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Learning about Jets from Observations of Blazars

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Abstract. Jets, paving their way outward through the inner regions of active nuclei, Compton-interact with the UV radiation from an accretion disc and broad emission line region. We calculate the predicted properties of the resulting spectral signatures of this bulk-Compton process, noting that they are *independent* on the fractional proton content or kinetic power of the jet, and use the presence or absence of such signatures to put constraints on the structure of jets near their bases.

1. Introduction

As it was pointed out by Begelman & Sikora (1987), the bulk-Compton interaction of a jet with the UV radiation of an accretion disc should lead to the production of the soft X-ray "bump" in the spectra of FSRQ (flat-spectrum-radio-quasars). Furthermore, the velocity modulation of the jet flow by the central engine should result in a formation of soft X-ray precursors of non-thermal flares produced in internal shocks (Sikora & Madejski 2002). The strength of such soft X-ray spectral features depends on the bulk Lorentz factor of a jet, Γ, the electron number flux, $\dot{N}_e$, and the energy density of the ambient radiation field, u_{ext}. Since u_{ext} depends on the distance from the central engine, constraints imposed by observations on the magnitude of the bulk-Compton features can be used to probe the spatial scale of the jet formation process. We calculate the luminosity of the soft X-ray features using Γ and $\dot{N}_e$ as derived from the EC (external Compton) model of γ-ray production in FSRQ (Sikora, Begelman, & Rees 1994) for two jet models: in one, the flow is steady-state, and in another, the jet is composed from discrete ejecta. In the former case, non-thermal events can be powered by reconnection of magnetic fields, as it is likely to take place in the Poynting flux dominated flows (see, e.g. Drenkhahn & Spruit 2002; Blandford 2000); in the latter case they are powered by collisions of ejecta which lead to formation of internal shocks (Sikora et al. 1994, 2001; Spada et al. 2001). We demonstrate that the lack of prominent soft X-ray excesses, and of soft X-ray precursors of the non-thermal flares in available data implies that quasar jets are formed on scales $> 10^{17}$cm, and/or that inner parts of an accretion disc are radiatively inefficient, where the angular momentum is transported outwards by other means than viscosity in the disk.

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2. Non-thermal radiation

One of the biggest surprises inferred from the EGRET data was the finding that during the high states of FSRQ the γ-ray fluxes exceed those in other spectral bands by a very large factor, $\sim$ 10-100 (von Montigny et al. 1995). Soon after that discovery it was realized that the exceptionally high γ-ray luminosities of FSRQ can result from Comptonization of external radiation fields. Indeed, the data collected during the entire period of the CGRO mission strongly supports that idea. All main features of the high energy spectra of FSRQs during outbursts can naturally be explained in terms of the external-Compton (EC) model (see review by Sikora & Madejski 2001). In particular, the distances of production of short γ-ray flares in a jet, as inferred from their variability time scales, agree well with the estimates of the distance based on the assumption that the spectral break observed in the $1 - 30$ MeV range results from the cooling break in the electron energy distribution.

In the simplest version of the EC model, electrons responsible for the nonthermal radiation in FSRQ are injected with a single power law distribution, $Q = K\gamma^{-p}$. They cool and evolve into a double-power law distribution, $N_\gamma \propto \gamma^{-s_{l,h}}$, with $s_h = p+1$ for $\gamma > \gamma_c$, and with $s_l = p$ for $\gamma < \gamma_c$, where the γ_c is determined by the equality of time scales of injection and electron energy loss. Electrons with $\gamma > \gamma_c$ produce γ-ray radiation with the energy flux distribution $F_\nu \propto \nu^{-\alpha_\gamma}$, where $\alpha_\gamma = (s_h - 1)/2 = p/2$, and electrons with $\gamma < \gamma_c$ produce X-rays with $\alpha_x = (s_l - 1)/2 = (p-1)/2$. Hence, the slope of the injected electrons, p, can be recovered from the slope of X-ray or γ-ray spectrum. Since the soft/mid X-rays are likely to be diluted by the contribution from the synchrotron-self Compton process (Kubo et al. 1998), a more reliable approach is to infer p from the γ-ray spectra. For FSRQ, $\alpha_\gamma \sim 1$ (Pohl et al. 1997), and therefore $p = 2$ can be used as a fiducial index.

