Gamma-ray flux depressions of the Crab nebula in the high-energy range

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ABSTRACT

The giant gamma-ray flares of the Crab nebula discovered by AGILE and Fermi observatories came as a surprise and have challenged the existing models of pulsar wind nebulae. We have carried out an analysis of 10.5 years of Fermi-LAT observations (Aug 2008 – Feb 2019) and investigated variability of the Crab nebula in the 100-300 MeV range. Besides the flares, we found several month long depressions of the gamma-ray flux and identified several cases of sharp flux drops, where during one week the flux decreased by an order of magnitude with respect to its average value. No statistically significant variations of the nebula flux in the $E > 10$ GeV range were found in the data. We discuss possible implications of the observed gamma-ray flux depressions on the model of synchrotron emission of the Crab nebula.

Key words: ISM: supernova remnants – gamma-rays – supernovae: individual (Crab nebula)

1 INTRODUCTION

The Crab nebula and the pulsar at the center of this nebula are among the most important objects of modern astrophysics (Hester 2008). Given its role as the primary test bench for studies of a broad class of pulsar wind nebulae (PWNe) and young pulsars, the Crab nebula have been observed with high cadence across the whole electromagnetic spectrum. Almost since its discovery in the high-energy range, the Crab nebula has been considered a perfect calibration source for many astronomical observations. Due to its spatial extent it was assumed that its flux in the X-rays and at higher energies should be rather stable. However, over the last 15 years observations revealed that this assumption is not always correct (Bühler & Blandford 2014): first, Fermi/GBM observations in the 15-50 keV range showed a $\sim 7\%$ flux decrease in a 2 years time span (2008-2010); this result was corroborated by observations with other instruments, such as Swift/BAT, RXTE/PCA, INTEGRAL/IBIS (Wilson-Hodge et al. 2011). Even more striking and unexpected was the discovery of flaring emission in the 0.1-0.5 GeV range made with AGILE and Fermi-LAT (Tavani et al. 2011; Abdo et al. 2011). The brightest flare detected to date occurred in April 2011 and lasted approximately 9 days, the peak flux above 100 MeV increased 30-fold compared to the average value (Buehler et al. 2012). The spectrum of gamma-ray emission changed drastically during the flares. During the steady state it is well reproduced by a combination of two components (see Fig. 1), the first one being a power law with a very soft spectral index $\gamma_s \sim 3.6$, and the second one – a broken power law with the spectral index gradually softening from $\gamma_{1,3} \sim 1.5$ at lower energies to $\gamma_{1,2} \sim 2.2$ at energies higher than 10 GeV. The first component is usually attributed to the synchrotron emission from short-lived PeV range electrons, while the latter is thought to be produced by an inverse Compton (IC) emission from a population of multi-GeV electrons. During the flares, the amplitude of the synchrotron component increased and also the spectral index became much harder, $\gamma_s \sim 1.3$ with emerging exponential cut-off at around 300 MeV. A summary of the flaring activity of the Crab nebula observed with Fermi-LAT for the last 11 years has been recently compiled by Huang et al. (2020).

The bulk emission of the Crab nebula from the radio band to the sub-GeV gamma-ray range is mainly due to the synchrotron radiation of relativistic electrons and positrons (see, e.g., Atoyan & Aharonian 1996). However, explanation of the GeV regime flares of the nebula with a synchrotron model is non-trivial. The fastest acceleration time of an elec-

