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Gamma-ray emission from interactions between jets and BLR clouds

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Resumen / Los blazares -nucleos galácticos activos en los que el *jet* apunta hacia nosotros- son las fuentes de rayos-γ detectadas más numerosas. Presentamos resultados preliminares de un modelo en el que nubes de alta velocidad que orbitan alrededor del núcleo galáctico penetran en el *jet* dando lugar a choques capaces de acelerar electrones relativistas; estos electrones emiten radiación γ al interactuar con los fotones provenientes de radiación térmica del disco reprocesada y re-emitida por las nubes de alta velocidad. De forma semianalítica calculamos la evolución dinámica de una nube dentro del *jet*, la distribución en energías de los electrones no-térmicos localmente acelerados, y la emisión en altas energías que éstos producen, teniendo en cuenta efectos relativistas. Analizamos la tasa de ocurrencia y duración de estas interacciones para dar cuenta de si son eventos discretos o continuos. Finalmente, comparamos los flujos predichos por nuestro modelo con las observaciones disponibles, y discutimos las implicancias en términos de eficiencia de aceleración de partículas y carga de masa en *jets* de blazares.

Abstract / Blazars -active galactic nuclei with a jet pointing towards the observer- are the most numerous γ-ray sources detected until date. In this work we show preliminary results of a model in which broad-line region (BLR) clouds penetrate in the jet, producing shocks capable of accelerating relativistic electrons; these electrons emit γ-rays when they interact with the photons coming from the BLR clouds. We calculate semi-analytically the dynamical evolution of a typical cloud inside the jet, the energy distribution of the locally accelerated electrons, and the high-energy emission the latter produce, taking into account relativistic effects. We estimate the duty-cycle of these interactions in order to find whether they occur as discrete events or almost continuous. We compare the observed γ-ray fluxes with the ones predicted by our model and discuss the implications in terms of particle acceleration efficiency and mass-loading in the blazar jets.

Keywords / gamma rays: galaxies — galaxies: active — radiation mechanisms: non-thermal

1. Introduction

The majority of the γ-ray sources detected by the *Fermi*/LAT instrument are associated with blazars, a type of active galaxies with powerful jets pointing directly at us (Ackermann et al., 2015). Flat-Spectrum Radio Quasars (FSRQs) are a subtype of the blazar population that present a rich environment surrounding the jet, including dense, high velocity clouds located at the broad line region (BLR). The spectral energy distribution (SED) of a blazar typically consists of two broad "humps", one at low energies (X-R at most), presumably of synchrotron nature, and one at high energy (HE), most likely due to inverse Compton (IC) scattering of BLR photons. A detailed study of the emission properties of the blazar population has been recently published by Ghisellini et al. (2017).

Here we investigate whether the scenario of jet-BLR cloud interactions (JCI) can account for the observed blazar HE emission. We consistently model the dynamics of the interaction, the evolution of the energy distribution of the accelerated non-thermal (NT) particles, and the γ-ray output including relativistic effects between the emitting blob (i.e., the shocked jet material surrounding the shocked cloud) reference frame (BF) and the observer reference frame (OF). Similar phenomenology is present in the NT emission from standing relativistic shocks of AGN jets interacting with stellar winds (e.g., Araudo et al., 2013; Vieyro et al., 2017) and microquasar jets interacting with stellar-wind clumps (Araudo et al., 2009; de la Cita et al., 2017).

2. Physical scenario

We revisit the model developed by Araudo et al. (2010) for γ-ray emission in FSRQs due to the penetration of dense BLR clouds into the jet. The impact of the relativistic jet in the cloud surface leads to the formation of two shocks, one in the cloud and another one -the bow shock- in the jet material. The later is suitable for the acceleration of NT particles (e.g., Araudo et al., 2009). We focus on the advanced stages of the JCI, which are particularly interesting for the case of jets aligned with the observer. The main effects to take into account are: i) the area of the bow shock increases due to the expansion of the blob inside the jet; ii) the IC cooling becomes more efficient when the blob reaches relativistic velocities because the BLR photon field is enhanced in the BF; iii) the emitted radiation is greatly enhanced in the

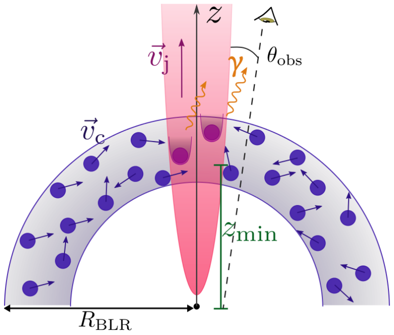

Figure 1: Schematic representation of the JCIs scenario.

