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THE HADRONIC ORIGIN OF THE HARD GAMMA-RAY SPECTRUM FROM BLAZAR 1ES 1101-232

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ABSTRACT

The very hard γ-ray spectrum from distant blazars challenges the traditional synchrotron self-Compton (SSC) model, which may indicate that there is a contribution from an additional high-energy component beyond the SSC emission. In this paper, we study the possible origin of the hard γ-ray spectrum from distant blazars. We develop a model to explain the hard γ-ray spectrum from blazar 1ES 1101-232. In the model, the optical and X-ray radiation would come from the synchrotron radiation of primary electrons and secondary pairs and the GeV emission would be produced by the SSC process, however, the hard γ-ray spectrum would originate from the decay of neutral pion produced through proton–photon interactions with the synchrotron radiation photons within the jet. The model can explain the observed spectral energy distribution of 1ES 1101-232 well, especially the very hard γ-ray spectrum. However, our model requires a very large proton power to efficiently produce the γ-ray through proton–photon interactions.

Key words: BL Lacertae objects: individual (1ES 1101-232) – galaxies: active – galaxies: jets – radiation mechanisms: non-thermal

Online-only material: color figures

1. INTRODUCTION

Blazars are a special subclass of active galactic nuclei (AGNs) with a relativistic jet oriented at a small angle with respect to the line of sight. They usually show extreme variability, a high degree of polarization, and a strong non-thermal continuum in the optical/ultraviolet (UV) bands. Blazars can be divided into two subclasses: flat-spectrum radio quasars (FSRQs) and BL Lac objects. BL Lacs are characterized by a lack of or weak emission lines, while FSRQs usually present strong, broad emission lines. The spectrum energy distributions (SEDs) of blazars are dominated by non-thermal emission and consist of two distinct, broad components: a low-energy component from the radio through UV or X-ray and a high-energy component from the X-ray to γ-ray. It is widely believed that the low-energy component of blazar SEDs is synchrotron emission from relativistic electrons in the jet, whereas the origin of the high-energy component is still a matter of debate. There are two classes of models to explain the high-energy emission: the leptonic model and the hadronic model. In the leptonic model, the high-energy emission is produced by inverse Compton scattering of electrons on a photon field (e.g., Böttcher 2007). Possible soft photons are the synchrotron photons produced within the jet (the synchrotron self-Compton, SSC, process; Maraschi et al. 1992; Bloom & Marscher 1996; Zhang et al. 2012) or the photons external to the jet (the External Compton process; Dermer & Schlickeiser 1993; Sikora et al. 1994; Bläzejewski et al. 2000), such as the accretion disk, the broad-line region, or the external torus. In the hadronic model, the high-energy emission is produced by proton synchrotron or secondary emission from proton–proton (pp) and proton–photon interactions (Mannheim 1993; Phol & Schlickeiser 2000; Mücke et al. 2003).

To data, more than 40 blazars have been detected in the TeV band; most of these objects are high-frequency-peaked BL Lac objects (HBLs). The primary TeV photons from distant blazars are absorbed due to pair production by interacting with the extragalactic background light (EBL) photons (Gould & Schreder 1966) and the intrinsic TeV spectrum is harder than observed one. The TeV emission from HBLs can generally explained well by the standard SSC model. However, the observations of blazars with very hard γ-ray spectra from some HBLs present a challenge to the standard SSC model. One characteristic case is the very high-energy (VHE) γ-ray emission from the distant blazar 1ES 1101-232, which is detected by the H.E.S.S. array of Cherenkov telescopes (Aharonian et al. 2006, 2007a). The VHE γ-ray data imply a very hard intrinsic spectrum with a peak in the SED above 3 TeV and a photon index Γ_{int} ≲ 1.5, even when corrected by absorption for the lowest EBL level (Aharonian et al. 2007a). A similar behavior has also been detected in the TeV blazar 1ES 0229+200 (Aharonian et al. 2007b), Mrk 501 (Neronov et al. 2012), and 1ES 0414+090 (Abramowski et al. 2012). It is very difficult to produce such hard γ-ray spectra in the context of the one-zone SSC scenario. The standard shock acceleration theory predicts an electron spectrum with index p ≥ 2, which corresponds to an intrinsic photon index Γ_{int} ≥ 1.5. On the other hand, the suppression of scattering cross section at high energies due to the Klein–Nishina effect would make the γ-ray spectrum steeper.

