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# Radiation from matter entrainment in astrophysical jets: the AGN case

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**Abstract.** Jets are found in a variety of astrophysical sources. In all the cases the jet propagates with a supersonic velocity through the external medium, which can be inhomogeneous, and inhomogeneities could penetrate into the jet. The interaction of the jet material with an obstacle produces a bow-like shock within the jet in which particles can be accelerated up to relativistic energies and emit high-energy photons. In this work, we explore the active galactic nuclei scenario, focusing on the dynamical and radiative consequences of the interaction at different jet heights. We find that the produced high-energy emission could be detectable by the current $\gamma$-ray telescopes. In general, the jet-clump interactions are a possible mechanism to produce (steady or flaring) high-energy emission in many astrophysical sources in which jets are present.

**Keywords.** galaxies: active, radiation mechanisms: nonthermal

## 1. Introduction

Jets at different scales are present in astrophysical sources such as protostars, microquasars and active galactic nuclei (AGN). The medium that surrounds the jets can be inhomogeneous and clumps from this external medium can interact with the jets.

In young stellar objects, the interaction of matter from the external medium with protostar outflows has been proposed to explain the formation of Herbig-Haro (HH) objects. The dynamical properties of this interaction have been numerically simulated by Raga *et al.* (2003), and they conclude that clumps with mass between $10^{-4}$ and 0.1 times the mass of a giant planet can significantly contribute to the molecular mass of HH outflows. However, the velocity of HH jets is not relativistic ($\sim$ hundred km s$^{-1}$), and particle acceleration in the bow shock formed in the jet might be inefficient or the possible non-thermal emission produced by accelerated particles might be hidden by thermal radiation.

In high-mass microquasars, the interaction of clumps from the companion stellar wind (Owocki & Cohen, 2006) with the jets of the compact object (black hole or neutron star) can produce strong bow-like shocks within the jet. Electrons and protons accelerated in those shocks can radiate significant amount of $\gamma$ rays in the form of flaring and steady emission (Araudo *et al.* 2009). In the case where only few clumps interact with the jet, the produced emission is sporadic and can explain the GeV flares detected from some $\gamma$-ray binaries (e.g. Abdo *et al.* 2009).

At extragalactic scales, AGN are composed by an accreting supermassive black hole (SMBH) at the center of the galaxy and relativistic jets. Surrounding the SMBH there is a population of clouds (Krolik *et al.* 1981) that move at velocities $> 1000$ km s$^{-1}$ forming the called broad line region (BLR). In the present contribution, we illustrate the most important dynamical and radiative consequences of the interaction of clouds from the BLR with the base of AGN jets. We found that $\gamma$ rays from jet-cloud interactions should be detectable by present and future instrumentation in nearby low-luminous AGN at high energy (HE) and very high energy (VHE), and in powerful and nearby quasars only at HE because the VHE radiation is absorbed by the dense nuclear photon fields. In the case of sources exhibiting boosted $\gamma$ rays (blazars), the isotropic radiation from jet-cloud interactions will be masked by the jet beamed emission, which will not be the case in non-blazar sources.

## 2. The jet-cloud interaction

We adopt clouds with density $n_{\rm c} = 10^{10}$ cm$^{-3}$, size $R_{\rm c} = 10^{13}$ cm, and velocity $v_{\rm c} = 10^9$ cm s$^{-1}$. The jet Lorentz factor is fixed to $\Gamma = 10$, implying a jet velocity $v_{\rm j} \approx c$, and the radius/height relation is fixed to $R_{\rm j} = 0.1\, z$. The jet density $n_{\rm j}$ in the laboratory reference frame (RF) can be estimated as $n_{\rm j} = L_{\rm j}/((\Gamma-1)\, m_{\rm p}\, c^3 \sigma_{\rm j})$, where $\sigma_{\rm j} = \pi R_{\rm j}^2$ and $L_{\rm j}$ is the kinetic power of the matter-dominated jet.

