Gamma-ray emission from Wolf-Rayet stars interacting with AGN jets

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Gamma-ray emission from Wolf-Rayet stars interacting with AGN jets

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Abstract. Dense populations of stars surround the nuclear regions of galaxies. In this work, we study the interaction of a WR star with relativistic jets in active galactic nuclei. A bow-shaped double-shock structure will form as a consequence of the interaction of the jet and the wind of the star. Particles can be accelerated up to relativistic energies in these shocks and emit high-energy radiation. We compute the produced γ-ray emission obtaining that this radiation may be significant. This emission is expected to be particularly relevant for nearby non-blazar sources.

Keywords: Galaxies: active; Radiation processes: non-thermal; Gamma-rays: theory
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INTRODUCTION

Active galactic nuclei (AGNs) consist of a supermassive black hole (SMBH) surrounded by an accretion disc in the center of a galaxy. Sometimes these objects present radio emitting jets originated close to the SMBH. Jets of AGN are relativistic ($v_{\rm j} \sim c$), with macroscopic Lorentz factors $\Gamma \sim 5-10$, and density $\rho_{\rm j} = L_{\rm j}/[(\Gamma-1)c^2\sigma_{\rm j} v_j]$, where $L_{\rm j}$ and $\sigma_{\rm j} = \pi R_{\rm j}^2$ are the jet kinetic luminosity and section, respectively, and $R_{\rm j}$ its radius. According to the current taxonomy of AGN, jets from type I Faranoff-Riley galaxies (FR I) are low luminous, with a kinetic luminosity $L_{\rm j} < 10^{44}$ erg s^{-1}, whereas FR II jets have $L_{\rm j} > 10^{44}$ erg s^{-1}.

In the nuclear region of AGNs there is matter in the form of diffuse gas, clouds, and stars, making jet medium interactions likely. Different models based on the interaction of jets with obstacles from the external medium have been proposed in order to explain the γ-ray emission produced in misaligned AGN jets [1,2]. In the present contribution we study a new scenario: the interaction of Wolf-Rayet (WR) stars with the jets.

JET-STAR INTERACTION

We consider that a WR star with mass loss rate $\dot{M}_{\rm w} = 10^{-4}$ M$_\odot$ yr^{-1} and terminal wind velocity $v_\infty = 3000$ km s^{-1} penetrates the jet at $z_{\rm int} = 5 \times 10^{-4}$ pc, that correspond to a value of 10 times the base of the jet that emanates from a SMBH of mass 10^7 M$_\odot$.

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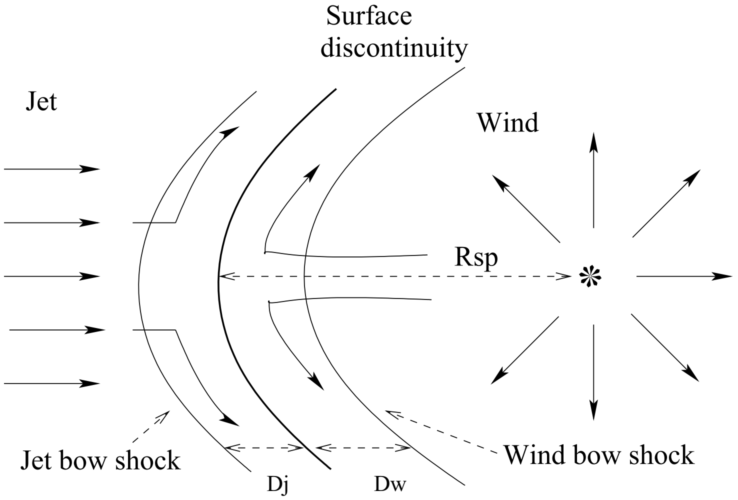

FIGURE 1. Left: Sketch of the scenario considered in the present study.