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tron in an ideal MHD flow with the frozen-in magnetic field should not be substantially shorter than a particle gyroperiod. Hence the energy $E_m$ of a synchrotron photon emitted by an electron or positron of the maximal energy in an accelerator with a steady magnitude of the root mean square (r.m.s.) magnetic field where the synchrotron cooling rate is balanced by the particle acceleration rate would be less than $\approx 30$ MeV (independent on the value of the magnetic field) (Arons 2012). It is difficult to overcome this limit in quasi-steady and statistically homogeneous systems. However, if electrons are accelerated at the wind termination surface with some r.m.s. magnetic field but radiate in higher field (in a transient regime) their synchrotron photons would have energies well above $E_m$. A flare can be produced by a filament of much higher magnetic field inflowing into the accelerator. The magnitude of the flux change depends on the magnetic field variation and it is highly amplified in the cut-off region of the electron spectrum (Bykov et al. 2012). A flare magnitude can be high in the sub-GeV synchrotron range while appearing very modest at lower synchrotron photon energies. Fast cooling in the high magnetic field filament then require some time to restore a population of the highest energy particles which is accompanied with photon flux depression. There are also models of the gamma-ray flares observed in the Crab nebula, based on pair acceleration by electric fields in magnetic reconnection regions, developed by Cerutti et al. (2013). Doppler boosting of the photons produced at energies below $E_m$ in the vicinity of the nebula’s termination shock was considered in the model by Komissarov & Lyutikov (2011). Discussions of various aspects of gamma-ray flare modeling can be also found in (Bühl & Blandford 2014; Sironi et al. 2015; Lemoine 2016; Zrake 2016; Werner et al. 2016; Porth et al. 2017; Sobacchi & Lyubarsky 2020; Pohl et al. 2020). A thorough analysis of the high energy variability of the Crab nebula is needed to reveal the physical nature of the puzzling flare phenomenon.

In this paper we have carried out an analysis of the high-energy variability of the Crab nebula through a more than 10 year time span (Aug 2008 – Feb 2019), primarily focusing at the 100-300 MeV range emission where the synchrotron component is prominent.

## 2 DATA AND METHODS

The analysis of the Crab nebula is strongly affected by a local background provided by a very bright Crab pulsar. In the latest 8-year source catalog 4FGL these sources are modelled using 3 independent components – nebula synchrotron and IC and pulsar proper (The Fermi-LAT collaboration 2019). The spectrum is shown in the Fig. 1. It can be seen that: 1) The flux from the pulsar completely dominates at energies above 100 MeV but below 10 GeV 2) the synchrotron component is considerably larger than the IC component in 100-300 MeV energy range 3) at energies higher than 10 GeV the most of the total flux is produced by the IC component.

It is evident that the investigation of the synchrotron component should be made in 100-300 MeV range, otherwise there would be strong confusion from the IC component.

In our analysis we have used 130 months of Fermi LAT data collected since 2008 Aug 04 ( MET =239557417 s) until 2019 Mar 01 (MET=573091205). We have selected events that belong to the ”SOURCE” class. The Pass 8R3 reconstruction and FermiTools $^1$ were used. A usual event quality cut, namely that the zenith angle should be less than 90$^\circ$ was imposed.

We took a circle of 15$^\circ$ radius around the position of the Crab pulsar ($\alpha_{2000} = 83^\circ.6331, \delta_{2000} = 22^\circ.0145$) as our region of interest (RoI).

It is absolutely necessary to suppress the contribution from the pulsar, and luckily it can be done because the pulse profile demonstrates large off-pulse region where the pulsar emission is essentially absent (Abdo et al. 2011). For further studies we have defined 0.5 $< \phi < 0.85$ as our off-pulse region, while the main peak maximum is located at $\phi_{\text{max}} = 0.965$ (see Fig. 2).

Each photon was assigned phase using gtpphase procedure of the FermiTools package. Time of arrival (ToA)  

$^1$ http://fermi.gsfc.nasa.gov/ssc/data/analysis/software/

![Figure 1. Spectrum of the Crab Nebula and the Crab pulsar based on the 4FGL catalogue spectral models.](image1)

![Figure 2. Phase profile obtained from gamma rays with energies above 100 MeV within 3$^\circ$ of the Crab pulsar (10.5 years of observations, 318255 events).](image2)
of photon and exact position of the satellite at that moment allow to calculate barycentric ToA. Pulsar rotational ephemeris – its frequency and its derivatives were needed to get pulse phases from the ToAs. As the Crab pulsar is very young, its rotation is highly irregular, sometimes it even experiences so-called glitches – rapid increases of rotational frequency. Because of that it is extremely difficult to construct ephemeris even for one year time span, let alone for more than decade. To overcome this difficulty we have used Jodrell Bank Crab pulsar monthly ephemeris (Lyne et al. 1993) 2. The data were split into segments according to the ephemeris bins, most of these segments coincide with calendar months. After that ToAs of photons in each segment were folded with corresponding ephemeris and phase was assigned to each photon.

