A NuSTAR Observation of the Gamma-Ray Emitting Millisecond Pulsar PSR J1723–2837

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Abstract

We report on the first NuSTAR observation of the gamma-ray emitting millisecond pulsar binary PSR J1723–2837. X-ray radiation up to 79 keV is clearly detected, and the simultaneous NuSTAR and Swift spectrum is well described by an absorbed power law with a photon index of ~1.3. We also find X-ray modulations in the 3–10, 10–20, 20–79, and 3–79 keV bands at the 14.8 hr binary orbital period. All of these are entirely consistent with previous X-ray observations below 10 keV. This new hard X-ray observation of PSR J1723–2837 provides strong evidence that the X-rays are from the intrabinary shock via an interaction between the pulsar wind and the outflow from the companion star. We discuss how the NuSTAR observation constrains the physical parameters of the intrabinary shock model.

Key words: binaries: close – pulsars: individual (PSR J1723–2837) – X-rays: binaries

1. Introduction

Thanks to the combined effort of continuous γ-ray all-sky observation and radio pulsation searches, the population of millisecond pulsars (MSPs) has expanded significantly in the recent years (see the review by Hui 2014). Among these newly discovered MSPs, one interesting new class that is usually referred as “redbacks” has emerged. They are characterized by their nondegenerate companions, with the mass ranges from ~0.2 M⊙ to ~0.7 M⊙, and with the orbital period P_b ≤ 20 hr (see Roberts 2013 for a review).

The first discovered redback MSP PSR J1023+0038 has provided us with the long-sought evidence of a compact binary transiting from an accretion-powered state to a rotation-powered state (Archibald et al. 2009). Theoretical models (Shvartsman 1970; Buder et al. 2011) have also suggested that these systems can swing between the rotation-powered and accretion-power states according to the mass transfer rate. Such behavior was also first seen in PSR J1023+0038 with the disappearance of radio pulsations (Stappers et al. 2014; Patruno et al. 2014); a newly formed accretion disk (Halpern et al. 2013); and the dramatic increase of UV, X-ray, and γ-ray emission (Li et al. 2014).

In this investigation, we focus on another redback, MSP PSR J1723–2837. Its spin period and spin-down rate are \( P \approx 1.86 \) ms and \( \dot{P} \approx 7.5 \times 10^{-21} \) s s\(^{-1}\), respectively (Crawford et al. 2013). This implies a spin-down power of \( \dot{E} \approx 4.6 \times 10^{34} \) erg s\(^{-1}\). Its distance that is inferred from the dispersion measure is \( d \approx 750 \) pc, which makes it the closest redback found in the Galactic field so far.\(^7\)

PSR J1723–2837 is in a binary orbit with a period of \( P_b \approx 14.8 \) hr. Its companion is a G-type star companion with the mass in a range of 0.4–0.7 M⊙ (Crawford et al. 2013). The orbit is almost circular with the projected semimajor axis of \( a \approx 1.23 \) lt-s. The interval of radio eclipse has covered ~15% of the orbit (Crawford et al. 2013). Through a long-term optical photometry of PSR J1723–2837, van Staden & Antoniadis (2017) found that the companion and the pulsar are not tidally locked.

No γ-ray counterpart of PSR J1723–2837 was found in the second Fermi point source catalog (2FGL; Nolan et al. 2012). Hui (2014) searched for the γ-ray emission from PSR J1723–2837 with ~3 yrs of Fermi data and found a possible counterpart of ~6σ at the pulsar position. While this source is not in the 2FGL catalog, an unidentified source (1FGL J1725.5–2832 in the first Fermi catalog; Abdo et al. 2010) is found in the proximity of the pulsar (see Figure 3 in Hui 2014). Since it is ≤ 1° away from the pulsar and its γ-ray properties are consistent with those found by Hui (2014), the author suggested that 1FGL J1725.5–2832 is the same γ-ray source associated with PSR J1723–2837. In the latest third Fermi catalog (Acero et al. 2015), a source, 3FGL J1725.1–2832, was also found to be associated with 1FGL J1725.5–2832, and its flux and spectrum are fully consistent with the possible gamma-ray counterpart of PSR J1723–2837.

