

Bethe-Heitler cascades as a plausible origin of hard spectra in distant TeV blazars

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ABSTRACT

Context. Very high-energy (VHE) γ -ray measurements of distant TeV blazars can be nicely explained by TeV spectra induced by ultra high-energy cosmic rays.

Aims. We develop a model for a plausible origin of hard spectra in distant TeV blazars.

Methods. In the model, the TeV emission in distant TeV blazars is dominated by two mixed components. The first is the internal component with the photon energy around 1 TeV produced by inverse Compton scattering of the relativistic electrons on the synchrotron photons (SSC) with a correction for extragalactic background light absorption and the other is the external component with the photon energy more than 1 TeV produced by the cascade emission from high-energy protons propagating through intergalactic space.

Results. Assuming suitable model parameters, we apply the model to observed spectra of distant TeV blazars of 1ES 0229+200. Our results show that 1) the observed spectrum properties of 1ES 0229+200, especially the TeV γ -ray tail of the observed spectra, could be reproduced in our model and 2) an expected TeV γ -ray spectrum with photon energy >1 TeV of 1ES 0229+200 should be comparable with the 50-h sensitivity goal of the Cherenkov Telescope Array (CTA) and the differential sensitivity curve for the one-year observation with the Large High Altitude Air Shower Observatory (LHAASO).

Conclusions. We argue that strong evidence for the Bethe-Heitler cascades along the line of sight as a plausible origin of hard spectra in distant TeV blazars could be obtained from VHE observations with CTA, LHAASO, HAWC, and HiSCORE.

Key words. BL Lacertae objects: individual: 1ES 0229+200 – radiation mechanisms: non-thermal

1. Introduction

A blazar is a special class of active galactic nucleus (AGN) with a non-thermal continuum emission that arises from the jet emission taking place in an AGN whose jet axis is closely aligned with the observer's line of sight (Urry & Padovani 1995). Blazars are dominated by rapid and large amplitude variability (e.g., Raiteri et al. 2012; Sobolewska et al. 2014). Multi-wavelength observations show that their broad spectral energy distributions (SED) from the radio to the γ -rays bands generally exhibits two humps, indicating two components. It is generally accepted that the low-energy component that extends from radio up to ultraviolet, or in some extreme cases to a few keV X-rays (Costamante et al. 2001), is produced by synchrotron radiation from relativistic electrons in the jet (Urry 1998), though the origin of the high-energy component that covers the X-ray and γ -ray energy regime remains an open issue. There are two kinds of theoretical models describing the high-energy photon emission in these blazars, the leptonic and the hadronic model. In the leptonic model scenarios, the high-energy component is probably produced from inverse Compton (IC) scattering of the relativistic electrons either on the synchrotron photons (e.g., Maraschi et al. 1992; Bloom & Marscher 1996; Mastichiadis & Kirk 1997; Konopelko et al. 2003) and/or on some other photon populations (e.g., Dermer et al. 1992; Dermer & Schlickeiser 1993; Sikora et al. 1994; Ghisellini & Madau 1996; Böttcher & Dermer 1998). In contrast, the hadronic model

argues that high-energy γ rays are produced by either proton synchrotron radiation in high enough magnetic fields (Aharonian 2000; Mücke & Protheroe 2001; Mücke et al. 2003; Petropoulou 2014), or mesons and leptons through the cascade initiated by proton-proton or proton-photon interactions (e.g., Mannheim & Biermann 1992; Mannheim 1993; Pohl & Schlickeiser 2000; Atoyan & Dermer 2001).

The imaging atmospheric Cherenkov Telescopes (IACTs) have so far detected about 50 very high-energy (VHE; $E_\gamma > 100$ GeV) γ -ray blazars with redshifts up to $z \sim 0.6$ ¹. It is believed that the primary TeV photons propagating through intergalactic space should be attenuated due to their interactions with the extragalactic background light (EBL) to produce electron-positron (e^\pm) pairs (e.g., Nikishov 1962; Gould & Schreder 1966; Stecker et al. 1992; Ackermann et al. 2012; Abramowski et al. 2013; Dwek & Krennrich 2013; Sanchez et al. 2013). However, the observed spectra from distant blazars do not show a sharp cutoff at energies around 1 TeV, which would be expected from simple γ -ray emission models with a correction for EBL absorption (e.g., Stecker et al. 2006; Aharonian et al. 2006a; Costamante et al. 2008; Acciari et al. 2009; Abramowski et al. 2012). Excluding a large uncertainty in the measured redshifts and in the spectral indices (Costamante 2013) and excluding the lower levels of EBL (Aharonian et al. 2006b; Mazin & Raue 2007; Finke & Razzaque 2009), the observed

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spectral hardening assumes either that there are axion-like particles (de Angelis et al. 2007; Simet et al. 2008; Sanchez-Conde et al. 2009) or a Lorentz invariance violation (Kifune 1999; Protheroe & Meyer 2000). Alternatively, now that the AGN jets are believed to be one of the most powerful sources of cosmic rays, as long as the intergalactic magnetic fields (IGMF) deep in the voids are less than a femtogauss, the point images of distant blazars, which are produced by the interaction of the energy protons with the background photons along the line of sight, should be observed by IACTs (Essey et al. 2011a). In this scenario, the hard TeV spectra can be produced by the cascade emission from high-energy protons propagating through intergalactic space (Essey & Kusenko 2010; Essey et al. 2010; 2011b; Razzaque et al. 2012; Aharonian et al. 2013; Takami et al. 2013; Zheng & Kang 2013).

In this paper, we study the possible TeV emission in distant TeV blazars. We argue that the TeV emission in distant TeV blazars is dominated by two components, the internal component with the photon energy around 1 TeV produced by IC scattering of the relativistic electrons on the synchrotron photons (SSC) with a correction for EBL absorption and the external component with the photon energy of more than 1 TeV produced by the cascade emission from high-energy protons propagating through intergalactic space. Generally, the external photons are generated in two types photohadronic interactions process along the line of sight. In the first, the proton interaction with cosmic microwave background (CMB) photons would produce e^\pm pairs, and the pairs would give rise to electromagnetic cascades. This process is called the Bethe-Heitler pair production (pe) process. In the second process, the proton interaction with EBL photons would produce pions, and the pion decay accompanying the photons. This process is called the photopion production ($p\pi$) process. Although the pe process contribution to the production of secondary photons is illustrated at the source (Dimitrakoudis et al. 2012; Murase 2012; Murase et al. 2012; Petropoulou 2014; Petropoulou & Mastichiadis 2015), the high-energy astrophysical interest focuses on the $p\pi$ process along the line of sight because the pe process is not associated with any neutrinos and neutrons (e.g., Inoue et al. 2013; Kalashev et al. 2013). The aim of the present work is to study in more detail the contribution of pairs injected by the pe process along the line of sight to the TeV spectra in distant blazars.

Throughout the paper, we assume the Hubble constant $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$, the matter energy density $\Omega_M = 0.27$, the radiation energy density $\Omega_r = 0$, and the dimensionless cosmological constant $\Omega_\Lambda = 0.73$.

2. The model

We calculate the spectra of the internal photon component within the traditional SSC model frame, and we focus on an overlooked Bethe-Heitler pairs cascade process along the line of sight for the spectra of the external photon component. In the following, we give a brief description of the model for possible TeV emission in a distant TeV blazar.

