Swift, XMM-Newton, and NuSTAR Observations of PSR J2032+4127/MT91 213

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Abstract

We report our recent Swift, NuSTAR, and XMM-Newton X-ray and Lijiang optical observations on PSR J2032+4127/MT91 213, the γ-ray binary candidate with a period of 45–50 years. The coming periastron of the system was predicted to be in 2017 November, around which high-energy flares from keV to TeV are expected. Recent studies with Chandra and Swift X-ray observations taken in 2015/2016 showed that its X-ray emission has been brighter by a factor of ~10 than that before 2013, probably revealing some ongoing activities between the pulsar wind and the stellar wind. Our new Swift/XRT lightcurve shows no strong evidence of a single vigorous brightening trend, but rather several strong X-ray flares on weekly to monthly timescales with a slowly brightening baseline, namely the low state. The NuSTAR and XMM-Newton observations taken during the flaring and the low states, respectively, show a denser environment and a softer power-law index during the flaring state, implying that the pulsar wind interacted with the stronger stellar winds of the companion to produce the flares. These precursors would be crucial in studying the predicted giant outburst from this extreme γ-ray binary during theperiastron passage in late 2017.

Key words: pulsars: individual (PSR J2032+4127) – stars: individual (MT91 213) – stars: winds, outflows – X-rays: binaries

1. Introduction

Gamma-ray binaries are a subclass of high-mass X-ray binaries (HMXBs) that harbor a compact object (neutron star or stellar-mass black hole) and a massive O or Be companion emitting modulated γ-ray emission at GeV/MeV and even TeV energies (Dubus 2013). For those with a highly eccentric orbit of $e \gtrsim 0.8$, the periastron passage of the compact object (probably a neutron star in these cases as pulsar wind is usually required in modeling; see, e.g., Dubus 2013; Tam et al. 2015 and references therein) through the stellar wind and/or the Be circumstellar disk (if present) can trigger extraordinary flares seen from radio to TeV γ-rays (e.g., PSR B1259–63/LS 2883; Wang et al. 2004; Aharonian et al. 2005; Abdo et al. 2011; Moldón et al. 2011; Tam et al. 2011, 2015; Calandra et al. 2015; Chernyakova et al. 2015, and HESS J0632+057/ MWC 148; Acciari et al. 2009; Hinton et al. 2009; Skilton et al. 2009; Bongiorno et al. 2011; Casares et al. 2012).

PSR J2032+4127/MT91 213 (J2032 hereafter) is a strong γ-ray binary candidate with a high eccentricity. It was first discovered as a γ-ray and radio-emitting pulsar with the Fermi Large Area Telescope (Abdo et al. 2009) and the NRAO Green Bank Telescope (Camilo et al. 2009), respectively, and later identified as a binary system with further γ-ray and radio observations (Lyne et al. 2015). While J2032 was initially thought to be a binary with a long period of ~20 years, Ho et al. (2017) refined the binary model and suggested an even longer period of 45–50 years. According to their timing solutions, a strong radio/γ-ray pulsation at $P = 6.98$ Hz with a strong spin-down rate of $\dot{P} = 6 \times 10^{-13}$ s$^{-1}$ (spin-down luminosity: $\dot{E} \sim 10^{35}$ erg s$^{-1}$) was detected, showing that it is a young pulsar of a characteristic age of ~200 kyr. A $V = 11.95$ mag Be star, MT91 213 (a member of the Cyg OB2 stellar association; about 1.5 kpc from us) is found at the inferred pulsar’s position as the high-mass companion of the pulsar. The best-fit ephemeris shows that the next periastron of the binary will be in late 2017 (i.e., MJD 58069 in the Model 2 of Ho et al. 2017).

Ho et al. (2017) found an X-ray counterpart of J2032 with Chandra and Swift/XRT, which was faint (i.e., $F_X = (1-5) \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$) before 2013, but was ~10 times brighter (i.e., $F_X \approx 3 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$) after 2015. This extraordinary X-ray brightening strongly indicates an intimate interaction between the pulsar and stellar winds (see Takata et al. 2017 for a detailed modeling). Since the brightening, a rapidly increasing trend seemingly appeared in the Swift/XRT lightcurve from 2015 September to mid-2016 (Ho et al. 2017; Takata et al. 2017), which is reminiscent of PSR B1259–63/LS 2883 just before the disk passage (see, e.g., Chernyakova et al. 2015; Tam et al. 2015).

In this paper, we report our recent Swift, NuSTAR, and XMM-Newton X-ray and Lijiang optical observations of J2032 and clarify the current status of the system based on the results.

