The binary nature of PSR J2032+4127

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ABSTRACT
PSR J2032+4127 is a γ-ray and radio-emitting pulsar which has been regarded as a young luminous isolated neutron star. However, its recent spin-down rate has extraordinarily increased by a factor of 2. We present evidence that this is due to its motion as a member of a highly-eccentric binary system with an $\sim 15-17\,M_\odot$ Be star, MT91 213. Timing observations show that, not only are the positions of the two stars coincident within 0.4 arcsec, but timing models of binary motion of the pulsar fit the data much better than a model of a young isolated pulsar. MT91 213, and hence the pulsar, lie in the Cyg OB2 stellar association, which is at a distance of only 1.4–1.7 kpc. The pulsar is currently on the near side of, and accelerating towards, the Be star, with an orbital period of 20–30 yr. The next periastron is well constrained to occur in early 2018, providing an opportunity to observe enhanced high-energy emission as seen in other Be-star binary systems.

Key words: binaries: eclipsing – stars: individual: MT91 213 – stars: neutron – pulsars: individual: J2032+4127, Be stars – open clusters and associations: individual: Cyg OB2.

1 INTRODUCTION
PSR J2032+4127 is a 143 ms pulsar discovered by the Large Area Telescope (LAT) of the Fermi Gamma-ray Space Telescope (Abdo et al. 2009) and subsequently detected at radio frequencies (Camilo et al. 2009). Using γ-ray data as well as radio data, pulse arrival-time analysis by those authors, and latterly by Ray et al. (2011), showed that the pulsar had a large slow-down rate, indicating that it was a young pulsar, a notion which has been supported by a recent glitch in its rotation rate. The timing analysis showed that the projected position of the pulsar lay close to a $V = 11.95\,\text{Be star}$, MT91 213 in the Cyg OB2 stellar association. However, Camilo et al. (2009) concluded that it was not a binary companion of PSR J2032+4127, based mainly upon the apparent lack of variations in the pulsar rotation rate that would arise from the Doppler effects of any reasonable (circular) orbital binary motion. Subsequent studies of the properties of the pulsar have all been based upon the assumption that it is a solitary young energetic pulsar. For instance, Aliu et al. (2014) present a VERITAS detection of TeV J2032+4130 and they discuss its likely association with PSR J2032+4127, noting that the extended nature of the source and the prevalence of pulsar wind nebulae (PWNe) in the Galactic TeV source population argues that it is a PWN powered by the pulsar. However they note that the extended X-ray emission that is also spatially coincident with the source (Butt et al. 2006; Horns et al. 2007; Murakami et al. 2011) is quite weak if it is from a PWN. Six years of both γ-ray and radio timing data are now available, and we revisit the possibility that the pulsar is in orbit with MT91 213.

2 OBSERVATIONS AND TIMING NOISE MODEL
Fermi LAT data were used from shortly after the start of the mission in 2008 August up to 2014 June (MJD 54682–56824). Following the maximum likelihood method of Ray et al. (2011), we constructed times-of-arrival (TOAs) with a 14-d cadence from ‘reprocessed’ Pass 7 Fermi LAT data. For this analysis, we used SOURCE class photons, excluding events with a zenith angle $>100^\circ$ and when the spacecraft rocking angle exceeds $52^\circ$. To improve sensitivity, we employed photon weighting using the spectral models available in the Second Fermi Large Area Telescope Catalog of Gamma-ray Pulsars (Abdo et al. 2013).

