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Application of the synchrotron proton blazar model to BL Lac objects

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Abstract. We apply the synchrotron proton blazar (SPB) model to the April 1997 flare of Markarian 501 and find we are able to fit the observed spectral energy distribution. We explore the effect of target photon density on the high energy part of the spectral energy distribution (SED) for fixed assumed magnetic field, emission region size and Doppler factor and find that the luminosity and peak frequency of the high energy part of the SED may depend on the luminosity of the low energy part of the SED in high-frequency peaked BL Lac objects (HBL).

INTRODUCTION

The spectral energy distribution of blazars typically has a double-humped appearance usually interpreted in terms of synchrotron self-Compton models. In proton blazar models, the SED is instead explained in terms of acceleration of protons and subsequent cascading. We discuss a variation of the Synchrotron Proton Blazar model in which the low energy part of the SED is mainly synchrotron radiation by electrons (e) co-accelerated with protons (p) which are assumed responsible for the high energy part of the SED. We consider the case where the maximum energy of the accelerated protons is above the threshold for pion photoproduction interactions on the synchrotron photons of the low energy part of the SED.

Using a Monte Carlo/numerical technique to simulate the interactions and subsequent cascading of the accelerated protons, we are able to fit the observed SED of the HBL Markarian 501 during the April 1997 flare for a 12 hour variability time scale. The parameters used for modeling the April 1997 flare are: $D = 12$, $B \approx 20$ G, radius of the emission region $R_{\mathrm{blob}} = 8 \times 10^{15}$ cm, giving a photon energy density of this radiation field of $u_{\mathrm{target}} = 60$ GeV/cm^{-3}. The relevant radiation and loss time scales for photomeson production, Bethe-Heitler pair production, p synchrotron radiation, and adiabatic losses due to jet expansion, are shown in Fig. 1 together with the acceleration time scale. Proton synchrotron losses, which

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turn out to be at least as important as losses due to photopion production in our model, limit the injected p spectrum to a Lorentz factor of $\gamma_p \approx 3 \times 10^{10}$ for the assumed model parameters. We adopt a Kolmogorov spectrum of turbulence for the magnetic field structure, and from variability arguments constrain the shock angle (angle between magnetic field and shock normal) to $\theta_1 \geq 75°$. Note that due to the non-zero shock angle, the acceleration time scale shown in Fig. 1 does not follow a strict power-law, but is curved (see ref. [1] for details).

The accelerated p are assumed to follow a power law $\propto \gamma_p^{-2}$ between $2 \leq \gamma_p \leq \gamma_{p,\max} = 3 \times 10^{10}$, and in order to fit the emerging cascade spectra to the data a p number density of $n_p \approx 250\ \mathrm{cm}^{-3}$, corresponding to an energy density of accelerated protons of $u_p \approx 11.6\ \mathrm{TeV/cm}^{-3}$ is required. With a magnetic field energy density of $u_B \approx 11.7\ \mathrm{TeV/cm}^{-3}$ our model satisfies $u_{\mathrm{target}} \leq u_p \approx u_B$ (all parameters are in the co-moving frame of the jet), confirming that a significant contribution from inverse-Compton scattering is not expected.

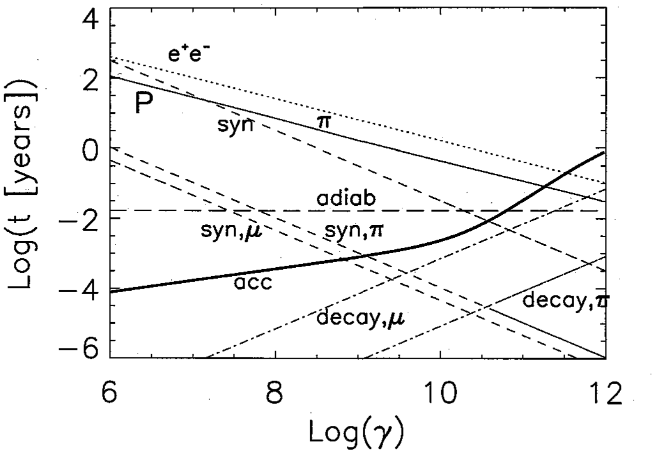

FIGURE 1. Mean energy loss time of p for π-photoproduction (π), Bethe-Heitler pair production (e^+e^-) and synchrotron radiation (syn). Loss times for $\pi^\pm$- and $\mu^\pm$ for synchrotron radiation (syn π, syn μ) are also shown and compared with their mean decay time scales (decay π, decay μ). The acceleration time scale (acc), based on Kolmogorov turbulence, is calculated for a compression ratio of 4, a shock velocity of $0.5c$ and shock angle $\theta_1 = 85°$. The adiabatic loss time (adiab) is assumed to be $2|B/\dot{B}| \approx R/u_1 \approx Dt_{\mathrm{var}}$. We adopt $B \approx 20$ G, and all quantities are in the co-moving frame of the jet. (Adapted from ref. [1])

RESULTS AND DISCUSSION

We use the Monte-Carlo technique to simulate particle production and cascade development, and this allows us to use exact cross sections. For photomeson production we use the Monte-Carlo code SOPHIA [2], and Bethe-Heitler pair production is simulated using the code of Protheroe & Johnson [3]. We calculate the yields for both processes separately, and the results are then combined according to their relative interaction rates. A detailed description of the code is given in ref. [1].