2. The 2016 Chandra Observation

We re-analyzed the 4.9 ks Chandra observation taken on 2016 February 24 (ID: 18788). While it has been well studied by Ho et al. (2017) for J2032, we focus on the three bright nearby X-ray sources (Cyg OB2.4, MT91 221, and CXOU J203213.5+412711), which are just marginally resolved by XMM-Newton and Swift, and unresolved by NuSTAR. The
The Astrophysical Journal, 843:85 (5pp), 2017 July 10

Li et al.

Table 1

| Source          | $N_H$ (10$^{22}$ cm$^{-2}$) | $\Gamma$ or $kT$ | Norm.$^a$ |
|-----------------|-----------------------------|-----------------|----------|
| Cyg OB2 4b      | 1.0                         | 0.5 keV         | $1.0 \times 10^{-4}$ |
| M97 11          | 0.5                         | 2.4             | $1.1 \times 10^{-5}$ |
| CXOU J203213.5  | 0.8                         | 2.4             | $8.6 \times 10^{-6}$ |

Notes.

$^a$ See https://heasarc.gsfc.nasa.gov/xanadu/xspec/manual/Models.html for the definitions.

The CIAO (v4.7.2) task specextract was used to extract the spectra with circular source regions of $r = 1.5$ and source-free background regions of $r = 10\theta$. The sources can be described by an absorbed power-law or an absorbed thermal mekal model (the best-fit parameters are listed in Table 1). These models will be included in the NuSTAR and XMM-Newton spectral fits (with frozen parameters) to subtract the field sources’ contributions. For J2032, we used and discussed the results presented in Ho et al. (2017) throughout this work.

3. Swift/XRT Observations

In 2016 March, we launched a bi-weekly monitoring campaign to follow up the X-ray brightening seen by Swift and Chandra (Ho et al. 2017). We once switched the observing cadence to one week from 2016 December to 2017 February. However, we changed it back to the two-week cadence in March, which is the best for the study. We also note that there is another Swift program on J2032, probably with a longer cadence (PI: Coe). Some of the Swift observations (i.e., data taken before 2016 September) have been reported in Ho et al. (2017) and Takata et al. (2017) and we extend the analysis with all the XRT observations taken before 2017 April 14 in this work.

The exposures range from <1 to 5 ks. Most of them are useful in building a long-term X-ray lightcurve, but the data qualities are still insufficient for meaningful spectral analyses and such analyses are therefore not included in this work. For the XRT lightcurve extraction, we used the Swift’s online analysis tool$^{10}$ (Evans et al. 2007, 2009) to rectify the bad pixels, vignetting, and point-spread function (PSF) corrections of the data. All parameters were left at program default values with the option binning by observation chosen. Figure 1 shows the XRT lightcurve after (i) removing the bad data (i.e., upper limits due to extremely short exposures, some data bins with S/N < 3, and a fake detection in 2006 due to a noisy background), (ii) re-binning the data points taken within 24 hr, and (iii) subtracting the expected contributions from the three bright X-ray sources (i.e., $1.7 \times 10^{-3}$ cts s$^{-1}$, estimated by PINMS with the parameters in Table 1).

As previously mentioned, the spectral information of the XRT data is poor. Given that J2032 showed strong spectral variability (see Table 2), we discuss the XRT lightcurve using the XRT count rate throughout the paper to avoid providing misleading information. We here give a counts-to-flux conversion factor of $9.5 \times 10^{-11}$ erg cm$^{-2}$ cts$^{-1}$ (absorption corrected), computed based on the best-fit model for the XMM-Newton data (see Section 5 and Table 2), for a rough reference.

4. NuSTAR Observation

We obtained a 45 ks (live time) NuSTAR ToO observation to study the J2032 on 2016 September 9–10 (Figure 1). In the NuSTAR FPMA/FPMB images, the stray light from the HMXB Cygnus X-3, 30’ away from J2032, created ghost ray patterns through single reflections (K. Madsen 2017, private communication). Fortunately, the contamination, especially for energies >5 keV, is not too severe, and the source was clearly detected with a net count rate of $\sim 0.02$ cts s$^{-1}$ (FPMA+B). A simultaneous 4 ks Swift observation was also obtained to extend the analysis down to 0.3 keV.

The HEAsoft (v6.19) task nuproducts with the CALDB (v20160731) was used to extract spectra and lightcurves from the FPMA/FPMB observations in the default energy range of 3–78 keV (channels: 35–1909). We adopted a circular source region of radius $r = 30\arcsec$, which is recommended for faint sources by the NuSTAR team. To minimize the effect of the stray light, we selected two source-free regions of $r = 30\arcsec$ at the respective positions of the source in the ghost patterns for the background extractions.