The completely penetration of a cloud into the jet, the ram pressure of the latter should not destroy the former before the cloud has fully entered into the jet. This means that the time required by the cloud to penetrate into the jet, $t_{\rm c}{\sim}2R_{\rm c}/v_{\rm c} = 2\times 10^4$ s, should be shorter than the cloud lifetime inside the jet. To estimate this cloud lifetime, we first compute the time required by the shock in the cloud to cross it ($t_{\rm cs}$). The velocity of this shock is $v_{\rm cs}{\sim}\chi^{-1/2}\, c$, where $\chi = n_{\rm c}/n_{\rm j}(\Gamma-1)$, is derived by ensuring that the jet and the cloud shock ram pressures are equal. This yields a cloud shocking time of

$$t_{\rm cs}{\sim}\frac{2R_{\rm c}}{v_{\rm cs}} \simeq 7\times 10^4 \left(\frac{R_{\rm c}}{10^{13}\ {\rm cm}}\right) \left(\frac{n_{\rm c}}{10^{10}\ {\rm cm}^{-3}}\right)^{1/2} \left(\frac{z}{10^{16}\ {\rm cm}}\right) \left(\frac{L_{\rm j}}{10^{44}\ {\rm erg\, s}^{-1}}\right)^{-1/2} {\rm s}\,. \quad (2.1)$$

Rayleigh-Taylor (RT) and Kelvin-Helmholtz (KH) instabilities produced in the cloud surface by the interaction with the jet material will affect the obstacle. The timescale in which these instabilities grow up to a scale length $\sim R_{\rm c}$ is $t_{\rm RT/KH}{\sim}t_{\rm cs}$. For this reason, we take $t_{\rm cs}$ as the characteristic timescale of our study. Therefore, for a penetration time ($t_{\rm c}$) at least as long as $\sim t_{\rm cs}$, the cloud will remain an effective obstacle for the jet flow. Setting $t_{\rm c}{\sim}t_{\rm cs}$, we obtain the minimum value for the interaction height $z_{\rm int}$, giving

$$z_{\rm int}^{\rm min} \approx 2.5\times 10^{15} \left(\frac{v_{\rm c}}{10^9\ {\rm cm\, s}^{-1}}\right)^{-1} \left(\frac{n_{\rm c}}{10^{10}\ {\rm cm}^{-3}}\right)^{-1/2} \left(\frac{L_{\rm j}}{10^{44}\ {\rm erg\, s}^{-1}}\right)^{1/2} {\rm cm}. \quad (2.2)$$

For $z_{\rm int} > z_{\rm int}^{\rm min}$, the jet crossing time $t_{\rm j}{\sim}2R_{\rm j}/v_{\rm c}$ results larger than $t_{\rm cs}$. Once the cloud is inside the jet, a bow shock around the cloud is formed on a time $t_{\rm bs}{\sim}Z/v_{\rm j}{\sim}10^2$ s at a distance $Z{\sim}0.3R_{\rm c}$ cm from the cloud. In this bow shock, particles can be accelerated up to relativistic energies more efficiently than in the cloud shock (because the bow-shock velocity is $v_{\rm bs} \gg v_{\rm cs}$).

## 3. Non-thermal emission

The non-thermal luminosity of particles accelerated in the bow shock can be estimated as a fraction $\eta_{\rm nt}$ of the bow shock luminosity: $L_{\rm nt}{\sim}\eta_{\rm nt}\, L_{\rm bs}$, where $L_{\rm bs}{\sim}(\sigma_{\rm c}/\sigma_{\rm j})\, L_{\rm j}$ and $\sigma_{\rm c} = \pi R_{\rm c}^2$. The accelerator/emitter magnetic field in the bow-shock RF ($B$) can be determined by relating $U_{\rm B} = \eta_{\rm B} U_{\rm nt}$, where $U_{\rm B} = B^2/8\pi$ and $U_{\rm nt} = L_{\rm nt}/(\sigma_{\rm c} c)$ are the magnetic and