Radio timing observations were made with the NRAO Green Bank Telescope (GBT) and the Lovell Telescope (LT) at Jodrell Bank. The GBT observations were primarily in bands centred on 820 MHz and 2000 MHz during the early part of this period (MJD 54836–55589) (Camilo et al. 2009), as well as MJD 56855–56857. Radio observations with the LT were made at approximately weekly intervals at around 1520 MHz for MJD 55222–56820. As described
by Camilo et al. (2009), the γ-ray and radio pulse profiles are very different in form. In order to establish the true alignment of the profiles, the dispersion measure (DM) was initially determined using only radio data. Inspection of the radio pulse profiles shows that there is little change in shape between 800 and 2000 MHz, and a single standard profile was used to obtain TOAs for all the radio observations. The DM was determined at three epochs, using the three 800-MHz TOAs and their neighbouring 1520-MHz and 2000-MHz TOAs. This allowed the time offset of the contemporaneous γ-ray TOAs to be established using the JUMP facility in TEMPO2 (Hobbs, Edwards & Manchester 2006). The mean value of these time offsets was consistent with the alignment obtained by Camilo et al. (2009) and was applied to all the γ-ray TOAs, allowing the delay between these TOAs and the radio TOAs to be used to determine the DM throughout the data set.

The radio TOAs have errors of ~300 μs, about half the errors of those provided by the Fermi LAT. In total, about 400 good TOAs are available over six years (MJD 54682–56857).

The pulsar shows substantial variations in rotation rate, indicating a large amount of ‘timing noise’, which is not unexpected in a young pulsar (i.e. having a large intrinsic spin-down rate). However, it has recently become clear that the magnitude of these variations far exceeds any previously encountered timing noise in a pulsar (e.g. Hobbs, Lyne & Kramer 2010). Fig. 1(a) presents the evolution of the barycentric rotation frequency of the pulsar over the 6-yr span of the timing data, showing a substantial reduction in frequency during this time. Also apparent is an increase in the magnitude of the slope, corresponding to an increase in the magnitude of the frequency derivative, shown in Fig. 1(b), by more than a factor of 2, and a decrease in the characteristic age by the same factor, confounding any interpretation in terms of conventional pulsar spin-down. However, there is also a barely-discernible minor glitch which occurred in 2011 September (MJD 55811) and which can be fitted by steps in frequency (∆ν) and frequency derivative (∆ν′). The whole set of TOAs can be well fitted by a model involving the position, three glitch parameters, the rotation frequency and 7-derivatives (Table 1, column 2).

The timing residuals (the difference between the observed and model-based TOAs) relative to this model, which we will henceforth refer to as the ‘noise model’, are shown in Fig. 1(c). The behaviour in the rotation seen in Figs 1(a) and (b) has never been seen in any other isolated pulsar, and is not characteristic of either a post-glitch recovery, during which the magnitude of the slow-down rate is usually observed to decrease (e.g. Espinoza et al. 2011), or of timing noise, which is usually characterized by switches, often quasi-periodic, between values of slow-down rate rather than the smooth variation seen here (Lyne et al. 2010; Lyne 2013). Most anomalous of all is the doubling of the slow-down rate, also not seen in any other isolated pulsar.

### 3 A BINARY MODEL

We believe that the only plausible origin of such a large variation in the observed slow-down rate of a pulsar lies in the Doppler effects of binary motion with another star. While we note the remark by Camilo et al. (2009) that there is no evidence of any short-period binary motion and that the binary period (of any circular orbit) must be in excess of 100 yr, we have explored the possibility that the pulsar is actually a member of a long-period binary system with a large orbital eccentricity.

