

## HAWC Observations of the Crab Nebula

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**Abstract:** We present observations of the Crab Nebula with the HAWC Observatory. HAWC is a gamma-ray shower array under construction at 4100 m on the volcano Sierra Negra in Mexico. When complete, HAWC will consist of 300 water-Cherenkov detectors (WCDs) measuring 7.3 m (diameter) by 4.5 m (height) and instrumented with four upward-facing large-photocathode PMTs. The modular design of HAWC allows for the operation of completed WCDs during construction. HAWC has been recording data with at least 28 WCDs since late 2012.

**Keywords:** HAWC, Crab, gamma-ray

### 1 Flares from the Crab Nebula

The Crab nebula is arguably the most well-observed gamma ray source in the sky. Observations at MeV to GeV energies are obtained from satellite-borne instruments including the Fermi Large Area Telescope (LAT) and AGILE. Observations at GeV to TeV energies are obtained by ground-based experiments in two categories. Imaging air-Cherenkov telescopes (IACTs), including VERITAS, MAGIC, and H.E.S.S., have a low duty cycle ( $\sim 10\%$ ) but excellent sensitivity over a narrow field-of-view ( $< 5^\circ$ ). Ground-based air shower observatories, including Milagro, ARGO-YBJ, and HAWC, have a continuous duty cycle and wide field-of-view ( $\sim 2$  steradians) of the overhead sky, but a comparatively lower instantaneous sensitivity at any given point in the sky. The Crab, at declination  $22^\circ$ , transits near zenith for these ground-based observatories and is observed once per day for five to six hours. The Crab nebula has historically been viewed by the gamma-ray community as a standard reference source because of its relative stability.

During September 2010, AGILE and Fermi LAT recorded a gamma ray flare from the Crab nebula of four times above the baseline flux at  $> 100$  MeV with a duration of 2 to 3 days [1, 2] and variability at time scales of 12 hours [3]. In response to these observations, ARGO-YBJ reported a  $4\sigma$  excess from the Crab at  $\sim$ TeV energies during the time of the flare [4], corresponding to a flux of 3 to 4 times the expected value. MAGIC and VERITAS monitored the Crab for several  $\sim 20$ -minute windows during this period, and each reported no excess above expectation from the Crab [5, 6].

Following the September 2010 flare, AGILE and Fermi published observations of previous flares from the Crab Nebula in 2007 [1] and 2009 [2], respectively. Milagro, which ceased operation in 2008, reported no increase in flux from the Crab Nebula during the 2007 flare [7], and ARGO-YBJ did not observe an excess during the 2009 flare [8].

In April 2011, the Crab Nebula produced an extreme flare that was observed by Fermi [9, 10] and AGILE [11], with fluxes at  $> 100$  MeV increasing by a factor of 30, with a doubling time of eight hours [10] and a new component

appearing in the Crab nebula spectral energy distribution. ARGO-YBJ reported an excess during this flare, observing  $3.2\sigma$  to  $3.4\sigma$ , on a  $0.53\sigma$  to  $0.62\sigma$  expectation from the Crab [8]. No IACT results were published for this flare.

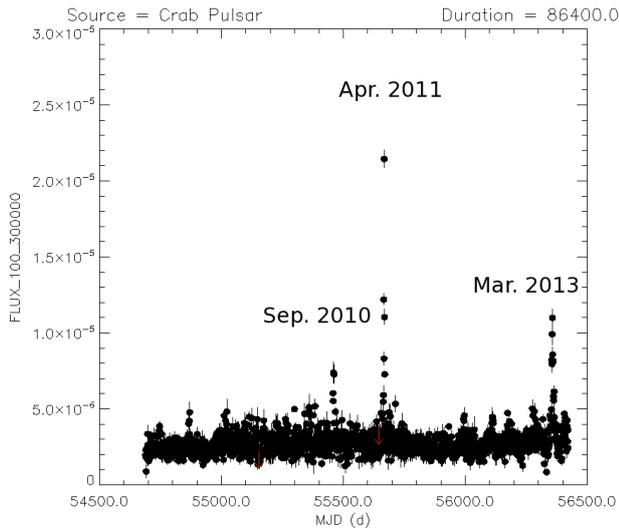
In July 2012, the Crab produced a fifth flare that was detected by LAT [12]. Again, ARGO-YBJ reported a  $4\sigma$  excess, corresponding to a flux of about eight times the expected value [13]; however, IACT observations were not possible, as the flare occurred during the daytime.

