A Search for Pulsed TeV Gamma Ray Emission from the Crab Pulsar

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Abstract

We present the results of a search for pulsed TeV emission from the Crab pulsar using the Whipple Observatory's 10 m gamma-ray telescope. The direction of the Crab pulsar was observed for a total of 73.4 hours between 1994 November and 1997 March. Spectral analysis techniques were applied to search for the presence of a gamma-ray signal from the Crab pulsar over the energy band 250 GeV to 4 TeV. At these energies we do not see any evidence of the 33 ms pulsations present at lower energies from the Crab pulsar. The 99.9% confidence level upper limit for pulsed emission above 250 GeV is derived to be $4.8 \times 10^{-12} \mathrm{cm}^{-2}\mathrm{s}^{-1}$ or $<3\%$ of the steady flux from the Crab Nebula. These results imply a sharp cut-off of the power-law spectrum seen by the EGRET instrument on the *Compton Gamma-Ray Observatory*. If the cut-off is exponential, it must begin at 60 GeV or lower to accommodate these upper limits.

1   Introduction

The Crab pulsar/Nebula system is one of the most intensely studied astrophysical sources with measurements throughout the electromagnetic spectrum from the radio to the TeV energy band. In most regions of the spectrum, the characteristic 33 ms pulsations of the pulsar are clearly visible. The pulse profile is unique amongst known pulsars in that it is aligned from radio to gamma-ray energies. The study of the pulsed emission in different energy ranges is of considerable importance to understanding the underlying emission mechanisms. In each of the two existing models which address the pulsed gamma-ray emission in detail, the outer gap model (Romani 1996) and the polar cap model (Daugherty & Harding 1982), the high energy flux arises from curvature radiation of electron/positron pairs as they propagate along magnetic field lines in the pulsar magnetosphere. The energy at which the pulsed flux begins to cut-off and the detailed spectral shape of the cut-off can help to distinguish between the two models. Given the detection of pulsations at energies up to 10 GeV by EGRET (Ramanamurthy et al. 1995) and the restrictive upper limits above 300 GeV (e.g., Reynolds et al. 1993), the cut-off must occur in the ~10 to 100 GeV energy range.

2   Analysis Technique and Selection Methods

The standard gamma-ray selection method utilized by the Whipple Collaboration is the Supercuts criteria (Reynolds et al. 1993). These criteria were optimized on contemporaneous Crab Nebula data to give the best sensitivity to point sources. In optimizing the overall sensitivity many showers below ~400 GeV are rejected.

In the context of a search for pulsed emission from the Crab pulsar, which must have a low energy cut-off to accommodate existing upper limits, it is clearlt desirable to include these low energy events. Accordingly, a modified set of cuts (Moriarty et al. 1997), developed to provide optimal sensitivity in the 200 to 400 GeV region and referred to hereafter as Smallcuts, was used for the events which failed the Supercuts pre-selection criteria. Simulations indicate that a combination of Supercuts and Smallcuts results in an energy threshold of ~250 GeV. This threshold is the energy at which the differential rate from a source with a spectral index equal to that of the steady Crab Nebula reaches its peak. The effective collection area is ~2.7×10^8 cm^2. Another selection process, known as Extended Supercuts (Mohanty et al. 1998), was used in a search for pulsed emission over the energy band 250 GeV to 4 TeV. This method is similar to Supercuts but instead scales the various cuts with the total shower *size* in ADC counts of each event and retains approximately 95% of gamma-ray events compared to approximately 50% of gamma-ray events passed by the Supercuts criteria. The effective energy threshold for the analysis can be increased by applying a lower bound on the *size* of an image. Lower bounds on the *sizes* of images of 500, 1000, 2000 and 5000 digital counts lead to energy thresholds of 0.6, 1.0, 2.0 and 4.0 TeV, respectively. The arrival times of the Cherenkov events were registered by a GPS clock with an absolute resolution of 250 μs. An oscillator, calibrated by GPS second marks (relative resolution of 100 ns), was used to interpolate to a resolution of 0.1 μs. The arrival times were transformed to the solar system barycentre and folded to produce the phase with respect to the radio ephemeris obtained from Jodrell Bank. An *optical* detection of the Crab pulsar was successfully carried out using the 10m reflector with a photometer at its focus (Srinivasan et al. 1997), confirming the validity of the timing of the experiment and the barycentering software used.

