THE HARD VHE $\gamma$-RAY EMISSION IN HIGH-REDSHIFT TeV BLAZARS: COMPTONIZATION OF COSMIC MICROWAVE BACKGROUND RADIATION IN AN EXTENDED JET?

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ABSTRACT

Observations of very-high-energy (VHE; $E > 250$ GeV) $\gamma$-ray emission from several blazars at $z > 0.1$ have placed stringent constraints on the elusive spectrum and intensity of the intergalactic infrared background radiation (IIBR). Correcting the observed VHE spectrum for $\gamma\gamma$ absorption, even by the lowest plausible level of the IIBR, provides evidence for a very hard (photon spectral index $\Gamma_{\text{int}} < 2$) intrinsic source spectrum out to TeV energies. Such a hard VHE $\gamma$-ray spectrum poses a serious challenge to the conventional synchrotron self-Compton (SSC) interpretation of the VHE emission of TeV blazars and suggests the emergence of a separate emission component beyond a few hundred GeV. Here we propose that such a very hard, slowly variable VHE emission component in TeV blazars may be produced via Compton upscattering of cosmic microwave background (CMB) photons by shock-accelerated electrons in an extended jet. For the case of 1ES 1101−232, this component could dominate the bolometric luminosity of the extended jet if the magnetic fields are of the order of typical intergalactic magnetic fields ($B \sim 10 \mu G$) and if electrons are still being accelerated out to TeV energies ($\gamma \geq 4 \times 10^9$) on kiloparsec scales along the jet.

Subject headings: BL Lacertae objects: individual (1ES 1101−232) — galaxies: active — gamma rays: theory — radiation mechanisms: nonthermal

1 INTRODUCTION

More than a dozen blazars have now been detected as sources of VHE $\gamma$-ray emission. Almost all of these objects are high-frequency–peaked BL Lac objects (HBLs) at low redshifts ($z \approx 0.2$). The low redshifts can be attributed to the absorption of VHE $\gamma$-rays by the IIBR. However, the level of the IIBR in the local universe and its evolution with redshift are very difficult to measure directly (e.g., Hauser & Dwek 2001). Consequently, the intensity and spectral energy distribution (SED) of the IIBR and the resulting optical depth of the universe to $\gamma\gamma$ absorption and pair production are still a matter of intensive debate (e.g., Dwek & Krennrich 2005; Aharonian et al. 2006; Stecker et al. 2006; Stecker & Scully 2006; Mazin & Raue 2007; Aharonian et al. 2007a).

The $\gamma\gamma$ opacity of the universe for GeV–TeV photons is generally increasing with increasing photon energy and with increasing redshift. Therefore, any observed VHE $\gamma$-ray spectrum with a local photon spectral index $\Gamma_{\text{obs}}$, for a $E^{-\phi_{\text{obs}}}(E)$ photons (cm$^{-2}$ s$^{-1}$) $\propto E^{-\Gamma_{\text{obs}}}$ corresponds to an intrinsic spectral index $\Gamma_{\text{int}} < \Gamma_{\text{obs}}$ at the source; i.e., the intrinsic VHE $\gamma$-ray emission at the source must not only be more luminous but its spectrum must also be harder than the observed one. A strict upper limit of $\approx 14$ nW m$^{-2}$ sr$^{-1}$ on the intensity of the IIBR at the maximum of its SED ($\sim 1.5 \mu m$) has been inferred by Aharonian et al. (2006) on the basis of the argument that any plausible mechanism of particle acceleration and radiative cooling will result in an effective particle spectral index $p \geq 2$ where $n(\gamma) \propto \gamma^{-p}$. For any plausible radiation mechanism (most notably Compton scattering), this would correspond to a limiting intrinsic photon spectral index of $\Gamma_{\text{int}} \geq 1.5$. According to Aharonian et al. (2006; see also Mazin & Raue 2007), the upper limit on the 1.5 $\mu m$ IIBR intensity from the requirement $\Gamma_{\text{int}} \geq 1.5$ for the case of 1ES 1101−232 is now rather close to the lower limit from direct galaxy counts (e.g., Madau & Pozzetti 2000). Requiring that $\Gamma_{\text{int}} > 2$ (Dermer 2007) allows for a low-intensity IIBR that is compatible with observations (Hauser & Dwek 2001). However, recent numerical simulations by Stecker et al. (2007) indicated that particle spectra with $q < 1.5$ can result from diffusive shock acceleration at relativistic shocks, which loosens the constraints on the IIBR inferred by Aharonian et al. (2006). In this context, it should also be mentioned that acceleration at shear flows (e.g., Stawarz & Ostrowski 2002; Rieger & Duffy 2006) as well as second-order Fermi acceleration (e.g., Virtanen & Vainio 2005) may lead to ultrarelativistic particle acceleration into particle distributions as hard as $q \sim 1$ or even injection of particle distributions with low-energy cutoffs at ultrarelativistic energies (Derishev et al. 2003; Stern & Poutanen 2008). Subsequent radiative cooling will then produce relativistic electron spectra with a canonical index of $p = 2$.

