



## Time-Dependent Observations of the Crab with Milagro

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**Abstract:** The Fermi and AGILE satellites both recorded a GeV gamma-ray flare from the Crab during September 2010. Observations of this event by ARGO suggest the flaring may extend into TeV energies. We report the result of a correlation analysis of a similar flare recorded by AGILE during October 2007 with data from the Milagro gamma-ray observatory, operational from December 2000 until March 2008. No significant increase in the Crab flux at TeV energies is observed during the flare, and we place limits on the corresponding TeV gamma-ray flux enhancement.

**Keywords:** Milagro Crab TeV

### 1 Overview

In September 2010, AGILE observed a gamma ray flare from the Crab Nebula of four times the Crab steady-state flux at  $>100$  MeV with a duration of 2–3 days [1]. The flare was subsequently confirmed by Fermi-LAT in a similar energy range [2]. In response to the satellite observations, the ARGO-YBJ observatory reported a  $4\sigma$  excess from the Crab at TeV energies during the time of the flare [3]. This corresponds to a factor 3–4 enhancement, similar in scale to the observations of AGILE and Fermi. MAGIC and VERITAS both were active during this period, and each reported no significant excess above expectation from the Crab [4, 5], making the picture at TeV energies less clear. Models suggesting that the GeV flaring is due to synchrotron radiation from regions of enhanced electron acceleration predict a corresponding increase in the TeV inverse Compton flux [6].

Following the September 2010 flare, investigation of AGILE data revealed an additional large flare from the Crab during October 2007 [1]. The Milagro air shower detector, operational from December 2000 until March 2008, was active during this period. Here we report observations of the Crab by Milagro during this flare.

### 2 The Milagro Observatory

The Milagro observatory [7] is a water-Cherenkov TeV air shower detector built in northern New Mexico, USA ( $36^\circ$  N,  $106^\circ$  W) at an elevation of 2650 m. The main component of Milagro is a covered pond measuring 80 m by 60

m at the surface, with sloping slides leading to a 50 m by 30 m bottom with a maximum depth of 7.5 m. The pond is instrumented with two layers of Hamamatsu R5912 PMTs; 450 PMTs are located 1.5 m below the surface and are used for core and angle reconstruction, and 273 PMTs 6 m below the surface are primarily used to identify a penetrating air shower component allowing the rejection of hadronic cosmic ray events. Later, 175 outriggers, Tyvek-lined plastic tanks with one PMT, were added in the area surrounding the pond to improve the reconstruction of events with cores landing outside of the pond.

In contrast to imaging air-Cherenkov telescopes, Milagro is operational during all parts of the day and not particularly biased toward any direction in the overhead sky. This continuous duty cycle and wide field of view make Milagro particularly suited to perform time-dependent surveys of the sky.

### 3 Results

During the period from September 2005 – March 2008, Milagro observed the Crab for 817 days integrated duration and obtained  $\sim 15\sigma$  excess, shown in figure 1, corresponding to  $\sim 0.5\sigma$  per transit. The median energy of gamma ray events from the Crab observed by Milagro is approximately 35 TeV, assuming an unbroken  $E^{-2.6}$  power law spectrum.

To perform our transit-by-transit survey of the Crab, we make the data more uniform by selecting only sidereal days with complete data. We eliminate days with incomplete observations by requiring that the Crab be at less than a 45 degree zenith angle at the start of the data, pass through

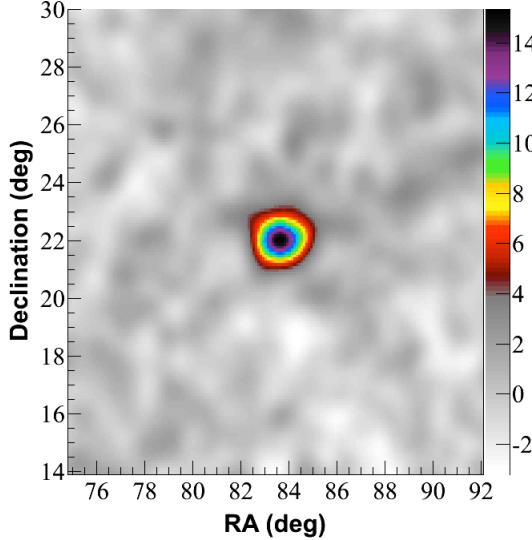


Figure 1: Milagro significances near the Crab from September 2005 – March 2008, in standard deviations.

zenith, and be a zenith angle of greater than 45 degrees at the end of the data. Days with an on-time of less than 90% of the duration of the data, determined by the first and last event, are also eliminated. Events are weighted according to the probability of originating from gamma rays [8] to reject the hadronic cosmic ray background and maximize the significances of gamma-ray sources. The background at the position of the Crab is calculated using the method of Atkins *et al.* [7], modified to use weighted events.

Observations of the Crab by Milagro are shown in figure 3 along with the AGILE light curve for the period of the October 2007 flare. No significant correlation between the AGILE flux and Milagro excess is observed. Limits on the Crab flux at 10 TeV during the most intense flaring (MJD 54376.8 – 54385.8) are shown in figure 2 along with Milagro measurements over the entire period from September 2005 – March 2008. The observations during the period of intense flaring are most compatible with the average flux observed by Milagro. A factor of 3 increase in flux at 10 TeV during the intense flaring is ruled out at 99% confidence level.

