DECELERATING FLOWS IN TeV BLAZARS: A RESOLUTION TO THE BL LACERTAE–FR I UNIFICATION PROBLEM

MARKOS GEORGANOPoulos1 AND DEMOSTHENES KAZANAS2
Laboratory for High Energy Astrophysics, NASA Goddard Space Flight Center, Code 661, Greenbelt, MD 20771
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ABSTRACT

TeV emission from BL Lacertae (BL) objects is commonly modeled as synchrotron self-Compton radiation from relativistically moving homogeneous plasma blobs. In the context of these models, the blob Lorentz factors needed to reproduce the TeV emission corrected for absorption by the diffuse infrared background are large (δ ≳ 50). The main reason for this is that stronger beaming eases the problem of the lack of ~IR-UV synchrotron seed photons needed to produce the deabsorbed ~few TeV peak of the spectral energy distribution. However, such high Doppler factors are in strong disagreement with the unified scheme, according to which BLs are FR I radio galaxies with their jets closely aligned to the line of sight. Here, motivated by the detection of subluminal velocities in the subparsec-scale jets of the best studied TeV blazars, Mrk 421 and Mrk 501, we examine the possibility that the relativistic flows in the TeV BLs decelerate. In this case, the problem of the missing seed photons is solved because of upstream Compton scattering, a process in which the upstream energetic electrons from the fast base of the flow “see” the synchrotron seed photons produced in the slow part of the flow relativistically beamed. Modest Lorentz factors (Γ ≃ 15), decelerating down to values compatible with the recent radio interferometric observations, reproduce the ~few TeV peak energy of these sources. Furthermore, such decelerating flows are shown to be in agreement with the BL–FR I unification, naturally reproducing the observed BL/Fr I broadband luminosity ratios.

Subject headings: galaxies: active — quasars: general — radiation mechanisms: nonthermal — X-rays: galaxies

1. INTRODUCTION

There is a small but growing family of blazars detected at TeV energies. These belong exclusively to the class of high peak frequency BL Lacertae objects (BLs), i.e., blazars whose synchrotron component peaks at X-ray energies. TeV emitting BLs are of particular interest because of the possibility of absorption of their TeV emission by the diffuse infrared background (DIRB) (Nikisov 1962; Gould & Schréder 1966; Stecker, de Jager, & Salamon 1992). Study of their spectra in the TeV range can be used to probe the properties of the DIRB as a function of redshift z (Salamon & Stecker 1998).

The absorption of the TeV photons of this blazar class suggests that both the intrinsic peak photon energy $E_p$ and peak luminosity $L_p$ of the high-energy (TeV) component are higher than those observed. Even for the nearby ($z = 0.031$) Mrk 421, $E_p$ can increase by a factor of ~10 after deabsorption to ~3–10 TeV (de Jager & Stecker 2002). The deabsorbed spectrum of H1426+428 at $z = 0.129$ is even more extreme, characterized by $E_p ≳ 10$ TeV (Aharonian et al. 2002).

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Modeling of these sources has been done in the framework of the homogeneous synchrotron self-Compton (SSC) model (e.g., Coppi 1992; Mastichiadis & Kirk 1997), according to which a blob of energetic plasma is moving with a constant Lorentz factor $\Gamma$ forming a small angle $\theta$ to the line of sight. Such models require high Doppler factors [$δ = 1/\Gamma (1 - \beta \cos \theta) ≳ 50$, where $\beta$ is the dimensionless speed of the flow and $\theta$ its angle to the observer’s line of sight] to reproduce the deabsorbed $E_p$ (e.g., Krawczynski, Coppi, & Aharonian 2002; see also § 2). However, even smaller values of $δ (~10)$ are in conflict (Chiaberge et al. 2000) with the unification scheme according to which BLs represent FR I radio galaxies viewed at small $\theta (\sim 1/\Gamma)$ (Urry & Padovani 1995). Also, these high values of $δ$ are in disagreement with the small values of the apparent velocities observed in the subparsec regions of the TeV BLs Mrk 421 and Mrk 501 (e.g., Marscher 1999). In this Letter we propose that the above issues can be resolved by postulating that the TeV blazar emission originates in a relativistic but decelerating flow. In § 2 we present a quantitative analysis and formulation of the above arguments, while in § 3 we outline the basic notions behind our proposal and explain why and how they resolve the outstanding issues discussed in § 2. Finally, in § 4 we discuss some further issues.

