Burst activity of the Crab Nebula and its pulsar at high and ultra-high energies

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Abstract Characteristics of the flares of gamma rays detected from the Crab Nebula by the AGILE and Fermi-LAT satellite instruments are compared with those of a gamma ray burst recorded by several air shower arrays on February 23, 1989 and with one recent observation made by ARGO-YBJ array. It is demonstrated that though pulsar-periodicity and energy spectra of emissions at 100 MeV (satellite gamma ray telescopes) and 100 TeV (EAS arrays) are different, their time structures seem to be similar. Moreover, may be the difference between "flares" and "waves" recently found in the Crab Nebula emission by AGILE team also exists at ultra-high energies.

Keywords: Crab Nebula, Gamma Ray Astronomy, Cosmic Rays, Extensive Air Showers

1. Introduction

Gamma-ray flares from the Crab Nebula were discovered in a few-hundred-MeV energy range by the AGILE [1] and Fermi LAT [2] satellite telescopes. Since then, both the telescopes continue recording such flares approximately once in a year, the strongest of them (super-flare) having been detected in April 2011 [7], [8]. The energy spectra of additional emission during the flares were measured to be different from those of the Nebula, however, "the mechanism driving the flares, their impulsive nature, the 12-month recurrence time, and the location, remain unknown" [12]. For all that, based on multi-wavelength campaign to study the Crab using Keck, Hubble Space Telescope (HST), and Chandra X-ray Observatory, the authors of [12] suggested the so-called "inner knot" to be just the emitting region for the flares. In addition, the analysis made by the AGILE collaboration for the September-October 2007 event has found a fine structure in the flare's time behavior [10]. They have demonstrated that there is a difference between shorter "flares" and longer "waves" in the Crab Nebula emission during this flare.

After sensational discovery of gamma ray flares by AGILE and Fermi LAT it was recalled [3] that one event of this type (though at much higher energies) had been discovered many years ago by several EAS arrays [4], [5], [6].

2. Gamma-Ray Emission Burst on February 23, 1989

The first announcement about this burst was made during the International Workshop on Gamma-Ray Astronomy in Crimea in 1989 [4]. An increase of intensity of extensive air showers (EAS) was detected by the Carpet air shower array of the Baksan Neutrino Observatory on February 23, 1989. After this communication the group at Kolar Gold Fields (KGF) in India confirmed this result of Baksan and published a paper [5] on simultaneous detection of a gamma-ray burst in the Crab Nebula at ultra high-energies independently by two EAS arrays. Final publication [6] by the Baksan and Durham University teams summarized the data of all arrays that could observe the source on this day. It was demonstrated that with different significance the burst was detected by all air shower arrays located in the longitude range from India to Italy (KGF, Tien Shan, Baksan and EAS TOP). The arrays located to the east and west from this interval (at that time OHYA MINE and Akeno SPICA in Japan and HEGRA at La Palma, Canary Islands, were in operation) showed no excess from the source direction. Thus, the total duration of the observed effect was no longer than about 7 hours. One can speak also about a possible decay of intensity whose maximum probably fell on observations with the KGF array. Figures 1 and 2 taken from paper [6] demonstrate the most remarkable features of the burst as detected by the Baksan Carpet air shower array.

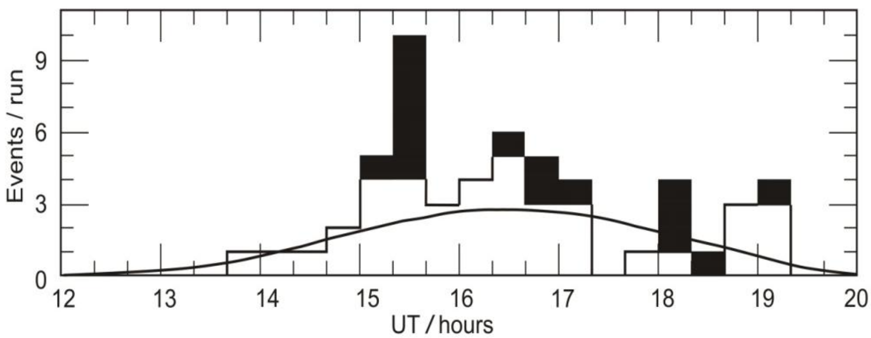

Fig1. *The number of events within the Crab cell per 20 min run for 23 February 1989. The smooth curve represents the expected background. The blacked events are from the 9th bin in Fig. 2.*

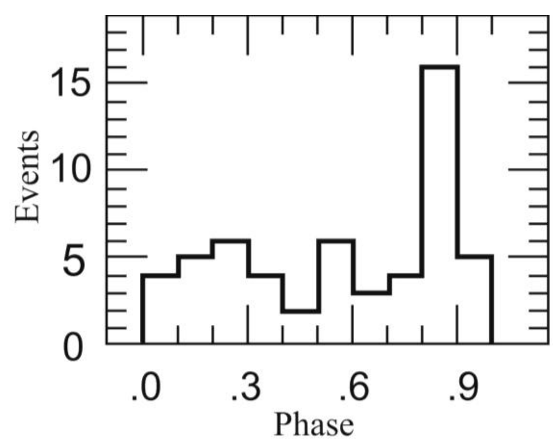

Fig2. *The relative phase distribution of the 55 events within the Crab cell after barycentring the arrival times and applying the values of the pulsar period and its derivative according to the Jodrell Bank Crab ephemeris.*