Hui (2014) also examined the X-ray properties of PSR J1723–2837 with XMM-Newton and Chandra. They have discovered the orbital modulation in 0.3–10 keV with the minimum coincides with the phase interval of radio eclipses. Its phase-averaged X-ray spectrum is purely nonthermal and can be modeled by a simple power law with \( \Gamma \approx 1.2 \). Significant spectral variation across the orbit was not found in this investigation. The authors have discussed the X-ray properties in the context of an intrabinary shock model. Assuming a synchrotron origin of the X-rays, Hui (2014) speculated if typical synchrotron energy is larger than ~10 keV. However, this scenario could not be examined in their work because both XMM-Newton and Chandra cannot provide spectral imaging data in the hard X-ray band.

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\(^{7}\) For updated information, please refer to https://apatruno.wordpress.com/about/millisecond-pulsar-catalogue/.
In this paper, we report a broadband X-ray analysis of PSR J1723–2837 with photon energies up to ∼79 keV using the data obtained from NuSTAR. This is also the second redback MSP observed with NuSTAR after PSR J1023+0038 (Li et al. 2014; Tendulkar et al. 2014).

2. Observations and Data Reduction

2.1. NuSTAR

PSR J1723–2837 was observed with NuSTAR (Harrison et al. 2013) between 2015 October 15–17 with an effective exposure time of ∼81 ks (ObsID 30101043002). We reprocessed the raw data with the NuSTAR Data Analysis Software (NuSTARDAS) v1.7.0 under HEAsoft version 6.20 and an updated NuSTAR calibration data (CALDB version 20170120). The calibrated and cleaned event files were produced with nuproducts. All the data products including images, light curves, X-ray spectra, and the corresponding response matrices were generated by the tool nuproducts.

We cleaned and filtered the events with the standard parameters suggested in the NuSTAR Data Analysis Software Guide. Both focal plane modules, FPMA and FPMB, were processed separately to extract the data products. In addition to standard processing, we also performed barycentric correction with the tool barycorr to the arrival times of all events based on the pulsar timing position at R.A. (J2000) = 17:23:23.1856, decl. = −28:37:57.17 (Crawford et al. 2013).

The X-ray counterpart of PSR J1723–2837 is clearly detected in both modules. Apart from PSR J1723–2837, a faint known X-ray source, 3XMM J172325.7−83631 (in 3XMM-DR6 catalog), is also detected at ∼1.5 arcmin northeast from PSR J1723–2837. This faint source is nearly a factor of 10 fainter than PSR J1723–2837.

To extract events for spectral and temporal analysis, we used data only in the range of 3–79 keV. We employed a circular region with a radius of 50 arcsec centered at the position of PSR J1723–2837. A circular source-free region on the same detector chip was used for background subtraction. The X-ray spectra of the source extracted from FPMA and FPMB were rebinned to have at least 30 counts per bin.

2.2. Swift

Three Swift snapshot observations with a total exposure time of about 5.3 ks were taken simultaneously with the NuSTAR observation. In this study, we use the imaging data taken with the X-ray Telescope (XRT) onboard Swift to constrain the soft (<3 keV) X-ray emission. We extracted the co-added X-ray spectrum (to improve the signal-to-noise ratio) and the corresponding response files by using the XRT products generator (Evans et al. 2007, 2009).

3. Data Analysis

3.1. Timing Analysis

PSR J1723–2837 is known to have a 14.8 hr X-ray orbital period using Chandra and XMM-Newton observations (Hui 2014). To search for the hard X-ray orbital modulation with NuSTAR, we combined the background subtracted light curves from FPMA and FPMB (Figure 1). In addition to the

3–79 keV light curve, we also extracted light curves from 3–10, 10–20, and 20–79 keV. Using the radio timing ephemeris (Crawford et al. 2013), we folded the barycentered events at the orbital period (Figure 2). The phase zero is defined as the time of the ascending node (MJD 55425.320466), which means that the inferior conjunction (when the companion star is between the pulsar and observer) is at phase 0.25. The orbital period is clearly shown in all energy ranges concerned. The profiles of the light curves are similar to that of Chandra and XMM-Newton (Hui 2014), and the minimum of the X-ray light curves (at phase ∼0.25) corresponds to the radio eclipse (Crawford et al. 2013). We also computed the ratios between different energy bands and there is no evidence of color variation throughout the orbital period (see Figure 2 for the flux ratio between 20–79 and 3–10 keV). We will show in Section 3.2 that the phase-resolved spectral fits of the minimum and maximum are statistically the same.

