PeV Emission of the Crab Nebula: Constraints on the Proton Content in Pulsar Wind and Implications

Ruo-Yu Liu1,2 and Xiang-Yu Wang1,2

1 School of Astronomy and Space Science, Nanjing University, Nanjing 210023, People’s Republic of China; ryliu@nju.edu.cn, xywang@nju.edu.cn
2 Key laboratory of Modern Astronomy and Astrophysics (Nanjing University), Ministry of Education, Nanjing 210023, People’s Republic of China

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Abstract

Recently, two photons from the Crab Nebula with energy of approximately 1 PeV were detected by the Large High Altitude Air Shower Observatory (LHAASO), opening an ultrahigh-energy window for studying pulsar wind nebulae (PWNe). Remarkably, the LHAASO spectrum at the highest-energy end shows a possible hardening, which could indicate the presence of a new component. A two-component scenario with a main electron component and a secondary proton component has been proposed to explain the whole spectrum of the Crab Nebula, requiring a proton energy of $10^{28}–10^{29}$ erg remaining in the present Crab Nebula. In this paper, we study the energy content of relativistic protons in pulsar winds using the LHAASO data of the Crab Nebula, considering the effect of diffusive escape of relativistic protons. Depending on the extent of the escape of relativistic protons, the total energy of protons lost in the pulsar wind could be 10–100 times larger than that remaining in the nebula presently. We find that the current LHAASO data allow up to (10–50)% of the spindown energy of pulsars being converted into relativistic protons. The escaping protons from PWNe could make a considerable contribution to the cosmic-ray flux of 10–100 PeV. We also discuss the leptonic scenario for the possible spectral hardening at PeV energies.

Unified Astronomy Thesaurus concepts: Cosmic rays (329); Pulsars (1306); Gamma-ray astronomy (628)

1. Introduction

A rotation-powered pulsar converts most of its rotational energy losses into a highly relativistic magnetized wind (e.g., Goldreich & Julian 1969; Kennel & Coroniti 1984b). The collision of the pulsar wind with the ambient supernova ejecta and/or interstellar material (ISM) results in a termination shock and creates a pulsar wind nebula (PWN), a region of up to tens of parsecs, filled with relativistic electrons and positrons (Rees & Gunn 1974; Reynolds & Chevalier 1984). It is widely believed that lower energy radiation in PWNe is produced by the synchrotron radiation of leptons in the magnetic field and that the higher energy part of the spectrum is produced by leptons in the inverse Compton scattering of the ambient photons (e.g., Kennel & Coroniti 1984a; de Jager & Harding 1992; Atoyan & Aharonian 1996).

The Crab Nebula is a unique representative of PWNe, characterized by a very broad spectral energy distribution (SED) that spans over 21 decades, from MHz radio wavelengths to ultrahigh-energy (UHE, $E > 100$ TeV) gamma rays. It is powered by the most energetic pulsar PSR J0534+2200 (or the Crab pulsar) found in our Galaxy, with a current spindown luminosity of $L_s = 4.5 \times 10^{38}$ erg s$^{-1}$. The pulsar has a characteristic age of $\tau_c = 1260$ yr while the record in Chinese chronicles shows its true age to be 967 yr (Lundmark 1921). In the Crab Nebula, several photon fields serve as targets for the inverse Compton (IC) radiation of electrons (Atoyan & Aharonian 1996). Three dominant IC components are contributed by the far-infrared, cosmic microwave background (CMB) radiation, and synchrotron photons. Up-scattering of synchrotron photons through the synchrotron–self-Compton (SSC) channel provides the major contribution at TeV energies. The synchrotron target is, however, characterized by a relatively high photon energy, therefore in the UHE band the SSC process is significantly suppressed because of the Klein–Nishina (KN) effect, and the IC scattering process of CMB photons is the dominant component.

