DERIVATION OF A RELATION FOR THE STEEPENING OF TeV-SELECTED BLAZAR $\gamma$-RAY SPECTRA WITH ENERGY AND REDSHIFT

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ABSTRACT

We derive a relation for the steepening of blazar $\gamma$-ray spectra between the multi-GeV Fermi energy range and the TeV energy range observed by atmospheric Cerenkov telescopes. The change in spectral index is produced by two effects: (1) an intrinsic steepening, independent of redshift, owing to the properties of emission and absorption in the source and (2) a redshift-dependent steepening produced by intergalactic pair production interactions of blazar $\gamma$-rays with low-energy photons of the “intergalactic background light” (IBL). Given this relation, with good enough data on the mean $\gamma$-ray spectral energy distribution of TeV-selected BL Lac objects, the redshift evolution of the IBL can, in principle, be determined independently of stellar evolution models. We apply our relation to the results of new Fermi observations of TeV-selected blazars.

Key words: BL Lacertae objects: general – radiation mechanisms: non-thermal

1. INTRODUCTION

Stecker & Scully (2006, hereafter SS06) derived a simple analytic expression for the change in spectral index of a TeV $\gamma$-ray source in the redshift range between 0.05 and 0.4. They showed that the change in the spectral index caused by intergalactic absorption is given by an approximately linear relation in redshift, i.e., $\Delta \Gamma \propto C + D z$.

The purpose of this Letter is to generalize this relation by including the effect of intrinsic steepening in the source spectra between the multi-GeV energy range observed by Fermi and the TeV range observed by atmospheric Cerenkov telescopes. Our general result is roughly independent of the specific model of the intergalactic background light (IBL) used, because it only depends on the shape of the average galaxy spectral energy distribution (SED) on the near-IR side of the starlight peak that determines the absorption in the TeV energy range.

We compare our result for the specific baseline and fast evolution models of Stecker et al. (2006, hereafter SMS06) with the results of recent Fermi observations of 13 TeV-selected BL Lac object active galactic nuclei (AGNs). We also show how it can be used to independently determine the redshift evolution of the IBL.

2. STEEPENING BY ABSORPTION

In order to determine the effect of intergalactic absorption, we use the results of SS06 demonstrating that $\tau(E, z)$ can be fitted to an approximately logarithmic function in $E$ in the energy range $0.2 \text{ TeV} < E < 2 \text{ TeV}$ and one which is linear on $z$ over the range $0.05 < z < 0.4$. It is important to note that our linear fit to the $z$ dependence is both qualitatively and quantitatively different from the linear dependence on redshift which would be obtained for small redshifts $z \ll 1$, and which simply comes from the fact that for small $z$ where luminosity evolution is unimportant and where $\tau \propto d$, with the distance $d \approx cz/H_0 \propto z$. Our quantitative fit for the higher redshift range $0.05 < z < 0.4$ comes from the more complex calculations based on the models of SMS06. For this reason, the linear fits in SS06 are not simply proportional to redshift.

SS06 found that $\tau(E, z)$ is well approximated by

$$\tau(E, z) = (A + B z) + (C + D z) \ln[E/(1 \text{ TeV})],$$

where $A$, $B$, $C$, and $D$ are constants. This expression holds over the energy and redshift ranges given above. The energy range of validity is the energy range to which the atmospheric Cerenkov telescopes are sensitive.

Following SS06, we assume an intrinsic source spectrum that can be approximated by a power law of the form $\Phi(E, \Gamma, z) \propto E^{-\Gamma(z)}$ over a limited energy range. Then, the spectrum that will be observed at the Earth following intergalactic absorption will be of the power-law form

$$\Phi_o(E) = k E^{-\Gamma(z)} e^{-\left(A z + B z^2 + C + D z\right)}.$$  (2)

This can be compared with the empirically observed TeV spectra that are usually presented in the literature to be good fits to power laws. The observed spectral index, $\Gamma_o, \text{TeV}$, will then be given by

$$\Gamma_o, \text{TeV} = \Gamma(z) + \Delta \Gamma(z).$$  (3)

where the intrinsic spectral index of the source is steepened by intergalactic absorption by an amount $\Delta \Gamma(z) = C + D z$.

On the other hand, in the multi-GeV range over which the Fermi Large Area Telescope (LAT) is sensitive, we expect essentially no steepening from absorption over the redshift range of validity, i.e., $\Delta \Gamma_o, \text{GeV}(z) \approx 0$.

The parameters $C$ and $D$ obtained by fitting the optical depths derived for the fast evolution and baseline models of SMS06 are given in Table 1.

3. INTRINSIC STEEPENING

The importance of synchrotron self-Compton emission in producing high-energy $\gamma$-rays in astrophysical sources was pointed out by Rees (1967). Particular applications to the Crab and other sources were discussed by Gould (1965) and Rieke & Weekes (1969). Today, given present observational studies of TeV-selected BL Lac object AGN, it is generally accepted that the synchrotron self-Compton mechanism is the primary
emission mechanism for producing γ-rays in the TeV energy range in TeV-selected BL Lac object AGN.

The γ-ray spectrum from Compton interactions is a smoothly varying one (Blumenthal & Gould 1970). Good empirical fits to the prediction of candidate BL Lac objects to be found by atmospheric Čerenkov telescopes in the TeV energy range vary among one (Blumenthal & Gould 1970). Good empirical fits on a set of SEDs of TeV-selected BL Lac objects and ensemble-averaged width of the parabola in log–log plots (Landau et al. 1986; Sambruna et al. 1996). In fact, these considerations led to the prediction of candidate BL Lac objects to be found by atmospheric Čerenkov telescopes in the TeV energy range (Stecker et al. 1996; Costamante & Ghisellini 2002).

