**XMM-Newton** and **NuSTAR** observations of the compact millisecond pulsar binary **PSR J1653–0158**

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(Received Sep 28, 2021; Revised June 14, 2022; Accepted June 14, 2022)

**ABSTRACT**

We have presented the first joint **XMM-Newton** and **NuSTAR** analysis of the millisecond pulsar (MSP) binary **PSR J1653–0158**. The 75-minute orbital period inferred from optical and gamma-ray observations together with the 1.97-ms pulsation in the gamma-rays indicate that this system is the most compact **Black Widow** MSP system known to date. The orbital period was not detected in the **XMM-Newton** and **NuSTAR** data, probably due to insufficient photon counts obtained in the observations. Fitting the joint X-ray spectrum of PSR J1653–0158 with a power law gives a photon index $\Gamma = 1.71 \pm 0.09$. The X-ray luminosity of the source in the $0.2-40$ keV band is deduced to be $1.1 \times 10^{31}$ erg s$^{-1}$, for an adopted distance of 0.84 kpc. We have shown that the broad-band X-ray spectrum can be explained by synchrotron radiation from electrons accelerated in the intra-binary shock, and the gamma-rays detected in the **Fermi** data are curvature radiations from electrons and positrons in the pulsar magnetosphere. Our kinematic analysis of the Tidarren systems PSR J1653–0158 and PSR J1311–3430 indicates that the two Tidarren systems are likely to have originated in the Galactic Disk.

**Keywords:** millisecond pulsars – binary pulsars – relativistic binary stars – shocks – gamma-ray sources – X-ray astronomy

1. **INTRODUCTION**

The **Fermi**-LAT source 4FGL J1653.6–0158 (=PSR J1653–0158) was proposed as a gamma-ray emitting millisecond pulsar (MSP) binary, when a variable X-ray and optical source with a 75-min periodicity was found within the gamma-ray positional uncertainty (Kong et al. 2014; Romani et al. 2014). The subsequent detection of a 1.97-ms pulsation in the gamma-ray band confirmed its nature as a MSP (Nieder et al. 2020). Compact MSP binary systems with binary periods as short as that of PSR J1653–0158 would have a low-mass semi-degenerate companion (see e.g. Bhattacharya & van den Heuvel 1991; Iben et al. 1997; Chen et al. 2013; Jia & Li 2014; Hui et al. 2018). The deduced mass of $\sim 0.014$ M$_\odot$ (Nieder et al. 2020) of the companion is above the critical mass limit $\sim 0.006$ M$_\odot$ for dynamically stable mass transfer (see e.g. Kiel & Taam 2013). With continuous ablation by the energetic particles and evaporation by the radiation from the MSP, the companion star may lose all its mass completely, leaving only an isolated MSP in the system (Kluźniak et al. 1988; Phinney et al. 1988; Ruderman et al. 1989; Faucher-Giguère & Kaspi 2006).

Compact MSP binaries exhibit two distinctive observational behaviors, by which they are classified into two groups, with names assigned after two spider families: the Redback (RB) and the Black Widow (BW) (see e.g. Chen et al. 2013; Roberts 2013). RBs are believed to be systems in the transition from/between accretion and rotation-powered phases. Their companions are mostly partially degenerate stars that are filling the Roche lobe or very close to filling the Roche lobe. The BW systems are characterised by the ablation of the highly degenerate companion. They are not powered by the accretion processes and therefore are not X-ray luminous. Although some compact MSP binaries can switch between being rotation powered and accretion powered (see...
e.g. Papitto et al. 2013), depending on the relative sizes of the companion stars and their Roche lobes, they would eventually become persistently rotation powered. These systems would resemble the BW systems if the companions fail to regain contact with their critical Roche surfaces. The currently known RB generally have companions with mass $M_c \gtrsim 0.1 M_\odot$ (see e.g. Hui & Li 2019), compact MSP binaries with companion mass $M_c \lesssim 0.05 M_\odot$ almost certainly belong to the BW group (see Fruchter et al. 1988; Stappers et al. 1996). Some studies (e.g. Chen et al. 2013) suggest that most RBs and BWs are descendants of different groups of systems, implying that the most of observed RB are unlikely to have evolved from the BW, despite that RB can switch off accretion permanently.

The detection of the millisecond gamma-ray pulsations in PSR J1653–0158 implies that the MSP is presently not accreting. The low luminosity of the X-rays, about $10^{31}$ erg s$^{-1}$, observed in the source (Kong et al. 2014) is consistent with no significant mass transfer within the system. This, together with the deduced low companion mass (Nieder et al. 2020), readily puts PSR J1653–0158 as a BW, with its pulsar emissions powered by the extraction of the rotational energy of the neutron star.