2.1. Internal photon component

We assume that a single homogeneous spherical radiation region filled with extreme-relativistic electrons, in which there is a randomly originated homogeneous magnetic field and constant electron number density. We adopt a broken power-law function

with a sharp cut-off to describe the electron energy distribution in the radiation region,

$$N_{e,\text{in}}(E_{e,\text{in}}) = \begin{cases} K_0 E_{e,\text{in}}^{-n_1}, & E_{e,\text{in},\text{min}} \leq E_{e,\text{in}} \leq E_{e,\text{in},\text{b}}; \\ K_1 E_{e,\text{in}}^{-n_2}, & E_{e,\text{in},\text{b}} \leq E_{e,\text{in}} \leq E_{e,\text{in},\text{cut}}, \end{cases} \quad (1)$$

where $E_{e,\text{in}}$ is the energy of electron in the internal emission region and $K_1 = K_0 E_{e,\text{in},\text{b}}^{(n_2-n_1)}$. Based on the above electron number density $N_{e,\text{in}}(E_{e,\text{in}})$, we can calculate the synchrotron intensity $I_s(E_\gamma)$ and the intensity of self-Compton radiation $I_c(E_\gamma)$, and then calculate the intrinsic photon spectrum $dN_\gamma^{\text{int}}(E_\gamma)/dE_\gamma$ at the observer's frame (e.g., Katarzynski et al. 2001; Zheng & Zhang 2011; Zheng & Kang 2013). Taking into account the absorption effect, the flux density observed at the Earth becomes

$$\frac{dN_\gamma^{\text{in}}(E_\gamma)}{dE_\gamma} = \frac{dN_\gamma^{\text{int}}(E_\gamma)}{dE_\gamma} \exp[-\tau(E_\gamma, z)], \quad (2)$$

where $\tau(E_\gamma, z)$ is the absorption optical depth due to interactions with the EBL (e.g., Kneiske et al. 2004; Dwek & Krennrich 2005; Franceschini et al. 2008). In our calculation, we use the absorption optical depth which is deduced by the EBL model in Dwek & Krennrich (2005).

2.2. External photon component

Active galactic nuclei are expected to accelerate cosmic rays to energies up to $\sim 10^{11}$ GeV during rare bursts or flares (Dermer et al. 2009; Murase & Takami 2009). The high-energy cosmic rays with energies below the Greisen-Zatsepin-Kuzmin (GZK) cutoff of about 5×10^{10} GeV can propagate cosmological distances without significant energy loss (Greisen 1966; Zatsepin & Kuzmin 1966). However, with a small probability, these protons should interact with the CMB photons and trigger electromagnetic cascades. The present work differs from the earlier studies on which the electromagnetic cascades were modeled using a standard Monte Carlo approach (e.g., Essey et al. 2010). We employ a Bethe-Heitler pair-creation rate in the δ -functional approximation and we concentrate on the protons with energy below the GZK cutoff, which would propagate through cosmological distances.

2.2.1. Bethe-Heitler pairs production

We consider an isotropic target photon field with energy $E_s = \epsilon_s m_e c^2$ interaction on the proton with energy $E_p = \gamma_p m_p c^2$. We let $N_p(E_p)$ and $N_{\text{ph}}(E_s)$ be functions characterizing the energy distributions of protons and soft photons and the collision rate in the unit of s^{-1} can be given by Romero & Vila (2008)

$$w_{p\gamma,e}(E_p) = \frac{m_p^2 m_e^2 c^9}{2E_p^2} \int_{E_{s,\text{min}}}^{\infty} \frac{N_{\text{ph}}(E_s)}{E_s^2} dE_s \int_{\epsilon'_{s,\text{min}}}^{\epsilon'_{s,\text{max}}} \sigma_{p\gamma,e}(\epsilon'_s) \epsilon'_s d\epsilon'_s, \quad (3)$$

where $\epsilon'_s = \gamma_p \epsilon_s (1 - \beta_p \cos \theta)$ is the energy of the photon in the rest frame of the proton with the angle between the proton and photon directions θ , and the proton's velocity β_p in units of c . Because the Bethe-Heitler pairs production are with a threshold energy of ~ 1 MeV for the photon in the proton rest frame, we can obtain $\epsilon'_{s,\text{min}} = 1 \text{ MeV}/(m_e c^2) \sim 2$, $E_{s,\text{min}} = 1/2\gamma_p \text{ MeV}$ (e.g., Mastichiadis & Kirk 1995). A head-on collision gives the

maximum energy of the photon in the rest frame of the proton $\epsilon'_{s,\max} = 2\gamma_p\epsilon_s$. The energy distribution of soft photons is described by

$$N_{\text{ph}}(E_s) = \frac{1}{\pi^2(\hbar c)^3} \frac{E_s^2}{\exp(E_s/kT) - 1}, \quad (4)$$

where the typical temperature $T = (1+z)2.73$ K with redshift z and k is the Boltzmann constant. The total cross section $\sigma_{\text{py},e}(\epsilon'_s)$ for which we use the Racah formula as parameterized by Maximon (1968). For $2 \leq \epsilon'_s \leq 4$, the expansion is given with a fractional error less than 1.1×10^{-3} (Maximon 1968),

$$\sigma_{\text{py},e}(\epsilon'_s) \approx \frac{2\pi}{3} \alpha_f r_0^2 Z^2 \left(\frac{\epsilon'_s - 2}{\epsilon'_s} \right)^2 \times \left(1 + \frac{1}{2}\eta + \frac{23}{40}\eta^2 + \frac{37}{120}\eta^3 + \frac{61}{192}\eta^4 \right), \quad (5)$$

where $\eta = (\epsilon'_s - 2)/(\epsilon'_s + 2)$, α_f is the fine structure constant, r_0 is the classical electron radius, and Z is the Atomic number of the target atom. In the larger photon energy regime, $\epsilon'_s \geq 4$, the expansion can be written with a fractional error less than 4.4×10^{-5} as (e.g., Chodorowski et al. 1992)

$$\sigma_{\text{py},e}(\epsilon'_s) \approx \alpha_f r_0^2 Z^2 \left\{ \frac{28}{9} \ln 2\epsilon'_s - \frac{218}{27} + \left(\frac{2}{\epsilon'_s} \right)^2 \times \left[6 \ln 2\epsilon'_s - \frac{7}{2} + \frac{2}{3} \ln^3 2\epsilon'_s - \ln^2 2\epsilon'_s - \frac{1}{3} \pi^2 \ln 2\epsilon'_s + 2\zeta(3) + \frac{\pi^2}{6} \right] - \left(\frac{2}{\epsilon'_s} \right)^4 \left(\frac{3}{16} \ln 2\epsilon'_s + \frac{1}{8} \right) - \left(\frac{2}{\epsilon'_s} \right)^6 \left(\frac{9}{9 \times 256} \ln 2\epsilon'_s - \frac{77}{27 \times 512} \right) \right\}, \quad (6)$$

where $\zeta(3) \approx 1.20206$. Now the Monte Carlo simulation shows that the mean inelasticity can be approximated by its values at the threshold $K_{\text{py},e}(\epsilon'_s) = 2m_e/m_p$ (Mastichiadis et al. 2005). Therefore, the Bethe-Heitler pair-creation rate in the δ -functional approximation is then given (Romero & Vila 2008) as

$$Q_c(E_{\text{py},e}) = 2 \int_{E_{\text{p,min}}}^{E_{\text{p,max}}} N_p(E_p) w_{\text{py},e}(E_p) \delta\left(E_{\text{py},e} - \frac{m_e}{m_p} E_p\right) dE_p = 2 \frac{m_p}{m_e} N_p\left(\frac{m_p}{m_e} E_{\text{py},e}\right) w_{\text{py},e}\left(\frac{m_p}{m_e} E_{\text{py},e}\right). \quad (7)$$

