Twelve-hour spikes from the Crab Pevatron

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http://www.isdc.unige.ch/images/results/101215_crab/crab_en.mov

Abstract

The Crab nebula displayed a large gamma-ray flare on 2010 September 18. To further explore the origin of this phenomenon, we analyzed the INTEGRAL (20-500 keV) and FERMI (0.1-300 GeV) data collected almost simultaneously before and during the flare.

No significant variations in the pulse profile and spectral characteristics are detected in the hard X-ray domain during the gamma-ray flare. In contrast, we identify three separate enhancements in the Fermi flux lasting for about 12 hours and separated by an interval of about two days from each other.

The spectral analysis shows that the flux enhancement, confined below ~1 GeV, can be modeled by a power-law with a high energy exponential cut-off, where either the cut-off energy or the model normalization increased by a factor of ~5 relative to the pre-flare emission. We also confirm that the gamma-ray flare is not pulsed.

We thus suggest that the gamma-ray flare is due to synchrotron emission from a very compact Pevatron located in the region of interaction between the pulsar wind and the surrounding nebula. These are the highest electron energies ever measured in a cosmic accelerator.

Introduction

With an integrated luminosity of about 5×10^{38} erg/s and a distance of ~2 kpc, the Crab supernova remnant is very bright from the radio domain to TeV energies (see e.g. Hester 2008, for a review). It is powered by a pulsar spinning on its axis in about 33 ms that injects energetic electrons into the surrounding nebula. The nebular emission up to 0.4 GeV is thought to be produced by synchrotron emission of these electrons in an average magnetic field of ~300 μG. At higher energies, inverse Compton (IC) cooling dominates.

The integrated high-energy flux of the nebula and the pulsar has been remarkably stable over the past few decades. The AGILE collaboration (ATel. #2855) reported the first gamma-ray flare from a source positionally consistent with the Crab, during which the flux above 100 MeV was a factor of 2 higher than its normal value. The gamma-ray flare on September 18 2010 from the direction of the Crab was confirmed by the Fermi collaboration (ATel. #2861), while observations from near-IR to hard X-ay did not reveal any significant variability within a few percents (ATeLs #2856, #2858, #2866, #2868, #2872). Also in the TeV range, the emission remained stable within 10% (ATeLs #2967, #2968). Radio timing observations did not evidence glitches and pulse profile changes during the flare (ATeL #2889).

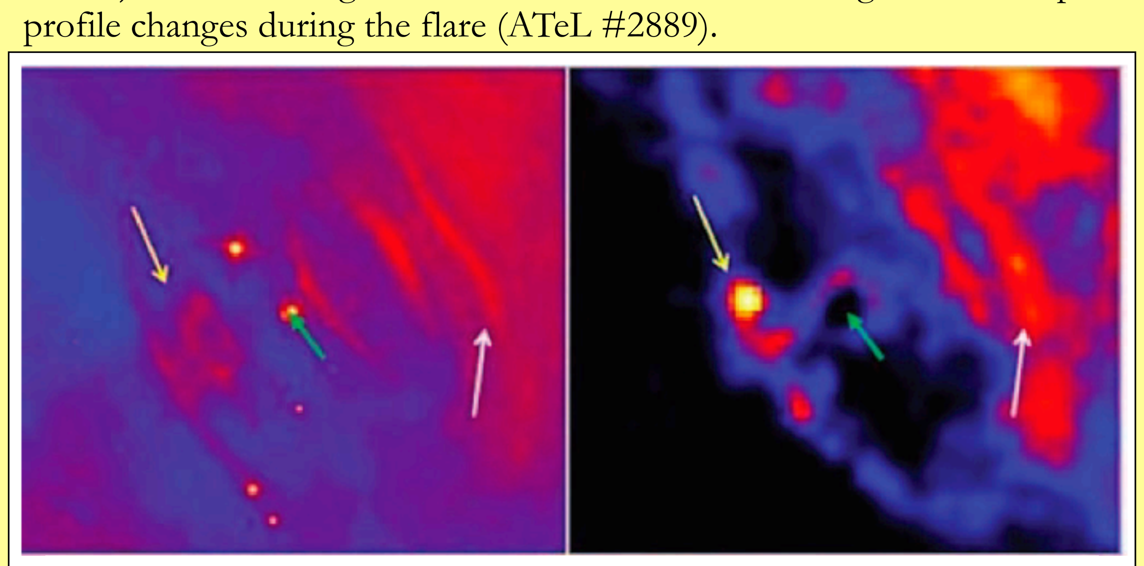

Fig. 1
Left: Optical image of the inner nebula region (ACS/HST, 3500-11 000 A). *Right*: X-ray image of the same region (ACIS/Chandra, 0.5-8 keV). The green arrow indicated the pulsar, white arrows indicate enhanced emission regions with respect to archival observations. The images are about 28"x28", north is up, east on the left (from Tavani et al., 2011).