This paper reports the findings from a joint multi-wavelength timing and spectral analysis of the XMM-Newton, NuSTAR and Fermi observations of PSR J1653–0158. §2 presents the observational set-ups and §3 reports the temporal and spectral analyses. §4 discusses the results from the analysis. We adopted an intra-binary shock model to explain the observed broadband X-ray spectral properties, as well as a magnetosphere model (Takata et al. 2012) to explain the gamma-ray spectral behavior. The origin of PSR J1653–0158 and its related compact MSP binaries are also discussed.

2. OBSERVATIONS

2.1. NuSTAR

PSR J1653–0158 was observed by NuSTAR (Harrison et al. 2013a) on May 29, 2017 for about 102 ks (ObsID: 30201017002; PI: Kong). The data were processed with the NuSTAR Data Analysis Software NUSTARDAS (v1.9.6), using the calibration data from CALDB version 20200813. Procedures with standard parameters in the NuSTAR Data Analysis Software Guide were adopted to clean and filter the event lists. The calibrated and cleaned event lists were processed with the tool nupipeline following standard procedures. The HEASoft tool nuproducts were used to construct the response matrices for each of the two focal plane modules, FPMA/B, and to produce images, light curves, spectra of the source. The FPMA/B net counts were $\sim 118$ counts and $\sim 78$ counts, respectively.

In our analysis, the energy range was set to be 3–40 keV as there were almost no source photons above 40 keV. Images, light curves, and spectra of the target were derived from the data extracted from a circular region with a radius of 20 arcsec centered at the X-ray position of PSR J1653–0158. An annulus region with a width of 40 arcsec and an inner radius of 20 arcsec centered at the source were used to derive the background photons. The spectra of the source from FPMA and FPMB observations were rebinned such that there were at least 10 counts in each spectral bin.

2.2. XMM-Newton

PSR J1653–0158 was observed by XMM-Newton on March 09, 2017 (ObsID: 0790660101; PI: Kong). The total exposure time was 53 ks, with data obtained from the EPIC (European Photon Imaging Camera) MOS1, MOS2 and pn CCD detectors. We followed the data analysis procedure detailed in the Data Analysis Threads Version 7.0 provided by SAS v19.0. Due to the very low signal-to-noise ratio of MOS1 and MOS2 data, we only used pn data in this work. The pn camera has a good sensitivity below 3 keV, which compensates the lack of sensitivity of NuSTAR in low energies, hence provides an essential constraint for the soft X-rays in spectral analysis. The raw data (ODF) were processed to be used with xspec and epproc, respectively. To filter the EPIC event lists for flaring background, the 10–12 keV light curve was examined with the SAS tool evselect and filtered the flare by setting Rate Expression `'RATE<=0.4'`. The effective exposure time is $\sim 25$ ks after background flaring filtering. The cleaned event lists were then used to produce the light curves and spectrum. The radius of the source is chosen as $\sim 10$ arcsec, and an annulus region with a width of 30 arcsec and an inner radius of 15 arcsec centered at the source were used to derive the background photons. After background subtraction, the net counts for pn are $\sim 893$ counts.

2.3. Fermi-LAT

The Fermi-LAT data (the latest version, P8R3) from August 04, 2008 to March 19, 2021 (spanning over 150 months) were analysed using the Fermi tools. The on-source data was extracted from a region of 20° radius centred at the 4FGL J1653.6–0158 position, (RA, Dec) $= (253.408, -1.97667)$, with energies between 100 MeV and 300 GeV. The tracker in the front and back sections of all the events were included, from which we selected `evtype = 3` and filtered the data with an event class `evclass = 128` assuming PSR J1653–0158 ($= 4FGL J1653.6–0158$)

1 https://heasarc.gsfc.nasa.gov/docs/nustar/analysis/nustar_swguide.pdf

2 https://heasarc.gsfc.nasa.gov/docs/xmm/abc
as a point source. To avoid the gamma-ray contamination coming from the Earth’s albedo, photons with zenith angles smaller than 90° were selected. Furthermore, the selection was restricted to high quality data in the time intervals (i.e. choosing DATA_QUAL>0). Binned likelihood analysis was performed using the Fermi science tool gtlike. To eliminate the background distribution, a background emission model, which included the Galactic diffuse emissions (gll_iem_v07.fits) and the isotropic diffuse emissions (iso_P8R3_SOURCE_V3_v01.fits) given by the Fermi Science Support Center, was applied. To obtain the best-fitting spectral model for 4FGL J1653.6–0158, we applied the user contributed tool make4FGLxml.py that uses the spectral model from the 4FGL catalog (Abdollahi et al. 2020) to calculate the flux contribution of each source in the 10 MeV to 300 GeV energies is 4643.61.

