Gamma-ray flare and absorption in the Crab nebula: lovely TeV–PeV astrophysics

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ABSTRACT
We spectrally fit the GeV gamma-ray flares that have recently been observed in the Crab nebula by considering a small blob Lorentz-boosted towards us. We point out that the corresponding inverse Compton flare at the TeV–PeV region is more enhanced than synchrotron emission by a Lorentz factor squared (\(\Gamma^2\)). This already excludes \(\Gamma^2 > 200\) and it will be detected by future TeV–PeV observatories, such as the Cherenkov Telescope Array (CTA), the Tibet Air Shower plus Muon Detector (Tibet AS+MD) array and the Large High Altitude Air Shower Observatory (LHAASO), for \(\Gamma > 30\). We also show that PeV photons emitted from the Crab nebula are absorbed by cosmic microwave background radiation through electron–positron pair creation.

Key words: pulsars: individual: Crab nebula – gamma-rays: stars.

1 INTRODUCTION
It is well known that the Crab nebula is one of the brightest objects in the hard X-ray and gamma-ray sky. Because its flux has been considered to be completely steady, it has been used as a standard candle to calibrate detectors and instruments in those energy ranges. Because the Crab nebula has a reputation as the most important strong and steady source in the high-energy gamma-ray sky, its impermanence will be a significant surprise.

Quite recently, AGILE (Tavani et al. 2011) and Fermi (Abdo et al. 2011; Buehler 2011) have reported gamma-ray flares with time-scales of 1 d from the Crab nebula in the \(\mathcal{O}(10^2)\)MeV–\(\mathcal{O}(1)\)GeV region. This means that the Crab nebula is no longer stationary. According to the spectral fitting of a stationary component, flares are most likely produced by synchrotron emission with an increase in the electron energy cut-off \(E_{\text{max},\gamma} \sim 10\) PeV and/or in the magnetic field \(B \sim 2\) mG. However, under the standard particle acceleration, the synchrotron energy loss limits the maximum synchrotron photons, irrespective of \(B\), below

\[ E_{\text{max},\gamma} \sim \frac{9m_e c^2}{4 \alpha} \sim 160\text{ MeV}, \]

which is violated in the flares. Possible solutions include the relativistic Doppler boost (e.g. Bednarek & Idec 2011; Komissarov & Lyutikov 2011; Yuan et al. 2011), the electric-field acceleration in the reconnection layer (e.g. Uzdensky, Cerutti & Begelman 2011), the sudden concentration of the magnetic field (e.g. Bykov et al. 2012) and a DC electric field parallel to the magnetic field (Sturrock & Aschwanden 2012). However, there has been no consensus yet.

In this paper, we consider the relativistic model in which a small blob is Lorentz-boosted towards us, emitting synchrotron radiation beyond \(E_{\text{max},\gamma}\) (see Buehler et al. 2012, and references therein). We stress that we can observe the corresponding inverse Compton flare, which is simultaneously emitted by the same electrons existing in the boosted blob. Interestingly, the Lorentz factor \(\Gamma\) of the blob has already been constrained by current TeV observations (Mariotti 2010; Ong 2010) and this will be further checked using future TeV–PeV gamma-ray observations by, for example, the Cherenkov Telescope Array (CTA), the Tibet Air Shower plus Muon Detector (Tibet AS+MD) array and the Large High Altitude Air Shower Observatory (LHAASO),1 because inverse Compton emission is more enhanced than synchrotron emission by a factor of \(\sim \Gamma^2\), approximately. In addition, it is remarkable that we must consider an absorption of PeV photons by cosmic microwave background (CMB) radiation via electron–positron pair creation, even for a Galactic source. This has not been taken into account so far. With the aim of discriminating between the theoretical models and discovering the new phenomenon of CMB absorption, the Crab nebula is an attractive experimental site for TeV–PeV astrophysics.

