High-energy emission from jet-cloud interactions in AGNs

Anabella T. Araudo
Instituto Argentino de Radioastronomía (CCT La Plata - CONICET), C.C.5, 1894 Villa Elisa, Buenos Aires, Argentina
Facultad de Ciencias Astronómicas y Geofísicas, Universidad Nacional de La Plata, Paseo del Bosque, 1900 La Plata, Argentina
aaraudo@fcaglp.unlp.edu.ar

Valenti Bosch-Ramon
Max Planck Institut für Kernphysik, Saupfercheckweg 1, Heidelberg 69117, Germany
Valenti.Bosch-Ramon@mpi-hd.mpg.de

Gustavo E. Romero
Instituto Argentino de Radioastronomía (CCT La Plata - CONICET), C.C.5, 1894 Villa Elisa, Buenos Aires, Argentina
Facultad de Ciencias Astronómicas y Geofísicas, Universidad Nacional de La Plata, Paseo del Bosque, 1900 La Plata, Argentina
romero@fcaglp.unlp.edu.ar

Active galactic nuclei present continuum and line emission. The emission lines are originated by gas located close to the central super-massive black hole. Some of these lines are broad, and would be produced in a small region called broad-line region. This region could be formed by clouds surrounding the central black hole. In this work, we study the interaction of such clouds with the base of the jets in active galactic nuclei, and we compute the produced high-energy emission. We focus on sources with low luminosities in the inner jet regions, to avoid strong gamma-ray absorption. We find that the resulting high-energy radiation may be significant in Centaurus A. Also, this phenomenon might be behind the variable γ-ray emission detected in M87, if very large dark clouds are present. The detection of jet-cloud interactions in active galactic nuclei would give information on the properties of the jet base and the very central regions.

Keywords: galaxies: active; galaxies: individual: Centaurus A; radiation mechanism: non-thermal

1. Introduction
Active galactic nuclei (AGN) are extragalactic sources composed by a super-massive black hole (SMBH), an accretion disk and bipolar relativistic jets. Some AGNs present continuum emission in the whole electromagnetic spectrum, from radio to γ-rays. Besides the continuum radiation, AGNs also have optical and ultra-violet line emission. Some of these lines are broad, emitted by gas moving at velocities $v_K > 1000 \text{ km s}^{-1}$ and located in a region close ($d \sim 10^{17} \text{ cm}$) to the SMBH. The structure of the matter in the broad line region (BLR) is not well known.
but some models assume that the gas could be clumpy. Dense clouds, confined by
the hot external medium or by magnetic fields, would be ionized by photons from
the accretion disk producing the emission lines broadened by the movement of the
clouds around the SMBH. In the particular case of Faranoff Riley (FR) I galaxies,
where the accretion disks have low luminosities, the photoionization of the clouds
will be inefficient to produce lines and the clouds might be dark.

Centaurus A (Cen A) and M87 are the closest AGNs, located at distances of
$\sim 4$ and $\sim 16$ Mpc, respectively. These AGNs are classified as FR I radio sources
and in the case of Cen A the nuclear region is obscured by a dense torus of gas and
dust. Although the BLRs of Cen A and M87 have not been detected$^1$, clouds with
similar characteristic to those detected in FR II AGNs may surround the SMBH$^2$.

We are interested in the high-energy emission produced by the interaction
of these possibly dark clouds with the jets of the AGN. We focus here on Cen A
and M87, since their moderate accretion rate would imply reduced photon-photon
opacities in the interaction region, allowing $\gamma$-rays to escape. Assuming standard
parameters for the clouds and jets, we study the main physical processes that take
place as a consequence of the interaction, and calculate the expected high-energy
emission.

2. Jet-cloud interaction

We consider that clouds with density $n_c = 10^{10}$ cm$^{-3}$ and size $R_c = 10^{13}$ cm
are surrounding the SMBH and one of these clouds penetrates into one of the relativistic
jets. We assume that the jet has a Lorentz factor $\Gamma = 10$ (i.e. a bulk velocity $v_j \sim c$),
a radius $R_j = 0.1z$ ($z$ is the distance to the black hole), and a kinetic luminosity
$L_j = 10^{44}$ erg s$^{-1}$.

