Doppler boosting effects on the radiation of relativistic jets in AGN

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Abstract: Active galactic nuclei are among the brightest sources in the Universe, with jets being detected in about a 10% of these objects. Studying the dynamics of these jets allows us to better understand the physics of these sources, and in particular why they are so powerful emitters. We model here the jets of active galactic nuclei as one dimensional supersonic relativistic fluids, assuming that they are described by the Bernoulli equation, plus a phenomenological prescription for their radius-height relation. With this model, we study the effects of relativistic Doppler boosting on the emitter structure and radiation intensity, which are sensitive to the viewing angle and radius-height jet relation.

I. INTRODUCTION

When we look to the Universe, we can observe different types of radiation coming from different heavenly bodies. In our case, we focus on active galactic nuclei (AGN) because they are among the brightest objects in the Universe, and as it is said in [1], AGN are thus special laboratories for extreme physics which we would like to understand, and they are also our principal probes of the Universe on large scales, so understand them is essential to study the formation and evolution of the Universe.

Active galactic nuclei host in their centre a supermassive black hole (SMBH) and an accretion disk around it. The ratio between the luminosity of the accreting SMBH and the Eddington luminosity (i.e. a luminosity high enough to expel accreted matter through radiation pressure) determines the main properties of the AGN, so the same ratio of these values will give similar properties as is said on [2]. The ratio between the black hole spin and the critical spin (an extreme spinning black hole is that thought unable to accept additional angular momentum; [3]), and the ratio between the magnetic field pressure and the matter pressure, are also relevant parameters to characterize AGN.

A particular type of AGN is the one that presents jets, as it is commented on [4]. The matter forms a disc and, in the narrow regions over the black hole poles, matter can be channelled at very high speeds, escaping the vicinity of the black hole in the form of supersonic and relativistic jets. At the high velocities of the plasma in the jet, close to the speed of light, non-thermal radiation is produced by charged particles spinning around the magnetic field at ultra-relativistic velocities (synchrotron radiation), or by the inverse Compton effect, processes described in [5]. Thermal radiation can be supposed negligible. If the radiation of the thermal and non-thermal particles is small, we can consider the jet adiabatic, since most of the energy is lost or exchanged through work, not radiation.

As jets move at relativistic velocities, the time and space intervals are different in the jet proper frame and in the observer one, and one has to account for Doppler boosting effects: red-blue Doppler shift, time shortening, and relativistic light aberration.

We study here the coupling between hydrodynamical effects and Doppler boosting and their impact on AGN jet emission as seen from the observer.

II. JET MODEL

We study the jet hydrodynamical and radiative properties assuming it is a stationary, relativistic, supersonic one dimensional flow, and focusing in the region between 1 pc and 100 pc from the jet base. At closer distances than 1 pc, the jet formation process is possibly still affecting the fluid dynamics, whereas beyond 100 pc the jet may be already significantly affected by interactions with the external medium. These scales are good candidates to be the location of high-energy emission [6].

To be able to see how the hydrodynamical and radiative properties of the jet evolve, we assume that the jet flow is characterized by the following laws:

-The conservation law of mass flux, as we consider that the jet is stationary and does not have sources or sinks of matter:

$$\sigma\rho\gamma v = A, \tag{1}$$

where ρ is the density, γ is the Lorentz factor, v is the velocity, A is a constant, and σ is the area of the jet section at a distance z defined by:

$$\sigma = \pi r^2. \tag{2}$$

-The conservation law of momentum flux:

$$\sigma(\rho\gamma^2 h v^2 + P) = B, \tag{3}$$

where P is the pressure, B is a constant, and h is the specific enthalpy that is defined by:

$$h = 1 + \frac{u}{\rho c^2} + \frac{P}{\rho c^2}, \tag{4}$$

where u is the internal energy density, c is de velocity of light, and h is the enthalpy per mass unit.

For the case we study, we assume that our jet is adiabatic, and the energy losses by radiation are negligible. This makes our jet matter obey the following equation:

$$P\rho^{-\gamma_{ad}} = P_0\rho_0^{-\gamma_{ad}}. \quad (5)$$

We adopt the equation of state:

$$u = \frac{P}{\gamma_{ad} - 1}, \quad (6)$$

where γ_{ad} is the adiabatic coefficient, taken 4/3 because we assume that the jet gas is relativistic and ideal.