We parameterize the proton injection spectrum by a constant power-law exponent α and maximum energy $E_{\text{p,max}}$:

$$N_p(E_p) = N_0 E_p^{-\alpha} \exp\left(-\frac{E_p}{E_{\text{p,max}}}\right), \quad E_{\text{p,min}} \leq E_p \leq E_{\text{p,max}}. \quad (8)$$

Where the normalization coefficient N_0 is determined from the jet power L_p of the protons. The observed data on the most distant sources shows that an effective luminosity of a single AGN in cosmic rays above 10^7 GeV was in the range $L_{\text{eff}} \sim 10^{47} - 10^{49}$ erg s $^{-1}$. Since the VLBI observation shows that the value of the Doppler factor δ is less than 10 (Wu et al. 2007), the flux can be beamed with the beaming factor $f_{\text{beam}} \sim 10 - 10^3$, which increases the flux of protons from a blazar with a jet pointing in the direction of Earth (Essey & Kusenko 2010)

$$L_{\text{eff}} \sim 10^2 f_p \times \left(\frac{f_{\text{beam}}}{100} \right) L_p, \quad (9)$$

where $f_p \leq 1$ is the fraction of protons.

2.2.2. Inverse Compton scattering from Bethe-Heitler pairs

Assuming that the energy of the Bethe-Heitler pairs is lost through interaction with the CMB photons at the cosmological distance D , we can deduce energy distribution of the secondary electrons or positrons from the well-known energy distribution equation

$$\frac{dN_{e,\text{ex}}(E_{e,\text{ex}})}{dE_{e,\text{ex}}} = \left(\frac{dE_{e,\text{ex}}}{dt} \right)^{-1} \int_{E_{e,\text{ex}}}^{E_{\text{py},e,\text{max}}} Q_c(E_{\text{py},e}) dE_{\text{py},e}, \quad (10)$$

where $dE_{e,\text{ex}}/dt = 4\sigma_T E_{e,\text{ex}}^2 / (3m_e^2 c^3 u_{\text{CMB}})$ is the Bethe-Heitler pairs energy loss rates with Thomson cross section σ_T and CMB energy density u_{CMB} . Then, the photon spectrum of the IC scattering is given by

$$\frac{dN_{\gamma}^{\text{ex}}(E_{\gamma})}{dE_{\gamma}} = \int_{E_{e,\text{ex,min}}}^{\infty} \frac{dN_{e,\text{ex}}(E_{e,\text{ex}})}{dE_{e,\text{ex}}} \left[\frac{d^2 N_{\text{ph}}(E_s)}{dE_s dt} \right]_{\text{ICS}} dE_{e,\text{ex}}, \quad (11)$$

with the spectrum of the IC scattered photons per electron (Blumenthal & Gould 1970)

$$\left[\frac{d^2 N_{\text{ph}}(E_s)}{dE_s dt} \right]_{\text{ICS}} = \int_{E_{s,\text{min}}}^{\infty} \frac{3\sigma_T m_e^2 c^5}{4E_{e,\text{ex}}^2} \frac{N_{\text{ph}}(E_s)}{E_s} dE_s \times \left[2q \ln q + (1+2q)(1-q) + \frac{(\Gamma q)^2(1-q)}{2(1+\Gamma q)} \right], \quad (12)$$

where $q = E_1/\Gamma(1-E_1)$, $\Gamma = 4\epsilon_s E_{e,\text{ex}}/m_e c^2$, and $E_1 = E_{\gamma}/E_{e,\text{ex}}$.

Therefore, the TeV photon spectrum that is observed at the Earth is given by

$$\frac{dN_{\gamma}(E_{\gamma})}{dE_{\gamma}} = \frac{dN_{\gamma}^{\text{in}}(E_{\gamma})}{dE_{\gamma}} + \frac{dN_{\gamma}^{\text{ex}}(E_{\gamma})}{dE_{\gamma}}. \quad (13)$$

3. Constraint on the energy of protons

The above scenario depends on the energy of protons. Since the IGMF would cause proton or electron deflection in the voids, and the energetic γ rays in the EBL photon fields should be absorbed, we can determine the ranges of a proton's energy through these physical process.

As long as the IGMF B_{IG} is less than 1 femtogauss, the Cosmic ray protons with energies $E_p \leq E_{\text{GZK}} = 5 \times 10^{10}$ GeV can provide an effective transport of the energy over a cosmological distance toward the observer (Essey et al. 2011a). Then they interact with the CMB photons and initiate electromagnetic cascades. On condition that the deflection broadening of the proton beam θ_p in IGMFs is less than the point spread function $\theta(E)$ of the detector, the resulting secondary photons are observed as arriving from a point source. The deflection angles dependence on the IGMF can be written (Aharonian et al. 2010)

$$\theta_p \approx 0.05 \text{ arcmin} \left(\frac{10^9 \text{ GeV}}{E_p} \right) \left(\frac{B_{\text{IG}}}{10^{-15} \text{ G}} \right) \left(\frac{l_c}{\text{Mpc}} \frac{d}{\text{Gpc}} \right)^{1/2}, \quad (14)$$

where l_c is a correlation length of the random fields and $d \sim cz/H_0$ is luminosity distance. We consider a VHE blazar with redshift z , and the typical point spread function of the HESS telescope array, $\theta(E) \approx 3.0$ arcmin. The constraint condition $\theta_p \leq \theta(E)$ could result in $E_p \geq E_{\text{p,low}} = 3.3 \times 10^7 z^{1/2} (l_c/1 \text{ Mpc})^{1/2} (B_{\text{IG}}/10^{-15} \text{ G}) \text{ GeV}$.

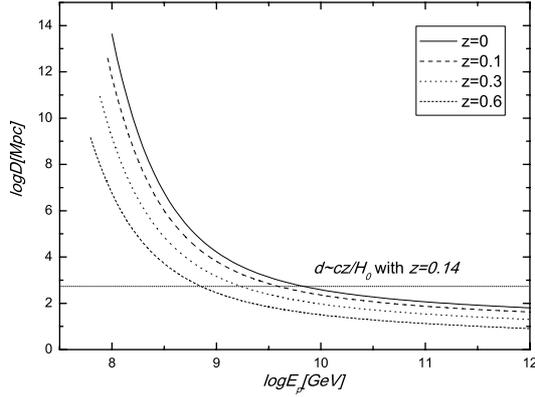


Fig. 1. Secondary emission region as a function of energy and redshift. The distance to the source that is estimated by using Hubble’s law with $z = 0.14$ is also exhibited as a short dotted line.

