GAMMA-RAY EMISSION FROM PSR J0007+7303 USING SEVEN YEARS OF FERMI LARGE AREA TELESCOPE OBSERVATIONS

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Received 2016 May 30; revised 2016 July 28; accepted 2016 July 28; published 2016 October 24

ABSTRACT

Based on more than seven years of Fermi Large Area Telescope Pass 8 data, we report on a detailed analysis of the bright gamma-ray pulsar (PSR) J0007+7303. We confirm that PSR J0007+7303 is significantly detected as a point source also during the off-peak phases with a test statistic value of 262 (~16σ). In the description of the off-peak spectrum of PSR J0007+7303, a power law with an exponential cutoff at 2.7 ± 1.2 ± 1.3 GeV (the first/second uncertainties correspond to statistical/systematic errors) is preferred over a single power law at a level of 3.5σ. The possible existence of a cutoff hints at a magnetospheric origin of the emission. In addition, no extended gamma-ray emission is detected that is compatible with either the supernova remnant (CTA 1) or the very high-energy (>100 GeV) pulsar wind nebula. A flux upper limit of 6.5 × 10−12 erg cm−2 s−1 in the energy range 10−300 GeV is reported, for an extended source assuming the morphology of the VERITAS detection. During on-peak phases, a sub-exponential cutoff is significantly preferred (~11σ) for representing the spectral energy distribution, in both the phase-averaged and phase-resolved spectra. Three glitches are detected during the observation period and we found no flux variability at the time of the glitches or in the long-term behavior. We also report the discovery of a previously unknown gamma-ray source in the vicinity of PSR J0007+7303, Fermi J0020+7328, which we associate with the z = 1.781 quasar S5 0016+73. A concurrent analysis of this source is needed to correctly characterize the behavior of CTA 1 and it is also presented in the paper.

Key words: gamma rays: stars – pulsars: individual (PSR J0007+7303, S5 0016+73) – supernovae: individual (G119.5+10.2)

1. INTRODUCTION

PSR J0007+7303 is a ~316 ms gamma-ray pulsar discovered by the Fermi Large Area Telescope (LAT) in a blind search (Abdo et al. 2008). Using the timing ephemeris from the LAT, X-ray pulsations from PSR J0007+7303 were detected by XMM-Newton (Caraveo et al. 2010; Lin et al. 2010). Deep searches for optical and radio counterparts of PSR J0007+7303 revealed none (Halpern et al. 2004; Migmani et al. 2013), leading to the characterization of PSR J0007+7303 as a radio-quiet gamma-ray pulsar similar to Geminga (Bertsch et al. 1992) and PSR J1836+5925 (Halpern et al. 2007; Abdo et al. 2010; Lin et al. 2014).

PSR J0007+7303 is one of the brightest pulsars in The Second Fermi Large Area Telescope Catalog of Gamma-Ray Pulars (Abdo et al. 2013, 2PC hereafter), providing enough statistics to investigate spectral and timing features and flux variability in detail. PSR J0007+7303 is associated with the composite supernova remnant (SNR) CTA 1 (G119.5+10.2), discovered by Harris & Roberts (1960). CTA 1 possesses a large radio shell that is incomplete toward the northwest (Pineault et al. 1993). ASCA and ROSAT observations revealed a central filled SNR with emission extending to the radio shell (Seward et al. 1995). Chandra observations resulted in the detection of a pulsar wind nebula (PWN) and a jet-like structure (Halpern et al. 2004). The age of CTA 1 is estimated to be around 10 kyr (Pineault et al. 1993; Slane et al. 1997, 2004) and the distance is estimated to be 1.4 ± 0.3 kpc based on the associated HI shell (Pineault et al. 1993).

The CTA 1 complex was established as an extended gamma-ray source above 500 GeV by VERITAS (Aliu et al. 2013). The extended morphology detected by VERITAS was approximated by a two-dimensional Gaussian with a semimajor (semiminor) axis of 0′′.30 ± 0′′.03 (0′′.24 ± 0′′.03). The origin of TeV photons was proposed to be the PWN associated with PSR J0007+7303 (Aliu et al. 2013). With two years of Fermi-LAT observations, the off-peak emission of PSR J0007+7303 appeared to be extended and the morphology was fitted with a disk of radius 0′′.7 ± 0′′.3 at 95% confidence level. Given the extension and spectral shape derived with the two-year statistics, the emission was proposed to be associated with CTA 1 (Abdo et al. 2012).