3. TEMPORAL AND SPECTRAL ANALYSIS

3.1. Temporal Behavior

PSR J1653–0158 has an orbital period of 0.0519 d shown in the optical (Kong et al. 2014; Romani et al. 2014), gamma-ray (Nieder et al. 2020), and possibly X-ray (Kong et al. 2014) wavebands. In a previous X-ray study, the 75-min orbital period found in optical is marginally shown in the Chandra data (Kong et al. 2014). By using the larger collecting area of XMM-Newton, we investigated the X-ray modulation in detail. We also used NuSTAR to investigate the light curve in the hard X-ray region.

Fig. 1 shows the XMM-Newton folded light curves in the 0.2 – 10 keV band with the gamma-ray epoch $T_{\text{asc}} = $ MJD 56513.479171(8) and an orbital period of 0.0519447575(4) d measured from Fermi gamma-ray observations (Nieder et al. 2020). To show the broadband X-ray variability, we also plotted the NuSTAR folded light curve (3 – 40 keV). Furthermore, we plotted the hardness ratio (H/S) between hard X-rays (10 – 40 keV) and soft X-rays (3 – 10 keV). We found no evidence for the 75-min orbital modulation in either XMM-Newton or NuSTAR data.

The modulations in the light curves were assessed using the Lomb-Scargle periodogram (Lomb 1976; Scargle 1982). For the XMM-Newton normalized light curve, the Lomb-Scargle power at the 75-min orbital period corresponds to a 99% false alarm probability. A 3-σ upper limit of 24% for the amplitude was obtained by fitting a sinusoidal function of 75-min period. The false alarm probability is 3.7% and the 3-σ upper limit for the amplitude is 80% for the NuSTAR light curve. The hardness ratio light curve is shown in Fig 1, for completeness, and it does not show evidence of spectral variations.

3.2. Spectral Properties

![Figure 1](image_url)

**Figure 1.** The folded light curves, in normalised counts, of PSR J1653–0158 from XMM-Newton (0.2–10 keV) and NuSTAR (3–40 keV) observations. Orbital cycles with different energy bands and hardness ratio (10 – 40 keV/3 – 10 keV) are shown for clarity. The light curves do not show the 75-min orbital period.

3.2.1. X-ray

We used XSPEC version 12.11 to perform X-ray spectral fitting. Since both the NuSTAR and XMM-Newton observations were taken at similar epochs in 2017, we fitted the energy spectra from XMM-Newton, NuSTAR’s FPMA and FPMB observations simultaneously to increase the signal-to-noise ratio. We also performed some simple spectral fits of individual spectra and they show no significant flux and spectral changes.

We employed different in-built models in XSPEC to perform spectral fitting. Based on previous X-ray study (Hui et al. 2015), we first tried an absorbed simple power-law model. In order to fit the spectra from the three cameras (pn and MOS1/2) of XMM-Newton and the two cameras of NuSTAR simultaneously, cross-calibration factors were taken into account in all the spectral models. In general, the 0.2–40 keV X-ray emissions can be well described with an absorbed power-law model ($\chi^2 = 51.35$ for 66 degrees of freedom (dof)) without obvious emission and absorption features (Fig. 2). The best-fit absorption value is (8.85 ± 2.29) $\times 10^{20}$ cm$^{-2}$, consistent with the extinction $A_V = 1.06$ obtained from light curve modelling (Nieder et al. 2020), while the best-fit photon index is 1.71 ± 0.09. The unabsorbed 0.2 – 40 keV flux is $1.40^{+0.13}_{-0.12} \times 10^{13}$ erg cm$^{-2}$ s$^{-1}$, corresponding to an X-ray luminosity of $1.18 \times 10^{31}$ erg s$^{-1}$ at a distance of 0.84 kpc from optical modeling (Nieder et al. 2020).

