DISCOVERY OF $\gamma$-RAY PULSATION AND X-RAY EMISSION FROM THE BLACK WIDOW PULSAR PSR J2051−0827

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ABSTRACT

We report the discovery of pulsed $\gamma$-ray emission and X-ray emission from the black widow millisecond pulsar PSR J2051−0827 by using the data from the Large Area Telescope (LAT) on board the Fermi Gamma-ray Space Telescope and the Advanced CCD Imaging Spectrometer array on the Chandra X-Ray Observatory. Using three years of LAT data, PSR J2051−0827 is clearly detected in $\gamma$-rays with a significance of $\sim 8\sigma$ in the 0.2−20 GeV band. The 200 MeV−20 GeV $\gamma$-ray spectrum of PSR J2051−0827 can be modeled by a simple power law with a photon index of $2.46 \pm 0.15$. Significant ($\sim 5\sigma$) $\gamma$-ray pulsations at the radio period were detected. PSR J2051−0827 was also detected in soft (0.3−7 keV) X-ray with Chandra. By comparing the observed $\gamma$-rays and X-rays with theoretical models, we suggest that the $\gamma$-ray emission is from the outer gap while the X-rays can be from intra-binary shock and pulsar magnetospheric synchrotron emissions.

Key words: gamma rays: stars – pulsars: individual (PSR J2051−0827) – X-rays: individuals (PSR J2051−0827)

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1. INTRODUCTION

It is widely accepted that millisecond pulsars (MSPs) have been spun up by accreting masses from a close binary companion (Alpar et al. 1982). A sub-class of binary systems consist of an MSP and a very-low-mass companion ($M_c < 0.05 M_{\odot}$) orbiting in a tight orbit ($P_b < 24$ hr). In such systems particles or $\gamma$-rays emitted from the pulsar are thought to be ablating the companion, which would eventually destroy the companion, resulting in a solitary MSP (Fruchter et al. 1995; Takata et al. 2012); MSPs in this kind of binary system are usually called black widow pulsars.

PSR J2051−0827 is the second black widow pulsar after PSR B1957+20 (Fruchter et al. 1988). PSR J2051−0827 was discovered in 1996 in the Parkes all-sky survey of the southern sky for low luminosity and MSPs (Stappers et al. 1996a). The spin period of PSR J2051−0827 is 4.5 ms. The MSP is orbiting around a very-low-mass companion ($m_c < 0.027 M_{\odot}$) with an orbital period of 2.4 hr, thus joining the black widow population (Stappers et al. 1996a). Since the discovery of this pulsar, follow-up observations have been performed to reveal the nature of this black widow system (Stappers et al. 1996b, 1999, 2001; Doroshenko et al. 2001; Lazaridis et al. 2011).

Before the launch of the Fermi Large Area Telescope (LAT), all black widow pulsars have been found by radio surveys but most of them are in globular clusters (GCs). As GCs usually hold a large number of MSPs and many GCs are $\gamma$-ray emitters (Abdo et al. 2010; Kong et al. 2010; Tam et al. 2011). However, we cannot resolve individual pulsars in $\gamma$-rays in GCs due to the limited angular resolution of Fermi-LAT, which makes studies of $\gamma$-ray black widow pulsars in GCs challenging. After the launch of Fermi-LAT, increasingly more field black widows were identified as Fermi sources, opening a new observation window of black widow pulsars studies, and providing a larger sample for characteristic studies on black widow pulsars. So far a total of 10 black widow pulsars have been found in the Galactic field, in which 7 of them are Fermi sources and at least 3 of them show pulsed $\gamma$-rays (Roberts 2011). Among those which have remained undetectable in $\gamma$-rays, PSR J2051−0827 is the closest one with a distance of $1.04 \pm 0.01$ kpc (Lazaridis et al. 2011), which increases the chance of detecting it in $\gamma$-rays despite it having a relatively low spin-down power $E = 5.3 \times 10^{34}$ erg s$^{-1}$ (Stappers et al. 1996a). In this paper, we present the discovery in $\gamma$-rays and X-rays using Fermi-LAT and Chandra data.

2. DATA ANALYSIS AND RESULTS

2.1. Gamma-Ray Data

In our analysis, we used the LAT data between 2008 August and 2011 September (~3 years of data). To reduce and analyze the data, the Fermi Science Tools v9r23p1 package, which is available from the Fermi Science Support Center, was used. We used Pass 7 data and selected events in the “Diffuse” class (i.e., event class 2) only. In addition, we excluded the events with zenith angles larger than 100° to reduce the contamination by Earth albedo gamma rays. The instrumental response functions “P7SOURCE_V6” were adopted throughout this study.

