FERMI OBSERVATION OF THE TRANSITIONAL PULSAR binary XSS J12270–4859

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Received 2014 November 13; accepted 2015 May 6; published 2015 July 15

ABSTRACT

Because of the disappearance of its accretion disk during the time period of 2012 November–December, XSS J12270–4859 has recently been identified as a transitional millisecond pulsar binary, joining PSR J1023+0038. We have carried out a detailed analysis of the Fermi Large Area Telescope data for this binary. While both spectra are well-described by an exponentially cut-off power law before and after the disk-disappearance transition, which is typical for pulsars’ emissions in Fermi’s 0.2–300 GeV band, we have detected a factor of 2 flux decrease related to the transition. A weak orbital modulation is possibly seen, but is only detectable in the after-transition data, making it the same as orbital modulations found in X-rays. In the long-term light curve of the source before the transition, a factor of 3 flux variations are seen. Compared to the properties of J1023+0038, we discuss the implications from these results. We suggest that since the modulation is aligned with the modulations in X-rays in the orbital phase, it possibly arises due to the occultation of the γ-ray emitting region by the companion. The origin of the variations in the long-term light curve is not clear because the source field also contains unidentified radio or X-ray sources and their contamination cannot be excluded. Multi-wavelength observations of the source field will help identify the origin of the variations by detecting any related flux changes from the in-field sources.

Key words: binaries: close – stars: individual (XSS J12270–4859) – stars: low-mass – stars: neutron

1. INTRODUCTION

It is now known that during the evolution from a low-mass X-ray binary (LMXB) to a millisecond pulsar (MSP; e.g., Bhattacharya & van den Heuvel 1991), a neutron star in such a system can switch between the states of being accretion-powered and rotation-powered, which is well illustrated by observational studies of the MSP binary J1824–2452I in the globular cluster M28 (Papitto et al. 2013). The neutron star in this binary, previously observed to be an MSP with radio pulsations, can appear to be in X-ray outburst showing phenomena characteristic of accretion-powered MSPs (Chakrabarty & Morgan 1998; Wijnands & van der Klis 1998). Before, indirect evidence had strongly suggested that several accreting MSPs in transient LMXBs probably switched to be rotation-powered during their quiescent states (Burderi et al. 2003; Wang et al. 2013b and references therein).

The discovery of the radio MSP binary J1023+0038 (Archibald et al. 2009) and follow-up studies indicate similar features for the likely end phase of the evolution process: this so-called transitional MSP binary can switch between the states of having an accretion disk and being disk-free. The binary, having an orbital period of 4.75 hr and containing a ~0.2 $M_\odot$ companion (Thorstensen & Armstrong 2005), was shown to have an accretion disk in 2000–2001 (Wang et al. 2009, 2013a and references therein). In the disk-free state, power-law emission with significant orbital modulation from the binary was seen in X-ray observations (Archibald et al. 2010; Bogdanov et al. 2011), which likely arises from an intrabinary shock due to the interaction between the outflow from the companion and pulsar wind. The modulation is caused by the occultation of the shock region by the companion (Bogdanov et al. 2011). This binary was also found to have γ-ray emission from the Fermi Large Area Telescope (LAT) data (Tam et al. 2010). Surprisingly, the binary was back to the active state with an accretion disk again in 2013 June. Since then, extensive multi-wavelength observations have revealed that it generally behaves like an LMXB (Archibald et al. 2015; Bogdanov et al. 2015; Coti Zelati et al. 2014; Patruno et al. 2014; Stappers et al. 2014), while the pulsar in the binary is possibly active but not observable during this state (Coti Zelati et al. 2014; Stappers et al. 2014). One interesting notable feature of the state transition is that the source’s γ-ray flux has had a 5–10 times increase (Stappers et al. 2014; Takata et al. 2014).

As pointed out by Roberts & van Leeuwen (2013), PSR J1023+0038 is also a prototypical, so-called “redback” system. Differing from the “black widow” MSP binaries (e.g., B1957+20; Fruchter et al. 1988) that contain very low-mass (~0.02 $M_\odot$) companions, redback systems have relatively massive secondaries (~0.1–0.6 $M_\odot$). Irradiation and/or evaporation of the companion by emission and pulsar wind, respectively, from the central neutron star, probably play an important role in forming black widow and redback systems (Chen et al. 2013; Benvenuto et al. 2014).

