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Gamma-Ray Flares from the Crab Nebula

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A young and energetic pulsar powers the well-known Crab Nebula. Here we describe two separate gamma-ray (photon energy > 100 MeV) flares from this source detected by the Large Area Telescope on board the Fermi Gamma-ray Space Telescope. The first flare occurred in February 2009 and lasted approximately 16 days. The second flare was detected in September 2010 and lasted approximately 4 days. During these outbursts the gamma-ray flux from the nebula increased by factors of four and six, respectively. The brevity of the flares implies that the gamma rays were emitted via synchrotron radiation from PeV (10^{15} eV) electrons in a region smaller than 1.4 × 10^{-2} pc. These are the highest energy particles that can be associated with a discrete astronomical source, and they pose challenges to particle acceleration theory.

The Crab Nebula is the remnant of an historical supernova (SN), recorded in 1054 C.E., located at a distance of 2 kpc (*1*). The SN explosion left behind a pulsar, which continuously emits a wind of magnetized plasma of electron/positron pairs (henceforth referred to as electrons). This pulsar wind is expected to terminate in a standing shock where the particles may undergo shock acceleration (*2*, *3*) As the electrons diffuse into the downstream medium they release energy through interactions with the surrounding magnetic and photon fields. This emission is observed across all wavebands from radio up to TeV gamma-ray energies and is referred to as a pulsar wind nebula (PWN). The efficiency of this process is remarkable. As much as 30% of the total energy released by the Crab pulsar is emitted by the PWN [(*4*) and references therein]. The Crab PWN has an approximately ellipsoidal shape on the sky with a size that decreases with increasing photon energy. At radio frequencies it extends out to $5'$ (3 pc) from the central pulsar. At X-ray wavelengths a bright torus surrounds the pulsar; its radius is $40''$ (0.4 pc) and jets emerge perpendicular to it in both directions.

Within the region encapsulated by the torus there are several small-scale structures. The inner nebula, which we define as the central $15''$ around the pulsar, has several small-scale regions of variable X-ray and optical brightness. The most prominent is an X-ray-bright inner ring with a radius of $10''$ (0.1 pc); this ring is thought to represent the termination shock of the PWN (*5*). Several knots with diameters of $\sim 1''$ (0.01 pc) are detected close to the inner ring and the base of the jets, and bright arcs of comparable width are observed moving outwards from the inner ring into the torus (*6*, *7*) The broad-band spectral energy distribution (SED) of the Crab Nebula is composed of two broad non-thermal components. A low-energy component dominates the overall output and extends from radio to gamma-ray frequencies. This emission is thought to be from synchrotron radiation. This notion is confirmed in radio to X-ray frequencies with polarization measurements (*8*–*10*). The emission of this synchrotron component peaks between optical and X-ray frequencies, where the emission is primarily from the torus (5). The emission site of higher-energy photons (beyond 100 keV) cannot be resolved due to the limited angular resolution of telescopes observing at these frequencies. The high-energy component dominates the emission above ~400 MeV and is thought to be emitted via inverse Compton (IC) scattering, predominantly of the synchrotron photons (*11*, *12*).

The large-scale integrated emission from the Crab Nebula is expected to be steady within a few percent and is thus often used to cross-calibrate X-ray and gamma-ray telescopes and to check their stability over time (*13*, *14*). Recently, variability in the x-ray flux from the nebula by ~3.5% yr^{-1} has been detected, setting limits on the accuracy of this practice (*15*). Yearly variations in the emission in the high-energy tail (1-150 MeV) of the synchrotron component has also been reported (*16*, *17*). No significant variations have been detected for the high-energy component of the nebula (*18*–*20*).

The Large Area Telescope (LAT) on board the Fermi Gamma-Ray Space Telescope (Fermi) has continuously monitored the Crab Nebula as a part of its all-sky survey since August 2008. The LAT detects gamma rays from 20 MeV to > 300 GeV, and this spans the transition region between the low and the high-energy components of the nebular spectrum. The average SED measured during the first 25 months of observations (Fig. 1) is well characterized by the sum of two spectral components, each with a power-law dependence on energy (*21*). The integrated flux of the low-energy component is (6.2 ± 0.3) × 10^{-7} cm^{-2} above 100 MeV with an photon index of 3.69 ± 0.11 (only statistical errors are given; see online supplements for a discussion of systematic errors). The high-energy component has an integral flux of (1.3 ± 0.1) × 10^{-7} cm^{-2} s^{-1} above 100 MeV with a photon index of 1.67 ± 0.04. Due to its hard energy spectrum the high-energy component dominates the emission above 426 ± 35 MeV.

