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Truncation of AGN jets by their interaction with a passing star cluster

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ABSTRACT
We are interested in the effects of interaction of jets in Active Galactic Nuclei when they encounter various obstacles, namely, stars in Nuclear Star Cluster surrounding the nucleus and globular clusters passing across the inner jet, as well as dense clouds from the Broad Line Region. The interaction provides a scenario to address non–thermal processes. In jet–star interactions a double bow–shock structure is formed where particles get accelerated via diffusive mechanism. Individual encounters have a limited effect, however, dense clusters of massive stars can truncate the jet as the cluster crosses the jet line near the jet launching region. Much of the jet kinetic energy density is transferred to the shock and it becomes available to accelerate particles. We conclude that the interaction of jets with clusters of massive stars is a promising way to explain detectable levels of gamma rays from Fanaroff–Riley class I of edge–brightened radio galaxies.

Keywords: galaxies: active – galaxies: jets – stars: clusters

1 INTRODUCTION

Active galactic nuclei (AGN) contain an accreting super–massive black hole (SMBH) in the center of a galaxy. In some cases these objects form powerful radio–emitting jets (Begelman et al., 1984). The emission from the jets is non–thermal and generated by a population of relativistic particles accelerated in strong shocks. This non–thermal emission is assumed to be produced by synchrotron and inverse Compton (IC) processes, although hadronic models have been also considered to explain gamma–ray detections.

The interaction of AGN jets with clouds from the Broad Line Region (BLR) was suggested by Blandford and Königl (1979) as a mechanism for knot formation in the M87 radio galaxy jet. Also, the gamma–ray production through the interaction of a cloud from the BLR with the AGN jet was studied by Dar and Laor (1997) and by Araudo et al. (2010). In the latter work, the authors showed that the jet–cloud interactions may generate detectable gamma–rays in non–blazar AGN, of transient nature in nearby low–luminous sources, and steady in the case of powerful objects.

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Stars surround the central region of AGN. Nuclear star clusters have been detected in majority of galaxies and they represent the densest stellar systems (Neumayer et al., 2011; Schödel et al., 2014). Also, the globular cluster population evolves within the galactic potential and it may provide stars into interaction region of jets (Gnedin et al., 2014; Fragione et al., 2017). Jet–star interactions have been studied as a possible mechanism of jet mass loading and deceleration. In the seminal work of Komissarov (1994), the interaction of low–mass stars with jets was considered to analyse the mass transfer from the former to the latter in elliptical galaxies, concluding that jet–star interactions can significantly affect the jet dynamics and matter composition in low–luminous jets. Later on, and motivated by the detection of gamma–ray emission in misaligned AGN jets, different authors considered jet–star interactions as a possible scenario to produce shocks, accelerate particles, and emit non–thermal photons.

The interaction of AGN jets with massive stars was investigated by a number of authors (see, e.g., Araudo et al. (2013); Wykes et al. (2015); Bednarek and Banasiński (2015), and further references cited therein). Barkov et al. (2010) studied the interaction of AGN jets with red giant stars. In all the cases, the conclusion is that in order to have a detectable level of gamma–ray emission, a large number of stars have to be simultaneously present within the jet. More recently, Vieyro et al. (2017) analyzed the collective non–thermal emission from AGN jets interacting with early–type stars. They conclude that, for the particular case of radio galaxy M87, the gamma–ray emission level produced by jet–star interactions is below the detected flux in the GeV domain.

Hubbard and Blackman (2006) analysed the mass loading and truncation of the jet by interactions with stars, also considering the case of an interposed stellar cluster. Bednarek and Banasiński (2015) investigated the interaction of globular clusters with jets at few kpc from the SMBH. They considered that the power of the collective wind of globular clusters is determined by the relativistic winds of individual milliarcsecond pulsars within the cluster. Even when pulsars have a relativistic wind, the collective wind has a size of ~ 1 pc in the case of Cen A where the jets have a kinetic luminosity $L_{\rm j} \sim 10^{43}$ erg s^{-1} (Wykes et al., 2015). Therefore, the collision of a single globular cluster cannot truncate the jet and about 10 clusters simultaneously within the jet are required to have a detectable level of non–thermal emission.

In the present contribution we study the interaction of AGN jets with a single cluster of massive stars. To this end we consider standard prescriptions for jets and stellar cluster collective winds.

2 JET–STELLAR CLUSTER INTERACTION

Jets from AGN are relativistic, with bulk Lorentz factors reaching $\Gamma \sim 10$ where the terminal velocity is thought to be set by the radiation drag and the ambient medium into which the jet propagates (Abramowicz et al., 1990; Vokrouhlicky and Karas, 1991; Fukue, 2005). The matter composition of these jets is not well known and two different prescriptions are commonly adopted: a jet composed only by electron–positron pairs (e.g. Komissarov (1994)), and a lepto–hadronic jet (e.g. Reynoso et al. 2011) with the same number density of protons and electrons, i.e. $n_e = n_p$.