The remarkable recent discovery of PeV photons from the Crab Nebula by the Large High Altitude Air Shower Observatory (LHAASO) is the first step toward the opening of the PeV window in the cosmic electromagnetic spectrum (LHAASO Collaboration 2021a, 2021b). Although the current data of of Crab Nebula measured by LHAASO are consistent with a single log–parabola-type spectrum with a photon index close to $–3.7$ at PeV energy, the highest-energy spectrum shows a possible hardening, implying the existence of a second spectral component of either leptonic or hadronic origin, as discussed by LHAASO Collaboration (2021a). A two-component scenario with a main electron component and a secondary proton component has been proposed to explain the whole spectrum of the Crab Nebula (LHAASO Collaboration 2021a). In fact, it has been suggested that a fraction of the spindown power of pulsars can be converted into a wind of nuclei (Hoshino et al. 1992; Arons & Tavani 1994; Gallant & Arons 1994). Nuclei can be accelerated in pulsar magnetospheres, as discussed by Cheng et al. (1986) and by Bednarek & Protheroe (1997). These nuclei may suffer partial photodisintegration in the nonthermal radiation fields of the pulsar’s outer magnetosphere. The products (protons and neutrons) of the photodisintegration and surviving heavier nuclei are injected into the PWN, and then interact with the ambient matter. Thus, gamma rays are produced via inelastic collisions, and this hadronic origin of gamma rays has been suggested as an alternative or an additional component to IC gamma rays in the literature (see e.g., Cheng et al. 1990; Atoyan & Aharonian 1996; Bednarek & Protheroe 1997; Aharonian & Atoyan 1998; Horns et al. 2006; Yang & Zhang 2009; Zhang & Yang 2009; Li et al. 2010).
Recently, Zhang et al. (2020) obtained an upper limit of 0.5% on the energy fraction of relativistic protons contained in the Crab Nebula by modeling the broadband spectrum, including the data of the Tibet ASγ experiment (Amenomori et al. 2019). It may be worth noting that, without considering the escape of protons from the nebula, the constraint does not reflect the true fraction of the energy channeled into relativistic protons from the pulsar wind. LHAASO Collaboration (2021a) found that accounting for PeV emission via the hadronic process requires a power of $10^{46}$ erg s$^{-1}$ for 10 PeV protons and an order of magnitude more for a broad $E^{-2}$ spectrum assuming the most effective confinement for protons. This power is approximately 0.2%–2% of the pulsar’s current spindown power.

In this paper, we will study the proton content in pulsar wind using the LHAASO data of the Crab Nebula and considering the diffusive escape effect. The rest of the paper is organized as follows. In Section 2, we study the constraint on the proton content in the Crab Nebula. In Section 3, we discuss the implications of the result, and in Section 4, we provide a summary.

2. The Effect of Diffusive Escape on Hadronic Emission

The possible hardening of the Crab Nebula spectrum at PeV energies could, in principle, be either leptonic or hadronic. In this section, we will focus on the hadronic scenario, while a brief discussion on the leptonic scenario is presented in the discussion section.

In the hadronic scenario, the PeV photons from the Crab Nebula arise from $pp$ collisions with the matter in the nebula. The energy of protons that produce $E_p = 1$ PeV is $E_p = 10E_\gamma = 10$ PeV. The collision loss time for relativistic protons interacting with the matter in the nebula is

$$ t_{pp} = \frac{1}{\xi_{pp} n \sigma_{pp} c} = 10^7 \text{yr} \left( \frac{n}{10 \text{ cm}^{-3}} \right)^{-1} \left( \frac{\xi_{pp}}{0.2} \right)^{-1}, $$

where $n$ is the average gas density in the nebula, $\sigma_{pp}$ is the cross-section for proton–proton interaction, and $\xi_{pp}$ is the inelasticity of pion production. The mass in the Crab filament is estimated to be $7.2 \pm 0.5 M_\odot$ (Owen & Barlow 2015), so the gas density is $10^3 \text{ cm}^{-3}$ for a volume of 30 pc$^3$. The luminosity of the PeV gamma-ray emission in the energy range of 0.5–1.1 PeV is approximately $L_\gamma \approx 5 \times 10^{31}$ erg s$^{-1}$ (LHAASO Collaboration 2021a). Then, the energy of protons producing these PeV gamma rays is approximately

$$ W_p \approx L_\gamma t_{pp} = 1.5 \times 10^{46} \text{ erg} \left( \frac{n}{10 \text{ cm}^{-3}} \right)^{-1}. $$

Assuming an $E^{-2}$ spectrum for protons, the total energy in relativistic protons will be larger by a factor of several. This energy is only a very small fraction of the total spindown energy of the Crab pulsar, which is approximately $10^{48}$ erg. Note, however, that $W_p$ is the energy of protons that remain in the Crab Nebula at present. The real energy of protons that were injected into the nebula could be much larger, as protons/
the best-fit parameter found by LHAASO Collaboration (2021a). Note that the mean free path of particle, \( \sim 3D/c \), is \( \lesssim 1 \) pc, which is smaller than \( r_{\text{crab}} \) even for 100 PeV in the scenario considered here; hence, a diffusion description for the particle transport in the nebula is roughly valid up to 100 PeV. A more strict treatment should include the ballistic propagation of the highest-energy particle in the core region of the nebula (see e.g., Aloisio et al. 2009; Prosekin et al. 2015), which may change the expected gamma-ray flux around 10 PeV.

