GEV EMISSION FROM TEV BLAZARS AND INTERGALACTIC MAGNETIC FIELDS

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Abstract

Several high-frequency peaked BL Lac objects such as Mrk 501 are strong TeV emitters. However, a significant fraction of the TeV gamma rays emitted are likely to be absorbed in interactions with the diffuse IR background, yielding electron-positron pairs. Hence, the observed TeV spectrum must be steeper than the intrinsic one. Using the recently derived intrinsic $\gamma$-ray spectrum of Mrk 501 during its 1997 high state, we study the inverse-Compton scattering of cosmic microwave photons by the resulting electron-positron pairs, which implies the existence of a hitherto undiscovered GeV emission. The typical duration of the GeV emission is determined by the flaring activity time and the energy-dependent magnetic deflection time. We numerically calculate the scattered photon spectrum for different intergalactic magnetic field (IGMF) strengths, and find a spectral turnover and flare duration at GeV energies which are dependent on the field strength. We also estimate the scattered photon flux in the quiescent state of Mrk 501. The GeV flux levels predicted are consistent with existing EGRET upper limits, and should be detectable above the synchrotron — self Compton (SSC) component with the Gamma-Ray Large Area Space Telescope (GLAST) for IGMFs $\lesssim 10^{-16}$ G, as expected in voids. Such detections would provide constraints on the strength of weak IGMFs.

Subject headings: BL Lacertae objects: general — BL Lacertae objects: individual (Markarian 501) — diffuse radiation — gamma rays: theory — magnetic fields

1. Introduction

Blazars including high-frequency peaked BL Lac objects (HBLs) are the most extreme and powerful sources among active galactic nuclei. The standard blazar model consists of a supermassive black hole ejecting twin relativistic jets, one of which is close to the line of sight. Several HBLs such as Mrk 501, Mrk 421, PKS 2155-304, 1ES 2344+514, H1 426+428 and 1ES1959+650 are of particular interest because they emit TeV photons (see Catanese et al. 2002). The detection and study of such photons can provide new insights on the energetics and physical conditions in the emission regions of such blazars (Katarzyński, Sol \\& Kus 2001; Kino, Takahara \\& Kusunose 2002). Also, constraints on the spectral energy distribution of the intergalactic infrared background can be inferred from the observations on TeV photons (for a review see Hauser \\& Dwek 2001). Stecker, De Jager \\& Salamon (1992) have emphasized that the high-energy gamma photon spectra from these blazars will be modified by strongly redshift-dependent absorption effects due to interactions of such photons with the intergalactic infrared-UV background, and indicated that the intrinsic spectrum of an observed TeV blazar can be derived by evaluating the optical depth to TeV photons. Such calculations were made for Mrk 501 during the 1997 flaring activity, leading to an inferred intrinsic high-energy spectrum with a broad, flat peak that is much higher than the observed one in the $5-10$ TeV range (Konopelko et al. 1999; De Jager \\& Stecker 2002, hereafter DS). The physical reason for this difference is that a significant fraction of the original high-energy gamma rays have been absorbed in $\gamma\gamma$ interactions with photons of the intergalactic infrared-UV background, leading to electron/positron pairs.

The purpose of this Letter is to suggest that inverse Compton (IC) scattering of the resulting electron/positron pairs against cosmic microwave background (CMB) photons may produce a new GeV emission component in TeV blazars. For gamma-ray bursts, such Compton scattering leads to an observable, delayed MeV-GeV emission component if the intergalactic magnetic fields (IGMFs) are very weak (Plaga 1995; Cheng \\& Cheng 1996; Dai \\& Lu 2002). A similar phenomenon is also expected from gamma-ray burst proton interactions with the CMB (Waxman \\& Coppi 1996). Here we discuss the well-studied blazar Mrk 501, both because the high-energy spectrum up to 20 TeV of strong flares of this blazar in 1997 has been observed by the HEGRA air Cerenkov telescope system (Aharonian et al. 1999, 2001), and because the intrinsic spectrum of Mrk 501 over two decades of energy has been derived based on the consistency between the Whipple telescope and HEGRA spectra (DS).