We performed analysis in 100–300 Mev energy range for three phase regions: off-pulse, on-pulse and full pulse. Light curves were obtained using two different types of binning – first, we used one-month bin. Also, due to the brightness of the source, it is possible to go even further and use smaller one-week bins.

We used standard glike utility for the analysis. The source model included 184 sources from the 4FGL catalogue (The Fermi-LAT collaboration 2019), contributing inside the RoI, the latest galactic interstellar emission model gll_iem_v07.fits, and the isotropic spectral template iso_PSR3 SOURCE_V2v1.txt3. We parametrized the contribution from the Crab with a simple power-law function with all parameters left free to vary. Apart from that only normalizations of the backgrounds were left free in the fitting procedure, all parameters of other sources were set to their values given in the 4FGL catalogue. The contribution from the Sun was studied and it was less than the errors of the fit even for weekly binning.

3 RESULTS AND DISCUSSION

The main results of the analysis are presented in Figs. 3 and 4. Flux of the pulsar $F_{\text{PSR}}$ in each bin was calculated as $F_{\text{PSR}} = F_{\text{on}} - \frac{1}{\Delta_{\text{off}}} F_{\text{off}}$, where $F_{\text{on}}, F_{\text{off}}$ are fluxes in on-pulse and off-pulse regions, $\Delta_{\text{off}} = 0.35$ is the phase duration of the off-pulse part. Similarly, flux of the nebula was calculated as $F_{\text{PWN}} = F_{\text{off}} / \Delta_{\text{off}}$.

Several strong flares are the most prominent features of the light curves at both binning scales. The pulsar emission was very stable during the considered time period. It was definitely not the case for the component coming from the nebula – apart from flares it demonstrated long rises and depressions. This behaviour was earlier found in the analyses of EGRET, AGILE and Fermi LAT (up to May 2012) data as well (de Jager et al. 1996; Striani et al. 2013). In the latter analysis (Striani et al. 2013) no specific selection of off-pulse photons was performed. In what follows we focus our analysis on the 'depression' episodes. The most prominent one had place during December 2011, and another strong depressions were observed in June and August 2015 and January 2018. Week light curve of the Oct 2011 - Jan 2012 interval is shown in Fig. 5. During this interval the PWN flux was considerably below its average value $F_{\text{PWN}} = 7.8 \times 10^{-7}$ ph cm$^{-2}$ s$^{-1}$ which was calculated using all epochs in absence of strong flares. But the most striking feature is a strong dip around MJD 55900 (first week of December 2011). In this bin the flux decreased to $F_{\text{min}} = (7 \pm 6) \times 10^{-8}$ ph cm$^{-2}$ s$^{-1}$ which is order of magnitude smaller than the average value and three times smaller than the flux in the previous bin. There are three additional examples of such extreme variability (epochs: MJD 57197, 57244, 58128) where the flux falls to comparable values. It can be seen that in the minimum the level of the nebula flux is very close to the level of contribution from the IC component (see Fig. 1), assumed to be non-variable.

It can be demonstrated that it is not an artefact of the fit. We combined count maps for 4 weeks with extremely low flux and 4 weeks where the flux was close to its average value (Fig. 6). In the first case the nebula is almost absent from the count map and the most prominent features belong to diffuse background. In the second case the very same features are

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2 http://www.jb.man.ac.uk/~pulsar/crab.html
3 http://fermi.gsfc.nasa.gov/ssc/data/ access/lat/BackgroundModels.html
clearly subdominant comparing to the emission from the nebula. The source in the first case were detected with very low significance, test statistics $TS \sim 2$, $F_{PWN} = (6.5 \pm 6.3) \times 10^{-5}$ cm$^{-2}$ s$^{-1}$, in sharp contrast with the second case: $TS \sim 160$, $F_{PWN} = (8.0 \pm 0.9) \times 10^{-5}$ cm$^{-2}$ s$^{-1}$.