For an instant injection of particle, the spatial distribution of particle density at an epoch \( t \) after the injection is proportional to \( (D(E)t)^{-3/2}\exp(-r^2/4D(E)t) \) assuming spherically symmetric diffusion (Atoyan et al. 1995). This means that the particle distribution remains approximately constant at \( r < r_{\text{diff}} \equiv 2[D(E)t]^{1/2} \), whereas it declines quickly at \( r > r_{\text{diff}} \). Therefore, the fraction of particles remaining inside the nebula is approximately \( f_p(E_p, t) = \min[1, (r_{\text{crab}}/r_{\text{diff}})^3] \). We assume that the CR injection luminosity is a fraction of \( \eta_p \) of the spindown luminosity of the pulsar, which evolves with time as \((1 + t/\tau_0)^{-\alpha}\) (Pacini & Salvati 1973), where \( \tau_0 \approx 680 \) yr is the initial spindown timescale and \( \alpha = 2.33 \) given that the Crab pulsar’s braking index is 2.5 (Lyne et al. 1988). The cumulative CR protons that are still confined inside the nebula can be given by

\[
\frac{dN_p}{dE_p} = \int_0^{\tau_{\text{crab}}} Q_0(E_p)f_p(E_p, t) \left[ 1 + (\tau_{\text{crab}} - t)/\tau_0 \right] dt
\]

where \( \tau_{\text{crab}} = 967 \) yr is the present age of the Crab pulsar. \( Q_0(E_p) = N_0E_p^{-\gamma_p}\exp(-E_p/E_{p,\max}) \) is the proton injection spectrum where \( N_0 \) is the normalization factor. The value of \( N_0 \) can be found by \( \int E_pQ_0(E_p)dE_p = \eta_pL_{\text{rad}} \) with \( L_{\text{rad}} = L_s(1 + \tau_{\text{crab}}/\tau_0)^d \) being the initial spindown luminosity of the pulsar.

We can find a critical energy \( E_c \) for protons by \( \tau_{\text{crab}} = r_{\text{crab}}^2/4D(E_c) \). For protons remaining in the nebula, the spectrum above this energy is modified by the energy-dependent escape and becomes softer than the injection spectrum. In contrast, the spectrum below this energy simply follows the injection spectrum. We therefore expect a softening in the proton spectrum beyond the energy \( E_c = E_0(r_{\text{crab}}^2/4\tau_{\text{crab}}D_0)^{1/2} \), and subsequently a corresponding softening in the pion gamma-ray spectrum beyond \( \approx 0.1E_c \). We calculate the expected spectrum of the hadronic emission from the proton spectrum given by Equation (3), following the semianalytical method developed by Kafexhiu et al. (2014). The attenuation of gamma-ray photons by the pair-production process on CMB is taken into account. We consider all the possible diffusion coefficients shown in Figure 1, and normalize the resulting 1 PeV gamma-ray flux to \( 10^{-12} \) erg cm \(^{-2}\) s \(^{-1}\) as constrained by the LHAASO observation. As such, a soft injection proton spectrum (e.g., \( \alpha > 2 \)) is not favored as it would overproduce the measured gamma-ray spectrum below PeV.

