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A MODEL FOR THE HIGH-ENERGY EMISSION FROM BLAZARS

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We study the production of VHE emission in blazars as a superposition of a steady a component from a baryonic jet, and a time-dependent contribution from an inner e^-e^+ beam launched by the black hole. Both primary electrons and protons are injected near the base of the jet, and the particle distributions along it are found solving a stationary one-dimensional transport equation accounting for convection and cooling. The short-timescale variability of the emission is explained by perturbations introduced by Kelvin-Helmholtz (KH) instabilities and their interaction with relativistic shocks. For illustration purposes, we apply the model to the case of PKS 2155-304.

1. Introduction

Blazars are Active Galactic Nuclei (AGNs) with a jet pointing close to the line of sight. They exhibit the most extreme high-energy phenomena in AGNs. Their spectral energy distributions (SEDs) are characterized by a non-thermal continuum spectrum with a broad component from X-rays to gamma-rays. Blazars show rapid variability across the entire electromagnetic spectrum. Variability timescales of a few minutes have been observed in some of them, such as PKS 2155-304.[1]

In this work, we outline a model based on relativistic leptons and hadrons, and aimed to explain the high energy emission from the jets of these objects. The quiescent component of the signal is assumed to be produced by a steady jet launched by the accretion disk, while the variable component is due to KH instabilities developed between an inner e^+e^- beam generated by the spinning black hole and the surrounding jet. We show the results obtained for the quiescent jet emission of PKS 2155-304, and also preliminary results for the possible variable signal in this case.

2. Model description

We assume that matter is captured by the central black hole through a dissipationless accretion disk, and that most of this accreted material is expelled by the accretion disk in two oppositely directed jets.[3] An inner beam of relativistic electrons and positrons is launched by the spinning black hole. This setup is similar to those proposed in two-fluid models.[6,8,9]Equipartition between jet kinetic energy and magnetic energy takes place at $z_0 = 50R_g$ from the black hole. The jet has a small half-opening angle $\xi_{\rm j}$, and a bulk Lorentz factor $\Gamma_{\rm j}$ at z_0 and a viewing angle $i_{\rm j}$. The bulk kinetic power of the jet at z_0 is a fraction $q_{\rm j}$ of the Eddington power, and the cold particle density in the jet is $n_{\rm j} = \dot{m}_{\rm j}/(m_p \pi z^2 \chi_{\rm j}^2 v_{\rm j})$, with $\chi_{\rm j} = \tan\xi_{\rm j}$. The magnetic field varies along the jet according to $B(z) = B_0 \left(\frac{z_0}{z}\right)^{m_{\rm j}}$ with $m_{\rm j} \in (1,2)$ and $\Gamma_{\rm j}$ increases slowly as magnetic energy density decreases along the jet. Acceleration of relativistic protons and electrons takes place at $z_{\rm acc} > z_0$, where primary relativistic particles are injected with a power $L_{\rm rel} = L_p + L_e$. This is a fraction of the bulk kinetic power of the jet, $L_{\rm rel} = q_{\rm rel} L_{\rm j}^{(\rm kin)}$, where $L_{\rm j}^{(\rm kin)} = \frac{q_{\rm j}}{2} L_{\rm Edd}$ with a factor $q_{\rm j} < 1$ (see Ref. 7). The distribution of particles in the steady jet is governed by an inhomogeneous transport equation with cooling and convection:

$$\frac{\partial\left(\Gamma_{\rm j} v_{\rm j} N(E,z)\right)}{\partial z} + \frac{\partial b(E,z) N(E,z)}{\partial E} + \frac{N(E,z)}{T_{\rm dec}(E)} = Q(E,z), \tag{1}$$

where $b(E,z) = -\frac{dE}{dt}$. The e^+e^--beam launched by the black hole's ergosphere, and its density is supposed to be $n_{\rm b} = \eta_{\rm b} n_{\rm j}$, with $\eta_{\rm b} < 1$. Its initial Lorentz factor is $\Gamma_{\rm b}^{(0)}$ at a distance $z_{\rm b}^{(0)} < z_0$, where equipartition with the beam magnetic energy is assumed. This fixes the value of $B_{\rm b}^{(0)}$. For $z > z_{\rm b}^{(0)}$ in the beam, the field decays as $B_{\rm b} = B_{\rm b}^{(0)} \left(z_{\rm b}^{(0)}/z\right)^{m_{\rm b}}$.