First, we sought fits of binary models to the rotation-frequency data of Fig. 1(a). While good fits to the data were possible using models for eccentric binary orbits with orbital periods P_0 in excess of about 6000 d (16 yr), it soon became clear that there were strong covariances between some of the fitted parameters, arising from the small orbital phase range of the available data. In particular, there were large covariances between the intrinsic pulsar slow-down rate, ν, the orbital period P_0 and the projected semi-major axis of the orbit x = (a/c) sin i, where a is the semimajor axis of the orbit, i is the inclination of the plane of the orbit to the plane of the sky and c is the speed of light. These covariances allowed many good, but not unique, fits to the data. We therefore explored fits to the data for a range of fixed values of P_0 between 6000 and 12 000 d at 500-d intervals, and, for each of these, a range of fixed values of x, corresponding to fixed values of mass function f_m of 2, 5, 10 and 20 M⊙. f_m is a function of the masses of the neutron star (M_p) and the
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Figure 1. The spin-frequency history of PSR J2032+4127 determined over six years. (a) The observed variation in the spin-frequency offset \( \Delta \nu \) from 6.980 83 Hz, determined from fits to 150-d sets of TOAs every 50 d, showing the monotonically spin-down of the pulsar. This spin-down is interrupted briefly by a small glitch close to MJD 55811, identified by an arrow. (b) The variation of the spin-frequency first derivative \( \dot{\nu} \) determined over the same time intervals as (a), showing a doubling of the magnitude. The fits for \( \nu \) and \( \dot{\nu} \) for (a) and (b) were conducted simultaneously with the position fixed at \( \alpha = 20^h 32^m 13^s.105, \delta = 41^\circ 27' 24".36. \) (c) The timing residuals relative to the 7-derivative noise model presented in Table 1, column 2. (d) The timing residuals relative to a 6-derivative noise model. (e) The timing residuals relative to the best-fitting 'binary' model, which has orbital period \( P_b = 8578 \) d and mass function \( f_m = 10 M_\odot \) (Table 1, column 4). In panels (c), (d) and (e), the colour of the points indicates whether they were obtained from the LAT (red), the LT (black), the GBT at 2000 MHz (green) or the GBT at \( \sim 820 \) MHz (blue). All three timing models used in Figs 1(c), (d) and (e) do in fact include fits for the glitch parameters. In the timing-noise models, there is significant covariance between glitch parameters and other polynomial parameters, so that some features of the glitch are absorbed in the polynomial parameters, leaving some sharp, unmodelled features of the glitch in the residuals. It seems that the glitch and Keplerian parameters are not so covariant, and the glitch is fitted well.

its companion (\( M_c \)), and orbital inclination \( i \) and is determined from \( P_b \) and \( x \) from Kepler's laws by

\[
\frac{x}{f_m} = \frac{M_c \sin i}{(M_p + M_c)^2} = \frac{4 \pi^2 x^3}{G P_b^2}.
\]

Figure 2. The orbital variation of the frequency \( \nu \) and the first derivative \( \dot{\nu} \) of PSR J2032+4127 for the best-fitting binary model, which has orbital period \( P_b = 8578 \) d and mass function \( f_m = 10 M_\odot \) (Table 1, column 4). The scale on the right-hand axis of the upper panel indicates the magnitude of the orbital radial velocity. The dotted line in the lower panel shows the variation in \( \dot{\nu} \) on a scale expanded by a factor of 100. The bold sections in the two plots indicate the range of the available data.

where \( G \) is Newton's gravitational constant. If \( M_p, M_c \) and \( f_m \) are in solar masses, \( x \) is in light-seconds and \( P_b \) in days, then

\[
x = 9.766 \sqrt{f_m P_b^2}.
\]

Fig. 2 shows an example of one of the best fits to the data, for \( P_b = 8578 \) d, \( f_m = 10 M_\odot \). Note that the data span occupies only about 20 per cent of the orbit. Remarkably, the root mean square (rms) of the frequency residuals (the differences between the measured and model frequency values) for this simple model was only approximately \( 10^{-5} \) of the total frequency variation during this time and is consistent with the measurement errors.