Since jets can present different shapes depending on the external medium properties, we study different cases depending on how the radius of the jet varies with distance:

$$r \propto z^{\alpha}, \quad (7)$$

where α is the power-law index that determines the dependence between the radius and the distance to the jet base.

The initial jet parameters considered are:

z_o=1pc ; r_0=0.1pc; γ_0=2; ρ_0=1.7 10^{-25} g/cm^3

P_0=1.53 10^{-2} dyn

We have decided to work with these parameters as an illustrative example because they are representative, intermediate values of jets parameter in AGN.

Once we have set the equations, and in front of the problem to solve the relativistic Bernoulli equation for our jet, we apply the Newton-Raphson method because it is a fast method to find the roots of an equation when we are close to them. We reproduce how the hydrodynamic and radiative properties vary with distance in our jet as a function of the dependence between r and z in Eq. (7). To have an idea of how the properties that we want to study vary depending on the parameter α, say if it is <1 , =1, or >1, we explore the cases where α=0.5, α=1.0, and α=1.5.

As the jet is relativistic, its radiation will suffer Doppler boosting, which we have to take into account to study the jet from the point of view of the observer.

The Doppler factor of the radiation emitted by a source moving at an angle θ to the line of sight is:

$$\delta = \frac{1}{\gamma(1 - \frac{v}{c}cos\theta)}. \quad (8)$$

The radiation luminosity integrated over frequency is multiplied by the factor δ^4 as is said in [7], because each frequency is multiplied by δ, time is shorter by δ (both due to time shortening by $1/\delta$), and light aberration effects ($\times\delta^2$).

Time shortening as seen by the observer is produced because the emitting flow is approaching, so time intervals seem shorter in the observer frame than in the flow and the laboratory frames.

The other phenomenon important is light aberration which causes light rays to appear angled or tilted towards the direction of motion compared to the case of a static emitter as is said in [8].

In what follows, we study how the hydrodynamical properties vary along the jet. We also study how the radiation will appear for different line of sights ($\theta = 0^o$ and 90^o).

III. RESULTS

Next, we present the results of the study of the jet, regarding its hydrodynamical and the radiative properties. We study them separately as the first ones do not depend, unlike the second ones, on the viewing angle.

A. Hydrodynamic properties

The hydrodynamic properties are intrinsic to the jet, and they do not depend on the angle with which we observe it.

We consider as representative quantities the following:

-The Lorentz factor, which gives an idea of how fast is the jet matter accelerated due to the present pressure gradient for each α-value.

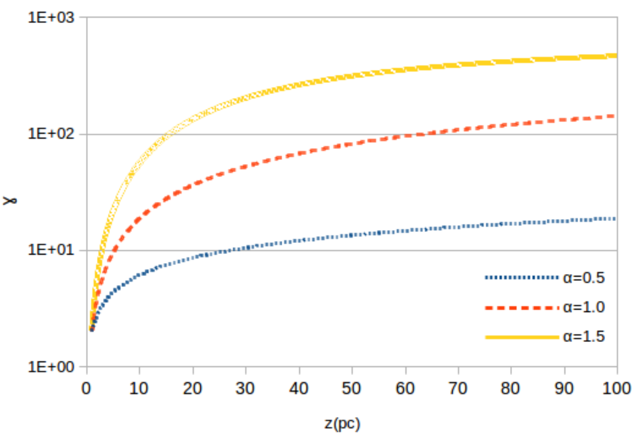

FIG. 1: Lorentz factor versus distance for different α values.

Figure 1 shows that γ grows faster for $\alpha > 1$ than for $\alpha \leq 1$, although the growth eventually slows down in all three cases and γ should saturate around $\gamma \to \gamma_0 h_0 \approx 800$ (not reached for any of the studied cases due to the short jet length covered).

-The relativistic Mach number as it is said on [9], which tells how much supersonic the jet is.