The strength of IGMFs has not been determined so far. Faraday rotation measures imply an upper limit of $\sim 10^{-9}$ G for a field with 1 Mpc correlation length (Kronberg 1994 for a review). Other methods were proposed to probe fields in the range $10^{-10}$ G to $10^{-20}$ G (Lee, Olinto \\& Sigl 1995; Plaga 1995). To interpret the observed $\mu$G magnetic fields in galaxies and X-ray clusters, the seed fields required in dynamo theories could be as low as $10^{-20}$ G (Kulsrud et al. 1997; Kulsrud 1999). Furlanetto \\& Loeb (2001) argued that quasar outflows may pollute the intergalactic medium, but the possible weak IGMFs in voids may remain uncontaminated. Theoretical calculations of primordial magnetic fields show that these fields could be...
of order $10^{-20}$ G or even as low as $10^{-29}$ G, generated during the cosmological QCD or electroweak phase transition respectively (Sigl, Olinto & Jedamzik 1997). In this Letter we propose that by observing a hitherto undiscovered GeV emission component from flares of TeV blazars such as Mrk 501, one may be able to obtain important information or constraints on the poorly known IGMFs.

2. PROPERTIES OF EXTERNAL IC EMISSION

We consider a strong flare, e.g. in Mrk 501, of duration $t_{\text{var}}$. A fraction of the high-energy $\gamma$-rays emitted during such a flare can be absorbed in the cosmic background radiation fields as these $\gamma$-rays travel towards the observer. The pair production optical depth $\tau_{\gamma\gamma}^{\text{opt}}$ depends strongly on the $\gamma$-ray energy ($E_\gamma$) and the redshift ($z$). DS numerically calculated $\tau_{\gamma\gamma}^{\text{opt}}$ as a function of the photon energy for low redshifts by using the models of Malkan & Stecker (2001) of the infrared background radiation, and extrapolating these models into the optical-UV range in terms of recent galaxy count data. DS considered both “fast evolution” and “baseline” cases, which may be considered to bracket the spectral energy distribution of the intergalactic infrared-UV background radiation. If primary photons of energy $E_\gamma$ are absorbed, the resulting electron/positron pairs have Lorentz factors $\gamma_e \simeq E_\gamma / (2m_e c^2) = 10^6 (E_\gamma / \text{1 TeV})$, where $m_e$ is the electron mass. The pairs will subsequently Compton scatter on the ambient CMB photons. As a result, the initial energy of a microwave photon, $\tilde{\epsilon}$, is boosted by IC scattering up to an average value $\sim \gamma_e^2 \tilde{\epsilon} \simeq 0.63 (E_\gamma / \text{1 TeV})^2 \text{ GeV}$, where $\epsilon = 2.7kT$ is the mean energy of the CMB photons with $T \simeq 2.73K$ and $k$ is the Boltzmann constant.

2.1. The GeV Emission Duration

Several timescales are involved in the emission process. The first is the well-known angular spreading time, $\Delta t_A \simeq R_{\text{pair}} / (2\gamma_e c) = 96 (\gamma_e/10^6)^{-2} (n_{\text{IR}}/1 \text{ cm}^{-3})^{-1} \text{s}$, where $R_{\text{pair}} = (0.26 \sigma_T n_{\text{IR}})^{-1} \simeq 5.8 \times 10^{24} (n_{\text{IR}}/1 \text{ cm}^{-3})^{-1}$ cm is the typical pair-production distance, $\sigma_T$ is the Thomson cross section, and $n_{\text{IR}}$ is the infrared photon number density (see Dai & Lu 2002). Therefore, primary TeV photons have a typical mean free path of a few Mpc, so that although the source may be in a region of a high field with $\sim 10^{-9}$ G, these photons may escape to much lower field regions. Six TeV blazars detected so far have redshifts of $\sim 0.03$ to $\sim 0.1$, implying that their luminosity distances are much larger than $R_{\text{pair}}$. Only in such cases are our calculations valid.

The IC cooling timescale (in the local rest frame) of relativistic electrons with Lorentz factor of $\gamma_e$ is $t_{\text{IC}} = 3 m_e c / (4 \pi \gamma_e \sigma_T u_{\text{ cmb}}) = 7.3 \times 10^{33} (\gamma_e/10^6)^{-1} \text{s}$, where $u_{\text{ cmb}}$ is the CMB energy density. Thus the typical flight path, in which most of the electron energy is lost, is $A_{\text{IC}} \simeq c t_{\text{IC}} = 2.2 \times 10^{23} (\gamma_e/10^6)^{-1} \text{ cm}$. This is much less than the distance from the source to the observer, implying that energy loss of the electron due to IC scattering is local. In the absence of any IGMF, the IC cooling timescale in the observer frame would be $\Delta t_{\text{IC}} \simeq t_{\text{IC}} / (2\gamma_e^2) = 37 (\gamma_e/10^6)^{-3} \text{s}$.