For each \( P_b, f_m \) pair, the ephemeris resulting from the frequency fit was subsequently used as the basis of a coherent timing analysis of the TOAs using TEMPO2. Keeping \( P_b \) and \( x \) at their fixed values, the three other Keplerian parameters, the pulsar position, DM and its first derivative, DM1, the rotation frequency and its first derivative, and three glitch parameters were all fitted to the TOAs. Fig. 3 summarizes the results of the fits. In particular, Fig. 3(a) shows
the rms of the timing residuals relative to the fitted model as a function of $P_b$ and $f_m$. There is a broad minimum in the rms with a value of about 0.6 ms for $7500 \text{ days} < P_b < 9500 \text{ days}$ and all values of $f_m \geq 5 \text{ M}_\odot$ provide indistinguishably good fits. Best-fitting models were obtained for $f_m = 10 \text{ M}_\odot$ and $f_m = 20 \text{ M}_\odot$ by including a fit for $P_b$, and the results are given in Table 1, columns 4 and 5. Because of the strong covariance between some of the parameters, we used a Monte Carlo method to estimate the errors in the fitted parameters that are given in the table. The Monte Carlo analysis used simulations of the pulsar observations seeded with the best-fitting parameter file. The simulated data sets had the same epochs of the combined LAT and radio TOAs, giving the same cadence and orbital coverage as the real data. A noise source was added to the data, defined by the power spectral density

$$P(f) = P_w + A \left( 1 + \left( \frac{f}{f_c} \right)^{\alpha} \right)^{-\frac{\nu}{2}} ,$$

where the white noise, $P_w = 6.5 \times 10^{-24} \text{ yr}^{-3}$, and the power-law parameters are $A = 9 \times 10^{-20} \text{ yr}^{-3}$, $f_c = 0.2 \text{ yr}^{-1}$ and $\alpha = -4$. The noise parameters were chosen to match the observed noise spectrum. The TOASIM plugins from TEMPO2 were used to generate $10^6$ realizations of the noise and the full fitting process was applied to each realization. The error estimates were determined from the variance of the resultant fit parameters.

Fig. 1(e) shows the timing residuals for the binary fit for $f_m = 10 \text{ M}_\odot$ given in Table 1, column 4, showing that the rms is almost entirely limited by measurement errors, with any remaining unmodelled systematic trends at a level that is comparable with those from pulsars of a similar age. We note that these binary models involve the fitting of 14 free parameters to achieve an rms residual of 0.57 ms. This is one parameter fewer than required for the timing-noise model with similar rms residuals that is presented in Fig. 1(c) and Table 1, and based upon a 7-derivative polynomial model, achieving an rms residual of 0.53 ms. Fig. 1(d) shows the residuals based upon a 6-derivative timing-noise model that has the same number of fitted parameters as the binary model and is clearly a poorer description of the data.

We conclude that there is a range of simple binary models that describe the TOA data very well. It is also clear that the reason we cannot define the orbit more precisely at present is that, because the data span covers only about 1/5 of an orbit, the differences between the models are buried within the measurement errors of the TOAs and likely timing noise.

However, Figs 3(b)–(f) show that the values of many of the fitted parameters do not change much near the rms residual minimum. For all the models near this minimum (Fig. 3a), the eccentricity increases from about 0.90 to 0.95 with increasing $f_m$ (Fig. 3c). However, the corresponding $T_0$ lies in a restricted range between MJD $58150$ and $58200$ (Figs 3b and 4). Thus, the next periastron passage will occur sometime during 2018 February or March. The intrinsic frequency derivative for all these models is about $-6(1) \times 10^{-13} \text{ s}^{-2}$ (Fig. 3d), corresponding to a characteristic age $\tau = \nu/2\delta$ of about 180 kyr, which is substantially greater than the (rapidly decreasing!) characteristic age of the pulsar in the young-isolated-pulsar model, which has changed from $\sim 120$ to $\sim 55$ kyr over the six years. The values of right ascension $\alpha$ and declination $\delta$ are not strongly model-dependent (Figs 3e and f) and are about $20^327^1\delta13(8)$ and $+41^27^2.36(10)$, consistent with the position of the Be star, MT91 213, which is at $20^327^1\delta137(18)$ and $+41^27^2.48(20)$,1 and which Camilo et al. (2009) considered, but rejected, as a possible companion of the pulsar. The conflicting conclusion of that study with this paper arose from their assumption of a circular orbit, and the happenstance that their observations were conducted near apastron, where the gravitational influence of the companion on the pulsar is small, so that Doppler effects result in a small value of the pulsar second rotational frequency derivative.

