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ASTRONOMY AND ASTROPHYSICS

Spectral Variability in PKS 0528+134 at Gamma-Ray Energies

M. Böttcher[1] **and W. Collmar**[2]

[1] Rice University, Space Physics and Astronomy Department, 6100 S. Main Street, Houston, TX 77005 – 1892, USA
[2] Max-Planck-Institut für Extraterrestrische Physik, Postfach 16 03, D — 85 740 Garching, Germany

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Abstract. We present model calculations to the observed spectral variability in the γ-ray spectrum of the ultraluminous blazar-type quasar PKS 0528+134. We argue that the observed appearance of a spectral break between the COMPTEL and the EGRET energy range can plausibly be explained by a variation of the Doppler beaming factor in the framework of a relativistic jet model for AGNs, combining the ERC and the SSC model. This may be an instructive example for the different dependence of these two spectral components on the Doppler factor, as predicted in earlier work.

Key words: galaxies: active — quasars: individual — gamma-rays: observations — gamma-rays: theory

1. Introduction

Up to now, more than 50 blazar-type AGN have been detected by EGRET as emiters of high-energy γ-rays above 100 MeV (Mattox et al. 1997). These sources are identified with flat-spectrum ($\alpha >$ -0.5) radio sources classified as QSOs and BL Lac objects. A large fraction of these blazars exhibits variability at γ-ray energies on time scales of days to months (Mukherjee et al. 1997). At radio wavelengths, all blazars can be recognized as bright, compact sources with a flat synchrotron spectrum emanating from outflowing plasma jets that are nearly aligned with our line of sight. Relativistic beaming is required in the objects in view of the luminosity and variability time scales (Dermer and Gehrels 1995), in accord with VLBI observations indicating that superluminal motion is a common feature in this class of AGN (e. g., Pohl et al. 1995, Barthel et al. 1995, Krichbaum et al. 1995).

One of the most luminous examples of this class of objects is the quasar PKS 0528+134. It is known as a bright radio source with a flat radio spectrum. Recent VLBI images show a one-sided core-jet structure of ~ 5 mas length and superluminal motion (Pohl et al. 1995). An optical spectrum, obtained in November 1991 with the ESO 3.6 m telescope at La Silla / Chile, revealed a redshift of z = 2.07 (Hunter et al. 1993). At X-rays, the source was first detected with the Einstein observatory (Bregman et al. 1985). At γ-ray energies, PKS 0528+134 is detected by EGRET, COMPTEL and OSSE aboard the Compton Gamma-ray Observatory (CGRO) (Mukherjee et al. 1996, Collmar et al. 1997, McNaron-Brown et al. 1995), showing a time-variable γ-ray flux with intensity variations up to a factor of $\sim$20 (Mukherjee et al. 1996). The broadband spectrum of PKS 0528+134 reveals that during γ-ray high states its total energy output is dominated by its γ-ray emission. Under the assumption of isotropic emission, the total luminosity of the object during γ-ray high states would be $L_{iso} \approx 10^{49}$ ergs s^{-1} (throughout this paper, we use $H_0 = 75$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$).

The strongest EGRET blazar detections can be characterized by a single power-law spectrum with differential photon spectral indices $1.5 \leq s \leq 2.7$ (Thompson et al. 1995). In some cases, such as PKS 0528+134 (Mukherjee et al. 1996), the EGRET spectrum (30 MeV - $\sim$10 GeV) seems to harden during γ-ray flares. A recent analysis of the first 3.5 years of COMPTEL observations of PKS 0528 +134 (Collmar et al. 1997) indicated a correlation between its γ-ray flux and the occurence of a spectral break at MeV energies. During states of high γ-ray intensity the combined EGRET and COMPTEL spectra ($\sim$1 MeV to $\sim$10 GeV) are characterized by a spectral break between the EGRET and the COMPTEL energy range, while during γ-ray low states the γ-ray spectrum from MeV to GeV energies is consistent with a single power-law.