2.1. *A variable component from the beam*

KH instabilities between the beam and the jet produce inhomogeneities in the beam and can force it to bend in a helical shape. Shock fronts propagate along the beam and interact with the inhomogeneities.[8] The jump conditions relate the density and pressure upstream and downstream.[2] If the Lorentz factor of the shock is $\gamma_{\rm s}$, the post-shock one is $\gamma_{\rm ps} \approx \gamma_{\rm s}/\sqrt{2}$. Its value in the frame of the undisturbed beam is $\gamma'_{\rm ps} = \gamma_{\rm ps}\gamma_{\rm b}(1 - \beta_{\rm ps}\beta_{\rm b})$. The observed variability timescale $t_{\rm v}$ can be associated to the linear size of the inhomogeneities:

$$l_{\rm size} = \frac{c\,t_{\rm v}}{1 + z_{\rm rs}} \frac{\sqrt{1 - \gamma_{\rm s}^{-2}}}{1 - \cos i_{\rm j}\,\sqrt{1 - \gamma_{\rm s}^{-2}}}. \tag{2}$$

A necessary condition for instabilities to develop is that B is below a critical value $B_{\rm c}^{(\rm KH)} = \sqrt{4\pi\, n_{\rm b} m_e c^2 (\gamma_{\rm b}^2 - 1)}/\gamma_{\rm b}$. The density in the post-shock region is $n_{\rm ps} = \eta_{\rm c} n_{\rm b}$, where the compression ratio is $\eta_{\rm c} = (\hat{\gamma}\gamma'_{\rm ps} + 1)/(\hat{\gamma} - 1)$, where $\hat{\gamma} = 4/3$ is the adiabatic index. The size of the shocked region is given by $\Delta z \approx z/{\gamma'_{\rm ps}}^2$

Table 1. Parameter values assigned and derived in this work.

Parameter	Description	Value
$M_{\rm bh}$	Black Hole mass	$10^9 M_\odot$
$q_{\rm j}^{\rm (kin)}$	jet to Eddington power ratio	0.1
$\Gamma_{\rm j}(z_0)$	jet's bulk Lorentz factor at z_0	10
$\xi_{\rm j}$	jet's opening angle	1.5°
$i_{\rm j}$	viewing angle	1°
$q_{\rm rel}$	jet's content of relativistic particles	0.1
a	hadron-to-lepton ratio	1
$m_{\rm j}$	jet's magnetic field exponent	1.8
z_0	jet's launching point	$50R_g$
$z_{\rm acc}$	position of jet injection zone	$325R_g$
$\Delta z_{\rm acc}$	extent of injection zone	$z_{\rm acc}\,\chi_{\rm j}/2$
η	acceleration efficiency	10^{-6}
α	spectral index of injection Q	2.1
$E_{\rm min,p}$	minimum energy protons	1 GeV
$E_{\rm min,e}$	minimum energy electrons	0.15 GeV
N_H	gas and dust column density	$1.3 \times 10^{20}{\rm cm}^{-2}$
$z_{\rm rs}$	redshift of the source	0.116
$t_{\rm v}$	variability timescale	30 min
$\gamma_{\rm s}$	Lorentz factor of the shock	60
$z_{\rm b}^{(0)}$	beam's launching point	$5R_g$
$\Gamma_{\rm b}(z_{\rm b}^{(0)})$	beam's Lorentz factor at $z_{\rm b}^{(0)}$	10
$m_{\rm b}$	beam's magnetic field exponent	2
$\eta_{\rm b}$	beam's acceleration efficiency	10^{-5}