Recently, Sahu et al. (2013a) studied the orphan TeV flare of 1ES 1959+650 based on the hadronic model and they explained this orphan TeV flare as the decay of neutral pions from the pp interactions with the low-energy tail of SSC photons. The decay of neutral pions is also applied to explain the multi-Tev γ-ray emission from the Centaurus A and M87 (Sahu et al. 2012, 2013b). Mastichiadis et al. (2013) studied the X-ray and γ-ray variability of Mrk 421 using the leptohadronic model and they suggested that the model based on pion decay can produce the quadratic variability between the X-ray and TeV band in a much more natural way. Moreover, the H.E.S.S. observation of 1ES 1101-232 shows no evidence for significant variability on any timescale. The hard γ-ray spectrum may indicate that...
there is the contribution of an additional spectral component beyond the common SSC emission. It is possible that the hard γ-ray spectrum has a hadronic origin. Motivated by the above arguments, in this paper we study the possible origin of the hard spectrum for a distant TeV blazar. We suggest that the hard γ-ray spectrum for the blazar 1ES 1101-232 may originate from the decay of neutral pions produced through proton–photon interactions with the synchrotron photons within the jet.

In Section 2, we give a brief description of the model. In Section 3, we apply the model to explain the very hard TeV interactions with the synchrotron photons within the jet. Throughout this paper, we adopt the cosmological parameters of $H_0 = 70 \text{km s}^{-1} \text{Mpc}^{-1}$, $\Omega_M = 0.3$, and $\Omega_L = 0.7$.

2. MODEL

2.1. SSC Emission

The SSC model has been successfully used to explain the multi-band SEDs of blazars. We use the model given by Finke et al. (2008) to calculate synchrotron and SSC flux. We assume a spherical blob of the jet moving with Lorentz factor $\Gamma$ at a small angle $\theta$ with the line of sight, which is filled by relativistic electrons with a uniform magnetic field. The observed radiation is strongly boosted by a Doppler factor $\delta_D = [\Gamma (1 - \beta \cos \theta)]^{-1}$. Since blazar jets are almost aligned with the line of sight of the observer, we assume a Doppler factor $\delta_D \simeq 1$. Throughout the paper, unprimed quantities refer to the observer’s frame and primed quantities refer to the frame of the blob.

We adopt a broken power-law function with a sharp cutoff to describe the electron energy distribution in the emission region:

$$N_e(y') = \begin{cases} \frac{K_e y'^{-n_1}}{y'^0}, & y' \leq y'_0, \\ \frac{K_e y'^{m_2 - n_1}}{y'^0}, & y' > y'_0, \end{cases}$$

(1)

where $y'_0$ is energy, $K_e$ is the normalization factor, and $n_1$ and $n_2$ are the electron power-law indexes below and above the break energy $y'_0$, respectively.

2.2. Secondary Emission from the Proton–Photon Interactions

The variable and non-thermal high-energy emission from blazars implies that the jet of blazars can efficiently accelerate particles to VHE by Fermi shock acceleration. The electron acceleration is limited by important radiative loss; protons should be accelerated with higher efficiency and can reach VHE by the same acceleration mechanisms. If protons are accelerated to sufficient high energy to reach the threshold for proton–photon interactions, the high-energy protons interact with the jet synchrotron photons to produce pions. The charged pions would decay to produce the neutrinos and secondary electrons/positrons. The neutrinos from the charged pions could be detected in neutrino telescopes, such as IceCube (Abbasi et al. 2011). Decay of neutral pions would result in high-energy γ-ray emission, which is directly observed by ground-based telescopes up to the TeV energy. Also, a correlation between the low-energy and high-energy bump is not necessary. On the other hand, the decay of neutral pions from proton–photon interactions would describe the high-energy bump of blazar SEDs.