The spectra (together with the simultaneous Swift/XRT spectrum extracted by the Swift’s online analysis tool) can be well described ($\chi^2 = 53.2/64$) by an absorbed simple power-law of $\Gamma = 2.7 \pm 0.2$, $N_H = 2.5^{+1.3}_{-0.9} \times 10^{22}$ cm$^{-2}$, and $F_{3–78} = 1.25^{+0.14}_{-0.13} \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ (or $F_{0.3–10}$ keV = $6.1^{+0.2}_{-0.3} \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$; absorption corrected), with no obvious high-energy exponential cutoff feature (Figure 2). The fitting result does not significantly change if the Swift data is not included (Table 2). An additional mekal thermal component with a plasma temperature of $T \approx 0.5$ keV can slightly improve the joint NuSTAR-Swift fit by $\Delta \chi^2 = 2.4$. We simulated 10,000 spectra based on the best-fit simple power-law and then fitted the simulated spectra with both power-law and power models. 46% of the simulations improve better than $\Delta \chi^2 = 2.4$, indicating that improvement is not significant. For the NuSTAR lightcurve, we binned it with 5 ks to achieve about 100 counts per bin and no strong variability can be seen.

5. XMM-Newton Observation

A 43 ks XMM-Newton ToO observation operated under the prime full window mode with the medium optical blocking filter was obtained on 2016 November 6–7 (Figure 1). Following the analysis threads in the XMM-Newton Science Operation center,$^{11}$ we used the metatask xmmextractor in SAS (v15.0.0) to extract the scientific products from the raw data in the Observation Data File.

The live times were 35 and 41 ks for PN and MOS1/2, respectively. After filtering the high background periods, usable live times were reduced to 27 ks (PN), 39 ks (MOS1), and 38 ks (MOS2). J2032 was detected in all EPIC cameras with net count rates of 0.1 cts s$^{-1}$ for PN and 0.03 cts s$^{-1}$ for each MOS in 0.3–10 keV. Similar to the NuSTAR lightcurve, no hourly variability can be seen in the PN (1 ks binned) and MOS12 (1.5 ks binned) lightcurves. We fitted an absorbed

$^{10}$ http://www.swift.ac.uk/user_objects/

$^{11}$ https://www.cosmos.esa.int/web/xmm-newton/sas-threads
Figure 1. The upper panel shows (i) the Swift/XRT lightcurve (0.3–10 keV) of J2032 (black bars); and (ii) the equivalent widths (EWs) of the Hα emission lines measured by the MDM 1.3/2.4 m and Liverpool 2 m telescopes in Ho et al. (2017; green squares) and the Lijiang 2.4 m telescope in this work (purple asterisks). In addition, the X-ray intensities measured by the Chandra (Ho et al. 2017), NuSTAR, and XMM-Newton observations were converted to the XRT count rates based on the best-fit power-law models and shown as circles in the plot. The shadowed regions indicate the possible periods when the X-ray source was in the low state. The dashed line represents the increasing trend of the low state \( \mu \cdot \left( \frac{t_p}{t_p + 1.2} \right)^{0.1} \), where \( t_p \) is the number of days from the periastron passage on MJD 58069; see a more detailed description in Section 7.1. The lower panel plots the Chandra (Ho et al. 2017) and Swift/XRT data taken before 2013 March, with the same dashed trend line as shown in the upper panel.

Table 2

| Date (MJD) | Instruments | \( C_1 \) | \( C_2 \) | \( N_H \) \( (10^{22} \text{ cm}^{-2}) \) | \( \Gamma \) | \( F_{0.3-10 \text{ keV}} \) \( (10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}) \) | \( \chi^2/\text{dof} \) |
|------------|-------------|---------|---------|----------------|--------|-------------------------|------------------|
| 2016 Sep 9–10 | NuSTAR and Swift | 1.0 ± 0.1 | 0.9 ± 0.4 | \( 2.5_{-0.9}^{+1.3} \) | 2.7 ± 0.2 | \( 6.1_{-0.9}^{+1.2} \) | 53.2/64 |
| 2016 Sep 9–10 | NuSTAR | 1.0 ± 0.1 | ... | <5.3 | 2.6_{-0.2}^{+0.3} | 5.0_{-0.8}^{+1.6} | 52.8/62 |
| 2016 Nov 6–7 | XMM-Newton | 0.91 ± 0.06 | 0.95 ± 0.06 | \( 0.70_{-0.07}^{+0.08} \) | 1.9 ± 0.1 | \( 0.87_{-0.06}^{+0.07} \) | 278.9/272 |