Furthermore, the X-ray light curves show a dipping feature on a timescale of about 3 hr in one occasion (see Figure 1). This feature happened in between the maximum and minimum of the light curve at the orbital phase of ∼0.9. To test the significance, we fit the light curve with a 14.8 hr sinusoidal plus a Gaussian centered at the dip. The addition of the Gaussian is significant at >99.9% level by using an F-test. We also checked the light curves in different energy bands and this feature may be seen in all bands, but it is statistically significant (>99.9%) only in the 3–10 keV band. For the other bands, the small numbers of photons do not allow us to claim a detection. The hardness ratio did not reveal any variability.

3.2. Spectral Analysis

We performed spectral analysis using XSPEC version 12.9.1. We first fit the phase-averaged spectrum with a simple absorbed power-law model. This is based on the fact that there isn’t an indication of any thermal emission from the 0.3–10 keV spectra (Hui 2014). To constrain the soft X-rays
below 3 keV (where NuSTAR is not sensitive), we performed a joint fit together with the simultaneous Swift/XRT data. We also included constants to take a cross-calibration between NuSTAR FPMA and FPMB and Swift/XRT into account. Figure 3 shows the broadband energy spectrum of PSR J1723–2837. The spectrum clearly extends up to about 70 keV without significant emission and absorption features and can be well described by an absorbed power-law model ($\chi^2 = 0.87$ for 289 degrees of freedom). The best-fit model parameters are $N_H = (3.9^{+2.3}_{-2.0}) \times 10^{21} \text{cm}^{-2}$ and $\Gamma = 1.28 \pm 0.04$. All quoted uncertainties in this paper are 90% confidence level. The best-fit $N_H$ is entirely consistent with the Galactic value ($\sim 4 \times 10^{21} \text{cm}^{-2}$; Kalberla et al. 2005). The unabsorbed 3–79 keV flux is $(9.6 \pm 0.5) \times 10^{-12} \text{ergs cm}^{-2} \text{s}^{-1}$, which corresponds to an X-ray luminosity of $(6.5 \pm 0.3) \times 10^{32} \text{ergs s}^{-1}$ ($d = 0.75 \text{ kpc}$).

We also fit the spectrum with a power-law model with a high-energy exponential cutoff. However, the fit was not significantly improved and the cutoff energy is unreasonably large (>300 keV). We therefore conclude that a simple power-law model is sufficient to describe the spectrum.

We next investigated two phase-resolved spectra covering the orbital phase of 0.2–0.4 and 0.7–0.9. These two phase ranges roughly correspond to the X-ray minimum (inferior conjunction) and maximum (superior conjunction), respectively. For the phase-resolved spectroscopy, we only used the NuSTAR data since the Swift observations do not have sufficient photons. We fixed the $N_H$ at the best-fit value determined from the phase-averaged spectrum. The best-fit $\Gamma$ is $1.32 \pm 0.12$ and $1.25 \pm 0.06$ for inferior and superior conjunction, respectively. Varying the $N_H$ within the 90% uncertainty gives consistent results. This shows that both spectra are statistically the same and are consistent with the phase-averaged spectrum. We conclude that there is no significant X-ray spectral variability throughout the binary orbit of PSR J1723–2837. The NuSTAR results are generally consistent with Chandra and XMM-Newton observations, but for the superior conjunction, the spectrum of NuSTAR is steeper than that of Chandra/XMM-Newton.