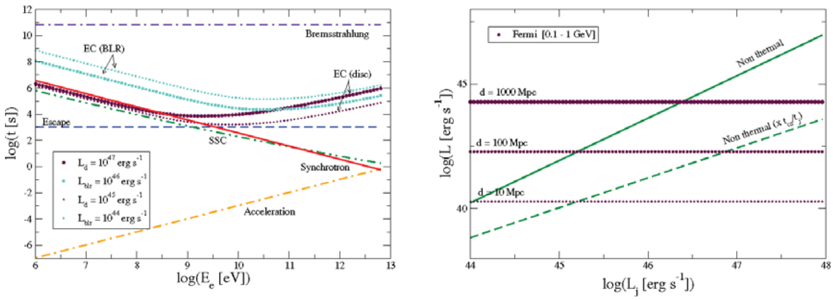

**Figure 1.** Left: acceleration gain, escape, and cooling lepton timescales are plotted. SSC is plotted when the steady state is reached and EC for both the BLR and disc photon fields are shown for the conditions of faint (BLR: $10^{44}$; disc: $10^{45}$ erg s$^{-1}$) and bright sources (BLR: $10^{46}$; disc: $10^{47}$ erg s$^{-1}$). Synchrotron and relativistic bremsstrahlung are also plotted. Right: Upper limits to the $\gamma$-ray luminosity produced by $N_{\rm c}^{\rm j}$ clouds inside the jet as a function of $L_{\rm j}$ in FR II sources. Two cases are plotted, one assuming that clouds cross the jet without disruption (green solid lines), and one in which the clouds are destroyed in a time as short as $t_{\rm cs}$ (green dashed lines). In addition, the sensitivity levels of *Fermi* in the range 0.1–1 GeV (maroon dotted lines) are plotted for three different distances $d = 10$, 100, and 1000 Mpc.

the non-thermal energy densities, respectively. Fixing $\eta_{\rm nt} = 0.1$ and $\eta_{\rm B} = 0.01$, we obtain $L_{\rm nt}{\sim}4 \times 10^{39}(L_{\rm j}/10^{44}\,{\rm erg\,s^{-1}})$ erg s$^{-1}$ and $B{\sim}10$ G. Regarding the acceleration mechanism, we adopt the following prescription for the acceleration rate: $\dot{E}_{\rm acc} = 0.1\,q\,B\,c$, where $q$ is the electron charge.

We assume that electrons and protons are injected into the bow-shock region following a power law in energy of index 2.2 and with an exponential cutoff at the maximum energy. The injection luminosity is $L_{\rm nt}$. Particles are affected by different losses that balance the energy gain from acceleration. The escape time downstream from the relativistic bow shock considers advection ($t_{\rm adv}{\sim}3\,R_{\rm c}/c{\sim}10^3$ s) and diffusion ($t_{\rm diff} = 3\,Z^2/2\,r_{\rm g}\,c$) timescales. In the latter expression, $r_{\rm g}$ is the particle gyroradius and the Bohm regime has been considered. The most important radiative losses that affect the lepton injection are synchrotron and SSC, determining a maximum energy $E_e^{\rm max}$ of several TeV, as is shown in Figure 1 (left). In the case of protons, $pp$ cooling is negligible in the bow-shock region and the maximum energy is constrained by equating the acceleration and diffusion timescales, given $E_p^{\rm max}{\sim}5 \times 10^3\,(B/10\,{\rm G})$ TeV. Then, protons with energies $> 0.4E_p^{\rm max}$ can reach the cloud by diffusion and radiate there via $pp$ more efficiently than in the jet, since $n_{\rm c} \gg n_{\rm j}(z_{\rm int})$.

## 4. Many clouds interacting with the jets

Many of the BLR clouds can be simultaneously inside the jet at different $z$, each of them producing non-thermal radiation. Therefore, the total luminosity can be much larger than that produced by just one interaction, which is $\sim L_{\rm nt}$. The number of clouds within the jets, at $z_{\rm int}^{\rm min} \leqslant z \leqslant R_{\rm blr}$, can be computed from the jet ($V_{\rm j}$) and cloud ($V_{\rm c}$) volumes, resulting in $N_{\rm c}^{\rm j} = 2\,f\,V_{\rm j}/V_{\rm c} \sim 9(L_{\rm j}/10^{44}\,{\rm erg\,s^{-1}})^2$, where the factor 2 accounts for the two jets and $f{\sim}10^{-6}$ is the filling factor of clouds in the whole BLR. In reality, $N_{\rm c}^{\rm j}$ is correct if one neglects the cloud disruption inside the jet. However, even under cloud fragmentation, strong bow shocks can form around the cloud fragments before these have accelerated up to close $v_{\rm j}$. Then, the real number of interacting clouds inside the jet is difficult to estimate, but it could be between $(t_{\rm cs}/t_{\rm j})\,N_{\rm c}^{\rm j}$ and $N_{\rm c}^{\rm j}$.