1See also a similar experiment, the Hundred Square km Cosmic Origin Explorer (HiSCORE; Tluczykont et al. 2011).
2 STATIONARY EMISSION FROM THE CRAB NEBULA

2.1 Theory and observation

First, we discuss the stationary components of Crab nebula’s emission. By assuming a broken power law with an exponential cut-off for the primary electron spectrum at the emission site, we parametrize it as

\[
\frac{dn_e}{dE_e} = A_e E_e^{-\alpha_e} \left( 1 + \frac{E_e}{E_{eb}} \right)^{-1} \left( 1 + \frac{E_e}{E_{ib}} \right)^{-1} \times \exp \left( -\frac{E_e}{E_{max,e}} \right). \tag{2}
\]

Here, \(n_e\) is the number density of electrons, \(E_e\) is the electron energy, \(E_{max,e}\) is the maximum cut-off energy, \(\alpha_e\) is the electron spectral index, \(E_{eb}\) is the cooling break energy, \(E_{ib}\) is the intrinsic break energy and \(A_e\) is the normalization. We determine \(E_{eb}\) by equating the age \(t_{age}\) with the cooling time \(t_{cool}\) resulting from the synchrotron energy loss. We assume that the exponent of energy on the exponential shoulder is not two but unity (Abdo et al. 2010). The emission below \(\sim \mathcal{O}(1)\) GeV can be fitted by synchrotron radiation. The observational data were provided by the Compton Telescope (COMPTEL; Kuiper et al. 2001) and Fermi (Abdo et al. 2010). We adopt the following values: \(t_{age} = 1240 \text{ yr}\), \(\alpha_e = 2.35\), magnetic field \(B = 90 \mu\text{G}\), the distance to the Earth \(d = 2.0\) kpc and the intrinsic breaking energy \(E_{ib}\) is 30 GeV. For the choice of these parameters, see, for example, Abdo et al. (2010) and Tanaka & Takahara (2010); for a discussion of the distance, see also Trimble (1973). Thus, the cooling energy is \(E_{ib} = 1.3\) TeV, and the cut-off energy is fitted to be \(E_{max,e} = 1.5\) PeV. Note that the corresponding synchrotron cut-off energy is \(\sim 10\) MeV, but the \(\nu F_\nu\) peak energy is \(\sim 4\) to five times larger than this because of the finite extent of the distribution.

The emission above \(\sim \mathcal{O}(1)\) GeV can be fitted by inverse Compton radiation because of the primary electron. Only the number density of the CMB photons is too small and insufficient as target photons to fit the whole data. Besides, we also consider the synchrotron photons and we adopt the synchrotron self-Compton (SSC) process. In order to obtain the target photon field for the SSC process, we integrate the photon number density in a volume where the SSC process occurs. In a one-zone approximation, we find

\[
\frac{dn_{\gamma,\text{target}}}{dE_\gamma} = \int d\nu F_\nu (\nu) \frac{d^2n_{\gamma,\text{target}}}{d\nu dE_\gamma} \frac{R_{\text{SSC}}}{c}, \tag{3}
\]

where \(\nu F_\nu\) is the photon energy, \(n_{\gamma,\text{target}}\) is the number density of the photon field produced by synchrotron radiation and \(R_{\text{SSC}}\) is the effective radius where the SSC process occurs. For similar parametrizations of the effective radius, see Atoyan & Naphtalin (1989), Atoyan & Aharonian (1996) and Tanaka & Takahara (2010). Observational data in \(\gtrsim\) TeV regions have been reported by the Major Atmospheric Gamma-ray Imaging Cherenkov (MAGIC) collaboration (Albert et al. 2008), the High-Energy Gamma-Ray Astronomy (HEGRA) collaboration (Aharonian et al. 2004), the Cherenkov Low Energy Sampling and Timing Experiment (CLEANSE; Smith et al. 2006), the High-Energy Stereoscopic System (HESS; Aharonian et al. 2006), the Very Energetic Radiation Imaging Telescope Array System (VERITAS; Celik 2008; Imran 2009) and the Collaboration between Australia and Nippon for a Gamma-Ray Observatory in the Outback (CANGAROO; Taninori et al. 1998), in addition to Fermi (Abdo et al. 2010), radio and optical observations (Baars et al. 1977; Macías-Pérez et al. 2010). To simultaneously fit these data, we find the effective radius to be \(R_{\text{SSC}} \sim 2.0\) pc.