Notes.

a The cross-calibration factor of FPMB (or MOS1) with regard to FPMA (or PN).

b The cross-calibration factor of XRT (or MOS2) with regard to FPMA (or PN).

c The fluxes have been absorption corrected.
simple power-law model to the spectra and found the best-fit parameters of $\Gamma = 1.9 \pm 0.1$, $N_H = 0.70^{+0.08}_{-0.07} \times 10^{22}$ cm$^{-2}$, and $F_{0.3-10\text{ keV}} = 0.87^{+0.06}_{-0.06} \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ (absorption corrected; $\chi^2 = 278.9/272$; Figure 2), which are all very different from that of the NuSTAR+Swift spectral fit (Table 2 and Figure 3). We also tried to add a mekal component to improve the fit, but the reduced $\chi^2$ was found to be even higher. All of the best-fit parameters (including the NuSTAR+Swift’s) are shown in Table 2.

### 6. The Lijiang 2.4 m Observations

To study the evolving H$\alpha$ emission line from the circumstellar disk of MT91 213 (Ho et al. 2017), two 120 and 180 s spectra were taken with the Yunnan Faint Object Spectrograph and Camera (YFOSC) on the Lijiang 2.4 m telescope on 2016 November 20 and December 11, respectively. The spectral resolutions are medium with Grism 15 (183 nm/mm) and Slit 3 (1’’/0) on December 11, and Grism 14 (92 nm/mm) and Slit 3 (1’’/8) on November 20. After the standard data reduction processes with IRAF, the H$\alpha$ emission line was clearly detected in both data sets, although the double-peaked line profile (Ho et al. 2017) is unresolved. Using the eqwidth task in the rvsao package, we computed the equivalent widths (EW) of the H$\alpha$ emission lines to be $-5.6$ and $-5.3$ Å on November 20 and December 11, respectively (Figure 1).

### 7. Discussion

Before 2013 March, the X-ray source was marginally detected by XRT at $C_{\text{XRT}} \sim 0.001$ cts s$^{-1}$. In 2015 September, it had brightened to $C_{\text{XRT}} \approx 0.008$ cts s$^{-1}$ after a 2.5-year observing gap. The X-ray emission then increased more rapidly from $C_{\text{XRT}} \approx 0.007$ cts s$^{-1}$ to $\approx 0.024$ cts s$^{-1}$ in 2016 April–July (Ho et al. 2017; Takata et al. 2017). While a continuous increase was theoretically expected (see, e.g., Takata et al. 2017), the X-ray emission returned back to $C_{\text{XRT}} \approx 0.006$ cts s$^{-1}$ in three months, confirmed by the XMM-Newton observation (Figure 1). The flux was increasing again afterwards, but a few declines are again shown later (Figure 1). More than one type of variation should be involved to result in the complexity seen in the X-ray lightcurve.

### 7.1. The Long-term Variability

By taking a closer look of the Swift/XRT lightcurve, one can easily identify some local flux minima, and the most obvious ones are indicated by the shadowed regions in Figure 1. We tried to fit these XRT minima in the shadow and the quiescent fluxes measured before 2013 (including the three Chandra measurement taken in 2002–2010; Ho et al. 2017) to a simple power-law, and the data can be well connected with $F_X \propto t_p^{1.2 \pm 0.1}$ (Figure 1), where $t_p$ is the number of days from the periastron passage (i.e., MJD 58069; Ho et al. 2017). Apparently, these low flux intervals could belong to the same emission state, which will be called the low state in the following discussion.

The momentum ratio of the stellar wind to the pulsar wind is one of the major factors in determining the X-ray luminosity of the wind–pulsar wind interacting shock in a γ-ray binary. The dependence can be even higher under a consideration of a non-constant magnetization of the shock along the distance from the pulsar (Takata et al. 2017). In J032, the slowly brightening low state is likely the consequence as the pulsar approaches the Be star and interacts with the stronger stellar wind. Because of the current large distance between the pulsar and the Be star, the rate of X-ray flux increase would be slow. However, this is still sufficient to develop the two distinct flux levels before/after the 2.5-year observing gap in 2013–2015, as observed by Swift/XRT and Chandra.

It is worth noting that the XMM-Newton data was taken during the low state. The best-fit hydrogen column density (i.e., $N_H = 7 \times 10^{21}$ cm$^{-2}$) is well consistent with the foreground value estimated by the optical color excess of MT91 213 (i.e., $N_H = 7.7 \times 10^{21}$ cm$^{-2}$; Camilo et al. 2009; Ho et al. 2017). In addition, the best-fit photon index (i.e., $\Gamma = 1.9$) is very close to that of those Chandra observations taken before 2016 (i.e., $\Gamma = 2$ with the foreground $N_H$; Ho et al. 2017), supporting our suggestion that the source was in the same low state during the Chandra observations.

