The Hour-timescale GeV Flares of PSR B1259–63 in 2017

P. H. T. Tam, X.-B. He, P. S. Pal, and Yudong Cui

School of Physics and Astronomy, Sun Yat-sen University, Zhuhai 519082, People’s Republic of China; tanbxuan@sysu.edu.cn, hexb7@mail2.sysu.edu.cn, parthasarathi_pal@gmail.com, cuiyd@mail.sysu.edu.cn

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Abstract

GeV flares from PSR B1259–63/LS 2883 were seen starting around 30 days after the two periastron passages in 2010 and 2014. The flares are clearly delayed compared to the occurrence of the X-ray and TeV flux peaks during the post-periastron disk crossing. Although several attempts have been put forward to explain this phenomenon, the origin of these GeV flares remains a puzzle. Here we present a detailed analysis of the observational data taken by the Fermi and Swift observatories over the 2017 September periastron passage. For the first time, we find short-lived but powerful GeV flares on timescales of days to three hours. The onset of the GeV flaring period in 2017 is also delayed compared to that seen in 2011 and 2014. Supplemented by a reanalysis of previous data, we compare the Fermi/LAT, Swift/XRT, and Swift/UVOT light curves in 2017 with those taken over the 2010 and 2014 periastrons, and differences in UVOT light curves are noted.

Key words: gamma rays: stars – pulsars: individual (PSR B1259–63) – X-rays: binaries

1. Introduction

Gamma-ray binary systems are high-mass X-ray binaries consisting of a neutron star or black hole in orbit with an O/B star. They provide a unique astrophysical laboratory to study the pulsar wind (PW) at subparsec scale through its interaction with the stellar wind. Currently, there are seven known γ-ray binaries (five listed in Dubus 2015, plus P3 in LMC (Corbet et al. 2016) and PSR J2032+4127, which has an orbital period of 45–50 years (Ho et al. 2016), but the PSR B1259–63/LS 2883 system remains the only γ-ray binary that (i) contains a pulsar and (ii) emits repetitive orbital phase-dependent radio, X-ray and γ-ray flares seen more than once. PSR B1259–63 (with a spin period of 47.8 ms) orbits around the Be star LS 2883 with a period of 3.4 years in a highly eccentric orbit (e ~ 0.87).

LS 2883 (Johnston et al. 1994) hosts a stellar disk that is inclined with respect to the pulsar orbital plane, such that the pulsar crosses the disk twice around each periastron passage (Chernyakova et al. 2006). The pulsar generates a powerful PW that interacts with the stellar wind/disk every time the two bodies are close to each other, emitting non-thermal, unpulsed radiation, in radio (e.g., Johnston et al. 2005), X-rays (e.g., Chernyakova et al. 2009), GeV γ-rays (Caliandro et al. 2015; Tam et al. 2015), and TeV γ-rays (Aharonian et al. 2005, 2009; H.E.S.S. collaboration 2013). The system was first detected in γ-rays by H.E.S.S. shortly before and for up to 100 days after its 2004 periastron passage (2004 March 7), making it the first variable Galactic TeV source (Aharonian et al. 2005). Since the X-ray and TeV flux peaks occur near the two disk passages, it is customary to explain the bulk of the X-rays and TeV γ-rays as a result of PW–stellar disk shock acceleration.

With the launch of the Fermi Gamma-ray Telescope in 2008, GeV γ-rays were first discovered from PSR B1259–63/LS 2883 around the 2010 periastron passage. In particular, a GeV flare was first seen about 30 days past periastron (Abdo et al. 2011; Tam et al. 2011). This GeV flare was not expected and is still one of the major unresolved questions in γ-ray binary studies (Dubus 2013). The GeV flare was found to repeat in 2014 at a similar orbital phase, confirming the repetitive nature of the GeV flaring period. In 2014, contemporaneous X-ray activity during the GeV flares was found by multiwavelength studies using NuSTAR, Swift, and Fermi data (Chernyakova et al. 2015; Tam et al. 2015). The GeV flares do not have a corresponding counterpart in TeV (H.E.S.S. collaboration 2013).