![Figure 1. Spectrum fitted to the stationary component of radiation from the Crab nebula. The solid line shows the total spectrum. The dashed and dotted lines represent the synchrotron and inverse Compton emissions, respectively. The upper and lower curves of the inverse Compton process at the TeV regions are for scattering off the synchrotron and CMB photons, respectively. Observational data are plotted as points with their error bars. We also show the sensitivities of future projects, such as CTA (Wagner et al. 2009; Actis et al. 2011), LHAASO (Cao et al. 2010) and Tibet AS+MD (Takita 2011) for 50 hours measurements denoted by (50h).](https://academic.oup.com/mnras/article-abstract/424/3/2249/977816)

In Fig. 1. we plot the theoretical fitting and the observational data. To perform the fitting, we use our original code, which has been developed by one of the current authors (KK) in a series of similar works (e.g. Yamazaki et al. 2006).

2.2 PeV gamma-ray absorption by CMB

A photon is absorbed if there is a sufficient number of background photons and if the electron–positron pair production is kinematically allowed with its energy exceeding the threshold \(E_{\gamma,\text{th}} = m_e c^2 / (2 \gamma c)\). The attenuation length is given by

\[
\frac{L_{\text{att}}(\gamma)}{E_\gamma} = \int d\nu F_\nu(\nu) \frac{d^2n_{\gamma,\text{target}}}{d\nu dE_\gamma} \frac{R_{\text{SSC}}}{c}, \tag{4}
\]

where

\[
\sigma(E_\gamma, E_{\gamma,\text{th}}) = \int_{E_{\gamma,\text{th}}}^{E_\gamma} d\mu \frac{1 - \mu}{2 \sigma_{\text{pair}}} \times (E_\gamma, E_{\gamma,\text{th}}, \mu). \tag{5}
\]

The pair-production cross-section through \(\gamma + \gamma \rightarrow e^+ + e^-\) is given by

\[
\sigma_{\text{pair}}(E_\gamma, E_{\gamma,\text{th}}, \mu) = \frac{1}{2} \pi \sigma^2 (1 - \beta^2) \times \left[ (3 - \beta^2) \ln \frac{1 + \beta}{1 - \beta} + 2 \beta (2 - \beta^2) \right], \tag{6}
\]

where \(\beta = \sqrt{1 - 4m_e c^2 / \gamma^2}\) and \(s = 2E_\gamma E_{\gamma,\text{th}}(1 - \mu)\). When we consider a 10^4 TeV (1 PeV) photon, the threshold energy of the target...
Figure 2. Gamma-ray horizon as a function of energy for incident photons. In this energy region, the electron–positron pair production through the scattering off the background CMB photon dominates the energy-loss rate.

Figure 3. Gamma-ray spectra with and without CMB absorption. We have also plotted the sensitivities of future projects, such as LHAASO (50 and 100 h), CTA (50 and 500 h) and Tibet AS+MD (50 and 500 h) with their observation times. Note that the vertical axis denotes $\nu F_\nu$.

Figure 4. Same as Fig. 3 but for the difference between two lines (with and without absorption). Note that the vertical axis denotes $E_\gamma^2 \Delta(\nu F_\nu)$ in linear scale.

