Learning about Jets from Observations of Blazars

Marek Sikora

*N. Copernicus Astronomical Center, Bartycka 18, 00-716 Warsaw, Poland*

Greg M. Madejski

*Stanford Linear Accelerator Center, Menlo Park, CA 94025, USA*

**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, $\Gamma$, the electron number flux, $\dot{N}_e$, and the energy density of the ambient radiation field, $u_{\text{ext}}$. Since $u_{\text{ext}}$ 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 $\Gamma$ and $\dot{N}_e$ as derived from the EC (external Compton) model of $\gamma$-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.
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 $\gamma$-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 $\gamma$-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 $\gamma$-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 non-thermal 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 $\gamma_c$ is determined by the equality of time scales of injection and electron energy loss. Electrons with $\gamma > \gamma_c$ produce $\gamma$-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 $\gamma$-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 $\gamma$-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 $\gamma$-ray data. Equating the $\gamma$-ray luminosity at a given frequency with the electron emissivity and noting that in the fast cooling regime ($\gamma > \gamma_c$) $N_\gamma|d\gamma/dt'| \simeq \int_\gamma Qd\gamma$, we obtain

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

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

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

where $t_{fl}$ is the observed time scale of the $\gamma$-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

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

(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

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

(4)

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

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

(5)

This luminosity should peak at $h\nu_{\text{BC}} \sim 2(\Gamma/15)^2(\bar{\nu}_{\text{BEL}}/10\text{eV})$ keV; its magnitude is already on the order of the observed soft X-ray luminosities in FSRQ. It implies that at distances $r < 10^{17}\text{cm}$, where bulk Comptonization of a direct disc radiation would strongly exceed $L_{BC}^{(\text{BEL})}$, 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 $\gamma$-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

$$L_{BC,i} \simeq D_i^4 \Gamma_i^2 \xi_i N_{e,i} c \sigma_T u_{\text{diff}},$$

(6)

where $i = 1, 2$ denotes the ejecta assumed to move prior to the collision with $\Gamma_2 > \Gamma_1 \gg 1$, $D_i$ are the respective Doppler factors and $\xi_i$ 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

$$\delta t_i \sim \frac{r_{fl}}{c \Gamma_i D_i} \sim \frac{\Gamma_i}{D_i} t_{fl}.$$

(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)

$$L_{BC,i}^{(\text{BEL})} \simeq D_i^4 \Gamma_i^2 \frac{\sigma_T u_{\text{BEL}}}{c m_e c^2} (\nu_{\gamma} L_{\nu_{\gamma}}) t_{fl} \xi_i,$$

(8)

where, for ejecta with equal masses and proper lengths, $\lambda_0, \xi_i \simeq \text{Min}[1, r_{\text{BEL}}/(\lambda_0 D_i)]$. From the shock model, $\lambda_0 = g_0 c D t_{fl}$, where $g_0$ depends on $\Gamma_2/\Gamma_1$ and on the
adiabatic index $\dot{\gamma}$ of the shocked plasma. For $\Gamma_2/\Gamma_1 = 2.5$ and $\dot{\gamma} = 5/3$, $g_0 \simeq 0.64$. With these particular parameters and noting that $\Gamma \simeq \sqrt{1/2}\Gamma_1$, one can find that for $\Gamma = 15$ and $\theta_{\text{obs}} = 1/\Gamma$ the precursors would have luminosities $L^{(\text{BEL})}_{BC,1} \sim 7.6 \times 10^{45}$ erg s$^{-1}$ and $L^{(\text{BEL})}_{BC,12} \sim 4.7 \times 10^{46}$ 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.

Acknowledgments. M.S. thanks to SOC for their invitation and generous hospitality. Support under the Chandra NASA grant (SAO number GO1 2113X) and Polish KBN grant 5 P03D 002 21 is gratefully acknowledged.

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., Błążejowski, 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