The radiation mechanisms of the broadband radiation from PSR B1259–63/LS 2883, as well as the GeV flare seen in early 2011, are unclear. Electrons accelerated in the shock between the PW and stellar wind can produce synchrotron radiation and/or upscatter stellar or disk photons from LS 2883 to produce inverse-Compton (IC) radiation (Tavani & Arons 1997; Kirk et al. 1999; Dubus 2006; Bogovalov et al. 2008; Khangulyan et al. 2011; Kong et al. 2011; Takata et al. 2012; Mochol & Kirk 2013). The unshocked PW particles may also generate γ-rays (Khangulyan et al. 2012). The interaction between the stellar disk and the pulsar (Chernyakova et al. 2014), as well as Doppler boosting (Dubus et al. 2010; Kong et al. 2012), was also suggested to play a major role in producing the GeV flares.

PSR B1259–63 crossed the periastron in 2017 September. In this paper, we present the Fermi/LAT and Neil Gehrels Swift Observatory’s XRT and UVOT analysis results of the binary PSR B1259–63/LS 2883 in 2017 and in previous passages. The 2010, 2014, and 2017 periastron times are taken to be 2010 December 14 UT 10:02:21 (MJD 55544.69377), 2014 May 04 UT 10:02:21 (MJD 56781.418298), and 2017 September 22 UT 03:25:40 (MJD 58018.142824), based on the most updated orbital parameters as presented in Shannon et al. (2014).

2. Data Analysis

2.1. Fermi

The Fermi/LAT data were analyzed using the Fermi Science Tools v10r0p5 package. For the 2010, 2014, and 2017 periastron passages, we used reprocessed Pass 8 data belonging...
to the SOURCE event class. We excluded events with zenith angle greater than 90° to reduce the photons from the Earth. The instrument response function used in our analysis was P8R2SOURCE_V6. We performed a binned maximum-likelihood analysis (gtlike) of the data within a circular region of interest with a radius of 20° centered on PSR B1259–63. We considered the background contribution of the Galactic diffuse model (gll_iem_v06.fits) and the isotropic background (iso_P8R2_SOURCE_V6_v06.txt), as well as known gamma-ray sources in the 3FGL catalog (Acero et al. 2015). The spectral parameters of the sources farther away than 5° from PSR B1259–63 were fixed to the catalog values. For the sources within 5°, the normalization is left free. The normalization factor of the two diffuse emission components was also allowed to vary. The spectrum of PSR B1259–63 is assumed to be a power law:

$$\frac{dN}{dE} = N_0 \left( \frac{E}{E_0} \right)^{-\gamma}. \quad (1)$$

In all plots showing *Fermi*-LAT data, detections are defined as having a test statistic (TS) value of 9 or above. When TS is smaller than 9, upper limits at the 90% confidence level are shown.

2.2. Swift

In 2017, a *Swift* monitoring campaign consisting of 22 observations was performed, resulting in a total exposure of 29.5 ks spanning from September 17 (MJD 58013.7, $t_p - 4.3$ days) to December 23 (MJD 58110.3, $t_p + 92.3$ days), as listed in the details given in Table 1.

For *Swift*-XRT data reduction, the level 2 cleaned event files of *Swift*-XRT are obtained from the events of the photon counting (PC) and window timing (WT) mode data with xrtpipeline. The spectra are extracted from a circular region in the best source position with 20 arcsec radius. The background is estimated from an annular region in the same position with radii from 30 to 60 arcsec. The ancillary response files are extracted with xrtmkarf. The PC redistribution matrix file (rmf) version (v.12) is used in the spectral fits. XRT-PC spectra are then analyzed with XSPEC(v12.9.1m) with a ztbabs * xpo model. The column density ($n_H$) is fixed within the range (5–7) × $10^{22}$ cm$^{-2}$ (Tam et al. 2015). From fitted spectra, unabsorbed flux is calculated from 0.3 to 10 keV in cgs units for all observations.

For *Swift*-UVOT data reduction, all extensions of the sky images are stacked with uvotimsum. The background images from all of the filters with uvotsource. The background position with an inner and outer radius of 10 arcsec and 20 arcsec, respectively.

### 3. Results

#### 3.1. Properties of the γ-Ray Light Curve in 2017

In Figure 1, the LAT light curves of PSR B1259–63 through the 2017 periastron passage with different data samplings (i.e., 3 hr, 1 day, and 5 day) are shown. The inset of the upper panel was obtained using aperture photometry with 3 hr sampling, in which 0.1–300 GeV photons were selected from a circle of radius 0.9 deg centered on PSR B1259–63; therefore, no background subtraction was done. The upper and lower panels were obtained using maximum-likelihood analysis as described in Section 2.1, using 1 day and 5 day samplings, respectively. For 1 day time bins, the TS values and the best-fit photon indices from the likelihood analysis are shown in the middle panel.