Table 1: Model parameters in cgs units.

Parameter	Value
Jet luminosity [erg s^{-1}]	$L_{\rm j} = 2.5 \times 10^{46}$
Jet Lorentz factor	$\Gamma_{\rm j} = 13$
Disk luminosity [erg s^{-1}]	$L_{\rm d} = 0.1 L_{\rm j}$
BLR luminosity [erg s^{-1}]	$L_{\rm BLR} = 0.1 L_{\rm d}$
BLR radius [cm]	$R_{\rm BLR} = 1.6 \times 10^{17}$
BLR cloud radius [cm]	$R_{\rm c,0} = 10^{13}$
BLR cloud number density [cm^{-3}]	$N_{\rm c,0} = 10^{10}$
BLR cloud mass [g]	$M_{\rm c} = 7 \times 10^{25}$
NT fraction (electrons)	$\xi_{\rm e} = 10^{-1}$
Acceleration efficiency	$\eta_{\rm acc} = 0.1$
Observing angle [rad]	$\theta_{\rm obs} = 0.1$

OF due to Doppler-boosting. All these phenomena lead to a substantially larger γ-ray emission.

We consider a scenario in which the BLR consists of a large number ($> 10^6$, Dietrich et al., 1999) of clouds of similar size ($R_{\rm c,0}$) and density ($N_{\rm c,0}$), distributed spherically around the nucleus (e.g., Kaspi et al., 2007). The properties of the BLR are determined solely by its outer radius $R_{\rm BLR}$ and its luminosity $L_{\rm BLR}$. These clouds reprocess and re-emit a $\sim 10\%$ of the disk luminosity almost isotropically inside the BLR (Ghisellini & Tavecchio, 2009). Typical values for the BLR are presented in Tab. 1, as well as the adopted parameters in our model. A sketch of the scenario is shown in Fig. 1.

2.1. Dynamics

For clouds to fully penetrate into the jet, the shock must propagate in the cloud with a velocity smaller than the cloud spatial velocity. From this condition a minimum penetration height $z_{\rm min} \sim 5 \times 10^{16}$ cm is derived (Araudo et al., 2010), while the maximum interaction height is $z_{\rm max} \approx R_{\rm BLR} \approx 3 z_{\rm min}$. We adopt an average value for the interaction, $z_{\rm c0} = \sqrt{z_{\rm max}\, z_{\rm min}}$, and calculate the dynamical evolution of the blob inside the jet by considering that it is fixed to the shocked cloud surface. We solve the differential equation for the cloud Lorentz factor ($\Gamma_{\rm c}$) given by Barkov et al. (2012). We consider that the blob expands isotropically with a velocity equal to the sound speed in the shocked cloud, and we fix the value of the magnetic field by assuming equipartition between the jet ram pressure and jet magnetic pressure in the BF. This assumption leads to an extreme value of the magnetic field of $B_{\rm BF} \sim 200$ G, though it drops significantly (< 2 G) once the blob accelerates (Fig. 2). We transform the time intervals in the BF to the OF using $\Gamma_{\rm c}$ and the angle between the line-of-sight and the jet-axis, $\theta_{\rm obs}$. The blob expands rapidly until it reaches a size of $\sim 10\%$ of the jet radius, and it accelerates to $\Gamma_{\rm c} > 2$ in close to 10^4 s in the OF, reaching $\Gamma_{\rm c} \approx \Gamma_{\rm j}$ after $\sim 5 \times 10^4$ s (Fig. 2).