In this paper, we report further analysis of PSR J0007+7303 and its related SNR CTA 1 using more than seven years of Fermi-LAT data and the newest response functions.

2. OBSERVATIONS

The Fermi-LAT data used for this paper cover 88 months, from 2008 August 4 (MJD 54682) to 2015 December 14 (MJD 57370), greatly extending the two years of data coverage reported in Abdo et al. (2012) and the three years of coverage of the 2PC. The LAT is described in Atwood et al. (2009). The analysis of Fermi-LAT data was performed using the Fermi Science Tools4, 10-00-05 release. Events from the “Pass 8” event class were selected. The “PSR2 V6 Clean” instrument response functions (IRFs) were used in the analysis. All gamma-ray photons within an energy range of 0.1−300 GeV and a circular region of interest of 10° radius centered on PSR J0007+7303 were considered. To reject contaminating gamma rays from the Earth’s limb, we selected events with a zenith angle <90°.

4 http://fermi.gsfc.nasa.gov/ssc/

http://fermi.gsfc.nasa.gov/ssc/
The spectral results presented in this work were calculated by performing a binned maximum likelihood fit (30 bins in the range 0.1–300 GeV) using the Science Tool gtlike. The spectral–spatial model constructed to perform the likelihood analysis includes Galactic and isotropic diffuse emission components (“gll_iem_v06.fits,” Acero et al. 2016, and “iso_P8R2_CLEAN_V6_v06.txt,” respectively) as well as known gamma-ray sources within 15° of PSR J0007+7303 included in the Fermi LAT Third Source Catalog (Acero et al. 2015, 3FGL hereafter). The spectral parameters and positions were fixed to the catalog values, except for the sources within 3° of our target. For these latter sources, the spectral parameters were left free. In the phased analysis, the prefactor parameters were scaled to the relative width of the phase interval. The test statistic (TS) was employed to evaluate the significance of the gamma-ray fluxes coming from the sources. The test statistic is defined as

$$TS = -2 \ln(L_{\text{max},0}/L_{\text{max},1}),$$

where $L_{\text{max},0}$ is the maximum likelihood value for a model without an additional source (the “null hypothesis”) and $L_{\text{max},1}$ is the maximum likelihood value for a model with the additional source at a specified location. The larger the value of TS, the less likely that the null hypothesis is correct (i.e., a significant gamma-ray excess lies at the tested position), and the square root of the TS is approximately equal to the detection significance of a given source.

To search for the possible extension of PSR J0007+7303 in the off-peak gamma-ray emission, we followed the method of

| Parameter                        | Value                                           |
|----------------------------------|-------------------------------------------------|
| Pulsar Name                      | PSR J0007+7303                                  |
| R.A. (J2000, Halpern et al. 2004) | 00:07:01.56                                     |
| Decl. (J2000, Halpern et al. 2004)| +73:03:08.1                                     |
| MJD range                        | 54686.16–57370.50                               |
| Pulse frequency, $\nu$ (s\(^{-1}\)) | 3.1658208(2)                                    |
| First derivative of pulse frequency, $\nu'$ (s\(^{-2}\)) | $-3.59(1) \times 10^{-12}$                     |
| Second derivative of pulse frequency, $\nu''$ (s\(^{-3}\)) | $2.92 \times 10^{-22a}$                       |
| Epoch of frequency determination (MJD) | 54952                                            |
| Glitch Epoch 1 (MJD)             | 54952.9239                                      |
| Glitch Epoch 2 (MJD)             | 55463.89923                                     |
| Glitch Epoch 3 (MJD)             | 56369.56142                                     |

Note.

* Model-predicted value assuming a braking index of 3.

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<http://fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html>
Figure 2. Weighted pulse profile of PSR J0007+7303 at different energies. Two rotational pulse periods are shown, with a resolution of 50 phase bins per period. The double Gaussian profile fitted to the light curves is shown with dashed red lines. The bottom panel shows the weighted pulse profile above 100 MeV. The Bayesian block decomposition is represented by red lines in the bottom panel. The region indicated by the red dashed lines is the off-peak phase.

