DISCOVERY OF GeV γ -RAY EMISSION FROM PSR B1259−63/LS 2883

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ABSTRACT

The binary system PSR B1259−63/LS 2883 consists of a 47.8 ms radio pulsar that orbits the companion Be star with a period of 3.4 years in a highly eccentric orbit. The system has been well sampled in radio, X-ray, and TeV γ -ray bands, and shows orbital phase-dependent variability in all observed frequencies. Here we report on the discovery of >100 MeV γ -rays from PSR B1259−63/LS 2883 through the 2010 periastron passage. Using data collected with the Large Area Telescope on board Fermi from 33 days before periastron to 75 days after periastron, PSR B1259−63/LS 2883 was detected at a significance of 13.6 standard deviations. The γ -ray light curve was highly variable over this period, with a changing photon index that correlates with the γ -ray flux. In particular, two major flares that occur after the periastron passage were observed. The onset of γ -ray emission occurs close to, but not at the same orbital phases as, the two disk passages that occur ~1 month before and ~1 month after the periastron passage. The fact that the GeV orbital light curve is different from that of the X-ray and TeV light curves strongly suggests that GeV γ -ray emission originates from a different component. We speculate that the observed GeV flares may be resulting from Doppler boosting effects.

Key words: gamma rays: stars – pulsars: individual (PSR B1259−63) – radiation mechanisms: non-thermal – X-rays: binaries

Online-only material: color figures

1. INTRODUCTION

The binary system PSR B1259−63/LS 2883 is comprised of a 47.8 ms radio pulsar that orbits the companion Be star with a period of 3.4 years in a highly eccentric orbit (Johnston et al. 1994). The high spin-down power of PSR B1259−63/LS 2883 (e ~ 0.87) orbit, the pulsar approaches the periastron every 3.4 years. The system has been well sampled in radio, X-ray, and TeV γ -ray bands, and shows orbital phase-dependent variability in all observed frequencies. Here we report on the discovery of >100 MeV γ -rays from PSR B1259−63/LS 2883 through the 2010 periastron passage. Using data collected with the Large Area Telescope on board Fermi from 33 days before periastron to 75 days after periastron, PSR B1259−63/LS 2883 was detected at a significance of 13.6 standard deviations. The γ -ray light curve was highly variable over this period, with a changing photon index that correlates with the γ -ray flux. In particular, two major flares that occur after the periastron passage were observed. The onset of γ -ray emission occurs close to, but not at the same orbital phases as, the two disk passages that occur ~1 month before and ~1 month after the periastron passage. The fact that the GeV orbital light curve is different from that of the X-ray and TeV light curves strongly suggests that GeV γ -ray emission originates from a different component. We speculate that the observed GeV flares may be resulting from Doppler boosting effects.

Key words: gamma rays: stars – pulsars: individual (PSR B1259−63) – radiation mechanisms: non-thermal – X-rays: binaries

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2. FERMI/LAT OBSERVATIONS AND RESULTS

The LAT on board the Fermi Gamma-ray Space Telescope can detect γ -rays with energies between ~20 MeV and >300 GeV (Atwood et al. 2009). The γ -ray data used in this work were obtained between 2008 August 4 and 2011 February 28. These data are available at the Fermi Science Support Center. Due to the discovery of γ -rays from PSR B1259−63/LS 2883, a modified sky survey was commenced from 2010 December 27

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for 10 days. In this mode the southern hemisphere receives 30% extra exposure. We used the Fermi Science Tools v9r18p6 package to reduce and analyze the data in the vicinity of PSR B1259–63/LS 2883. Only events that are classified as the “diffuse” class or the “data-clean” class were used. To reduce the contamination from Earth albedo $\gamma$-rays, we excluded events with zenith angles greater than 105°. The instrument response functions “P6_V3_DIFFUSE” were used.