Another transitional MSP binary, XSS J12270–4859, was recently identified, as the accretion disk in the system was found to have disappeared during the period of 2012 November–December (Bassa et al. 2014; de Martino et al. 2014). Discovered by the RXTE (Sazonov & Revnivtsev 2004) and initially thought to be a cataclysmic variable (Masetti et al. 2006), the binary was considered a peculiar LMXB associated with the γ-ray source 2FGL J1227.7–4853 (Hill et al. 2011; de Martino et al. 2013 and references therein). After its transition to be disk-free, multiple energy observations have revealed its full nature. The detection of a 1.69 ms radio pulsar was reported (Ray et al. 2014; Roy et al. 2015). Optical observations have found that its orbital period is 6.9 hr (Bassa et al. 2014; de Martino et al. 2014), and the companion is a mid G-type, under-massive donor star with a mass of 0.17–0.46 $M_\odot$ (de Martino et al. 2014; Roy et al. 2015),
establishing it as another redback system. At X-ray energies, the binary is an order of magnitude fainter than before, with orbital modulation present (Bogdanov et al. 2014). Compared to that seen in J1023+0038 in the disk-free state (Archibald et al. 2010; Bogdanov et al. 2011), the X-ray emission likely has an intrabinary-shock origin (Bogdanov et al. 2014) due to the interaction between the outflow from the companion and the pulsar wind. At γ-ray energies, a possible flux decrease was also reported in an astronomer’s telegram (Tam et al. 2013), and very recently a marginal detection of pulsed emission was reported by Johnson et al. (2015). These properties are highly comparable to that of J1023+0038.

The source field of 2FGL J1227.7−4853 was found to contain three radio sources (Hill et al. 2011), one of which, Source 1, had a flat radio spectrum and was found by Bassa et al. (2014) to be at least a factor of 6 fainter during 2013. These properties, in line with those recently observed for J1023+0038 (Deller et al. 2014), indicate that the source is likely the radio counterpart to XSS J12270−4859. The brightest radio source J122806−485218 (named in Hill et al. 2011 and hereafter used in this paper) is located at R.A. = 12^h 28^m 06^s.04, decl. = −48°52′18″05 (equinox J2000.0). It has extended radio emission, although its radio properties likely do not support its classification as a blazar (Hill et al. 2011), the class that is the major population detected by Fermi LAT (e.g., Nolan et al. 2012). It is suggested in Hill et al. (2011) that the γ-ray emission is from either XSS J12270−4859 or J122806−485218, and is more likely from XSS J12270−4859. X-ray observations did not reveal any physical connection between XSS J12270−4859 and J122806−485218, but found a possible, previously uncataloged galaxy cluster (designated as J122807.4−48532 in Bogdanov et al. 2014 and hereafter used in the paper) that is located at R.A. = 12^h 28^m 07^s.427, decl. = −48°53′23″561 (equinox J2000.0) and approximately 1′ away from XSS J12270−4859 (Bogdanov et al. 2014).

Given the above details and the recent identification of the transitional MSP binary nature for XSS J12270−4859, detailed analysis of the Fermi data is needed, which possibly helps our understanding of the physical processes in this system. Previously, Hill et al. (2011) and de Martino et al. (2013) analyzed approximately 2 years and 4 years, respectively, of Fermi data for 2FGL J1227.7−4853, mainly studying its γ-ray spectral properties. We have carried out our analysis to identify the properties of the associated γ-ray source, study its long-term flux variability, and search for modulation signals. In this paper, we report the results from the analysis. We describe the Fermi observation data in Section 2, and present the data analysis and results in Section 3. Our results are discussed in Section 4.

2. OBSERVATION

LAT is a γ-ray imaging instrument on board Fermi. It conducts all-sky surveys in an energy range from 20 MeV to 300 GeV (Atwood et al. 2009). In our analysis, we selected LAT events from the Fermi Pass 7 Reprocessed (P7REP) database inside a 20° × 20° region centered at the position of XSS J12270−4859, which is R.A. = 12°28′58″748, decl. = −48°33′42″88 (equinox J2000.0) obtained from 2MASS (Cutri et al. 2003) and used in Bogdanov et al. (2014) for X-ray studies of orbital modulation of this source. We only observed events during the time period from 2008

August 04 15:43:36 (UTC) to 2014 July 10 18:16:37 (UTC) and in the energy range of 100 MeV to 300 GeV. In addition, only events with zenith angles less than 100° and during good time intervals were selected. The former prevent the Earth’s limb contamination, and for the latter, the quality of the data was not affected by the spacecraft events.