Lande et al. (2012). The source is assumed to be spatially extended with a symmetric disk model and we fitted its position and extension with the Pointlike analysis package (Kerr 2011). The significance of the extension was defined as $T_{\text{test}} = 2 (\ln L_{\text{disk}} - \ln L_{\text{point}})$, in which $L_{\text{disk}}$ and $L_{\text{point}}$ were the gtlike global likelihood of the point source and the extended source hypotheses, respectively. The TS maps (i.e., maps of the value of TS for trial positions of an additional source) in this paper are produced with Pointlike.

The systematic errors have been estimated similarly to other Fermi-LAT reports, by repeating the analysis using modified IRFs that bracket the effective area (Ackermann et al. 2012), and artificially changing the normalization of the Galactic diffuse model by ±6% (2PC). The energy dispersion is not considered in the data analysis, which may be important below 100 MeV but is not expected to produce significant changes in the energy range 100 MeV–300 GeV considered here.

For the Swift/XRT data included in our analysis, we selected data in photon counting (PC) mode\(^6\) with event grades 0–12 (Burrows et al. 2005). Source events were accumulated within a circular region with a radius of 30 pixels (1 pixel = 2.36 arcsec). Background events were accumulated within a circular, source-free region with a radius of 60 pixels. Exposure maps were generated with the task XRTEXPMAP. Ancillary response files were generated with XRTMKARF, which accounts for different extraction regions, vignetting, and corrections for point-spread function (PSF). We analyzed the Swift/XRT 0.3–10 keV data using HEASoft version 6.14\(^7\), whereas the spectral fitting was performed using XSPEC V.12.8.1.

3. OFF-PEAK AND ON-PEAK PHASE SELECTION

We selected photons from PSR J0007+7303 within a radius of 1°.2 and a minimum energy of 200 MeV, which maximized the $H$-test statistics (de Jager et al. 1989; de Jager & Büsching 2010). Adopting the most current ephemeris for PSR J0007+7303, which includes three glitches (M. Kerr 2016, private communication; Table 1), we assigned pulsar rotational phases to each gamma-ray photon that passed the selection criteria, using Tempo2 (Hobbs et al. 2006) with the Fermi plug-in (Ray et al. 2011). The details of the timing analysis and the full timing parameters will be published in the future (M. Kerr et al. 2016, in preparation).\(^8\) The phase reference in our ephemeris is the same as in the 2PC, so that the profiles could be compared directly. We adopted the Chandra position from Halpern et al. (2004) since the timing noise of PSR J0007+7303 leads to a much lower precision for the measured gamma-ray position (Kerr et al. 2015). The large timing noise also does not allow a reasonable measurement of the proper motion and braking index of PSR J0007+7303. The timing results are shown in Figure 1. The $H$-test TS increases linearly with time, indicating that the timing ephemeris is valid for the entire data coverage.

We divided the pulse phase of PSR J0007+7303 into two parts, off-peak and on-peak intervals. We begin by deconstructing the pulsed light curve into simple Bayesian blocks using the same algorithm that is described in the 2PC, by Jackson et al. (2005), and by Scargle et al. (2013). To produce Bayesian blocks on the pulsation light curve, we extended the data over three rotations, by copying and shifting the observed phases to cover the phase range from $-1$ to 2. We define the final blocks to be between phases 0 and 1. The lowest Bayesian block is defined as the off-peak phase. To avoid potential contamination from the trailing and/or leading edge of the peaks, we reduce the extent of the block by 10% on each side, referenced to the center of the block. The off-peak phase is located between $\phi = 0.511$ and 0.909, and is consistent with the off-peak definition for PSR J0007+7303 in the 2PC. The on-peak phase is located at $\phi = 0.0$–0.511 and $\phi = 0.909$–1.0. In Figure 2, the bottom panel shows the Bayesian block decomposition and the off-peak phase range. More discussion of Figure 2 is presented in Section 6.

