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Jet-cloud interactions in the BLR of Centaurus A

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Abstract. Active galactic nuclei present continuum and line emission. Some of these lines are broad, and would be produced by clouds located in a region close to the central black hole. Centaurus A is the nearest active galactic nuclei and it has an obscured nucleus likely harboring clouds. In this work, we study the interaction of these clouds with the jet and compute the produced non-thermal emission. The resulting radiation may be detectable.

Resumen. Los núcleos galácticos activos presentan emisión continua y de líneas. Algunas de estas líneas son anchas y podrían ser producidas por nubes que se encuentran cerca del agujero negro central. Centaurus A es el núcleo galáctico activo más cercano, con una región nuclear oscurecida donde podrían existir nubes. En este trabajo estudiamos la interacción de estas nubes con el jet y calculamos la emisión no-térmica producida. Esta radiación sería detectable.

1. Introduction

Active galactic nuclei (AGN) are extragalactic sources mainly composed by a super-massive black hole (SMBH), an accretion disk and bipolar relativistic jets. AGN present continuum radiation in the whole electromagnetic spectrum, from radio to γ-rays, and optical and ultra-violet line emission. Some of these lines are broad and could be formed in a clumpy region close to the SMBH: the Broad Line Region (BLR). Clouds in the BLR are ionized by photons (from the jets or from the disk) and then lines are emitted. These lines are broadened by the movement of the clouds around the SMBH.

Centaurus (Cen) A is the closest AGN, located at a distance ~ 3 Mpc. This source is classified as a Faranoff-Riley (FR) I radio galaxy and as a Seyfert 2 optical object. The nuclear region of Cen A is obscured by a dense region of gas and dust, probably as a consequence of a recent merger (Mirabel et al. 1999). Although the BLR of Cen A has not been detected, we can assume that clouds with similar characteristic of those detected in FR II AGN are surrounding the SMBH of Cen A.

In this work we study the interaction of BLR clouds with the jets of Cen A. We estimate the main dynamical processes that take place as a consequence of the jet-cloud interaction and compute the non-thermal emission.

2. The physical scenario

We consider that clouds with a density and size $n_{\rm c} = 10^{10}$ cm^{-3} and $R_{\rm c} = 10^{13}$ cm, respectively, are surrounding the SMBH of Cen A and one of these clouds penetrate into one of the relativistic jets. We assume that the jet has a Lorentz factor $\Gamma = 10$ (i.e. a velocity $v_{\rm j} \sim c$), a radius $R_{\rm j} = 0.1z$ (z is the height of the jet), and a kinetic luminosity $L_{\rm j} = 10^{44}$ erg s^{-1}.

The penetration time of the cloud into the jet is determined by $t_{\rm c} \sim 2R_{\rm c}/v_{\rm c} = 2 \times 10^4$ s, where $v_{\rm c} = 10^9$ cm s^{-1} is the cloud velocity. As a consequence of the interaction of the jet material with the cloud, in the contact surface between them two shocks are formed. One of these shocks propagates back in the jet with a velocity $v_{\rm bs} \sim v_{\rm j}$, forming a bow shock. This bow shock reaches the steady configuration (i.e. at rest in the cloud reference frame) in a time $t_{\rm bs} \sim x_{\rm bs}/v_{\rm bs}$, where the stagnation point is located at a distance $x_{\rm bs} \sim R_{\rm c}/5$ from the cloud. On the other hand, a shock propagates in the cloud at a velocity $v_{\rm sc}$, and in a time $t_{\rm cc} \sim 2R_{\rm c}/v_{\rm sc}$ the whole cloud is shocked. To determine $v_{\rm sc}$ we impose that $t_{\rm cc} = 2t_{\rm c}$, giving $v_{\rm sc} = 5 \times 10^8$ cm s^{-1}.