Normalization of the electron injection function, K, is also based on the γ-ray data. Equating the γ-ray luminosity at a given frequency with the electron emissivity and noting that in the fast cooling regime ($\gamma > \gamma_c$) $N_\gamma |d\gamma/dt'| \simeq \int_\gamma Q d\gamma$, we obtain

$$K \simeq \frac{2(\nu_\gamma L_{\nu_\gamma})}{m_e c^2} \frac{\Gamma^2}{\mathcal{D}^6} \, , \tag{1}$$

where $\mathcal{D} = [\Gamma(1 - \beta_\Gamma \cos\theta_{obs})]^{-1}$. (Note that the factor $\Gamma^2/\mathcal{D}^6$ comes from the fact that for the EC process $L \simeq (\mathcal{D}^6/\Gamma^2)L'$ [Dermer 1995]). Hence, the total number of relativistic electrons involved in production of a nonthermal flare is

$$N_e \simeq \mathcal{D} t_{fl} \int_1 Q \, d\gamma \simeq \mathcal{D} t_{fl} K \simeq \frac{2t_{fl}(\nu_\gamma L_{\nu_\gamma})}{m_e c^2} \frac{\Gamma^2}{\mathcal{D}^5} \, , \tag{2}$$

where t_{fl} is the observed time scale of the γ-ray flare.

3. Bulk-Compton radiation

Steady-state flow

Electrons which prior to the dissipative event are cold and are streaming steadily through the external UV radiation field produce soft X-ray radiation with the apparent luminosity

$$L_{BC} \simeq \mathcal{D}^2 \int n_e c\sigma_T u_{diff} \Gamma^2 \, dV \, , \tag{3}$$

where $dV = \Sigma dr$ is the volume element and n_e is the electron number density. Noting that $n_e \simeq \dot{N}_e/(c\Sigma)$, where $\dot{N}_e \sim N_e/(\lambda/c)$ is the flux of electrons and $\lambda \simeq ct_{fl}$ is the longitudinal extension of the non-thermal source, we obtain

$$L_{BC} \simeq \frac{2\sigma_T}{m_e c^2} \frac{\Gamma^4}{\mathcal{D}^3} (\nu_\gamma L_{\nu_\gamma}) \int u_{diff} \, dr \, . \tag{4}$$

The value of L_{BC} can be easily calculated by assuming that $u_{diff} \simeq u_{BEL}$. At $r \leq r_{BEL}$, where r_{BEL} is the distance of the broad emission line region, $u_{BEL} \simeq 3 \times 10^{-3}$erg cm^{-3} (Peterson 1993) and drops very fast at $r > r_{BEL}$. In this case, assuming $\theta_{obs} = 1/\Gamma$, Eq.(4) gives

$$L_{BC}^{(BEL)} \simeq 6.8 \times 10^{46} \mathrm{erg\,s^{-1}} \, \frac{r_{BEL}}{3 \times 10^{17}\mathrm{cm}} \, \frac{\Gamma}{15} \, \frac{\nu_\gamma L_{\nu_\gamma}}{10^{48}\mathrm{erg\,s^{-1}}} \, . \tag{5}$$

This luminosity should peak at $h\nu_{BC} \sim 2(\Gamma/15)^2(\bar{\nu}_{BEL}/10\mathrm{eV})$ keV; its magnitude is already on the order of the observed soft X-ray luminosities in FSRQ. It implies that at distances $r < 10^{17}$cm, where bulk Comptonization of a direct disc radiation would strongly exceed $L_{BC}^{(BEL)}$, the jet is still not fully developed (accelerated/collimated) and/or the inner parts of a disc are radiatively inefficient, in turn suggesting that the outward transport of angular momentum occurs via other means (e.g. a disk wind) rather than viscosity in the disk.

Discrete ejecta

In the simplest version of the popular internal shock model for production of γ-ray flares, the dissipative events involve collisions of ejecta propagating down the jet with different velocities. In this case, prior to the collision, the cold ejecta produce soft X-ray flares with the apparent luminosity

$$L_{BC,i} \simeq \mathcal{D}_i^4 \Gamma_i^2 \xi_i N_{e,i} c\sigma_T u_{diff} \, , \tag{6}$$

where $i = 1, 2$ denotes the ejecta assumed to move prior to the collision with $\Gamma_2 > \Gamma_1 \gg 1$, $\mathcal{D}_i$ are the respective Doppler factors and ξ_i is the fraction of $N_{e,i}$ contributing to the radiation observed at a given instant (see Sikora & Madejski 2002). These soft X-ray flares are predicted to precede the non-thermal flares by

$$\delta t_i \sim \frac{r_{fl}}{c\Gamma_i \mathcal{D}_i} \sim \frac{\mathcal{D}\Gamma}{\mathcal{D}_i \Gamma_i} t_{fl} \, . \tag{7}$$

