

# On magnetic fields in broad-line blazars

M. Sikora<sup>1</sup>, R. Moderski<sup>1</sup>, & A. Gałkowska<sup>2</sup>

<sup>1</sup>Nicolaus Copernicus Astronomical Center, Bartycka 18, 00-716 Warsaw, Poland

<sup>2</sup>Nicolaus Copernicus University, Inst. of Astronomy, Chopina 12/18, 87-100 Toruń, Poland

July 28, 2006

## Abstract

High energy spectra of broad-line blazars can be reproduced by both synchrotron-self-Compton (SSC) models and external-Compton (EC) models. However, as is known from numerical modeling, SSC scenarios require much weaker magnetic field than EC ones. In this paper we quantify these results analytically. We show that for blazars with  $q \equiv F_\gamma/F_{syn} \gg 1$  the SSC models predict a magnetic-to-electron energy density ratio lower than  $1/q^2$ , and that EC models allows equipartition between magnetic fields and electrons for any high  $q$  provided  $\Gamma \sim 16(q/10)^{1/2}(F_{syn}/F_d)^{1/4}$ , where  $\Gamma$  is the Lorentz factor of the source and  $F_d$  is the radiation flux from the accretion disk.

## 1 INTRODUCTION

Blazars – the AGNs dominated by the Doppler boosted radiation of the relativistic jets – provide an exceptional opportunity for studies of physics of innermost parts of AGN jets. However, to take advantage of this opportunity the radiative mechanisms of the jet emission must be identified. While a low-energy component of blazar spectra is uniquely identified as due to the synchrotron process, the nature of a high-energy component is still uncertain. It can be contributed by inverse-Compton (IC) radiation of directly accelerated electrons (hereafter by electrons we mean both electrons and positrons), by synchrotron radiation of pair cascades powered by hadronic processes and accompanying pair cascades, and, finally, by synchrotron emission of protons and muons (see review by Sikora & Madejski 2001). Seed photons for the IC process are provided by locally operating synchrotron mechanism as well as by external sources, like broad line region (BLR) and/or dusty tori. The IC models involving Comptonization of local synchrotron radiation are called synchrotron-self-Compton (SSC) models, and those involving Comptonization of external radiation are usually coined external-Compton (EC) models.

In this presentation we focus on blazars with a dense radiative environment, i.e. those hosted by quasars. Their  $\gamma$ -ray fluxes usually exceed fluxes of a low-energy, synchrotron spectral component by a large factor, and their X-ray spectra are often very hard. About 30% of them have X-ray spectral index  $\alpha_X < 0.5$  (Cappi et al. 1997; Reeves & Turner 2000; Donato, Sambruna, & Gliozzi 2005). Such spectra cannot be produced in a fast cooling regime. This practically eliminates models which predict production of X- and  $\gamma$ -rays by synchrotron emission of

ultrarelativistic electrons, and also put severe constraints on SSC models. We demonstrate that spectra of such blazars can be explained in terms of the SSC models only for magnetic fields much below the equipartition with electrons and that no such constraint applies for EC models provided a bulk Lorentz factor of the source is sufficiently high.

## 2 MAGNETIC FIELDS IN SSC AND ERC MODELS

We investigate here broad-line blazars (those hosted by quasars) with  $q \equiv F_\gamma/F_{syn} \gg 1$  and assume that their  $\gamma$ -ray component is produced by IC process. Both components are assumed to be produced by the same population of electrons which in the source co-moving frame have the isotropic distribution. Since in the broad-line blazars the KN and pair production effects are likely to be insignificant (Moderski et al. 2005), we ignore them in our considerations below. With all these assumptions

$$u'_\gamma/u'_{seed} = u'_{SSC}/u'_{syn} = u'_{syn}/u'_B = u'_{EC}/u'_{ext} = A \quad (1)$$

where  $A$  is the Thomson amplification factor,  $u'_B$  is the magnetic energy density, and  $u'_\gamma$ ,  $u'_{seed}$ ,  $u'_{syn}$ ,  $u'_{SSC}$ ,  $u'_{ext}$ ,  $u'_{EC}$ , are energy densities of  $\gamma$ -ray, seed photon, synchrotron, SSC, external and EC radiation fields, respectively, all as measured in the source co-moving frame.