3 FITTING TO FLARE COMPONENT

Recently, some observations have shown that the Crab nebula is no longer stationary, with flares at around $\mathcal{O}(1)$ GeV (Buehler 2011; Tavani et al. 2011; Buehler et al. 2012). Fig. 5 shows these data points. The duration $\Delta t_{\text{obs}}$ is typically of the order of 1 d. In this section, we discuss how we can explain these flares in terms of synchrotron emission by accelerated electrons. We consider Lorentz-boosted blob models in which a small blob is boosted with a Lorentz factor $\Gamma$ and an off-axis viewing angle $\theta$. In addition, as discussed later, it should be natural to assume accelerated electrons and magnetic field in the blob. Electrons emit synchrotron radiation by using the local magnetic field in the rest frame of the blob. This model can produce $\mathcal{O}(1)$ GeV synchrotron photons in the observer frame, unlike non-relativistic models where the synchrotron photon energy cannot exceed $E_{\text{max}}^{\text{syn}} \sim 10^2$ MeV in equation (1). Here, $E_{\text{max}}^{\text{syn}}$ is independent of $B$ because $E_{\text{max}}^{\text{syn}}$ is limited by balancing the synchrotron cooling time with the acceleration time. Here, we do not specify the...
Considering the Klein–Nishina effect, the enhancement could be smaller than $\Gamma^2$.  

Next, we discuss our choice of model parameters. If the maximum electron energy in the rest frame of the blob is limited by synchrotron cooling, the bulk Lorentz factor should be $\lesssim 10$ in order to explain the energy shift of the maximum energy $E_{\text{max}}$ shown in equation (1) at the flare. In this case, the synchrotron cooling time should be shorter than the variability time-scale, which gives

$$E_{\text{max},e} > 170 \text{TeV} \left( \frac{B}{3 \text{ mG}} \right)^{-2} \left( \frac{\delta}{10} \right)^{-1} \left( \frac{\Delta t_{\text{obs}}}{8 \text{ h}} \right)^{-1},$$  \hspace{1cm} (11)$$

where $E_{\text{max},e}$ is the maximum energy of electrons and $B$ is the magnetic field in the rest frame of the blob.

The Lorentz factor can be larger than $\gtrsim 10$ because the maximum electron energy is not necessarily limited only by cooling, but also by the size of the blob (e.g. Ohira et al. 2011). When the maximum electron energy is limited by the size of the blob, the Larmor radius of electrons with maximum energy would be comparable to the size of the blob, $\sim 3 m G$ in the rest frame of the blob, which gives

$$E_{\text{max},e} = 790 \text{ TeV} \left( \frac{B}{3 \text{ mG}} \right) \left( \frac{\delta}{10} \right) \left( \frac{\Delta t_{\text{obs}}}{8 \text{ h}} \right).$$  \hspace{1cm} (12)$$

Comparing equation (11) with equation (12), we obtain a threshold magnetic field in the rest frame of the blob:

$$B_{\text{th}} = 1.8 \text{ mG} \left( \frac{\delta}{10} \right)^{-2/3} \left( \frac{\Delta t_{\text{obs}}}{8 \text{ h}} \right)^{-2/3}. \hspace{1cm} (13)$$

For $B > B_{\text{th}}$, the maximum electron energy is limited by the synchrotron cooling. However, $B_{\text{th}}$ is much larger than that expected from the standard model of the steady-state Crab nebula (e.g. Kennel & Coroniti 1984). Therefore, we also consider the case $B < B_{\text{th}}$, where the maximum electron energy is limited by the size of the blob. Because the observed energy of synchrotron photons for a monoenergetic electron is written as

$$E_{\text{syn}} = 95 \text{ MeV} \left( \frac{\delta}{10} \right)^2 \left( \frac{E_{\text{max},e}}{500 \text{ TeV}} \right) \left( \frac{B}{3 \text{ mG}} \right),$$  \hspace{1cm} (14)$$

by removing $E_{\text{max},e}$ from equation (12), the magnetic field in the rest frame of the blob is obtained as

$$B' = 2.2 \text{ mG} \left( \frac{E_{\text{syn}}}{10^8 \text{ MeV}} \right)^{1/3} \left( \frac{\delta}{10} \right)^{-1} \left( \frac{\Delta t_{\text{obs}}}{8 \text{ h}} \right)^{-2/3}. \hspace{1cm} (15)$$