We carried out unbinned maximum-likelihood analyses (gtlike) of the circular region with a 15° radius centered on the $\gamma$-ray position of PSR B1259–63 (see the following text). We subtracted the background contribution by including the Galactic diffuse model (gll_iem_v02.fit) and the isotropic background (isotropic_iem_v02.txt), as well as all sources in the first Fermi/LAT catalog (1FGL; Abbdo et al. 2010b) within the circular region of 25° radius centered on the $\gamma$-ray position of PSR B1259–63. We assumed single power laws (PLs) for all 1FGL sources considered, except for $\gamma$-ray pulsars of which the spectra follow PLs with exponential cutoff (Abbdo et al. 2010a). The spectral parameter values for sources within 10° from PSR B1259–63 as well as the normalization parameters of the diffuse components were set as free.

No significant emission was found before 2010 November 11. We derived upper limits of $\gamma$-ray flux from PSR B1259–63/LS 2883 using data obtained between 2008 August 4 and 2010 November 10 (see Figure 1). However, the source became active

Figure 1. X-ray, GeV, and TeV observations of PSR B1259–63/LS 2883. The error bars represent 68% confidence-level uncertainties. (a) Light curve derived from Fermi/LAT data taken from 2008 August 4 to 2011 February 21. For better visualization in the true anomaly scale, bins span variable time duration: between 2010 November 18 and 2011 February 9, three-day bins were used, apart from the quiescent period (Q1) between 2010 December 15 and 2011 January 13. Power law is assumed in deriving the flux with the photon index being free. For periods without significant detection (i.e., TS < 5), two confidence-level upper limits were calculated assuming $\Gamma = 2.1$; (b) LAT photon index variation over time; (c) X-ray light curve over the 2010 and previous periastron passages. 2004 XMM-Newton observations (Chernyakova et al. 2006) are marked with triangles, 2007 Suzaku observations with circles, 2007 Swift observations with crosses, 2007 Chandra observations with solid circles (Chernyakova et al. 2009), and 2010/2011 Swift observations with stars (this work); (d) evolution of the X-ray photon index. Notations are the same as in panel (c); (e) gamma-ray light curve above 1 TeV. The measurements were carried out by H.E.S.S. through the 2004 (fluxes using a bin width of two days; Aharonian et al. 2005) and 2007 (monthly fluxes) periastron passages (Aharonian et al. 2009). Also shown are 2005 and 2006 data (Aharonian et al. 2009).
roughly when PSR B1259−63 entered the stellar disk (Tam et al. 2010; Abdo et al. 2010d).

We first analyzed 0.2–100 GeV data from 2010 November 11 to 2011 February 28. Using a PL description of PSR B1259−63, the maximized test-statistic (TS) value (Mattox et al. 1996) obtained for PSR B1259−63 is 184, corresponding to a detection significance of 13.6σ. This allows us to classify PSR B1259−63/LS 2883 as a new GeV γ-ray source. The best-fit position of the γ-ray emission is estimated by gtfindsrc to be at right ascension (J2000) = 195°67 and declination (J2000) = −63°73 with statistical uncertainty 0.06 (0°14) at the 68% (95%) confidence level, which is consistent with the position of PSR B1259−63. The systematic uncertainty is estimated to be up to ~40% (Abdo et al. 2009a).

2.1. Light Curve

We then derived a 0.2–100 GeV light curve composed mostly of 3 day bins (Figure 1). Such bin size ensures enough photon statistics without loosing information on short timescale variability. Finer binning (e.g., 1 day) results in low significance for most of the days and high statistical uncertainties in deriving fluxes and photon indices, except for the flaring period that occurs between 2011 January 14 and February 3. For data taken more than one month before and two months after the 2010 periastron passage, larger bins were employed for better visualization. From 2010 December 15 to 2011 January 13, no evidence for γ-ray emission was found, as first noted in Kong et al. (2011a). We therefore derive an upper limit for the above quiescent period. Data points represent the flux values with TS > 5, for which photon indices are also shown. Otherwise, an upper limit is derived.

