Searching for Variability of the Crab Nebula Flux at TeV Energies using MAGIC Very Large Zenith Angle Observations

36th International Cosmic Ray Conference
July 29th, 2019

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The Crab Nebula

- Pulsar wind nebula
- SED well described by one-zone synchrotron – SSC model

- Brightest persistent source in gamma rays
- ‘Standard Candle’ of VHE gamma-ray astronomy
Why search for variability?

- Observation of flares for first time in 2010 by AGILE & Fermi-LAT (Tavani et al., Abdo et al., 2011)
- Since then ~1 flare per year
- Origin not fully understood
- No counterpart at other wavelengths detected

(Meyer et al. 2010)
Flares in the Crab Nebula

Brightest Fermi flare: April 2011 (arxiv:1112.1979)

Using naima-package: Fermi-LAT data approximated by introducing additional e⁻ population

With standard Crab nebula parameters:

\[ B \approx 125 \, \mu \text{G} \]

\[ R \approx 2 \, \text{pc} \]

Inverse Compton component around \( \sim \text{PeV} \)
Flares in the Crab Nebula

Standard Crab nebula parameters:
- $B_{\text{Crab}} \approx 125 \mu G$
- $R_{\text{Crab}} \approx 2 \text{ pc}$

Short timescale of flares → emission region $\ll R_{\text{Crab}}$
- $R_{\text{flare}} \sim 10^{-4} \text{pc} \sim 10^{14} \text{ cm}$
  (plus locally strongly enhanced magnetic fields, Doppler boosting)

IC counterpart would appear in very high TeV energies

Difficulty: For low state Crab at 10 TeV $<10$ Events per hour per 1km$^2$ expected (at 300 GeV $\sim 1$ Event per second)
The MAGIC Telescopes

- Two Imaging Air Cherenkov Telescopes (IACTs) working in stereoscopic mode
- Located at Roque de los Muchachos Observatory on La Palma at 2200m a.s.l.

- Energy range from 30 GeV to 100 TeV
- Energy resolution between 15% and 25%
- Field of view 3.5°
- Sensitivity of ~0.5% Crab Nebula Flux in 50hrs above ~400GeV
- Typical effective area: $10^3 – 10^5$ m$^2$
VLZA Observations with the MAGIC Telescopes

VLZA = Very Large Zenith Angles: 70° - 80°

A new efficient tool to study the highest energy gamma rays

Larger distance from the air shower → boost in effective area to > 1km²

See also:

Crab spectrum at ~100 TeV
Michele Peresano
Presentation, GAI9d
July 30th
PoS(ICRC2019)759

VLZA-technique
Martin Will
Poster, Session 3, #86
July 30th & 31st
PoS(ICRC2019)828
Multi-year Light Curve

- Data taken between December 2014 and April 2018
- Zenith Angles: 70° - 80°
- ~ 50 hours of good quality data

Light Curve:
- Energy threshold: 10 TeV
- Monthly bins
Multi-year Light Curve

Light Curve:
- Energy threshold: 10 TeV
- Monthly bins

Constant Fit:
- Poisson statistics
- Maximum likelihood

Goodness of Fit:
- Simulation of equivalent LCs
- Compute logL for each
- P-value from CDF of simulated logL-values

Fit:
- \( F_{\text{fit}} = (0.25 \pm 0.03) \cdot 10^{-12} \text{ cm}^{-2} \text{ s}^{-1} \)
- \( p = 0.99 \quad X^2/Ndf = 21.27/20 \)

Data in good agreement with a constant fit → No evidence for variability
Upper Limits on Variability

Common quantification of variability:

- **Fractional Variation**

\[ F_{\text{var}} = \frac{\sqrt{\sigma^2 - \delta^2}}{\langle f \rangle} \]

- \( \sigma^2 = \frac{1}{N} \sum_{i=1}^{N} (f_i - \langle f \rangle)^2 \)
  - Mean squared deviation from fit
- \( \delta^2 = \frac{1}{N} \sum_{i=1}^{N} \delta_i^2 \)
  - Mean squared uncertainty of data (only statistical here)
- \( \langle f \rangle \)
  - Fitted flux

- Same set of simulated light curves as for goodness of fit estimation
- Calculate \( F_{\text{var}} \) for each
- From cumulative distribution obtain upper limits

99.7\% upper limit for variability above 10 TeV: \( F_{\text{var}} = 1.86 \) (preliminary)
Which scale of fluctuations in the Crab nebula flux could we detect?

- Simulations of light curves as before, but allowing flux to fluctuate within certain range \([-s, s]\)
  
  \[ f = f_{\text{fit}} + \Delta f \cdot f_{\text{fit}}, \] \( \Delta f \) drawn from uniform distribution between \([\max(-1,-s), s]\)

- Produce distribution of fractional variation \(F_{\text{var}}\)

- Repeat for different scales

- Calculate probability for \(F_{\text{var}}\) distribution to overlap with \(F_{\text{var}}\) distribution from constant flux assumption

\[ P_{\text{overlap}} \leq 0.3\% \text{ for } s \geq 2.25 \]

Sensitive to fluctuations on top of Crab nebula flux above 10 TeV within at least

\[ 2.25 \cdot f_{\text{fit}} = 0.56 \cdot 10^{-12} \text{ cm}^{-2} \text{ s}^{-1} \text{ (preliminary)} \]
Sensitivity to fluctuations

Which scale of flux increase could we detect within a given time?

Compare distribution of expected number of On-source counts for certain flux increase to expectation for nominal flux above 10 TeV

→ For different flux increases
→ For different exposures

Sensitivity to increase of Crab Nebula flux above 10 TeV
VLZA Case ($A_{\text{eff}} = 1.34 \text{km}^2$)

Note: 1h per night at VLZA
→ 5 nights for 5 hours of observation time
Summary & Outlook

- VLZA observations open window for MAGIC towards the highest TeV energies
- Technique and analysis well under control
- No variability found in 3.5 year light curve → Crab is still our “standard candle”
- Sensitive to overall fluctuations of within $2.25 \cdot F_{\text{crab}}$
- Sensitive to flares with factor $\sim 3$ flux increase in $< 4$ hours

- Still exploring possibilities of improving VLZA analysis to increase sensitivity
- Large and interesting data set → room for more detailed studies
- Will keep monitoring Crab nebula at VLZA
- Hope for Crab to be nice to us and bless us with a BIG flare!