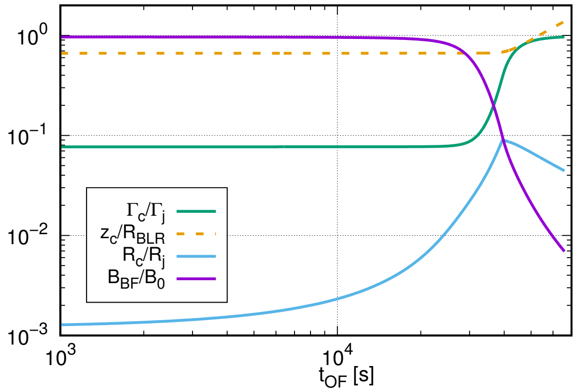

Figure 2: Dynamical evolution of a single JCI.

2.2. Particle energy distribution, non-thermal emission, and γ-ray absorption

We consider that a fraction $\xi_{\rm e}$ of the available injected energy in the shock goes into accelerating relativistic electrons with an energy distribution $Q'(E') = K E'^{-p} \exp\left(-E'/E'_{\rm max}\right)$, with $p = 2$. The solution for the transport equation is $N'_{\rm e}(E') = \dot{E'}^{-1} \int_{E'}^{E'_{\rm max}} Q'_{\rm e}(\tilde{E}') d\tilde{E}'$, with $\dot{E}' = E'/t'_{\rm cool}$, as it reaches a steady state for each time step. The energy densities of the disk and torus photon fields decrease in the BF by a factor $\sim \Gamma_{\rm c}^2$, while the isotropic BLR photon field is enhanced by a factor $\sim \Gamma_{\rm c}^2$. Therefore, the only relevant cooling mechanism during the late stages when $\Gamma_{\rm c} \gg 1$ is external Compton with BLR photons (IC-BLR). We calculate the IC emission considering a monochromatic, homogeneous, and isotropic BLR photon field. For the stage when the emission is largest, the photon field is nearly mono-directional in the BF due to relativistic effects, and the IC-BLR interactions occur as head-on collisions.

γ-ray photons emitted at the shock can interact with ambient photons through the channel $\gamma + \gamma \rightarrow e^+ + e^-$, resulting in the annihilation of the emitted HE photon. This absorption process is more effective when the photons interact head-on and if the ambient photon field is intense. At first order, we can consider the γ-ray emission to be unabsorbed below ~ 30 GeV and totally absorbed above ~ 30 GeV, as γ-rays with energies between 30 GeV and $\sim$ TeV emitted within $R_{\rm BLR}$ are completely absorbed in the BLR photon field (e.g., Abolmasov & Poutanen, 2017), and the torus radiation field is opaque to γ-rays with energies exceeding a few TeV for even larger distances (Donea & Protheroe, 2003).

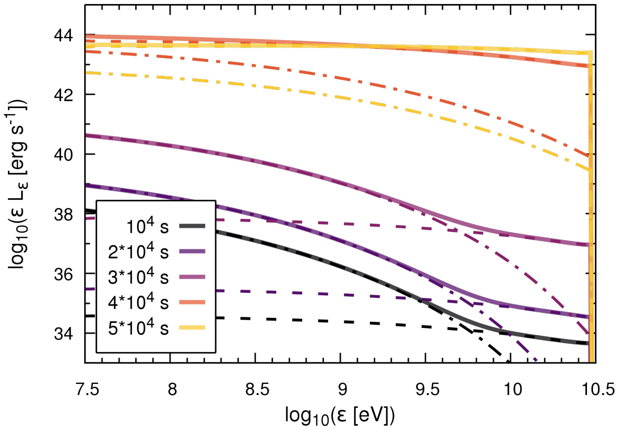

Figure 3: SEDs for different times in the OF. Dashed lines represent the IC component, dash-dotted the synchrotron component, and solid lines the sum of both.