3. DATA ANALYSIS AND RESULTS

3.1. Source Identification

To create the source model, we included all sources within 16° in the Fermi second source catalog (Nolan et al. 2012), centered at the position of XSS J12270−4859. The spectral function forms of the sources are provided in the catalog. The spectral normalization parameters of the sources within 8° from XSS J12270−4859 were set free, and all other parameters of the sources were fixed at their catalog values. We used the spectrum model glf_lem_v05_rev1.fits and the spectrum file iso_source_v05.txt for the Galactic and extragalactic diffuse emission, respectively, in the source model. The normalizations of the diffuse components were set as free parameters.

Using the LAT science tools software package v9r33p0, we performed a standard binned likelihood analysis of the LAT data in the 0.2−300 GeV range. Events below 200 MeV were rejected because of the relatively large uncertainties of the instrument response function of the LAT in the low energy range. We extracted the test statistic (TS) map of a 2° × 2° region centered at the position of XSS J12270−4859 (Figure 1), with all sources in the source model considered except for the candidate γ-ray counterpart (2FGL J1227.7−4853) of XSS J12270−4859. We noted that no catalog sources except for 2FGL J1227.7−4853 are within the square region. The TS value at a specific position, calculated from TS = −2 log(L0/L1) (where L0 and L1 are

Figure 1. 0.2−300 GeV TS map of a 2° × 2° region centered at the position of XSS J12270−4859. The image scale of the map is 0′.04 pixel−1. All sources in the source model were considered and removed. The dark cross, green cross, magenta cross, and the dashed black circle mark the 2MASS position of XSS J12270−4859, the nearby brightest radio source J122806−485218, the nearby galaxy cluster J122807.4−48532, and the 2σ error circle of the best-fit position obtained from the Fermi data, respectively. The color bar indicates the TS value range.
the maximum likelihood values for a model without or with an additional source, respectively), is a measurement of the fit improvement by including the source, and is approximately the square of the detection significance of the source (Abdo et al. 2010).

As shown in Figure 1, the γ-ray emission near the center was detected with TS ≈ 1440, indicating an ∼37σ detection significance. We ran gtfindsrc in the LAT software package to find the position of the γ-ray source and obtained R. A. = 186°.99, decl. = −48°.90 (equinox J2000.0), with a 1σ nominal uncertainty of 0°.03. This best-fit position is consistent with the 2MASS position of XSS J12270−4859 (marked by a dark cross in Figure 1). The offset between the two positions is only ∼0°.01. The nearby radio source J122806−485218 and possible galaxy cluster J122807.4−48532 are also within the 2σ error circle, which are ∼0°.04 and ∼0°.03 away from the best-fit position, respectively.

Including the γ-ray source in the source model at the 2MASS position of XSS J12270−4859, we performed a standard binned likelihood analysis of the LAT data in a 0.2−300 GeV range, with the emission of this source modeled with a simple power law and an exponentially cutoff power law. The latter is characteristic of pulsars because pulsars detected in the Fermi γ-ray band generally follow this spectral shape (e.g., Abdo et al. 2013). For the former model, a photon index Γ = 2.41 ± 0.03 with a TSpl value of ∼1446 was obtained, and for the latter, Γ = 2.11 ± 0.08 and cutoff energy $E_c = 6 \pm 2$ GeV, with a TSexp value of ∼1466, was obtained. These results are also given in Table 1. The fit improvement between the models with and without the cutoff was quantified by the TScutoff value, which is estimated from $TS_{\text{exp}} - TS_{\text{pl}}$ and is approximately the square of the detection significance of the cutoff (Abdo et al. 2013). The low-energy cutoff was thus detected with >4σ significance ($\sqrt{TS_{\text{cutoff}}}$, where TScutoff ≈ TSexp − TSpl ≈ 20). The result favors the association of the γ-ray source with the pulsar binary system XSS J12270−4859.