In the present work we consider a lepto–hadronic jet. Concerning the kinetic luminosity ($L_{\rm j}$), jets from type I Faranoff–Riley (FR I) galaxies are less luminous, with $L_{\rm j} < 10^{44}$ erg s^{-1}, whereas FR II jets have $L_{\rm j} > 10^{44}$ erg s^{-1}. The jet kinetic pressure is

$$P_{\rm j} = \frac{L_{\rm j}}{\sigma_{\rm j} c} \sim 10^{-8} \left(\frac{R_{\rm j}}{\rm pc}\right)^{-2} \left(\frac{L_{\rm j}}{10^{40}\,{\rm erg\,s^{-1}}}\right) {\rm erg\,cm^{-3}} \tag{1}$$

where $\sigma_{\rm j} = \pi R_{\rm j}^2$ is the jet cross section and $R_{\rm j}$ is the jet width. The former, less energetic sources are particulary interesting from the viewpoint of our current considerations.

The collective wind (i.e., the superposed wind from cluster members; CW) of a cluster of massive stars interacting with an AGN jet can block a significant fraction of the jet cross section (Hubbard and Blackman, 2006). Cantó et al. (2000) performed a hydrodynamical study of the collective wind of a dense cluster of massive stars. It can be described as a single wind with mass–loss rate $\dot{M}_{\rm cw} \sim 10^{-4}\ M_\odot$ yr^{-1} and velocity $v_{\rm cw} \sim 1000 - 2000$ km s^{-1} (Torres and Domingo-Santamaría, 2007).

The interaction of a stellar cluster with the jet produce a double bow–shock structure as described in e.g. Araudo et al. (2013). The shock in the jet is relativistic whereas the shock in the collective wind is non–relativistic with a velocity $\sim v_{\rm cw}$. The contact discontinuity is located at a distance $R_{\rm sp}$ from the center of the cluster, where the jet and cluster wind $P_{\rm cw} = \dot{M}_{\rm cw} v_{\rm cw}/(\pi R_{\rm sp}^2)$ ram pressures are equated. By equating $P_{\rm cw} = P_{\rm j}$ we find

$$\frac{R_{\rm sp}}{R_{\rm j}} = 0.5 \left(\frac{\dot{M}_{\rm cw}}{10^{-4}\,{\rm M_\odot yr^{-1}}}\right)^{0.5} \left(\frac{v_{\rm cw}}{2000\,{\rm km\,s^{-1}}}\right)^{0.5} \left(\frac{L_{\rm j}}{10^{40}\,{\rm erg\,s^{-1}}}\right)^{-0.5} . \tag{2}$$

We can see that a cluster of massive stars can truncate the jets in FR I radio galaxies (i.e. $R_{\rm sp}/R_{\rm j} \sim 1$) and therefore most of the jet kinetic luminosity is transferred to the shock and available to accelerate particles, as we discuss in the next section.

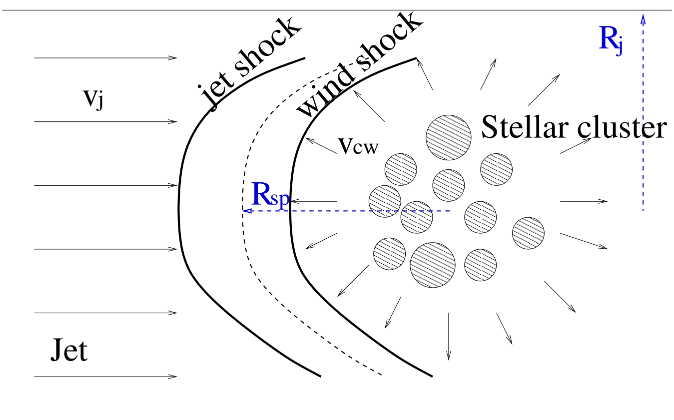

Figure 1. Sketch of the jet-stellar cluster interaction. Two shocks develop and a transition region, as described in the text.

3 PARTICLE ACCELERATION AND NON–THERMAL EMISSION

Particles can be accelerated in both jet and CW shocks, and emit non–thermal emission in the shocked plasma. Diffusive acceleration of particles in relativistic and non–relativistic shocks has been studied by different authors with detailed semi–analytical and numerical approaches (e.g. Kirk et al. (2000); Park et al. (2015)). Here we follow a simple description.