In the presence of IGMFs with strength $B_{\text{IG}}$, the electrons will be deflected. The deflection angle is estimated by $\theta_B \simeq A_{\text{IC}} / R_L = 1.3 \times 10^{-5} (\gamma_e/10^6)^{-2} (B_{\text{IG}}/10^{-20} \text{G})$, where $R_L = \gamma_e m_e c^2 / (4 B_{\text{IC}}) = $ the Larmor radius of the electrons. The contribution to the emission time due to magnetic deflection becomes $\Delta t_B \simeq (1/2) t_{\text{IC}} \theta_B^2 \simeq 6.1 \times 10^4 \gamma_e/10^6)^{-3} (B_{\text{IG}}/10^{-20} \text{G})^2 \text{s}$, where $\theta_B \ll 1$. This may provide a probe of weak IGMFs and its application to the delayed high-energy emission of GRB 940217 yields IGMFs which are as weak as $B_{\text{IG}} \sim 10^{-20}$ G.

Therefore, the duration estimate of the IC emission from electron/positron pairs scattering off the CMB is $\Delta t = \max(\Delta t_A, \Delta t_B)$. Taking $\Delta t_B = t_{\text{var}}$, which implies a scattered photon energy $E_{\text{turn}} = 0.22 (B_{\text{IG}}/10^{-20} \text{G})^{4/5} (t_{\text{var}} / \text{1 day})^{-2/5} \text{GeV}$, we find that the duration of the expected GeV emission is always given by the variability timescale of the TeV gamma-ray flux for photon energies larger than $E_{\text{turn}}$, and it is given by $\Delta t_B$ for photon energies smaller than $E_{\text{turn}}$.

2.2. The Emission Spectrum

The optical depth ($\tau_{\gamma\gamma}^{\text{opt}}$) to high-energy photons was used by DS to derive the intrinsic $\gamma$-ray spectrum of Mrk 501 during its 1997 high state, which can be parameterized as

$$E_\gamma^2 dN_\gamma / dE_\gamma = KE_\gamma^{-\Gamma_1} \left[ 1 + \left( E_\gamma / E_B \right)^{\Gamma_1 - \Gamma_2} \right]^{(\Gamma_1 - \Gamma_2) / f},$$

where $E_\gamma = 1 (\gamma_e/10^6)$ TeV, and the parameters $E_B$ (in TeV), $K$ (in $10^{-10}$ ergs cm$^{-2}$ s$^{-1}$), $\Gamma_1$, $\Gamma_2$ and $f$ are shown in Table 3 of DS. Please note that equation (1) is a time-averaged spectrum of a long-term outburst of about 6 months in 1997. During this period Mrk 501 has shown a number of one-day flares, whose gamma-ray flux values appear to be larger than the time-averaged ones by a factor of $\eta$ with $1 \lesssim \eta \lesssim 3$. Thus, for accurate calculations of the GeV emission one should use the specific flux values for the flare considered. Here we take $\eta = 1$ as a conservative value. Letting the luminosity distance to the source be $D_L \simeq 5 \times 10^{26}$ cm, we have the total electron energy spectrum (including the positrons),

$$dN_{\gamma_e} / d\gamma_e = C E_{\gamma_e}^{-\Gamma_1} \left[ 1 + \left( E_\gamma / E_B \right)^{\Gamma_1 - \Gamma_2} \right]^{(\Gamma_1 - \Gamma_2) / f} \left( 1 - e^{-\tau_{\gamma\gamma}^{\text{opt}}} \right),$$

where $C = 5 \pi \times 10^{-6} D_L^2 K$. Therefore, the observed time-averaged scattered-photon spectrum is given by (Blumenthal & Gould 1979)

$$dN_{\gamma_e}^{\text{SC}} / dE_{\gamma_e} = 1 / 4 \pi D_L^2 \int \int \left( dN_{\gamma_e} / d\gamma_e \right) \left( dN_{\gamma_e} / dtt_{\text{IC}} \xi d\gamma_e \right) \left( f_{\gamma_e} / f \right),$$

