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Multi-Wavelength Variability in PKS 2155-304

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Abstract. We study multi-wavelength variability in BL Lacertae object PKS 2155-304 in the frame of the time dependent one-zone synchrotron self-Compton (SSC) model, where stochastic particle acceleration is taken into account. In this model, a homogeneously and isotropically spherical structure is assumed, the Fokker–Planck type equation which describes the evolution of the particles energy is numerically solved, and the synchrotron and self-Compton components from the spherical blob are calculated. Our results can reproduce observed spectra energy distribution (SED) and give definite predictions for the flux and spectral variability of PKS 2155-304. We find that particle injection rate, magnetic field and Doppler factor in the acceleration zone are important parameters for explaining its flaring behaviour.

Key words. Radiation mechanisms: non-thermal—galaxies: active—galaxies: individual: PKS 2155-304.

1. Introduction

PKS 2155-304 is a typical high energy peak BL Lac object (HBL), characterized by two bumps in the spectral energy distribution (SED). So far HBLs have been successfully explained with a pure and homogeneous synchrotron self-Compton model (e.g., Mastichiadis & Kirk 1997; Krawczynski *et al*. 2002). On the nights of July 27–28 and July 29–30, 2006, PKS 2155-304 was exceptionally active, with two major γ-ray flares. During the latter nights, simultaneous observations performed with Chandra, HESS, and Bronberg optical observatory showed a surprising behaviour (Aharonian *et al*. 2009). In this paper, using the simultaneous observational results of BL Lacertae object PKS 2155-304 in July 2006 (Aharonian *et al*. 2009), we attempt to model the multi-wavelength variability in PKS 2155-304. We assume that the acceleration process is a stochastic process and we describe it as the diffusion of the particle momentum. Throughout the paper, we assume the Hubble constant $H_0 = 70$ km s^{-1}Mpc^{-1}, the matter energy density $\Omega_M = 0.27$, the radiation energy density $\Omega_r = 0$ and the dimensionless cosmological constant $\Omega_\Lambda = 0.73$.

2. The model

Assuming that accelerated particles have an isotropic diffusion in momentum space, the evolution of the energetic particle distribution can be described by the momentum diffusion equation (Tverskoi 1967). For a specific source, we have assumed that the particles are ultra-relativistic, $\beta \approx 1$, so the momentum becomes equivalent to the Lorentz factor of particle ($p = \gamma$). After including injection, radiation and escape of the particles, the momentum diffusion equation can be rewritten as:

$$\frac{\partial N(\gamma,t)}{\partial t} = \frac{\partial}{\partial \gamma}\left\{[C(\gamma,t) - A(\gamma,t)]N(\gamma,t) + D(\gamma,t)\frac{\partial N(\gamma,t)}{\partial \gamma}\right\} + Q(\gamma,t) - E(\gamma,t) \ ,$$

where $C(\gamma,t) = (\mathrm{d}\gamma/\mathrm{dt})_{\mathrm{syn}} + (\mathrm{d}\gamma/\mathrm{d}t)_{\mathrm{IC}}$, is the radiative cooling parameter that describes the synchrotron and inverse-Compton cooling of the particles; $N(\gamma,t)$ is the particle distribution function at time t:

$$A(\gamma,t) = \frac{\gamma}{t_{\mathrm{acc}}} = \frac{2D(\gamma,t)}{\gamma}$$

is the acceleration term that describes the particle energy gain per unit time and the acceleration time $t_{\mathrm{acc}} = \gamma^2/2D(\gamma,t)$ is used; $D(\gamma,t)$ is the momentum-diffusion coefficient due to interactions with magnetohydrodynamic waves; $E(\gamma,t)$ represents escape term; $Q(\gamma,t)$ is the source term, here we consider continuous injection case, i.e., the particles are continuously injected at the lower energy ($1 \le \gamma \le 2$) and systematically accelerated up to the equilibrium energy (γ_{e}), where the acceleration l is fully compensated by cooling. In our model, for simplification, we take into account the decrease of the scattering efficiency in the Klein–Nishina regime using the approximation (Zdziarski 1986).

If the electron number density $N(\gamma,0)$ at time $t = 0$ is given, then the number density $N(\gamma,\Delta t)$ can be calculated at time $t = \Delta t$. The iteration of the above prescription gives the electron number density at an arbitrary time t (e.g., Chaiberge & Ghisellini 1999). After calculating the electron number density $N(\gamma,t)$ at time t, we can use the formulae given by Katarzynski *et al.* (2001) to calculate the synchrotron intensity $I_{\mathrm{s}}(\nu,t)$ and the intensity of the self-Compton radiation $I_{\mathrm{c}}(\nu,t)$, and then calculate the flux density observed at the Earth. Since at high energies the Compton photons may produce pairs by interacting with the synchrotron photons, this process may decrease the high energy radiation (Coppi & Blandford 1990; Finke *et al.* 2008). Katarzynski *et al.* (2001) analysed the absorption effect due to pair-production inside the source, they found that its process is almost negligible. On the other hand, very high energy (VHE) γ-photons from the source are attenuated by photons from the extragalactic background light (EBL). In our calculation, we use the absorption optical depth which is deduced by the average EBL model in Dwek & Krennrich (2005).