2. PROBLEMS WITH UNIFORM-VELOCITY TeV BLAZAR MODELS

The blazar spectra.—One of the characteristics of the synchrotron components of the TeV blazar spectra is a break at an energy $e_b \sim 10^{-4}$ to $10^{-6}$ (unprimed energies are in the observer frame, while primed ones in the flow rest frame, all normalized to the rest mass of the electron $m_c c^2$), with most of the (comoving) synchrotron energy density above $e_b'$, a feature that significantly affects their TeV emission: because of the reduction in the inverse Compton (IC) scattering cross section in the Klein-Nishina ($K$-$N$) regime and the break in the photon energy density at $e' < e_b'$, electrons with energies $\gamma \sim 1/e_b$ will channel a decreasing fraction of their energy to IC scattering, leading to a peak in the IC luminosity at $e'_b = 1/e_b$ even if the maximum electron energy is $\gamma_{\text{max}} \gg 1/e_b$. For a source moving with a Doppler factor $\delta$ relative to the observer, $e'_b$ and $e_b'$ will be $e'_b = \delta e_b$ and $e_b' = \delta e'_b$, yielding

$$\delta^2 (e_b e'_b) \approx (\delta e_p)$$

or

$$\delta \approx (e_b e'_b)^{1/2} = 40 (\nu_{b,16} E_{p,10 \text{TeV}})^{1/2},$$

(1)

1 Also NAS/NRC Research Associate; markos@milkyway.gsfc.nasa.gov.
2 demos.kazanas-1@nasa.gov.
where $\nu_{\text{obs}}$ is the observed synchrotron break frequency in units of $10^{16}$ Hz and $E_{\gamma,0}$ is the energy of the deabsorbed IC peak in units of 10 TeV. Deabsorbed $E_{\gamma}$-values in excess of 10 TeV then imply relativistic flows in blazars with $\Gamma \gtrsim 40$. The crucial point in the above argument, namely, that the IC luminosity peaks at $\epsilon_{\gamma} \ll 1/\epsilon_{e}$, can be demonstrated explicitly within the homogeneous SSC models; assume, as customary, continuous injection of a power-law electron distribution within a uniform source at a rate $Q(\gamma) \propto \gamma^{-\gamma} \gamma \lesssim \gamma_{\max}$. The steady state electron distribution is then

$$n(\gamma) \propto \gamma^{-\gamma} \gamma \lesssim \gamma_{\max},$$

(2)

where $\gamma_{\gamma}$ is the electron energy below which electrons escape from the source faster than they radiatively cool. The corresponding comoving synchrotron energy density distribution is

$$u(\epsilon') \propto \left(\frac{\epsilon'}{\epsilon_{\max}}\right)^{(1-2)} \epsilon' \leq \epsilon_{\max},$$

(3)

where $\epsilon_{\gamma} = b \gamma^2 \epsilon_{\max} = b \gamma_{\max}^2$ and $b$ is the comoving magnetic field in units of its critical value $B_{\text{cr}} = m_e c^2/\hbar c = 4.4 \times 10^{13}$ G. Fits to the synchrotron spectra of TeV blazars require $1 < s < 2$, with comoving peak synchrotron luminosity at $\epsilon_{\max}$. We now examine the energy $\epsilon''$ at which the IC luminosity peaks as a function of the maximum electron energy $\gamma_{\max}$. The K-N influence on the cross section begins at $\gamma_{\max} \approx 1/\epsilon'_{\max}$. Above that energy the electrons interact only with the fraction of the synchrotron spectrum at energies less than $\epsilon' \ll 1/\gamma_{\max}$, while the maximum photon energy resulting from the IC is $\epsilon''_{\max} \approx \gamma_{\max}$. If $L(\epsilon'_{\gamma})$ is the photon scattering rate to energy $\epsilon''_{\max}$, the IC luminosity at this energy is

$$\epsilon''_{\max} L(\epsilon'_{\gamma}) \propto \epsilon''_{\max} n(\gamma_{\max}) e'u(\epsilon') \gamma_{\max}.$$  