### 2.1 Magnetic vs. radiation energy density

In the SSC model  $u'_{seed} = u'_{syn}$  and  $u'_\gamma = u'_{SSC}$ . Therefore,

$$q = \frac{F_\gamma}{F_{syn}} = \frac{u'_{SSC}}{u'_{syn}} = A, \quad (2)$$

and

$$\frac{u'_B}{u'_\gamma} = \frac{u'_{syn}}{u'_{SSC}} \frac{u'_B}{u'_{syn}} = \frac{1}{A^2} = \frac{1}{q^2}. \quad (3)$$

In the EC model  $u'_{seed} = u'_{ext}$  and  $u'_\gamma = u'_{EC}$ , and, therefore,

$$q = \frac{F_\gamma}{F_{syn}} = \frac{f u'_{EC}}{u'_{syn}}, \quad (4)$$

and

$$\frac{u'_B}{u'_\gamma} = \frac{u'_{syn}/A}{u'_{EC}} = \frac{f}{Aq}, \quad (5)$$

where the factor  $f \simeq (\mathcal{D}/\Gamma)^2$  accounts for anisotropy of IC radiation in the source comoving frame (Moderski et al.

2003) and  $\mathcal{D} \equiv 1/[\Gamma(1 - \beta \cos \theta_{obs})]$  is the Doppler factor. Note that here, in general,  $q \neq A$ .

Hence, in SSC models  $q \gg 1$  is possible only for  $u'_B \ll u'_\gamma$ , while EC can give  $q \gg 1$  even for  $u'_B > u'_\gamma$ , provided  $A < f/q$ .

## 2.2 Electron vs. radiation energy density

Let us approximate the geometry of the source as a piece of a cylinder, of a cross-sectional radius  $R$  and height  $\lambda'$  as measured in the source co-moving frame. An amount of energy accumulated in relativistic electrons during the time period of the injection of relativistic electrons is

$$E'_e = (1 - \eta_{rad})L'_{e,inj}t'_{inj}, \quad (6)$$

and energy density of the relativistic electrons is

$$u'_e = \frac{E'_e}{\pi R^2 \lambda'} = \frac{(1 - \eta_{rad})L'_{e,inj}t'_{inj}}{\pi R^2 \lambda'}, \quad (7)$$

where  $L'_{e,inj}$  is the the rate of the energy injection via acceleration of relativistic electrons,  $t'_{inj}$  is the injection time scale, and  $\eta_{rad}$  is the fraction of the total electron energy converted via radiative processes to photons. Energy of the radiation produced during the flare is  $E'_{rad} = \eta_{rad}L'_{e,inj}t'_{inj}$ , and energy density of the emitted radiation is

$$u'_{rad} = \frac{\eta_{rad}L'_{e,inj}}{2\pi R^2 c}, \quad (8)$$

provided  $\lambda' < R$ . Hence,

$$\frac{u'_{rad}}{u'_e} = \frac{\kappa \eta_{rad}}{1 - \eta_{rad}}. \quad (9)$$

where  $\kappa = \lambda'/(2t'_{inj}c)$ .