4. OFF-PEAK ANALYSIS

4.1. Discovery and Analysis of Fermi J0020+7328

Figure 3 (left panel) shows a TS map of the off-peak phase of PSR J0007+7303. In the vicinity of PSR J0007+7303 there is a previously unknown gamma-ray source. Applying

\(^6\) https://www.swift.ipsa.edu/xrt/software.html

\(^7\) http://heasarc.nasa.gov/lheasoft/

\(^8\) The timing model will be made available as usual from http://fermi.gsfc.nasa.gov/ssc/data/access/lat/ephems/.
Pointlike, the best-fit position of this gamma-ray source above 100 MeV is R.A.$_{J2000}$ = $4^\circ973$ and decl.$_{J2000}$ = $73^\circ462$, with a 95% confidence error circle of radius 0.044. By using the fitted position and assuming a power-law spectral shape ($dN/dE = N_0(E/E_0)^{-\Gamma} cm^{-2} s^{-1} GeV^{-1}$), the *gtlike* analysis of this gamma-ray source resulted in a TS value of 315 (we shall refer to this source as Fermi J0020+7328 hereafter). The TS value of PSR J0007+7303 is 281 in the off-peak phases.

Assuming a power-law spectral shape, we produced the monthly binned long-term light curve of Fermi J0020+7328 (Figure 4, panels (a) and (b)). The 95% flux upper limits are calculated with Helene’s method (Helene 1983) assuming a photon index of 2.0 if the TS value is below 9. Besides occasional fluctuations in flux, two large flares are apparent, each lasting more than a month, which are indicated in Figure 4, panels (a) and (b). Weekly light curves with an expanded scale for the two flares are shown in Figure 4, panels (c)–(f). The flaring periods are MJD 56298–56335 (flare 1) and MJD 56769–56797 (flare 2), both of which are indicated in Figure 4, panels (c)–(f). TS maps of the PSR J0007+7303 region during flaring and non-flaring phases are shown in Figure 3.

The spectra of Fermi J0020+7328 in the different periods, both during the flares and in the off-flare period, are modeled by a power law and a power law with an exponential cutoff ($dN/dE = N_0(E/E_0)^{-\Gamma} \exp(-E/E_0) cm^{-2} s^{-1} GeV^{-1}$). We compare the two models using the likelihood ratio test (Mattson et al. 1996). The $\Delta$TS between the two models is less than 9, which indicates that a cutoff is not significantly preferred. The best-fit spectral parameters and corresponding TS values are listed in Table 2, while the spectral energy distributions (SEDs) are shown in Figure 5. The gamma-ray flux is $\sim$12 times higher and the spectrum is harder during the flare period than outside it. We investigated the two flares individually. The flux levels of flares 1 and 2 are consistent within errors while the spectrum of flare 1 is softer than that of flare 2 (Table 2).

Active galactic nuclei (AGNs) are the dominant source population of the GeV sky (Ackermann et al. 2015). Since the gamma-ray flux of Fermi J0020+7328 is variable, it displays flares, and its spectrum is consistent with those of gamma-ray-detected AGNs (Ackermann et al. 2015), it is possible that this gamma-ray source is indeed an AGN.

Between 2006 and 2016 there have been seven observations of Fermi J0020+7328 with *Swift*. However, only two observations, on 2006 November 4 (observation ID 00036187001) and 2009 September 11 (observation ID 00036187005), have sufficient *Swift/XRT* exposure (9.6 ks and 7.4 ks, respectively) for spectral analysis. The map of *Swift/XRT* counts is shown in Figure 6, left panel. The quasar S5 0016+73 is the only X-ray source detected within the error circle of gamma-ray source Fermi J0020+7328 and is only 0.01 away, which argues for a possible association. S5 0016+73 is a flat-spectrum radio quasar (FSRQ) with redshift of 1.781 (Lawrence et al. 1986). The *Swift/XRT* X-ray spectrum of S5 0016+73 is well fit with a power law and the spectral parameters are shown in Table 3. The X-ray photon index measured by *Swift* is consistent with a previous *ROSAT* result (Donato et al. 2001). Between the two *Swift/XRT* observations, there is also significant variability in the X-ray flux. However, because of the large uncertainty in the spectral index for the 2009 September 11 observation (ID 00036187005), we cannot claim a spectral change. With archival multi-wavelength data collected using the ASDC online services9, we show the SED of S5 0016+73 including *Swift/XRT* data and the off-flare SED of Fermi J0020+7328 measured by *Fermi-LAT* in Figure 6, right panel. The off-flare SED of Fermi J0020+7328 is consistent with the overall SED of S5 0016+73. We propose that Fermi J0020+7328 is the GeV counterpart of S5 0016+73. Its gamma-ray photon index and flux level during the off-flare period are at the average of *Fermi-LAT*-detected FSRQs (Ackermann et al. 2015). The flux level of S5 0016+73 during its flare period is at the upper end of gamma-ray-detected FSRQs. Considering its distance, the gamma-ray luminosity of S5 0016+73 is common among *Fermi-LAT*-detected FSRQs.