### 3.2. Variability Analysis

We obtained the light curve of the source in a 0.2−300 GeV energy range to search for flux variations, particularly around the state-transition time period (MJD 56245−56283; Bassa et al. 2014) of XSS J12270−4859. A point source with a $\Gamma = 2.41$ power-law emission (Section 3.1) at the 2MASS position was considered. We also included the nearby blazar candidate PMN J1225−4936 (0.8 from XSS J12270−4859) in the source model, modeling its emission using a power law with $\Gamma = 2.4$ (Johnson et al. 2015). Johnson et al. (2015) pointed out that this source had one γ-ray flare around MJD 55702−55732, but otherwise was nearly undetectable (only TS ∼ 4 was obtained from the entire LAT data). In Figure 2, the light curve and the TS curve are shown. The flux before the state transition is approximately in a range from $< 2 \times 10^{-8}$ to $\sim 5 \times 10^{-8}$ photons cm$^{-2}$ s$^{-1}$, while the TS varies between 10 and 60. After the state change, γ-ray emission was relatively stable, with the flux and TS of $\sim 2 \times 10^{-8}$ photons cm$^{-2}$ s$^{-1}$ and ∼20. We noted that there were two unreliable data points at the time bins of MJD 56573−56603 and 56663−56693. The obtained TS values are smaller than 1 (marked by open symbols in Figure 2). During these times, there were two target-of-opportunity observations that caused data gaps of ∼5 and ∼12 days, respectively.

We performed a standard binned likelihood analysis of the LAT data in >0.2 GeV range for the time periods before and after the state change. When a power-law spectrum was assumed for the former data, we found $\Gamma = 2.42 \pm 0.04$ with TSpl ∼ 1247 and for the latter, $\Gamma = 2.42 \pm 0.09$ with TSpl ∼ 183. When an exponentially cutoff power law was considered, the respective results were $\Gamma = 2.13 \pm 0.08$ and $E_c = 6 \pm 2$ GeV with TSexp ∼ 1262, and $\Gamma = 1.8 \pm 0.3$ and $E_c = 2 \pm 1$ GeV with TSexp ∼ 192. Therefore, the low-energy cutoff was detected with TScutoff values of ∼15 and ∼9, which correspond to the detection significance of ∼3.8σ and ∼3σ before and after the state change, respectively. These results indicate that the γ-ray emission from the source is likely better described by a spectrum characteristic of pulsars, and the emission after the state transition is harder. For the exponentially cut off power-law spectra, the >0.2 GeV γ-ray fluxes were $3.2 \pm 0.2 \times 10^{-8}$ and $1.7 \pm 0.2 \times 10^{-8}$ photons cm$^{-2}$ s$^{-1}$ during the time periods before and after the state change, respectively. Therefore, a factor of ∼2 decrease in flux was likely related to the state change. These results are summarized in Table 1, and the fluxes and uncertainties are marked in Figure 2. We also tested adding the blazar candidate to the source model. Consistent results were obtained.

We further investigated the flux variations during the transition time period. We constructed a 30-day light curve by shifting each time interval by 1 day forward and obtaining the flux during such a 30-day interval (see, e.g., Takata et al. 2014). The candidate blazar was considered. The resulting fine smooth light curve is shown in the inset box of Figure 2. A factor of 2 flux decrease is visible, from $\sim 4 \times 10^{-8}$ to $< 2 \times 10^{-8}$ photons cm$^{-2}$ s$^{-1}$. Although the large uncertainties in the light curve do not allow us to draw a clear conclusion, it is likely that the flux decrease, which was significantly detected in the above maximum likelihood analysis, occurred because of the state transition.
The long-term light curve also indicates that the $\gamma$-ray emission from the source is not stable during the time period before the state change, as a factor of $\sim 3$ flux variations is visible. Based on the light curve, we defined three time periods, which are approximately MJD 54682–55400 (Period I; MJD 54682 is the start date of the Fermi data), MJD 55400–55800 (Period II), and MJD 55800–56245 (Period III). The $\gamma$-ray emission during Period I and Period III is relatively stable, while that during Period II is more variable. We performed likelihood analyses during Period I and Period III and obtained $>0.2$ GeV $\gamma$-ray fluxes of $2.5 \pm 0.2 \times 10^{-8}$ and $3.8 \pm 0.3 \times 10^{-8}$ photons cm$^{-2}$ s$^{-1}$, respectively, for the exponentially cut off power-law spectra. Whether or not the blazar candidate was considered, the results were consistent within uncertainties, while its flare only affected two data points in Period II (Figure 2). Comparing the fluxes and uncertainties, marked by red dotted lines and error bars in Figure 2, there is a $3.6\sigma$ flux increase from Period I to Period III. The data points during Period II, although containing large uncertainties, still have up to $>2\sigma$ significant variations compared to the fluxes of the whole time period before the state change, Period I, or Period III. These significant variations indicate the variability of the $\gamma$-ray emission from XSS J12270–4859 prior to the state transition.

