described in Figure 6.

![Figure 5. The eccentricities of DNS systems with known or bounded masses as a function of the companion’s mass. Points of differing color (red or blue) imply a different theorised evolution pathway as described in the text. The golden point represents PSR J1829+2456.](image)

![Figure 6. The space velocities of DNS systems with respect to the orbital eccentricity. The red points represent those systems believed to have been formed from a violent asymmetric SN, whereas points in blue represent the symmetric pathway. The golden point is PSR J1829+2456.](image)

### 3.5 Binary evolution

Under the assumption that the total space velocity for PSR J1829+2456 is not entirely in the radial direction, so that our Monte Carlo approximation for $v_{\text{trans}}$ holds, the relatively low magnitude of the total proper motion ($\mu_{\text{tot}}$) when compared with other DNS systems supports a formation scenario for the companion NS that involves a low-kick supernova, which would be expected from a symmetric event (Hills 1983; Tauris et al. 2015). This is further supported by its observed low eccentricity when compared with other Galactic DNSs (see e.g. Tauris et al. 2017). This evolutionary pathway is similar to the systems containing PSRs J1756–2251 and J0737–3039A. The eccentricity of the orbit is inconsistent with the asymmetric SN pathway described in some models which relate eccentricity to the orbital separation for symmetric and asymmetric SN (e.g. Fryer & Kalogera 1997; Willems & Kalogera 2004; Tauris et al. 2017).

We have also ruled out post second-SN evolution based on neutron driven kick (Janka 2013) due to the pulsar’s surface magnetic field, derived from the product of $P$ and $\dot{P}$ (See for example Li et al. 2012) to be $1.44 \times 10^9$ G, six orders of magnitude too low to fit either theory in this category.

### 4 CONCLUSIONS

We have presented an updated timing solution for the PSR J1829+2456 DNS system. We have made precise measurements of both the pulsar and companion mass, finding them to be of similar mass, and have precisely determined a low proper motion of the system. This implies a low tangential velocity suggesting an evolution involving a symmetric second supernova in which only a small kick was imparted following a short-duration mass accretion process. The eccentricity, velocity, and system masses, all found through timing, are similar to the evolutionary models of PSRs J0737–3039, J1518+4904, J1756–2251 and...
Table 3. Parameters for various DNS systems in which the pulsar is the recycled NS. This list does not include systems in globular clusters, which were likely formed via exchange encounters.

| PSR* | $P$ (ms) | $P_0$ (days) | $\epsilon$ | Companion mass (M⊙) | $\mu_{\text{tot}}$ (mas yr$^{-1}$) | d (kpc)$^x$ | $v^{18}$SR (km s$^{-1}$)$^x$ |
|------|----------|-------------|-----------|-----------------|-----------------|---------|------------------|
| J0453+1550$^1$ | 45.8 | 4.072 | 0.113 | 1.174 | 7.997 | 0.52 | $29^{+34}_{-19}$ |
| J0509+3801$^2$ | 76.5 | 0.380 | 0.586 | 1.46(8) | - | - | 7.08 |
| J0737–3039A$^3$ | 22.7 | 0.102 | 0.088 | 1.249 | 3.885 | 1.17 | $55^{+69}_{-56}$ |
| J1411+2551$^4$ | 62.4 | 2.615 | 0.169 | > 0.92 | - | 12 | 1.13 | 85$^{+120}_{-151}$ |
| J1518+4904$^5$ | 40.9 | 8.634 | 0.249 | 1.05$^{+1.21}_{-0.11}$ | 8.512 | 0.96 | 36$^{+55}_{-22}$ |
| B1534+12$^6$ | 37.9 | 0.421 | 0.274 | 1.346 | 25.34 | 0.93 | 120$^{+184}_{-78}$ |
| J1753–2240$^7$ | 95.1 | 13.638 | 0.304 | - | - | 6.93 | - |
| J1756–2251$^8$ | 28.5 | 0.320 | 0.181 | 1.230 | 5.928 | 0.95(50) | 42$^{+63}_{-25}$ |
| J1757–1854$^9$ | 21.5 | 0.183 | 0.606 | 1.3946(9) | - | 19.6 | - |
| J1811–1730$^{10}$ | 104.2 | 18.779 | 0.828 | > 0.93 | - | 10.16 | - |
| J1829+2456$^{11}$ | 41.1 | 1.176 | 0.139 | 1.31 | 9.400 | 0.91 | 46$^{+72}_{-30}$ |
| J1913+1102$^{12}$ | 27.3 | 0.206 | 0.090 | 1.273 | 9.286 | 7.14 | 112$^{+175}_{-73}$ |
| B1913+16$^{12}$ | 59.0 | 0.323 | 0.617 | 1.389 | 1.404 | 5.25 | 157$^{+242}_{-100}$ |
| J1930–1852$^{13}$ | 185.5 | 45.060 | 0.399 | > 1.30 | - | 2.48 | - |
| J1946+2052$^{14}$ | 16.9 | 0.078 | 0.064 | 1.26 | - | 3.51 | - |

*References: (1) Martinez et al. (2015), (2) Lynch et al. (2018), (3) Tauris et al. (2017), (4) Martinez et al. (2017), (5) Janssen et al. (2008), (6) Fonseca et al. (2014), (7) Keith et al. (2009), (8) Ferdman et al. (2014), (9) Cameron et al. (2018), (10) Corongiu et al. (2007), (11) Ferdman et al. (2020), (12) Weisberg & Taylor (2005), (13) Swiggum et al. (2015), (14) Stovall et al. (2018).

$^x$Distances used were derived from the YMW16 Galactic free electron distribution model (Yao et al. 2017) with DMs found using the ATNF Pulsar Catalogue (Manchester et al. 2005) except in the case of PSR J1756–2251, where the distance is given by Ferdman et al. (2014).

$^\dagger$Median $v^{\text{LSR}}$ and $2\sigma$ (95% confidence level) errors were calculated using the Monte-Carlo method described in section 3.2 and rounded to the nearest integer.

J1946+2052, in which the second-formed NS was formed as a result of rapid electron capture onto a He-star’s O-Ne-Mg core followed by a symmetric supernova. In contrast, evidence suggests that the second-formed NS in DNSs such as J1913+16 and B1534+12 were created from an asymmetric SN due to violent core-collapse scenarios.

Due to the limited number of known DNS systems, evolutionary scenarios are difficult to determine. Knowledge of the relative abundances of each type of DNS will allow us to better determine which parameters are most sensitive to evolution and better understand the DNS population as a whole.

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DATA AVAILABILITY

All data available from the author upon request.

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