Events were selected within a circular region of interest (ROI) centered at the nominal position of PSR J2051−0827 (i.e., R.A. = $20^\circ51^\prime07^\prime.51$, decl. = $18^\circ27^\prime37^\prime.7$). In order to reduce systematic uncertainties and achieve a better background modeling, a circular ROI with a diameter of 10° was adopted throughout the unbinned likelihood analysis. For a preliminary inspection of the chosen part of the sky around PSR J2051−0827, a binned photon count map in 1–20 GeV was produced with task gbind (see Figure 1). $\gamma$-ray excess can be clearly identified around the nominal position of PSR J2051−0827 even before subtracting the background.

To investigate the spectral characteristics of PSR J2051−0827, we performed an unbinned likelihood analysis with gtlike, by assuming a power law (PL) as well as a power law with

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$^{4}$ http://fermi.gsfc.nasa.gov/ssc/data/analysis/software/
an exponential cutoff (PLE) model for a point \( \gamma \)-ray source at the nominal position of PSR J2051–0827. Photon energies are restricted to 200 MeV–20 GeV. In the background model, we included the Galactic diffuse model (gal_2yearp7v6_v0.fits) and the isotropic background (iso_p7v6source.txt), as well as all point sources reported in the Second Fermi-LAT Source (2FGL) catalog within 10° from the center of the ROI. All these 2FGL sources were assumed to be point sources which have the specific spectrum suggested in the 2FGL catalog (Abdo et al. 2011). While the spectral parameters of the 2FGL sources located within the ROI were set to be free, we kept the parameters for those lie outside our adopted ROI fixed at the values given in the 2FGL catalog (Abdo et al. 2011). We also allowed the normalization factors of the two diffuse background components to vary. The best-fit PL model yields a photon index of \( \Gamma = 2.46 \pm 0.15 \) and a test-statistic (TS) value of 66, which corresponds to a significance of \( \sim 8 \sigma \). Its photon flux in this band is found to be \( (6.62 \pm 1.29) \times 10^{-9} \text{ cm}^{-2} \text{ s}^{-1} \). The corresponding integrated energy flux is \( f_\gamma = 5.92^{+4.75 \times 10^{-12}}_{-3.24 \times 10^{-12}} \text{ erg cm}^{-2} \text{ s}^{-1} \).

For the PLE model, the best-fit results in a photon index of \( \Gamma = 1.75 \pm 0.58 \) and a cutoff energy of \( E_{\text{cutoff}} = 2.5 \pm 2 \text{ GeV} \), giving a TS value of 70, which corresponds to a significance of \( \sim 8.4 \sigma \). Based on the likelihood ratio test, the PLE models are not statistically required to fit the observed \( \gamma \)-ray spectrum. This may be due to the low photon statistic and the contamination from the diffuse \( \gamma \)-ray background. The binned spectrum is displayed in Figure 2.

As PSR J2051–0827 is not reported in the 2FGL catalog (Abdo et al. 2011), we tried to reproduce the non-detection result using binned likelihood analysis by defining a 7° × 7° square ROI, together with the same time span (two years) and energy cut (0.1–300 GeV) as in the 2FGL catalog (Abdo et al. 2011). The resulting TS is below 25, lower than the selection criteria.

\footnote{The quoted errors of the energy flux have taken the statistical uncertainties of both photon index and prefactor into account.}
Figure 2. *Fermi*-LAT spectrum of PSR J2051−0827 in the 0.2–10 GeV band. The curve and straight line represent the best-fit PLE and PL model, respectively.

set by the 2FGL catalog (TS > 25). Therefore it is expected that PSR J2051−0827 was not in the 2FGL catalog. After reproducing the non-detection result, we expand the time span by using \(\sim\)3 years of photon data to perform a binned likelihood analysis again to check whether PSR J2051−0827 will be detectable with a longer exposure. By assuming a simple PL model, the best-fit model yields a photon index of \(\Gamma = 2.39 \pm 0.13\) and a TS value of 49. The photon index is consistent with the unbinned likelihood analysis using 2 years of photon data with the same energy cut, and therefore PSR J2051−0827 is detected with \(\sim\)3 years of LAT data.

We generated a 2° × 2° TS map in 1–20 GeV centered at the nominal position of PSR J2051−0827 by using *gttsmap*. This is shown in Figure 3. With the aid of *gtfindsrc*, we determined the best-fit position of PSR J2051−0827 in 1–20 GeV to be R.A. = 20h51m17.8s, decl. = −08°26′22.6″ (J2000) with a 1σ error radius (statistical) of 0.09, which is illustrated with a black circle in Figure 3.