In order to search for flux variability of both spectral components in the LAT band, we grouped the flux measurements into monthly time bins. The high-energy component was found to be stable. The low-energy component was found to vary on these time scales (Fig. 2); the probability that the measured flux variations are statistical measurement fluctuations in a constant source is less than 10^{-5}. No significant spectral variations were detected for either component on monthly time scales. Flux variability was also searched for on sub-monthly time scales, for which the low-energy component of the nebula is significantly detected by the LAT only in high-flux states. The flux of the low-energy component was significantly enhanced compared to the average values in February 2009 and September 2010 (Fig. 2). No variations were found for the high-energy component. The September flare was first announced by the AGILE gamma-ray mission (*22*), which additionally reports a flare in October 2007, before the start of Fermi observations (*23*). The Fermi-LAT detected flare in February 2009 was not detected by AGILE as the instrument was pointing at a different part of the sky.

The February flare had a duration of ~16 days. The average integral flux above 100 MeV of the low-energy component between MJD 54857.73 and 54873.73 was $(23.2 \pm 2.9) \times 10^{-7}$ cm^{-2} s^{-1}, corresponding to an increase by a factor 3.8 ± 0.5 compared with the average value; the increase is significant at > 8-σ level. The September flare lasted for only ~ 4 days. The integral flux above 100 MeV between MJD 55457.73 and 55461.73 was $(33.8 \pm 4.6) \times 10^{-7}$ cm^{-2} s^{-1}, corresponding to an increase by a factor 5.5 ± 0.8 with respect to the average and a significance of > 10 σ.

The February flare has a soft spectrum with a photon index of 4.3 ± 0.3 (Fig. 1). The spectral slope is compatible with the average 25-month value within two standard deviations. The energy spectrum for the second flare was significantly harder, with a photon index of 2.7 ± 0.2, and was still detected above 1 GeV at a 3-σ-level. The average power released in each of the gamma-ray flares was approximately 4×10^{36} erg s^{-1}, for the case of isotropic emission. No significant variations in the emission of the pulsar were detected on monthly and four-day time scales through the period of observations. Examination of the timing residuals of the pulsed emission indicated no significant variations during either flares nor any significant glitch activity during the first 25 months of LAT observations.

No variations in the synchrotron component between infrared and X-ray frequencies were seen about the average nebular flux level during the second flare (*24*). We analyzed data collected by the BAT instrument on board the Swift satellite (*25*), which continuously monitors the sky at photon energies of 15−150 keV. The mean flux measured during the first flare was $(2.0 \pm 0.1) \times 10^{-8}$ erg cm^{-2} s^{-1}, the flux during the second flare was $(2.0 \pm 0.1) \times 10^{-8}$ erg cm^{-2} s^{-1}. Both observations are therefore within 5% of the average flux of $(2.09 \pm 0.10) \times 10^{-8}$ erg cm^{-2} s^{-1} measured by BAT in this energy range (*26*), and show no correlation to the gamma-ray flares. The angular resolution of the BAT only allows for the measurement of the spatially integrated spectrum. Sub-arc-second resolution images were taken in X-rays by the Chandra observatory and optical by the Hubble Space Telescope a few days after the second flare. Although both images show no unusual activity compared to previous observations, both show a brightening $3''$ east of the pulsar (*27*). In the Chandra image this brightening is associated with a knot of $\sim 1''$ diameter that might be associated with the inner ring or the base of the jet. Such a brightening might be interpreted as an afterglow at lower frequencies of the gamma-ray flare, but no conclusions can be drawn based on one event.