1 Owing to a typographical error, Camilo et al. (2009) listed the last digits of declination of MT91 213 as 24.28; the correct value is 24.48 as used here.
also provide satisfactory fits to the data, they are inconsistent with a companion that has the mass of MT91 213.

Two other pulsar/Be-star binary systems are known, PSR B1259-63/SS 2883 (Johnston et al. 1992) and PSR J1638−4725 (Lorimer et al. 2006; Lyne 2008), having orbital periods \( P_b \) of 1237 d and 1941 d, respectively, and companion masses \( M_c \) of \( \sim 4 \) and \( \sim 8 \) M\(_{\odot}\). The PSR J2032+4127/MT91 213 system is more extreme than either of these, with \( P_b \sim 9000 \) d and \( M_c \sim 15 \) M\(_{\odot}\). Fig. 5 shows the most likely orbital configuration. The pulsar is presently on the Earth side of the Be star and is beginning to move rapidly in towards periastron, after which it will move behind the star and any circumstellar disc. Such stars have substantial stellar winds and, in the cases of both PSR B1259−63 and PSR J1638−4725, as well as radio eclipses, there are increases in both DM and multi-path scattering close to periastron, which arise as the pulsar becomes more embedded in the dense circumstellar environment. No significant change has yet been detected in the scattering or DM of PSR J2032+4127, with the fitted values of its first derivative DM1 consistent with zero (Table 1), but it is still far from periastron and this is not unexpected. Following periastron in early 2018, the pulsar will move behind MT91 213 and may be eclipsed, at least in the radio, by its atmosphere or disc, depending upon the inclination of the orbit to the line of sight.

Such a large, long-period system is unique, but its existence and its survival of the velocity kick that the pulsar probably experienced when it was formed is perhaps not surprising, because of the deep gravitational well of the \( \sim 15\) M\(_{\odot}\) companion. The separation of the markers in Fig. 5 gives an indication of the orbital velocity, showing that, although the velocity at apastron is only a few km s\(^{-1}\), at periastron the velocity is in excess of 100 km s\(^{-1}\). It is a system that, unlike the majority of pulsars, did not quite become unbound after the neutron star formation.

In all the allowed binary models, periastron will occur in just over three-years time. Much of the degeneracy present in the fits will be resolved as periastron is approached. In particular, the rapid increase in slow-down rate during the next 1–2 years will establish the magnitude of the eccentricity and hence the stellar separation at periastron. All evidence indicates that MT91 213 is in the Cyg OB2 stellar association, which is located at a distance of 1.4–1.7 kpc, determined both by spectroscopic parallax and by VLBI (very long baseline interferometry) determination of the trigonometric parallax of masers associated with the association stars (Massey & Thompson 1991; Hanson 2003; Rygl et al. 2012); in the binary hypothesis, this is therefore also the distance of PSR J2032+4127. We note that, at this distance, the projected major axis of the pulsar binary orbit will subtend about 25 mas viewed from the Earth. It should be possible to track the pulsar around the orbit using a VLBI network such as the VLBA or the EVN, hence establishing the size and the projected eccentricity of the orbit. Together with timing measurements, such observations permit the direct determination of the inclination \( i \) of the orbit to the plane of the sky and the distance of the system from the Earth.