Using 5 day sampling, significant GeV emission was observed between $t_p - 10$ days to $t_p + 15$ days and $t_p + 40$ days to $t_p + 75$ days, and we regard the second period as the major
GeV flaring period. However, as seen from the smaller time bins (i.e., 3 hr and 1 day), the GeV emission during this flaring period is highly variable over much shorter timescales, and several well-separated, sporadic major GeV flares can be seen. For example, the daily flux reaches $5 \times 10^{-6}$ cm$^{-2}$ s$^{-1}$ (the highest daily flux; the daily TS value is 220) on the 71st day after periastron and quickly drops below the 1 day sensitivity of the Fermi/LAT on the following day (with a TS value of 0), resulting in an upper limit of $1.3 \times 10^{-6}$ cm$^{-2}$ s$^{-1}$. On four occasions, the daily photon flux is $\gtrsim 3 \times 10^{-6}$ cm$^{-2}$ s$^{-1}$ (which occurs 42, 57, 59, and 71 days after periastron, and with TS values all above 130 during these four days). After that, the GeV emission is no longer detected, apart from a short episode in $t_p + 92$–93 days.

We show in Figure 1 the evolution of the photon index on a daily timescale. In contrast to the photon flux, the photon index does not change significantly over time, and remains at about 3.0.

Using 3 hr sampling, it can be seen that the daily variation comes from shorter time variation down to a few hours. The flux change can be up to more than one order of magnitude within 3 hr. This is the first time such a very fast and large variation has been reported for PSR B1259–63/LS 2883.

### 3.2 Properties of the γ-Ray Light Curves in 2017 Compared to Those in 2011 and 2014

Figure 2 shows the LAT daily flux variation of PSR B1259–63 during and after the three periastrons. The
The top panel shows the flux variation during the 2010 periastron with black points. The middle panel shows the flux variation during the 2014 periastron with blue points. The bottom panel shows the flux variation during the 2017 periastron with red points. For all three panels, the shaded regions indicate the stellar disk passage of PSR B1259−63, which we inferred from the X-ray data taken over the 2017 periastron (see Section 3.4). It is clear that all major GeV flares occur at orbital phases well after the second disk crossing, and the 2017 flares start at an orbital phase clearly different from those in 2011 and 2014. The light curves also differ; e.g., in 2017, the flares are more short-lived, while the GeV flares in 2011 and 2014 are more slowly varying, including the onset of the flares at \( t_p + 30–40 \) days.

To check whether the 2017 three-hour timescale flares are due to different data samplings, we also present 3 hr light curves in 2011 and 2014, again using aperture photometry, in Figure 3. One can see that the general flux variation over the two previous periastrons does not occur on such short timescales. Furthermore, even though some \( \sim 3 \) hr timescale flares are also seen in 2011 and 2014, the peak flux is the highest in 2017. This demonstrates that the difference in the appearance of the flares as seen in the year 2017 (as compared to 2011 and 2014) is robust against the different time bins used.

### 3.3. Characterizing the GeV Emission Before and During the Periastron

Using data for the three periastrons, we attempt to characterize the GeV emission before and during periastron. Data for each periastron as well as combined data from the three passages are shown in Figure 4. Since there is no evidence of short flares, 5 day sampling is employed to increase the photon statistics. Figure 4 shows the GeV emission before, during, and shortly after each periastron.

From GeV data taken during three periastrons, it is now established that there is clearly a GeV enhancement or brightening from about \( t_p - 20 \) days to \( t_p + 20 \) days (when stacked data from the three passages are used), which is well separated in time from the post-periastron GeV flare emission.

### 3.4. The X-Ray and \( \gamma \)-Ray Light Curves in 2014 and 2017

In X-rays, the 2017 light curve (also presented in Table 2) is similar to the 2014 one (Figure 5), and the slight difference could be caused by the inhomogeneous Be disk or the disk evolution. Since the X-ray light curve is best sampled in 2017, we obtain the Be disk crossing time of the pulsar using the two X-ray broad peaks in 2017 (using Gaussian fits), which is well explained by the terminal shock model of the PW (Chernyakova et al. 2006). The Gaussian fits return two peaks centered at \( t_p - 11.5 \) days and \( t_p + 21.5 \) days and an FWHM width of...
10.5 days each. We suggest that the first disk crossing is from \( t_p - 22 \) to \( t_p - 1 \) days, and the second crossing is from \( t_p + 12 \) to \( t_p + 31 \) days based on the X-ray data obtained in 2017. In 2014, only the post-periastron peak is evident, and it is centered at \( t_p + 20.5 \) days with an FWHM width of 6.5 days.