On the basis of the IIBR spectrum inferred from the constraints described above, Aharonian et al. (2007a) reconstructed the intrinsic VHE $\gamma$-ray spectrum of the HBL 1ES 1101−232 at $z = 0.186$, which has recently been detected as a VHE $\gamma$-ray source by the H.E.S.S. array (Aharonian et al. 2006). Their reconstruction was based on the limiting value of the intrinsic spectral index of $\Gamma_{\text{int}} \sim 1.5$, corresponding to $p \sim 2.0$ (for Compton emission in the Thomson limit). Even for the minimum plausible value of the IIBR intensity, they inferred that the peak of the high-energy component of the SED must be located at $E_{\gamma} \geq 3$ TeV. While the broadband SEDs of HBLs detected at VHE $\gamma$-rays can generally be fit with basic SSC models (for PKS 2155−304, however, see Finke et al. 2008), they are very hard pressed to reproduce such an extremely hard GeV–TeV spectrum (see, e.g., Aharonian et al. 2007a). This is because, at those energies, the SSC spectrum exhibits strong intrinsic curvature due to Klein-Nishina effects: the number of soft photons that can efficiently be scattered (in the Thomson regime) steadily decreases with increasing scattered ($\gamma$-ray) photon energy. Therefore, even an electron spectrum with $p = 2$ will generally produce an SSC spectrum with local spec-
tral index at GeV–TeV energies of $\Gamma_{\text{int}} > 1.5$. One way to over-
come this problem could be a very high low-energy cutoff of the
electron energy distribution ($\gamma_{\text{min}} \geq 10^3$), as recently sug-
gested by Katarzyński et al. (2006). However, maintaining such 
a high-energy cutoff over the relevant radiative timescale would 
require that the emission region be radiatively inefficient, which 
is unlikely, given the short radiative cooling timescales at these
energies.

The extremely hard intrinsic GeV–TeV spectrum of 1ES 1101–232 might suggest that there is an additional, very hard 
spectral component emerging above the SSC emission at those 
photon energies. Here we propose that such a component could 
be produced through Compton upscattering of the CMB ra-
diation in the extended region of the jet. This mechanism has 
previously been considered as a way to explain the hard X-ray 
emission in the extended jets of several radio quasars and radio 
galaxies spatially resolved with Chandra (e.g., Sambruna et al. 2004; see, however, Atoyan & Dermer 2004). The X-ray spectra 
of many of those extended jet components are very hard, with 
$\Gamma_\gamma \sim 1.5$, suggesting that, even in the case of mildly beamed 
jets of a nonblazar radio-loud active galactic nucleus (AGN), 
such emission might extend into the MeV–GeV range. It seems 
then worthwhile to investigate whether, in the case of blazars, 
such an emission component could even extend into the GeV–
TeV regime and produce a quasi-steady plateau of very hard 
VHE emission.