It is clearly seen that the Baksan array data demonstrate an obvious dependence of the effect on the pulsar phase: events from a single phase bin can produce the entire observed excess of intensity (the KGF group also found some phase irregularity, though not so well pronounced). Summarizing, one can state that with a rather high probability (the combined probability of random coincidences was estimated in [6] as $1.25 \cdot 10^{-7}$) a gamma-ray burst from the Crab Nebula was detected on February 23, 1989 in the energy range $10^{14} – 10^{15}$ eV, and excess emission in this burst is somehow connected with the pulsar’s activity.

3. Different or Similar Types of Flares at Different Energies?

3.1. Temporal Structure

In [3] attention was attracted to the fact that three-pulse temporal structure in the event of February 23, 1989 might be reproduced at least in one of the AGILE flare events (September 2007). A bit later it has been discovered [10] that in addition to flares there exists another type of intensity increase called waves. And exactly during the September 2007 three short flares (F1, F2, and F3) were identified together with two waves W1 and W2 (see Fig. 3).

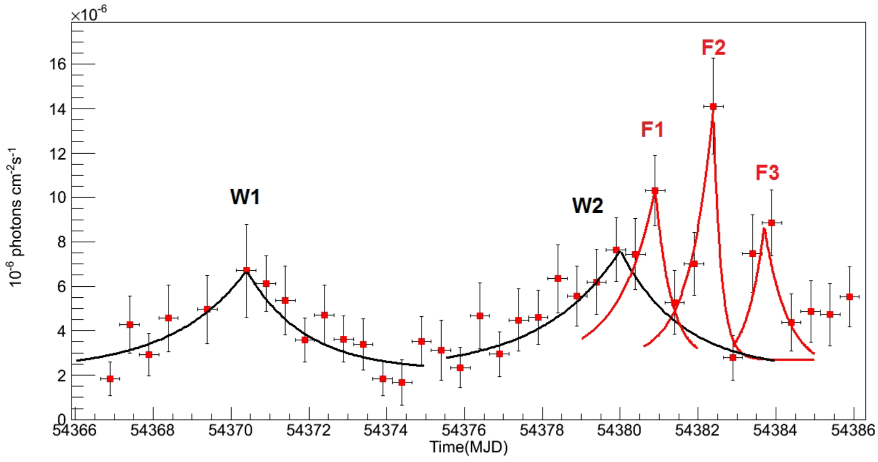

Fig3. *The difference between flares and waves in the Crab Nebula gamma-ray emission according to Striani et al. [10]. The three-flare structure of the event is similar to three bunches of narrow-phase emission constituting almost all excess counts in Fig. 1.*

Similarity of the temporal structures for events of Fig. 1 and Fig. 2 is obvious. In one case three bunches shorter than one hour are repeated with a period slightly longer than one hour. The other event includes three flares with duration of about one day, and they are repeated with a period a bit longer than one day. So, a sort of a stable pattern with a scale factor is observed at drastically different energies of gamma rays. It should be noted that the fine temporal structure was also reported by the Fermi LAT team for the March 2013 flare: “The light curve shows three sharp spikes (MJD 56357.1, 56357.9, 56360.1) on top of a strongly increased flux level.” [15]. Here, the period between the spikes is not so constant, but its duration, nevertheless, is close to that of Fig. 3 event.

The results of AGILE and Fermi LAT stimulated other groups to search for possible Crab flares, and one of them at first seemed to be successful. The ARGO-YBJ array after processing the data for Crab direction has found [9] an enhancement for the period September 19-26, 2010, which is shown in Fig. 4 for a 10-day period of averaging. The same event is presented in Fig. 5 with averaging over 2 days. This result was obtained at energies (about 1 TeV) intermediate between two region considered above. Nevertheless, there is a temptation to think that ratio of durations (several hours for 1989 event and about a week in this case) gives some evidence in favor of existence of the same “flares and waves” dichotomy at ultra-high energies. However, in the next publication [11] of ARGO-YBJ this piece of data was partially disavowed, though another interesting fact was presented: a correlation between Fermi and ARG-YBJ Crab intensities: “Even if the ARGO-YBJ rate variations are consistent with statistical fluctuations, the Fermi and ARGO-YBJ data seems to follow a similar trend. The ARGO-YBJ rate appears higher in the “hot” Fermi periods.” [11].