The brief flare time scales and the requirement that the emission volume be causally connected imply that the flaring region must have been compact. If L is the diameter of the flaring region along the line-of-sight and t is the flare duration, then $L < Dct$, where the Doppler factor D accounts for relativistic boosting effects. The Doppler factor is expected to be moderate within the Crab Nebula, as the typical velocities observed are smaller than 0.9 c (*7*). Even if the emission region was moving directly toward us, this yields $D < 4.4$. For a flare duration of 4 days this results in $L < 1.4 \times 10^{-2}$ pc, which corresponds to $< 1.5''$ projected on the sky. Structures this small are found only in the inner part of the nebula, close to the termination shock, the base of the jet or the pulsar, suggesting that the gamma-ray emission detected in the flare originated from these regions. This is in agreement with expectations of relativistic magnetohydrodynamic simulations, in which the gamma-ray emission of the synchrotron component originates close to the termination shock (*28*, *29*).

The extrapolation of the the LAT spectrum of low-energy component to lower frequencies suggest that it represents synchrotron emission (Fig. 1). The brevity of the gamma-ray flares strengthens this scenario: If the flare were instead produced by IC radiation or Bremsstrahlung, the cooling time of the emitting electrons would greatly exceed the flare duration. The cooling via Bremsstrahlung in particle densities < 10 cm^{-3} (*30*) happens over ~10^{6} years. Similarly, electrons cooling via IC emission of 100 MeV gamma rays on the photons of the synchrotron component of Crab Nebula have cooling times >~ 10^{7} years. The average magnetic field inside the Crab Nebula is estimated to be ~ 200 μG, as deduced from modeling of the broad-band SED (*12*, *21*), and might be enhanced locally by up to an order of magnitude in the inner nebula (*31*). These fields imply synchrotron cooling times <~15 days, comparable to the flare duration, leaving synchrotron radiation as the only plausible process responsible for the gamma-ray emission during the flares.

The detection of synchrotron photons up to energies of > 1 GeV confirms that electrons are accelerated to energies of >~1 PeV in the Crab Nebula (*32*). These are the highest energy particles that can be associated directly with any astronomical source, and they pose special challenges to particle acceleration theory. Because synchrotron losses are so efficient, there must be a strong electric field E to compensate radiation reaction, given by:

$$E/B \approx r_L/\ell_{cool} \gtrsim (1.3\alpha\mathcal{E}_{\gamma pk}/m_e c^2) \approx (\mathcal{E}_{\gamma pk}/50\ \mathrm{MeV}) \quad (1)$$

where r_L is the Larmor radius, ℓ_{cool} is the radiative cooling length, α is the fine structure constant and $E_{\gamma pk}$ is the peak synchrotron frequency at which the most energetic electrons are emitting (*33*, *17*). Due to the detection of gamma-ray emission beyond 1 GeV $E_{\gamma pk}$ can be conservatively estimated to be greater than 200 MeV. The electric field is unlikely to exceed the magnetic field; if it did, there would be a local reference frame with a pure electric field in which vacuum breakdown would occur quickly. We conclude that the electric field, as measured in the Crab frame, is close in magnitude to the magnetic field in the region where the highest energy synchrotron photons were emitted. This subsumes the possibility of bulk relativistic motion. Furthermore, the resistive force due to radiation reaction is competitive with the Lorentz force and the cooling length is comparable with the Larmor radius. This poses severe difficulties to the widely-discussed acceleration mechanism of diffusive shock acceleration (*34*, *35*). The proposed acceleration due to absorption of ion cyclotron waves does not suffer from these constraints (*36*). However, it appears to operate on time scales which are too long to accommodate the fast variability seen during the flares. Alternatively, the acceleration could be related directly to the electric field from the pulsar.

The Crab Nebula is powered by the central neutron star which acts as a DC unipolar inductor and a source of an AC striped wind (*2*, *3*). What happens to the DC and AC current flows is controversial. It is widely supposed that ~90% of the DC current returns in an outflowing wind that becomes particle-dominated and encounters a (mostly invisible) termination shock at a radius ~0.1 pc (*37*), but the wind could also remain electromagnetically dominated (*38*, *33*). For the measured spin-down rate, a moment of inertia of $\sim 1 \times 10^{45}$ g cm2 and a force-free model of the magnetosphere, the total induced potential difference is ~50 PV, high enough to accelerate particles to the required energies. The current associated with this potential is ~300 TA yielding a DC power per hemisphere of $\sim 1.5 \times 10^{38}$ erg s−1, a factor ~40 larger than the power released in the flares. Another interesting possibility is that particle acceleration takes place in the AC striped wind of the pulsar due to magnetic reconnection, although it is not clear if this process can accelerate particles to PeV energies on the required time scales (*39*, *40*).