Throughout this Letter, we refer to $\alpha$ as the energy spectral 
index, so that $F_\gamma [\text{Jy}] \propto \nu^{-\alpha}$ and the photon spectral index 
$\Gamma_{\text{ph}} = \alpha + 1$. A cosmology with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, 
and $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ is used. In this cosmology, and using 
the redshift of $z = 0.186$, the luminosity distance of 1ES 1101–232 is $d_L = 905 \text{ Mpc}$. 

2. COMPTON UPCAScARING OF THE CMB TO VHE $\gamma$-RAYS

The CMB at the source at redshift $z$ is a thermal blackbody 
spectrum with a temperature $T_{\text{CMB}} = (1 + z) \times 2.72 \text{ K}$. Its 
local energy density is $u_{\text{CMB}} = (1 + z)^4 \times 4.02 \times 10^{-13} \text{ ergs cm}^{-3}$. For the purpose of an analytical estimate, the CMB can be 
approximated as a monochromatic radiation field at a 
normalized mean photon energy $\bar{\epsilon}_{\text{CMB}} \equiv \langle h\nu_{\text{CMB}}/m_e c^2 \rangle \approx (1 + z) \times 1.2 \times 10^{-9}$. If the emission region is moving with respect 
to the local AGN frame with a bulk Lorentz factor $\Gamma$, the CMB radiation field is boosted into the comoving frame by a factor of $\Gamma$ in photon energy and a factor of $\Gamma^2$ in energy density. In 
the following, we scale $\Gamma = 10\Gamma_1$, and, accordingly, the Doppler 
boosting factor $D = \langle \Gamma(1 - \beta \cos \theta_{\text{obs}}) \rangle^{-1} \approx 10\Gamma_1$, where $\theta_{\text{obs}}$ is the observing angle. Primed quantities refer to the 
comoving frame of the emission region.

Efficient Compton upscattering of the CMB into the $\gamma$-ray 
regime with the observed very high intrinsic spectrum of 1ES 1101–232 requires that the scattering occur in the Thomson 
regime, which is possible for electrons with Lorentz factors of 
$\gamma \lesssim (4\Gamma_{\text{CMB}})^{1/2} = 2.1 \times 10\Gamma_1^{-1}(1 + z)^{-1}$. Such electrons 
will Compton-scatter CMB photons up to energies of $\epsilon_{\text{obs max}} \approx 5.3 \times 10^5 D_G \Gamma_{\text{CMB}}^{-1}(1 + z)^{-2}$ or $\epsilon_{\text{obs max}} \approx 27 D_G \Gamma_{\text{CMB}}^{-1}(1 + z)^{-2}$ TeV in the observer’s frame. Thus, if electrons can be 
accelerated to TeV energies, they will be able to upscatter CMB photons into the TeV regime in the Thomson limit. Specifically, 
to scatter a CMB photon up to 1 TeV in the observer’s frame, 
a comoving electron Lorentz factor of $\gamma_{\text{TeV}} = 4.0 \times 10^6(D_G \Gamma_{\text{CMB}})^{1/2}$ is required. The radiative cooling timescale due 
to Compton cooling in the comoving frame is

$$\tau_{\text{CMB}}(\gamma_{\text{TeV}}) = 6.3 \times 10^4 D_G^{-1/2} \Gamma_{\text{CMB}}^{-3/2}(1 + z)^{-1} \text{ yr}. \quad (1)$$

On the basis of this cooling timescale, it will in principle be 
possible to accelerate electrons out to $\gamma_{\text{TeV}}$ for magnetic field 
values exceeding $B' \approx 1.2 \times 10^{-12} D_G^{-1} \Gamma_{\text{CMB}}^{-1}(1 + z)^{-1} \text{ G}$, which 
does not impose a serious constraint. CMB Compton cooling 
will dominate over synchrotron cooling for a comoving mag-
netic field value of

$$B' \approx 3.2 \times 10^{-5} \Gamma_{\text{CMB}}^{-1}(1 + z)^{-1} \text{ G}. \quad (2)$$