Finally, we have studied the behaviour of the source at high energies, $E > 10$ GeV, where the hard, presumably IC component from the nebula starts to dominate over the pulsar. Thus it is possible to use full phase window without losing almost two thirds of information because of application of gating procedure. Flux is considerably lower at these energies and shear lack of statistics does not allow to obtain meaningful results with binning finer than one month when performing maximum likelihood analysis with the \textit{gtlike} utility. However, much improved angular resolution at these energies makes possible robust check with means of aperture photometry – we took selection radius equal to 0.5 which is close to the value of $PSF_{50}$ (point-spread function which contains 95% of all photons from the source). The Crab nebula is by far the brightest source at energies $E > 10$ GeV so we operated in virtually background-free regime. Photon counts and exposures were calculated for two types of bins (month, week) which allowed to calculate expected number of counts in bins. No significant fluctuations were found – in case of weeks the lowest local p-value was equal to $1.2 \times 10^{-3}$ which gave the global p-value around 0.6, the lowest global p-value for one-month binning was equal to 0.3.

We have tried to interpret the observed depressions in the model by Bykov et al. (2012) where the pulsar wind in the upstream flow is inhomogeneous and can fluctuate by factor several comparing to its mean value. The high energy electrons which are responsible for the synchrotron emission at the frequency $\nu_{100}$ corresponding to 100 MeV energy are concentrated in a narrow layer with the width of $L_{\text{rem}} = 5U_{\text{d,cm/s}}H_g^{-1/2} \tau_{\text{p}}^{-1/2}$ cm near the termination shock. For the downstream speed $U_{\text{d,cm/s}} = c/3$ and magnetic field $H_g = 2 \times 10^{-4}$ G this is $L_{\text{rem}} = 2 \times 10^{16}$ cm which corresponds to the characteristic time of the flux change equal to $\tau \sim 2 \times 10^6$ s. If the electron concentration meets a region with enhanced magnetic field, a flare occurs. In opposite case, when the magnetic field is temporarily lower than its average value, there is a decrease in the synchrotron emission. The termination shock region is an extended object and the time delay of photons that come to the observer from different parts smears the light curve of the emission. It could be not too important for a flaring case, when depending on a degree of the magnetic field enhancement, the ‘hot-spot’ could overshadow the rest of the emission layer, but it strongly affects the opposite case of flux depression.

Based on Chandra data and distance estimation of 2 kpc we assume the termination shock radius to be $4 \times 10^{17}$ cm and the pulsar equatorial plane inclination angle to the line of sight to be $\sim 30^\circ$. Here we consider a model, where the pulsar wind is inhomogeneous but axially symmetric. As the wind with lower magnetic field reaches the termination shock, its emission is turning off. However, due to the time delay we can still see the emission from the farther parts of the termination shock during the time $\tau \sim 2.3 \times 10^3$ s. Within such a model, the observable lightcurve is also sensitive to the duration of travel of the pulsar wind carrying a decreased magnetic field through the termination shock. Figure 7 shows simulated light curves for two different assumptions on this duration.

Whole emission at the energies larger than 100 MeV is concentrated in a thin layer with $2 \times 10^{16}$ cm thickness which can be spatially resolved by the Chandra X-ray observatory. The expected variation of the observed X-ray flux from this layer should be low, because the emission in a $\mathcal{O}(\text{keV})$ energy range contains a substantial background fraction accumulated along the line of sight from the much wider region of the nebula, precluding large variations in the Chandra data.

The model of a filament in non-relativistic flow could explain both flares and flux depressions at longer time scales (several month) but can not explain sharp drops of flux, like observed in December 2011, when the flux decreased by a factor of several at $\mathcal{O}(10^6)$ s timescales. If instead the relativistic upstream flow produces the emission or if the termination shock is oblique and the downstream flow is relativistic, then different parts of the emitting surface have different Doppler factors and the bulk of the emission comes from the regions moving ahead to the observer. In this case the characteristic variability time is determined not by the time delay of the photons coming from the whole layer, but only by those coming from a small region where plasma flows towards the observer. Thus the variabiliy timescale can be considerably smaller and even be close to the limit.

Figure 5. Light curve of the Crab nebula Oct 2011- Jan 2012.

Figure 6. Left panel: count map for 4 weeks with extremely low flux. Right panel: count map for 4 weeks with flux close to its average value.
\( \tau \sim L_{\text{mm}} / U \sim 2 \times 10^6 \text{ s} \) as estimated above for the 100 MeV emission.