Then, the condition $B' < B_{\text{th}}$ gives lower bound on the Doppler factor

$$\delta > 22 \left( \frac{E_{\text{syn}}}{10^8 \text{ MeV}} \right).$$  \hspace{1cm} (16)$$

By removing $\delta$ from equation (12) with equation (14), we obtain the maximum electron energy in the rest frame of the blob:

$$E_{\text{max},e} = 480 \text{ TeV} \left( \frac{E_{\text{syn}}}{10^8 \text{ MeV}} \right)^{1/3} \left( \frac{\Delta t_{\text{obs}}}{8 \text{ h}} \right)^{1/3}. \hspace{1cm} (17)$$

This depends only on observables. In this size-limiting case, the variability time-scale should be determined by the dynamics of the blob, because the cooling time-scale is longer than that. This might be useful to explain the comparable time-scales of rise and decay in the observed flares.

In Fig. 5, we plot the theoretical calculations of the spectrum fitted to the flare component, adopting a scaling law for the magnetic field

\[ \frac{v F_{\gamma}}{v F_{\gamma}^\text{syn}} = \Gamma^2 \frac{v F_{\gamma}^\text{obs}}{v F_{\gamma}^\text{obs}^\text{syn}}, \]  \hspace{1cm} (10)$$

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{spectrum_fit.png}
\caption{Spectrum fitted to the flare component of radiation from the Crab nebula. We have adopted observational data for the flare reported by Fermi (Buehler 2011; Buehler et al. 2012), denoted by Fermi2011. The thick solid line shows the theoretical prediction with $\Gamma = \delta = 10^2$. The thin solid lines denote $\Gamma = \delta = 30$ and $\Gamma = \delta = 700$, respectively. The corresponding models with low-energy cut-off ($E_{\text{cut}} = 10^2 \text{ TeV}$) are represented by the lighter solid lines. The meanings of the other lines and the observational data are the same as those in Fig. 1.}
\end{figure}
$B' = 220 \mu$G ($\delta/10^2$)$^{-1}$ in equation (15) and the maximum electron energy obtained in equation (17). The thick solid line shows the result with $\Gamma = \delta = 10^2$ and $B = 223$ $\mu$G. We call this set of parameters the fiducial model. Because the electrons in the blob cannot be cooled in such a short time, the cooling break does not appear in the GeV region. Thus, the spectral electron index could be the same as the initial value, $n_e \sim 2.35$. Consequently, the photon index of synchrotron radiation ($F_{\nu}/\nu$) at around $O(10^3)$ MeV becomes $(n_e + 1)/2 \sim 1.5$, which is consistent with the observation ($1.27 \pm 0.12$) reported by Buehler (2011). Below $O(10)$ MeV, the synchrotron flare component is smaller than the stationary component. We also plot the high and low $\Gamma$ models with $\Gamma = \delta = 700$ and $\Gamma = \delta = 30$, by using the same scaling law for the magnetic field.

However, in the TeV–PeV region, it is remarkable that the inverse Compton radiation of the flare component can exceed the stationary component significantly at $E_{\gamma} \gtrsim O(10)$ TeV for the fiducial model. In part, this is also because the inverse Compton power is enhanced more than the synchrotron power as a result of the boosted target photon distribution by a factor of $\Gamma^2$, as shown in equation (10). From Fig. 5, we find that a higher Lorentz factor than $\Gamma \gtrsim 700$ has already been excluded by the current GeV observations, and $\Gamma \gtrsim 200$ by TeV observations (Mariotti 2010; Ong 2010).