Alternatively, VHE γ -ray photon emission from the region is attenuated by photons from the EBL (e.g., Kneiske et al. 2004; Dwek & Krennrich 2005). It is well-known that the γ -ray zone can be defined by the γ -ray absorption mean free path $\lambda_{\gamma\gamma} \sim 190(n_{\text{IR}}/0.01 \text{ cm}^{-3})^{-1} \text{ Mpc}$ with the infrared photon number density n_{IR} (e.g., Venters 2010). As long as the magnetic field is significantly small, an extremely efficient cascade development could enlarge the γ -ray zone, typically $\lambda_{\gamma,\text{eff}} \sim 2\text{--}3\lambda_{\gamma\gamma}$ (Aharonian et al. 2013). In this scenario, we argue that if the Bethe-Heitler cascades contribution to the observed hard spectra behavior of blazars is true, the secondary γ -ray emission region D should satisfy a relation $d - D \leq \lambda_{\gamma,\text{eff}}$. In our work, due to the cascades the electrons are the main origin of the pe process, the adoption $D \simeq \lambda_{p\gamma,e} = c/t_{p\gamma,e}^{-1}(E_p)$ is justified. Here,

$$t_{p\gamma,e}^{-1}(E_p) = \frac{m_p^2 m_e^2 c^9}{2E_p^2} \int_{E_{s,\text{min}}}^{\infty} \frac{N_{\text{ph}}(E_s)}{E_s^2} dE_s \times \int_{\epsilon'_{s,\text{min}}}^{\epsilon'_{s,\text{max}}} K_{p\gamma,e}(\epsilon'_s) \sigma_{p\gamma,e}(\epsilon'_s) \epsilon'_s d\epsilon'_s \quad (15)$$

is the cooling rate of the protons in CMB photon fields (Romero & Vila 2008). Obviously, in the case of a broad energy distribution of protons, the main contribution to the secondary γ -ray flux comes from some energetic proton ranges in which the secondary γ -ray emission region is comparable to the distance of the source, i.e., $D \sim d$. We show the secondary emission region as a function of energy and redshift in Fig. 1. It can be seen that the characteristic energy of proton $E_p^* \sim 6.3 \times 10^9 \text{ GeV}$ should be found in Fig. 1 as the point where the distance to the source is equal to the mean free path of protons at the present epoch ($z = 0$). The above issues give a strong constraint on the range of energy of the protons from $E_{p,\text{min}} = E_{p,\text{low}}$ to $E_{p,\text{max}} = \min[E_p^*, E_{\text{GZK}}]$.

4. Apply to 1ES 0229+200

1ES 0229+200 resides in an elliptical host galaxy at a redshift of $z = 0.1396$ (Woo et al. 2005). The source has been classified as a high-frequency peaked BL BLac object (HBL) due to its X-ray to radio flux ratio (Giommi et al. 1995). As a special source, the spectrum of 1ES 0229+200 was measured extended up to 10 TeV with a hard archival spectral index at VHE of 2.5 ± 0.19 (Aharonian et al. 2007; Aliu et al. 2014). Compiling with the VERITAS measured spectrum averaged over all three

Table 1. Linear regression analysis of the observed spectrum of 1ES 0229+200 in the MeV–TeV energy band.

Photon energy	MeV – GeV	$\geq 1 \text{ TeV}$
$\Gamma(\sigma)$	1.93 ± 0.06	2.27 ± 0.13
r	0.99	0.98
N	13	13
p	< 0.0001	< 0.0001

Notes. The linear regression is obtained by considering the photon energy E_γ to be the independent variable and assuming a relation $dN_\gamma(E_\gamma)/dE_\gamma \propto E_\gamma^{-\Gamma}$; N is the number of points, r is the correlation coefficient, and p is the chance probability.

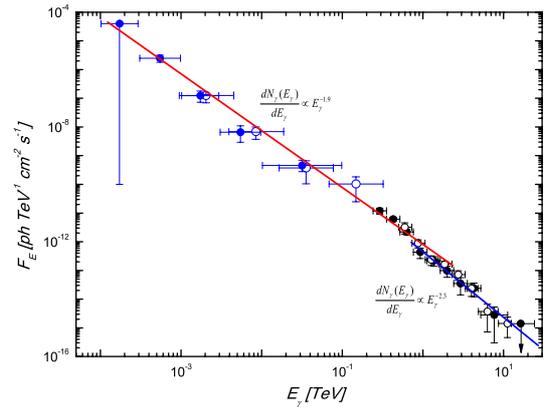


Fig. 2. Observed photon spectrum of 1ES 0229+200. The solid lines are the linear regression results in the MeV–GeV and TeV energy bands. The *Fermi*-LAT observed data come from the second catalog (blue open circle) and third catalog (blue solid circle). The HESS observed data (black open circle) come from Aharonian et al. (2007) and VERITAS observed data (black solid circle) come from Aliu et al. (2014).

seasons (Aliu et al. 2014), and four years of *Fermi*-LAT observed results², we reanalyze the spectrum of 1ES 0229+200 assuming a relation $dN_\gamma(E_\gamma)/dE_\gamma \propto E_\gamma^{-\Gamma}$ in Fig. 2. The results of linear regression analysis are listed in Table 1. It can be seen that the spectrum should be fitted by a power-law relation with the spectra index $\Gamma_{\text{MeV-GeV,obs.}} = 1.93 \pm 0.06$ in the MeV–GeV energy band, and $\Gamma_{\text{TeV,obs.}} = 2.27 \pm 0.13$ in the TeV energy band. Now that the model argues that the TeV emission in distant TeV blazars is dominated by two components, the external TeV photons could significantly repair the EBL attenuation, and leave a hard spectra to 100 TeV energy band. Using the model in Sect. 2, we should expect to reproduce the hard TeV γ -rays spectra.

In order to do so, first we search for the internal γ -ray component in the one-zone homogeneous SSC frame. Assuming the density normalization $K_0 = 5.57 \times 10^3 \text{ erg}^{-1} \text{ cm}^{-3}$, we calculate the high-energy electron distribution with a broken power law between $E_{e,\text{in,min}} = 4.34 \text{ GeV}$ and $E_{e,\text{in,cut}} = 4.5 \times 10^4 \text{ GeV}$ with a break at $E_{e,\text{in,b}} = 4.49 \times 10^2 \text{ GeV}$, where the energy index of the particles between $E_{e,\text{in,min}}$ and $E_{e,\text{in,b}}$ is set to $n_1 = 2.2$ and the energy index of the particles between $E_{e,\text{in,b}}$ and $E_{e,\text{in,cut}}$ is set to $n_2 = 4.0$. The parameters are used as follows: the magnetic field strength is $B = 0.06 \text{ G}$, the emission region size is $R_e = 2.77 \times 10^{16} \text{ cm}$, and the Doppler factor is $\delta = 10.7$. We assume that relativistic electrons are in the steady state during