S5 0016+73 is only $\sim$1° away from PSR J0007+7303 and is more significant than the pulsar during off-peak phases (Figure 3, left panel). Taking the proximity and the size of the *Fermi-LAT* PSF into consideration, S5 0016+73 may affect the results obtained from PSR J0007+7303. To minimize its influence, we carried out the *Fermi-LAT* analysis of PSR J0007+7303 during the non-flare period of S5 0016+73 for both the off-peak and on-peak phases of PSR J0007+7303.

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9 http://tools.asdc.asi.it/SED/
The off-peak emission of PSR J0007+7303 was reported by Abdo et al. (2012) as an extended gamma-ray source. In modeling the off-peak phase of PSR J0007+7303, we fitted an extended disk to PSR J0007+7303 using Pointlike, yielding a TS$_{\text{ext}} = 1.3$; the disk is not favored. The off-peak gamma-ray emission of PSR J0007+7303 is not extended.

As a check, adopting only the two years of data analyzed by Abdo et al. (2012), we fitted an extended disk to PSR J0007+7303 during the off-peak phases using Pointlike with Fermi J0020+7328 included in the model, leading to TS$_{\text{ext}} = 2.3$ (87% confidence level), which is consistent with the 95% confidence level measured by Abdo et al. (2012) and does not imply a significantly extended emission either. For a further check, we excluded Fermi J0020+7328 from the model and repeated the above analysis. This leads to a disk of radius $0.62 \pm 0.13$ located at RA$_{\text{J2000}} = 13^\circ 847$ and Decl$_{\text{J2000}} = 73^\circ 219$ and a TS$_{\text{ext}} = 9.4$ (99.9% confidence level). These values are consistent with the extension of $0.7 \pm 0.3$ at 95% confidence level reported in Abdo et al. (2012). Thus, considering both the hint of the spectral cutoff at more than 3$\sigma$ and the point-like morphology, we propose that the off-peak gamma-ray emission of PSR J0007+7303 originates from the magnetosphere of the pulsar rather than the PWN or the SNR CTA 1.

### 5. ON-PEAK ANALYSIS

For the on-peak analysis, the normalizations of all 3FGL sources within 3$^\circ$ of PSR J0007+7303 were left free in the model. For Fermi J0020+7328 and all the 3FGL sources beyond 3$^\circ$, the normalizations adopted were that of the off-peak fitted values rescaled to the ratio of the widths of the on-peak and off-peak phase intervals and then fixed. All other spectral parameters were fixed at the off-peak fitted value except for PSR J0007+7303. In modeling the on-peak phase of PSR J0007+7303, we have first considered a power law with an exponential cutoff. The best-fit parameters are shown in Table 4.

The SED of the on-peak phase is shown in Figure 7 and the fitted power law with an exponential cutoff spectral shape is shown with a red line. At higher energies, the SED points deviate from the fitted spectral shape. We studied alternative spectral shapes, specifically a power law with a sub-exponential cutoff ($dN/dE = N_0(E/E_0)^{-\alpha} \exp(-E/E_b) b^{-1}$ cm$^{-2}$ s$^{-1}$ GeV$^{-1}$, leaving the exponential index $b$ free). The best-fit parameters are shown in Table 4. The parameter $b$ is found to be $0.57 \pm 0.04 \pm 0.06$ (the first/second uncertainties correspond...
to statistical errors, which is consistent with the $b$ value for young pulsars derived by a stacking analysis (McCann 2015). Using the likelihood ratio test, the $\Delta$TS between the two models of the region is 125, which indicates that the significance of the sub-exponential cutoff is $\sim 11\sigma$. The fitted power law with sub-exponential cutoff spectral shape is shown with a blue line in Figure 7, and it models the SED well.