Although an absorbed power-law model can provide a reasonable best-fit, we also investigated if neutron star thermal emission from PSR J1653–0158 contributes part of the X-
ray emissions (e.g. Kong et al. 2018). We included a non-magnetic neutron star atmosphere component in the absorbed power-law model (nsatmos model in XSPEC; Heinke et al. 2006). We fixed the mass of the neutron star to be 2.17 M⊙ (Nieder et al. 2020). Without losing generality, we adopted a value of 10 km as the radius of the neutron star (see Lattimer & Prakash 2001; Abbott et al. 2018). The effective temperature derived from the model is $7.99^{+4.02}_{-2.68} \times 10^3$ K and the unabsorbed flux in 0.2 – 40 keV is $6.27^{+0.35}_{-0.33} \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$, corresponding to a luminosity of $5.29 \times 10^{30}$ erg s$^{-1}$ for a distance of 0.84 kpc. The best-fitting parameters from both spectral models are presented in Table 1. We applied a likelihood ratio test to test the validity of an extra component. A ratio of 0.988 suggests that a simple power-law model is sufficient. Furthermore, we used F-test to investigate if the additional neutron star atmosphere component is significant. The F-test probability is 0.0186 indicating that the additional component is not statistically required.

3.2.2. Gamma-ray

For the GeV band, we divided the Fermi-LAT photon counts data into 8 energy segments to obtain the gamma-ray spectrum (see blue crosses in Fig 3). We fitted the gamma-ray spectrum of PSR J1653–0158 with a power-law and an exponential cutoff model:

$$
\frac{dN}{dE} = N_0 \left( \frac{E}{E_0} \right) ^ \Gamma \exp(-aE^b),
$$

(1)

where $N$ is the photon counts per unit time, unit area and $E$ is the photon energy, $N_0$ and $E_0$ are the normalization factors, $\Gamma$ is the spectral index and $a$ is the exponential factor. By setting $b = 2/3$ (an empirical value chosen for pulsars, see Abdollahi et al. 2020), $a = (8.4 \pm 0.74) \times 10^{-3}$ MeV$^{-2/3}$ and $\Gamma = 1.58 \pm 0.05$ were obtained. Note that the total flux is $F = (5.06 \pm 0.19) \times 10^{-8}$ photons cm$^{-2}$ s$^{-1}$.

4. DISCUSSION

4.1. Theoretical Interpretation for the High-energy Emissions

We present an analysis of the broad-band (0.2 – 40 keV) X-ray data of the compact BW PSR J1653–0158 obtained by XMM-Newton and NuSTAR. While the Chandra observation in the 0.3 – 8 keV energy band indicated a possible period of about 75 min (Kong et al. 2014), we found no clear modulation in the XMM-Newton and NuSTAR data. The null detection could be due to poorer photon statistics, as the point spread functions of XMM-Newton and NuSTAR are much broader than that of Chandra. The background contribution of the XMM-Newton and NuSTAR light curves is 27% and 52–65%, respectively. On the other hand, the background contribution is negligible (almost 0%) in the Chandra light curve.

![Figure 2](image.png)

Figure 2. Model fit to the XMM-Newton (0.2 – 10 keV) and NuSTAR (3 – 40 keV) spectra of PSR J1653–0158. The best-fitting model is an absorbed power-law with a photon index $\Gamma = 1.71$ (shown as the dark solid line).

Table 1. Spectral fits for PSR J1653–0158. Fluxes $F$ are from combined XMM-Newton and NuSTAR unabsorbed flux and a distance of 0.84 kpc is assumed in calculations.

| Model | $N_H (10^{20} \text{ cm}^{-2})$ | $\Gamma$ | $F_{0.2-40} (10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1})$ | $\chi^2$/dof |
|-------|---------------------------------|---------|-------------------------------------------------|--------------|
| Power-law | 8.85 $\pm$ 2.29 | 1.71 $\pm$ 0.09 | 1.40$^{+0.13}_{-0.12}$ | 0.78/66 |
| Power-law + H atmosphere$^a$ | 24.38 $\pm$ 14.31 | 1.60 $\pm$ 0.15 | 7.99$^{+4.02}_{-2.68}$ | 6.27$^{+0.35}_{-0.33}$ | 0.71/64 |

Note—$^a$ The mass and radius of the neutron star were fixed to be 2.17 M⊙ (Nieder et al. 2020) and 10 km, assuming a distance of 0.84 kpc.

Although a composite model, consisting of a power-law and a neutron star atmosphere component, fits the X-ray spectrum (up to about 40 keV) of PSR J1653–0158 well, a single component absorbed power-law model is sufficient. The parameters of $\Gamma = 1.71 \pm 0.09$ and $N_H = (8.86 \pm 2.29) \times 10^{20}$ cm$^{-2}$ obtained from the absorbed power-law fit is consistent with those obtained in the previous analysis of Chandra observation (Kong et al. 2014; Romani et al. 2014). The photon index
Optical light curve modeling must include a non-thermal veiling modulation and flat orbital minima in the blue colors. The existence of the ablating wind can also be inferred by optical observations, as indicated by the decreasing modulation and flat orbital minima in the blue colours. Optical light curve modeling must include a non-thermal veiling flux component which could be explained by synchrotron emission from an intra-binary shock (Romani et al. 2014; Nieder et al. 2020).