Measurements of broadband spectral variability in γ-ray blazars can put the most severe constraints on models for these objects. By now, it is widely accepted that the high-energy emission of flat-spectrum radio quasars and BL Lac objects is produced by inverse-Compton scattering of soft radiation off ultrarelativistic electrons (and positrons) in a relativistic jet directed at a small angle

Send offprint requests to: M. Böttcher with respect to our line of sight (e. g. Schlickeiser 1996). A major subject of debate is the source of the soft photons which are upscattered to γ-ray energies. These can be synchrotron photons produced by the jet itself (the SSC model, e. g. Maraschi et al., 1992, Bloom & Marscher 1996), accretion disk radiation entering the jet directly (the ERC model, Dermer, Schlickeiser & Mastichiadis 1992, Dermer & Schlickeiser 1993) or after being rescattered by the broad line regions (Sikora, Begelman & Rees 1994), or jet radiation being reflected by a torus of cold material and reentering the jet (Ghisellini & Madau 1996).

Detailed investigations of the ERC model and of the SSC model have recently been presented by Dermer, Sturner & Schlickeiser (1997) and by Bloom & Marscher (1996), respectively. These reveal that sharp spectral breaks in the γ-ray spectra of blazars at several MeV favor the ERC mechanism as a possible explanation because such breaks cannot be produced by a homogeneous SSC model. In contrast, a smooth transition from a hard spectrum at X-ray and soft γ-ray energies to a softer EGRET spectrum seems indicative of SSC being the dominant radiation mechanism. Nevertheless, a pure version of one of these models seems to be an unrealistic simplification since both of these radiation mechanisms are plausibly at work in relativistic AGN jets. A synthesis of both models has been investigated in detail by Böttcher, Mause & Schlickeiser (1997).

Dermer et al. (1997) have shown that the ERC radiation exhibits a stronger dependence ($F_{ERC}(\epsilon) \propto D^{3+s}$) on the Doppler factor $D = (\Gamma\,[1 - \beta_\Gamma \cos\theta_{obs}])^{-1}$ than the SSC component ($F_{SSC}(\epsilon) \propto D^{(5+s)/2}$). Here, $\Gamma = (1-\beta_\Gamma)^{-1/2}$ is the bulk Lorentz factor of the ultrarelativistic jet plasma and s is the spectral index of the initial particle distribution function. The kind of spectral variability as observed in PKS 0528+134 can therefore easily be explained by a change in the Doppler factor (i. e. a change in the bulk Lorentz factor or in the angle θ_{obs} between the direction of motion and the line of sight) in the framework of a combined SSC/ERC model. According to this idea, we suggest that in the case of PKS 0528+134 the SSC radiation dominates the γ-ray spectrum in the γ-ray low state (with no spectral break in the COMPTEL regime required), while in the γ-ray high state an additional ERC component becomes dominant in the γ-ray spectrum at energies around 10 MeV. In this Letter, we present model calculations demonstrating the viability of this idea.

2. The model

To produce spectral fits to PKS 0528+134 we use the combined ERC/SSC model described in detail by Böttcher et al. (1997). We assume a spherical blob filled with ultrarelativistic pair plasma which is moving out along an existing jet structure perpendicular to an accretion disk around a black hole of $M = 5\cdot10^{10} M_\odot$. The luminosity of the accretion disk is assumed to be $L_0 = 5\cdot10^{46}$erg s^{-1}. The blob moves with a constant bulk Lorentz factor Γ. The particles inside the blob are isotropically distributed according to a power-law $n(\gamma) \propto \gamma^{-s}$ for $\gamma_1 \le \gamma \le \gamma_2$ in the rest frame of the blob. We assume reacceleration in the initial phase to be inefficient in comparison to radiative cooling of the pairs and follow the self-consistent evolution of the pair distribution as the blob moves out, taking into account synchrotron radiation, SSC scattering to arbitrarily high order, ERC scattering, γ-γ absorption and pair production. Comparison to observations is made on the basis of the time-averaged flux of a blob since the inferred cooling timescale of the material in the blob (in the observer's frame) is shorter than the time resolution of COMPTEL and EGRET.

