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The properties of jet in luminous blazars under the equipartition condition

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HIGHLIGHTS

- The SEDs of 27 blazars were modeled under the equipartition relation.
- We derived the relations between observable quantities and physical parameters.
- The gamma-ray emission is dominated by superposition of different external components.

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ABSTRACT

In this work, we study the physical properties of the high-energy (HE) emission region by modeling the quasi-simultaneous multi-wavelength(MWL) spectral energy distributions (SEDs) of 27 Fermi-LAT detected low-synchrotron-peaked (LSP) blazars. We model the jets MWL SEDs in framework of a well accepted single-zone leptonic model including synchrotron self-Compton and external Compton (EC) processes for the jets in a state of equipartition between particle and magnetic field energy densities. In the model the GeV γ-ray spectrum is modeled by a combination of two different external Compton-scattered components: (i) EC scattering of photons coming from disk and broad line region (BLR), and (ii) EC scattering of photons originating from the dust tours (DT) and BLR. We find that the SEDs can be well reproduced by the equipartition model for the most majority of the sources, and the results are in agreement with many recent studies. Our results suggest that the SEDs modelling alone may not provide a significant constraint on the location of the HE emission region if we do not know enough about the physical properties of the external environment.

1. Introduction

Blazars are a subclass of radio-loud active galactic nuclei (AGNs), and typically exhibit substantial variability across the electromagnetic spectrum from radio to γ rays originating in a relativistic jet pointing toward us (Urry and Padovani, 1995). Traditionally, blazars are comprised of flat spectrum radio quasars (FSRQs) and BL Lac objects. In particular, FSRQs are the most interesting γ ray objects for studying the effects of jet acceleration as well as its interaction with the surrounding ambient medium. FSRQs show strong broad prominent emission lines and are commonly associated with high luminosity radio galaxies (Fanaroff-Riley type II [FR II]; Fanaroff and Riley, 1974) whereas BL Lacs have weak or absent emission lines and are associated with the lower luminosity Fanaroff-Riley type I [FR I]. The broadband continuum spectra of blazars are dominated by non-thermal emission and consist of at least two clearly distinct broad spectral components. In FSRQs the first component is usually in the infrared regime, while for BL Lacs it is between infrared and hard X-rays. It is commonly accepted that the first component is usually interpreted as synchrotron emission of electrons while the second component is believed to originate from inverse-Compton (IC) up-scattering off synchrotron (SSC; Maraschi et al., 1992; Bloom and Marscher, 1996) or external photons from the disk (ECD; Dermer and Schlickeiser, 1993; Dermer et al., 2009), or radiation reprocessed and scattered in nearby clouds (ECC; Sikora et al., 1994; Hu et al., 2015), and/or infra-red (IR) photons from the dusty obscuring torus (ECT; Blazejowski et al., 2000).

Therefore, the simultaneous and/or quasi-simultaneous MWL SEDs are a basic tool to study the underlying mechanisms of energy dissipation (Vlahakis and Königl, 2004; Marscher et al., 2008), and the physics properties of blazars, such as magnetic field strength, the Doppler factor, the and dimension and location

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of HE emission region. Based on the simultaneous and/or quasi-simultaneous MWL SEDs, many authors have studied the relevant properties of blazars in the framework of the leptonic model (e.g., Ghisellini et al., 2010; 2011; Ghisellini and Tavecchio, 2014; Gao et al., 2011; Yan et al., 2012; Kang et al., 2014). These works are based on the assumption of a spherical geometry model for the BLR and/or DT. However, some of the basic facts concerning the BLR in particular are still under debate. For instance, it is unclear whether the BLR has a spherical or flat geometry (Jarvis and McLure, 2006; Labita et al., 2006; Decarli et al., 2008; 2011). The knowledge of the BLR geometry of AGN plays a crucial role in estimating sites of the observed radiation spectra and black hole masses from the widths of the broad emission lines (Peterson, 1993; Peterson et al., 2004, and references therein). In addition, there is some observational evidence that BLR material may be present downstream of the radio core located at parsec scales from the central black hole (León-Tavares et al., 2010; 2013). Moreover, the location of the blazar γ-ray emission site is regarded as one of the central questions debated in the Fermi era. To date, it does not make clear whether the γ-ray emission is produced inside the sub-pc size BLR or further out at scales of about 1 - few pc where the IR photon field of the DT dominates over that of the UV field of the BLR (e.g., Tavecchio et al., 2010; Marscher et al., 2010; Agudo et al., 2011; Liu et al., 2011; Dotson et al., 2012; Harris et al., 2012; Orienti et al., 2013; Kang et al., 2014; Nalewajko et al., 2014).