Future gamma-ray observatories, such as CTA, Tibet AS+MD and LHAASO, will be able to probe $\Gamma$ down to $\sim 30$ using 8-h observations (over one night). The sensitivities are shown in Fig. 5 by conservatively linearly scaling them from 50 h to 8 h. Even if the flare flux is less than the stationary flux, we can detect it down to the statistical error of photons. Note that the ratio of inverse Compton to synchrotron power depends only on $\Gamma$ in equation (10), not on $\delta$, so we can constrain $\Gamma$ even for an off-axis event. Note also that the cooling effects can be seen a little in the $\gtrsim$PeV region for $\Gamma \lesssim 30$.

To be more conservative, we also show similar calculations but adding an artificial low-energy cut-off for the electron spectrum where we have taken zero flux for $E_e < E_{\text{cut}} \sim 10^3$ TeV in the rest frame of the blob, which is represented by the shallower thick solid lines (this could explain the X-ray feature; Tavani et al. 2011). Even in this case, we can probe $\Gamma$ down to $\sim 700$.

Therefore, we can distinguish the model from non-relativistic models for the flares at $O(1)$ GeV by observing the inverse Compton radiation in the $O(10)$ TeV–$O(1)$ PeV energies.

Here, it should be meaningful to check the energy ratio of electrons to the magnetic field in the blob. The flare luminosity in the rest frame of the blob, $L'$, is given by

$$L' = 4\pi d^2 (n_e)_{\text{obs}} \delta^{-4}. \quad \text{(18)}$$

Assuming that this luminosity is produced by synchrotron radiation of electrons with a typical maximum energy, the luminosity is written as

$$L' = N'_e (E_{\text{max},e})^{2} 4/3 \sigma_T c \left( \frac{B^2}{8\pi} \right) \left( \frac{E_{\text{max},e}}{m_e c^2} \right)^2, \quad \text{(19)}$$

where $N'_e (E_{\text{max},e})$ is the number of electrons with maximum energy in the rest frame of the blob. From equations (15), (17), (18) and (19), we obtain the total energy of electrons with $E_{\text{max},e}'$.

$$U'_e = N'_e (E_{\text{max},e}') E_{\text{max},e}' = 1.3 \times 10^{57} \text{erg}$$

$$\times \left( \frac{E_{\text{syn}}}{10^5 \text{MeV}} \right)^{-7/6} \left( \frac{\delta}{10} \right)^{-2} \left( \frac{\Delta t_{\text{obs}}}{8 \text{h}} \right). \quad \text{(20)}$$

However, from equation (15), the total energy of the magnetic field in the rest frame of the blob is given by

$$U'_B = \frac{B^2}{8\pi} \frac{4}{3} \pi (\delta \Delta t_{\text{obs}})^3 = 4.8 \times 10^{41} \text{erg}$$

$$\times \left( \frac{E_{\text{syn}}}{10^5 \text{MeV}} \right)^{2/3} \left( \frac{\delta}{10} \right) \left( \frac{\Delta t_{\text{obs}}}{8 \text{h}} \right)^{5/3} \quad \text{(21)}$$

for the size-limiting case $B' < B'_0$. Then, we find the ratio of the electron energy to the magnetic energy to be

$$\frac{U'_e}{U'_B} = 2.6 \times 10^{-5} \left( \frac{E_{\text{syn}}}{10^5 \text{MeV}} \right)^{-11/6} \left( \frac{\delta}{10} \right)^{-3} \left( \frac{\Delta t_{\text{obs}}}{8 \text{h}} \right)^{-2/3}. \quad \text{(22)}$$