### 3.3. Spectral Analysis

We report our spectrum results of the $\gamma$-ray source by considering the emission as a point source with a power-law spectrum at the 2MASS position. The photon index was fixed to the value we obtained above using the total data (see Table 1). The spectrum was extracted by performing maximum likelihood analyses of the LAT data in 10 evenly divided energy bands in logarithms from 0.1 to 300 GeV. Only spectral points with TS $\geq 4$ were kept. We extracted $\gamma$-ray spectra for the time periods before and after the state change, respectively. The obtained spectra are shown in the left panel of Figure 3, and the energy flux values are given in Table 2. The spectrum extracted by this method is less model dependent and provides a good description of the $\gamma$-ray emission of the source.

In order to investigate the variability before the state transition, we also extracted $\gamma$-ray spectra from the data in the time intervals of TS $\geq 30$ (“high” state) and TS $\leq 20$ (“low” state). The obtained spectra are shown in the right panel of Figure 3, with the energy flux values given in Table 2. The candidate blazar was considered in the analysis. Comparing the two spectra, we found the source appeared brighter across nearly the entire energy range in the high state. At 0.15 GeV the two spectral points are consistent. We noted that the instrument response function of the LAT has relatively large uncertainties in the low energy range, which might affect the results.

### 3.4. Orbital Variability

We performed timing analysis of the LAT data of XSS J12270–4859 to search for possible orbital modulations. Considering that the X-ray orbital modulation was only...
detected after the state change (Bogdanov et al. 2014), we first folded the LAT data of the γ-ray source during the time period at the orbital parameters given in the radio ephemeris (Roy et al. 2015). The position given in the ephemeris was used for the barycentric corrections to photon arrival times, and photons within 1°2 from the position were collected. Different energy ranges (0.2–300, 0.3–300, 0.5–300, 1–300, and 2–300 GeV) were tested during folding. No significant modulations were detected with an H-test value of <1. However, we note that the ephemeris was not found to be applicable to the total data after the state change (Johnson et al. 2015). When we instead used the orbital frequency of 4.018 ± 0.001 × 10^{-3} Hz given in Bassa et al. (2014; which is less accurate but consistent with the parameters given in Roy et al. 2015) and the 2MASS position for the barycentric corrections, a marginal signal was detected. The highest orbital signal was revealed in the >0.3 GeV energy range, with an H-test value of ~11 (corresponding to nearly 3σ detection significance, de Jager et al. 1989). The folded light curve is shown in the right panel of Figure 4, which has a χ²-test value of ~21 (for 9 degrees of freedom, corresponding to nearly 3σ detection significance; Leahy et al. 1983). The phase zero is set at the ascending node of the pulsar in XSS J12270−4859 (Bass et al. 2014). Although the significance is not high, we note that the folded light curve is nearly aligned with the X-ray one given in Bogdanov et al. (2014), obtained using the same orbital parameters, which likely strengthens the modulation detection.

As a test, we folded the LAT data of XSS J12270−4859 before the state change at the optical orbital frequency. No significant γ-ray modulation was detected with an H-test value of ~3. As a comparison, we show the folded light curve in the left panel of Figure 4.

