How is the blazar GeV emission really produced?

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Abstract. We show that the external Compton (EC) model for the production of the GeV emission in blazars makes specific predictions for the spectrum and variability of those blazars characterized by a high Compton dominance (Compton to synchrotron luminosity ratio). These unavoidable features have not been observed, casting doubt on the validity of this popular model. We argue that synchrotron-self Compton (SSC) models including the higher orders of Compton scattering are more promising, and we briefly discuss the implications of our findings for the geometry of the broad line region (BLR).

Introduction. The GeV emission from the relativistic jets of blazars is believed to be due to energetic electrons that inverse-Compton (IC) scatter to $\gamma$-ray energies lower energy photons. These photons can be synchrotron photons produced in the source (synchrotron-self Compton, SSC; e.g. Maraschi et al. 1993) and/or external photons such as the BLR UV photons (Sikora et al. 1994) which, as reverberation mapping shows, are produced at distances of $\sim 10^{17−18}$ cm from the central engine (Kaspi et al. 2000). The second case is believed to be favored, because variability arguments show that the site of the blazar emission is at a comparable distance, and, therefore, it is exposed to the BLR photon field, which has a photon energy density in the jet frame boosted by $\Gamma^2$, where $\Gamma \sim 10$ is the Lorentz factor of the jet bulk motion.

Cooling in the Klein-Nishina (KN) regime. In several cases, the Compton dominance can reach values as high as a few hundred (e.g. PKS 4C 38.31; Kubo et al. 2000). In such cases IC is the dominant energy loss mechanism, and to produce the few GeV photons with energy $\epsilon \sim 10^4$ (in units of $m_e c^2$), electrons of at least the same Lorentz factor are required, $\gamma \sim 10^4$. Given that the typical BLR photon energy is $\epsilon_0 \sim 10^{-4}$, the GeV emission comes from scatterings in the area between the Thomson and Klein-Nishina regimes, since $\epsilon_0 \gamma \sim 1$.

Consider a case where the only loss mechanism we have is IC. In the Thomson regime ($\epsilon_0\gamma \ll 1$), the electron energy loss rate $\dot{\gamma} \propto \gamma^2$, and the electron cooling time $\tau_c = \gamma/\dot{\gamma} \propto 1/\gamma$. In the KN regime $\dot{\gamma} \propto \gamma^0$ (there is a slow logarithmic increase of $\dot{\gamma}$ with $\gamma$ which we do not consider here), and $\tau_c = \gamma/\dot{\gamma} \propto \gamma$. So, while the cooling time decreases linearly with $\gamma$ in the Thomson regime, it increases linearly in the KN regime. The behavior around $\epsilon_0 \gamma \sim 1$ is flat, with a practically energy independent cooling time, as a numerical calculation (Fig. 1) shows. Assuming that a power law electron distribution $\propto \gamma^{-p}$ is injected in the emission zone and that the electrons escape after time $t_{esc}$, the steady-state
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Figure 1. A homogeneous source. Bottom panel: the cooling time as a function of electron $\gamma$ for electrons cooling due to IC scattering off a monoenergetic photon field with $\epsilon_0 = 10^{-4}$. Only electrons with $\gamma_{b1} < \gamma < \gamma_{b2}$ have time to cool. Top panel: the steady-state electron energy distribution $n(\gamma)$ (multiplied by $\gamma^2$ for visualization reasons) for an injected distribution $\propto \gamma^{-2}$.

electron distribution $n(\gamma)$ will retain the same slope for $\gamma < \gamma_{b1}$, $\gamma > \gamma_{b2}$, where $\gamma_{b1}$ and $\gamma_{b2}$ are the electron energies for which $\tau_c = t_{esc}$. To obtain $n(\gamma)$ for $\gamma_{b1} < \gamma < \gamma_{b2}$, we solve the steady-state kinetic equation $\partial(\dot{\gamma}n)/\partial \gamma \propto \gamma^{-p}$ to obtain $n \propto \gamma^{1-p}/\dot{\gamma}$. In the Thomson regime $\dot{\gamma} \propto \gamma^2$ and $n(\gamma) \propto \gamma^{-(p+1)}$, resulting in a distribution steeper than the injected one. Contrary to this well known result, in the KN regime $\dot{\gamma} \propto \gamma^0$, and $n(\gamma) \propto \gamma^{-(p-1)}$, resulting in an electron distribution flatter than the injected one (e.g. Moderski et al. 2005). The general case is shown in the top panel of Fig. 1. Note that around $\epsilon_0 \gamma = 1$, $n(\gamma)$ retains its initial slope as in the non-cooling parts $\gamma < \gamma_{b1}$, $\gamma > \gamma_{b2}$, although these electrons are the fastest cooling.