The observations reported here have raised compelling questions on our understanding of particle acceleration and motivate more detailed calculations; together with the ongoing gamma-ray observations of the LAT and observational campaigns at X-ray and optical wavelengths they might soon pinpoint the gamma-ray emission site in the Crab Nebula.

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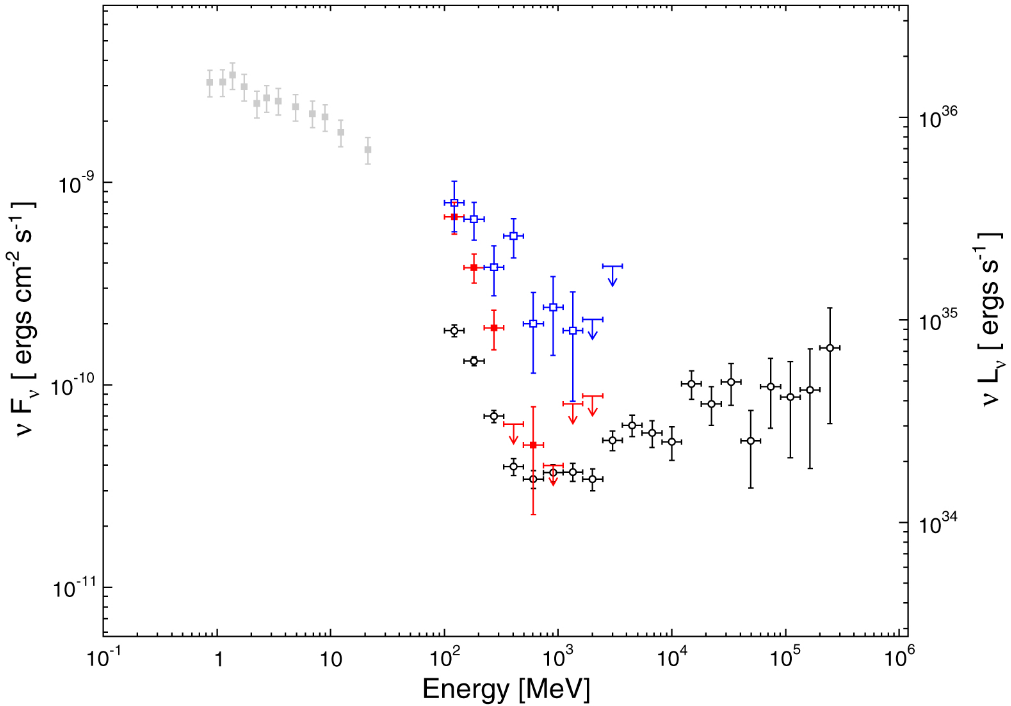
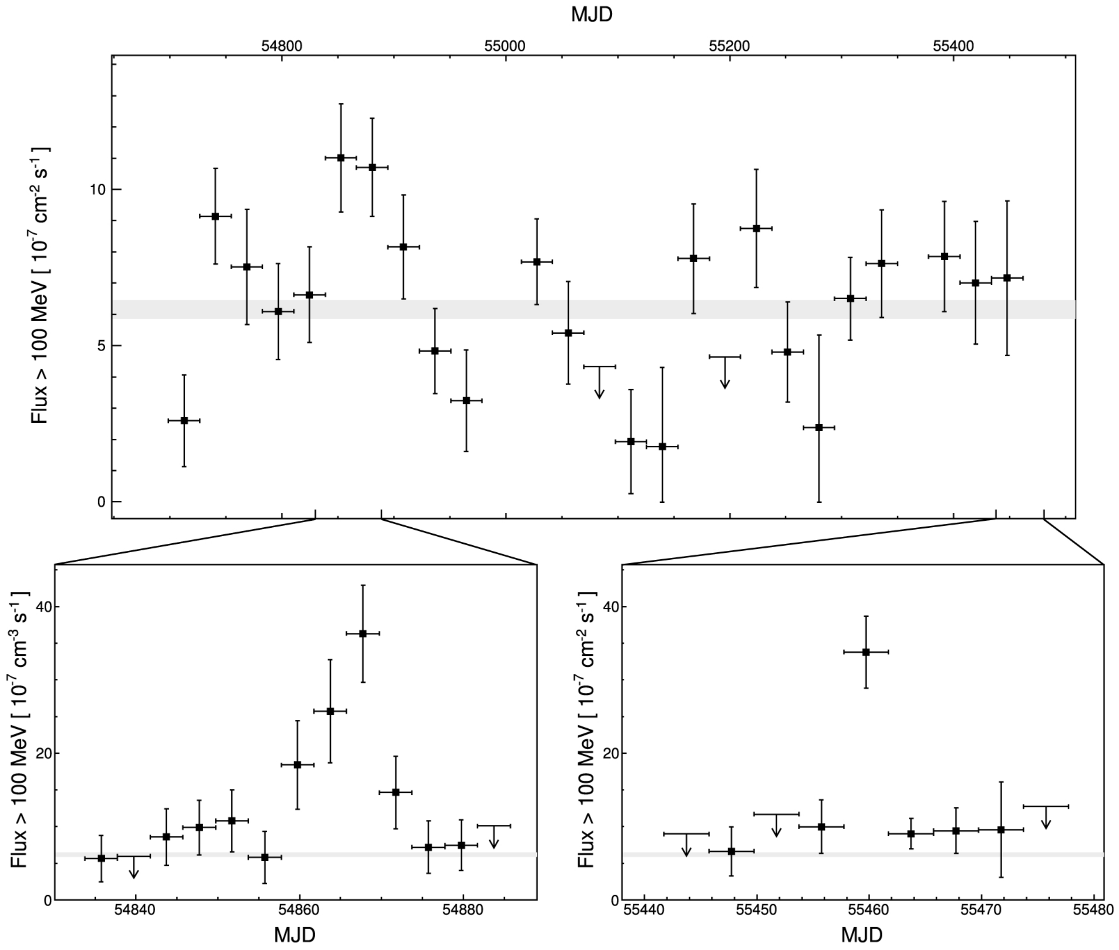
Fig. 1: Spectral energy distribution of the Crab Nebula. Black open circles show the average spectrum measured by the LAT in the first 25 months of observations. Red squares show the energy spectrum during the flare of February 2009 (MJD 54857.73-54873.73) and blue open squares the spectrum in September 2010 (MJD 55457.73-55461.73). Gray squares show historical long-term average spectral data from the COMPTEL telescope with 15% systematic errors (*41*). Arrows indicate 95% confidence flux limits.

Fig. 2: Gamma-ray flux above 100 MeV as a function of time of the synchrotron component of the Crab Nebula. The upper panel shows the flux in four-week intervals for the first 25 month of observations. Data for times when the sun was within 15° of the Crab Nebula have been omitted. The gray band indicates the average flux measured over the entire period. The lower panel shows the flux as a function of time in four-day time bins during the flaring periods in February 2009 and September 2010. Arrows indicate 95% confidence flux limits.


νF_ν [ergs cm^{-2} s^{-1}]
10^{-9}
10^{-10}
10^{-11}
νL_ν [ergs s^{-1}]
10^{36}
10^{35}
10^{34}
10^{-1}
1
10
10^2
10^3
10^4
10^5
10^6
Energy [MeV]


MJD
54800
55000
55200
55400
Flux > 100 MeV [10^{-7} cm^{-2} s^{-1}]
10
5
0
Flux > 100 MeV [10^{-7} cm^{-3} s^{-1}]
40
20
0
54840
54860
54880
MJD
Flux > 100 MeV [10^{-7} cm^{-2} s^{-1}]
40
20
0
55440
55450
55460
55470
55480
MJD