The resulting synchrotron emission produced by electrons 
with energy $\gamma_{\text{TeV}}$ will peak at $\nu_{\text{obs max}} \approx 2.19 \times 10^{16}(1 + z) \text{ Hz}$, i.e., typically in the UV or soft X-ray bands. The dominance 
of CMB Compton cooling over synchrotron cooling is required in 
order for the CMB Compton emission to be at least at a 
comparable level to the synchrotron emission from the same 
electrons. The required low magnetic fields are much lower 
than the magnetic field strengths inferred for the presumably 
near-central (subparsec) regions of the jet from where the bulk 
of the observed optical–X-ray–GeV $\gamma$-ray emission from blazars 
is generally believed to originate. This points toward an 
origin in the outer (parsec–kiloparsec scale) regions of the jet, 
where the magnetic fields might approach characteristic inter-
stellar magnetic field values of a few tens of microgauss.
The resulting magnetic jet luminosity will be $L_{\text{jac}} \sim 1.5 \times 10^{40} R_{\text{jet}}^{-3} \Gamma_1^4 \text{ ergs s}^{-1}$, where $R_{\text{jet}}$ is the (poorly constrained) 
cross-sectional radius of the jet in units of $10^8 \text{ cm}$, and thus several 
orders of magnitude less than the total luminosity required to 
power the emission. This indicates that the jets must be particle-
dominated at the site of the VHE $\gamma$-ray production through 
CMB upscattering, even for a parsec-scale transverse extent of 
the jet.

A key prediction from the inferred long cooling timescale 
given above is that the CMB Compton emission, as well as the 
synchrotron emission associated with the same emission 
region, will be slowly variable. This is another reason why the 
magnetic field energy density in the VHE-emitting region 
should be lower than the CMB energy density, otherwise this 
would contradict the observations of rapid variability through-
out the synchrotron component (in particular, at optical and X-
ray frequencies) of most blazars, including 1ES 1101–232 
(e.g., Remillard et al. 1989; Romero et al. 1999; Wolter et al. 
2000). We therefore argue that the rapidly variable synchrotron 
emission originates on substantially smaller (subparsec) scales 
along the jet than does the VHE emission.

3. RESULTS FOR 1ES 1101–232

On the basis of the similarity of the optical and X-ray char-
acteristics of 1ES 1101–232 (Remillard et al. 1989; Falomo 
et al. 1994) with previously known TeV blazars, Wolter et al. 
(2000) and Costamante & Ghisellini (2002) predicted that 1ES 
1101–232 might be detectable by the now operating generation 
of VHE $\gamma$-ray detectors. Prompted by these predictions, Ahar-
onian et al. (2006) performed three sets of coordinated optical–
X-ray–VHE $\gamma$-ray observations in 2004 and 2005, which re-
resulted in its detection at VHE $\gamma$-rays. This made 1ES 
1101–232 the highest redshift BL Lac object detected in VHE $\gamma$-rays at the time (now surpassed by 1ES 1011+496 at $z = 0.212$; Albert et al. 2007) and the second-farthest VHE $\gamma$-ray
described in detail in Böttcher & Chiang (2002). We used the code of CMB Compton scattering into the jet radiation transfer code for a relativistic jet component, we have incorporated the process using an extended version of the code of Böttcher & Chiang (2002). The H.E.S.S. data have been fitted with $\Gamma = 15$, $B' = 10$ $\mu$G, $\gamma_1 = 100$, $\gamma_{10} = 6.0 \times 10^3$, $q = 1.5$, and $L_{\nu\gamma} = 1.5 \times 10^{40}$ ergs s$^{-1}$. The individual curves represent CMB Compton emission (dot-dashed curve), SSC emission (double-dot-dashed curve), and total emission (solid curve) from the VHE-emitting region. The dashed curve, fitting the synchrotron component, has been computed with parameters more appropriate to the inner-jet region, with $\Gamma = 25$, $\gamma_1 = 1.3 \times 10^3$, $\gamma_{10} = 7.5 \times 10^3$, $q = 3.2$, $L_{\nu\gamma} = 2.0 \times 10^{40}$ ergs s$^{-1}$, and $R_B' = 6 \times 10^{10}$ cm, and a magnetic field in equipartition with the relativistic electron plasma, at $B' = 0.06$ G. The X-ray/\gamma-ray portion of the dashed curve represents the inner-jet SSC emission.