Defining c_s as the internal sound speed, and then γ_s as Lorentz factor for this speed, we get that the Mach number is:

$$M = \frac{\gamma v}{\gamma_s c_s}. \tag{9}$$

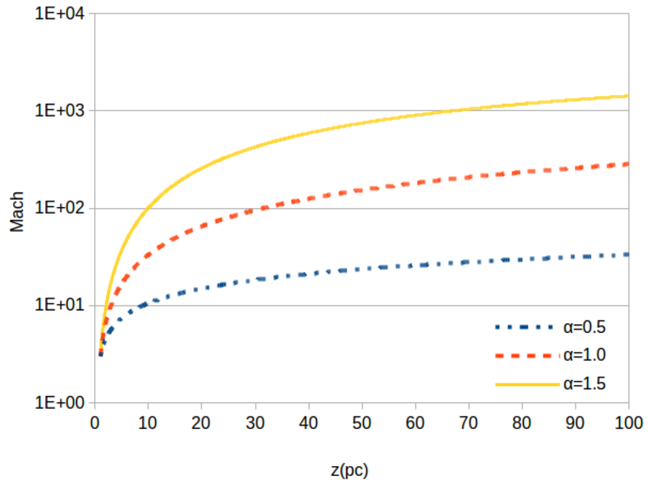

FIG. 2: Relativistic Mach number versus distance for different α values.

Figure 2 shows that for α >1 the Mach number reaches larger values than for α <1.

Also, it is important to see how the pressure and the density of the jet mass vary, to have an idea of how strong is the pressure gradient and jet flow dilution:

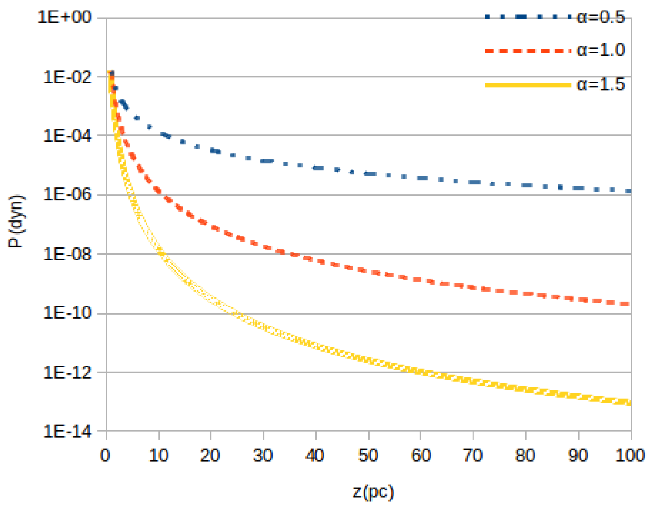

FIG. 3: Pressure versus distance for different α values.

Figure 3 shows that pressure decreases stronger with z for larger α-values, consistent with the evolution of the other quantities presented. The faster r grows with z, the faster pressure decreases. This effect is also seen in Fig. 4 for the density.

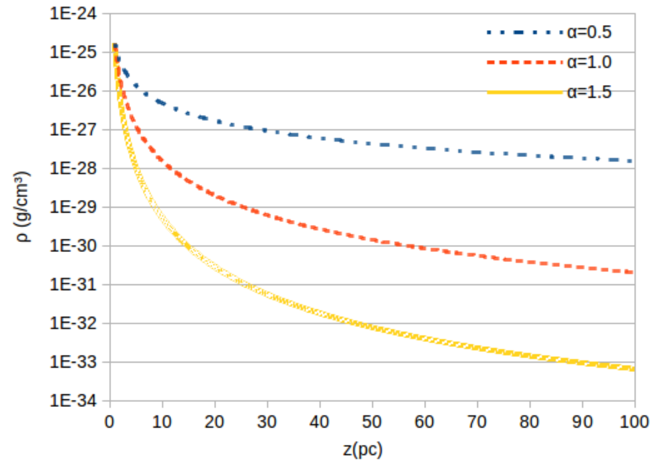

FIG. 4: Density versus distance for different α values.

B. Radiative properties

The radiative properties, unlike the hydrodynamical ones, depend on the viewing angle. It is for that reason that we present two extreme cases of θ to derive the quantities that we have considered more important.

One of the quantities to highlight is the Doppler factor δ, relevant as the jet is relativistic, and for which the angle between the jet and the direction towards the observer, θ, is needed.