Figure 1: Search for TeV gamma rays from the Crab pulsar. The dashed lines depict the EGRET main pulse and intrapulse phase ranges. Error bars have been included on bins with the maximum and minimum number of counts.

3   Results

The phases of the events passing cuts are shown in Figure 1. We find no evidence for emission pulsed at the radio period. To calculate upper limits for pulsed emission we have used the pulse profile seen at lower energies by EGRET (Fierro et al. 1998). That is, we assume emission occurs within the phase ranges of both the main pulse, phase 0.94-0.04, and the intrapulse, phase 0.32-0.43. The number of events
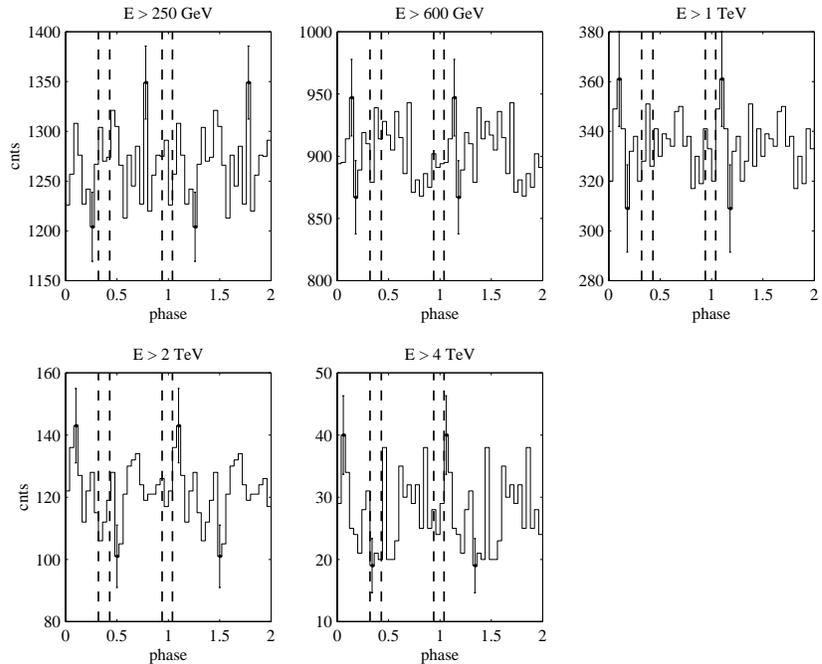
with phases within these intervals constitutes the number of candidate pulsed events, N_{on}. N_{off}, an estimate of the numbers of background events, is obtained by multiplying the number of events with phases outside these pulse intervals by the ratio of ranges spanned by the pulse and non-pulse regions. The results are given in Table 1. The statistical significance of the excess is calculated using the maximum likelihood method of Li & Ma (1983). The 99.9% confidence level upper limits calculated using the method of Helene (1983) are also given in Table 1. A few reports have described episodes of pulsed emission from the Crab pulsar at very high energies with time scales of several minutes (e.g., Bhat et al. 1986). For this reason we have performed a run-by-run search for periodic emission from the Crab pulsar based on the above pulse profile. The results were consistent with the null hypothesis that there were no episodes of emission with timescales of the order of 28 minutes, the duration of each run.

Figure 2: The pulsed photon spectrum of the Crab pulsar. The thin solid line is the polar cap model fit to the EGRET data (Harding 1999). The dotted line is the outer gap model for the Vela pulsar (scaled to match the EGRET Crab pulsar flux at peak intensity) and is included to indicate the shape of the cut-off this model predicts (Romani 1999). The dashed line represents the power-law fit to the EGRET data (Nolan et al. 1993). The dot-dashed line represents Equation 1 with a cut-off energy $E_o = 60$ GeV. The thick solid curve depicts the model of unpulsed GeV - TeV emission from the Crab Nebula (Hillas et al. 1998)

4 Discussion

Data taken with the Whipple Observatory's 10 m gamma-ray telescope have been used to search for pulsations from the Crab pulsar above 250 GeV. We find no evidence for emission pulsed at the radio period and upper limits on the integral flux have been calculated.