As shown in Figure 1, the γ-ray light curve is highly variable through the 2010 periastron passage: (1) the source started to be active in γ-rays about a month before 2010 periastron passage (P1); (2) it remains undetected for about one month since mid-December (Q1); (3) subsequently, a major flaring period was identified; it peaks at ~35 days after periastron. Having an average flux higher than that in P1 by an order of magnitude, this flare lasted for only ~7 days (P2); (4) a second flare that peaks at ~46 days after periastron, however, lasted longer, so that the source was detected until the end of February (P3 and P4). To probe shorter timescale variability during the flaring period (i.e., P2 and P3), we also produced the light curve with 1 day binning during January 14 to February 4 (Figure 2). Here 0.1–100 GeV photons were used to increase photon statistics. To better demonstrate the variability, we plot data points with TS > 5 (rather than the more standard criterion of TS > 9) as flux values since a substantial number of data are of TS between 5 and 9. It can be seen that γ-rays from PSR B1259−63/LS 2883 undergo rapid variations down to a timescale of one day. Such variability is one of the fastest detected from any Galactic GeV source on the sky. No emission was detected during January 22–26, indicating that the source underwent a short quiescent period between the two major flares.

We also show in Figure 1 the orbital X-ray and TeV light curves. The GeV orbital light curve is different than the X-ray and TeV light curves, suggesting that the origin of GeV γ-rays is different than the others.

2.2. Spectral Analysis

As the derived photon indices change significantly with time, we defined four periods that are indicated in Figure 1 and Table 1. We further divided the 0.1–300 GeV γ-rays arriving during P1, P2, P3, and P4, respectively, into six energy bins of logarithmically equal bandwidths and reconstructed the flux using glike for each band independently. A PL model for each bin was assumed and the photon spectral index was fixed at a representative value ηγ = 2.8. While the emission is detected (i.e., TS > 5) from 1.4 GeV to 20 GeV for P1, no γ-ray source was apparent at the PSR B1259−63 position in the four bins above 1.4 GeV (the derived TS values <5) in the likelihood analysis for P2, P3, and P4, indicating a cutoff at energy ~1 GeV during the flaring period. See Figure 3 for the spectrum derived from a combined analysis of P2 and P3. We therefore attempted to fit the 0.1–100 GeV spectrum with a PL, with an exponential cutoff (PLE), as well as a broken PL. We found that PLE describes the spectrum even better during the periods P2, P3, and P4, by being free are not well constrained; we therefore do not consider this model.

At a distance 2.3 kpc (Negueruela et al. 2011), the average energy flux during the flares of ~3 × 10^{-10} erg cm^{-2} s^{-1} corresponds to the γ-ray luminosity 1.9 × 10^{35} erg s^{-1}. Given the pulsar spin-down luminosity ~8 × 10^{35} erg s^{-1}, the average γ-ray efficiency is about 25% during the flares.

To demonstrate that GeV emission originates from a component that is temporally and spectrally different than the TeV emission, we put together the 100 MeV to 300 GeV spectra and the >300 GeV γ-ray spectra obtained for different orbital phases in Figure 3. It is clear that the GeV emission evolves differently compared with the TeV emission, assuming that the TeV behavior does not change dramatically between 2004 and 2010 periastron passages. We note a substantial difference in the GeV spectra during P1 and that in the “brightening period” as in Abdo et al. (2011). The difference is partly caused by the different periods used. The “brightening period” in Abdo et al.
estimating the background. Abdo et al. (2011) essentially includes P1 and Q1. It is clear from Figure 3 that the spectrum for Q1 is much softer than for P1. Moreover, Abdo et al. (2011) uses an internal 18 month source catalog in estimating the background.

Table 1
0.1–100 GeV γ-ray Properties During Different Periods Through the 2010 Periastron Passage