The luminosity of the shock in the jet is $L_{\rm sh,j} = (R_{\rm sp}/R_{\rm j})^2 L_{\rm j}$ giving

$$\left(\frac{L_{\rm sh,j}}{\rm erg\,s^{-1}}\right) = 2.5\times10^{39}\left(\frac{\dot{M}_{\rm cw}}{10^{-4}\,{\rm M_\odot yr^{-1}}}\right)\left(\frac{v_{\rm cw}}{2000\,{\rm km\,s^{-1}}}\right). \tag{3}$$

The shock in the collective wind have a luminosity $L_{\rm sh,cw}\sim L_{\rm cw}$, where

$$\left(\frac{L_{\rm cw}}{\rm erg\,s^{-1}}\right) \sim 10^{38}\left(\frac{\dot{M}_{\rm cw}}{10^{-4}\,{\rm M_\odot yr^{-1}}}\right)\left(\frac{v_{\rm cw}}{2000\,{\rm km\,s^{-1}}}\right)^2. \tag{4}$$

By assuming that a fraction $\zeta_{\rm nt}\sim 0.01-0.1$ of $L_{\rm sh,j}$ and $L_{\rm cw}$ goes to non–thermal particles, the luminosity in non thermal electrons (L_e) and protons (L_p) is $L_{\rm nt} = L_e + L_p = \zeta_{\rm nt} L_{\rm sh}$. The magnetic field B plays an important role in the acceleration of particles. By assuming that the magnetic energy density $U_{\rm mag} = B^2/8\pi$ is in equipartition with non–thermal particles, i.e. $U_{\rm mag} = U_{\rm nt}$, where $U_{\rm nt} = L_{\rm nt}/(\pi R_{\rm sp}^2 c)$, we find the upper limit

$$\left(\frac{B_{\rm eq}}{\mu{\rm G}}\right) = 50\left(\frac{\zeta_{\rm nt}}{0.01}\right)^{0.5}\left(\frac{R_{\rm j}}{\rm pc}\right)^{-1}\left(\frac{L_{\rm j}}{10^{40}\,{\rm erg\,s^{-1}}}\right)^{0.5} \tag{5}$$

in the jet shock downstream region, and

$$\left(\frac{B_{\rm eq,cw}}{\mu{\rm G}}\right) = 20\left(\frac{\zeta_{\rm nt}}{0.01}\right)^{0.5}\left(\frac{v_{\rm cw}}{2000\,{\rm km\,s^{-1}}}\right)^{0.5}\left(\frac{R_{\rm j}}{\rm pc}\right)^{-1}\left(\frac{L_{\rm j}}{10^{40}\,{\rm erg\,s^{-1}}}\right)^{0.5} \tag{6}$$

in the CW shock downstream region.

Accelerated particles are injected in the shock downstream region following a power–law energy distribution $N_{e,p}\propto E_{e,p}^{-\beta}$, with $\beta\sim 2$ in non–relativistic shocks (i.e. the collective wind) and $\beta\sim 2.2-2.4$ in relativistic shocks (i.e. the jet). The energy density in particles with energy $E_{e,p}$ is $U_{e,p}\propto N_{e,p}E_{e,p}^2$, resulting the same amount of energy in every energy decade when $\beta = 2$, whereas most of the energy is concentrated in low–energy particles when $\beta > 2$ (Bell et al., 2018). Therefore, even when the energy budget to accelerate particles in the jet shock is larger than in the collective wind (i.e. $L_{\rm sh,j} > L_{\rm cw}$), the energy density at the highest energies can be comparable.

Gamma–rays can be produced by proton–proton (pp) collisions with a cooling rate$dE_p/dt \propto n_p$ (e.g. Kelner et al. (2006)). Stellar winds are denser that AGN jets where jet–stellar cluster interactions can take place, and therefore, there are more targets for pp collisions in the collective wind than in the jet. A large density contrast, combined with the fact that the spectrum of non–thermal protons accelerated in relativistic shocks is steeper than in non–relativistic shocks, can produce a gamma–ray flux in the shocked collective wind larger than in the shocked jet region.

4 CONCLUSIONS

We study the interaction of a cluster of massive stars with AGN jets as a continuous process that must occur repetitively in galactic nuclei and a promising mechanism that can trigger production of high–energy particles. We show that stellar clusters with mass loss rate $\dot{M}_{\rm cw} \sim 10^{-4} M_{\odot}$ yr^{-1} and velocity $v_{\rm cw} \sim 2000$ km s^{-1} can truncate an AGN jet with kinetic luminosity $L_{\rm j} \sim 10^{40}$ erg s^{-1}. Therefore, this scenario is very promising option for particle acceleration given that most of the jet kinetic luminosity will be transferred to the bow shock and therefore there is sufficient energy budget to accelerate particles and produce detectable levels of non–thermal emission, in particular in the gamma–ray domain.

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