and the kinetic power to be injected is applied to normalize the e^+e^- injection: $L_{e^\pm} = (\gamma_{\rm ps} - 1)\gamma_{\rm ps} n_{\rm ps} v_{\rm ps} \pi z^2 \chi_{\rm b}^2 m_e c^2$. The injection term in the post-shock frame is $Q_{e^\pm}(E') = K_e E'^{-\alpha} \exp\left(-\frac{E'}{E_{\rm max}}\right)$, and the normalization constant can be found as in Ref. 7, taking into account the energy $E_{\rm max}$ for which the cooling rate equals the acceleration rate with an efficiency $\eta_{\rm b}$. The distributions $N_{e^\pm}(E')$ are found using the simple balance equation in the post-shock frame, at each position in the beam $\frac{\partial[bN_{e^\pm}]}{\partial E'} + \frac{N_{e^\pm}}{T_{\rm esc}} = Q_{e^\pm}$. The resulting radiative output corresponds to different emission times, and the main processes are synchrotron and IC emission. Here we have assumed that as a consequence of KH instabilities, the beam develops a helical shape with a step of $l_{\rm size}$ per turn, and with a radius $r_{\rm h}(z) = z_{\rm b}^{(0)} \frac{\chi_{\rm b}}{2} (z/z_{\rm b}^{(0)})^{0.5}$. This enables to obtain the instantaneous viewing angle from $\cos i_{\rm b}(t) = \hat{r}_{\rm obs} \cdot \hat{v}_{\rm b}$, where $\hat{r}_{\rm obs}$ and $\hat{v}_{\rm b}$ are the unit vectors in the direction of the line of sight and tangent to the beam path, respectively. Then, the Doppler factor corresponding to the emission from the beam depends on this angle: $D_{\rm b}(t) = (1 - \beta_{\rm ps} \cos i_{\rm b}(t))^{-1} \gamma_{\rm ps}^{-1}$. In Table 1 we show the list of parameters assumed and derived in order to account for the quiescent state of PKS 2155-304. The SEDs presented in Fig. 1 have been corrected by the effect of $\gamma\gamma$ absorption with the extragalactic background light (EBL), according to the model by Dominguez et al..[4] In Fig 1 we show separately the contribution of the steady emission from the jet, and the total emission at

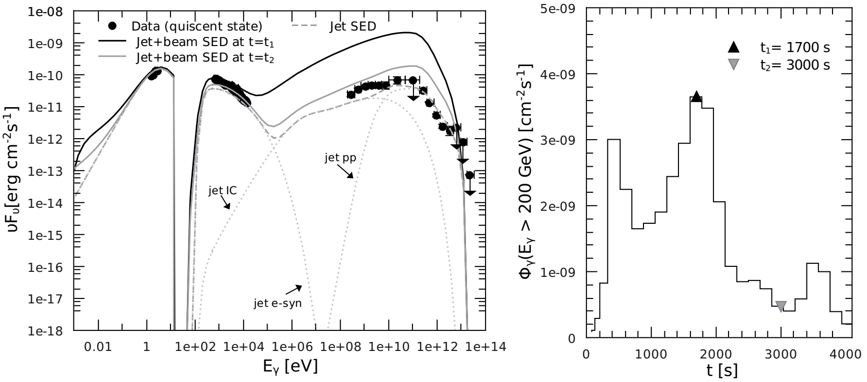

Fig. 1. Left: quiescent state data (black circles); SED due to the jet (grey dashed line); electron synchrotron, IC and pp emission from the jet (light-grey dotted lines); total SED (jet+beam) at t_1 and t_2 (black and grey lines). Right: Gamma-ray flux above 200 GeV as a function of time.

different times t_1 and t_2. These times are indicated in the right panel, which shows the integrated gamma-ray flux above 200 GeV.

3. Discussion

We have shown how the variable emission from blazars can be described in terms of a steady component from a barionic jet, plus a variable component from an inner e^-e^+ beam. As illustrated for the case of PKS 2155-304, the variable emission can be originated by KH instabilities that cause the beam to adquire a helical structure, which results in a time-dependent Doppler factor. This repeatedly boosts the synchrotron and IC emission from the beam in the observer frame. As for the emission from the steady jet, if *pp* interactions are responsible for the VHE gamma-rays, a strong neutrino signal should be expected. The study of this issue will be presented elsewhere.

Acknowledgments

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References

1. F. Aharonian *et al.*, *Astrophys. J. Lett.* **696** L150 (2009).
2. R. D. Blandford and C. F. McKee, *Phys. Fluids* **19**, 1130 (1976).
3. S. V. Bogovalov and S. R. Kelner, *Int. J. Mod. Phys. D* **19**, 339 (2010).
4. A. Domínguez *et al.*, *Mon. Not. R. Astron. Soc.* **410**, 2556 (2010).
5. A. Ferrari, E. Trussone and L. Zaninetti, *Mon. Not. R. Astron. Soc.* **196**, 1051 (1981).
6. G. Ghisellini, F. Tavecchio and M. Chiaberge, *Astron. Astrophys.* **432**, 401 (2005).
7. M. M. Reynoso, M. C. Medina and G. E. Romero, *Astron. Astrophys.* **531**, A30 (2011).
8. G. E. Romero, *Astrophys. Space Sci.* **234**, 49 (1995).
9. H. Sol, G. Pelletier and E. Asséo, *Mon. Not. R. Astron. Soc.* **237**, 441 (1989).