(4)

Setting $\epsilon' = 1/\gamma_{\max}$ as the appropriate seed photons (photons of larger energy are in the K-N regime, and photons of lower energy give lower $\epsilon''_{\gamma}$) and using equation (2) and (3), we obtain

$$\epsilon''_{\max} L(\epsilon'_{\gamma}) \propto \left[\left(\frac{\epsilon''_{\max}}{\epsilon'_{\gamma}}\right)^{(1-2)} \epsilon''_{\max} \leq 1/\epsilon''_{\gamma}, \epsilon''_{\max} \geq 1/\epsilon''_{\gamma}\right].$$

(5)

where we have also used $\epsilon''_{\max} = \gamma_{\max}$. Therefore, for $1 < s < 2$ the luminosity at maximum photon energy $\epsilon''_{\max} L(\epsilon'_{\gamma})$ increases with $\gamma_{\max}$ for $\epsilon''_{\max} = 1/\epsilon''_{\gamma}$ and decreases for $\epsilon''_{\max} \geq 1/\epsilon''_{\gamma}$, achieving its peak luminosity at energy $\epsilon''_{\gamma} \approx 1/\epsilon''_{\gamma}$.

Blazar unification.—According to the unification scheme of radio-loud active galaxies (e.g., Urry & Padovani 1995) BLs are FR I radio galaxies with their jets oriented close to the line of sight. The average Lorentz factor $\Gamma$ of the jet flows, derived by matching the luminosity functions of BL and FR I samples, was estimated to be $\Gamma \sim 3-5$ (Urry & Padovani 1991; Hardcastle et al. 2003), in clear disagreement with the values of the Doppler factors required by the homogeneous SSC models for the TeV blazars. The high Doppler factors estimated on the basis of homogeneous SSC models imply that for $\Gamma = \delta = 50$, $\theta \approx 1/\Gamma \approx 10^9$ requiring sources very well aligned to the line of sight, thus grossly overpredicting the number of FR I galaxies above a given limiting flux (this actually would be the case even with the much smaller value of $\Gamma \approx 10$; Hardcastle et al. 2003). In a different aspect of the same problem, Chiaberge et al. (2000) showed that the FR I nuclei are overluminous by a factor of $10^{-3}$ compared with their luminosity should they have been misaligned BLs harboring Lorentz factors $\Gamma \sim 15$. Applying to subparsec scales the arguments of Laing et al. (1999) concerning the structure of FR I kiloparsec-scale jets, they opted for jets with a high $\Gamma$ “spine” surrounded by a lower $\Gamma$ sheath. For a source at a small angle to the line of sight the emission is dominated by the fast spine, while at large angles this radiation is beamed out of the observer’s direction and the observed spectrum is dominated by the mildly beamed emission by the slower sheath.

However, recent VLBI (Marscher 1999), VLBI (Edwards & Piner 2002) and combined VSOP and VLBI (Piner et al. 1999) studies do not detect any high-velocity components in the jets of the two TeV sources Mrk 421 and Mrk 501. These observations are compatible with subluminal ($\beta_{\text{app}} \sim 0.3-0.6$; Piner et al. 1999; Edwards et al. 2002) or mildly relativistic ($\beta_{\text{app}} \sim 2$; Marscher 1999) subparsec velocities. A value of $\delta \sim 50$, as needed in modeling the TeV emission of these sources, could produce the observed velocities only for $\theta \lesssim 0.1$. Rather than assuming such an extraordinary jet alignment for both sources, Marscher (1999) suggested that the flow in the subparsec environment of these sources has already decelerated substantially. Additional support for slow flows in subparsec scales comes from Jorstad et al. (2001), who showed that in several cases VLBI components in BLs move with $\beta_{\text{app}} \sim 1-2$. That low jet velocities at parsec scales are real and not the result of projection effects is supported by the observation of subluminal velocities at the jet of the FR I galaxy 3C 279, which are thought to be at large angle to the observer’s line of sight (Piner, Jones, & Wehrle 2001).