When the jet interacts with the star a double bow shock is formed around it, as is shown in Figure 1. The location of the stagnation point is at a distance $R_{\rm sp}$ from the stellar surface, where the wind and jet ram pressures are equal. From $\rho_{\rm w}\, v_\infty^2 = \rho_{\rm j}\, c^2\, \Gamma$, where $\rho_{\rm w} \sim \dot{M}_\star/(4\pi R_{\rm sp}^2 v_\infty)$ is the wind density, we obtain

$$\frac{R_{\rm sp}}{R_{\rm j}} \sim 0.1 \left(\frac{\dot{M}_{\rm w}}{10^{-4}\,{\rm M_\odot\,yr^{-1}}}\right)^{1/2} \left(\frac{v_\infty}{3000\,{\rm km\,s^{-1}}}\right)^{1/2} \left(\frac{L_{\rm j0}}{10^{42}\,{\rm erg\,s^{-1}}}\right)^{-1/2} \left(\frac{\Gamma-1}{9}\right)^{1/2}. \tag{1}$$

PARTICLE ACCELERATION AND LOSSES

Particles can be accelerated up to relativistic energies in both the jet and wind shocks. Relativistic electrons and protons are injected in the downstream regions following a distribution $Q_{e,p} \propto E_{e,p}^{-2}$. The luminosity of particles accelerated in the jet and in the wind bow shocks is $L_{\rm ntj} \sim 0.1(R_{\rm sp}/R_{\rm j})^2 L_{\rm j}$ and $L_{\rm ntw} \sim 0.1 L_{\rm w}/4$, respectively, where $L_{\rm w} = \dot{M}_{\rm w} v_\infty^2/2$. We estimate the magnetic field in the jet shocked region, $B_{\rm jbs}$, assuming that the magnetic energy density is a fraction $\eta_{\rm B}$ of the energy density of the jet shocked matter, resulting in

$$B_{\rm jbs} \sim 17 \left(\frac{\eta_{\rm B}}{0.01}\right)^{1/2} \left(\frac{L_{\rm j}}{10^{42}\,{\rm erg\,s^{-1}}}\right)^{1/2} \left(\frac{z}{z_{\rm int}}\right)^{-1}\ {\rm G}. \tag{2}$$

The main radiative losses that affect the evolution of Q_e are synchrotron radiation and Inverse Compton (IC) scattering. For the later we have considered stellar target photons with an energy ~ 7.9 eV and luminosity $L_\star = 10^{39}$ erg s^{-1}. In addition to radiative losses, electrons can escape from the emitter by advection or diffusion. For the wind we assume the parametrization of the magnetic field $B_{\rm w}$ given in [5], with a value in the stellar surface of about 10 G.

TABLE 1. Bolometric luminosities of synchrotron emission ($L_{\rm syn}^{\rm j,w}$) and IC scattering ($L_{\rm IC}^{\rm j,w}$) in the jet and in the wind. Values are given in erg s^{-1} units.

	$L_{\rm j} = 10^{42}$	$L_{\rm j} = 10^{45}$	$L_{\rm j} = 10^{48}$		$L_{\rm j} = 10^{42}$	$L_{\rm j} = 10^{45}$
$L_{\rm syn}^{\rm j}$	8.6×10^{38}	1.2×10^{39}	3.2×10^{42}	$L_{\rm syn}^{\rm w}$	1.2×10^{33}	1.0×10^{36}
$L_{\rm IC}^{\rm j}$	9.1×10^{38}	3.3×10^{39}	4.4×10^{40}	$L_{\rm IC}^{\rm w}$	6.5×10^{37}	4.1×10^{39}