In Figure 5, the X-ray and \( \gamma \)-ray flux variations over the 2017 and 2014 periastrons are compared. In 2014, meanwhile, there are correlated X-ray/\( \gamma \)-ray activities during the GeV flares (c.f. Chernyakova et al. 2015; Tam et al. 2015); no correlation is visible in 2017. This may, however, be due to much sparser data coverage during the GeV flares by \textit{Swift} in 2017.

3.5. \textit{UVOT Results of the Last Three Periastrons}

In Figure 6, the X-ray and UV/optical variation is compared during the three periastron passages. There is no significant change in the magnitudes shown for the 2014 periastron. In 2017, the situation is rather different: (1) there is significant evolution in the W2 magnitude as well as in the M2 magnitude and (2) the W2 magnitude seems to follow the trend seen by XRT, which is observed for the first time. These changes may be related to the two disk crossings as the UVOT flux changes are most visible before or after the disk crossings.

4. Discussion

The most striking feature from this work is the different temporal evolution of the GeV flare occurring in 2017 compared to that seen in 2011 and 2014.

Previous \textit{Fermi} analysis works by Tam et al. (2015), Chernyakova et al. (2015), and Caliandro et al. (2015) have argued that the GeV light curves in 2010 and 2014 seem to show very similar onset times of the GeV flares \( \sim 30 \) days after the periastron passage and, to a lesser extent, the flare evolution
Figure 5. Left panel: comparison between the XRT (black) and LAT (blue) observations (1 day sampling) of the 2017 periastron. The Gaussian fits (in red) return two X-ray peaks centered at $t_p - 11.5$ days and $t_p + 21.5$ days and an FWHM width of 10.5 days each. Right panel: comparison between the XRT (black) and LAT (blue) observations (1 day sampling) of the 2014 periastron. In X-rays, only the post-periastron peak is evident, and the Gaussian fit is centered at $t_p + 20.5$ days and has an FWHM width of 6.5 days.

Table 2

| $t - t_p$ Days | $n_H$ $10^{22}$ cm$^{-2}$ | $\Gamma$ | XRT Flux $\times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$ | $\chi^2$ (df) |
|----------------|--------------------------|--------|-----------------|----------------|
| $-$4.30        | 0.69                     | 2.19$^{+0.34}_{-0.35}$ | 2.51$^{+0.25}_{-0.26}$ | 0.75(49)       |
| 0.82           | 0.5                      | 1.66$^{+0.48}_{-0.40}$ | 1.58$^{+0.26}_{-0.25}$ | 0.89(21)       |
| 6.00           | 0.5                      | 1.77$^{+0.99}_{-0.47}$ | 1.29$^{+0.31}_{-0.36}$ | 1.23(8)        |
| 13.67          | 0.5                      | 1.58$^{+0.16}_{-0.16}$ | 3.31$^{+0.26}_{-0.26}$ | 0.84(11)       |
| 16.85          | 0.6                      | 1.69$^{+0.32}_{-0.30}$ | 4.79$^{+0.34}_{-0.35}$ | 0.97(104)      |
| 19.90          | 0.68                     | 1.51$^{+0.32}_{-0.30}$ | 5.25$^{+0.59}_{-0.51}$ | 0.81(62)       |
| 21.62          | 0.7                      | 1.80$^{+0.16}_{-0.22}$ | 4.79$^{+0.35}_{-0.35}$ | 0.86(99)       |
| 22.69          | 0.7                      | 1.82$^{+0.19}_{-0.31}$ | 5.01$^{+0.44}_{-0.44}$ | 0.70(70)       |
| 24.01          | 0.5                      | 1.66$^{+0.31}_{-0.24}$ | 5.13$^{+0.27}_{-0.27}$ | 1.04(175)      |
| 25.87          | 0.6                      | 1.42$^{+0.25}_{-0.25}$ | 5.89$^{+0.57}_{-0.57}$ | 0.82(61)       |
| 28.20          | 0.5                      | 1.43$^{+0.14}_{-0.24}$ | 3.39$^{+0.24}_{-0.24}$ | 0.79(105)      |
| 31.34          | 0.57                     | 1.52$^{+0.24}_{-0.19}$ | 2.69$^{+0.22}_{-0.22}$ | 0.80(85)       |
| 34.24          | 0.5                      | 1.43$^{+0.27}_{-0.33}$ | 2.24$^{+0.25}_{-0.25}$ | 0.93(46)       |
| 35.90          | 0.7                      | 1.63$^{+0.17}_{-0.17}$ | 2.24$^{+0.20}_{-0.20}$ | 1.07(74)       |
| 38.03          | 0.5                      | 1.41$^{+0.24}_{-0.24}$ | 2.14$^{+0.25}_{-0.25}$ | 0.77(43)       |
| 39.15          | 0.5                      | 1.63$^{+0.20}_{-0.20}$ | 2.57$^{+0.26}_{-0.26}$ | 0.64(55)       |
| 41.01          | 0.7                      | 1.54$^{+0.18}_{-0.14}$ | 2.82$^{+0.20}_{-0.20}$ | 0.86(113)      |
| 57.68          | 0.5                      | 1.39$^{+0.25}_{-0.22}$ | 2.04$^{+0.22}_{-0.22}$ | 0.71(47)       |
| 69.05          | 0.5                      | 1.47$^{+0.23}_{-0.25}$ | 1.05$^{+0.13}_{-0.13}$ | 0.70(40)       |
| 78.01          | 0.6                      | 1.64$^{+0.20}_{-0.20}$ | 1.15$^{+0.14}_{-0.14}$ | 1.14(43)       |
| 90.10          | 0.5                      | 1.65$^{+0.42}_{-0.34}$ | 0.68$^{+0.12}_{-0.12}$ | 0.9(17)        |
| 92.31          | 0.7                      | 1.44$^{+0.26}_{-0.26}$ | 0.91$^{+0.15}_{-0.15}$ | 0.8(18)        |