A set of three 5 ks Chandra observations were performed on 2010-09-28, (ATeL #2882), 2010-10-28 (ATeL #2994)., and 2010-11-28 (ATeL #3058) to monitor the morphology of the inner nebula. There are no striking variations with respect to the previous observations, with the possible exception of an anomalous extension of a bright knot closer (down to 3") to the pulsar. A subsequent HST optical observation of the Crab confirmed this increased emission (ATel. #2903, see Fig. 1). However, it remains unclear whether this feature is related to the gamma-ray event.

The Crab gamma-ray flux returned to its usual level on 2010 September 23, less than a week after the onset of the flare (ATel. #2879).

FERMI/LAT results

Each point in the source light-curve (Fig. 2) is obtained by means of a single likelihood analysis using a PowerLaw2 model. to represent the total emission of the Crab. Three distinct peaks are clearly visible, which exceed by a factor of ~3 the pre-flare flux level, corresponding to a detection significance >15σ. The first increase occurs between 6:00 and 18:00 UTC on September 18. The second spike occurs about two days after, between 12:00 and 24:00 on September 20. The last flux increase was detected between 18:00 on September 21 and 18:00 on September 22. In all cases, the flare decay time was about 1 day.

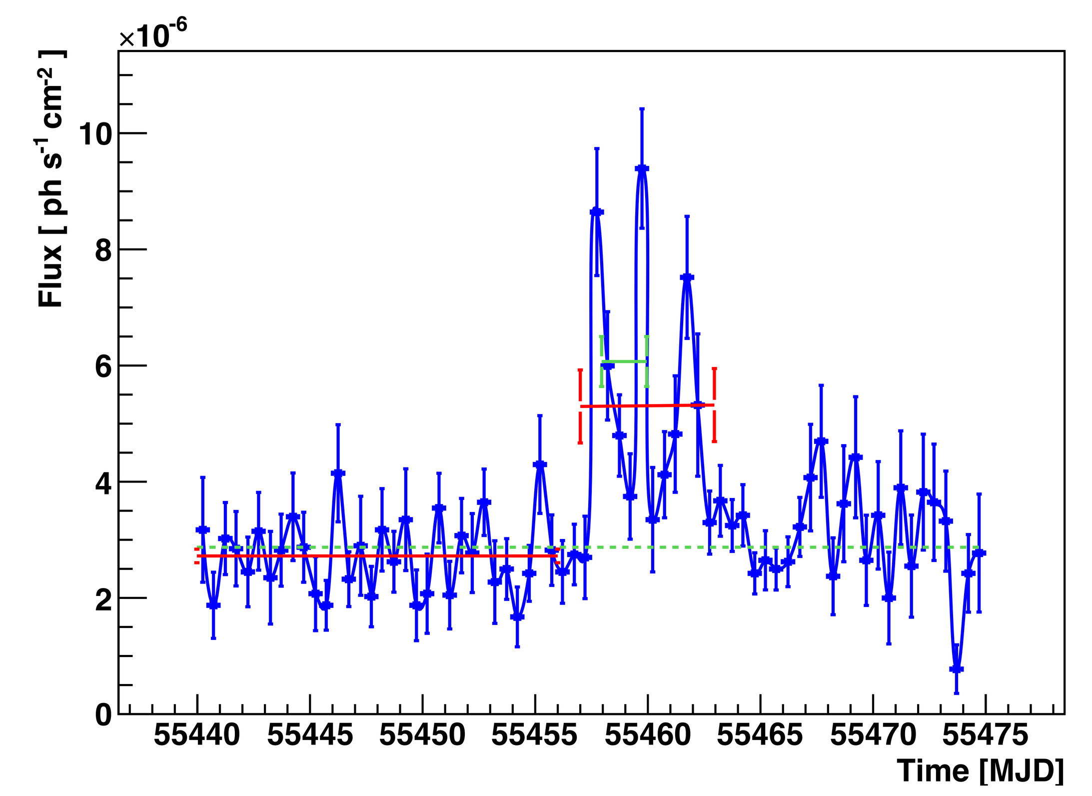

Fig. 2
FERMI/LAT light curve of the Crab in the 0.1-300 Gev energy range with 12h time bins. The green dashed line indicates the steady flux of the Crab estimated over all the Fermi operation period. The green solid line is the average flux between September 19 and 21. The red lines represent the average fluxes before and during the flares.