We considered an intra-binary shock and a magnetosphere model (Takata et al. 2012) to explain the general spectral behavior in the X-ray and gamma ray bands. This intra-binary model was previously applied to explain the broad-band high-energy spectrum of the RB system PSR J2129–0429 (Kong et al. 2018), which has a non-degenerate companion star. In PSR J2129–0429, the intra-binary shock has a momentum ratio of $\eta_b \approx 7$ (where $\eta_b$ is the ratio between the stellar magnetic pressure and the ram pressure of the pulsar wind). As the stellar wind dominated the flow, the intra-binary shock wrapped around the pulsar. In this study, we considered that the intra-binary shock in PSR J1653–0158 was produced by the collision of an isotropic pulsar wind with an envelope of material ablated from a white-dwarf companion.

### Table 2. Physical Parameters of PSR J1653–0158 and the other Tidarren systems

| Source                  | $D$ (kpc) | $P$ (ms) | $L_X$ ($10^{31}$ erg s$^{-1}$) | $L_{sd}$ ($10^{33}$ erg s$^{-1}$) | $P_{\text{orb}}$ (day) | $M_{\text{com}}$ ($M_\odot$) | $M_{\text{NS}}$ ($M_\odot$) | DM (pc cm$^{-3}$) |
|-------------------------|-----------|----------|--------------------------------|---------------------------------|------------------------|-----------------------------|-----------------------------|------------------|
| PSR J1653–0158          | 0.84$^a$  | 1.97     | 1.18                           | 4.4                            | 0.052                  | 0.013                       | 1.62                        | –                |
| PSR J0636+5129          | 0.5$^b$   | 2.8      | 4.48$^c$                       | 5.6                            | 0.066                  | 0.0068                      | –                           | 11.1             |
| PSR J1311–3430          | 1.4$^d$   | 2.56     | 5.6                            | 49                             | 0.065                  | 0.011                       | 1.53                        | 37.8             |

Note—$^a$ The distance of 840 ± 40 pc is obtained from optical modelling (Nieder et al. 2020).

### Table 3. Location and kinetics of PSR J1653–0158 and the other Tidarren systems

| Source                  | $R_\odot$ (kpc) | $l$ (deg) | $b$ (deg) | $z$ (kpc) | $\mu_\alpha$ (mas yr$^{-1}$) | $\mu_\delta$ (mas yr$^{-1}$) | $V_r$ (km s$^{-1}$) | Ref |
|-------------------------|-----------------|----------|-----------|-----------|-------------------------------|-----------------------------|---------------------|-----|
| PSR J1653–0158          | 7.28            | 16.61    | 24.93     | 0.36      | $-19.62 \pm 1.86$             | $-3.74 \pm 1.12$            | $-174.6 \pm 5.1$     | $a$ |
| PSR J0636+5129          | 8.46            | 163.91   | 18.64     | 0.16      | $3.22 \pm 0.03$               | $-1.61 \pm 0.06$            | –                   | $b$ |
| PSR J1311–3430          | 6.89            | 307.68   | 28.17     | 0.79      | $-6.8 \pm 0.6$               | $-3.5 \pm 0.8$             | $62.5 \pm 4.5$       | $c$ |

Note—$a$ Romani et al. (2014); Nieder et al. (2020); $b$ Stovall et al. (2014); Guillot et al. (2019); $c$ An et al. (2017); Romani et al. (2012)

The definitions of the symbols are $R_\odot$: Distance to Galactic center, adopting the distance from the Sun to the Galactic centre $R_0 = 8$ kpc (Camarillo et al. 2018); $l$: Galactic longitude; $b$: Galactic latitude; $z$: Distance to the Galactic plane; $\mu_\alpha$, $\mu_\delta$: Proper motions in right ascension and declination; $V_r$: mean radial velocity of the binary system.

The reference is: $^a$ Romani et al. (2014); $^b$ Stovall et al. (2014); $^c$ An et al. (2017); Romani et al. (2012).
The intra-binary shock accelerated the electrons and positrons to relativistic energies and they emitted synchrotron X-rays. Different to PSR J2129–0429, the intra-binary shock in PSR J1653–0158 was located closer to the white-dwarf companion and wrapped around it. We adopted a magnetization parameter $\sigma = 0.1$, for the ratio of the magnetic energy and kinetic energy of the pulsar wind, and a momentum ratio $\eta_b \approx 0.7$ in the model to fit the X-ray spectra of PSR J1653–0158. The pulsar wind carried out the spin-down power and was compressed by the shock. The shock provided a mean to accelerate the charged electrons to relativistic energies, which emitted the synchrotron X-rays. Fig. 3 shows the X-ray intra-binary model (dashed line) fit to the observed broad-band X-ray spectrum.