As mentioned above, one should take into account such uncertainties as location of blazar zone and geometry of the external radiation fields. The paper is structured as follows: Section 2 provides a description of the SEDs modeling for a sample of Fermi-detected blazars. Section 3 describe the sample, and Section 4 show the results of the SEDs modeling. The summary and discussions are presented in Section 5. Throughout the work, we adopted a standard cosmology with parameters $H_0 = 70\,\mathrm{km/s/Mpc}$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$.

2. The modeling procedure of the observed SEDs for fermi-detected blazars

In a relativistic jet, an emission region responsible for the high energy γ ray emission propagates with relativistic speed $\beta_b = (1 - 1/\Gamma_b)^{1/2}$ outward along the jet, which is directed at an angle $\theta_{obs} = \cos^{-1}\mu_{obs}$ with respect to the line of sight. Thus, the observed photons are beamed and Doppler-boosted towards the observer, and the Doppler boosting of emission is determined by the Doppler factor $\delta_b = [\Gamma_b(1 - \beta_b\mu_{obs})]^{-1}$. The emission region is modeled as a spherical magnetized plasma cloud of radii R'_b which consists of a randomly oriented magnetic field B' and a population of isotropic relativistic particles. The electron energy distribution (EED) reconstructed from the observed SEDs of luminous blazars is best approximated by a broken power law form with normalization k'_e between $\gamma'_{\min}$ and $\gamma'_{\max}$, with slopes p_1 and p_2 below and above the break at γ'_{br}, and is given by,

$$n'_e(\gamma') = k'_e \begin{cases} (\gamma'/\gamma'_{br})^{-p_1} & \text{for} \quad \gamma'_{min} \le \gamma' \le \gamma'_{br} \\ (\gamma'/\gamma'_{br})^{-p_2} & \text{for} \quad \gamma'_{br} < \gamma' \le \gamma'_{max} \end{cases} \tag{1}$$

In the HE emission region, the electrons emit via synchrotron and IC mechanisms, which are well known as the basic radiative processes in blazar jets (e.g., Ludovic and Gilles, 2004; Crusius and Schlickeiser, 1986; Blumenthal and Gould, 1970; Dermer and Schlickeiser, 2002; Dermer et al., 2009; Tang et al., 2010).

In order to deduce model parameters including δ_b, B', R'_b, γ'_{br}, and k'_e, we infer the analytic relations between the relevant physical parameters of the considered model and the observable quantities provided by the observed SEDs including the peak synchrotron frequency $\nu_{s,\,pk}$, its luminosity $\nu^{pk}_{syn}L^{pk}_{syn}$, the SSC dominance factor ξ_s (or the peak SSC luminosity $\nu^{pk}_{ssc}L^{pk}_{ssc}$) and the peak SSC frequency ($\nu_{c,\,pk}$). The analytic results are described in Appendix A, where we also show how the other parameters characterising the non-thermal EED are constrained by the observed SEDs. In our fitting procedure, a visual inspection of the fitted SEDs is used, and the parameters are estimated in such a way as to best reproduce the observed MWL SEDs of all LSP blazars, and we would like to do this by varying the least number of parameters possible between objects. Finally, the model parameters are used to calculate the synchrotron, synchrotron Self-Compton and external Compton-scattered fluxes, and the formula for calculating the SEDs are given in Finke et al. (2008) and Dermer et al. (2009). In our numerical calculation the higher-order SSC components and synchrotron self-absorption (SSA) are considered consistently. In particular, we assume that a equipartition relation holds between the magnetic-field and relativistic electron energy densities, i.e., $\xi_e = 1$, which is supported by previous works (e.g., Ghisellini et al., 2010; Yan et al., 2012; Cao and Wang, 2013) and numerical modeling of the observed SEDs (e.g., Böttcher and Chiang, 2002; Schlickeiser and Lerche, 2007; 2008). The principle of equipartition provides a minimum power solution for blazars jet emissions, when the synchrotron peak dominated (Dermer and Atoyan, 2004; Finke et al., 2008; Dermer et al., 2014).

