Fermi-Large Area Telescope Observations of the Crab Pulsar and Nebula

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on behalf of the Fermi Large Area Telescope Collaboration and the Pulsar Timing Consortium

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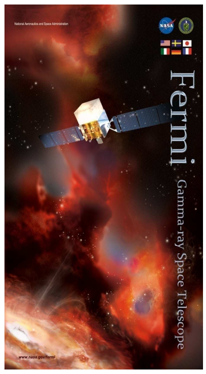


Summary: Previously detected by EGRET, the Crab Pulsar and Nebula have been extensively observed in the gamma-ray energy band by the Large Area Telescope (LAT) on board the *Fermi* satellite during its first months of data taking. Results of these analyses are reported here.

Abstract

The Crab Pulsar and Nebula are the remnants of the supernova SN 1054. Previously detected by EGRET, both sources have been extensively observed in the gamma-ray energy band by the Large Area Telescope (LAT) on board the *Fermi* satellite during its first months of data taking. LAT data have been used to determine the Crab pulsar light curve and spectrum. The precise measurement of the cut-off energy, which could not be determined accurately with EGRET, allows better constraint of the emission models. A complete spectral analysis of the unpulsed gamma-ray emission in the 100 MeV - 300 GeV energy range was also performed. The spectrum of the nebula is well described by the sum of two power-laws corresponding to the falling edge of the synchrotron and the rising edge of the inverse Compton components. The latter nicely connects with the observations from Earth-based telescopes at about 100 GeV, thus providing a direct way to cross-calibrate these instruments. The obtained spectral parameters, combined with the spectrum from other wavelengths, also give direct information about the electron spectrum, magnetic field and others physical parameters of the nebula.

Fermi-LAT data analysis

We report on γ-ray observations of the Crab Pulsar and Nebula using 8 months of survey data with the *Fermi*-Large Area Telescope (LAT).

Data selection :

- Time interval : August 4, 2008 to April 7, 2009
- Region of interest of 20° around the pulsar radio position
- Events from the "Diffuse" class (highest quality photon data).

Temporal analysis performed with the TEMPO2 timing package and using an accurate ephemeris built from observations made with the Nançay and Jodrell Bank radio-telescopes (210 times of arrival at 1.4 GHz and 488 times of arrival at 600 MHz).

Spectral analysis performed using two spectral methods :

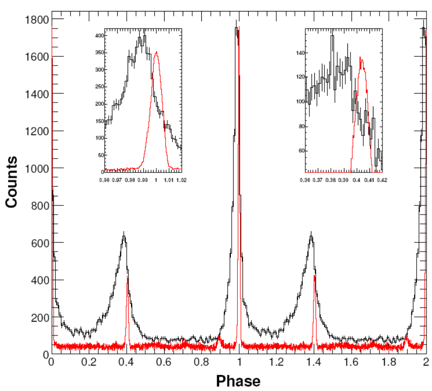
- A maximum-likelihood method implemented in the *Fermi* Science Support Center science tools : *gtlike*
  - Bright (significance level larger than 5σ) nearby sources are taken into account
  - Galactic diffuse emission, extragalactic and instrumental background described by GALPROP and a single isotropic component respectively
  - Unbinned and binned analyses are performed on the entire energy range and in individual energy bins respectively.
- An unfolding method based on Bayes' theorem, which takes into account the energy dispersion introduced by the instrument response function. The results from this analysis are consistent with those from the likelihood analysis.

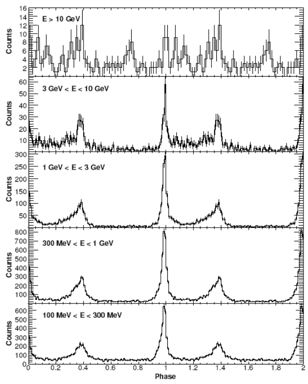
Crab Pulsar light curves

The high quality light curve of the Crab Pulsar in the 100 MeV – 300 GeV energy range exhibits two peaks P1 and P2, located at phases $\phi 1=0.9915\pm0.0005$ and $\phi 2=0.3894\pm0.0022$ respectively and stable in phase with energy. The phase 0 is taken at the maximum of the main radio peak observed at 1.4 GHz.

The ratio P1/P2 decreases with the energy.

The first γ-ray pulse leads the radio main pulse by (281±12±21) μs.





Left : Light curve of the Crab Pulsar obtained with photons above 100 MeV and binned to 0.01 in phase. The 1.4 GHz pulse profile is overlaid (red line) for comparison. Insets show the pulse shapes near the peaks, binned to 0.002 in phase. Two cycles are shown.