Figure 1.—Simultaneous optical–X-ray–VHE $\gamma$-ray SED of 1ES 1101–232 on 2005 March 5–16 (from Aharonian et al. 2007a). The VHE measurements have been corrected for absorption by the IIBR, as described in Aharonian et al. (2006). The optical data points are an upper and a lower $R$-band limit, respectively, derived from simultaneous ROTSE 3c observations in the 400–900 nm bandpass (Aharonian et al. 2007a). The curves indicate a model fit computed with parameters more appropriate to the inner-jet region, with $\Gamma = 25$, $\gamma_1 = 1.8 \times 10^3$, $\gamma_{10} = 1.5 \times 10^3$, $q = 2.5$, $L_{\nu\gamma} = 1.45 \times 10^{40}$ ergs s$^{-1}$, $R_B' = 6 \times 10^{10}$ cm, and $B' = 0.05$ G.

In order for the (nonvariable) synchrotron emission from the jet to not dominate the observed X-ray emission region on large scales than inferred for the synchrotron component, we have chosen the magnetic field in equipartition with relativistic electrons injected into the kiloparsec-scale jet, and a comoving magnetic field of $B' = 10$ $\mu$G. Obviously, these parameters are not tightly constrained, given that only the rather small spectral range of the VHE spectrum is fitted.

As expected (and required), the predicted synchrotron emission from the extended jet region is about two orders of magnitude below the measured SED for both observation periods. In order to provide a fit to the synchrotron component of 1ES 1101–232, we chose parameters more appropriate for the inner (subparsec) region of the jet, as listed in the figure captions. Note that the jet powers quoted there refer only to the power carried by the ultrarelativistic particle content. In the fits to the synchrotron component, we have chosen the magnetic field in equipartition with the ultrarelativistic electron population in the emission region in order to reduce the number of free parameters.

Although the parameters for the fits to both the synchrotron and the VHE components are not very well constrained, the general picture that emerges is that the CMB-Compton interpretation for the VHE emission requires a substantially larger kinetic luminosity of ultrarelativistic electron injection into the emission region on large scales than inferred for the synchrotron component at subparsec scales. This suggests that a substantial fraction of the total jet luminosity is carried out to large distances by the nonleptonic content of the jet. If our assumption of a magnetic field in equipartition with relativistic electrons on subparsec scales is realistic, this would suggest that most of the kinetic power of the jet might be carried by hadrons and dissipated on parsec–kiloparsec scales, leading to the acceleration of ultrarelativistic electrons in the extended jet. This is in perfect agreement with results of several other authors, suggesting that the parsec-scale jets of blazars are dominated in number by electron–positron pairs, which are responsible for the high-energy emission produced at subparsec scales, whereas the bulk of the regime to treat the Compton scattering process and describe the CMB as a thermal blackbody at $T_{\text{CMB}} = 2.72(1+z)$ K.

A reasonable representation of the VHE $\gamma$-ray spectrum, as shown in Figure 1, can be achieved using an electron injection index of $q = 1.5$, a luminosity of $L_{\nu\gamma} = 1.5 \times 10^{41}$ ergs s$^{-1}$ in relativistic electrons injected into the kiloparsec-scale jet, and a comoving magnetic field of $B' = 10$ $\mu$G. Obviously, these parameters are not tightly constrained, given that only the rather small spectral range of the VHE spectrum is fitted. The fits are insensitive to a low-energy cutoff of $\gamma_1$ of the electron spectrum, at least as long as $\gamma_1 \lesssim 10^3$. The same choice of parameters provides an equally acceptable fit to the SED of 2004 June 5–10, as shown in Figure 2.