The penetration time of the cloud into the jet is determined by $t_c \sim 2R_c/v_c =
2 \times 10^4$ s, where $v_c = 10^9$ cm s$^{-1}$ is the cloud velocity. As a consequence of
the interaction of the jet material with the cloud, two shocks form. One of these shocks
propagates back in the reference frame of the jet with a velocity $v_{bs} \sim v_j$, producing
a bow shock. This bow shock reaches the steady state configuration in a time $t_{bs} \sim
x_{bs}/v_{bs}$, where the stagnation point is taken at a distance $x_{bs} \sim 0.3R_c$ from the
cloud (this value is obtained considering particle flux conservation and assuming an
escape velocity equal to the downstream sound speed). On the other hand, a shock
propagates inside the cloud at a velocity $v_{sc} \sim v_j(\Gamma - 1)/\chi$, where $\chi \equiv n_c/n_j$ and
$n_j = L_j/(\pi R_j^2(\Gamma - 1)m_p c^2 v_j)$ is the jet density in the shock reference frame. In a
time $t_{cc} \sim 2R_c/v_{sc}$ the whole cloud is shocked.

The permanence of the cloud into the jet is determined by the passage time of the
cloud into the jet, defined by $t_j \sim 2R_j/v_c$. However, the cloud is accelerated by the
jet, starting to move with the outflow. The acceleration of the cloud is $g \sim v_j^2(\Gamma -
1)/(\chi R_c)$. The acceleration timescale can be estimated from $t_a \sim \sqrt{R_c/g} \sim t_{cc}$,
which is the time required to accelerate the cloud up to $v_{sc}$ in the jet direction, hence
one can assume that the bow shock will remain strong only during several times
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t_{cc}. As a consequence of the pressure exerted by the jet onto the cloud, Rayleigh-Taylor (RT) instabilities can develop in the interface. In addition, Kelvin-Helmholtz (KH) instabilities can grow as a result of the high relative velocity between the jet shocked material and the cloud. In a first order approach, we obtain that RT and KH instabilities grow sufficiently to destroy the cloud on a timescale $t_{RT} \sim t_{KH} \sim t_{cc}$. In order to estimate the lifetime of the cloud into the jet, we compare $t_j$ and $t_{cc}$. We can parametrize $t_{cc} = \zeta t_c$, $\zeta > 1$, obtaining $v_{sc} = v_c/\zeta$. Considering that $v_{sc}$ depends on $z$ through the parameter $\chi$, we can obtain the interaction height: $z_{int} = \zeta 2.5 \times 10^{15}$ cm. Adopting $\zeta = 2$ results $t_j \sim 10^7$ s and $t_{cc} \sim 2 \times 10^4$ s, i.e. the cloud will be destroyed by the jet before escaping or approaching the jet velocity (with the subsequent weakening of the shock).

![Acceleration and cooling timescales for relativistic electrons accelerated in the bow shock of the jet-cloud interaction.](image)

3. Particle acceleration

In this work we consider only the particle acceleration in the bow shock, neglecting the contribution from the shock in the cloud. We assume that particles are accelerated up to relativistic energies, being injected in the downstream region of the bow shock following a distribution $Q_{e,p} \propto E_{e,p}^{-2-2}$ ($e$ and $p$ for electrons and protons, respectively). Assuming that a 20% of the jet luminosity that reaches the cloud goes to accelerate particles, the luminosity of these will be $L_{nt} \sim 0.2(R_c/R_j)^2L_j$. Considering that the magnetic energy density in the bow-shock region is the 10% of the non-thermal one, we obtain a magnetic field $B \sim 10$ G in that region.
The main radiative losses that affect the evolution of $Q_e$ are synchrotron radiation and synchrotron self-Compton (SSC) scattering. On the other hand, considering ultra-violet seed photons with a luminosity $\sim 10^{42}$ erg s$^{-1}$ (a larger value is unlikely in the nuclear region of FR I galaxies) the external Compton (EC) cooling is not relevant, as shown in Fig. 1. Relativistic Bremsstrahlung losses produced by the interaction with the jet matter in the bow-shock downstream region is not important either. In addition to the radiative losses, electrons escape from the emitter on a time $t_{\text{esc}} \sim 3R/c$. As we can see from Fig. 1 the maximum energy is determined by synchrotron losses, given $E_{\text{max}}^e \sim 1$ TeV. To obtain the distribution $N_e$ of relativistic electrons, we solve the kinetic equation (see Ref. 3) but taking into account not only the losses mentioned above but also the synchrotron photon field as SSC target, for which we need to use an iterative approach due the non-linear nature of the problem to solve. We obtain that the steady state is reached on a timescale $\ll t_{cc}$. The energy distribution of electrons $N_e(E_e)$ has a break at energy $E_b \sim 1$ GeV due to electron escape (see Fig. 1).