The pion production channels through the $p\gamma$ interactions are

$$p + \gamma \rightarrow \begin{cases} p + \pi^0, \\ n + \pi^+, \end{cases}$$

(2)

The relevant pion decay channels are

$$\pi^+ \rightarrow \mu^+ + \nu_\mu + e^+ + \nu_e + \pi^0 + \nu_\mu,$$

(3)

$$\pi^0 \rightarrow \gamma + \gamma.$$  

(4)

The threshold condition for the $p\gamma$ interactions is given by (Kelner & Aharonian 2008)

$$2E_p \epsilon_p(1 - \beta_p \cos \theta) = (2m_n m_p + m_\pi^2)c^4,$$

(5)

where $E_p$ and $\epsilon_p$ are the proton and soft photon energy in the comoving frame, respectively. For high-energy protons, we set $\beta_p \simeq 1$. In the case of a head-on collision ($\theta = \pi$), Equation (5) implies:

$$E_p \epsilon_p \simeq 0.07 \text{GeV}^2.$$  

(6)

In the single-pion production channels, each pion carries ~0.2 of proton energy. Considering that each $\pi^0$ decay into two γ-ray photons, the observed γ-ray energy from $\pi^0$ decay is

$$E_\gamma = \frac{\delta_D}{10 + z} E_p.$$  

(7)

We follow the method of Atoyan & Dermer (2003) to calculate the spectrum from $\pi^0$ decay. The cooling rate due to the $p\gamma$ interactions with the synchrotron radiation field is given by (Stecker 1968)

$$t^{-1}_{p\gamma,\pi}(y') = \frac{c}{2y'^2_\gamma} \int_{\frac{E_\gamma}{y'_0}}^\infty d\epsilon'_\gamma \frac{n'_\pi(\epsilon'_\gamma)}{\epsilon'_\gamma} \int_{\epsilon'_\gamma_0}^{2\epsilon'_\gamma} d\epsilon' \sigma_{p\gamma}(\epsilon') K_{p\gamma}(\epsilon'E'),$$

(8)

where $\epsilon'_\gamma = 145 \text{ MeV}$ is the photon threshold energy and $n'_\pi$ is the number density of the synchrotron radiation given by Finke et al. (2008). The cross section $\sigma_{p\gamma}(\epsilon')$ is approximately given by (Atoyan & Dermer 2003; Reynoso & Romero 2009)

$$\sigma_{p\gamma}(\epsilon') = \frac{3.4 \times 10^{-28} \text{cm}^2 \Theta(\epsilon' - 200 \text{MeV})\Theta(500 \text{MeV} - \epsilon')} + 1.2 \times 10^{-28} \text{cm}^2 \Theta(\epsilon' - 500 \text{MeV})$$

(9)

and the inelasticity coefficient is

$$K_{p\gamma}(\epsilon'E') = 0.2 \Theta(\epsilon' - 200 \text{MeV})\Theta(500 \text{MeV} - \epsilon') + 0.6 \Theta(\epsilon' - 500 \text{MeV}).$$  

(10)

The corresponding collision rate is given by a similar expression:

$$\omega_{p\gamma,\pi}(y'_p) = \frac{c}{2y'^2_\gamma} \int_{\frac{E_\gamma}{y'_0}}^\infty d\epsilon'_\gamma \frac{n'_\pi(\epsilon'_\gamma)}{\epsilon'_\gamma} \int_{\epsilon'_\gamma_0}^{2\epsilon'_\gamma} d\epsilon' \sigma_{p\gamma}(\epsilon') E'',$$

(11)

The photon emissivity from $\pi^0$ decay in the $\delta$-function approximation given by (Atoyan & Dermer 2003; Romero & Vila 2008):

$$j'(E'_\gamma) = 20N_p(10E'_\gamma)\omega_{p\gamma,\pi}(10E'_\gamma)n'_{\pi^0}(10E'_\gamma),$$

(12)

where $n'_{\pi^0} = p_1/2 + p_2$ is the mean number of neutral pions created per collision, $p_1$ and $p_2 = 1 - p_1$ are possibilities that the $p\gamma$ interacts in single-pion and multi-pion channels, respectively, and $N_p$ is the proton energy distribution. We can define a mean inelasticity as $K_{p\gamma,\pi} = t^{-1}_{p\gamma,\pi}(y'_p)\omega_{p\gamma,\pi}(y'_p)$. Then, the possibilities $p_{1,2}$ can be calculated from the relation of
where \( p_1 = (K_2 - K_{\gamma})/(K_2 - K_1) \), where \( K_1 = 0.2 \) and \( K_2 = 0.6 \). Taking into account the relativistic and cosmological effects, we obtain the observed flux from the secondary emission as (Lind & Blandford 1985)

\[
F(E_\gamma) = \frac{\delta_2^4 (1 + z) V'}{d_L^2} \frac{\nu_\gamma}{E_\gamma^{\prime} \beta_2} \frac{E_\gamma^{\prime}}{e^{-\beta_2 E_\gamma^{\prime}}},
\]

where \( z \) is the redshift of the source, \( d_L \) is the luminosity distance, \( V' \) is the volume of the emission region, and \( E_\gamma^{\prime} = \delta_2 E_\gamma^{\prime}/(1 + z) \) is the photon energy in the observed frame.