Assuming that the number of electrons is the same in both ejecta ($N_{e,i} = N_e/2$), we obtain using Eqs. (2) and (6)

$$L_{BC,i}^{(BEL)} \simeq \frac{\mathcal{D}_i^4 \Gamma_i^2 \Gamma^2}{\mathcal{D}^5} \frac{c\sigma_T u_{BEL}}{m_e c^2} (\nu_\gamma L_{\nu_\gamma}) t_{fl} \xi_i \, , \tag{8}$$

where, for ejecta with equal masses and proper lengths, λ_0, $\xi_i \simeq \mathrm{Min}[1, r_{BEL}/(\lambda_0 \mathcal{D}_i)]$. From the shock model, $\lambda_0 = g_0 c\mathcal{D} t_{fl}$, where g_0 depends on Γ_2/Γ_1 and on the adiabatic index $\hat{\gamma}$ of the shocked plasma. For $\Gamma_2/\Gamma_1 = 2.5$ and $\hat{\gamma} = 5/3$, $g_0 \simeq 0.64$. With these particular parameters and noting that $\Gamma \simeq \sqrt{\Gamma_2\Gamma_1}$, one can find that for $\Gamma = 15$ and $\theta_{obs} = 1/\Gamma$ the precursors would have luminosities $L_{BC,1}^{(BEL)} \sim 7.6 \times 10^{45}$ erg s^{-1} and $L_{BC,12}^{(BEL)} \sim 4.7 \times 10^{46}$ erg s^{-1}, would precede the non-thermal flares by $\delta t_1 \sim 1.7 t_{fl}$ and $\delta t_2 \sim 0.7 t_{fl}$, and their spectra would peak at $\nu_{BC,1} \simeq 1.3$ keV and $\nu_{BC,2} \simeq 3.2$ keV.

Additional contribution to $L_{BC,i}$ from Comptonization of direct radiation of the accretion disc would lead to precursors so prominent that they should have been detected in the available data. The lack of any such detections implies that, just as in the steady state case, the acceleration phase extends up to distances $r > 10^{17}$ cm, and/or that central parts of the disc are radiatively inefficient. Such precursors should be easily detected by the current missions such as XMM even if they are produced at $r > 10^{17}$cm, unless the nonthermal flares arise from instabilities triggered *in situ*, rather than due to modulation of the flow by the central engine.

It should be emphasized here that all above results do not *explicitly* depend on the proton number and magnetic field intensities and on related issues as the pair content and the jet power. These aspects become crucial when the mechanisms and the energetics of the dissipative events are addressed.

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References

Begelman, M.C. & Sikora, M.: 1987, ApJ, 322, 650

Blandford, R.D.: 2002, in "Current High Energy Emission around Black Holes," eds. C.-H. Lee & H.-Y. Chang (Hong Kong: World Scientific), 199

Dermer, C.D.: 1995, ApJ, 446, L63

Drenkhahn, G. & Spruit, H.C.: 2002, A&A, 391, 1141

Kubo, H., et al.: 1998, ApJ, 504, 693

Peterson, B.M.: 1993, PASP, 105, 247

Pohl M., Hartman, R.C., Jones, B.B., & Sreekumar, P.: 1997, A&A, 326, 51

Sikora, M., Begelman, M.C., & Rees, M.J.: 1994, ApJ, 421, 153

Sikora, M., Błażejowski, M., Begelman, M.C., & Moderski, R.: 2001, ApJ, 554, 1

Sikora, M., & Madejski, G.M.: 2001, in "High Energy Gamma-Ray Astronomy", AIP Conf. Proc. 558, eds. F.A. Aharonian & H.J. Völk (New York: AIP), 275

Sikora, M., & Madejski, G.M.: 2002, in "Current High Energy Emission around Black Holes," eds. C.-H. Lee & H.-Y. Chang (Hong Kong: World Scientific), 132

Spada, M., Ghisellini, G., Lazzati, D., & Celotti, A.: 2001, MNRAS, 325, 1559

Tavecchio, F., et al.: 2000, ApJ, 543, 535

von Montigny, C., et al.: 1995, ApJ, 440, 525