We assume such an approximation here, i.e.,

\[ E^x \frac{dN_\gamma}{dE} = f(x), \]

where \( x = \log E \) with the simplification that \( E \) is in dimensionless fiducial units (i.e., \( E/E_f \)), and

\[ f(x) = -\frac{(x - x_0)^2}{2A} + B. \]

Here, \( A \equiv \log(W) \) is a constant parameter based on the ensemble-averaged width of the parabola in log \( E \) space based on a set of SEDs of TeV-selected BL Lac objects and \( x_0 = \log E_0 \) where \( E_0 \) is the energy at which the Compton peak of the average BL Lac object SED is a maximum. We note that for some BL Lac objects electron scattering in the Klein–Nishina regime will distort our parabolic assumption on the high-energy end of their SEDs, possibly reducing \( \log(W) \) by a small amount (Tavecchio et al. 1998). However, this does not significantly affect our formalism.

We find that the change in the slope of the intrinsic source spectrum occurring between some average observed energy in the GeV range \( \langle E_{\text{GeV}} \rangle \) and some average observed energy in the TeV range \( \langle E_{\text{TeV}} \rangle \) is approximately given by a constant,

\[ \log \langle E_{\text{TeV}} \rangle - \log \langle E_{\text{GeV}} \rangle \approx K. \]

Thus, the ensemble-averaged intrinsic BL Lac object source spectrum in going from the GeV range to the TeV range is independent of redshift within the errors in the observational data. We will therefore approximate the average intrinsic steepening over an observed set of TeV-selected blazars by

\[ \Gamma_{s,\text{TeV}} - \Gamma_{s,\text{GeV}} = \Delta \Gamma_s = K. \]

4. THE RELATION FOR THE TOTAL STEEPENING BETWEEN GeV AND TeV ENERGIES

The total steepening, expected between the GeV and TeV energy ranges, is then given by the relation

\[ \Delta \Gamma = \Delta \Gamma_s + \Delta \Gamma_n = (C + K) + D \Delta z. \]

The parameters \( C \) and \( D \) obtained by fitting the optical depths derived for the fast evolution and baseline models of SMS06 are given in Table 1. The parameter \( K \) is then derived by performing a \( \chi^2 \) fit to the observed steepening data obtained by the Fermi collaboration (Abdo et al. 2009) in order to find \( (C + K) \). The parameter \( K \) is also given in Table 1 for the FE and B models. The data on the TeV-selected BL Lac objects from Abdo et al. (2009) are shown in Figures 1 and 2, along with the best-fit linear relations for the models indicated. It can be seen that, given the present limited data set and large error bars, one cannot uniquely determine the parameters \( C, D, \) and \( K \). However, in principle, with a good enough data set, one could determine \( K \) uniquely from Equation (6). Then, since \( K \gg C \), one could use Equation (8) to determine the parameter \( D \). This will then give a determination of the redshift evolution of the IBL independently of models of the star formation rate.

Figures 1 and 2 show the fits of the parameters given in Table 1 to the linear dependence in and redshift given by Equation (8).

5. CONCLUSIONS

We have derived a simple analytic approximation for determining the steepening in the spectra of TeV-selected BL Lac object AGN and compared our results with recent observational data on 13 TeV-selected BL Lac object AGNs. Our relation is in excellent agreement with the observational data and provides

| Steepening Parameters | \( C \) | \( D \) | \( K \) |
|-----------------------|-------|-------|-------|
| Fast Evolution        | -0.0972 | 10.6  | 0.427 |
| Baseline              | -0.0675 | 7.99  | 0.716 |

Figure 1. Fits obtained for the linear functions \( C + D \Delta z \) (dashed line) and \( C + D \Delta z + K \) (solid line) shown for the SMS06 baseline model as described in the text. These are fit to the data on 13 BL Lac objects given by Abdo et al. (2009).

Figure 2. Fits obtained for the linear functions \( C + D \Delta z \) (dashed line) and \( C + D \Delta z + K \) (solid line) shown for the SMS06 fast evolution model as described in the text. These are fit to the data on 13 BL Lac objects given by Abdo et al. (2009).
a framework for understanding and interpreting both these and observational data.

SS06 have shown that the effect of intergalactic absorption on the spectra of AGN in the energy range $0.2 \text{ TeV} < E_\gamma < 2 \text{ TeV}$ and the redshift range $0.05 < z < 0.4$ is a simple power-law to power-law steepening. Absorption in this energy range is primarily produced by interactions with near-IR photons from the low-energy sides of the starlight peaks in galaxy SEDs. The shape of the resulting peak in the intergalactic SED produces an approximately logarithmic energy dependence for the function $\tau(E_\gamma)$. This energy dependence should be roughly the same for all models of the IBL. Therefore, our general result of a linear $\Delta \Gamma = (C + K) + Dz$ relationship is roughly independent of the specific IBL model used, because it only depends on the shape of the average galaxy SED on the near-IR side of the IBL starlight peak. The parameters $C$, $D$, and $K$ will be different for the different models since the absolute value of $\tau$ varies from one IBL model to another.

Given our derived relation between $\Delta \Gamma$ and redshift, and with good enough data on the mean $\gamma$-ray SED of TeV-selected BL Lac objects used to determine $K$, the redshift evolution of the IBL can, in principle, be determined independently of stellar evolution models.

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