The emissivity of secondary pairs can be estimated in the same way. Both in the single-pion and multiple-pion channel, each charged pion has an energy \( \sim 0.2 E_p \). This energy is equally distributed among the products of its decay, hence the energy of each electron/positron is \( E_e \sim 0.05 E_\gamma^{\prime} \). The emissivity of secondary pairs is given by (Romero & Vila 2008):

\[
Q'(E_e^{\prime}) = 20N_p'(20E_e^{\prime})\omega_{\nu_{\gamma},\gamma}(20E_e^{\prime})n_p^{\prime}(20E_e^{\prime}),
\]

where \( n_p^{\prime} = p_1/2 + 2p_2 \) is the mean number of charged pions created per collision. If we neglect the electron escape, the steady electron distribution can be calculated as

\[
N'(E_e^{\prime}) = 4\pi \left( \frac{dE_e^{\prime}}{dt} \right)^{-1} \int_{E_e^{\prime}}^{E_{e,\text{max}}} dE' Q'(E_e^{\prime}),
\]

where \( (dE_e^{\prime}/dt) = (4/3)c\sigma_T \gamma_e^3 U_B \) is the electron energy loss rate and \( U_B = (B^2/8\pi) \) is the magnetic energy density. In the following, we use the method of Finke et al. (2008) to calculate the synchrotron radiation from the secondary electrons.

Protons should be co-accelerated together with electrons by the Fermi acceleration mechanism, which predicts the particle distribution index \( \alpha > 2 \). We adopt the proton injection spectrum with an exponential cutoff power law:

\[
N_p = N_0 E_p^{\prime - \alpha} \exp(-E_p^{\prime}/E_{p,\text{min}}), \quad E_p^{\prime,\text{min}} \leq E_p^{\prime} \leq E_p^{\prime,\text{max}},
\]

where \( N_0 \) is the initial proton distribution. In our calculation, we assume that the proton injection index is \( \alpha = 2.2 \) and that the minimum energy of the injection proton is \( E_{p,\text{min}} = 145 \text{ MeV} \), which is the threshold energy of proton–photon interactions.

3. APPLICATIONS

1ES 1101-232 resides in an elliptical galaxy at a redshift of \( z = 0.186 \) (Remillard et al. 1989). The source has been detected by a range of X-ray instruments in both the soft and hard X-ray bands (Wolter et al. 2000; Reimer et al. 2008). It has been classified as an HBL object due to its synchrotron peak in the X-ray band (Donato et al. 2001). Wolter et al. (2000) and Costamante & Ghisellini (2002) predicted that 1ES 1101-232 is a very promising candidate for TeV detection. Motivated by these predictions, Aharonian et al. (2007a) performed coordinated optical–X-ray–VHE \( \gamma \)-ray observation in 2004 and 2005, which resulted in the discovery of VHE \( \gamma \)-ray. Taking the VHE data from the H.E.S.S. observation, together with measurements in the X-ray and optical bands, Aharonian et al. (2007a) constructed the truly simultaneous SED of 1ES 1101-232 from the optical to the VHE band in 2004 and 2005. However, no simultaneous GeV observation was performed in this multi-wavelength campaign. The GeV data are important to constrain the radiation model of blazars. In the GeV band, EGRET did not detect emission from 1ES 1101-232 (Lin et al. 1996). The detections of 1ES 1101-232 were also not reported in the Large Area Telescope (LAT) Bright Active Galactic Nuclei Source List (Abdo et al. 2009). Fermi-LAT reported the significant detections of 1ES 1101-232 in the First LAT AGN Catalog (Abdo et al. 2010a) and in the Second LAT AGN Catalog (Ackermann et al. 2011). However, only the flux upper limits are available from the literature (Neronov & Vovk 2010; Tavecchio et al. 2010). Finke et al. (2013) analyzed the Fermi-LAT 3.5 yr data collected from 2008 August to 2012 February and reported the GeV spectrum of 1ES 1101-232. The previous SSC model indicated that the IC peak is expected to be around 100 GeV (Wolter et al. 2000; Costamante & Ghisellini 2002). However, new observational results from H.E.S.S. indicate that the source shows a hard VHE spectrum with a peak in the SED above 3 TeV, when corrected by absorption for the lowest EBL level (Aharonian et al. 2007a). In this paper, we use simultaneous SEDs of 1ES 1101-232 collected by Aharonian et al. (2007a) in 2004 and 2005 and the GeV data given by Finke et al. (2013).