\section*{4 CONCLUSIONS}

With 10.5 years of the Fermi-LAT observations we have investigated variation of emission from the Crab nebula in the 100-300 MeV range. Besides already well known flares we have found several month long flux depressions and identified several cases of sharp flux drops, where during one week the gamma-ray flux decreased by an order of magnitude with respect to its average value and by the factor of three compared to the previous week. However, no significant variations in the \( E > 10 \text{ GeV} \) energy range were found. This picture is consistent with the hypothesis that the emission above GeV is dominated by the inverse-Compton scattered photons from a quasi-steady accelerator of PeV regime electron-positron pairs. The observed strong drops of the 100-300 MeV flux indicate the variability of the total gamma-ray flux in the synchrotron cut-off regime. While the previously discovered giant gamma-ray flares could be explained as a separate component over the quiescent synchrotron gamma-ray flux, the flux drops we have found indicate the presence of coherent variations of the whole source of the 100-300 MeV photons. This may provide important constraints for the models of synchrotron gamma-ray radiation in PWNe. Indeed the models of impulsive acceleration of multi-PeV regime pairs by a reconnection event or a short pulse of Doppler boosted gamma-rays from some localized regions can be responsible for the flares, but on another hand, the strong drops of the gamma-ray flux can be associated with variations of magnetic field within the source of the synchrotron gamma-ray photons (e.g., the wind termination surface). We have shown that relatively modest variations of magnetic field can produce strong flux variations in the synchrotron cut-off regime. In such a simple model the variable flux emerges near the PWN termination surface due to the inhomogeneities of the pulsar wind magnetic field inflowing into the quasi-steady distribution of the locally accelerated PeV regime pairs. This simple approach could explain both the long flares and long depressions, while the sharp drops can be due to Doppler boost of the emitting region in relativistic flow or fast cooling of the highest energy pairs. Future observations of multi-TeV photons from the Crab nebula and especially observations of variability patterns in this energy range, would certainly help us to distinguish between different models of high energy emission of the nebula.

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\section*{REFERENCES}

Abdo A. A., et al., 2011, Science, 331, 739
Arons J., 2012, Space Sci. Rev., 173, 341
Atoyan A. M., Aharonian F. A., 1996, MNRAS, 278, 525
Buehler R., et al., 2012, ApJ, 749, 26
Bühler R., Blandford R., 2014, Rep.Prog.Phys., 77, 066901
Bykov A. M., Pavlov G. G., Artemyev A. V., Uvarov Y. A., 2012, MNRAS, 421, L67
Cerutti B., Werner G. R., Uzdensky D. A., Begelman M. C., 2013, ApJ, 770, 147
Hester J. J., 2008, ARA&A, 46, 127
Huang X., Yuan Q., Fan Y.-Z., 2020, p. arXiv:2003.02865
Komissarov S. S., Lyutikov M., 2011, MNRAS, 414, 207
Lemoine M., 2016, Journal of Plasma Physics, 82, 635820401
Lyne A. G., Pritchard R. S., Graham Smith F., 1993, MNRAS, 265, 1003
Pohl M., Hoshino M., Niemiec J., 2020, Progr Part Nucl Phys, 111, 103751
Porth O., Buehler R., Olmi B., Komissarov S., Lamberts A., Amato E., Yuan Y., Rudy A., 2017, Space Sci. Rev., 207, 137
Sironi L., Keshet U., Lemoine M., 2015, Space Sci. Rev., 191, 519
Sobacchi E., Lyubarsky Y. E., 2020, MNRAS, 491, 3900
Striani E., et al., 2013, ApJ, 765, 12
Tavani M., et al., 2011, Science, 331, 736
The Fermi-LAT collaboration 2019, p. arXiv:1902.10045
Werner G. R., Uzdensky D. A., Cerutti B., Nalewajko K., Begelman M. C., 2016, ApJ, 816, L8
Wilson-Hodge C. A., et al., 2011, ApJ, 727
Zrake J., 2016, ApJ, 823, 39
de Jager O. C., Harding A. K., Michelson P. F., Nel H. I., Nolan P. L., Sreekumar P., Thompson D. J., 1996, ApJ, 457, 253

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