The results are shown in Figure 2 for a spectral index of \( \alpha_p = 2 \) but with different maximum energies of accelerated protons (upper panel) and for a fixed maximum energy of protons at 100 PeV but with different spectral indexes \( \alpha_p \) (lower panel). A leptonic component accounting for the multilwave-length emission is also shown, employing the same parameters given by LHAASO Collaboration (2021a) in their lepton–hadron scenario. The hadronic emission component is harder than the leptonic emission above PeV even if an extremely large \( E_{p,\max} \) is invoked. Thus we can diagnose the presence of the hadronic component with the measured gamma-ray spectrum above PeV. Currently, the large statistical uncertainties of the LHAASO measurement at PeV energies do not allow a strong statement about the spectral hardening. In a more conservative way, the LHAASO data shown in the figures can be regarded as the upper limit of the contribution from the possible hadronic component. This translates to an upper limit on the total energy in relativistic protons from the pulsar wind (i.e., \( \eta_p \)). In the case of the proton spectral slope being fixed at \( \alpha_p = 2 \), we found \( \eta_p = (10–57)\% \), \( (13–39)\% \), and \( (21–36)\% \) for \( E_{p,\max} = 10 \) PeV, 30 PeV, and 100 PeV, respectively. In the case of the maximum proton energy being fixed at \( E_{p,\max} = 100 \) PeV, we found \( \eta_p = (8–14)\% \), \( (11–18)\% \), and \( (26–43)\% \) for \( \alpha_p = 1.6 \), 1.8, and 2.0, respectively. The range of \( \eta_p \) is due to the uncertainty of the diffusion coefficient considered in the calculation. In general, we see that the current LHAASO data allow a fraction of 10%–50% spindown energy to be converted to the relativistic proton energy in our model.

The above discussions have assumed that the hadronic component in the pulsar wind is pure protons. However, the composition is not well known, and heavier nuclei could show...
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Figure 2. Upper panel: Possible hadronic gamma-ray components for a fixed proton injection spectral index of $\alpha_p = 2$ for the Crab Nebula. The blue, yellow, and red bands represent the cases of $E_{p,max} = 10$ PeV, 30 PeV, and 100 PeV with $\eta_p = (10-57)$%, $(13-39)$%, and $(21-36)$%, respectively. The solid black curve represents the electron IC flux, obtained by LHAASO Collaboration (2021b) for the multiwavelength emission modeling. Lower panel: Similar to the upper panel but for a fixed setup of the electron component as well as the electromagnetic environment are included. The Fermi-LAT data are taken from Arakawa et al. (2020), while the LHAASO data are taken from LHAASO Collaboration (2021a). The spectral parameters of the electron component as well as the electromagnetic environment are the same as those in Figure S4 or S5 in LHAASO Collaboration (2021a), that is, assuming a spectral of $d\phi\propto E^{-\gamma_p} \exp[-(E/E_0)\Delta\alpha]$, where $\alpha = 3.42$, $\Delta\alpha = 1.76$, $E_0 = 0.76$ TeV, and $E_0 = 450$ TeV. The target radiation field includes the synchrotron radiation in a magnetic field of $B = 112$ μG, a dust emission of 70 K with an energy density of 0.5 eV cm$^{-3}$, the interstellar radiation field, and the CMB.

up in the nebula if the photodisintegration effect is not important. For nuclei with a mass number $A$, the cross-section of the hadronuclear interaction becomes $A$ times larger, but the energy fraction lost into created pions in one collision is also reduced by 1/$A$. As a result, even if heavier nuclei are presented in the nebula, it would not change the above result significantly.

3. Discussions

3.1. Possible Contribution to Cosmic Rays above the Knee

In our scenario, a considerable fraction of Crab pulsar’s spindown energy could be converted into relativistic protons, but most of them have already escaped the Crab Nebula, becoming cosmic rays. Considering that the age of the pulsar is approximately 1000 yr and that it is located at 6500 light years ($\sim$2 kpc) away from Earth, protons that escape at the earliest epoch have traveled a distance of $2\sqrt{D_{\text{ISM}} \times 7500}$yr. Assuming the cosmic-ray diffusion coefficient in the ISM $D_{\text{ISM}} \approx 4 \times 10^{28}(E/1 \text{GeV})^{1/3}\text{cm}^2\text{s}^{-1}$ (e.g., Trotta et al. 2011), those protons can have traveled to a distance of $l = 0.9(E_p/10 \text{PeV})^{1/6}$ kpc, and have not arrived at Earth. On the other hand, if all the pulsars are cosmic-ray proton accelerators, they might contribute to the measured cosmic ray flux. According to the ATNF Pulsar Catalogue (Manchester et al. 2005), the sum of spindown luminosities of Galactic pulsars is approximately $L_{\text{tot}} \approx 10^{35}\text{erg s}^{-1}$. Assuming that such a luminosity is stable over millions of years and that $\eta_p$ is the same for all pulsars, we may roughly estimate the flux of cosmic rays produced by pulsars, in the framework of the leaky box model, by