3. Multi-wavelength variability in PKS 2155-304

Using the one-zone SSC model for a spherical geometry, we can calculate multi-wavelength spectra in the lowest and highest states of PKS 2155-304 in July 2006.

Table 1. The modelling parameters for PKS 2155-304.

State	Lowest	Highest
Minimum Lorentz factor: $\gamma_{\rm min}$	1	1
Maximum Lorentz factor: $\gamma_{\rm max}$	10^7	10^7
Initial distribution of particles: $N_{\rm ini}$ (10^{-6}cm^{-3})	1.0	1.0
Size of the emission region: R (10^{17}cm)	0.55	0.55
Magnetic field: $B[G]$	0.033	0.013
Doppler factor: δ	21	24
Injection rate: $Q_{\rm inj}$ (10^{-6}cm^{-3}s^{-1})	7.0	for $t < 0.5R/c$, 175 otherwise, 7.0
Evolution time scales: $t_{\rm evo}$ $[R/c]$	15	15+6.8

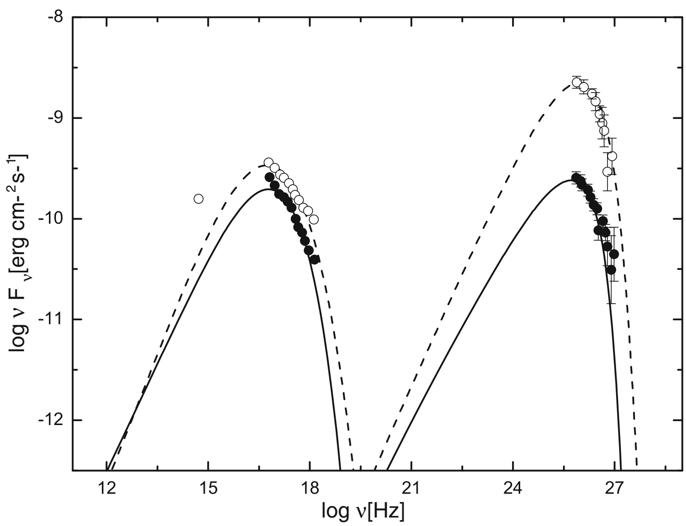

Figure 1. Comparison of predicted multi-wavelength spectra with observed data of PKS 2155-304 on July 29–30, 2006. Solid and dashed curves represent the lowest and the flaring (or highest) state spectra, respectively. The data points come from Aharonian *et al.* (2009).

We assume that relativistic electrons are in the steady state during the lowest state. Therefore, we can calculate the lowest multi-wavelength spectrum in the one-zone SSC model using the steady state electron spectrum (the parameters are shown in Table 1). In Fig. 1, we show predicted lowest spectrum from multi-wavelength (solid curve). For comparison, observed data of PKS 2155-304 in July, 2006 (Aharonian *et al.* 2009) are also shown, where black solid circles with error bars represent the observed values at the lowest state. It can be seen that the observed data in the lowest state can be reproduced in the SSC model. Then, we consider the properties of γ-ray flare of PKS 2155-304 in 2006 July. We use the physical parameters selected above and consider the resulting steady state spectrum as an initial condition, but we change the injection rate of the electron population, magnetic field and Doppler factor. Under the above assumptions, we reproduce the observed multi-wavelength photon spectrum (dashed curve) of PKS 2155-304 on July 29–30, 2006 in Fig. 1.

4. Discussions and conclusions

Despite the simple model, we have been successful in producing the spectra energy distribution (SED) and make definite predictions for the flux and spectral variability that can be seen in the synchrotron and self-Compton components. It is well known that two basic types of models can explain intrinsic variability. The first scenario assumes that the observed variations are related to changes in the geometry of emitting sources (Camenzind & Krockenberger 1992; Gopal-Krishna & Wiita 1992). When the emission blobs move with finite angular momentum on a helical trajectory, variabilities are generated by change of beaming factors (e.g., Wagner *et al*. 1995). The second scenario assumes that variabilities are generated by change of emission condition inside the jet. Typical examples are the injection of fresh particles, or acceleration of particles by a shock wave (Marscher & Gear 1985; Celotti *et al*. 1991; Kirk *et al*. 1998; Moraitis & Mastichiadis 2010). For fits to the highest state data of the BL Lac object PKS 2155-304, we change the injection rate of the electron population, magnetic field and Doppler factor. We reproduce the observed highest multi-wavelength photon spectrum of PKS 2155-304.

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