2.1. Calculations of external Compton scattering

In the case of isotropic soft photon field, the Compton spectral flux is calculated by

$$\epsilon F^{iso}_{\epsilon} = \frac{cV'_b\epsilon_s^2\delta_b^3}{4\pi d_L^2}\int_0^\infty d\epsilon_*\frac{u_*(\epsilon_*)}{\epsilon_*}\int_{\gamma_{min}}^{\gamma_{max}} d\gamma\, n'_e(\gamma/\delta_b)P_{iso}(\epsilon_s,\gamma,\epsilon_*) \tag{2}$$

where $\epsilon = (1+z)\epsilon_s$, $V'_b = 4\pi R'^3_b/3$ is the comoving volume of the blob, and the differential scattering cross section is $P_{iso}(\epsilon_s,\gamma,\epsilon_*) = \frac{3\sigma_T}{4\epsilon_*\gamma^2}\left[2x\ln x + x + 1 - 2x^2 + \frac{(4\epsilon\gamma x)^2}{2(1+4\epsilon\gamma x)}(1-x)\right]H(x;\,\frac{1}{4\gamma^2},1)$, with $x = \frac{\epsilon_s}{4\epsilon_*\gamma(\gamma-\epsilon_s)}$. The lower limit $\gamma_{\min}$ and the upper limit $\gamma_{\max}$ implied by the kinematic limits on x are given by

$$\gamma_{min} = \frac{1}{2}\epsilon_s\Big(1+\sqrt{1+\frac{1}{\epsilon_*\epsilon_s}}\Big), \quad \text{and},$$
$$\gamma_{max} = \frac{\epsilon_*\epsilon_s}{\epsilon_* - \epsilon_s}H(\epsilon_* - \epsilon_s) + \delta_b\gamma'_{max}H(\epsilon_s - \epsilon_*), \tag{3}$$

where the Heaviside function $H(x) = 0$ for $x < 0$ and $H(x) = 1$ for $x \geq 0$. The specific energy density $u_*(\epsilon_*)$ is expressed as a graybody, and is given by Planck's law:

$$u_*(\epsilon_*) = \varsigma\frac{8\pi m_e c^2}{\lambda_c^3}\frac{\epsilon_*^3}{\exp(\epsilon_*/\Theta)-1} = \frac{15u_*}{(\pi\Theta)^4}\frac{\epsilon_*^3}{\exp(\epsilon_*/\Theta)-1} \tag{4}$$

where $\lambda_c = h/m_e c = 2.43\times10^{-10}\,\mathrm{cm}$ is the electron Compton wavelength, m_e is the rest mass of electron, c is the speed of light, and h is Planck's constant. Here, the factor $\varsigma \equiv \frac{u_*}{aT_*^4}$, where u_* is the energy density of the external radiation field with a dimensionless temperature $\Theta \equiv k_B T_*/m_e c^2$, and the radiation constant can be defined in terms of the Boltzmann's constant k_B as $a \equiv \frac{8\pi^5 k_B^4}{15h^3c^3} = 7.57\times10^{-15}\,\mathrm{ergs/cm^3/K^4}$. Thus, a blackbody is a graybody with $\varsigma = 1$.

In the case of anisotropic soft photon field from an accretion disk, the ϵF_ϵ flux is given by

$$\epsilon F^{aniso}_{\epsilon} = \frac{cV'_b\epsilon_s^2\delta_b^3}{4\pi d_L^2}\oint d\Omega_*\int_0^\infty d\epsilon_*\frac{u_*(\epsilon_*,\Omega_*)}{\epsilon_*}$$
$$\times\int_{\gamma_{min}}^{\infty} d\gamma\, n'_e(\gamma/\delta_b)P_{ho}(\epsilon_s,\gamma,\overline{\epsilon}) \tag{5}$$

where the differential scattering cross section is $P_{ho}(\epsilon_s,\gamma,\overline{\epsilon}) = \frac{3\sigma_T}{8\gamma^2\epsilon_*}\left[y + y^{-1} - \frac{2\epsilon_s}{\gamma\overline{\epsilon}y} + \left(\frac{\epsilon_s}{\gamma\overline{\epsilon}y}\right)^2\right]H(\epsilon_s;\,\frac{\overline{\epsilon}}{2\gamma},\frac{2\gamma\overline{\epsilon}}{1+2\overline{\epsilon}})$, with $y \equiv 1 - \frac{\epsilon_s}{\gamma}$. Here the invariant energy $\overline{\epsilon} = \gamma\epsilon(1-\beta\cos\psi) \simeq \gamma\epsilon(1-\mu\mu_{obs})$,