| Period | Year | Date       | True Anomaly | Model | Photon Flux (cm² s⁻¹) | Energy Flux (erg cm⁻² s⁻¹) | Photon Index | Cutoff Energy (MeV) | TS/ sig | ∆TS/ sig |
|--------|------|------------|--------------|-------|-----------------------|-----------------------------|--------------|---------------------|--------|---------|
| P1     | 2010 | Nov 11–Dec 14 | −115.3–2.1  | PL    | (9.9 ± 4.1) × 10⁻⁶    | (5.8 ± 1.6) × 10⁻¹¹         | 2.1 ± 0.2    | 31/5.6σ            |        |         |
| P2     | 2011 | Jan 14–Jan 22 | 111.7–120.0 | PL, PLE | (1.5 ± 0.2) × 10⁻⁶  | (2.9 ± 0.3) × 10⁻¹⁰         | 3.0 ± 0.1    | 163/12.8σ          |        |         |
| P3     | 2011 | Jan 26–Feb 3  | 122.2–127.2 | PL    | (1.4 ± 0.2) × 10⁻⁶    | (3.1 ± 0.4) × 10⁻¹⁰         | 2.8 ± 0.1    | 109/4.6σ           |        |         |
| P4     | 2011 | Feb 4–Feb 21  | 127.2–135.1 | PL, PLE | (8.7 ± 1.1) × 10⁻⁷   | (1.9 ± 0.2) × 10⁻¹⁰         | 2.8 ± 0.1    | 97/9.9σ            |        |         |

Figure 4. Photon flux vs. photon index in the 0.2–100 GeV band. Data are binned in the same manner as in Figure 1. Data obtained during periods P1, P2, P3, and P4 are shown in black, red, blue, and green, respectively.

(A color version of this figure is available in the online journal.)

2.3. Correlation Between Flux and Photon Index

In Figure 4 we plot γ-ray flux versus photon index, showing a correlation between these two quantities. We carried out a non-parametric correlation analysis. The computed Spearman rank correlation coefficient between two quantities is −0.7363. The probability that this coefficient is different than zero is 0.9959. We have also calculated the linear correlation coefficient (i.e., Pearson’s r), resulting in Pearson’s r = −0.7874 and the probability that this coefficient is different than zero is 0.9986.

3. DISCUSSION

High-energy emissions from γ-ray binaries (PSR B1259−63, LS 5039, and LS I+61°303) have been discussed using leptonic models (e.g., Tavani & Arons 1997; Dubus 2006; Takata & Taam 2009) and hadronic models (e.g., Kawachi et al. 2004; Chernyakova et al. 2009). In leptonic models, PW particles (electrons and positrons) are accelerated at the shock where the dynamical pressure of the PW and that of the stellar wind are in balance. These particles in turn emit non-thermal photons over a wide range of energies via synchrotron radiation (radio to GeV γ-rays) and inverse-Compton (IC) upscattering off star light (>10 GeV γ-rays), resulting in two peaks in the broadband spectrum. In hadronic models (e.g., Chernyakova et al. 2006, 2009), the IC emission of high-energy electrons resulting from π⁰-decay is responsible for emission from optical up to TeV
energies. In this case, the broadband spectrum is rather flat in the energy range of 0.1–100 GeV.

During the pre-periastron epoch, GeV emission at a flux level ~6 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1} is detected from mid-November through mid-December. The fitted spectrum during this period (P1) is relatively hard ($\Gamma_\gamma \sim 2$). Such hardness may be consistent with both the hadronic and the leptonic models (see below for a discussion of the leptonic interpretation during this period).

The onset of the flare-like GeV emission at the true anomaly $110^\circ$–130$^\circ$ occurred close to the disk passage at the true anomaly $80^\circ$–140$^\circ$, suggesting that the origin of the $\gamma$-rays might be related to the disk passage. On one hand, the observed cutoff at several hundred MeV does not favor hadronic models. On the other hand, it may be difficult to explain the flare-like GeV emission using simple leptonic models as well. First, leptonic models predict a cutoff around 100 MeV for a synchrotron spectrum (e.g., Takata & Taam 2009). Second, the stellar disk pushes the shock toward the pulsar when the pulsar encounters the disk. Although the increase of the magnetic field enhances the synchrotron power, it also reduces the synchrotron cooling time of the accelerated particles. As GeV photons are emitted by fast-cooling particles, these two effects should compensate each other. Consequently, the shift of the shock position due to the stellar disk cannot enhance the GeV emission to the level that we observe.