Finally, in March 2013, the Crab produced another flare detected by Fermi-LAT [14] and AGILE [15], the sixth flare in six years. The Fermi-LAT data show flare lasted about a week, with the  $> 100$  MeV flux peaking at a factor 4–5 above the quiescent flux. No observations of the Crab by ARGO-YBJ or IACTs during the flare have been published. The HAWC Observatory was operational with 28 tanks during the majority of this flare. The Fermi-LAT light curve of Crab is shown in Fig 1.

Analysis of Crab nebula energy spectra during the April 2011 flare obtained by Fermi LAT [10] and AGILE [11] strongly suggests that the emission at MeV to GeV energies is synchrotron radiation from a population of freshly accelerated PeV electrons that rapidly cool. The mechanism responsible for this acceleration is not yet understood. The accelerated electrons will also emit inverse Compton radiation at TeV to PeV energies, with an intensity and spectrum determined by the properties of the emission region. Measurements of this inverse Compton component therefore can constrain the properties of the emission region [17], including Lorentz factor, and constrain acceleration models e.g. [18, 19]. Current measurements in the  $> \text{TeV}$  energy range are unclear, but the marginal ARGO-YBJ excesses suggest that these studies may be within the reach of HAWC.

### 2 The HAWC Observatory

HAWC is a gamma-ray air-shower observatory under construction at 4100 m on the volcano Sierra Negra, near Puebla, in Mexico. HAWC consists of a densely-packed

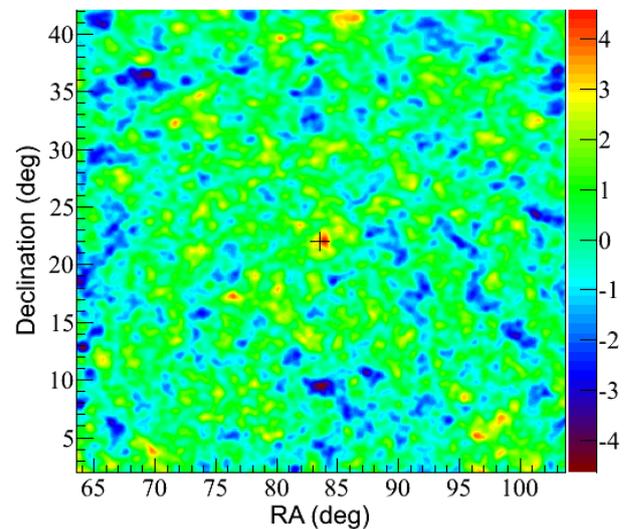
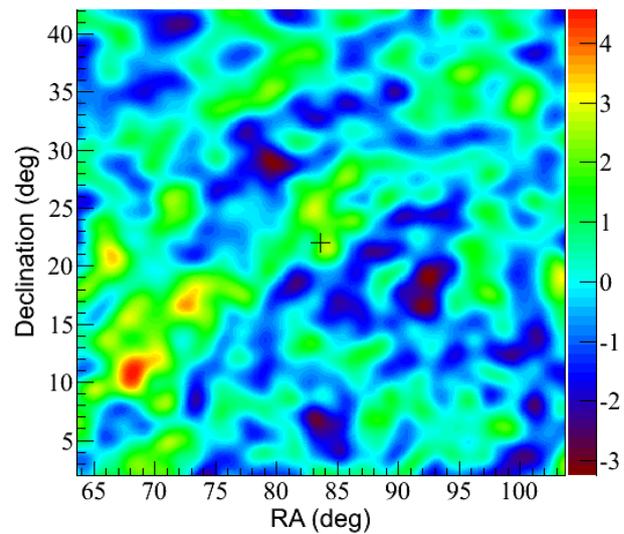


**Fig. 1:** Fermi-LAT light curve of the Crab at  $>100$  MeV showing the September 2010, April 2011, and March 2013 flares [16].

array of WCDs sensitive to air showers. Each WCD consists of a 7.3 m (diameter) by 4.5 m (height) corrugated steel tank with a plastic bladder inside that holds  $\sim 200,000$  L of purified water. Four photomultiplier tubes (PMTs) are deployed in each tank: One central 10-inch Hamamatsu R7081 HQE PMT and three outer 8-inch Hamamatsu R5912 PMTs. Signals from the PMTs are processed by scalers and TDCs. PMT timing and charge information from the TDCs is used to reconstruct the core location and axis of air showers landing on the array. At the time of the flare, HAWC recorded air showers at a rate of  $\sim 8$  kHz. The vast majority of these events are hadronic showers from cosmic rays.

HAWC is designed to be completely modular. Tanks are added to the data stream soon after they are constructed, increasing the sensitivity of HAWC over time. HAWC initially operated with 28 tanks from late 2012 through mid-April 2013. HAWC then operated with 43 tanks until mid-May, and has since been operating with 77 tanks. HAWC will operate with 111 tanks by the end of summer 2013 and is scheduled to be complete with 300 tanks before the end of 2014.