As previously reported for the Vela and Geminga pulsars (Abdo et al. 2010; Bonnefoy et al. 2015), a value of $b < 1$ could be interpreted as a blend of different phase-resolved $b = 1$ spectra having different cutoff energies. To explore this possibility, we carried out a phase-resolved spectral analysis. The best-fit model from the on-peak phase-averaged fit is used as the input model for the phase-resolved fit; i.e., for this analysis, all parameters except those associated with the pulsar

| Time Interval               | Spectral Index | TS  | Energy Flux, 0.1–300 GeV $(10^{-11}$ erg cm$^{-2}$ s$^{-1}$) |
|----------------------------|----------------|-----|------------------------------------------------------------|
| Flaring intervals combined | 2.36 ± 0.01 ± 0.04 | 357 | 16.7 ± 0.8 ± 0.3                                           |
| Flare 1 (MJD 56298–56333)  | 2.43 ± 0.02 ± 0.03 | 197 | 16.4 ± 0.8 ± 0.5                                           |
| Flare 2 (MJD 56769–56797)  | 2.22 ± 0.12 ± 0.07 | 134 | 16.6 ± 3.2 ± 1.5                                           |
| Non-flaring intervals      | 2.54 ± 0.06 ± 0.16 | 201 | 1.4 ± 0.2 ± 0.1                                            |

Note. The first (second) uncertainties correspond to statistical (systematic) errors.
were fixed to the value derived from the on-peak phase fit. In each phase range, the pulse shape is modeled as both a power law with a simple exponential cutoff and one with a sub-exponential cutoff. Figure 8 shows the phase-resolved spectral parameters of PSR J0007$^+$7303 in different phase bins. From the phase-resolved fits, we note that the $b$ parameter is consistently lower than 1 in all tested phase bins. We further note that, for each phase bin, the significance of the sub-exponential cutoff is greater than 3σ. Thus, for the first time we have shown that both the on-peak averaged spectrum as well as the phase-resolved spectra of PSR J0007$^+$7303 are better described by a power law with a sub-exponential cutoff function.

### 6. ANALYSIS OF THE LIGHT CURVE AND SPECTRAL VARIABILITY

To check for long-term flux variability of PSR J0007$^+$7303 we performed a phase-averaged likelihood analysis similar to that done in Section 5. We selected the length of the time bin as 60 days and used the same model as described in Section 5 but rescaled to the overall pulse phase. PSR J0007$^+$7303 is modeled as a power law with an exponential cutoff instead of a sub-exponential cutoff because of the lower statistics in each time bin. The top panel of Figure 9 shows the resulting long-term light curve of PSR J0007$^+$7303, which is well fitted by a constant light, yielding a reduced $\chi^2$ of 1.36. No significant flux variation is detected. Three glitches have been detected from PSR J0007$^+$7303 (Table 1) and no flux variations are detected in the long-term light curve around the glitches. We have checked for any changes in the spectrum of the pulsar around the glitches. To accomplish this, the *Fermi*-LAT data were split into four bins around the glitches. Adopting the model of a power law with exponential cutoff, we performed a likelihood analysis for PSR J0007$^+$7303 in these four time bins. The flux and spectral parameters are shown in Figure 9 and are similar in the four epochs. No change in the integral flux above 100 MeV is seen.

Adopting the best-fit spatial and spectral model derived from the above phase-averaged analysis, we calculated the probabilities of photons coming from PSR J0007$^+$7303 within a radius of 3° using *gtscprob* and produced a weighted pulsed light curve based on them. The bottom panel of Figure 2 shows the folded, pulsed light curve above 100 MeV. The remaining panels of the same figure show the light curve in narrower energy bands. The light curve shows two distinct peaks, which is consistent with the profile reported by Abdo et al. (2012) and the 2PC. To locate the two peaks, we fitted the light curve with a double Gaussian profile (Figure 2). The first (P1) and second (P2) peaks are at $\phi = 0.113 \pm 0.001$ and $\phi = 0.293 \pm 0.001$, respectively. The separation between the means of the two peaks is $0.180 \pm 0.002$. The widths of P1 and P2 evolve with energy, leading to narrower peaks at higher energies (Figure 10, top and middle). A similar evolution was also observed in Geminga (Abdo et al. 2010). The strength of P1 relative to P2 decreases significantly from low to high energies (Figure 10, bottom panel), which again is consistent with what was first reported by Abdo et al. (2012).