4. Discussion

We have investigated hard X-ray (3–79 keV) properties of the MSP binary PSR J1723–2837 with NuSTAR. The 14.8 hr binary orbital period of the system is clearly shown in hard X-ray (Figures 1 and 2) and the profile is similar to that seen in Chandra and XMM-Newton (Hui 2014). The broadband (0.3–79 keV) energy spectrum from the joint Swift and NuSTAR data show an absorbed power law with $\Gamma = 1.28$ and an X-ray (3–79 keV) luminosity of $6.5 \times 10^{32} \text{ergs s}^{-1}$. The NuSTAR results strongly support the nonthermal nature of the X-ray emission as already indicated in previous studies with Chandra and XMM-Newton (Hui 2014). To produce such a hard X-ray spectrum, it is suggested that the X-rays are from an intrabinary shock due to interaction between pulsar wind and outflow from the companion star (Li et al. 2014; Takata et al. 2014). This model also explains the X-ray orbital modulation naturally.

The NuSTAR result is not only consistent with previous results based on soft (<10 keV) X-ray data, but is also similar to the transitional redback MSPs PSR J1023+0038, PSR J1023+0038 is the first redback MSP observed with NuSTAR (Li et al. 2014; Tendulkar et al. 2014). During its rotation-powered state, PSR J1023+0038 shows a hard spectrum ($\Gamma = 1.2$) compared to a relatively soft ($\Gamma = 1.7$) spectrum seen in a low-mass X-ray binary state. The hard X-ray luminosity of the
two objects during their rotation-powered state is also the same. Interestingly enough, the GeV spectra of the two sources taken with Fermi are also very similar with a power-law photon index of ~2.5 (Hui 2014; Patruno et al. 2014; Takata et al. 2014). With the new information provided by NuSTAR, we explain the X-ray emission of PSR J1723–2837 with a revised intrabinary shock model.

The orbit-modulating X-rays of PSR J1723–2837 are likely produced by the intrabinary shock like other redback MSP binary such as PSR J1023+0038 (Li et al. 2014; Takata et al. 2014) and PSR J2339–0533 (Kong et al. 2012). The observed radio eclipse at several GHz lasts only 15% of its binary orbit, which suggests that the shock wraps the companion star and its distance from the pulsar is of order of the orbit separation, which is of order of a ~ 5 × 10^10 cm (Crawford et al. 2013). The magnetic fields at the shock may be estimated as B_0 ≈ (L_0 σ / 2π^2 c^2)^(1/2) ~ 7.8 G, where we used L_0 = 4.6 × 10^{44} erg s^-1, a = 5 × 10^{10} cm, and σ = 0.1 as the the ratio of the magnetic energy to the kinetic energy of the relativistic pulsar wind (Tam et al. 2017). At the shock, the kinetic energy of the pulsar wind is converted into the internal energy, and the pulsar wind particles are accelerated beyond the Lorentz factor of the cold relativistic pulsar wind in the upstream region. We may estimate the maximum Lorentz factor of the accelerated particle by balancing the accelerating timescale, τ_acc, and its distance from the pulsar is of order of the orbit separation.

\[ \tau_{\text{acc}} \sim \Gamma_{\text{max}} m_e c / (\xi B_0) \]  

where \( \xi < 1 \) is the efficiency of shock acceleration, and synchrotron cooling timescale, \( \tau_c \sim 9 m_e c^3 / (4e^2 B_0^2 \Gamma_{\text{max}}^5) \), which yields \( \Gamma_{\text{max}} \sim 4 \times 10^5 \xi^{1/2} (B_0 / 10 \text{ G})^{-1/2} \). These TeV electrons accelerated at the shock will produce the very high-energy photons by scattering off the soft photons from the internal energy, and the pulsar wind particles are accelerated at the shock will produce the very high-energy photons by scattering off the soft photons from the shock front via a clumpy pulsar wind or an outflow variation from the companion. For instance, if the outflow velocity from the companion has a sudden drop, the momentum ratio of the stellar wind and the pulsar wind will drop accordingly and result in a smaller fraction of the pulsar wind stopped by the outflow.

In summary, we found modulating X-ray radiation at the 14.8 hr binary orbit of PSR J1723–2837 up to 79 keV with NuSTAR. The energy spectrum is a simple power law with a photon index of ~1.3 and does not show evidence of spectral variability throughout the orbital cycle. Such radiation can be explained with an intrabinary shock model.

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Facilities: NuSTAR, Swift.

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