By using the latest radio timing ephemeris reported from Lazaridis et al. (2011), we searched for \(\gamma\)-ray pulsations on PSR J2051−0827 by phase binning *Fermi*-LAT photons received within \(\sim\)3 years photon data using the *Fermi* plugin for TEMPO2, *Fermi*-LAT photons were corrected to the solar system barycenter using the JPL DE405 solar system ephemeris. To achieve the best \(\gamma\)-ray pulse profile, we test on two parameters: the radius of the aperture (0.1 < \(r < 1°\)) and the lowest photon energy (100 < \(E_{\text{min}} < 1000\) MeV), with an \(E_{\text{max}}\) at 300 GeV. The best signal for \(\gamma\)-ray pulsation of PSR J2051−0827 (\(r = 0.5, E_{\text{min}} \geq 200\) MeV) is presented in Figure 4 with an \(H\)-test TS of 35 (de Jager & Büsching 2010), corresponding to a detection significance of 4.9\(\sigma\). We are therefore confident that the newly discovered \(\gamma\)-ray source is associated with PSR J2051−0827.

Since orbital modulations were observed in both radio and optical bands, we attempted to search for any evidence on orbital modulations by phase folding the \(\gamma\)-ray photons with the orbital parameter using TEMPO2, but no positive result has been found using the orbital parameter obtained by Lazaridis et al. (2011).

2.2. X-Ray Data

PSR J2051−0827 was observed five times with the *Chandra X-Ray Observatory* on 2009 March 22, 30, and July 5 (Observatory ID (ObsID) 10106–10110). All the observations were taken using the Advanced CCD Imaging Spectrometer (ACIS-S) array with the very faint mode. Data were collected with a frame transfer time of 3.2 s and the exposure time for each observation is about 9 ks. We used CIAO\(^6\) version 4.3 and XSPEC\(^7\) version 12.7 packages to perform data reduction and analysis. We reprocessed the raw data to apply the most up-to-date calibration and to make use the very faint mode. In order to reduce the background, we restricted the photon energies between 0.3 and 7.0 keV for all our data analysis. We also inspected the background count rates from the S1 chip and no flaring event was found in any of the observations.

PSR J2051−0827 is marginally seen in each observation with less than 10 counts. We therefore combined all five observations with a total exposure time of \(\sim\)44 ks for subsequent analysis. We extracted the energy spectrum from a 2 arcsec circular region centered on PSR J2051−0827; a total of 43 counts were extracted. For the background, we selected a source-free region with a radius of 30 arcsec, which results in 1.1 background counts in the source region. We therefore did not subtract the background for spectral analysis. Response matrices of each observation were generated and co-added with CIAO. Because of the low count statistic, we fit the unbinned spectrum with absorbed PL and absorbed blackbody models. We fixed the absorption at the Galactic value (\(N_{\text{H}} = 6 \times 10^{20}\) cm\(^{-2}\)) and used Cash statistics (Cash 1979) to estimate the best-fit parameters and their errors. Both models provide an acceptable fit. The best-fit photon index is 2.51 ± 0.47 (90% confidence) yielding an unabsorbed 0.3–10 keV flux of 8.5 × 10\(^{-15}\) erg cm\(^{-2}\) s\(^{-1}\). For the blackbody model, the best-fit temperature is \(kT = 0.25 \pm 0.05\) keV and the unabsorbed 0.3–10 keV flux is 4.9 × 10\(^{-15}\) erg cm\(^{-2}\) s\(^{-1}\). We also binned the data with at least 5 counts per spectral bin and used \(\chi^2\) statistics to derive

\(^{6}\) http://cxc.harvard.edu/ciao/

\(^{7}\) http://heasarc.nasa.gov/xanadu/xspec/
3. DISCUSSION

We report the discovery of the $\gamma$-ray pulsation and the X-ray detection from the second black widow system PSR J2051−0827 using Fermi-LAT and Chandra/ACIS-S data. We compute the rotation energy loss, $\dot{E} = 4\pi^2 I P^3 / P^3$, where $I$ is the pulsar’s moment of inertia. We assume $I = 10^{45}$ g cm$^2$ for an ordinary MSP, which gives an $\dot{E} = 5.49 \times 10^{33}$ erg s$^{-1}$. By adopting a distance of 1.04 kpc from Lazaridis et al. (2011), the $\gamma$-ray and the X-ray luminosity are found to be $L_\gamma = 7.66 \times 10^{32}$ erg s$^{-1}$ and $L_X = 1.01 \times 10^{30}$ erg s$^{-1}$ in 0.2–20 GeV and 0.3–10 keV, respectively. Therefore the $\gamma$-ray luminosity is $\sim 14\%$ of the spin-down power of PSR J2051−0827, consistent with other MSPs in the Galactic field.