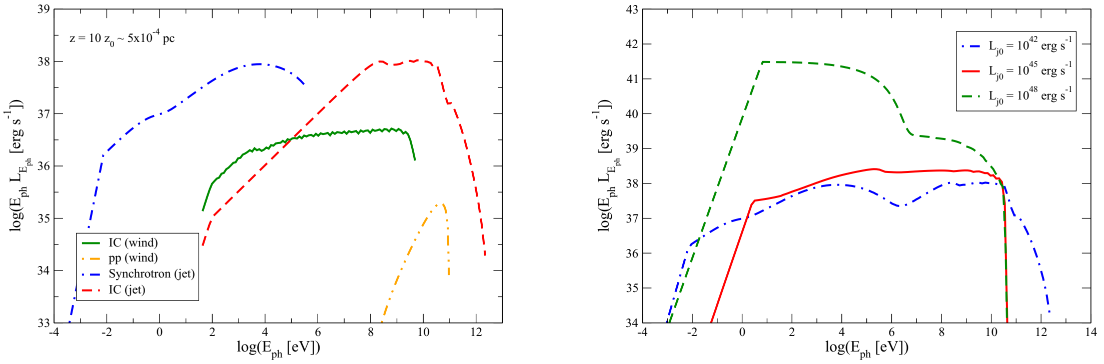

FIGURE 2. *Left*: Synchrotron emission, IC scattering (in the jet and in the wind), and *pp* components for the case of $L_{\rm j} = 10^{42}$ erg s^{-1}. *Right*: Spectral energy distributions where all the contributions were added. The main contributions to the SED are synchrotron radiation and IC scattering in the jet. In the case of $L_{\rm j0} = 10^{42}$ erg s^{-1} IC radiation in the wind is also relevant.

At $z_{\rm int}$, the maximum energy of electrons accelerated in the jet bow shock is constrained by synchrotron losses, reaching a value $E_e^{\rm max} \sim 3$ TeV. Inverse Compton scattering is also an important channel of electron cooling (in the jet and in the wind) as a consequence of the large value of the energy density of the WR radiation field at $R_{\rm sp}$: $U_{\rm ph\star} \sim 2.4$ erg cm^{-3}. This process constrains the maximum energy of electrons accelerated in the wind bow shock, yielding a value of ~ 10 GeV. The decay of π^0 produced in *pp* interactions is not relevant compared with IC emission (see Fig. 2-*Left*). Bolometric luminosities achieved by different radiative processes and jet luminosities are listed in Table 1. Absorption of γ rays by stellar photons is important at photon energies $E_{\rm ph} > 30$ GeV. In Fig. 2 (*Right*), the computed spectral energy distributions (SEDs) for the cases of $L_{\rm j} = 10^{42}$, 10^{45}, and 10^{48} erg s^{-1} are shown.

Gamma-ray emission

The achieved emission levels in γ rays in the case of $L_{\rm j} = 10^{48}$ erg s^{-1} ($\sim 3 \times 10^{39}$ erg s^{-1}) could be detectable by the *Fermi* satellite in nearby AGNs. The radiation produced by a WR interacting time to time with a jet will be transient. It is noteworthy that one or few WR may be permanently present within the jet at $z > z_{\rm int}$, where radiative cooling is still dominant, adding up to the contribution of the many-star persistent emission studied in [5]. In fact, WR could be important contributors of their own to the non-thermal output of misaligned AGN jets.

DISCUSSION

The interaction of a WR star with the jet can produce significant amounts of γ rays only if the interaction height is below the z at which advection escape dominates the whole particle population. Also, $\sigma_{\rm sp}$ should be a significant fraction of $\sigma_{\rm j}$. In this context, we have considered the interaction of a powerful WR star at $z = 5 \times 10^{-4}$ pc (for which the bow shock covers $\sim 1\%$ of the jet section). The emission produced by IC scattering achieves values as high as 5×10^{39} erg s^{-1} in the *Fermi* range. Such an event would not last long though, about $R_{\rm j}/v_\star \sim 10^7\,(R_{\rm j}/10^{16}\,{\rm cm})\,(10^9\,{\rm cm\,s^{-1}}/v_\star)^{-1}$ s, where $v_\star$ is the velocity of the WR.

Since jet-star emission should be rather isotropic, it would be masked by jet beamed emission in blazar sources. However, when radio loud AGN jets do not display significant beaming, these objects may emit detectable γ rays from jet-star interaccions. The emission level achieved by the interaction of a WR with a jet close to the jet base could be detectable by *Fermi* only for very nearby sources, like Centaurus A or M87. The interaction of a star even more powerful than a WR, like a Luminous Blue Variable, may provide $R_{\rm sp} \sim R_{\rm j}$, making available the whole jet luminosity budget for particle acceleration. After few-year exposure times of *Fermi*, a significant signal from close and powerful sources could be detectable. Their detection can shed light on the jet matter composition as well as on the stellar populations in the vicinity of AGNs.

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