## 4 Summary

A significant flare from the Crab was observed by AGILE at  $>100$  MeV in October 2007. No evidence of an increase in the Crab gamma ray flux at TeV energies was observed by Milagro during this flare. When complete, HAWC will observe the Crab at  $6\sigma$  daily assuming the emission follows an unbroken power law with  $\gamma = -2.63$  [9], an improvement of over an order of magnitude from Milagro. HAWC will therefore strongly constrain the TeV component of similar flares occurring in the future.

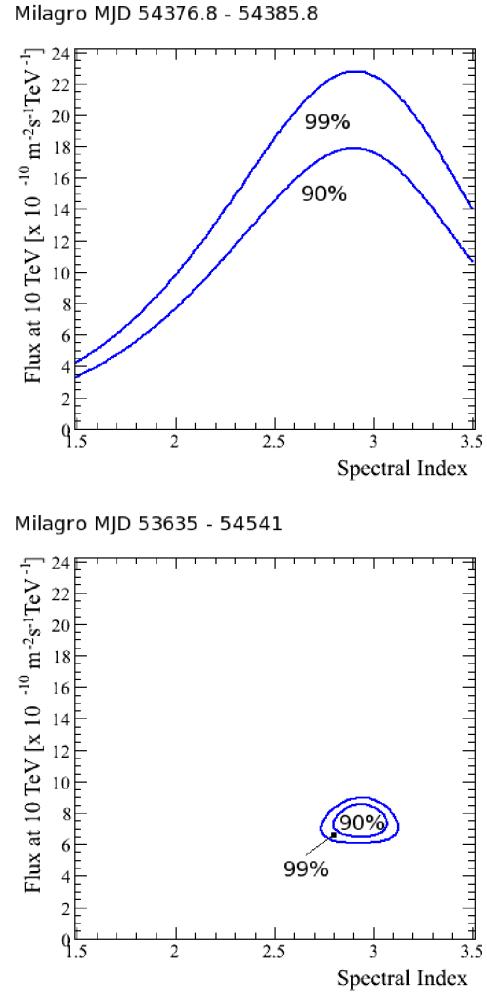


Figure 2: 90% and 99% confidence limits for the Crab flux at 10 TeV as a function of spectral index for the period of strongest flaring (MJD 54376.8 – 54385.8) (top) and for September 2005 – March 2008 (bottom).

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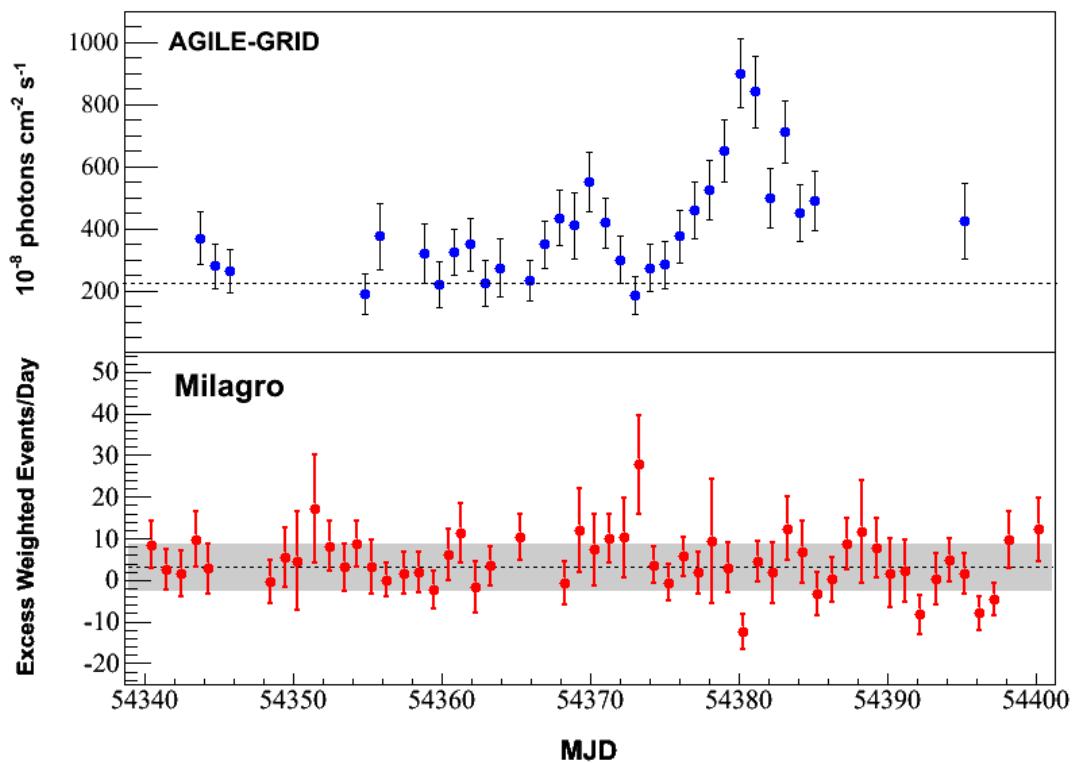


Figure 3: Observations of the Crab by AGILE [1] (top) and Milagro (bottom) for the period MJD 54340–54400. Dotted lines indicate the quiescent excess, and the grey band is  $\pm 1\sigma$  of this value.