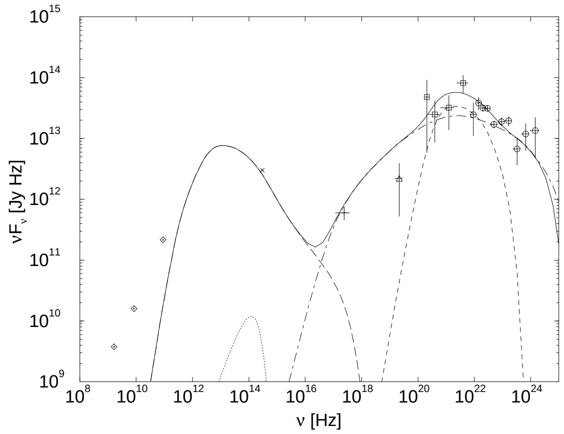

Fig. 1. Fit to the (non simultaneous) broadband spectrum of PKS 0528+134. Parameters: $\gamma_1 = 2\cdot10^3$, $\gamma_2 = 9\cdot10^4$, $s = 3.0$, $n = 60\,\mathrm{cm}^{-3}$, $R_B = 4\cdot10^{16}$ cm, $B = 1.3$ G, $z = 4\cdot10^{-1}$ pc, $L_0 = 5\cdot10^{46}$ erg s^{-1}, $\Gamma = 20$, $\theta = 2.5°$. Dashed: ERC, dot-dashed: SSC, long dashed: synchrotron, dotted: accretion disk, solid: total

In our model we assume the ejection of individual plasma blobs with different bulk Lorentz factors and slight differences in the internal energy distributions of the material in the blob. These are described by the following parameters: $\gamma_{1,2}$ (the low- and high-energy cutoffs in the Lorentz factors of the electrons), s (the power-law index of the electon distribution), B (the magnetic field), Γ (the bulk Lorentz factor of the blob), θ_{obs} (the angle between the line of sight and the jet axis), z (the starting height of the center of the blob above the accretion disk).

3. Spectral fits

In this section, we compare the results of model calculations to the spectra of PKS 0528+134 demonstrating the viability of the combined ERC/SSC model to explain the broadband spectrum as well as the peculiar spectral variability of this object. As a first step, we produce a fit to the (non simultaneous) broadband spectrum of PKS 0528+134 which is shown in Fig. 1. The radio data are taken from Reich et al. (1993). The optical data point is still under debate because PKS 0528+134 is located behind a strongly absorbing cloud of interstellar material, and the correct dereddening factor is unclear (Wagner 1997, private communication). Here, we use the same optical point as used by Mukherjee et al. (1996). The ROSAT point is taken from Zhang et al. (1994), and the OSSE data point is from McNaron-Brown et al. (1995). The contemporaneous COMPTEL and EGRET data from Viewing Period (VP) 0 (April 1991) are taken from Collmar et al. (1997).

Even though the broadband spectrum shown in Fig. 1 is not measured simultaneously, it gives us an idea of the parameters to be used in the detailed fits to the γ-ray spectra in the high and low states of PKS 0528+134, as presented by Collmar et al. (1997). In the model described above, it is assumed that the radio spectrum (below $\sim$ 100 GHz) is predominantly produced in the more distant parts of the jet, because the γ-ray emitting plasma is optically thick to synchrotron self-absorption at radio frequencies. The OSSE data point is not reproduced by our fit because it has not been measured contemporaneously with the γ-ray spectrum and does therefore not correspond to the γ-ray high state. (Figure 2, however, illustrates that our spectral fit to the γ-ray low state is in good agreement with the OSSE spectrum at that time.)