Comparing PSR J2051−0827 with those black widow pulsars with both $\gamma$-ray and X-ray emissions detected (PSR B1957+20, Huang & Becker 2007; R. H. H. Huang et al. in preparation; PSR J2214+3000, Ransom et al. 2011; and PSR J2241-5236, Keith et al. 2011), they all show similar X-ray properties in terms of their blackbody temperature ($\sim 0.25$ keV) and X-ray luminosity ($\sim 10^{30}$–$31$ erg s$^{-1}$). It is worth noting that except for PSR B1957+20, all sources have only less than 90 X-ray photons for spectral analysis and the blackbody model may not be the only acceptable spectral component. For instance, we cannot rule out a PL model for PSR J2051−0827. Furthermore, a deep Chandra observation of PSR B1957+20 shows that an additional PL component is required (R. H. H. Huang et al. in preparation). Unlike the other three black widow systems, PSR J2051−0827 is a previously uncataloged $\gamma$-ray source and the discovery of the $\gamma$-ray emission is entirely driven by the radio observations. In all four $\gamma$-ray and X-ray emitting black widow pulsars, X-ray pulsation was only detected for PSR B1957+20 (Guillemot et al. 2012).

Takata et al. (2012) study the X-ray and $\gamma$-ray emissions from the MSP in black widow systems. They discuss $\gamma$-ray emission

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**Figure 3.** Test-statistic (TS) map in 1–20 GeV of a region of $2^\circ \times 2^\circ$ centered at the nominal position of PSR J2051−0827 (magenta cross). The color scale that was used to indicate the TS values is shown by the scale bar below. The circle in black represents the $1\sigma$ positional error circle determined by gfindsrc. (A color version of this figure is available in the online journal.)
et al. (2012) estimated both components can contribute to the observed emissions. Either from the magnetospheric synchrotron emissions, or the emissions from the heated polar cap region due to the return interaction between the pulsar wind and the matter injected by the particles accelerated at the intra-binary shock due to the emission will be originated from the synchrotron emissions from the outer gap accelerator and predict its luminosity to be $L_{y} \sim 8 \times 10^{32}$ erg s$^{-1}$ for PSR J2051−0827, which is consistent with the results of the present observation. The observed X-ray emissions from black widow system must be composed of several components. For example, Guillemot et al. (2012) found that the first $\gamma$-ray black widow system, PSR B1957+20, shows that the total X-ray emissions are composed of the non-pulsed ($\sim 67\%$) and pulsed emissions ($\sim 33\%$). The non-pulsed emission will be originated from the synchrotron emissions from the particles accelerated at the intra-binary shock due to the interaction between the pulsar wind and the matter injected by the companion star. For the emissions from the pulsars, the emissions from the heated polar cap region due to the return current or from the magnetospheric synchrotron emissions, or both components can contribute to the observed emissions.

If the X-ray emissions are from an intra-binary shock, Takata et al. (2012) estimated $L_{x}(0.5\text{--}10\text{ keV}) \sim 2 \times 10^{30}$ erg s$^{-1}$ for PSR J2051−0827, if the magnetization parameter (the ratio of the magnetic energy and the particle energy) is $\sigma \sim 0.1$ and the power index of energy distribution of the emitting particles is $\sim 3$. Such a model will produce an X-ray spectrum with a photon index of $\sim 2$ which is consistent with the observed value. For the magnetospheric synchrotron emissions, Takata et al. (2012) estimate $L_{\gamma} \sim 5 \times 10^{29}$ erg s$^{-1}$, which may be slightly smaller than the observation. For the 0.3−10 keV bands, the so-called core component of the heated polar cap emissions, which have a temperature $\sim 10^{6}$ K and effective radius of $10^{4}$ cm, will contribute to the observed emissions. Using Equation (28) in Takata et al. (2012), the temperature and luminosity of the core component for PSR J2051−0827 are estimated as $\sim 0.25$ keV and $L_{\gamma} \sim 4 \times 10^{30}$ erg s$^{-1}$, respectively, where the effective radius is assumed to be $R \sim 0.1$ km. This is consistent with the observed values.

Note that Lazaridis et al. (2011) have shown the secular variations on the orbital period of PSR J2051−0827, in which the timing model is valid until MJD 54888, which do not cover the whole range of the Fermi-LAT data used in folding the $\gamma$-ray light curve. Although there is no indication of any orbital period variation in the $\gamma$-ray light curve, as the orbital parameters are subjected to change over time, further radio/optical observations are necessary to refine the $\gamma$-ray pulse profile.

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Figure 4. $\gamma$-ray light curve of PSR J2051−0827 using the Fermi plugin for TEMPO2.

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