This ratio can increase by $\sim (E_{\text{max},e}/E_0)^{\gamma - 2}$ for $2 < n_e < 3$ if we include the low-energy electrons. Even in this case, the boosted blob might be magnetically dominant. Because the position of the blob, $\Gamma \delta \Delta t_{\text{obs}} \sim 8.6 \times 10^{16} \Gamma^2 \text{cm}$, could also be much smaller than the radius of the termination shock, $3 \times 10^{17}$ cm, the blob might be produced in the pulsar wind before the magnetic energy is converted to the bulk kinetic energy. Alternatively, the observed flares might be off-axis flares with small $\delta(\sim 1)$. In this case, we predict larger flares than have ever before been detected. Moreover, a flare might consist of many pulses with $\Delta t_{\text{obs}} < 8$ h, for example, $U'_e \sim U'_B$ for $\Delta t_{\text{obs}} < 35$ ms (pulsar period). This could be the reason for the scarcity of flares (i.e. a flare needs many pulses; see also Clausen-Brown & Lyutikov 2012).

If we need the blob energy $\Gamma U'_B$ to be less than the spin-down energy during the flare $\dot{E} \Delta t_{\text{obs}} \delta^{-2} / \Gamma$ in the observer frame, we have $\Gamma^2 \gtrsim 300 (E_{\text{syn}}/10^5 \text{MeV})^{-2/3} (\Delta t_{\text{obs}}/8 \text{h})^{-2/3}$ for the size-limiting case $B' < B'_0$. Thus, if we find $\Gamma > 30$, we also imply that a flare consists of many pulses with $\Delta t_{\text{obs}} < 8$ h.

We have not specified the radiation region, which could be the pulsar wind or the shock at the knot of the inner nebula. We have inferred the physical condition and we have found several possibilities, such as the magnetically dominant case, the off-axis case and the superposition of many pulses, which might be discriminated by future TeV–PeV observations, as argued after equation (22).

As mentioned in Section 1, so far there has been no consensus concerning the theoretical models. In the model in which only the maximum electron energy is increased, such as by electric acceleration, there is surely an excess in the PeV region for the inverse Compton flare component. However, in order to detect this excess with LHAASO, we need approximately a few tens of hours for the observation time, which is longer than the typical duration of the flare. In the model in which only the magnetic field is increased, such as by rapid compression, the inverse Compton flare is highly suppressed.

4 SUMMARY AND CONCLUSION

In order to explain the origin of the GeV flare in the Crab nebula, we have studied models in which a small blob is boosted (e.g. with a Lorentz factor $\Gamma \gtrsim 30$) and emits a synchrotron photon higher than the maximum synchrotron energy $E_{\text{syn}}$ shown in equation (1). We have also discussed the possibility that we can distinguish the model from other models, such as non-relativistic models, by observing the corresponding inverse Compton flare component. We have pointed

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out that the inverse Compton flare can appear in the \( \gtrsim \mathcal{O}(1) \) TeV region accompanied by the GeV flare in this type of boosted-blob model with a large Lorentz factor, because the inverse Compton power is boosted more than the synchrotron power by \( \sim \Gamma^2 / \Gamma_1^2 \). High \( \Gamma_1 \) models have been already excluded for \( \Gamma \gtrsim 200 \) by current TeV observations and these will be down further to \( \Gamma \sim 30 \) for future TeV–PeV observatories, such as CTA, Tibet AS+MD and LHAASO. In addition, by considering this enhancement in the TeV–PeV region, in the near future we might be able to observe ‘orphan TeV flares’, which do not even have a GeV flare.

Even for the stationary component of the Crab nebula, we have also pointed out for the first time that the absorption of PeV photons by CMB radiation through pair creation \( \gamma + \gamma_{\text{CMB}} \rightarrow e^+ + e^- \) is important. We must consider this effect whenever we fit the spectrum of the Crab nebula in the \( \mathcal{O}(1) \)PeV regions.

It is worth noting that we will be able to accomplish these studies for observations of the Crab nebula at \( \mathcal{O}(1) \)TeV–\( \mathcal{O}(1) \)PeV energies by using future gamma-ray telescopes, such as CTA, Tibet AS+MD and LHAASO. We hope for the earliest possible completion of this type of new gamma-ray telescope.

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