The permanence of the cloud into the jet is determined by the passage time of the cloud for the jet, defined by $t_{\rm j} \sim 2R_{\rm j}/v_{\rm c}$. However, the cloud could be accelerated by the jet material starting to move with the jet. The acceleration applied to the cloud is $g \sim v_{\rm j}^2(\Gamma - 1)/(\chi R_{\rm c})$, where $\chi \equiv n_{\rm c}/n_{\rm j}$ and $n_{\rm j}$ is the jet density, and the acceleration timescale results $t_{\rm acc} \sim \sqrt{R_{\rm c}/g}$. As a consequence of this acceleration exerted by the jet in the cloud, Rayleigh-Taylor (RT) instability can develop in the cloud. In addition to that, Kelvin-Helmholtz (KH) instability can grow as a result of the high relative velocity between the jet shocked material and the cloud. In our first order of approximations, we obtain that RT and KH instabilities grow sufficiently to destroy the cloud in a timescale $t_{\rm RT} \sim t_{\rm KH} \sim t_{\rm cc}$. Then, to estimate the lifetime of the cloud into the jet, we compare $t_{\rm j}$, $t_{\rm acc}$ and $t_{\rm cc}$. For that we have to know the interaction height $z_{\rm int}$ of the cloud into the jet and the jet density at $z_{\rm int}$. Assuming that pressure equilibrium is established between the shocked jet and cloud regions, we obtain $n_{\rm j} \sim 2.3 \times 10^5$ cm^{-3} and $z_{\rm int} = 4.6 \times 10^{15}$ cm, resulting $t_{\rm j} \sim 10^7$ s and $t_{\rm acc} \sim 2 \times 10^4\,{\rm s} \sim {\rm t}_{\rm cc}$.

3. Particle acceleration and losses

In addition to the dynamical processes described above, particles can be accelerated up to relativistic energies in the two shocks. However, being the bow shock the most efficient ($v_{\rm bs} > v_{\rm sc}$) for that, we will focus on the bow-shock particle acceleration in this work. We assume that the luminosity $L_{\rm nt}$ of the accelerated particles is the 20% of the jet luminosity that reach the bow shock, i.e. $L_{\rm nt} = 0.2(\sigma_{\rm c}/\sigma_{\rm j})L_{\rm j} = 8 \times 10^{39}$ erg s^{-1}, where $\sigma_{\rm c}$ and $\sigma_{\rm j}$ are the sections of the cloud and jet, respectively. Then, the energy density of relativistic particles

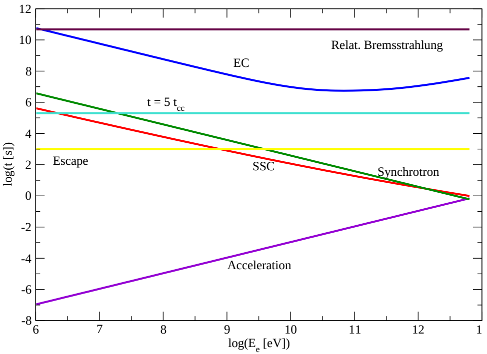

Figure 1. Acceleration and loss timescales for electrons.

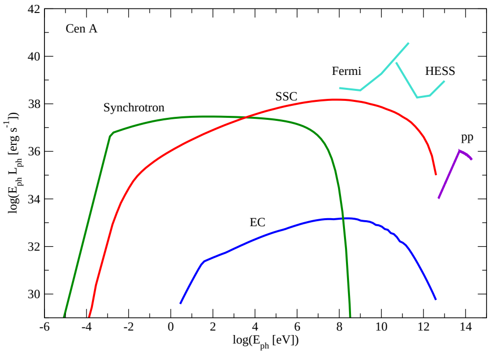

Figure 2. Spectral energy distribution.

is $U_{\rm nt} \sim 8.5 \times 10^2$ erg cm^{-3}. Considering that the magnetic energy density is $U_{\rm B} = 0.1 U_{\rm nt}$, the magnetic field in the bow-shock region results $B \sim 10$ G. The population of accelerated particles injected in the downstream region of the bow shock follow a power-law energy distribution:

$$Q_{e,p}(E_{e,p}) = K_{e,p}\, E_{e,p}^{-2.2}\, e^{-E_{e,p}/E_{e,p}^{\rm max}}, \tag{1}$$

where e and p stands for electrons and protons, respectively. The maximum energy is $E_{e,p}^{\rm max}$ and the normalization constant is $K_{e,p} \sim 1.2 \times 10^{38}$ erg$^{1.2}$ s^{-1}.