In the case of protons, these particles can lose energy via $pp$ interactions in the bow-shock region but the diffusion losses are more important, constraining the maximum energy to $E_{\text{max}}^p \sim 3 \times 10^3$ TeV. The most energetic protons, $E_p > 1$ TeV, diffuse up to the cloud before escaping advected by the shocked material of the jet.

4. High-energy emission

In the bow-shock region, using standard formulae and the electron energy distribution, we compute the synchrotron and SSC emission. In the cloud, energetic protons that arrive from the bow shock are not confined and escape from the cloud on a time $t_{\text{cl}} \sim R/c$ before radiating a significant part of their energy. Considering that the distribution of protons in the cloud is $N_p \sim Q_p t_{\text{cl}}$, we compute the $pp$ emission following the formulae given in Ref. 5.

The synchrotron emission is self-absorbed at energies $E_{\text{ph}} < 10^{-4}$ eV, but at higher energies auto-absorption and $\gamma\gamma$ absorption (see Ref. 6) are negligible in the region of interest. The achieved luminosity at energies $\sim 0.1 - 10$ GeV is $L_{\text{SSC}} \sim 2 \times 10^{39}$ erg s$^{-1}$, being slightly less than the sensitivity of HESS and Fermi at the distance of Cen A as is shown in Fig. 2. Note that we show the result of the interaction of only one cloud with the jet, but many clouds could simultaneously interact with the jet.

5. Discussion

The total luminosity produced by jet-cloud interactions depends on the number of clouds inside the jet, each one producing a spectral energy distribution (SED) with similar characteristics and luminosity levels to those shown in Fig. 2.

The number of clouds inside the jet is $N_{cj} = fV_j/V_c$, where $f$ is the filling factor of dark clouds, and $V_j$ and $V_c$ are the jet and the cloud volume, respectively. Considering $V_j$ up to $z \sim 10^{16}$ cm and $f \sim 5 \times 10^{-6}$ (in FR II galaxies $f \sim 10^{-6}$),
we obtain $N_{cj} \sim 10$. In the whole sphere of size $\sim 10^{16}$ cm the number of clouds is $\sim 5 \times 10^3$ for the considered value of $f$. The simultaneous interaction of $\sim 10$ clouds with the jet will produce more luminosity than the one produced by only one interaction. If all the clouds have the same properties (i.e. $n_c$, $R_c$ and $v_c$) and are located at $z \sim z_{\text{int}}$ in the jet, then the contribution of 10 clouds will produce a SED with a similar appearance than that shown in Fig. 2 but with a luminosity $\sim 10$ times larger, being now detectable by HESS and Fermi telescopes in the case of Cen A, as is shown in Fig. 3. The emission detected by these instruments from Cen A is larger than the luminosity predicted by our model. However, if clouds are larger than $10^{13}$ cm, the luminosity level detected by HESS and Fermi could be achieved. A more detailed calculation of the emission produced by many clouds interacting with the jet at different $z$ will be presented in a future work.

In the case of M87, the jet base is expected to be at $z_0 \sim 50R_{\text{Sch}} \sim 4 \times 10^{16}$ cm. At such a height on the jet, the jet-cloud interaction will be inefficient producing high-energy emission due to the small cloud to jet section ratio. In order to obtain a detectable luminosity, clouds with a radius $\sim 10^{14}$ cm would be necessary. In the case of a very big cloud entering the jet close to $z_0$ in M87, the interaction might produce the variable luminosity detected by HESS.

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References
1. D. M. Alexander, J. H. Hough, S. Young, J. A. Bailey, C. A. Heisler, S. L. Lumsden and A. Robinson, MNRAS 303 (1999) L17.
2. B. Wang, H. Inoue, K. Koyama and Y. Tanaka, PASJ 38 (1986) 635.
3. V. L. Ginzburg and S. I. Syrovatskii, The Origin of Cosmic Rays (Pergamon Press, New York, 1964).
4. G. R. Blumenthal and R. J. Gould, Rev. Mod. Phys. 42 (1970) 237.
5. S. R. Kelner, F. A. Aharonian and V. V. Vugayov, V.V., Phys. Rev. D 74 (2006) 034018.
6. F. M. Rieger and F. A. Aharonian, A&A 506 (2009) L41.
7. F. A. Aharonian et al. (HESS collaboration), ApJ 695 (2009) L40.
8. F. A. Abdo et al. (Fermi collaboration), ApJ (2010), submitted [arXiv:1002.0150]
9. A. T. Araudo, V. Bosch-Ramon, and G. E. Romero, in preparation.
10. F. A. Aharonian et al. (HESS collaboration), Science 341 (2005) 1424.