Right : Light curves for the Crab Pulsar in different energy bands. Two cycles are shown.

Spectral analysis of the Crab Nebula

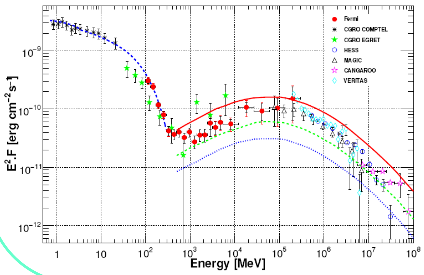
The analysis of the Crab Nebula is performed in the off-pulse window, defined as the 0.52-0.87 pulse phase interval. The nebular spectrum is well described by the sum of two power-laws identified as the falling edge of the synchrotron component and the rising edge of the inverse Compton component :

$$dN/dE = N_{sync}(E/E_0)^{-\Gamma sync} + N_{IC}(E/E_0)^{-\Gamma IC}$$

with $N_{sync} = (9.1\pm2.1_{stat}\pm0.7_{sys})\times10^{-13}$ cm^{-2}s^{-1}MeV^{-1}, $\Gamma_{sync} = 3.99\pm0.12_{stat}\pm0.08_{sys}$, $N_{IC} = (6.4\pm0.7_{stat}\pm0.1_{sys})\times10^{-12}$ cm^{-2}s^{-1}MeV^{-1}, $\Gamma_{IC} = 1.64\pm0.05_{stat}\pm0.07_{sys}$ and E_0 = 1GeV.

The flux above 100 MeV is $(9.8\pm0.7_{stat}\pm1.0_{sys})\times10^{-7}$ cm^{-2}s^{-1}.

The LAT spectrum links up naturally with results of Cherenkov experiments.



Spectral energy distribution of the Crab Nebula from soft to very high energy γ-rays. The *Fermi*-LAT results are represented by red points. The predicted inverse Compton spectra from Atoyan and Aharonian (1996) are overlaid for three different values of the mean magnetic field: 100 μG (solid red line), 200 μG (dashed green line) and the canonical equipartition eld of the Crab Nebula 300 μG (dotted blue line).

References: CGRO COMPTEL and EGRET: Kuiper et al. (2001); MAGIC: Albert et al. (2008); HESS: Aharonian et al. (2006); CANGAROO: Tanimori et al. (1997) VERITAS: Celik (2007)

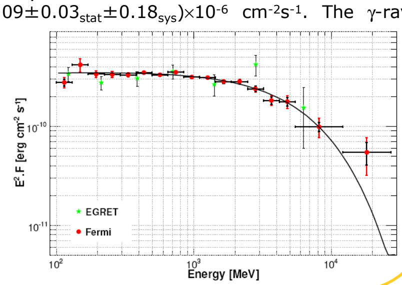
Spectral analysis of the Crab Pulsar

Pulsed γ-ray photons are observed up to ~20 GeV. The pulsar spectrum is well modeled by a power-law with an exponential cut-off:

$$dN/dE = N(E/E_0)^{-\Gamma}\exp(-E/E_{cut})$$

with N = $(2.36\pm0.06_{stat}\pm0.15_{sys})\times10^{-10}$ cm^{-2}s^{-1}MeV^{-1}, $\Gamma = 1.97\pm0.02_{stat}\pm0.06_{sys}$, $E_{cut} = (5.8\pm0.5_{stat}\pm1.2_{sys})$ GeV and E_0=1GeV. Different functional forms were tested and did not improve significantly the fit.

The flux above 100 MeV is $(2.09\pm0.03_{stat}\pm0.18_{sys})\times10^{-6}$ cm^{-2}s^{-1}. The γ-ray efficiency is estimated at 0.1 %.



Spectral energy distribution of the Crab Pulsar. The *Fermi*-LAT results are represented by red points. EGRET spectral data points are overlaid for comparison *(Kuiper et al. 2001)*.

Conclusions

The high energy behavior of the Crab Pulsar and Nebula was analyzed using 8 months of LAT survey data:

- The high quality light curve of the Crab Pulsar above 100 MeV presents two peaks stable in position with the energy.
- In the LAT energy range, the falling edge of the synchrotron component and the rising edge of the inverse Compton component of the Crab Nebula spectrum can be well modeled by two power-laws. The LAT spectrum is consistent with previous γ-ray experiments and connects nicely with Earth-based telescopes results.
- The Crab Pulsar spectrum presents a cut-off at a few GeV
- Results of temporal and spectral analyses of the Crab Pulsar preclude emission near the stellar surface.