We use the model described in Section 2 to model the simultaneous SED of 1ES 1101-232 in 2004 June and 2005 March. The observed data are taken from Aharonian et al. (2007a) and Finke et al. (2013). The VHE data are corrected for the EBL absorption considering the low EBL level, as described in Aharonian et al. (2007a). The modeling parameters are listed in Tables 1 and 2. It can be found that the Poynting flux power \( L_B \) is slightly larger than the electron power \( L_e \), the relativistic proton power \( L_p \) is far larger than the Poynting flux \( L_B \), and the total jet power is dominated by relativistic protons. Our model requires the extreme proton power \( L_p \gtrsim 10^{52} \text{ erg s}^{-1} \) to produce the \( \gamma \)-ray through the proton–photon interactions efficiently. Böttcher et al. (2013) used the leptonic and hadronic models to fit the observed SED of a set of Fermi-LAT-detected blazars and they also showed that the hadronic model usually requires extreme jet powers, in some case exceeding \( 10^{49} \text{ erg s}^{-1} \) in relativistic protons. The corresponding SED modeling is

### Table 1

| Parameters | 2005       | 2004       |
|------------|------------|------------|
| \( \gamma_{\text{min}} \) | \( 1 \times 10^{2} \) | \( 1 \times 10^{3} \) |
| \( n_0 \) | \( 1 \times 10^{5} \) | \( 9.5 \times 10^{4} \) |
| \( \gamma_{\text{max}} \) | \( 2 \times 10^{7} \) | \( 2 \times 10^{7} \) |
| \( K_e (\text{cm}^{-3}) \) | 54.1 | 103.3 |
| \( \alpha \) | 2 | 2 |
| \( n_1 \) | 4 | 3.4 |
| \( \delta_2 \) | 0.4 | 0.38 |
| \( c (\text{cm}^{2} \text{s}^{-1}) \) | \( 4.0 \times 10^{16} \) | \( 2.8 \times 10^{16} \) |
| \( L_e (\text{erg s}^{-1}) \) | \( 1.9 \times 10^{43} \) | \( 8.7 \times 10^{43} \) |
| \( L_B (\text{erg s}^{-1}) \) | \( 2.2 \times 10^{44} \) | \( 9.5 \times 10^{43} \) |

### Table 2

| Parameters | 2005       | 2004       |
|------------|------------|------------|
| \( E_{p,\text{min}} (\text{eV}) \) | \( 1.45 \times 10^{8} \) | \( 1.45 \times 10^{9} \) |
| \( E_{p,\text{max}} (\text{eV}) \) | \( 1 \times 10^{14} \) | \( 1 \times 10^{14} \) |
| \( E_e^\prime (\text{eV}) \) | \( 2.8 \times 10^{12} \) | \( 2.8 \times 10^{12} \) |
| \( N_0 (\text{eV}^{-1} \text{cm}^{-3}) \) | \( 5.0 \times 10^{30} \) | \( 9.3 \times 10^{32} \) |
| \( \alpha \) | 2.2 | 2.2 |
| \( L_e (\text{erg s}^{-1}) \) | \( 2.7 \times 10^{83} \) | \( 2.4 \times 10^{52} \) |
Figure 1. SED of 1ES 1101-232 on 2005 March 5–16. The blue circles are the simultaneous optical, X-ray, and TeV data. The LAT spectrum is shown as the bowtie. The blue solid curves represent the synchrotron and SSC emission, respectively (from left to right). The blue dot-dashed curve represents the synchrotron emission from the secondary pairs. The blue dashed curve represents the secondary emission from the \( \pi^0 \) decay. The red solid curve is the total emission from the all-spectrum components. (A color version of this figure is available in the online journal.)