² http://fermi.gsfc.nasa.gov/ssc/data/access/lat/4yr_catalog/

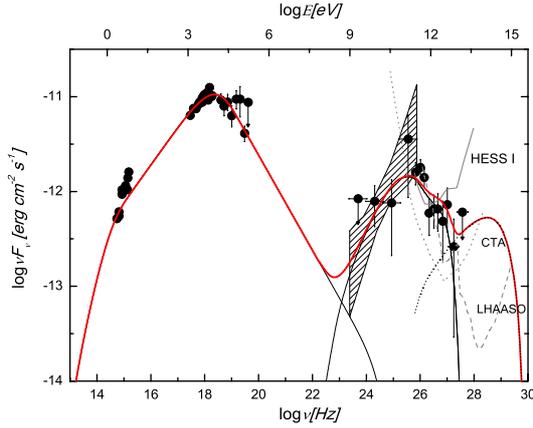


Fig. 3. Multiwavelength SED of the distant TeV blazar 1ES 0229+200. The solid black curve represents the internal component spectra with the absorption optical depth that is deduced by the LLL EBL model in Dwek & Krennrich (2005), and the dotted black curve represents the external component spectra. The superposed model spectrum is plotted as a red curve. The observed data come from Aliu et al. (2014) (solid circle). The shaded area shows the *Fermi* upper bounds at the 99% confidence level. The differential sensitivity curve for the 50-h observation with HESS I³, gray solid curve, the 50-h differential sensitivity goal of the CTA (Actis et al. 2011, gray dashed curve), and the differential sensitivity curve for the one-year observation with LHAASO (Cui et al. 2014, gray dotted curve) are also shown.

the observational epoch. Therefore, we can calculate the TeV γ -ray spectrum in the one-zone homogeneous SSC frame using the broken power-law electron spectrum.

We now consider the external TeV photons production along the line of sight. We argue that the sites of electron acceleration may also accelerate protons in the jet. If the acceleration site is full of electrically neutral nonthermal plasma, the proton-to-electron ratio depends on the spectral indices of injection electron and proton spectra (e.g., Schlickeiser 2002; Persic & Rephaeli 2014). As a simple case, we do not specify the proton-to-electron ratio and leave it as a free parameter with L_p and L_e . Assuming the protons are accelerated to extra-relativistic energy in the acceleration region through some mechanisms and then escape from the region without energy loss. We calculate the Bethe-Heitler pairs distribution along the line of sight with a proton injection spectrum between $E_{p,\min}$ and $E_{p,\max}$, where, in this case, the correlation length of the random fields is set to $l_c = 1$ Mpc, the IGMF is set to $B_{\text{IG}} = 10^{-15}$ G (e.g., Tavecchio et al. 2010), and the power-law exponent $\alpha = 2.0$ is adopted by fitting to the ultra high-energy cosmic rays data at the lower energies (Berezinsky et al. 2006). Since the typical luminosity range of AGNs are in 10^{45} – 10^{47} erg s⁻¹ (e.g., Ghisellini et al. 2014), in our calculation we set the jet power of protons $L_p = 0.3 \times 10^{46}$ erg s⁻¹. We assume that the energy of the Bethe-Heitler pairs is lost through interaction with the CMB photons at the cosmological distance D during the observational epoch. Therefore, we can calculate the external TeV γ -ray spectrum along the line of sight using the injection electron spectrum.

We show the predicted internal component spectrum, external component spectrum, and the superposed model spectral in Fig. 3. For comparison, the differential sensitivity curve for the 50-h observation with HESS I³, the 50-h differential

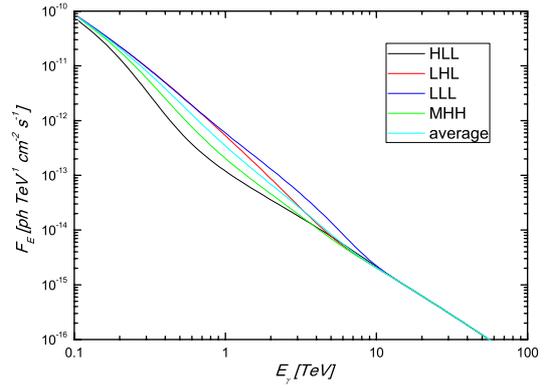


Fig. 4. Model spectra with different EBL absorption optical depths. It is indicated that, dependent of the EBL absorption optical depth, the photon spectra with the photon energy between 0.1 TeV and 10 TeV could be described by a relation $dN_\gamma(E_\gamma)/dE_\gamma \propto E_\gamma^{-\Gamma}$ with a small photon spectral index $1.5 < \Gamma < 2.5$, and even flatter in a higher energy band.

Table 2. Physical parameters of the model spectra.

Internal component		External component	
Parameters	Value	Parameters	Value
K_0 [erg ⁻¹ cm ⁻¹]	5.57×10^3	$E_{p,\max}$ [GeV]	6.3×10^9
n_1	2.2	α	2.0
n_2	4.0	B_{IG} [G]	1.0×10^{-15}
$E_{e,\text{in},\min}$ [GeV]	4.34	l_c [Mpc]	1.0
$E_{e,\text{in},b}$ [GeV]	449	L_p [erg s ⁻¹]	0.3×10^{46}
$E_{e,\text{in},\text{cut}}$ [GeV]	4.5×10^4	D [Gpc]	1.0
B [G]	0.06	–	–
δ	10.7	–	–
R_e [cm]	2.77×10^{16}	–	–

sensitivity goal of the Cherenkov Telescope Array (CTA, Actis et al. 2011), the differential sensitivity curve for the one-year observation with the Large High Altitude Air Shower Observatory (LHAASO, Cui et al. 2014), and the multi-wavelength observed data of 1ES 0229+200 (Aliu et al. 2014) are also shown. All of the physical parameters of the internal component and external component spectra are listed in Table 2. It can be seen that 1) the observed spectrum properties of 1ES 0229+200, especially the TeV γ -ray tail of the observed spectra, were reproduced in our model; 2) an expected TeV γ -ray spectrum with photon energy > 1 TeV of 1ES 0229+200 should be comparable with the 50-h sensitivity goal of the CTA and the differential sensitivity curve for the one-year observation with the LHAASO.

In order to intensively examine the hard spectra properties of 1ES 0229+200 in the TeV energy bands. We show the model spectra with different EBL absorption optical depths in Fig. 4. Now that the predicted spectral shape of external photons is not very sensitive to the variations in the proton spectrum index α (e.g., Essey et al. 2010), we do not take into account the effect of α on the model spectra. It is indicated that, dependent of the EBL absorption optical depth, the photon spectra with the photon energy between 0.1 TeV and 10 TeV could be described by a relation $dN_\gamma(E_\gamma)/dE_\gamma \propto E_\gamma^{-\Gamma}$ with a small photon spectral index $1.5 < \Gamma < 2.5$, and even flatter in a higher energy band. As a special case with the LLL EBL model in Dwek & Krennrich (2005), in Fig. 5 we compare the predicted differential photon