$$F(E_p) = \frac{c}{4\pi} \frac{\eta_p L_{\text{tot}} t_{\text{esc}}}{2\pi R_{\text{Gal}}^2 H_{\text{CR}} \ln(E_{p,max}/E_{p,\text{min}})} \approx 2 \times 10^3 \frac{f_{\text{pul}} \eta_p L_{\text{tot}} t_{\text{esc}}}{10^{39}\text{erg s}^{-1}} \frac{E_p}{10 \text{PeV}}^{-1/3} \left(\frac{H_{\text{CR}}}{4 \text{kpc}}\right) \left(\frac{R_{\text{Gal}}}{15 \text{kpc}}\right)^2 \text{eV cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$$

(4)

where $t_{\text{esc}} = H_{\text{CR}}^2/4D_{\text{ISM}}$ is the cosmic-ray residence time in the Galaxy, with $H_{\text{CR}}$ being the scale height of the cosmic-ray halo. $R_{\text{Gal}}$ is the radius of the Galaxy. $f_{\text{pul}} (\geq 1)$ accounts for the contribution of off-beamed pulsars that we cannot observe, and its value could be a factor of a few according to the study by Tauris & Manchester (1998). Here we have assumed a flat proton spectrum with $\ln(E_{p,max}/E_{p,\text{min}}) \approx 20$. The KASCADE–Grande experiment has revealed a cosmic-ray proton flux of $\sim 3000 \text{ eV cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$ at 10 PeV and $\sim 1000 \text{ eV cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$ at 100 PeV (Apel et al. 2013). It implies that Galactic pulsars may have a significant contribution to the cosmic-ray proton flux between 10 and 100 PeV provided an approximate choice of the value of $\eta_p$, which is consistent with the previous suggestion (Bednarek & Bartosik 2004).

3.2. The Second Leptonic Component

The spectral hardening of the Crab Nebula at PeV energies could also be due to a second electron component. LHAASO Collaboration (2021a) studied such a scenario with the assumption of a Maxwellian-type spectrum (see also Aharonian & Atoyan 1998; Khangulyan et al. 2020) and an $E^{-1.5}$ spectrum for the second electron component. We here explore more general cases with the hard electron spectrum, considering the maximum energy $E_{e,\text{max}}$ and the slope of the electron spectrum $\alpha$ as free parameters to study their influences, where the electron
spectrum is defined as \( d\mathcal{N}/dE_e \propto E_e^{-\alpha} \exp(-E_e/E_{e,\text{max}}) \) (for details, see Appendix).

The results of the spectra are shown in Figure 3. We find that, although the electron IC radiation suffers the KN effect at such high energies, it could still account for a spectral hardening up to several PeV (or even higher) energy, provided that the electron spectrum is sufficiently hard and the maximum energy is sufficiently high. The critical point is whether the required maximum electron energy and the hard spectrum can be generated. The former can be determined by the balance between the acceleration and the synchrotron energy lose rates, which reads (LHAASO Collaboration 2021a)

\[
E_{e,\text{max}} = \left( \frac{B}{100\mu G} \right)^{-1/2} \text{PeV},
\]  

in the most efficient acceleration case. Although \( B \approx 100\mu G \) is obtained via the SED fitting in the one-zone model, the magnetic field strength inside the nebula could be weaker at the termination shock (i.e., the acceleration site) than at larger distance (Kennel & Coroniti 1984b; Atoyan & Aharonian 1996). Thus, acceleration of \( \sim 10 \text{ PeV} \) electrons in the nebula may still be possible. On the other hand, the hard spectrum may be achieved in the magnetic reconnection process in optimistic conditions (Guo et al. 2014; Sironi & Spitkovsky 2014; Werner et al. 2016). Therefore, it may not be easy to distinguish between the hadronic and the leptonic origins for the spectral hardening (if confirmed) solely from the UHE spectrum measurement. Future sensitive neutrino telescopes (e.g., IceCube Gen-2) might be able to distinguish between the leptonic and hadronic scenarios for the spectral hardening (Aartsen et al. 2021), since the hadronic scenario predicts a neutrino flux comparable to the PeV gamma-ray flux.
To summarize, based on the latest measurement of PeV emission of the Crab Nebula by LHAASO, we put a constraint on the proton content accelerated in pulsar wind by taking into account the particle escape effect. We found that the current LHAASO data allow up to (10–50)% of the spindown energy to be converted to relativistic protons. This is much larger than previous limits obtained without considering the diffusive escape effect (Zhang et al. 2020). Future observations with the full LHAASO will be able to determine reliably whether there is a hard component in the spectrum of the Crab Nebula. If this hadronic component is confirmed in the future, our results may imply that a significant fraction of spindown power is converted into relativistic ions in the pulsar wind. In addition, Galactic pulsars may make a considerable contribution to the cosmic-ray proton spectrum measurement, but the future neutrino observation could provide an important test.