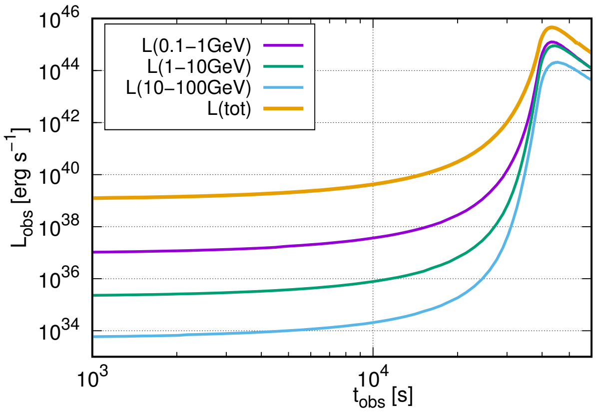

Figure 4: Lightcurves in the OF for different energy bands.

3. Results for a typical interaction

In Fig. 3 we show the time evolution of the synchrotron and IC SEDs. During the early stage, electrons cool down more efficiently through synchrotron, although this process hardly generates emission above 0.1 GeV. For later stages, IC-BLR dominates the radiative cooling and $L_{\rm IC}$ becomes larger than $L_{\rm sy}$. The IC-BLR process is responsible for most of the emission in the $1-30$ GeV energy band. Doppler boosting effects displace the SEDs a factor $\approx 2\,\Gamma_{\rm c}$ to higher energies and enhance the flux by a factor $\approx (2\,\Gamma_{\rm c})^4$, i.e., almost 5 orders of magnitude during late stages. Thus, the Doppler boosting has a major impact in the observed SED.

In the OF, the emission from a single BLR cloud-jet interaction lasts for $t_{\rm OF} \approx 5 \times 10^4$ s, with a sharp peak at $t_{\rm OF} \approx 4 \times 10^4$ s (Fig. 4). The time averaged luminosity of the interaction in γ-rays with energies between $0.1-30$ GeV is $\langle L_\gamma \rangle \approx 5 \times 10^{43}$ erg s^{-1}, with an average spectral index of ≈ -0.3.

4. Interaction rates

In order to determine if the JCIs give rise to transient or steady emission, we need to take into account the rate at which the events occur and their duration. We define the duty-cycle as $DC = \dot{N}\,t_{\rm int,OF}$, where $\dot{N} \sim 3 \times 10^{-4}$ is the amount of clouds entering into the jet per unit time and $t_{\rm int,OF}$ is the time during which the JCI is visible in the OF. We estimate $\dot{N}$ taking into account the time of residence of clouds within the jet volume and the quantity of clouds inside the jet. The later depends on the jet solid angle, the minimum velocity required for a cloud to enter the jet, and the total number of clouds in the BLR, $N_{\rm c,tot} \sim 10^6 - 10^8$ (which is not well constrained). In the OF, the interaction lasts $t_{\rm int,obs} \sim 5 \times 10^4$ s, so $DC \sim 11$. Therefore, the emission we expect from JCI events is steady, with a typical variability timescale of $t_{\rm int,obs}/DC \sim$ an hour, and a relative flickering amplitude $\sqrt{DC} \sim 3$. The expected luminosity is then DC times the luminosity of a single JCI, i.e., $\sim 10^{45}$ erg s^{-1}. This is close to the average emission detected from blazars with the assumed jet power (Ghisellini et al., 2017).

5. Discussion

Mainly under the assumption of a spherical BLR geometry, JCIs can account for a significant amount of the observed $0.1-30$ GeV γ-ray emission from blazars if $\xi_{\rm e} \sim 0.1$. However, the mass-loading rate produced by the multiple JCIs is not dynamically relevant as $\dot{N} M_{\rm c} \sim 1.5 \times 10^{22}$ g s^{-1} $\ll L_{\rm j}/(\Gamma_{\rm j} c^2) \sim 2 \times 10^{24}$ g s^{-1}. We note that, given the large number of clouds in the BLR and that the shocked cloud radius is $R_{\rm c} \lesssim 0.1 R_{\rm j}$ during most of the interaction time, the shoked clouds can occupy a significant portion of the jet section.

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