³ <http://www.mpi-hd.mpg.de/hfm/HESS/pages/home/proposals/>

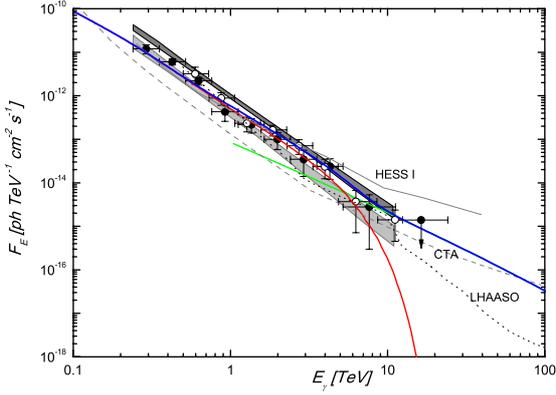


Fig. 5. Comparisons of predicted TeV photon spectra with observed data of the distant TeV blazar 1ES 0229+200. The upper and lower shaded regions show the spectral shape during the flaring and low periods. The red curve represents the internal component spectra with the absorption optical depth that is deduced by the LLL EBL model in Dwek & Krennrich (2005), and the green curve represents external component spectra. The superposed model spectrum is plotted as a blue curve. The HESS Observed data (open circle) come from Aharonian et al. (2007) and VERITAS observed data (solid circle) come from Aliu et al. (2014). The integral sensitivity curve for the 50-h observation with HESS I³, gray solid curve, the 50-h integral sensitivity goal of the CTA (Actis et al. 2011, gray dashed curve), and the integral sensitivity curve for the one-year observation with LHAASO (Cui et al. 2014, gray dotted curve) are also shown.

spectrum in the ≥ 1 TeV γ -ray energy bands (blue solid curve) with observed data of 1ES 0229+200 at HESS (Aharonian et al. 2007) and VERITAS (Aliu et al. 2014) energy bands. Our result shows that in this special case, superposed model spectra with the photon energy between 1 TeV and 10 TeV could be described by a photon spectral index $\Gamma = 2.4$. This is in agreement with the result that is found by reanalysis of the spectrum of 1ES 0229+200.

5. Discussion and conclusions

As an open issue, VHE γ -ray measurements of distant TeV blazars can be explained by TeV spectra induced by ultra high-energy cosmic rays (Essey & Kusenko 2010; Essey et al. 2010; 2011b; Murase 2012; Murase et al. 2012; Razzaque et al. 2012; Takami et al. 2013; Zheng, et al. 2013). In this paper, We develop a model for a possible TeV emission in distant TeV blazars. The aim of the present work is to study in greater detail the contribution of pairs injected by the pe process along the line of sight to the TeV spectra in distant blazars. In the model, the TeV emission in distant TeV blazars is dominated by two mixed components: the first is the internal component where the photon energy around 1 TeV is produced by IC scattering of the relativistic electrons on the synchrotron photons (SSC) with a correction for EBL absorption, and the second is the external component where the photon energy more than 1 TeV is produced by the cascade emission from high-energy protons propagating through intergalactic space. Assuming a suitable model parameters, we apply the model to observed spectra of distant TeV blazars of 1ES 0229+200. Our results show that 1) the observed spectrum properties of 1ES 0229+200, especially the TeV γ -ray tail of the observed spectra, could be reproduced in our model and 2) an expected TeV γ -ray spectrum with photon energy >1 TeV of 1ES 0229+200 should be comparable with

the 50-h sensitivity goal of the CTA and the differential sensitivity curve for the one-year observation with LHAASO. We argue that strong evidence for the Bethe-Heitler cascades along the line of sight as a plausible origin of hard spectra in distant TeV blazars could be obtained from VHE observations with CTA and LHAASO.

The present work differs from the earlier studies that assume that the pairs cascade process induced by ultra high-energy cosmic rays occurs at the source (e.g., Murase 2012; Murase et al. 2012; Petropoulou & Mastichiadis 2015). We concentrate on the protons with energy below the GZK cutoff, which would propagate through cosmological distances. We argue that the outflows of the jets from AGNs are likely to contain coherent magnetic fields aligned with the jet, so that the accelerated protons remain in the scope of the initial jet rather than getting deflected. Since the pe process takes place outside the galaxy clusters of both the observer and the source, the cluster magnetic fields are irrelevant to this issue. Although we expect larger fields in the filaments and wall, only the IGMF present deep in the voids along the line of sight is important (Essey & Kusenko 2010). Within the host galaxy, the propagated directions of the protons could be changed by the galactic magnetic fields, the broadening of the image due to deflections in it should less than $\Delta\theta_{\max} \sim r/D_{\text{source}}$ (Essey et al. 2010), where r is the size of the host galaxy, and D_{source} is the distance to the host galaxy. Furthermore, the possible thin walls of magnetic fields that might intersect the line of sight could not cause a deflection of more than $\Delta\theta \sim h/D_{\text{wall}}$ (Essey et al. 2010), where h is the wall thickness and D_{wall} is the distance to the wall. The model also does not take into account both the γ -ray photon spectrum and the pairs cascade from the decay of pions π^0 , π^+ , and π^- . We argue that the characteristic energy of both decay induced photons $E_\gamma \sim 0.1E_p > 10^3$ TeV and pairs cascade from the decay of pions induced photons $E_\gamma \sim (0.05E_p/m_e c^2)^2 E_{\text{CMB}} > 10^4$ TeV with IGMF $B_{\text{IG}} = 10^{-15}$ G and correlation length of the random fields $l_c = 1$ Mpc. This energy is far from the TeV energy band.

It is noted that small photon indices are not easy to achieve in traditional leptonic scenarios, although the stochastic acceleration model (Lefa et al. 2011) and the leptohadronic model (Cerruti et al. 2015) can also explain the spectral hardening of TeV blazars because radiative cooling tends to produce particle energy distributions that are always steeper than E^{-2} . The above distribution results in a TeV photon index $\Gamma_{\text{TeV,int}} \geq 1.5$, and even steeper at VHE due to the suppression of the Klein-Nishina effects of the cross-section (e.g., Chiang & Böttcher, 2002). Even when the absorption effect by the lowest level EBL is used, the emitted spectra still tend to be steeper with an observed photon index $\Gamma_{\text{TeV,obs}} \geq 2.5$ (e.g., Aharonian et al. 2007; Dwek & Krennrich 2012). Because the Bethe-Heitler pair-creation rate is smoothed in the model, we argue that the spectral shape of the external component spectrum is not very sensitive to the proton injection spectrum (Essey et al. 2010); it is determined primarily by the spectrum of the CMB photons and the Bethe-Heitler pairs energy loss process, which result in hard TeV photons spectra.

Alternatively, the secondary e^\pm pairs that are produced by $\gamma + \gamma \rightarrow e^+ + e^-$ pair creation generate a new γ -ray component through IC scattering of these e^\pm pairs against target photons of the CMB, initiating an electromagnetic cascade if the produced γ ray is subsequently absorbed (e.g., Dai et al. 2002; Fan et al. 2004; Yang et al. 2008; Neronov et al. 2012). In order to reproduce a hard spectra, we include an external γ -ray component with photon energy around ~ 10 – 100 TeV. Using the photon energy of the external γ -ray component, we