3. DECELERATING FLOWS AND UPSTREAM COMPTON EMISSION

Motivated by the above issues, we propose that in the high-energy emitting region of the TeV BLs the plasma flow is relativistic and decelerating (a similar proposal was advanced to unify the broadband properties of the hot spots of FR II radio galaxies and quasars; Georganopoulos & Kazanas 2003). Our proposed scheme for the BL flows involves the injection of a power-law electron distribution at the base of a relativistic flow which decelerates while at the same time the electron distribution cools radiatively. The highest synchrotron frequencies originate at the fast base of the flow where the electrons are more energetic. As both the flow velocity and energy flow drop with radius, the locally emitted synchrotron spectrum shifts to lower energies while its beaming pattern becomes wider. At small angles the observed spectrum is dominated by emission from the higher $\Gamma$ base of flow, where the most energetic electrons reside. At larger angles this emission from the inner, fast flow section is beamed away from the observer and the major contribution to the spectrum comes from its slower parts, which contain less energetic electrons, leading to softer spectra.

The inverse Compton emission of such a flow behaves in a more involved way: electrons will upscatter the locally produced synchrotron seed photons, giving rise to a local SSC emission with $\delta$-dependence similar to that of synchrotron. However, the electrons of a given radius will also scatter those synchrotron photons produced downstream in the flow. The energy density of the latter will appear Doppler boosted in the fast (upstream) part of the flow by $\sim \Gamma_{\text{rel}}^2$ (Dermer 1995), where $\Gamma_{\text{rel}}$ is the relative Lorentz factor between the fast and slow parts of the flow. With their maximum energy being lower
The need for additional seed photons in modeling the \( \sim \) few TeV peak emission of the TeV blazars drives homogeneous SSC models to \( \delta \approx 50 \), values in conflict with the presumed unification between FR I’s and BLs. The problem of the missing seed photons can be resolved if one considers a relativistic flow decelerating from \( \Gamma_1 \sim 15 \) down to \( \Gamma_2 \sim \) few: in this case UC emission produces spectra that can easily provide the observed deabsorbed \( E_\gamma \) without the need to invoke values of \( \delta \) greater than \( \delta \approx 15 \). Such decelerating flows are consistent with the low, possibly subluminal, speeds observed in the subparsec-scale jets of Mrk 421 and Mrk 501 without unreasonable alignment requirements (for \( \Gamma_2 = 4 \) and \( \beta_{\text{app}} = 1 \) the corresponding value of the observing angle is \( \theta = 2^\circ \)). It also resolves the
problem of FR I–BL unification, which fails for flows with constant Lorentz factors even as low as $\Gamma \sim 10$.

The spatial separation of different frequencies seen in Figure 1 has interesting consequences for the expected variability. In homogeneous SSC models a variation of the number of the injected electrons produces a linear response in the synchrotron flux and a quadratic one in the SSC flux. This is because both the number of the electrons and the synchrotron energy density increase linearly and the SSC flux increases quadratically because it is proportional to their product. For decelerating flows, fast variations (faster than the light crossing time of the separation between the X-ray emitting region and the downstream region responsible for most of the synchrotron seed photons used to produce the TeV emission) should result to approximately linear variations of the TeV relative to the X-ray flux. This is because the freshly injected high-energy electrons UC scatter mostly synchrotron photons produced downstream before the injection and therefore contribute an undisturbed photon energy density.

A physically plausible scenario for the flows we consider may be that suggested by Marscher (1999), according to which the energy dissipated at the shock is converted into a non-thermal electron component, whose radiative losses lead to the deceleration of the relativistic flow. In this case the deceleration length scale would be approximately equal to that of radiative losses, an assumption we have employed in our calculations.

A similar scenario has been proposed for the hot spots of large-scale jets, and it seems possible that relativistic and decelerating flows exist in different astrophysical environments that exhibit similar characteristics and, in particular, a stronger that anticipated high-energy emission due to UC scattering.

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