shown in Figures 1 and 2. It can be seen that the optical and X-ray radiation comes from the synchrotron radiation of primary electrons and secondary pairs and that the GeV emission is produced by the SSC process. The hard TeV emission originates from the \( \pi^0 \) decay produced through proton–photon interactions with the synchrotron photons. Our model can reproduce the observed SED of 1ES 1101-232 well, particularly the very hard \( \gamma \)-ray spectrum. In our model, the energy of secondary pairs is \( E_{\gamma}^{\prime} \simeq 0.05E_p^{\prime} \simeq 0.14 \) TeV and the corresponding synchrotron frequency in the observed frame is \( \nu_c = 1.4 \times 10^{18}(B/0.4)(d_D/15) \) Hz, which could not contribute to the GeV and TeV emission. Moreover, the synchrotron emission from secondary pairs makes a small contribution to the optical and X-ray flux compared with that from the primary electrons.

We can estimate the proton energy through the observed VHE \( \gamma \)-ray energy. For the source 1ES 1101-232, the highest photon energy is \( E_{\gamma} \sim 3.7 \) TeV. From Equation (7), we can obtain that the proton energy in the comoving frame is \( E_p^{\prime} \sim 2.9 \) TeV, which is comparable with the value derived from our SED modeling. This value in the observed frame is \( E_p \sim 37 \) TeV, if the proton can escape the source and reach the observer without energy loss. Therefore, the observed proton energy is \( E_p \simeq 37 \) TeV. The observed \( \gamma \)-ray energy is in the range \( 0.36 \) TeV \( \lesssim E_{\gamma} \lesssim 3.70 \) TeV. Using Equations (6) and (7), we can obtain that the corresponding target photon energy in proton–photon interactions is in the range \( 7.19 \times 10^{19} \) Hz \( \lesssim \nu_{ph} \lesssim 7.31 \times 10^{20} \) Hz, which exactly falls in the high-energy part of the synchrotron spectrum; the SSC flux in this energy range is negligible compared with the synchrotron flux. This indicates that the hard \( \gamma \)-ray spectrum may come from the \( \pi^0 \) decay produced through proton–photon interactions with the synchrotron photons. It should be noted that the target photon energy of proton–photon interactions lies in the low-energy tails of the SSC spectrum in the papers by Sahu et al. (2012, 2013a, 2013b), rather than the synchrotron photons. Moreover, the hard X-ray emission at an energy of \( \gtrsim 100 \) KeV has been detected by the Swift Burst Alert Telescope in several TeV blazars (Abdo et al. 2011a, 2011b). Kaufmann et al. (2011) presented hard X-ray observations of the TeV blazar 1ES 0229+200, showing that the X-ray spectrum is extended up to \( \sim 100 \) KeV without any significant cutoff. It is possible that the hard \( \gamma \)-ray spectrum originates in the \( \pi^0 \) decay produced through proton–photon interactions with the high-energy parts of the synchrotron photons within the jet.

The efficiency of the proton–photon interaction depends on the density and distribution of the target photons. In our model, the high-energy proton efficiently interacts with the high-energy parts of the synchrotron photons to produce the \( \gamma \)-rays. Therefore, the efficiency of the proton–photon interactions depends on the distribution of the synchrotron photons.
However, the distribution of the synchrotron photons in turn depends on the maximum Lorentz factor $\gamma_{\text{max}}$. In Figure 3, we show the modeling spectrum with various values of the maximum Lorentz factor $\gamma'_{\text{max}}$. It can be seen that the synchrotron flux at high energies decreases with decreasing maximum Lorentz factor, which results in a decreasing efficiency of the $\gamma$-ray production through the proton–photon interactions. Our model requires the maximum Lorentz factor $\gamma'_{\text{max}} \geq 2 \times 10^7$ in order to fit the hard $\gamma$-ray spectrum from the blazar 1ES 1101-232. The acceleration timescale of electrons is $t_{\text{acc}} = \eta \left( \gamma' m_e c / eB \right)$. The synchrotron cooling timescale is $t_{\text{syn}} = (6\pi m_e c / \sigma_T \gamma' B^2)$. Then, the maximum Lorentz factor $\gamma'_{\text{max}}$ can be determined by the condition $t_{\text{acc}} = t_{\text{syn}}$, as

$$\gamma'_{\text{max}} \approx 7 \times 10^7 \left( \frac{B}{0.4} \right)^{-\frac{1}{2}} \left( \frac{\eta}{10} \right)^{-\frac{1}{2}}.$$  \hspace{1cm} (17)

Hence, the required maximum Lorentz factor $\gamma'_{\text{max}} \geq 2 \times 10^7$ is achievable by the Fermi acceleration mechanism in the jet of the blazar 1ES 1101-232.