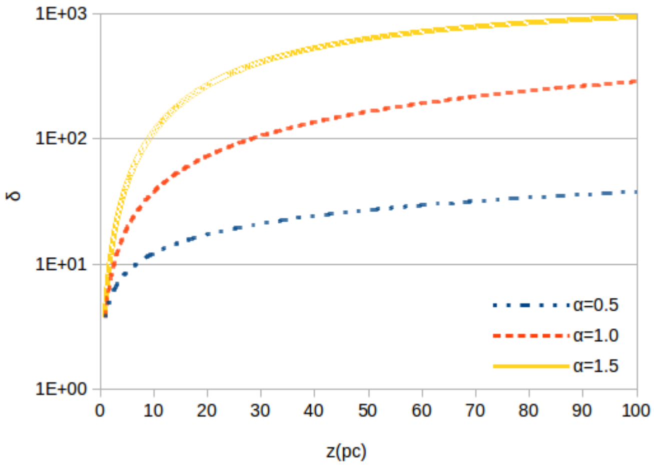

FIG. 5: Doppler factor versus distance for three values of α with θ=0°.

Figure 5 shows that δ grows faster for larger α-values.

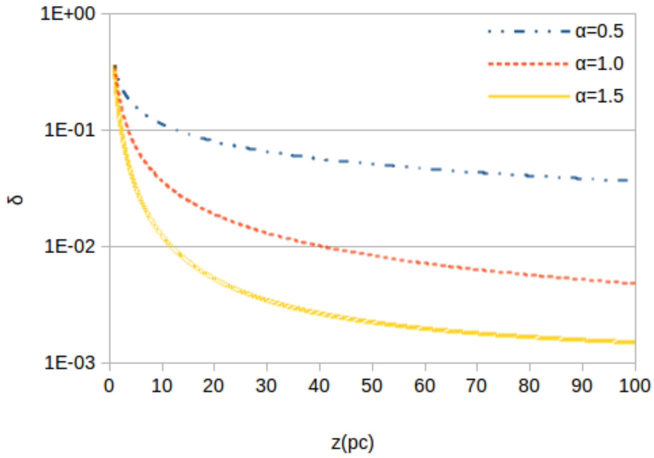

FIG. 6: Doppler factor versus distance for three values of α with θ=90°.

Figure 6 shows that δ decrease faster for larger α-values. The reason is that for the slower regions of the jet Doppler boosting is less important and, therefore, when θ becomes large emission from those regions is less attenuated than emission from further out.

The radiation enhancement because of Doppler boosting for each θ presents is δ^4.

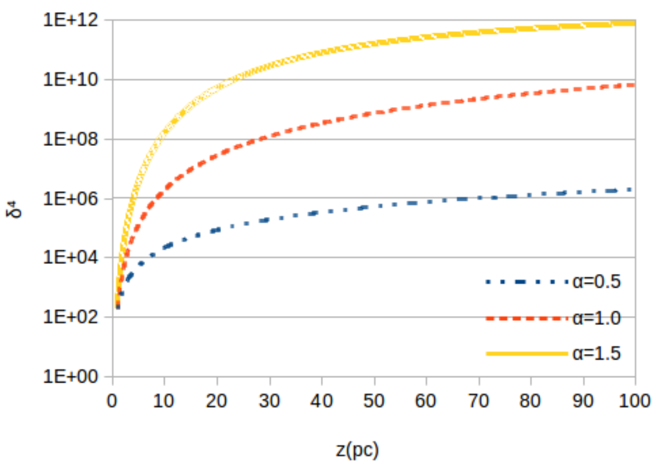

FIG. 7: Radiation enhancement versus distance for three values of α with θ=0°.

Figure 7 shows that the radiation enhancement grows faster for larger α-values, and its behaviour is like δ but stronger, as we expected as well.

Figure 8 shows that the radiation enhancement decrease faster for larger α-values. Again, for the same reason as δ.

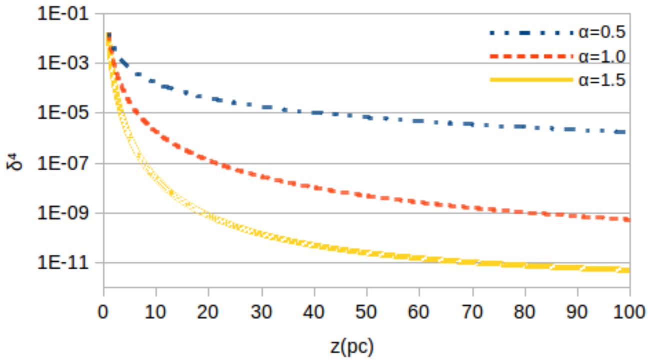

FIG. 8: Radiation enhancement versus distance for three values of α with θ=90°.