Fig. 1 demonstrates that the spectral break between the COMPTEL and the EGRET energy range can well be explained by an ERC component dominating the spectrum at energies around 10 MeV in the γ-ray high state. The strong spectral break being located at $\sim$ 10 MeV constrains the input soft photons to the component causing this break to a relatively low energy. Given the required total luminosity of the disk photon field, this leads us to the conclusion of an accretion disk radiates at only ≈ 1 % of the Eddington luminosity for a central black-hole mass of $\sim 5 \cdot 10^{10}\, M_{\odot}$, which is consistent with dynamical studies of the central region of PKS 0528+134. The size of the emitting region of $R_B = 4 \cdot 10^{16}$ cm is consistent with the timescale of $\sim$ 2 days for intensity variations of order 100 % as found recently by Wagner et al. (1997).

The low state, as shown in Fig. 2, could well be reproduced by a pure SSC model. For our fit to this state we used basically the same set of parameters as for the high state (Fig. 1), but a lower bulk Lorentz factor ($\Gamma = 7$ in the low state versus $\Gamma = 20$ in the high state). The different dependence of the SSC and the ERC component on the Doppler factor (Dermer et al. 1997) then causes the observed spectral variability in the γ-ray regime. Since we have no simultaneous observations at other wavelength bands, the fit to the non simultaneous radio to soft X-ray spectrum using our parameters for the low state (which is equally good as the one shown in Fig. 1) does not yield any physically relevant information. In all figures the SSC and ERC components are plotted without taking γ-γ absorption into account. In the calculation of the total spectrum as well as for the simulation of the evolution of the jet material, γ-γ absorption and pair production are included self-consistently. This is the reason for the (unabsorbed) SSC contribution being higher than the total escaping flux at high energies in the figures.

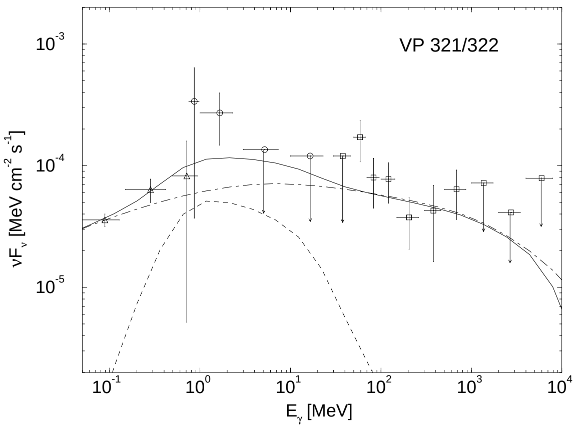

Fig. 2. Fit to the γ-ray (OSSE: triangles, COMPTEL: circles, EGRET: squares) spectrum of PKS 0528+134 in its low state (combined VP 321/322). Parameters are the same as for Fig. 1, except $\Gamma = 7$, $s = 2.8$. Dashed: ERC, dot-dashed: SSC, solid: total

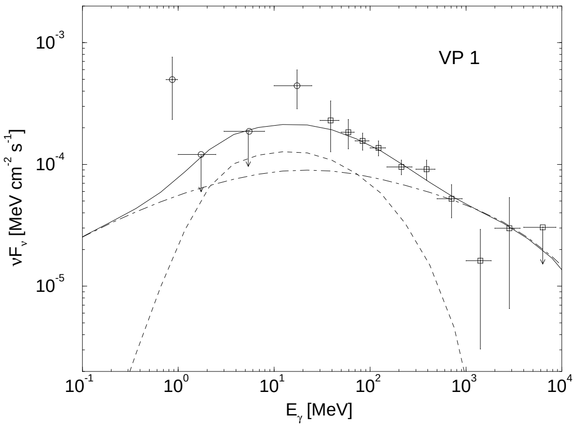

Fig. 3. Fit to the γ-ray (COMPTEL and EGRET) spectrum of PKS 0528+134 in its high state in VP 1. Parameters are the same as for Fig. 1, except $\gamma_1 = 2.4 \cdot 10^3$, $\gamma_2 = 8 \cdot 10^4$, $s = 3.1$, $\Gamma = 22$. Dashed: ERC, dot-dashed: SSC, solid: total