### 7. DISCUSSION

Using more than seven years of *Fermi*-LAT data and a contemporaneous ephemeris, we carried out a detailed analysis of PSR J0007$^+$7303 during its off-peak and on-peak phase intervals.

During the off-peak phase, PSR J0007$^+$7303 is significantly detected with a TS value of 262. An exponential cutoff at 2.7 ± 1.2 ± 1.3 GeV is tentatively detected in its spectrum, with a significance of 3.5σ. We explored the possible extension of PSR J0007$^+$7303 during the off-peak phase, but a point-like source is favored (TS$_{ext}$ = 1.3). The point-like nature of the emission together with the potential cutoff at GeV energies argue for a magnetospheric origin of the off-peak gamma-ray emission of PSR J0007$^+$7303.

Neither a point-like source nor extended gamma-ray emission was detected from PSR J0007$^+$7303 between 10 and 300 GeV during the off-peak phase. By removing the point-source model of PSR J0007$^+$7303, assuming the same position and the extension of 0.3 detected by VERITAS (Aliu et al. 2013), we calculated an upper limit for the possible emission coming from the PWN or the SNR CTA 1 of $6.5 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ at 99% confidence level with Helene’s method (Helene 1983), assuming a photon index of 2.0 and considering the systematics (10–300 GeV). In the case of the highest energies, the TeV emission detected by VERITAS is most likely coming from the PWN. The molecular mass in the vicinity of the complex is not sufficient to explain the TeV emission even under favorable assumptions for the

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**Table 3**

| Observation ID | Date       | Spectral Index | Flux, 0.3–10 keV (10$^{-12}$ erg cm$^{-2}$ s$^{-1}$) | $N_{eff}$ (10$^{22}$ cm$^{-2}$) | Reduced $\chi^2$/dof |
|---------------|------------|----------------|-------------------------------------------------|---------------------------------|----------------------|
| 00036187001   | 2006 Nov 4 | 1.51 ± 0.16    | 4.1 ± 0.3                                       | 0.18 ± 0.07                     | 0.59 (21)            |
| 00036187005   | 2009 Sep 11| 1.81$^{+0.16}_{-0.11}$ | 1.4$^{+0.26}_{-0.15}$                           | 0.31$^{+0.04}_{-0.03}$          | 1.38 (3)             |

**Table 4**

| Phase Interval | Spectral Index | Cutoff Energy (GeV) | b     | TS   | Flux, 0.1–300 GeV (10$^{-11}$ erg cm$^{-2}$ s$^{-1}$) |
|----------------|----------------|---------------------|-------|------|-----------------------------------------------------|
| Off-peak       | 2.09 ± 0.21 ± 0.83 | 2.7 ± 1.2 ± 1.3     | 0     | 262  | 1.4 ± 0.2 ± 0.1                                    |
| On-peak        | 1.44 ± 0.01 ± 0.03 | 5.2 ± 0.1 ± 0.4     | 0     | 19037| 8.6 ± 0.3 ± 0.0                                    |
|                | 1.13 ± 0.06 ± 0.15 | 1.14 ± 0.36 ± 0.50  | 0.57 ± 0.04 ± 0.06 | 190278 | 7.1 ± 0.5 ± 1.5                                    |

Note. The first (second) uncertainties correspond to statistical (systematic) errors.
The cosmic-ray acceleration properties of the SNR (see the discussion by Martin et al. 2016). The new upper limit we impose on the GeV emission from the PWN is not in conflict with detailed multi-frequency models (Aliu et al. 2013; Torres et al. 2014). This PWN remains, however, a difficult case: it is unique in requiring a relatively high magnetization (as compared with other PWNe detected). The latter and the estimated age of the SNR may indicate that the nebula (or at least part of it) is already contracting. However, even considering that the PWN could already have passed reverberation, the required magnetization is still high (Martin et al. 2016).