The observed gamma-rays are not emitted from the high-energy electrons associated with the shock but are instead produced by the energetic charged particles in the pulsar magnetosphere (Cheng et al. 1986; Dyks & Rudak 2003; Watters et al. 2009). They are curvature radiation from relativistic electrons and positrons created through pair processes in the pulsar magnetosphere. This scenario provides an explanation to the double-peak features observed in the gamma-ray light curves of MSP binaries (e.g. Huang et al. 2012; Li et al. 2014).

We applied a three-dimensional two-layer outer gap model of Wang et al. (2011) to calculate the gamma-ray spectrum of PSR J1653–0158. We estimated, from the spin period and the surface magnetic field, that the thickness of the outer gap is about 60% of the light cylinder radius. This indicates that the large fraction of the volume in the outer magnetosphere is occupied by the outer gap. We considered that the outer gap exists between the null charge surface of the Goldreich-Julian charge density and the light cylinder. This would produce a pulse profile consistent with the broad pulse profile as observed and also the high-efficiency ($L_\gamma/L_{sd} \sim 66\%$) in the GeV energies (see Nieder et al. 2020). We assumed a value for the electric current corresponding to $\sim 50\%$ of Goldreich-Julian density and calculated the electric field along the magnetic field line. Fig. 3 shows the spectrum of the curvature gamma-rays produced by our model$^3$, together with the Fermi data.

4.2. **Origin of PSR J1653–0158**

We showed all spider MSP systems which has the characteristic eclipsing light curve in the Galactic field in Fig. 4. The RBs and BWs are distinguished by their companion mass, whereas the subclass Tidarren (Tid) is distinguished from the main BW class by their companion mass as well as orbital period. The $p$-values resulting from the two-sample Kolmogorov-Smirnov (KS) tests between Tid and BW are $2.7 \times 10^{-3}$ for mass and $5.4 \times 10^{-4}$ for period, indicating the differences between the two classes.

PSR J1653–0158 and two other compact MSP systems, PSR J0636+5129 and PSR J1311–3430 (see Draghan & Romani 2018; van Haafken et al. 2012; Romani et al. 2015; Spiewak et al. 2018), are known as the Tidarren (Romani et al. 2016). As a subclass of the BW systems, they have a very low mass companion star and extremely short orbital period (Romani et al. 2016), and their properties are shown in Table 2. The companion stars in the Tidarren systems have strongly heated sides facing the pulsar. This leads to periodic variations in the optical emissions of the system, providing us a mean to derive the orbital velocities of the companion stars (see e.g. Draghan et al. 2019; Kandel et al. 2019). The companion stars of the Tidarren systems have an extremely low mass. Their hydrogen is almost completely stripped, and hence they often appear as helium WDs. The Tidarren systems are therefore more likely to be the progenitors of isolated MSPs than the other subclass of MSP binaries.

The formation of eclipsing MSP systems in the Galactic field is thought to undergo the recycled process similar to the evolution of CV-like LMXBs (Chen et al. 2013; Ginzburg & Quataert 2021). The bimodal distribution of the RBs and BWs can be explained by different evaporation efficiency. However, none of the evolution tracks can match the observed quantities of the Tidarren systems. A different formation mechanism is proposed by King et al. (2003, 2005) that a MSP-WD binary is originally formed in the globular clusters (GC) and exchange its companion to a main-sequence star and subsequently ejected to the Galactic field or entered the

$^3$GeV gamma-rays can be produced in the pulsar magnetosphere when low-energy photons are Compton up-scattered by relativistic electrons and positrons (see e.g. Grenier & Harding 2015).
field populations when their host GCs dissociated (Gnedin & Ostriker 1997). Therefore, We assessed the possibilities of Tidarren origin by comparing the trajectories of the two systems with the distributions of binaries populations from the Galactic Disk or GCs.