4. DISCUSSION AND CONCLUSIONS

$pp$ interactions with ambient matter can produce TeV $\gamma$-rays, as has been proposed to explain the observed SEDs of blazars (Dar & Laor 1997; Phol & Schlickeiser 2000; Beall & Bednarek 1999). However, the $pp$ interaction usually requires the high plasma density $n_{\text{H}} > 10^6 \text{ cm}^{-3}$ (Aharonian 2000); such a high density would not be expected in the environment of BL Lac objects due to small accretion rate. Therefore, the $pp$ interaction is less efficient than the $p\gamma$ interaction. Different theoretical models have been proposed to explain the hard $\gamma$-ray spectrum. Katarzynski et al. (2006) suggested that the hard $\gamma$-ray spectrum can be explained in the SSC scenarios by assuming a narrow distribution of high-energy electrons with the high low-energy cutoff. It is difficult to maintain such high low-energy cutoff because of the relevant radiation cooling at these energies. The internal absorption of the TeV $\gamma$-ray spectrum by a very narrow distribution of optical UV photons in the vicinity of an AGN can explain the observed hard $\gamma$-ray spectrum (Aharonian et al. 2008; Zacharopoulou et al. 2011). However, there is no indication for the presence of such narrow radiation fields in the vicinity of BL Lac objects. A two-component model has been proposed to explain the observed SED of 1ES 1101-232 (Böttcher et al. 2008; Yan et al. 2012). In this model, the low-frequency emission is assumed to originate in the inner region of jet and the hard $\gamma$-ray spectrum can be produced via Compton upscattering of cosmic microwave background in an extend jet. However, this scenario requires that the electrons can be accelerated to TeV energy on kpc scales along the jet. The hard $\gamma$-ray spectrum can be explained by the secondary emission produced along the line of sight by the interactions of the cosmic ray protons with the background photons (Essey et al. 2010, 2011). In this scenario, low extragalactic magnetic fields (EGMFs) not larger than $10^{-15} \text{ G}$ are needed to avoid the significant deflection of cosmic ray protons and secondary electrons,
but the strength of EGMFs along with the line of sight remains large uncertain. On the other hand, the predicted secondary spectrum fits the hard TeV spectrum well only for the high-level EBL model of Stecker et al. (2006), which is excluded by the Fermi-LAT and H.E.S.S. results (Abdo et al. 2010b; Aharonian et al. 2006). Alternatively, new particles (de Angelis et al. 2007; Horns & Meyer 2012) and Lorentz invariance violation (Protheroe & Meyer 2000) have been invoked to explain the data.

A number of blazars are found to exhibit the correlated variability between the low-energy and VHE band. Several blazars have displayed minute-timescale variability in the TeV band (Aharonian et al. 2007c; Albert et al. 2007). No significant correlated variability between the optical/X-ray and γ-ray bands was observed from this source. At the same time, the VHE data from H.E.S.S. show no sign of variability on any timescale. This seemly supports a hadronic origin of the hard γ-ray spectrum from blazar 1ES 1101-232. In this paper, we study the possible origin of the hard γ-ray spectrum. We propose a model to explain the hard γ-ray spectrum from the blazar 1ES 1101-232. In this model, the optical and X-ray radiation comes from the synchrotron radiation of primary electrons and secondary pairs, in which the synchrotron radiation from the secondary pairs makes a small contribution to the optical and X-ray flux and the GeV emission is attributed to the SSC process. However, the hard γ-ray spectrum originates in the π⁰ decay produced through proton–photon interactions with the synchrotron photons within the jet. Assuming suitable electron and proton spectra, we obtain a excellent fit to the observed spectrum of blazar 1ES 1101-232. The very hard γ-ray spectrum can be explained well by secondary emission from the π⁰ decay in the source. However, our model requires extreme proton power in order to efficiently produce the γ-ray through proton–photon interactions. Neutrino populations can be expected in the pγ interaction; their observation will be the subject of future work.

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