where $\xi \equiv \Delta t / \Delta t_A$, $E_{\gamma_e}$ is the externally scattered photon energy, $t$ is the time measured in the local rest frame, and $dN_{\gamma_e} / dtt_{\text{IC}}$ is expressed by equation (2.48) of Blumenthal & Gould (1979) using the Klein-Nishina (KN) cross-section formula, is the spectrum of photons scattered by an electron with Lorentz factor of $\gamma_e$ from a segment of the CMB photon gas of differential number density $n(e) de$. If the electron energy spectrum is simplified as $\propto \gamma_e^{-8}$, then a primary analysis similar to Dai & Lu (2002) shows that in the Thomson limit the scattered photon spectrum $\propto E_{\gamma_e}^{-(\Gamma_1 + 3)/2}$ for $\Delta t_B (\gamma_e) \ll t_{\text{var}}$ and $\propto E_{\gamma_e}^{-(\Gamma_1 - 3)/2}$ for $\Delta t_B (\gamma_e) \gg t_{\text{var}}$, implying a spectral turnover at scattered photon energies of $\sim E_{\text{turn}}$. Figure 1 shows the energy...
spectra of scattered photons for different assumed IGMFs during the 1997 flaring activity of Mrk 501. For an IGMF \( \gtrsim 10^{-20} \) G, we indeed see a spectral turnover, whose energy is strongly dependent on the field strength. Figure 2 presents the emission spectra for different flare durations, and we find that for a fixed IGMF, the longer the duration, the smaller the turnover energy becomes and thus the emission becomes easier to detect.

3. COMPARISON WITH THE SSC SPECTRUM

The observed low-energy lump of Mrk 501 is usually thought to be due to synchrotron radiation from a relativistic plasma blob. The comoving spectral synchrotron photon energy density is given by

\[
u\gamma = \frac{2D_L^2\Phi}{\alpha_0^2} \left( \frac{e_{br}}{e_{pk}} \right) \left( \frac{\delta}{\delta_{\gamma}} \right)^{-\alpha_1+1} \left( \frac{\delta_{\gamma}}{\gamma_{\gamma}} \right)^{-\alpha_2+1},
\]

for \( \gamma_{\gamma} < \gamma_{\gamma}' \). Thus, the optical depth is

\[
\tau_{\gamma\gamma}^{\text{in}} = (11/180)\sigma_T n'(\gamma_{\gamma}'e_{\gamma})r_b,
\]

where \( \sigma_T \) is the averaged cross section assuming an \( F(\epsilon_{\gamma}) \propto \epsilon_{\gamma}^{-1} \) spectrum (Svensson 1987; also see Lithwick & Sari 2001 and Zhang & Mészáros 2001). Inserting equation (4) into the above equation yields

\[
\tau_{\gamma\gamma}^{\text{in}} = \hat{\tau}(E_{\gamma}/m_e c^2)^{\alpha_1} \delta^{-2\alpha_1-4},
\]

for \( \alpha_1 = \alpha_2 = 1 \), equation (5) becomes \( \tau_{\gamma\gamma}^{\text{in}} \propto \delta^{-6} \), which is consistent with the previously used optical depth (see Aharonian et al. 1999; DS). Inserting the observed values of the parameters into equations (5) and (6), we have \( \tau_{\gamma\gamma}^{\text{in}} \gtrsim 0.015(E_{\gamma}/1 \text{ TeV})^{1/4}(\delta/10)^{-4.8}(t_{\text{var}}/1 \text{ day})^{-1} \). The observed highest energy \( E_{\gamma} \approx 20 \) TeV implies that the optical depth to a photon with such an energy is less than unity. This provides a lower limit to the Doppler factor \( \delta \gtrsim 5.4(E_{\gamma}/20 \text{ TeV})^{1/12}(t_{\text{var}}/1 \text{ day})^{-1/4.8} \), i.e., the photon-energy cutoff due to pair production in the blob can be larger than 20 TeV for \( \delta > 5.4 \).

3.2. The SSC Spectrum

We next discuss the SSC spectrum from the blob. We assume the accelerated electrons in the blob to have a power-law energy distribution with an index of \( p \) and the maximum Lorentz factor of \( \gamma_M \). We also assume that the magnetic field strength in the blob is \( B' \). Since the synchrotron peak of the \( \phi(\epsilon_{\gamma}) \) flux corresponds to the emission from electrons with the maximum Lorentz factor, we obtain \( \gamma_M = 2.93 \times 10^6(\delta/10)^{-1/2}(B'/0.1 \text{ G})^{-1/2}(e_{pk}/100 \text{ keV})^{1/2} \). Because of \( \gamma_M \), the relativistic electron energy reach the Compton regime. We estimate the lower limit to the observed gamma energy at which the KN effects should be considered, \( E_{\gamma} \propto (\delta m_e c^2)^{2}e_{br}/m_e c^2 = 1.5(\delta/10)^{1/2}/(B'/0.1 \text{ G})^{-1/2}(e_{pk}/100 \text{ keV})^{1/2} \). Thus, the SSC photon spectrum is related to the lower limit to the observed gamma energy at which the KN effects should be considered, \( E_{\gamma} \propto (\delta m_e c^2)^{2}e_{br}/m_e c^2 = 1.5(\delta/10)^{1/2}/(B'/0.1 \text{ G})^{-1/2}(e_{pk}/100 \text{ keV})^{1/2} \). Thus, the SSC photon spectrum is consistent with the existing observations by EGRET and large enough to be detected by GLAST.
formula for the optical depth due to pair production in a relativistic blob, \( \tau_{\gamma\gamma}^{\text{opt}} \propto \delta^{2-2\alpha} \), where \( \delta \) is the Doppler factor and \( \alpha \) is the index of the softer photon energy spectrum. This optical depth is not only consistent with the previously used formula in the \( \alpha = 1 \) case but can also be generalized to broader cases.