Note. $n_H$ is the interstellar absorption obtained for the TRabbs model. $\Gamma$ is the power-law index of the XRT spectrum. Unabsorbed flux is calculated for the energy range $0.3–10$ keV.

So far, the GeV flaring periods lasting for 1–2 months, which are still periodic (i.e., occurring after the second disk crossing), suggest that the GeV flares are likely associated with the pulsar passing through the dense gas in the Be star disk. Meanwhile, the random short flares seen especially in 2017 require a source other than the accelerated particles in the terminal shock. This terminal shock model has explained the periodic light curve of the non-thermal X-ray emission very well; see, e.g., Takata et al. (2012). In a previous modeling work on the GeV flare, Khangulyan et al. (2012) used the IC scattering of the unshocked PW off soft photons from the Be star, while Dubus & Cerutti (2013) brought up an IC model using the X-ray synchrotron radiation from the shock as the IC target photons. Kong et al. (2012) used the synchrotron model with relativistic flows beaming toward Earth along the bow shock tails. All of these previous models, which are heavily dependent on the terminal shock geometry, lack an explanation for either the delay of the GeV flaring period or the sporadic hour-timescale flares.

Notably, to explain the GeV flares with timescales of several days in the Crab Nebula, Lyutikov et al. (2012) introduced the corrugation perturbations of the terminal shock, which allow fast changes in the Doppler beaming of the post-shock synchrotron emission, and the GeV timescale of such a model relies on the overall dynamics of the termination shock rather than on the decaying time of the high-energy particles. However, in such a case, we can only see GeV flares when the terminal shock is formed on the observer’s side. As another option to explain the fast GeV flares in PSRs, magnetic reconnection is also a plausible choice; see, e.g., Cerutti et al. (2014).

Recently, Yi & Cheng (2017) raised the idea that the delay of the entire GeV flare package could be explained by the timescale of formation of an accretion disk. This work used the accretion disk to gain sufficient soft photons for the IC process of the PW, yet it did not provide an explanation for the very short flares. GeV emission regions with length scales down to the size of the accretion disk or even down to the NS itself remain possible candidates in explaining the <3 hr GeV flares. So far, there have been no direct observational evidences of an accretion disk or a periodic NS glitch that corresponds to each periastron passage (Yi & Cheng 2018).

up to $t_p + 75$ days. However, during the most recent 2017 periastron passage, our Fermi analysis work has discovered very short yet very powerful GeV flares on timescales down to 3 hr in 2017, which is limited by the cadence of the Fermi observations of the source in the all-sky observing mode. In sharp contrast to the light curve, the GeV spectrum remains rather stable both over each periastron passage and between flares that are separated by 3.4 years.
Apart from the GeV flares, in this work we also established the GeV brightening from about \( t_p - 20 \) days to \( t_p + 20 \) days, which is well separated in time from the flares. The origin and emission mechanism of this brightening are unclear, and it would be interesting to see if it is due to either the close encounter between the pulsar and the massive star (Tavani & Arons 1997; Kirk et al. 1999), or to the pre-periastron disk passage (Yi & Cheng 2017).