could estimate the boosting energy through the IC process of $E_\gamma \sim \gamma_{e\pm}^2 \epsilon_{\text{CMB}} \sim 0.01\text{--}1.0$ TeV. In this view, the resultant secondary photons should contribute to the TeV γ -ray flux and we expect to find a complex spectrum around 1 TeV. However, ultra high-energy cosmic rays with $E_p \sim 10^{19}$ eV have energy loss paths $\lambda_{p\gamma,e} \sim 1$ Gpc for Bethe-Heitler pair production, whereas 10–100 TeV γ -ray only travel $\lambda_{\gamma,\text{eff}} \sim 3\text{--}200$ Mpc before being absorbed by $\gamma\gamma$ pairs production. Now that we assume the cascade emission region $D \sim \lambda_{p\gamma,e}$, the source at a redshift of $z < 1.0$ allows the Bethe-Heitler pair to be injected and cascade to such energy far from the source. Thus, some TeV photons can reach the Earth before being attenuated even when $\tau(E_\gamma, z) \gg 1$, without any spectral shape transformation (Takami et al. 2013). On the other hand, although we focus on spectral information to the possible TeV emission in distant blazars, variability is also another important clue. Murase et al. (2012) argue that the cascade components would not have short variability timescales, since the shortest time scales are $\sim 1.0(E_\gamma/10 \text{ GeV})^{-2}(B_{\text{IG}}/10^{-18} \text{ G})^2 \text{ yr}$ in the γ -ray induced cascade case, and $\sim 10(E_\gamma/10 \text{ GeV})^{-2}(B_{\text{IG}}/10^{-18} \text{ G})^2 \text{ yr}$ in the ultra high-energy cosmic ray induced cascade case. The above issue suggests that strong variability is possible in the γ -ray induced cascade case, and this means that the cascaded γ -ray should be regarded as a mixture of attenuated and cascade components, and then the cascade component could be suppressed. Instead, in the ultra high-energy cosmic ray induced cascade case, the variability could not be found (Takami et al. 2013). The lack of strong evidence of variability in 1ES 0229+200 above the HESS energy band (Aharonian et al. 2007; Aliu et al. 2014) suggests that the ultra high-energy cosmic ray induced cascade component might dominate on the TeV γ -ray spectrum. Since, in our issue, the TeV emission in distant TeV blazars is dominated by two components, the external TeV photons could significantly repair the EBL attenuation, and leave a hard spectra to 100 TeV energy band.

It is clear that the jet power of protons plays an important role in determining an emission intensity. In our results, in order to obtain the TeV emission of the 1ES 0229+200, we adopt the jet power of protons $L_p = 0.3 \times 10^{46} \text{ erg s}^{-1}$. It is well known that the jets of AGN are powered by the accretion of matter onto a central black hole (e.g., Urry & Padovani 1995). On the assumption that the radiation escapes isotropically from the black hole, the balancing of the gravitational and radiation force leads to the maximum possible luminosity due to accretion $L_{\text{edd}} \sim 1.26 \times 10^{38} M/M_\odot \text{ erg s}^{-1}$ (e.g., Dermer & Menon 2009). When the total emission of an AGN is not super-Eddington, the Eddington luminosity is the maximum power available for the two jets, $P_{\text{jet}} \leq L_{\text{edd}}/2$. In this view, the required power in protons could easily be provided by the source with mass $M = 1.44 \times 10^9 M_\odot$ (Wagner 2008).

A potential drawback of the model is that the shape of the model spectra in the 1–10 TeV energy ranges strongly depends on the level of the EBL. As a check, we constrain the shape of the model of spectra depending on a general EBL model. On the basis of the model results, we argue that the predicted TeV spectra properties of the above-mentioned model should be testable in the near future since the secondary emission process will expect CTA to detect more than 80 TeV blazars in the above 1 TeV energy band (Inoue et al. 2013). We note that the neutrino populations could be expected in $p\gamma$ interactions, and it should be given a clearer predictive character with the IceCube observations. Unfortunately, the pe process does not contain any neutrino populations. We defer this possibility to future work. Although our model focuses on the contribution of pairs injected

by pe process along the line of sight to the TeV spectra, the γ -ray induced cascade is also another important scenario for the possible TeV emission in distant blazars (e.g., Vovk et al. 2012; Takami et al. 2013). We leave this possibility to the observation of CTA (Actis et al. 2011), LHAASO (Cao 2010; Cui et al. 2014), HAWC (Sandoval et al. 2009), and HiSCORE (Hampf et al. 2011).

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References

- Abramowski, A., Acero, F., Aharonian, F., et al. 2013, *A&A*, **550**, A4
 Acciari, V. A., Aliu, E., Arlen, T., et al. 2009, *ApJ*, **693**, L104
 Ackermann, M., Ajello, M., Allafort, A., et al. 2012, *Science*, **338**, 1190
 Actis, M., Agnetta, G., Aharonian, F., et al. 2011, *Exp. Astron.*, **32**, 193
 Aharonian F. A. 2000, *New Astron.*, **5**, 377
 Aharonian, F., Akhperjanian, A. G., Bazer-Bachi, A. R., et al. 2006a, *Nature*, **440**, 1081
 Aharonian, F., Akhperjanian, A. G., Bazer-Bachi, A. R., et al. 2006b, *Science*, **314**, 1424
 Aharonian, F., Akhperjanian, A. G., Barres de Almeida, U., et al. 2007, *A&A*, **475**, L9
 Aharonian, F. A., Kelner, S. R., & Prosekin, A. 2010, *Phy. Rev. D*, **82**, 043002
 Aharonian, F., Essey, W., Kusenko, A., & Prosekin, A. 2013, *Phy. Rev. D*, **87**, 063002
 Aliu, E., Archambault, S., Arlen, T., et al. 2014, *ApJ*, **782**, 13
 Atoyan, A., & Dermer, C. D. 2001, *Phys. Rev. Lett.*, **87**, 221102
 Berezhinsky, V., Gazizov, A. Z., & Grigorjeva, S. I. 2006, *Phy. Rev. D*, **74**, 043005
 Bloom S. D., & Marscher A. P. 1996, *ApJ*, **461**, 657
 Blumenthal, G. R. 1970, *Phys. Rev. D*, **1**, 1596
 Böttcher, M., & Dermer, C. D. 1998, *ApJ*, **501**, L51
 Cao, Z. 2010, *Chin. Phys. C*, **34**, 249
 Cerruti, M., Zech, A., Boisson, C., & Inoue, S. 2015, *MNRAS*, **448**, 910
 Chiang, J., & Böttcher, M. 2002, *ApJ*, **564**, 92
 Chodorowski, M. J., Zdziarski, A. A., & Sikora, M. 1992, *ApJ*, **400**, 181
 Costamante, L. 2013, *Inter. J. Mod. Phys. D*, **22**, 30025
 Costamante, L., Ghisellini, G., Giommi, P., et al. 2001, *A&A*, **371**, 512
 Costamante, L., Aharonian, F., Buhler, R., et al. 2008, in High Energy Gamma-ray Astronomy, eds. F. A. Aharonian, W. Hofmann, & E. Rieger (Melville, NY: AIP), *AIP Conf. Proc.*, **1085**, 644
 Cui, S. W., Liu, Y., Liu, Y. J., et al. 2014, *Astropart. Phys.*, **54**, 86
 Dai, Z. G., Zhang, B., Gou, L. J., et al. 2002, *ApJ*, **580**, L7
 de Angelis, A., Roncadelli, M., & Mansutti, O. 2007, *Phy. Rev. D*, **76**, 121301
 Dermer, C. D., & Menon, G. 2009, High Energy Radiation from Black Holes: Gamma Rays, Cosmic Rays, and Neutrinos
 Dermer, C. D., & Schlickeiser, R. 1993, *ApJ*, **416**, 458
 Dermer, C. D., Schlickeiser, R., & Mastichiadis, A. 1992, *A&A*, **256**, L27
 Dermer, C. D., Razzapue, S., Finke, J. D., & Atoyan, A. 2009, *New J. Phys.*, **11**, 065016
 Dimitrakoudis, S., Mastichiadis, A., Protheroe, R. J., & Reimer, A. 2012, *A&A*, **546**, A120
 Dwek, E., & Krennrich, F. 2005, *ApJ*, **618**, 657
 Dwek, E., & Krennrich, F. 2013, *Astropart. Phys.*, **43**, 112
 Essey, W., & Kusenko, A. 2010, *Astropart. Phys.*, **33**, 81
 Essey, W., Kalashev, O. E., Kusenko, A., & Beacom, J. F. 2010, *Phys. Rev. Lett.*, **104**, 141102
 Essey, W., Ando, S., Kusenko, A. 2011a, *Astropart. Phys.*, **35**, 135
 Essey, W., Kalashev, O. E., Kusenko, A., & Beacom, J. F. 2011b, *ApJ*, **731**, 51
 Fan, Y. Z., Dai, Z. G., & Wei, D. M. 2004, *A&A*, **415**, 483
 Finke, J. D., & Razaque, S. 2009, *ApJ*, **698**, 1761
 Franceschini, A., Rodighiero, G., & Vaccari, M. 2008, *A&A*, **487**, 837
 Ghisellini, G., & Madau, P. 1996, *MNRAS*, **280**, 67
 Ghisellini, G., Tavecchio, F., Maraschi, L., et al. 2014, *Nature*, **515**, 376
 Giommi, P., Ansari, S. G., & Micol, A. 1995, *A&AS*, **109**, 267
 Gould, R., & Schreder, G. 1966, *Phys. Rev. Lett.*, **16**, 252
 Greisen, K. 1966, *Phys. Rev. Lett.*, **16**, 748
 Hampf, D., Tluczykont, M., & Horns, D. 2011, Proc. of TEXAS 2010 Conf. in Heidelberg [[arXiv:1104.2336](https://arxiv.org/abs/1104.2336)]