The results for the Markarian 501 flare are shown in Fig. 2. We find that the emerging cascade spectra initiated by gamma-rays from π^0 decay and by $e^\pm$ from $\mu^\pm$ decay turn out to be relatively featureless, synchrotron radiation produced by $\mu^\pm$ from $\pi^\pm$ decay, and even more importantly by protons, and subsequent synchrotron-pair cascading, is able to reproduce well the high energy part of the SED. For this fit we find that synchrotron radiation by protons dominates the TeV emission, pion photoproduction being less important with the consequence that we predict a significantly lower neutrino flux than in other proton blazar models.

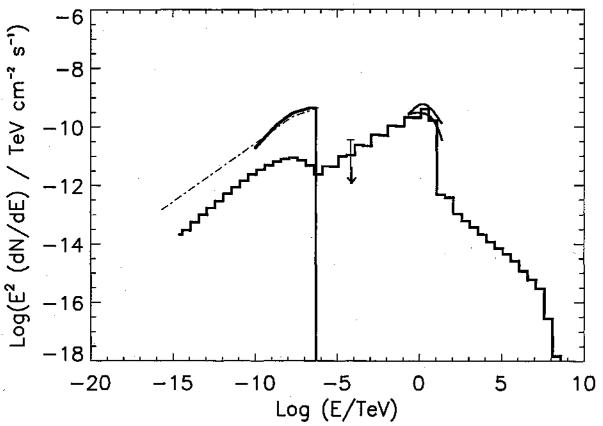

FIGURE 2. Best-fit model (histogram) in comparison with the data of the 16 April 1997-flare of Mkn 501. Photon absorption on the cosmic diffuse background radiation field is not included. Straight solid lines: parametrization of the observed synchrotron spectrum (BeppoSAX & OSSE) and observed TeV-emission corrected for cosmic background absorption for two different IR background models [4]; the 100 MeV upper limit is from ref. [5] (observed 9-15 April 1997); dashed-dotted line: input target spectrum. (Adapted from ref. [1])

We are in the process of applying the SPB model to other blazars and have made predictions of the high energy part of the SED at the source (i.e. not taking account of propagation to Earth through the IR background). We show in Fig. 3 preliminary results [6] for HBLs assuming $B = 30$ Gauss, $D = 10$, and $R = 10^{16}$ cm, but for different e-synchrotron luminosities. The broken power law curves at the left give the assumed e-synchrotron spectra (which serve as the target field for pair-cascading and pion production) for $\log(\nu L_\nu^{\rm max,syn}/{\rm erg\ s^{-1}}) = 42.5$, 43.5, 44.5, and 45.5, and the histograms to the right give the corresponding contribution to the SED due to p acceleration and interaction. The cutoff energy of the p particle spectrum increases with decreasing target photon density $u_{\rm phot}$, and is determined by pion production for high $u_{\rm phot}$ and by p synchrotron radiation for low $u_{\rm phot}$.

The required total jet luminosity is $(L_{\rm jet}/10^{46}{\rm erg\ s^{-1}}) = 2$, 2, 2 and 2.5 corresponding to the four $\nu L_\nu^{\rm max,syn}$ values above. For decreasing target photon densities (i.e. lower $\nu L_\nu^{\rm max,syn}$) the contribution of the total power from accelerated p to the low energy part of the SED diminishes due to the lower contribution of synchrotron radiation from muons produced as a result of pion production and as a result of lower target photon density for pair synchrotron cascading. The ratio of the low to high energy peak of the cascade spectrum is mainly determined by opacity effects.

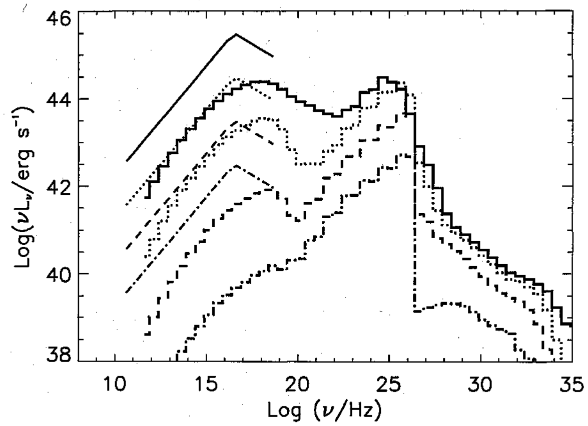

FIGURE 3. SPB model predictions for HBL with broken power-law synchrotron photon spectra $\propto \nu^{-1.5}$ below $\nu_b = 5 \times 10^{16}$ Hz (observer frame) and $\propto \nu^{-2.25}$ above ν_b with $\log(\nu L_\nu^{\rm max,syn}/{\rm erg\ s^{-1}}) = 42.5$, 43.5, 44.5, 45.5, and $B = 30$ Gauss, $D = 10$, $u_B = u_P$, $R = 10^{16}$ cm (jet frame) giving $\log(u_{\rm phot}/{\rm eV\ cm^{-3}}) = 9$, 10, 11 and 12, respectively.

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