To conclude, we found short-lived but powerful GeV flares on timescales of down to about three hours, after the recent 2017 periastron passage. The onset of the GeV flaring period in 2017 is also delayed compared to that seen in 2011 and 2014. On the other hand, the X-ray flux shows a similar variation from 2010 to 2017. During the 2017 passage, the UV flux shows significant variation in two filters, and it may be correlated to the X-ray flux variation. Observing PSR B1259−63/LS 2883 in subsequent periastron passages will help us to obtain more knowledge on the hidden physics and emission mechanisms that produce the GeV flares.

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**References**

Abdo, A. A., Ackermann, M., Ajello, M., et al. (Fermi/LAT Collaboration) 2011, ApJL, 736, L11

Acero, F., Ackermann, M., Ajello, M., et al. 2015, ApJS, 218, 23

Aharonian, F. A., Akhperjanian, A. G., Anton, G., et al. (H.E.S.S. Collaboration) 2009, A&A, 507, 389

Aharonian, F. A., Akhperjanian, A. G., Aye, K.-M., et al. (H.E.S.S. Collaboration) 2005, A&A, 442, 1

Bogovalov, S. V., Khangulyan, D. V., Koldoba, A. V., Ustyugova, G. V., & Aharonian, F. A. 2008, MNRAS, 387, 63

Caliandro, G. A., Cheung, C. C., Li, J., et al. 2015, ApJ, 811, 68

Corbet, R. H. D., Chomiuk, L., Coe, M. J., et al. 2016, ApJ, 829, 105

Dubus, G. 2006, A&A, 451, 9

Dubus, G. 2013, A&ARv, 21, 64

Dubus, G. 2015, CRPhys, 16, 661

Dubus, G., & Cerutti, B. 2013, A&A, 557, A127

Dubus, G., Cerutti, B., & Henri, G. 2010, A&A, 516, 18

H.E.S.S. collaboration, 2013, A&A, 551, A94

**ORCID iDs**

P. H. T. Tam @ https://orcid.org/0000-0002-1262-7375

**Figure 6.** Comparison between the XRT and UVOT observations of the 2010, 2014, and 2017 periastrons. The W2 filter magnitude is offset by +0.4 and the U filter by −0.6.
Ho, W. C. G., Ng, C. Y., & Lyne, A. G. 2016, MNRAS, 464, 1211
Johnston, S., Ball, L., Wang, N., & Manchester, R. N. 2005, MNRAS, 358, 1069
Johnston, S., Manchester, R. N., Lyne, A. G., Nicastro, L., & Spyromilio, J. 1994, MNRAS, 268, 430
Khangulyan, D., Aharonian, F. A., Bogovalov, S. V., & Ribó, M. 2011, ApJ, 742, 98
Khangulyan, D., Aharonian, F. A., Bogovalov, S. V., & Ribó, M. 2012, ApJL, 752, L17
Kirk, J. G., Ball, L., & Skjæraasen, O. 1999, APh, 10, 31
Kong, S. W., Cheng, K. S., & Huang, Y. F. 2012, ApJ, 753, 127
Kong, S. W., Yu, Y. W., Huang, Y. F., & Cheng, K. S. 2011, MNRAS, 416, 1067
Lyutikov, M., Balsara, D., & Matthews, C. 2012, MNRAS, 422, 3118
Mochol, I., & Kirk, J. G. 2013, ApJ, 776, 40
Shannon, R. M., Johnston, S., & Manchester, R. N. 2014, MNRAS, 437, 3255
Takata, J., Okazaki, A. T., Nagataki, S., et al. 2012, ApJL, 750, L10
Tam, P. H. T., Li, K. L., Takata, J., et al. 2015, ApJL, 798, L26
Tavani, M., & Arons, J. 1997, ApJ, 477, 439
Yi, S.-X., & Cheng, K. S. 2017, ApJ, 844, 114
Yi, S.-X., & Cheng, K. S. 2018, MNRAS, 476, 766