The spin-down luminosity of PSR J2032+4127 in the binary models presented here is \( \dot{E} = 1.7 \times 10^{35} \) erg s\(^{-1}\), 62 per cent of the Camilo et al. (2009) isolated-pulsar value. The efficiency in converting rotational kinetic energy to \( \gamma \)-ray luminosity \( \dot{L}_{\gamma} \), \( \eta \equiv L_{\gamma}/\dot{E} \), is therefore increased by a factor of 1.6. Using the distance of 1.4–1.7 kpc and the updated \( L_{\gamma} \) from Abdo et al. (2013), and assuming as usual an isotropic \( \gamma \)-ray beam, then \( \eta \approx 15–20 \) per cent, which is unremarkable for a young pulsar (the much higher value of \( \eta \) presented in Abdo et al. (2013) uses the DM-based distance of 3.7 kpc).
We also note that this system is still fairly young, the pulsar having a characteristic age of 180 kyr, and the Be star having a total lifetime of only a few million years, which needs to encompass the lifetimes of the pulsar progenitor star and of the pulsar itself.

The fact that PSR J2032+4127 is a member of a long-period binary system with a massive companion star means that we should revisit the interpretation of the spatially coincident extended TeV γ-ray and X-ray emission (Aliu et al. 2014). Kargaltsev et al. (2014) have recently shown that the similar system PSR B1259−63 exhibits variable extended X-ray emission that is located outside the binary system and is moving away. It may be that this is emission that is associated with a circumbinary shock which can be generated between the winds of a pulsar and a massive star (Bosch-Ramon et al. 2012). We also note that if the interpretation of the TeV emission extension is to do with the proper motion of the binary then the increased age will result in a reduced transverse velocity of less than 30 km s\(^{-1}\) compared to that derived by Aliu et al. (2014).

In conclusion, there is a restricted range of binary orbits that describe the observed timing data very well, and explain the extraordinary and unique growth in the observed rate of rotational slow-down. This and the coincidence of the precise positions of the pulsar and MT91 213 all point to the two stars comprising a neutron-star/Be-star binary system in the Cyg OB2 association. Near periastron, the pulsar may well become obscured in the radio by free–free absorption and by severe pulse scattering in the Be-star circumstellar wind and disc as it passes behind the star, in the same way as the Be star SS 2883 obscures PSR B1259−63 at periastron (Johnston et al. 1996). However, studies of PSR J2032+4127’s DM and rotation measure (RM) variations are likely to present a rare opportunity to study the density of the stellar wind, and any circumstellar disc and the magnetic field of the Be star. Although it may become obscured in the radio for a short while, it should be possible to track its rotation and orbit around periastron by observation in γ-rays. Close to periastron, the MT91 213 Be star may also display optical and/or X-ray variability as a direct result of its interaction with the pulsar. Even now MT91 213 displays X-ray variability (e.g. Rauw et al. 2014) and optical variability (e.g. Salas, Maíz Apellániz & Barbá 2014; see also Camilo et al. 2009), although these are not atypical of the intrinsic variability observed in other Be stars, and almost surely have nothing to do with the neutron star.

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Figure 5. Schematic diagram showing the approximate orbital motions of PSR J2032+4127 and its Be-star companion MT91 213 about their common centre of mass for the binary model given in Table 1, column 4 for \(f_m = 10 M_\odot\), projected on to the plane containing the line of sight and the major axis of the orbit. The inclination \(i\) of the plane of the orbit to the plane of the sky is assumed to be 60°. The markers are at 200-d intervals and indicate the time from periastron. The thick line shows the portion of the pulsar orbit covered by the observations reported here. The pulsar is moving counter-clockwise in the diagram and is currently (MJD 56912) on the near side of the Be star, and about 1300 d before periastron passage. Note that the orbital velocity is proportional to the separation of the markers, a 1000-light-second separation indicating a velocity of about 18 km s\(^{-1}\). The small ellipse near the origin shows the orbit of the Be star, assuming that it has a mass of 15 M_\odot and that the pulsar has a mass of 1.35 M_\odot. At an estimated distance of 1.7 kpc, the projected major axis of the pulsar orbit will subtend an angle of about 25 mas.
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