Doppler boosting may provide a plausible mechanism to produce the GeV flares during 2011 January 14 to February 3 (see also Kong et al. 2011b). Numerical simulations in the hydrodynamic limit imply that the post-shock bulk flow for the binary system can be accelerated in relativistic regime because of a rapid expansion of the flow in the downstream region (Bogovalov et al. 2008). For example, Dubus et al. (2010) discussed the effects of Doppler boosting on the orbital modulations of the X-ray and TeV emission. If the bulk flow is relativistic and oriented radially away from the star, the Doppler effect may be at work close to the true anomaly corresponding to the direction of the Earth ($\sim 130^\circ$). This is approximately the time when the GeV flares were observed (i.e., $110^\circ$–130$^\circ$). The Doppler effect increases the photon energy as $E = D E' \alpha$ and the intensity as $I_\gamma \propto D^{3+\alpha} I'_\gamma$, where $D$ is the Doppler factor and $\alpha = \Gamma - 1$ is the spectral index. Non-prime and prime notations represent quantities in the observer and comoving frames, respectively.

In $\gamma$-rays, $\alpha_\gamma \sim 1$–2 is expected from synchrotron radiation models, which is consistent with the Fermi results. An enhancement factor of 5–10 in flux during flares (P2 and P3) compared to the emission before periastron (P1; see Table 1 for details) suggests $D \sim 1.5$–2.

Suzaku observations indicate a low-energy break, i.e., around 10 keV (Uchiyama et al. 2009). Because the photon index of the synchrotron spectrum below the break is $\alpha = -1/3$, the enhancement factor becomes $D^{3-1/3} \sim 3$. Thus, the enhancement in X-rays is suppressed compared to $\gamma$-rays. It is important to obtain simultaneous observations in X-rays and gamma-rays during the flaring period to test the boosting model.

In leptonic models, the correlation between $\Gamma_\gamma$ and flux (Figure 4) may be understood as follows. If the Doppler effect is responsible for the flares, photons are boosted to higher energies and the observed synchrotron flux is amplified. However, the Doppler boost does not affect much the photon flux of the IC component, since more scatters between particles and incident photons would occur in the Klein–Nishina regime. Consequently, the increase in the IC flux by the Doppler boosting and the decrease due to the Klein–Nishina effect will compensate each other. The energy flux of the synchrotron radiation becomes much higher than the IC radiation, causing the 0.1–100 GeV spectrum to be dominated by the high-energy tail of the synchrotron spectrum. This gives rise to the steep spectrum ($\sim 3$; corresponding to flare emission) shown in Figure 4. The emission before periastron (with $\Gamma_\gamma \sim 2$) may be related to emission originating just behind the shock where the bulk Lorentz factor is $\sim 1$. Some leptonic models (e.g., Takata & Taam 2009; Dubus et al. 2010) have predicted similar energy fluxes of synchrotron and IC radiation just behind the shock, hence $\Gamma_\gamma \sim 2$, which is close to the observed value in the PL fit. Although there is no evidence for two spectral components during the pre-periastron period (see Figure 3), this possibility cannot be excluded given the relatively low significance detection, i.e., $\sim 5\sigma$, during this period.

PSR B1259–63/LS 2883 is the third known binaries with significant detection in GeV, after LS I+61$^\circ$303 (Abdo et al. 2009b) and LS 5039 (Abdo et al. 2009c). It may be intuitive to compare the three $\gamma$-ray binaries.

1. For LS I+61$^\circ$303 and PSR B1259–63, the GeV gamma-ray peak occurs after periastron (and before apastron), though not in the same orbital phase. For LS 5039, the gamma-ray emission peaked at periastron.

2. While no orbital phase-related spectral change has been reported in LS I+61$^\circ$303, the “softer when brighter” behavior of GeV $\gamma$-rays has been found for both LS 5039 and PSR B1259–63.

3. In all three systems, spectral cutoff is observed at GeV energies during at least part of the orbit.

4. In all three systems, the X-ray and TeV light curves are more correlated whereas GeV $\gamma$-rays always come out in different orbital phases (Anderhub et al. 2009; Takahashi et al. 2009). This strongly suggests that GeV $\gamma$-rays originate from components different than the other two energy bands.

PSR B1259–63/LS 2883 is the only system among these three for which the nature of the compact object is certain. Given the similarities of some emission features of these systems, the results presented here should shed light on the GeV radiation mechanism of the other systems.

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