In Fig. 3, we compare the pulse profile measured before and during the flares. We conclude that the flux from the nebula increased by a factor 3.33±0.46 during the flares. In contrast, the pulsar flux remained constant within the errors.

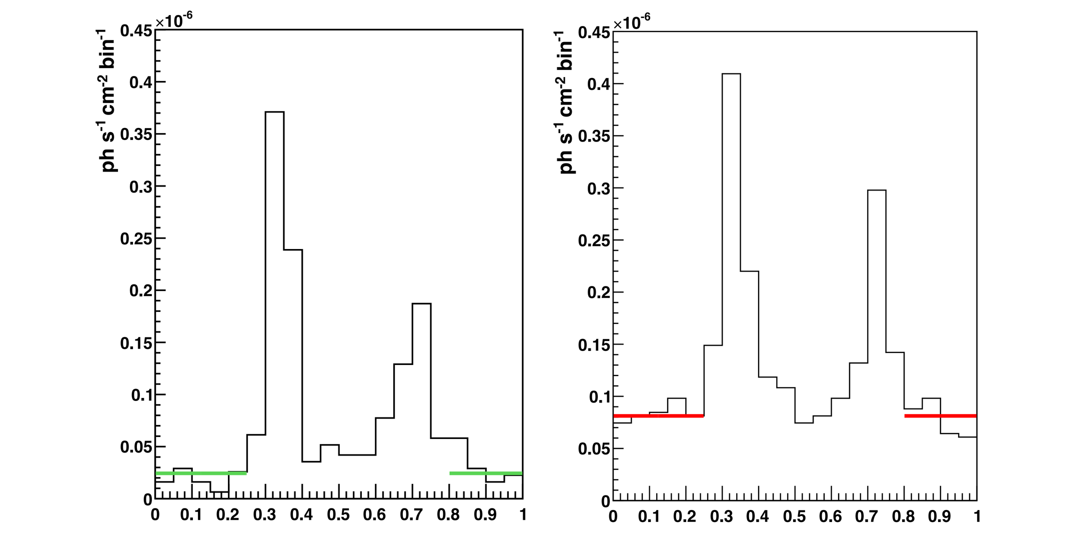

Fig. 3
Exposure corrected Crab pulse profiles in the Fermi energy band (0.1-300 GeV). *Left panel*: before the flares. *Right panel:* during the flares. The horizontal green and red lines indicate the off-pulse averages. We conclude that the flare concerns only the un-pulsed component.

We measure the spectral points before, during and after the flare exploiting the ML technique and a model made of a cut-off power-law for the pulsar and two power-laws for the nebular emission, which represent the synchrotron and IC components. We fix the pulsar and IC to their average values (Abdo et al, 2010), as they did not vary during the flare, and fit the synchrotron component. Subsequently, we make a simultaneous fit of the FERMI spectral points with the CGRO/COMPTEL data (0.75-30 MeV) using a cut-off power-law for the synchrotron emission (Fig. 4). We find that the difference between the quiescent and flaring spectra can be understood by considering two different extreme cases of either a constant power-law normalization, or a constant cut-off energy. In the former case, an increase in the energy cut-off by a factor ~5, from 77±15 MeV to 367±45 MeV, is needed. In the latter case, the spectral variability can be explained by raising the continuum normalization by a factor of ~5.