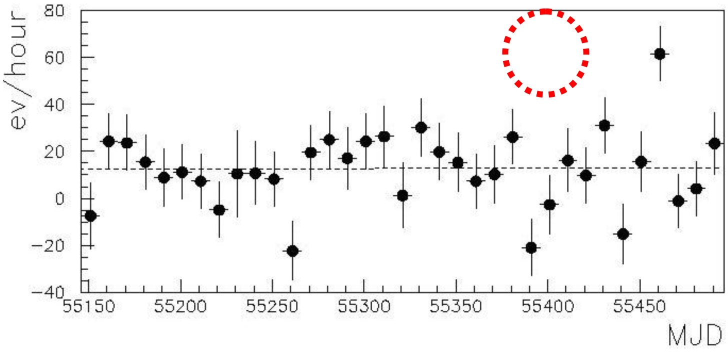

Fig4. The Crab light curve obtained in September 2010 by the ARGO-YBJ array with 10-day bins. The flare recorded by satellite gamma-ray telescopes took place on September 8-22. The point in red dashed circle is for September 19-26, 2010. Its significance is 5.4 standard deviations.

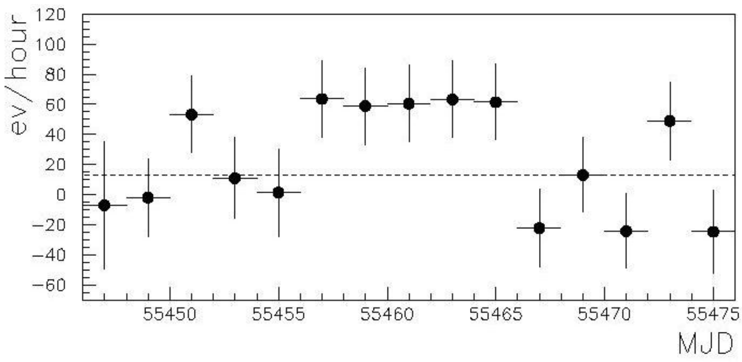

Fig5. The same data as in Fig. 4, but for the 2-day bin. The average rate in 8 days is 61 ± 13 ev/h, which is 4.8 times larger than the average rate in 3 years: 12.8 ± 1.3 ev/h.

3.2. Energy Spectra

It is commonly believed that the energy spectrum of the Crab Nebula is formed by synchrotron emission below 1 GeV and by inverse Compton radiation at higher energies. As far as flaring radiation is concerned, it is presumed to be associated with the synchrotron component. Spectral behavior of the flares appeared to be rather different: according to Fermi LAT, the flare in 2009 February exhibited only a flux increase with no spectral change. On the contrary, the flares in 2010 September and 2011 April had fluxes strongly correlated with the spectral index. In the March 2013 flare "the spectrum of the synchrotron nebula hardens as the flux increases" [15]. At the same time, according to an analysis made in [15], within the measurement accuracy the spectrum of the pulsar did not change in the entire analysis window with respect to the all-time average, and only synchrotron component of the Crab Nebula is rapidly variable.

For the ultra-high energy bursts at the moment no information on spectra is available.

3.3. Pulsar Periodicity

The Crab pulsar emission has a very complicated energy dependence. In the radio waveband in addition to the main pulse (MP) and interpulse (IP) there are a precursor of the MP, low-frequency component (LFC) and two high-frequency components (HFC1 and HFC2), as well as giant radio pulses that randomly appear on different phases. At higher energies the Crab light curve becomes more regular and the gamma-ray domain has only two pulses P1 and P2. The amplitudes of these two pulses depend on energy. For example, the P2 pulse is twice larger in amplitude than P1 at energy less than 10 MeV (COMPTEL), but already at energy > 30 MeV (EGRET) the situation is opposite. At the energy exceeding 100 GeV (the data of Cherenkov telescopes VERITAS and MAGIC) the pulse P2 becomes dominant again. There are also some indications to the possible appearance of a new pulse P3. So, it would be not surprising if at still higher energy only a single pulse survives, as it takes place in Fig. 2.

4. Discussion and Conclusion

Interpretation of gamma-ray flares as produced by synchrotron radiation of accelerated electrons in compact regions of intensified magnetic field (plasma instabilities) requires the energy of such electrons as high as 10^{15} eV (for example, [10]). If these electrons do really exist, one can recall the idea of Atoyan and Aharonian [16] that Crab Nebula wisps probably have sufficient amount of matter to make bremsstrahlung radiation effective. If so, 1000 TeV electrons can easily produce 100 TeV gamma rays. Even without this hypothesis accelerated particles can produce simultaneously multi-TeV emission via inverse Compton effect and hundred-MeV - GeV emission through synchrotron radiation [17]. When explaining two sets of data discussed in this paper, the problem is that at ultra-high energies the pulsar periodicity takes place, while it is not observed in hundred-MeV flares. As possible explanation one can suggest that at lower energies an observer receives gamma rays from a larger quasi-spherical surface of the pulsar-wind driven shock, so that the phase is randomized because of path differences.

Nevertheless, many details of the mechanisms of flare generation (like, for example, triple scaled temporal structure and distinction between flares and waves) are unclear as before, and the Crab Nebula still remains an enigmatic “astrophysical chimera” [13]. One can hope, however, that the above juxtaposition of data at different energies will be useful for construction of a realistic model of the source internal mechanism.

Acknowledgments

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