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Jet-Cloud Interactions in AGNs

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Active galactic nuclei present continuum and line emission. The former is produced by the accretion disk and the jets, whereas the latter is originated by gas located close to the super-massive black hole. The small region where the broad lines are emitted is called the broad-line region. The structure of this region is not well known, although it has been proposed that it may be formed by small and dense ionized clouds surrounding the supermassive black-hole. In this work, we study the interaction of one cloud from the broad line region with the jet of the active galactic nuclei. We explore the high-energy emission produced by this interaction close to the base of the jet. The resulting radiation may be detectable for nearby non-blazar sources as well as for powerful quasars, and its detection could give important information on the broad line region and the jet itself.

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1. Introduction

Active galactic nucleus (AGNs) are systems mainly composed by a supermassive black-hole (SMBH), an accretion disk, and bipolar relativistic jets. AGNs produce non-thermal continuum emission along the whole spectrum, from radio to γ-rays. The high-energy non-thermal radiation is expected to come from the jets, which are formed by a magnetized plasma moving relativistically. Besides the emission in the continuum, AGNs present optic and UV lines. Some of these lines are observed with a broad FWHM, with an associated velocity for the emitting gas of $\sim 10^9$ cm s^{-1}.

The region where these lines are formed is called the broad line region (BLR), and surrounds the SMBH. The size of the BLR is related to its luminosity, $L_{\rm BLR}$ [1]. For instance, for $L_{\rm BLR} \sim 10^{44}$ erg s^{-1} (Faranoff-Riley (FR) I case), $R_{\rm BLR} \sim 6\times10^{16}$ cm, and for $L_{\rm BLR} \sim 10^{46}$ erg s^{-1} (FR II case) $R_{\rm BLR} \sim 5\times10^{17}$ cm. The BLR is thought to be filled with a clumpy medium composed by cold clouds ($T \sim 10^4 - 10^5$ K) of radius $R_{\rm c} \sim 10^{13}$ cm [2]. In this work we study the interaction between a cloud of the BLR with the relativistic jet close to the SMBH in an AGN. Assuming standard values of the cloud parameters, and adopting a hydrodynamical supersonic jet, we estimate the high-energy emission produced by this interaction for two different kinds of AGN: a non-blazar source of FR I type, and a powerful flat-spectrum radio quasar of FR II type.

2. The physical scenario

A cloud with a radius $R_{\rm c}$ that moves with a velocity $v_{\rm c} = 10^9$ cm s^{-1}, completely enters into the jet in a time $t_{\rm c} \sim 2\,R_{\rm c}/v_{\rm c} \sim 2\times10^4$ s. For an effective penetration of the cloud into the jet, a huge contrast between the cloud and the jet densities ($\chi = n_{\rm c}/n_{\rm j} \gg 1$) is necessary. The cloud density $n_{\rm c}$ is fixed to $\sim 10^{10}$ cm^{-3} [3, 4] and the density of the jet, $n_{\rm j}$, is determined through the equation: $L_{\rm j} = \sigma_{\rm j}(\Gamma-1)n_{\rm j}m_{\rm p}v_{\rm j}c^2$, where $v_{\rm j} \sim c$ is the velocity of the jet, $\Gamma \sim 10$ the jet Lorentz factor, and $\sigma_{\rm j} = \pi R_{\rm j}^2$ is the section of the jet at the interaction height $z_{\rm int}$, where $R_{\rm j} \sim 0.1 z_{\rm int}$. In order to obtain $n_{\rm j}$ we need to fix $z_{\rm int}$ at which the cloud penetrates into the jet.