All the known Tidarren systems are located at substantial Galactic latitude (with $|b| > 12$ deg). From their measured distances to Earth, we determined their vertical distances to the Galactic plane $z$. The $z$ of all Tidarren systems are larger than the scale height of the Galactic Thin Disk ($\sim 0.12$ kpc), and two of them, PSR J1653–0158, PSR J1311–3430, have $z$ larger than the scale height of the Galactic Thick Disk ($\sim 0.3$ kpc; de Jong et al. 2010; Jurić et al. 2008). Adopting the distance from the Sun to the Galactic centre $R_0 = 8$ kpc (see Eisenhauer et al. 2003; Francis & Anderson 2014; Vallée 2017; Camarillo et al. 2018; Griv et al. 2021), we derived the distances of all known Tidarren systems to the Galactic center $R_C$ in Table 3. The values of their $R_C$ are about 6.6–8.5 kpc, larger than 2 kpc, the radius of the Galactic bulge (see Zoccali & Valenti 2016). We therefore conclude that the currently known Tidarren systems are not in the Galactic bulge or in the Galactic Thin Disk. A possible explanation for the spatial locations of the Tidarren systems is that they originated from globular clusters (GCs). To examine the scenario that the Tidarren systems were produced in GC, we first compared the population of BWs and binary MSP in GC and in the field. The current version of ATNF Pulsar Catalogue$^4$, listed 64 GC binary MSPs and 163 field binary MSPs, and a recent study by Hui & Li (2019) listed 17 BWs in GC and 29 BWs in field. This gives a ratio of 0.26 for BWs among binary MSPs in GC and 0.16 for BWs among binary MSPs in the field, consistent with that BWs have no preference to reside in a GC (cf. King et al. 2003).

Among the three systems listed in Table 3, PSR J1653–0158 and PSR J1311–3430 have both mean radial velocity and proper motion measurements. The orbits of these systems in the Milky Way can therefore be computed. We used ga1py (Bovy 2015)$^5$ to track back the orbit of them in the past 1 Gyr.

Fig. 5 shows the orbits of PSR J1653–0158 and PSR J1311–3430 and binary populations from Galactic Thin Disk or GC on the $\log R_g-Z_g/R_g$ plane, where $R_g$ is the radial distance from the Galactic Centre, $Z_g$ is the $z$ component of Galactocentric Cartesian coordinate and $Z_g/R_g = \cos \theta$ where $\theta$ is the polar angle. The time-averaged absolute values of the Galactic latitude ($\langle |b| \rangle_t$) is 2.5$^\circ$ for PSR J1653–0158 and 3.7$^\circ$ for PSR J1311–3430. This gives the time-averaged absolute distances ($\langle |z| \rangle_t$) of 0.3 kpc to the Galactic plane for PSR J1653–0158 and of 0.45 kpc for PSR J1311–3430. The time-averaged distances to the Galactic centre is 9.7 kpc for PSR J1653–0158 and 8.4 kpc for PSR J1311–3430. As their distances to the Galactic Centre are larger than 2 kpc, PSR J1653–0158 and PSR J1311–3430 are unlikely associated with the Galactic bulge stellar population. The binary populations in Fig. 5 are obtained as follows. We used Monte Carlo (MC) methods to sample the binary populations from the Galactic Thin Disk, where the thin disk assumes a scale height of 0.12 kpc (Rix & Bovy 2013) and a scale length of 4.0 kpc (de Jong et al. 2010), in the panel A of Fig. 5. The GC populations in panel B was read directly from the Harris (1996) catalogue (2010 edition). Only position information of these populations are shown in panels A and B, and no orbital integration were preformed.

For panels C and D, we made further assumptions about the initial velocities for these binaries populations, and also about the kick velocities they received. We sampled $N = 10^5$ systems from the Galactic Thin Disk and $N = 10^5$ systems from GCs and performed orbital integration of those systems and calculated their time-averaged $R_g$ and $Z_g$.

$^4$ http://www.atnf.csiro.au/research/pulsar/psrcat

$^5$ ga1py can be downloaded from http://github.com/jobovy/galpy.
For panel C, the binary population from the Galactic Thin Disk, their initial velocities on the plane before kicks were calculated following the rotation curve from (Sofue 2017), and the vertical velocity was assumed to be 0. The Maxwellian distribution of the kick velocity is characterised by $\sigma_v = 200$ km s$^{-1}$, appropriate for the kick received by the binary in the supernova explosion that produced the neutron stars.

For the binary population from GCs in panel D, the initial 3D velocity follows a Maxwellian distribution (d.o.f=3). The parameter which determines the distribution was calculated by $\sqrt{3} a_1$, where $a_1 = 75.33$ km s$^{-1}$ is the parameter obtained by fitting the radial velocities of GCs with a Maxwellian distribution (d.o.f=1). We added small kicks with velocities following a Maxwellian distribution with $\sigma_v = 50$ km s$^{-1}$, corresponding to the recoil velocity of the system when leaving the GC. All the kick velocities are isotropic (evenly distributed over $4\pi$ solid angle) in the rest frame of the binaries.