Strongly Compton dominated blazars. In this case, a proper calculation requires the inclusion of the synchrotron and SSC losses, as well as the emission due to these processes and EC scattering. We present results of such a numerical calculation (Georganopoulos et al., in prep.) in Fig. 2, for a source in which the ratio of the energy density $U_{ext}$ in the jet comoving frame of the external (BLR) photon field is 100 times larger than the magnetic field energy density $U_B$. This guarantees that the EC emission will be much more powerful than the synchrotron component, while an adequately large source size ($R = 5 \times 10^{16}$ cm) guarantees that the SSC component is much weaker than the EC one.
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Figure 2. Model of an EC dominated blazar. Bottom panel: the electron cooling time as a function of $\gamma$. Middle panel: the electron distribution. Top panel: the emitted power. Solid line for the total power, and dotted lines for the synchrotron (leftmost), SSC (central), and EC (rightmost and most powerful) components. The gray band is roughly the EGRET - GLAST regime.

Note that the cooling time (bottom panel of Fig. 2) for electrons with $\gamma$ greater than $\sim 10^3$ is practically constant. This implies that the IR to UV variability, produced by the synchrotron emission of these electrons, should be achromatic, contrary to observations (e.g. Ulrich et al. 1997, see however Perlman et al. 2003. It also implies achromatic variations in the one to several GeV range, something that will be tested by GLAST. Also, as can be seen in the middle panel of Fig. 2, the electron distribution, after it softens due to cooling in the Thomson regime, it becomes harder due to the onset of the reduced efficiency KN cooling. This is reflected in the emitted spectrum with a hump in the synchrotron component, something that is also not observed in blazars (e.g. Kubo et al. 1998). Note finally the flat/rising GeV component, something rarely seen by EGRET (the typical GeV spectrum is steep; e.g. Kubo et al. 1998).

The spectral and temporal characteristics we presented here are unavoidable for blazars with high Compton dominance, and the fact that these characteristics are not seen is a strong argument against the EC model.
Revisiting SSC. Given the problems of the EC interpretation of the GeV emission, we turn to the SSC interpretation. One of the main reasons that SSC models for the blazar GeV emission were disfavored, was an analytical argument that SSC variability is quadratic as compared with that seen in the synchrotron component, contrary to the superquadratic variations seen in 3C 279 (Wehrle et al. 1998). Interestingly, the currently favored EC mechanism can only produce linear variations in a simple fashion, and modeling superquadratic variations requires a carefully selected change of more than one model parameter.

The argument for the solely quadratic SSC variations was based on the assumption that the SSC power is much smaller than the synchrotron one. In the more general and observationally relevant case of an SSC power comparable or higher than the synchrotron one, superquadratic variations are the norm, particularly so when second order (SSC2) scattering is relevant (see Fig. 3).
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The BLR geometry. Given that the blazar emission site cannot be placed much further out than $10^{18}$ cm from the central engine, it is interesting to ask under what conditions the photon field of the BLR is not an important seed photon mechanism for IC emission. Reverberation mapping provides us with a typical size of the BLR region (for a powerful blazar like 3C 279, this is $\sim 1.5 \times 10^{17}$ cm, following Kaspi et al. 2000), but not with its geometry. If the BLR has a flattened geometry (see Fig. 4) with radius $\sim 10^{17}$ cm, then at a distance of $\sim 10^{18}$ cm from the central engine, where the blazar emission site lies, the BLR photons illuminate the blazar from behind, and their comoving energy density scales as $1/\Gamma^2$, instead of $\Gamma^2$ for the case where the BLR enclosed the blazar site. This results to a strong decrease of the EC emission. We note that several independent arguments (e.g. Wills & Browne 1986, Maiolino et al. 2001, Rokaki et al. 2003) for a flattened BLR geometry have been advanced in the literature, making this scenario very plausible.

GLAST observations of high Compton dominance blazars will be critical in establishing this new picture that not only address the mechanism of the GeV emission, but also provide constraints on the spatial distribution of the gas clouds close to the central engine.

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Figure 4. A pita-like BLR on top of the accretion disk with a size $\sim 10^{17}$ cm and a blazar emission site at $\sim 10^{18}$ cm. In this geometry, the BLR comoving energy density drops by up to $\Gamma^4$ relative to the case of a spherical or shell-like BLR that encloses the blazar emission site.