## 2.3 Magnetic vs. electron energy density

Noting that for  $q \gg 1$ ,  $u'_{rad} \simeq u'_\gamma$ , and combining equations (3), (5), and (9), we obtain for SSC model

$$\frac{u'_B}{u'_e} = \frac{1}{q^2} \frac{\kappa \eta_{rad}}{1 - \eta_{rad}}, \quad (10)$$

and for EC model

$$\frac{u'_B}{u'_e} = \frac{f}{Aq} \frac{\kappa \eta_{rad}}{1 - \eta_{rad}}. \quad (11)$$

In the broad-line blazars radiation efficiency  $\eta_{rad}$  is typically of the order of 0.5, and then, for  $\lambda' < 2ct'_{inj}$ , the SSC models of the high- $q$  blazars require magnetic fields much below equipartition,  $u'_B/u'_e < 1/q^2$ .

In the case of EC models, equipartition of magnetic fields with electrons is possible for any  $q$ , but requires

$$A \sim \frac{f}{q} \frac{\kappa \eta_{rad}}{1 - \eta_{rad}}. \quad (12)$$

Noting that

$$u'_{EC} = \frac{L'_\gamma}{2\pi R^2 c} = \frac{2F_\gamma}{c} \left(\frac{d_L}{R}\right)^2 \frac{1}{f\mathcal{D}^4} \quad (13)$$

and

$$u'_{ext} = \Gamma^2 \frac{\xi L_d}{4\pi r^2 c} = \Gamma^2 \frac{\xi F_d}{c} \left(\frac{d_L}{r}\right)^2, \quad (14)$$

we obtain

$$A = \frac{u'_{EC}}{u'_{ext}} = \frac{2F_\gamma}{\xi F_d} \frac{1}{f\mathcal{D}^4(\Gamma\theta_j)^2}, \quad (15)$$

where  $\xi$  is the fraction of the disk radiation reprocessed into broad lines and/or IR dust radiation at a distance  $r$  at which the flare is produced,  $\theta_j = R/r$ , and  $d_L$  is the luminosity distance of the blazar. Combining equations (12) and (15) gives the condition for the Doppler factor  $\mathcal{D}$  to have  $u'_B = u'_e$ ,

$$\mathcal{D} = \left(\frac{2q(1 - \eta_{rad})F_\gamma}{f^2 \eta_{rad} \kappa (\Gamma\theta_j)^2 \xi F_d}\right)^{1/4}. \quad (16)$$

For  $\mathcal{D} \sim \Gamma \sim 1/\theta_j$ ,  $\eta_{rad} \sim 0.5$ , and noting that  $F_\gamma/F_d = (F_\gamma/F_{syn})(F_{syn}/F_d) = q(F_{syn}/F_d)$ , we obtain

$$\Gamma \sim 16 \left(\frac{q}{10}\right)^{1/2} \left(\frac{\kappa}{(\xi/0.3)} \frac{F_{syn}}{F_d}\right)^{1/4}. \quad (17)$$

## 3 CONCLUSIONS

- **Large  $\gamma$ -ray excesses ( $q \gg 1$ ), observed in many broad-line blazars can be produced by SSC process only if  $B \ll B_{equip}$ .**
- **No such constraint applies to the ERC model, provided a jet Lorentz factor is respectively high:  $B \sim B_{equip}$  fits the model if  $\Gamma \sim (q/10)^{1/2}(F_{syn}/F_d)^{1/4}$ .**

## REFERENCES

- Cappi, M. et al. 1997, *ApJ*, 478, 492  
 Donato, D., Sambruna, R.M., & Gliozzi, M. 2005, *A&A*, 433, 1163  
 Moderski, R., Sikora, M., Błażejowski, M. 2003, *A&A* 406, 855  
 Moderski, R., Sikora, M., Coppi, P.S., Aharonian, F. 2005, *MNRAS*, 364, 1488  
 Reeves, J.N., & Turner, M.J.L. 2000, *MNRAS*, 316, 234  
 Sikora, M., Begelman, M.C., Madejski, G.M., Lasota, J.-P. 2005, *ApJ*, 625  
 Sikora, M., Madejski, G.M. 2001, in "High Energy Gamma-Ray Astronomy", AIP Conference Proceedings 558 (eds F.A. Aharonian & H.J. Völk), p. 275