The trajectories of PSR J1653–0158 and PSR J1311–3430 tend to coincide with systems of Galactic Disk origins rather than systems of GC origins. For the cases with position information only (without orbital integration), the trajectories of the two systems are consistent with systems of Galactic Disk and GC populations. When the kinetic of the systems of the two populations are properly accounted for, the trajectories of PSR J1653–0158 and PSR J1311–3430 are consistent with the expectations from the systems associated with the Galactic Disk but inconsistent with the systems associated with GCs. This can be understood as follows. The velocities of the population of systems from the Galactic Disk are jointly determined by their rotational motion around the Galactic centre and their kick velocity. Among the two velocities, the rotation component do not affect the time-averaged positions of the systems during orbital integration, and it also dilutes the effects brought by the kick velocity. For the population of systems from GCs, the kick velocity is relatively small, and the movements were determined by the (3D) velocities of GCs. In our calculations, the velocities of GCs were derived from radial velocities provided by the GC catalogue, and a significant fraction of the systems have relatively large radial velocities in Galactocentric coordinate. This introduces substantial scatters towards larger $R_\odot$ in the distribution, which is at odd to the expected locations of PSR J1653–0158 and PSR J1311–3430 from their computed past trajectories. In summary, our kinematic analyses have shown that PSR J1653–0158 and PSR J1311–3430 are more likely to have originated from the Galactic Disk rather than GCs.

5. CONCLUSION

We presented a broadband timing and spectral analysis of the BW MSP binary PSR J1653–0158 using XMM-Newton,
**NSR J1653** was not statistically significant. 

Gamma-rays are produced by curvature radiation from energetic charged particles in the pulsar magnetosphere. The intra-binary shock is formed when the pulsar wind collides with the media ablated from the semi-degenerate companion, and the synchrotron X-rays are emitted from the electrons accelerated by the shock. The gamma-rays are produced by curvature radiation from energetic charged particles in the pulsar magnetosphere.

The origin of **NSR J1653** and its similar systems were discussed. We grouped the BW systems with extremely low mass companion star and extremely short orbital period as the Tidarren systems and conducted an analysis of their spatial location in the Milky Way and their kinetic properties. We found that these Tidarren systems have radial distances $R_C \sim 6.6$–8.5 kpc to the Galactic center and vertical distances $z \sim 0.16$–0.79 kpc to the Galactic plane, implying that they are not currently located in the Galactic bulge or the Galactic Thin Disk.

The possibilities that the two Tidarren systems originated from Galactic Disk or GCs were assessed using their computed past trajectories of the Galactic Centre. **NSR J1653** had a radial distance of $9.7$ kpc from the Galactic Centre and a time-averaged distance of $0.3$ kpc from the Galactic plane. **NSR J1311–3430** had a time-averaged distance of $8.4$ kpc to the Galactic Center and a time-averaged distance of $0.45$ kpc from the Galactic plane. We further conducted a more detailed kinematic analysis of the populations of similar compact binaries, assuming origins from the Galactic Disk and GCs. Comparing their distributions with the computed past trajectories of **NSR J1653** and **NSR J1311–3430** suggests that the two Tidarren systems are likely to have originated in the Galactic Disk.

**ACKNOWLEDGEMENTS**

We thank the referee for the critical comments and useful suggestions that led to substantial improvement of the science of this work. This work is supported in part by the Ministry of Science and Technology of Taiwan (ROC) under the grants 109-2628-M-007-005-RSP and 110-2628-M-007-005 (PI: A. Kong). KW is supported in part by a UK STFC Consolidated Grant to UCL-MSSL. JT acknowledges the support by National Key R&D Program of China, 2020YFC2201400, NSFC U1838102. CYH is supported by the National Research Foundation of Korea through grants 2016R1A5A1013277 and 2019R1F1A1062071. KLL is supported by the Ministry of Science and Technology of Taiwan (ROC) through grant 109-2636-M-006-017, and by the Ministry of Education of Taiwan (ROC) through a Yushan (Young) Scholarship. Analyses conducted by QH at UCL-MSSL were supported by a UCL Overseas Research Scholarship and a UK STFC PhD Studentship. This work has made use of NASA’s Astrophysics Data System and the CSIRO ATNF Pulsar Catalogue (Manchester et al. 2005). The updated list of eclipsing spider MSP binaries in the Galactic field is provided by Jane Yap.

**Software:** XSPEC (v12.11; Arnaud (1996)), SAS (v19.0; Gabriel et al. (2004)), NUSTARDAS (v1.9.6; Harrison et al. (2013b)), Fermi tools (Fermi Science Support Development Team 2019), make4FGLxml.py, galpy (Bovy 2015)

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