Off-peak emission of 26 young pulsars and eight millisecond pulsars has been significantly detected (2PC). Their off-peak luminosities range from \( \sim 10^{35} \) to \( \sim 10^{38} \) erg s\(^{-1}\) and PSR J0007+7303 is near the geometric average \( (L_{\text{off peak}} = 3.5 \times 10^{36} \text{ erg s}^{-1}) \). Considering a distance of 1.4 kpc and a spin-down power \( E = -\dot{I} \Omega \) (\( I \) is the pulsar’s moment of inertia, \( \sim 10^{45} \text{ g cm}^2 \); \( \Omega \) and \( \dot{\Omega} \) are the pulsar’s spin frequency and its first derivative) of \( 4.5 \times 10^{35} \) erg s\(^{-1}\), the off-peak emission efficiency \( (L_{\text{off peak}} / E) \) of PSR J0007+7303 is \( \sim 0.8\% \), which is among the lowest of pulsars with magnetospheric off-peak emission (2PC, Figure 14). The on-peak emission efficiency \( (L_{\text{on peak}} / E) \) of PSR J0007+7303 is \( \sim 36.5\% \).

For the on-peak phase, PSR J0007+7303 could be modeled by a power law with a sub-exponential cutoff, which is favored over an exponential cutoff with a significance above 11\( \sigma \) for the phase-averaged spectrum (Table 4) and of 3\( \sigma \) for the phase-resolved spectra (Figure 8). This makes PSR J0007+7303 the fourth pulsar to have an established sub-exponential cutoff.
exponential cutoffs can also be due to the contribution of a second component, arising from inverse Compton emission of electrons upscattering off soft photon fields (Lyutikov 2013; Hirotani 2015). However, we note that the physical interpretation of the meaning of $b < 1$ should be considered as provisional, since it may simply depend on our sensitivity. With increased statistics we have seen that values of $b < 1$ are needed to fit first the phase-averaged spectrum, then the phase-resolved ones. It may well be that even in the smaller phase bins considered we are summing up contributions having different acceleration features and thus producing sub-exponential cutoffs as a result of this sum. By reducing the phase bins even further, we would come to a situation in which cutoff power laws with $b = 1$ and with $b < 1$ would not produce significantly different fits. The extent to which the existence of $b < 1$ is physical and not a problem of sensitivity (phase bins too large for the level of statistics attained) is still a subject of controversy. For a phase-averaged analysis, we found no flux variability in the long-term light curve. The integrated flux level and spectral parameters are consistent during all epochs preceding and following the glitches.

We have identified Fermi J0020+7328, a previously unknown, flaring gamma-ray source appearing (due to the relative strength of the two sources) only during the off-peak phases of PSR J0007+7303. The most probable counterpart for this source is S5 0016+73.

The Fermi LAT Collaboration acknowledges generous ongoing support from a number of agencies and institutes that have supported both the development and the operation of the LAT as well as scientific data analysis. These include the National Aeronautics and Space Administration and the Department of Energy in the United States, the Commissariat à l’Energie Atomique and the Centre National de la Recherche Scientifique/Institut National de Physique Nucléaire et de Physique des Particules in France, the Agenzia Spaziale Italiana and the Istituto Nazionale di Fisica Nucleare in Italy, the Ministry of Education, Culture, Sports, Science and Technology (MEXT), High Energy Accelerator Research Organization (KEK), and Japan Aerospace Exploration Agency (JAXA) in Japan, and the K. A. Wallenberg Foundation, the Swedish Research Council, and the Swedish National Space Board in Sweden.

Additional support for science analysis during the operations phase is gratefully acknowledged from the Istituto Nazionale di Astrofisica in Italy and the Centre National d’Études Spatiales in France.

We acknowledge the assistance from Dr. M. Kerr with the gamma-ray ephemeris for PSR J0007+7303, and Dr. M. Razzano and Dr. P. Saz Parkinson for discussions. We acknowledge the support from the grants AYA2015-71042-P, SGR 2014-1073 and the National Natural Science Foundation of China via NSFC-11473027, NSFC-11503078, NSFC-11133002, NSFC-11103020, XTP project XDA 04060604 and the Strategic Priority Research Program “The Emergence of Cosmological Structures” of the Chinese Academy of Sciences, Grant No. XDB09000000.

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