### 7.2. The Short Variability

In addition to the possible long-term brightening trend, multiple flares on weekly to monthly timescales are obviously present in the XRT lightcurve (Figure 1). Our NuSTAR observation provides a good X-ray spectroscopic study of some of these flares. Compared with the low state spectrum taken by XMM-Newton, the NuSTAR spectrum is significantly softer in the photon index, with a heavier $N_H$ absorption (Figure 3). This high $N_H$ strongly implies a denser medium around the pulsar during the flare, probably caused by an occasional strong wind from the Be star. Using the binary orbit presented in Ho et al. (2017) and the mass-loss rate of $m = 4\pi r^2 \sin i \rho_\nu$ (where $r$ is the distance from the star, $\nu_\nu \sim 1000$ km s$^{-1}$ is the wind speed, and $\rho_\nu$ is the density of the wind at $r$) for a steady and spherically symmetric wind, we integrated the density along the line-of-sight and found that $m \sim 10^{-5} - 10^{-4} M_\odot \text{ yr}^{-1}$ is required to accumulate the intrinsic $N_H$ to $\sim 10^{22}$ cm$^{-2}$. This inferred rate is several orders of magnitude higher than the typical value for B type stars (Krtička 2014), suggesting that the wind is likely compact and clumpy (i.e., the pulsar was hitting compact wind clumps, instead of a homogeneous wind). When impacting the pulsar, this strong clumpy wind probably pushed the shock toward the pulsar side to cause a stronger magnetic field at the emission region (Takata et al. 2017). In
this case, *NuSTAR* might observe the emissions from the particles in both the slow and fast cooling regimes in the flaring state, while only the emission from the slow cooling regime was observed by *XMM-Newton* in the low state, possibly explaining the observed divergence in photon index.

In the Hα line study of Ho et al. (2017), the circumstellar disk of the Be star was expanding from $R_{\text{disc}} \approx 0.2$ to 0.4 au (i.e., EW: from $-3.3$ to $-10.2$ Å) in 3–4 months during the first few X-ray flares (see also Figure 1). Our *Lijiang* spectra indicate that the circumstellar disk shrank back to $R_{\text{disc}} \approx 0.3$ au (converted from EW using the equation in Hanuschik 1989) a few months later while the X-ray source was likely in the low state. We suspect that the disk expansion is an indication of the hypothetical strong clumpy wind to trigger the observed flares. On the other hand, the activity of the circumstellar disk could be induced by the approaching pulsar as shown in PSR B1259–63/LS 2883 (Chernyakova et al. 2014, 2015), although the separation between the pulsar and the Be star in J2032 was much larger.

Finally, we note that PSR B1259–63/LS 2883 did not show such pre-periastron-passage flares previously (see, e.g., Chernyakova et al. 2006). However, when PSR B1259–63 entered the circumstellar disk in 2004, the X-ray emission, $N_{\text{H}}$, and the photon index were all increasing (Chernyakova et al. 2006). In J2032, a very similar spectral change is seen when transitioning from the low state to the flaring state (Table 2 and Figure 3), although the photon indexes of PSR B1259–63/LS 2883 are generally harder (i.e., increased from $\Gamma = 1.2$ to 1.8) than that of J2032 (i.e., from $\Gamma = 1.9$ to 2.7). It would be intriguing to ask whether this is a common feature in γ-ray binaries when the pulsars entering from a lighter medium to a denser medium.

8. Conclusion

With the *NuSTAR* and *XMM-Newton* X-ray observations, we identify two very different spectral states, namely the low state (i.e., low X-ray flux and $N_{\text{H}}$ with a hard spectrum) and the flaring state (i.e., high X-ray flux and $N_{\text{H}}$ with a soft spectrum). The *Swift* XRT lightcurve suggests that the low state has been slowly evolving, possibly following $F_x \propto t_p^{-1.2}$, while the flares are likely on weekly to monthly timescales. In addition, these flares could be correlated to the size of the circumstellar disk of M79 213, indicated by the Hα emission line studies (see also Ho et al. 2017). The physical origin of these flares and the implication of the slowly brightening low state are still not entirely clear. Hopefully, continuous multi-wavelength monitoring observations (e.g., from *Swift* and *Fermi*) will be useful in studying these flares as well as any pre-periastron activities before the periastron passage in late 2017.

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Facilities: *Swift*, *NuSTAR*, *XMM*, YAO:2.4m, and CXO.

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