We note that even if a source such as Mrk 501 is not in a void, primary TeV photons emitted from the source have such a long mean free path that electron/positron pairs may be produced in void regions. Thus, detections on the GeV emission would provide a sensitive probe for weak IGMFs, of consequence for cosmogonical and galactic dynamo theories.

Our results are also relevant for the quiescent state of HBLs such as Mrk 501. Aharonian, Coppi, & Völk (1994) and Coppi & Aharonian (1997) discussed a similar model for very high energy emission (\( > 100 \) GeV) from blazars in the quiescent state. We here use the recent models for the intergalactic infrared-UV background radiation to discuss lower energy emission from TeV blazars. According to Catanese et al. (1997), the Whipple telescope detected a flux of \( \phi(E_\gamma \approx 1 \text{ TeV}) = 8 \pm 3 \times 10^{-12} \text{ ergs cm}^{-2} \text{ s}^{-1} \) in the quiescent state of this HBL. The external pair-production optical depth \( \tau_{\gamma\gamma}^{\text{ex}}(E_\gamma = 1 \text{ TeV}) \simeq 0.5 \) and 0.6, and thus the flux of the externally scattered photons with an energy of \( \sim 0.6 \text{ GeV} \) is estimated as \( \phi(E_\gamma \simeq 0.6 \text{ GeV}) \simeq \phi(E_\gamma \simeq 1 \text{ TeV}) \times \text{exp}(\tau_{\gamma\gamma}^{\text{ex}}) - 1 \sim 5 \times 10^{-12} \text{ ergs cm}^{-2} \text{ s}^{-1} \) and \( 7 \times 10^{-12} \text{ ergs cm}^{-2} \text{ s}^{-1} \) for the “baseline” and “fast-evolution” models of DS, respectively. These values of the GeV emission flux are much larger than \( \sim 1.0 \times 10^{-13} \text{ ergs cm}^{-2} \text{ s}^{-1} \), the sensitivity of GLAST at energy \( \sim 0.6 \text{ GeV} \) for steady sources in a one-year survey. Therefore, even in the quiescent state of Mrk 501, its externally scattered emission may also be detected by GLAST. It should be pointed out that such detections are possible for a magnetic deflection angle that is less than the blazar jet opening angle. This also requires that the field strength be below \( \sim 10^{-16} \text{ G} \), similar to the flare case, for an opening angle \( \sim 0.1 \). Above this value of the magnetic field, the steady GeV emission may be suppressed.

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Fig. 1.— High-energy $\gamma$-ray spectra of Mrk 501 for a flare with $t_{\text{ms}} = 0.5$ days and $\eta = 1$. The spectral data are those measured by HEGRA (circles, Aharonian et al. 1999, 2001) and Whipple (squares, Krennrich et al. 1999), and their fitting is shown by line A. The EGRET upper limit at 100 MeV is from Catanese et al. (1997). Thick solid (B) and dashed (B’) lines are synchrotron self-Compton intrinsic spectra, derived from the observed spectrum A after correction for absorption on the IR background “fast-evolution” and “baseline” models of DS, respectively. Thin lines (C and C’) are the secondary photon spectra calculated in the text from the resulting pairs interacting with the CMB. The thin lines labelled with numbers 0 – 5 correspond to intergalactic magnetic fields of zero, $10^{-20}$, $10^{-19}$, $10^{-18}$, $10^{-17}$, and $10^{-16}$ G, respectively. The thick dot-dash line represents the GLAST sensitivity computed for an exposure time of 0.5 days.
Fig. 2.— Same as Fig. 1 but for different flare durations and “fast-evolution” IR background. The predicted signals are thin lines while three thick lines are the GLAST sensitivity, both for a given integration time. The solid, dot-dash and dashed lines correspond to $t_{\text{var}} = 3$ days, 0.5 days and 1 hour for $B_{\text{IG}} = 10^{-18}$ G. The thin dotted line is the signal for $t_{\text{var}} = 3$ days and $B_{\text{IG}} = 10^{-16}$ G.