To model the pulsed gamma-ray spectrum, a function of the form

$$dN/dE = KE^{-\gamma}e^{-E/E_o} \tag{1}$$

was used, where E is the photon energy, γ is the photon spectral index and E_o is the cut-off energy. The source spectrum in the EGRET energy range is well fitted by a power law with a photon spectral index of -2.15 ± 0.04 (Nolan et al. 1993). The pulsed upper limit above 250 GeV reported here is ∼3 orders of magnitude below the flux predicted by extrapolation of the EGRET power law. Equation 1 was used to extrapolate the EGRET spectrum to higher energies constrained by the TeV upper limit reported here and indicates a cut-off energy $E_o \leq 60$ GeV for pulsed emission (see Figure 2).

The sharpness and location of the spectral cut-off can be used to discriminate between the emission models. Current observations and the derived cut-off given above indicate that the cut-off must lie in the 10-60 GeV range. However, the upper limits reported here are well above the flux predicted by the polar cap and outer gap models and offer no discrimination between them.

The outer gap model of Romani (1996) also predicts a component of emission peaking around 1 TeV arising from the synchrotron-self-Compton mechanism. The non-detection of such a TeV peak does not rule
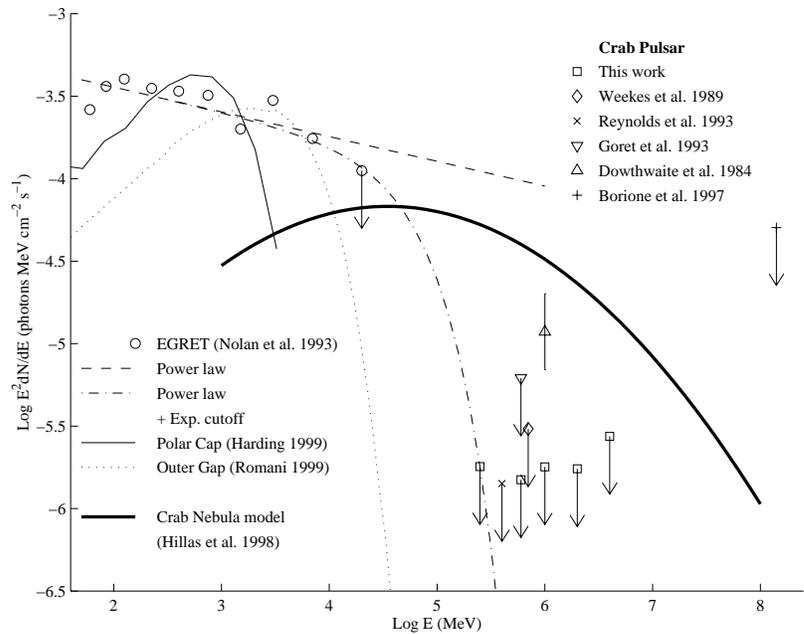
Table 1: Selected events for periodic analysis. N_{on} are the number of events with phases within the EGRET pulse profile and N_{off} are the background estimated from events falling outside the EGRET pulse profile.

Selection Method	N_{on}	N_{off}	Significance σ	Periodic Emission Upper Limit $(\mathrm{cm}^{-2}\mathrm{s}^{-1})\times 10^{-13}$	Threshold (TeV)
Supercuts + Smallcuts	6696	6636	0.65	<48.2	≥ 0.25
Extended Supercuts ($size > 500$)	4709	4748	-0.50	<16.7	≥ 0.6
Extended Supercuts ($size > 1000$)	1738	1762	-0.51	<12.0	≥ 1.0
Extended Supercuts ($size > 2000$)	602	649	-1.67	<5.9	≥ 2.0
Extended Supercuts ($size > 5000$)	125	150	-1.88	<4.6	≥ 4.0

out this mechanism since the flux produced is also dependent on the density of local soft photons which are upscattered by the high energy electrons.

Acknowledgements

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