The radiative losses that affect the evolution of Q_e are synchrotron radiation, relativistic Bremsstrahlung, and synchrotron self-Compton (SSC) and external Compton (EC) scattering. For EC cooling we have considered target photons produced in the nuclear region with a luminosity $L_{\rm nuc} = 10^{42}$ erg s^{-1} and distributed in a sphere of radius $R_{\rm nuc} = 10^{17}$ cm. In addition to radiative losses, the escape of relativistic electrons of the emitter (considered equal to the accelerator) also produce energy losses, with a timescale $t_{\rm esc} \sim R_{\rm c}/v_{\rm dj}$, where $v_{\rm dj} = v_{\rm j}/3$ is the velocity of the jet shocked material. In Fig. 1 the lepton loss times are plotted together with the acceleration time. As we can see in the Figure, the maximum energy is determined by synchrotron losses, given $E_e^{\rm max} \sim 1$ TeV. We solve the kinetic equation (Ginzburg & Zyrovatskii, 1964) and we obtain that the steady state distribution of electrons, $N_e(E_e)$, is reached in a time $< t_{\rm cc}$. $N_e(E_e)$ has a break at the energy $E_{\rm b} \sim 1$ GeV, where the escape losses are equal to synchrotron ones (see Fig. 1), and for $E_e > E_{\rm b}$ the spectrum is $N_e(E_e) \propto E_e^{-3.2}$.

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 in $E_p^{\rm max} \sim 3 \times 10^3$ TeV. On the contrary of electrons, protons do not reach the steady state in the bow-shock region. The most energetic protons, $E_p \gtrsim 1$ TeV, can diffuse up to the cloud before escape advected by the shocked material of the jet.

4. High-energy emission

In the bow-shock region, the most relevant radiative processes are leptonic. Using standard formulas (Blumenthal & Gould, 1970) we estimate the specific luminosity $E_\gamma L_\gamma$ for synchrotron, SSC and EC emission. In the cloud, energetic protons that arrive from the bow-shock are not confined and escape from the cloud in a time $t_{\rm cl} \sim R_{\rm c}/c$, before radiate a significant part of their energy. Considering the the distribution of protons in the cloud is $N_p \sim Q_p\, t_{\rm cl}$ we estimate the pp emission following the formulas giving by Kelner et al. (2006).

In Fig. 2 all the radiative processes mentioned above are plotted, together with the sensitivities of the γ-ray telescopes HESS and *Fermi.* The synchrotron emission is self absorbed at energies $E_{\rm ph} \lesssim 10^{-4}$ eV, but at higher energies autoabsorption and $\gamma\gamma$ absorption are negligible. The achieved luminosity at energies $\sim 0.1 - 10$ GeV is $L_{\rm SSC} \sim 2 \times 10^{39}$ erg s^{-1}, being less than the sensitivity of the mentioned instruments. However, Fig 2 shows the spectral energy distribution (SED) produced by the interaction of one cloud with the jet, but many clouds could simultaneously stay inside the jet.

The number of clouds in the whole BLR can be estimated as $N_{\rm c} \sim L_{\rm nuc}/L_{\rm c} \sim 3.3 \times 10^6$, where $L_{\rm c} \sim 3 \times 10^{35}$ erg s^{-1} is the line luminosity of each cloud. We have estimated this value using the cooling function for emission lines and considering that the cloud has a temperature $\sim 10^4$ K. The number of clouds inside the jet is $N_{\rm cj} = ff V_{\rm j}/V_{\rm c}$, where $ff = N_{\rm c} V_{\rm c}/V_{\rm blr}$ is the filling factor of the clouds and $V_{\rm j}$, $V_{\rm c}$ and $V_{\rm blr}$ are the jet, the cloud and the nuclear region volume, respectively. We obtain $N_{\rm cj} \sim 10$. Then, the simultaneously interaction of ∼10 clouds with the jet will produce a SED with a similar appearence than that shown in Fig. 2, but with a lumnisotity ∼10 times larger, being now detectable by HESS and *Fermi* telescopes.

5. Conclusions

In the present contribution we study the interaction of clouds present in the nuclear region of Cen A with the jet. As a result of the interaction, a significant amount of high energy emission is produced, which could be detected by the current γ-ray observational facilities. The detection of this emission could give information on the properties of the obscured nuclear region and the jet base of Cen A.

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