We made two 0.3−300 GeV TS maps over the phase ranges of 0.2−0.5 (named Phase I) and 0.7−1.0 (named Phase II), which are approximately the bottom and peak of the orbital modulation, respectively (Figure 4). The obtained TS maps are shown in Figure 5. The source during Phase II is more significantly detected than that during Phase I, as the TS values are ~89 and ~22, respectively. We ran gtfindsrc to determine the positions of the γ-ray emission during the two phases, and found that they are consistent with the position of XSS J12270−4859 within 2σ error circles. The analysis confirms the detection of orbital modulation from the photon folding.

| E (GeV) | $F_{\text{low}}/10^{-12}$ (erg cm$^{-2}$ s$^{-1}$) | $F_{\text{high}}/10^{-12}$ (erg cm$^{-2}$ s$^{-1}$) | $F_{\text{before}}/10^{-12}$ (erg cm$^{-2}$ s$^{-1}$) | $F_{\text{after}}/10^{-12}$ (erg cm$^{-2}$ s$^{-1}$) |
|---------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| 0.15    | 15 ± 2                          | 12 ± 4                          | 13 ± 2                          | 6 ± 3                           |
| 0.33    | 8 ± 2                           | 15 ± 2                          | 11.9 ± 0.8                      | 6 ± 1                           |
| 0.74    | 8 ± 1                           | 12 ± 1                          | 9.5 ± 0.6                       | 6 ± 1                           |
| 1.65    | 6.4 ± 0.8                       | 11 ± 1                          | 7.7 ± 0.6                       | 5.7 ± 0.9                       |
| 3.67    | 2.5 ± 0.7                       | 7 ± 2                           | 4.1 ± 0.6                       | 1.9 ± 0.7                       |
| 8.17    | 0.7 ± 0.5                       | 3 ± 2                           | 2.2 ± 0.6                       | 0.8 ± 0.6                       |
| 18.20   | ...                             | 2 ± 2                           | 1.2 ± 0.7                       | ...                             |

Note. Columns 2 and 3 list the energy flux ($E^2 \times dN/dE$) in each energy bin during the low and high states before the state change, respectively. Columns 4 and 5 list the energy flux ($E^2 \times dN/dE$) in each energy bin during the observations before and after the state change, respectively.
Spectra were also obtained during Phase I and Phase II, but due to limited numbers of photons, the uncertainties on the flux data points are too large to allow any further detailed analysis. We performed binned likelihood analysis of the 0.3–300 GeV data during Phase I and Phase II, and obtained fluxes of $7.9 \pm 2.1 \times 10^{-9}$ and $18.4 \pm 2.7 \times 10^{-9}$ photons cm$^{-2}$ s$^{-1}$, respectively.