- Inoue, Y., Kalashev, O. E., & Kusenko, A. 2013, *Astropart. Phys.*, **54**, 118
- Kalashev, O. E., Kusenko, A., & Essey, W. 2013, *Phys. Rev. Lett.*, **111**, 041103
- Katarzynski, K., Sol, H., & Kus, A. 2001, *A&A*, **367**, 809
- Kifune, T. 1999, *ApJ*, **518**, L21
- Kneiske, T. M., Bretz, T., Mannheim, K., & Hartmann, D. H. 2004, *A&A*, **413**, 807
- Konopelko, A., Mastichiadis, A., Kirk, J., de Jager, O. C., & Stecker, F. W. 2003, *ApJ*, **597**, 851
- Lefa, E., Rieger, F. M., & Aharonian, F. 2011, *ApJ*, **740**, L64
- Mannheim, K. 1993, *A&A*, **269**, 67
- Mannheim, K., & Biermann, P. L. 1992, *A&A*, **253**, L21
- Maraschi, L., Ghisellini, G., & Celotti, A. 1992, *ApJ*, **397**, L5
- Mastichiadis, A., & Kirk, J. G. 1995, *A&A*, **295**, 613
- Mastichiadis, A., & Kirk, J. G. 1997, *A&A*, **320**, 19
- Mastichiadis, A., Protheroe, R. J., & Kirk, J. G. 2005, *A&A*, **433**, 765
- Maximon, L. C. 1968, *J. Res. Natl. Bur. Std.*, **72**, 79
- Mazin, D., & Raue, M. 2007, *A&A*, **471**, 439
- Mücke, A., & Protheroe, R. 2001, *Astropart. Phys.*, **15**, 121
- Mücke, A., Protheroe, R. J., Engel, R., Rachen, J. P., & Stanev, T. 2003, *Astropart. Phys.*, **18**, 593
- Murase, K. 2012, *ApJ*, **745**, L16
- Murase, K., & Takami, H. 2009, *ApJ*, **690**, L14
- Murase, K., Dermer, C. D., Takami, H., & Migliori, G. 2012, *ApJ*, **749**, 63
- Neronov, A., Semikoz, D., & Taylor, A. M. 2012, *A&A*, **541**, A31
- Nikishov, A. 1962, *J. Exp. Theor. Phys.*, **14**, 393
- Persic, M., & Rephaeli, Y. 2014, *A&A*, **567**, A101
- Petropoulou, M. 2014, *MNRAS*, **442**, 3026
- Petropoulou, M., & Mastichiadis, A. 2015, *MNRAS*, **447**, 36
- Pohl, M., & Schlickeiser, R. 2000, *A&A*, **354**, 395
- Protheroe, R. J., & Meyer, H. 2000, *Phys. Lett. B*, **493**, 1
- Raiteri, C. M., Villata, M., Smith, P. S., et al. 2012, *A&A*, **545**, A48
- Romero, G. E., & Vila, G. S. 2008, *A&A*, **485**, 623
- Sanchez, D. A., Fegan, S., & Giebels, B. 2013, *A&A*, **554**, A75
- Sanchez-Conde, M. A., Paneque, D., Bloom, E., Prada, F., & Dominguez, A. 2009, *Phys. Rev. D*, **79**, 123511
- Sandoval, A., Alfaro, R., Belmont, E., et al. 2009, Fermi Symp., eConf Proc. C091122 [[arXiv:0912.3329](#)]
- Schlickeiser, R. 2002, *Cosmic Ray Astrophysics* (Berlin: Springer), 472
- Sikora, M., Begelman, M. C., & Rees, M. J. 1994, *ApJ*, **421**, 153
- Simet, M., Hooper, D., & Serpico, P. D. 2008, *Phys. Rev. D*, **77**, 063001
- Stecker, F. W., de Jager, O. C., & Salamon, M. H. 1992, *ApJ*, **390**, L49
- Stecker, F. W., Malkan, M. A., & Scully, S. T. 2006, *ApJ*, **648**, 774
- Sobolewska, M. A., Siemiginowska, A., Kelly, B. C., & Nalewajko, K. 2014, *ApJ*, **786**, 143
- Takami, H., Murase, K., & Dermer, C. D. 2013, *ApJ*, **771**, L32
- Tavecchio, F., Ghisellini, G., Foschini, L., et al. 2010, *MNRAS*, **406**, L70
- Urry, C. M. 1998, *Adv. Space Res.*, **21**, 89
- Urry, C. M., & Padovani, P. 1995, *PASP*, **107**, 803
- Venters, T. M. 2010, *ApJ*, **710**, 1530
- Vovk, I., Taylor, A. M., Semikoz, D., & Neronov, A. 2012, *ApJ*, **747**, L14
- Wagner, R. M. 2008, *MNRAS*, **385**, 119
- Woo, J. H., Urry, C. M., van der Marel, R. P., Lira, P., & Maza, J. 2005, *ApJ*, **631**, 762
- Wu, Z. Z., Jiang, D. R., Gu, M. F., & Liu, Y. 2007, *A&A*, **466**, 63
- Yang, C. Y., Fang, J., Lin, G. F., & Zhang, L. 2008, *ApJ*, **682**, 767
- Zatsepin, G. T., & Kuzmin, V. A. 1966, *J. Exp. Theor. Phys. Lett.*, **4**, 78
- Zheng, Y. G., & Kang, T. 2013, *ApJ*, **764**, 113
- Zheng, Y. G., & Zhang, L. 2011, *ApJ*, **728**, 105