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**Appendix**

**Electron Inverse Compton radiation at Ultrahigh Energy**

We consider the secondary electron spectrum in the PWN to be a power-law function with an exponential cutoff, \( dN_e/dE_e \propto E_e^{-\alpha} \exp(-E_e/E_{e,\text{max}}) \). Because we are interested in the spectrum of gamma rays above 100 TeV, we only consider the CMB as the target photons, neglecting the contribution by the dust emission and the synchrotron radiation of electrons due to the severe KN suppression effect. The maximum energy \( E_{e,\text{max}} \) may depend on the strength of the magnetic field in the particle acceleration zone (LHAASO Collaboration 2021a), but here we consider it as free parameter to study its influence.

Because the information of the target photons (i.e., the CMB) for the IC emission is known, the IC spectrum is only dependent on the electron spectral slope \( \alpha \) and the maximum energy. For a hard electron spectrum, we here consider \( \alpha = -2, -1, 0, 1 \) and show the scaled IC spectrum in Figure 3 considering a different maximum energy \( E_{e,\text{max}} \). Note that the spectrum with \( \alpha = -2 \) is the Maxwellian-type distribution. The local photon indexes \( \Gamma \) (defined as \( dN_\gamma/d\gamma \propto \gamma^{-\Gamma} \)) with \( E_{\gamma,\text{max}} \to \infty \) are shown in the corresponding lower panels. As can be seen from Figure 3, the IC spectrum is softer than the case without consideration of the KN effect. However, with a hard electron spectrum, the resulting gamma-ray spectrum can be quite flat or even harder. This could be also understood analytically. Bearing in mind that \( E_\gamma \sim E_e \) in the deep KN regime, the IC energy spectrum can be approximated by

\[
L_{\gamma,\text{IC}}(E_\gamma) \approx \frac{E_\gamma^2 dN_e/dE_e}{\Gamma_e(E_e)} \propto \frac{E_\gamma^{2-\alpha}}{E_e^{\alpha/2}} \propto E_\gamma^{1.3-\alpha}. \tag{A1}
\]

Here, \( \Gamma_e(E_e) \propto E_e^{0.7} \) is the cooling timescale of electrons via the IC process in the deep KN regime (Khangulyan et al. 2014). We then can find the photon index \( \Gamma = \alpha + 0.7 \). On the other hand, in the deep KN regime, the IC spectrum at the low-energy limit (i.e., \( E_i \ll E_e \)) is \( dN_\gamma/d\gamma \propto E_\gamma^{\alpha} \) for a single IC scattering event. As a result, the low-energy IC spectrum would be dominated by the low-energy tail emitted by electrons around the cutoff energy \( E_{\gamma,\text{max}} \) if \( \alpha < -0.7 \), leading to \( \Gamma \approx 0 \), which is consistent with the results shown in the panels for \( \alpha = -2 \) and \( \alpha = -1 \).

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4 According to Blumenthal & Gould (1970), the distribution of IC scattered photon spectrum can be given by \( F(E_\gamma) = 2q \ln q + (1 + 2q)(1 - q) + (1 - q)(1 + 2q) \), where \( \Gamma = 4e/mc^2 \), \( E_i = \Gamma_i (1 - E_i) \), and \( E_\gamma = E_i/E_e \). In the deep KN regime (\( \Gamma_i \gg 1 \)) and the low-energy limit \( (E_i \ll 1) \), we have \( q \ll 1 \) and \( \Gamma_i \ll 1 \), leading to \( F(E_\gamma) \to 1 \).

**ORCID iDs**

Ruo-Yu Liu @ https://orcid.org/0000-0003-1576-0961
Xiang-Yu Wang @ https://orcid.org/0000-0002-5881-335X