To maximize the statistical significance of gamma-ray sources, HAWC will reject hadronic cosmic ray events based on event morphology. Hadronic showers produce pions and muons which may have large transverse momentum and carry energy away from the shower core, whereas electromagnetic showers produced by gamma-ray events are more compact. Using the largest-amplitude PMT signal outside an exclusion radius of 40 meters as a statistic, in the 300-tank configuration HAWC will reject 99% of hadronic cosmic ray events above a few TeV, with negligible loss of gamma-ray events. In this configuration, HAWC will observe more than  $7\sigma$  on the Crab with each transit. With 28 tanks, hadronic cosmic ray rejection is not possible due to the small spatial extent of the detector, and only  $\sim 0.3\sigma$  is expected from each transit of the Crab. With 77 tanks, HAWC is large enough to reject a fraction of hadronic events. We expect approximately  $1.5\sigma$  per Crab transit in this configuration.



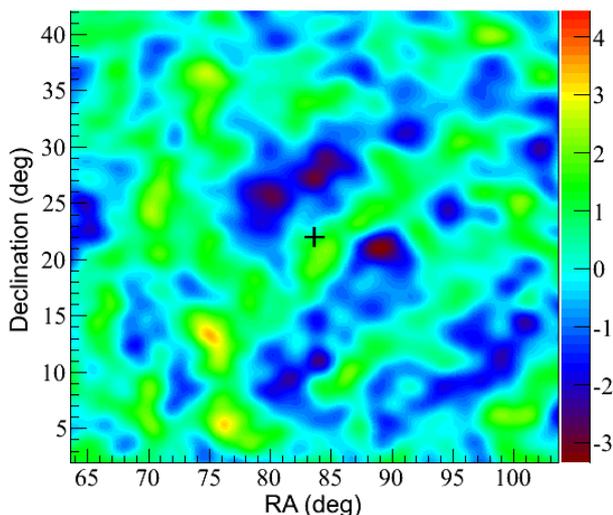
**Fig. 2:** 135-day HAWC 28-tank (top) and 14-day HAWC 77-tank (bottom) significance skymaps for the region of the Crab. The color scale units are standard deviations.  $2\sigma$  and  $3.5\sigma$  were observed at the position of the Crab in the 28-tank data and 77-tank data, respectively.

### 3 HAWC Observations of the Crab

From October 2012 to May 2013, HAWC observed the Crab for 135 days. HAWC observed a  $2\sigma$  excess at the location of the Crab during this period, shown in figure 2, roughly in-line with expectations from Monte Carlo. HAWC has now recorded approximately 14 days of data in the 77-tank configuration and observes a  $\sim 3.5\sigma$  excess at the location of the Crab, shown also in figure 2.

### 4 HAWC Observations during the March 2013 Flare

The March 2013 flare from the Crab began on March 4 and faded slowly after March 8. HAWC was in the 28-tank configuration during this flare. HAWC observed the Crab for a majority of the transit on each of these five days. HAWC observations are shown in figure 3. The measurement at



**Fig. 3:** 5-day HAWC 28-tank significance skymap for the region of the Crab from March 4–8, 2013. The color scale units are standard deviations.  $0.7\sigma$  was observed at the position of the Crab.

the position of the Crab was consistent with background, with an excess of  $0.7\sigma$ . This measurement rules out a very large TeV component from this flare; however, our data is preliminary, so we do not currently set a limit on the flux.

## 5 Performance of HAWC for Future Flares From the Crab

HAWC will operate with 111 tanks beginning in August 2013. In this configuration, HAWC expects to record  $2\sigma$  with each Crab transit and approximately  $5\sigma$  for a 5-day period. Therefore, for a similar five-day flare from the Crab, HAWC will be capable of measuring changes in the TeV flux of the Crab at the level of 20%. When complete in 2014 with 300 tanks, HAWC will observe  $7\sigma$  with each transit of the Crab. At this significance level, HAWC will measure the TeV flux of the Crab to better than 20% for each day of the year, enabling long-term studies of the Crab at TeV energies.

We acknowledge the support from: US National Science Foundation (NSF); US Department of Energy Office of High-Energy Physics; The Laboratory Directed Research and Development (LDRD) program of Los Alamos National Laboratory; Consejo Nacional de Ciencia y Tecnología (CONACyT), México; Red de Física de Altas Energías, México; DGAPA-UNAM, México; and the University of Wisconsin Alumni Research Foundation.

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