The presence of many clouds inside the jet implies that the total non-thermal luminosity available in the BLR-jet intersection region is

$$L_{\rm nt}^{\rm tot} \sim 2 \int_{z_{\rm int}^{\rm min}}^{R_{\rm blr}} \frac{{\rm d}N_{\rm c}^{\rm j}}{{\rm d}z} L_{\rm nt}(z)\,{\rm d}z \sim 2\times 10^{40} \left(\frac{\eta_{\rm nt}}{0.1}\right) \left(\frac{R_{\rm c}}{10^{13}\,{\rm cm}}\right)^{-1} \left(\frac{L_{\rm j}}{10^{44}\,{\rm erg\,s^{-1}}}\right)^{1.7} \frac{\rm erg}{\rm s}, \quad (4.1)$$

where ${\rm d}N_{\rm c}^{\rm j}$ is the number of clouds located in a jet volume ${\rm d}V_{\rm j} = \pi\,(0.1z)^2\,{\rm d}z$. In all the calculations $L_{\rm blr}$ has been fixed to $0.1\,L_{\rm j}$, as approximately found in FR II galaxies, and $R_{\rm blr}$ has been derived from Kaspi *et al.* (2005).

In Fig. 1 (right), we show estimates of the $\gamma$-ray luminosity when many clouds interact simultaneously with the jet. For this, we have followed a simple approach assuming that most of the non-thermal luminosity is converted into $\gamma$ rays. This will be the case as long as the escape and synchrotron cooling time are longer than the IC cooling time (EC+SSC) at the highest electron energies. In Araudo *et al.* (2010), we present more detailed calculations by applying the model presented in this contribution to two characteristic sources, Cen A and 3C 273.

## 5. Discussion

We have studied the interaction of clouds from the BLR with the base of jets in AGNs. For very nearby sources, such as Cen A, the interaction of large clouds ($R_{\rm c} > 10^{13}$ cm) with jets may be detectable as a flaring event, although the number of these large clouds and thereby the duty cycle of the flares are difficult to estimate. Given the weak external photon fields in these sources, VHE photons can escape without experiencing significant absorption. Therefore, jet-cloud interactions in nearby FR I may be detectable in both the HE and the VHE range as flares with timescales of about one day.

In FR II sources, many BLR clouds could interact simultaneously with the jet. The number of clouds depends strongly on the cloud lifetime inside the jet, which could be of the order of several $t_{\rm cs}$. Nevertheless, we note that after cloud fragmentation many bow shocks may still form and efficiently accelerate particles if these fragments move more slowly than the jet. Since FR II sources are expected to exhibit high accretion rates, radiation above 1 GeV produced in the jet base can be strongly attenuated by the dense disc and the BLR photon fields, although $\gamma$ rays below 1 GeV should not be affected significantly. Since jet-cloud emission should be rather isotropic, it would be masked by jet beamed emission in blazar sources, although since powerful/nearby FR II jets do not display significant beaming, these objects may produce detectable $\gamma$ rays through jet-cloud interactions. As shown in Fig. 1 (right), close and powerful sources could be detectable by deep enough observations of *Fermi*.

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**Discussion**

Mirabel: Can you apply the same model to the MQSO Cyg X-3 that has a WRayet donor and LGRBs that usualy have WRayet progenitors?

Araudo: We have applied the model to high-mass microquasars (HMMQ), studying the interaction between clumps from the wind of the companion star with the jet of the compact object (Araudo, Bosch-Ramon & Romero 2009). In this work, we have considered a source with similar parameters to the system Cygnus X-1. Now, we are working on the application of the model to the HMMQ Cygnus X-3. We have not applied the model to gamma-ray bursts.

Perucho: Stellar winds shocked by the jet flow could also be an interesting scenario to check. Have you considered it?

Araudo: We have not considered the interaction between stars and jets in AGNs, but we are going to do this in the near future. A similar scenario has been studied by Bednarek & Protheroe (1997).

Drappeau: How do calculate the number of clouds at any given time? i.e. What is the destruction rate and the entrainment rate of clouds in jets?

Araudo: To estimate the number of clouds into the jet, we calculate $N_c{\sim}2xfxV_j/V_c$, where $f{\sim}10^{-6}$ is the filling factor of clouds in the broad line region (BLR), $V_c$ is the volume of the clouds, and $V_j$ is the volume of the jet intesected by the BLR. In this estimation, we not consider the destruction of clouds into the jet. The previous equation for $N_c$ takes into account that the entrainment is equal to the escape rate of the jet, and is independent of time.