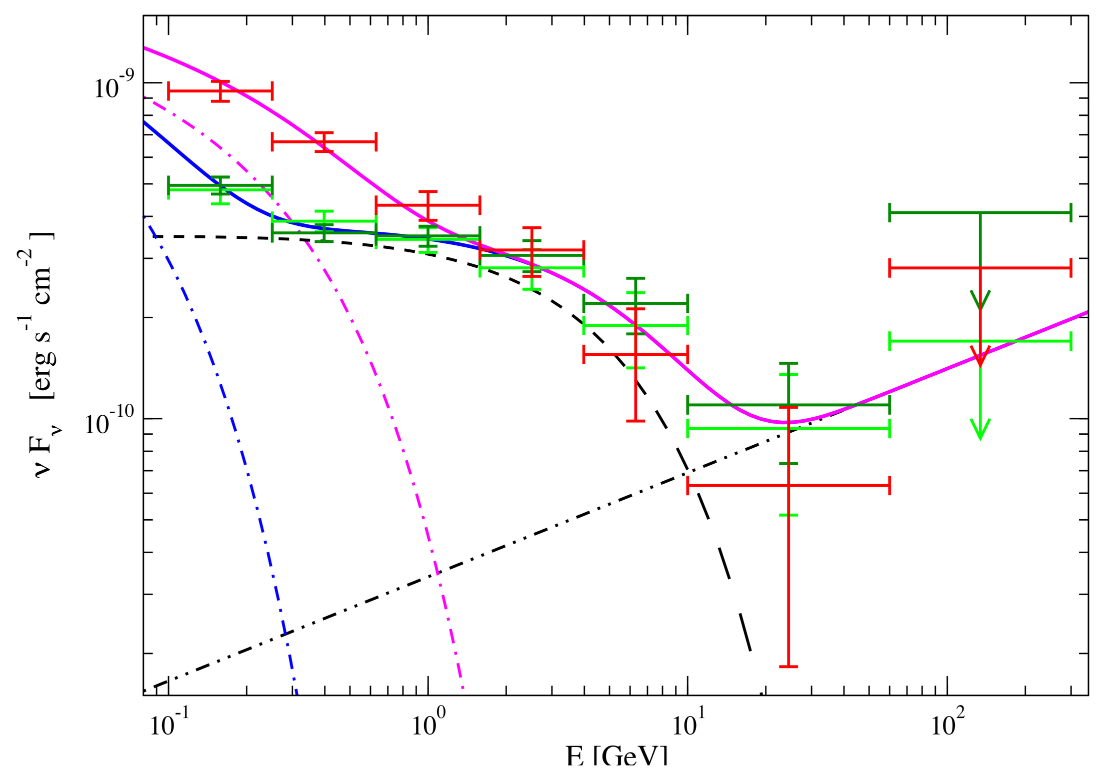

Fig 4
Crab spectral energy distribution in the 0.1-300 GeV energy range. The points with error bars are the Fermi detections before (dark green), during (red), and after the flare (light green). The black dashed line represents the contribution from the pulsar. The black dot-dot-dashed line is the IC emission from the nebula. The blue and magenta dot-dashed and solid lines are the synchrotron nebula and the total emission before and during the flare, respectively. Arrows indicate the upper limits at 95% confidence level.

INTEGRAL results

We analyzed the data taken from the spectrometer SPI (20 keV-1MeV) and the imager IBIS/ISGRI (20-500 keV) before and during the flare. The flux measured by SPI is constant within a 10% uncertainty, while the pulse profiles measured by ISGRI pose a 99% c.l. limit on a possible variability ranging from 4% in the 20-40 keV band to 30% above 150 keV.