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kinetic power of the jets is carried by a relativistic hadron population (e.g., Sikora & Madejski 2000; Ghisellini & Celotti 2001; Kino & Takahara 2004; Sikora et al. 2005).

4. SUMMARY AND DISCUSSION

We have presented a possible explanation for the hard VHE spectra of high-redshift γ-ray blazars, when corrected for the expected amount of γγ absorption by the IIBR. We suggest that ultrarelativistic electrons may be accelerated on large (kilo-parsec) scales, where magnetic fields are so low that synchrotron cooling becomes negligible compared to Compton cooling on the CMB. Consequently, VHE emission from Compton upscattering of the CMB by ultrarelativistic electrons may produce a separate, slowly variable VHE component beyond the rapidly variable broadband continuum from radio through GeV γ-ray energies that might be dominated by emission from the subparsec scale, inner regions of the jet.

Currently, the VHE emission of most distant TeV blazars, e.g., 1ES 1101−232 (Aharonian et al. 2007a), 1ES 0229+200 (Aharonian et al. 2007c), and 1ES 1011+496 (Albert et al. 2007), has shown no evidence of variability on any timescale while the VHE emission of the nearby TeV blazars has shown evidence of substantial variability on timescales from years down to a few minutes (e.g., Aharonian et al. 2007b). This could indicate that CMB Compton scattering constitutes an underlying nonvarying VHE component in TeV blazars, which would be more likely to be detected in high-redshift sources because the energy density of the CMB increases with redshift as (1+z)^4. However, one has to caution that small-amplitude variability would generally be much harder to detect for the much fainter high-redshift TeV sources.

We have applied this idea to two simultaneous SEDs of 1ES 1101−232. Although the parameters of our fits are rather poorly constrained, they seem to indicate that only a small portion of the kinetic energy of the jet is dissipated on subparsec scales, whereas the bulk of this energy is transported outward to kiloparsec scales, in agreement with earlier suggestions that the kinetic power of blazar jets might generally be dominated by their hadronic content and might only be dissipated on large scales.

Alternative explanations for the very hard VHE emissions include Compton upscattering of infrared emission from dust in the vicinity of the AGN (e.g., Bläzzejowksi et al. 2000), or signatures of pion decay in hadronic blazar models (e.g., Mücke et al. 2003). However, it should be noted that Compton scattering of infrared radiation with a characteristic wavelength of λ = λ_i μm would also be affected by Klein-Nishina effects at energies of E ≳ 0.2λ_i TeV, so a photon index of Γ_{int} ≳ 1.5 out to multi-TeV energies might be difficult to explain with this mechanism. It is also possible to produce VHE spectra of arbitrary hardness if they are affected by γγ absorption intrinsic to the source through interaction with narrowband emission from the vicinity of the AGN (Aharonian et al. 2008). However, it is not obvious why such a feature should be observed preferentially in high-redshift TeV blazars, or why it would lead to less variable TeV emission than in the low-redshift TeV blazars, if the lack of variability is confirmed by future observations.

Our CMB-Compton interpretation for the VHE emission of 1ES 1101−232 is obviously not applicable to high-redshift VHE sources that seem to show substantial variability on timescales of days or even shorter (e.g., 3C 279; Teshima et al. 2007), since it requires a parsec-scale extent of the emission region. The interpretation of the unexpectedly hard VHE spectrum through such a scenario would predict that any emission at lower (GeV) energies might be produced in the inner (sub-parsec) region of the jet and might be much more rapidly variable than the VHE emission. Whether or not this is the correct interpretation for the hard spectrum of 1ES 1101−232, a Compton-scattered CMB component from blazar jet emission will accompany synchrotron emission and could potentially be observed with γ-ray telescopes.

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REFERENCES