Figs. 3 and 4 illustrate that slight changes in the intrinsic particle distribution functions and the bulk Lorentz factor as compared to the fit shown in Fig. 1, lead to a good fit to the γ-ray high states observed in viewing period 1, while the state showing the highest flux in the history of these observations, found in VP 213, seems indeed to be exceptional and requires a very high bulk Lorentz factor and a significantly harder particle spectrum than the other states. Its γ-ray spectrum could equally well be

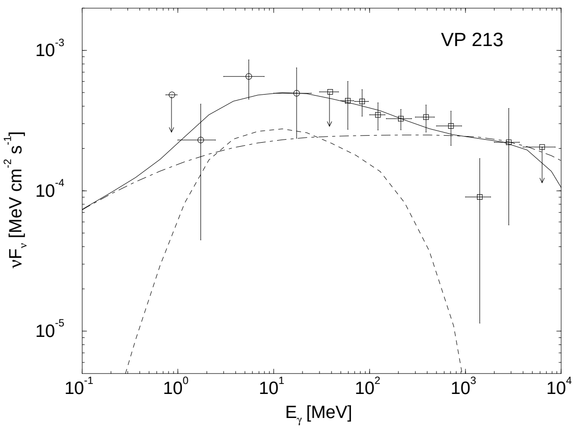

Fig. 4. Fit to the γ-ray (COMPTEL and EGRET) spectrum of PKS 0528+134 in its high state in VP 213. Parameters are the same as for Fig. 1, except $\gamma_2 = 10^5$, $s = 2.4$, $\Gamma = 25$. Dashed: ERC, dot-dashed: SSC, solid: total

reproduced with a pure ERC model, thus confirming the trend that the more luminous the object is in γ-rays the more dominant is the ERC component. The relevant parameters of the different fits are given in Table 1.

Table 1. Interesting model parameters for the different observational periods. F_{1-10^4} is the integrated flux F_ν from 1 MeV to 10 GeV of our model fits in units of keV cm^{-2} s^{-1}. The different γ-ray fluxes reflect mainly the different Lorentz factors Γ of the individual blobs.

Parameter	VP 321/322	VP 0	VP 1	VP 213
γ_1	$2 \cdot 10^3$	$2 \cdot 10^3$	$2.4 \cdot 10^3$	$2 \cdot 10^3$
γ_2	$9 \cdot 10^4$	$9 \cdot 10^4$	$8 \cdot 10^4$	10^5
s	2.8	3.0	3.1	2.4
Γ	7	20	22	25
F_{1-10^4}	0.6	1.1	1.1	3.3

4. Summary and conclusions

We presented model calculations on the spectral variability observed in the MeV to GeV spectrum of the ultraluminous blazar-type quasar PKS 0528+134. This quasar exhibits a peculiar spectral behavior between its γ-ray low and high states, indicative of an additional spectral component showing up around several MeV in the high state.

Our model fits demonstrate that a combined ERC / SSC model is very well suited to reproduce this behavior, based on the different dependence of the ERC and the SSC component on the Doppler boosting factor. In the γ-ray low state, the γ-ray spectrum can basically be reproduced as a pure SSC spectrum, while in the γ-ray high state, due to an increase in the bulk Lorentz factor of the jet, the ERC component becomes dominant over a significant part of the γ-ray spectrum, producing a spectral break around several MeV.

The spectral variability in PKS 0528+134 appears to be an interesting manifestation of the different Doppler boosting patterns of the ERC and the SSC radiation, as predicted earlier. A similar variation of the Doppler factor can, of course, also result from a change in the viewing angle. For example, the reduction of the beaming factor as appropriate to explain the spectrum of VP 321/322 (Fig. 2) can equally result from assuming a viewing angle of 4.7° (instead of 2.5° as used for our simulations) when leaving the bulk Lorentz factor constant at $\Gamma = 20$. The diagnostic on the Doppler factor presented in this Letter cannot distinguish between these two effects.

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