When the cloud penetrates into the jet, a shock is formed and propagates through the cloud at a velocity $v_{\rm sh} = v_{\rm j}((\Gamma-1)/\chi)^{1/2}$. In a time $t_{\rm cc} \sim 2\,R_{\rm c}/v_{\rm sh}$ the shock crosses the whole cloud. We focus on the stage when the cloud is inside the jet ($t_{\rm cc} > t_{\rm c}$) at the zero order approximation, implying that the interaction should take place at least at $z_{\rm int} = 2.5\times10^{15}$ and 2.5×10^{16} cm for an FR I ($L_{\rm j} \sim 10^{44}$ erg s^{-1}) and an FR II ($L_{\rm j} \sim 10^{46}$ erg s^{-1}), respectively. At such $z_{\rm int}$, we obtain for all cases $n_{\rm j} = 1.2\times10^6$ cm^{-3} and $\chi \sim 10^4$.

The shock heats the cloud material up to a temperature $T \sim 2\times10^9$ K. The hot plasma cools via thermal Bremsstrahlung radiation with a thermal luminosity $\sim 10^{38}$ erg s^{-1}, peaking at soft γ-rays. A bow shock is also formed in the jet, reaching the steady state at a distance $\sim R_{\rm c}$ from the cloud in a time $t_{\rm bs} \sim R_{\rm c}/v_{\rm j} \ll t_{\rm cc}$. The cloud could escape from the jet in a time $t_{\rm j} \sim 2\,R_{\rm j}/v_{\rm c} \sim 5\times10^5$ (FR I case) and 5×10^6 s (FR II case), being $t_{\rm j} \gg t_{\rm cc}$, although Kelvin-Helmholtz and Rayleigh-Taylor instabilities can destroy the cloud in a time $t_{\rm KH/RT} \sim$ few times $t_{\rm cc}$, shorter than $t_{\rm j}$. We note that the shocked cloud is also accelerated by the jet and might reach a velocity $\sim v_{\rm j}$, but it is likely that before this happens the cloud escapes from the jet.

3. Non-thermal emission

In the bow shock, particles can be accelerated via relativistic Fermi-I mechanism. Given the much lower velocity of the cloud shock, we will neglect at this stage its role to accelerate particles. The acceleration rate of particles, for which we adopt here a phenomenological prescription: $\dot{E} = 0.1\, qBc$, depends on the magnetic field B in the post-shock region of the bow shock [5]. We will consider three different cases, varying the value of B and the luminosity of the jet: i) case 0, with $L_{\rm j} \sim 10^{44}$ erg s^{-1} and $B = 2.8 \times 10^{-2}$ G (FR I case; dominant BLR photon energy density); ii) case I, with $L_{\rm j} \sim 10^{46}$ erg s^{-1} and $B = 4.1 \times 10^{-3}$ G (FR II case; dominant BLR photon energy density); and iii) case II, with $L_{\rm j} \sim 10^{46}$ erg s^{-1} and $B = 1.1{\times}10^{3}$ G (FR II case; dominant magnetic energy density, 10% of equipartition with the post-shock matter). The magnetic fields for cases 0 and I are very much below equipartition. These cases are considered to explore the situation when external Compton dominates the radiation output, where the external (BLR) energy density is $u_{\rm BLR} \sim L_{\rm BLR}/\pi R_{\rm BLR}^2 c$. In case II, for B-values close to equipartition, synchrotron emission will dominate. Work on the case when synchrotron self-Compton is the dominant radiation channel is on-going.

The maximum energy ($E_{\rm max}$) achieved by electrons is constrained by the escape of these particles from the bow-shock region, advected by the shocked material of the jet on a time $t_{\rm esc} \sim 3\, R_{\rm c}/c$ (case 0: 2×10^{13} eV and case I: 4×10^{12} eV), and by synchrotron losses (case II: 5×10^{11} eV). For protons the maximum energy is determined by the size of the acceleration region, $\sim R_{\rm c}$ (case 0: 8×10^{13} eV, case I: 10^{13} eV, and case II: 3×10^{18} eV).