4. DISCUSSION

From our analysis of the Fermi data of 2FGL J1227.7–4853, we have detected a flux decrease during the state transition of XSS J12270–4859, which occurred around 2012 November–December. We have also detected orbital modulation only in the data after the transition. Although the detection is weak, the orbital-modulated light curve is consistent with that from the X-ray observation of XSS J12270–4859 (Bogdanov et al. 2014). Both detections provide strong evidence for the association between the two sources. In addition, the exponentially cut off power-law model, which is a typical spectrum for pulsar emission at the Fermi LAT γ-ray energy range (Abdo et al. 2013), is preferred for describing the source’s emission during both before and after the transition time periods. This result supports the association as well. Given these results, our analysis has confirmed the previous identification that 2FGL J1227.7–4853 is the γ-ray counterpart of XSS J12270–4859 (Hill et al. 2011; de Martino et al. 2013).
From extensive observations of the state transition of PSR J1023+0038 that occurred in 2013 June, particularly at the γ-ray band, it has become understood that in the state of having an accretion disk, γ-ray emission is brighter than that in the disk-free state: there was an order of magnitude flux increase in J1023+0038 accompanying the state transition (Stappers et al. 2014; Takata et al. 2014). What we have detected in XSS J12270−4859 is the opposite of the J1023+0038 case in 2013 June. While the flux change is smaller, the γ-ray flux of XSS J12270−4859 in the latter state is approximately two times lower than that in the former. It is very likely that γ-ray emission in the disk-free state originates from the magnetosphere of the pulsar, while the brighter emission in the accretion state has been proposed to be due to inverse Compton (IC) scattering of a cold pulsar wind off the optical/infrared photons from the accretion disk (Takata et al. 2014) or self-synchrotron Compton processes at the magnetospheric region of a propelling neutron star (Papitto et al. 2014). Similar to that in J1023+0038, $\Gamma = 1.8 \pm 0.2$ and $E_c = 2.3 \pm 0.9$ GeV to $1.4 \pm 0.6$ and $0.7 \pm 0.4$ GeV from the accretion state to disk-free state, spectral changes were also detected in XSS J12270−4859, as $\Gamma \sim 2.13$ and $E_c \sim 6$ GeV in the former changed to $\sim 1.8$ and $\sim 2$ GeV in the latter. Although they contain large uncertainties, these measurements provide possible evidence that the exact same physical processes occurred in XSS J12270−4859. Probably because J12270−4859 is approximately three times brighter than J1023+0038 in the disk-free state (Tam et al. 2010), we have likely detected its orbital modulation. Such γ-ray modulation, which was marginally seen in the black widow binary PSR B1957+20 (Wu et al. 2012; and the candidate MSP binary 2FGL J0523.3−2530; Xing et al. 2014), has been suggested to arise due to the view angle of the intrabinary interaction region (Wu et al. 2012; Bednarek 2014). However, the modulation, approximately aligned with that at X-rays (Bogdanov et al. 2014), has a brightness peak in the orbital phase of 0.5−1.0 (around the superior conjunction when the companion is behind the neutron star). This orbital variation is different from that in B1957+20, as its brightness peak is at the opposite phase region. For B1957+20, the IC processes, which produce extra γ-ray emission around the inferior conjunction phase, has been suggested to be viewed as a head-on collision between the pulsar wind and the soft photons from the pulsar or the companion (Wu et al. 2012; Bednarek 2014). For XSS J12270−4859, we suspect that its modulation may arise because of the occultation of the photon-emitting region by the companion, which explains the X-ray modulation in PSR J1023+0038 (see Bogdanov et al. 2011 for details). We note that the inclination angle of the binary was estimated to be 45°−65° (de Martino et al. 2014), which is similar to that of PSR J1023+0038 (Wang et al. 2009). Unfortunately, the photon counts were too low to allow a comparison of the phase-resolved spectra (obtained in the bright and faint phase ranges), which might help identify the cause of the modulation. If it were due to the occultation, no spectral changes would be expected. In addition to the flux change related to the state transition, our data analysis possibly shows a factor of ~3 flux variations during the time period before the state change. The spectrum comparison between the high (with a TS greater than 30) and low (with TS lower than 20) states indicates that the flux changes were across the entire energy range. Such flux variations have not been seen before in MSP binaries. Recently, in the candidate MSP binary 2FGL J0523.3−2530, significant flux variations were detected, but they were caused by the presence of a 2−3 GeV component in the high state (Xing et al. 2014). Given that there are other radio sources and a possible galaxy cluster in the source field, contamination from them cannot be totally excluded. Since active galactic nuclei (AGNs) account for the majority of the population (nearly 80%) of Fermi γ-ray sources and are the most commonly seen variable sources in the γ-ray band, if one of the nearby sources is associated with an unidentified AGN, its 0.3−300 GeV flux would likely be $<7.9 \times 10^{-9}$ photons cm$^{-2}$ s$^{-1}$, the value obtained for the faint orbital phase range (see Section 3.4). Its variability thus would have caused the flux changes across the Fermi energy (e.g., Williamson et al. 2014). In addition, there might be other unknown AGNs in the source field that could cause the variability. We note that no other sources were found even in the high state (Section 3.3). Therefore, the possibility of having an unknown γ-ray-emitting AGN in the 0°6 radius (2σ) error circle of XSS J12270−4859 is generally low ($\sim 7 \times 10^{-4}$, see, e.g., Xing et al. 2014), suggesting that the γ-ray variability is not likely to be caused by an unknown AGN. In order to determine the possibility of emission contamination from nearby sources, multi-wavelength observations can be carried out when 2FGL J1227.7−4853 shows significant brightening again. Related flux changes at radio or X-ray energies would be seen from one of the known nearby sources.

This research was supported by the Shanghai Natural Science Foundation for Youth (13ZR1464400), the National Natural Science Foundation of China (11373055), and the Strategic Priority Research Program “The Emergence of Cosmological Structures” of the Chinese Academy of Sciences (grant No. XDB09000000). Z.W. is a Research Fellow of the One-Hundred-Talents project of the Chinese Academy of Sciences.

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