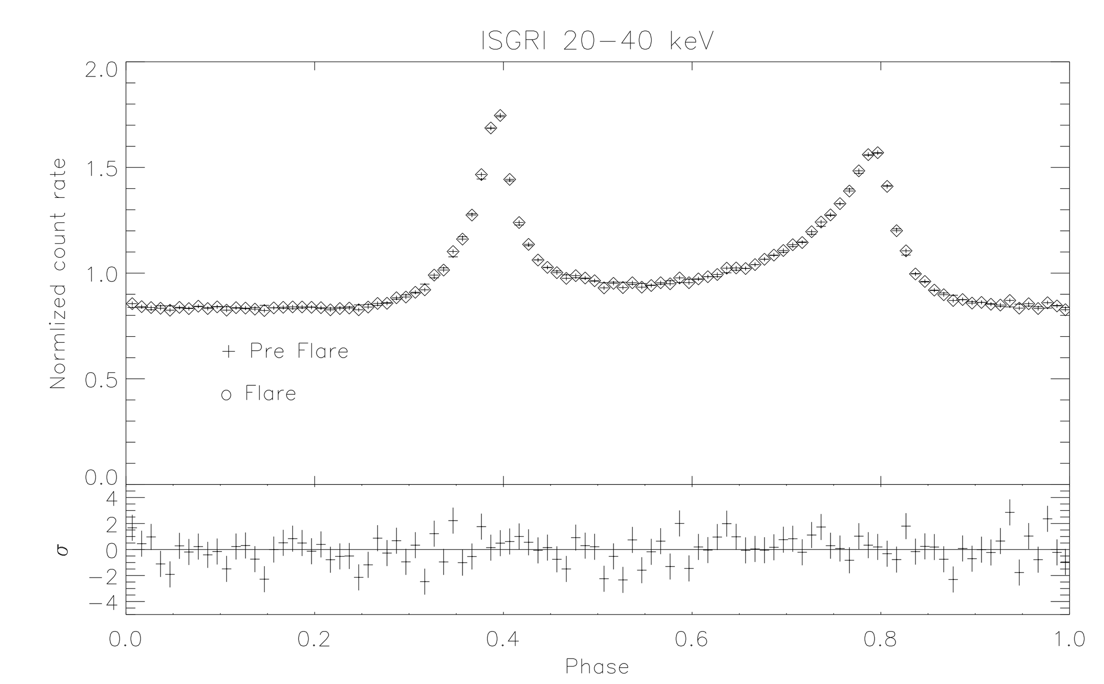

Fig. 5
Upper panel: pulse profiles measured by IBIS/ISGRI in the 20-40 keV energy band: crosses and diamonds represent the pulse profile before and during the Crab flare, respectively. *Lower panel*: significance in standard deviations of the difference between the pulse profile during and before the flare.

Discussion

From the analysis of the Crab pulse profiles, we confirmed that the gamma-ray variability originates in the nebula and not in the pulsar..

The presence of a population of electrons residing in compact regions, was invoked to justify the flattening of the Crab spectrum in the 0.75-30 MeV band by Aharonian & Atoyan (1998), who also argued that gamma-ray variability on days time scale, when detected, would have confirmed their hypothesis. The luminosity of this component is less than 1% of that of the whole nebula.

The short duration of the spikes in the 0.1-300 GeV light-curve, the absence of variability at other wavelengths and the lack of striking features in the Chandra and HST images of the Crab nebula all concur to confirm this scenario..

However, we are not able to differentiate between the two possibilities of enlarged emission regions or increased maximum energy of electrons, as several electron populations are probably present in the nebula and we do not have access to the few MeV energy band during the flare.

The cutoff in the synchrotron spectrum occurs at a characteristic frequency $\nu_{peak}\sim4.2\times10^6$ B γ^2 Hz, where B is the magnetic field intensity in Gauss and γ is the electron gamma factor. Provided that synchrotron radiation is the dominant mechanism through which particles loose their energy, by equating the acceleration and cooling time-scale, it is possible to obtain an electron synchrotron energy cutoff ≈160 η^{-1} MeV (η is the acceleration efficiency, see e.g., Aharonian, 2000). A higher value, as suggested by our analysis, may imply that the conditions in the accelerator differ from those in the emission region, e.g., there is a lower magnetic field in the former, or that the synchrotron gamma-rays are produced in a relativistically moving region, which implies a shift in the energy cutoff to higher energies by the corresponding Doppler factor δ. In this scenario, a value δ~367/160≈2.3 would be required to explain the energy cutoff obtained during the flaring episode.

The duration of the three short flares limits the size of the emitting region(s) to ≤ 10^{15} cm. The peak luminosity of these flares is higher than 10^{35} erg/s, i.e. ,~0.5 ‰ of the Crab spin-down luminosity, assuming an isotropic distribution. The distance between the emitting region and the pulsar can thus be constrained to be ≤6×10^{16} cm, i.e., not larger than 15% of the size of the bright synchrotron torus observed by Chandra and HST, and probably consistent with the half-width of this torus. The emitting region could therefore be linked to the interaction zone between the jet and the torus. The three flares separated by two days could possibly be related to various emitting knots in this region.

Conclusions

The flare relative short durations (< 1 day), their soft spectrum, and the analysis of the pulse profile in the 0.1-300 GeV indicate that one or more compact portions (≤ 10^{15} cm or < 0.1") of the synchrotron nebula are responsible for the flares. In these region(s), freshly accelerated PeV electrons are rapidly cooling, causing the observed variability.

Since the first event, many more flares have been detected from the Crab nebula, roughly once per year. Despite being challenging, the observation of this source in the very low energy range of CTA could provide constraints in the emission regions and test the different models invoked to accelerate particles in the nebula at such energies. The same electron population could also interact with the less energetic photons (e.g. cosmic microwave background, near- and far- infrared, photon background fields, synchrotron emission) via inverse-Compton process, providing another gamma-ray source of variability at much higher energies. Unfortunately, such radiation seems to be hardly detectable by CTA, because overwhelmed by the large nebula luminosity, except in the case of soft particle spectra (Γ_e>2.5) and strong magnetic fields (~mG), which would allow re-acceleration of particles.

References

Abdo, A. A., et al. 2010, ApJ, 708, 1254
Aharonian F. A. 2000, New A, 5, 377
Aharonian, F. A. & Atoyan, A. M. 1998, in Neutron Stars and Pulsars: Thirty Years after the Discovery, ed. N. Shibazaki, 439
Hester, J. J. 2008, ARA&A, 46, 127
Tavani, M., et al. 2011, Science, 331, 776