We assume here that the 20% of the $L_{\rm j}$ fraction transferred to the cloud is converted into (non-thermal) luminosity of the accelerated particles, i.e. $L_{\rm NT} = 0.2\,(\sigma_{\rm c}/\sigma_{\rm j})\, L_{\rm j}$. We determine the constant $K_{e,p}$ of the injection function Q, assuming a power-law with an index $p = -2.2$ and a cut-off at higher energies: $Q_{e,p} = K_{e,p}\, E^{-p}\, e^{-E/E_{\rm max}}$. The electron energy distribution, N_e, is determined by the escape of particles and radiation losses (synchrotron and inverse Compton (IC)), reaching the steady state on a time $\ll t_{\rm cc}$. The steady distribution of these relativistic leptons is $N_e = Q_e\, t_{\rm esc} \propto E^{-p}$ (in cases 0 and I; escape dominance) and $N_e = Q_e\, t_{\rm synch} \propto E^{-p-1}$ (in case II; synchrotron cooling). On the other hand, protons escape from the bow-shock region after losing a negligible fraction of their energy by *pp* interactions.

As noted above, the most important emission process is IC scattering in cases 0 and I. In the former, the achieved luminosities are $L_{\rm synch} \sim 10^{36}$ and $L_{\rm IC} \sim 10^{38}$ erg s^{-1} (peaking in hard X-rays and in γ-rays, respectively), and in the latter, $L_{\rm synch} \sim 10^{34}$ and $L_{\rm IC} \sim 10^{37}$ erg s^{-1} (peaking in soft X-rays and in γ-rays, respectively). In case II, corresponding to the larger value of B, the synchrotron emission is the most important channel of energy loss, peaking in the the infrared and decreasing smoothly afterwards up to soft γ-rays. In this case, synchrotron and IC luminosities reach values $\sim 10^{39}$ and 10^{32} erg s^{-1}, respectively. The IC maximum is always in the sub-TeV range, given the strong photon-photon absorption in the BLR photon field, producing pairs that will also generate synchrotron and IC radiation (e.g. [6]). Regarding relativistic protons, since the density of particles in the bow-shock region is much lower than that of the cloud density, *pp* interactions are not an effective radiative process. For this reason, the most energetic protons ($E_p \sim E_{\rm max}$) can reach the cloud via diffusion before being advected away from the bow-shock region. Inside the cloud, the relativistic protons lose energy via pp collisions, yielding (absorbed) γ-ray luminosities $L_{pp} \sim 10^{36}$, 10^{38} and 10^{39} erg s^{-1} for the cases 0, I and II, respectively. Case II is an interesting one since radiation above 100 TeV may be detectable. We note that secondary leptons and neutrinos with luminosities similar to those of γ-rays, would be also produced inside the cloud due to pp interactions, and their study will be carried out in future work.

4. Final remarks

The relation flux/luminosity/distance: $F \sim 10^{-12}(L_{38}/d_{\rm Mpc}^2)$ erg s^{-1} cm^2, and the luminosity values given above, show that one-cloud/jet interaction fluxes predicted in the present contribution could be detectable at X- or γ-rays up to distances of $\sim$ 10 Mpc. The interaction of a cloud at the adopted $z_{\rm int}$ could lead either to persistent but variable emission if there were many clouds interacting with the jet [7], or to sporadic emission with a certain duty cycle if clouds interact with the jet from time to time. For the parameters adopted here, the jet-cloud interaction would be a persistent activity if the number of clouds is $N_{\rm c} > 10^8$ (for an FR II and assuming a life time of a cloud in the jet of $\sim t_{\rm j}$), and sporadic if $N_{\rm c}$ is smaller. In the former case, the actual luminosities should be obtained here multiplying by $(N_{\rm c}/10^8)$, and in the latter, the interaction duty cycle would be proportional to $100 \times (N_{\rm c}/10^8)$%. Notice that at larger $z_{\rm int}$, the emission will be reduced even if a larger number of clouds could penetrate the jet, given the smaller cloud to jet section ratio. Finally, we remain that given the properties of the emitter, the jet-cloud interaction radiation is not beamed and almost isotropic.

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