We adopt as a proxy for the internal energy in the jet proper frame, at an spatial scale z, the following quantity:

$$U' \propto \pi r^2 u z \gamma. \tag{10}$$

This quantity, together with the radiation efficiency, whose functional dependence with r can be simplified to $1/r$ (see below), plus the Doppler boosting effect (δ^4), allows one to write the approximate z-dependence of the apparent emission produced in the jet for different values of θ (normalized to the value at the jet base):

$$\zeta = \delta^4 U' r_0 / \delta_0^4 U_0' r. \tag{11}$$

The $1/r$-dependence of the radiation efficiency in the jet comes from the adiabatic evolution assumption, plus the $1/r$ and $1/r^2$ dependences of the adiabatic and the (negligible) radiation losses, respectively:

$$\dot{E}_{rad}/\dot{E}_{ad} \propto 1/r. \tag{12}$$

Note that we have assumed that there are emitting particles present in the jet. As our results are presented in relative terms, it is not important whether these emitting particles are all the fluid particles or a small fraction. We have also assumed that all the fluid components follow Eq. (5).

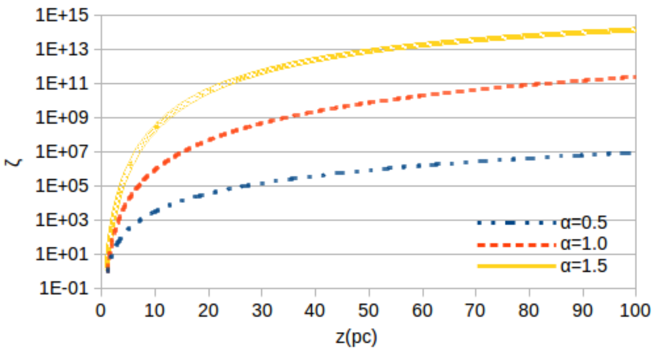

FIG. 9: Jet radiation efficiency versus distance for three values of α with θ=0°.

Figure 9 shows that the jet radiation efficiency grows faster for larger α-values.

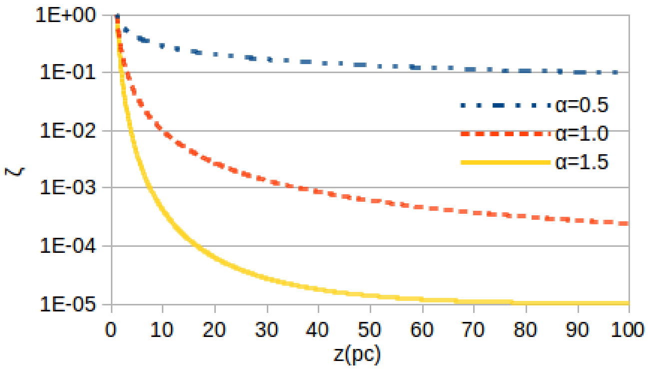

FIG. 10: Study of jet radiation efficiency versus distance for three cases of α with θ=90°.

Figure 10 shows that the jet radiation efficiency decrease faster for larger α-values.

The behaviour of Fig. 9 and Fig. 10 is similar to Fig. 7 and Fig. 8 respectively, so radiation enhancement is the dominant term in jet radiation efficiency as seen by the observer.

IV. CONCLUSIONS

- **Hydrodynamics**

  We conclude that there is a strong acceleration due to a strong pressure gradient in the beginning of the jet, and there is a moderate acceleration farther out. This implies that the initial thermal energy has been transformed into kinetic energy.

  It is interesting to note in the plot of the Mach number that for a supersonic stationary fluid, the solution of the Bernoulli equation is always supersonic. If our jet were initially subsonic, it would have been remained subsonic for any α and z value, as trials with different parameters (not presented here) showed.

- **Observational consequences:**

  Depending on the angle with which we observe the jet, we will see that radiation coming from slower or faster regions, and therefore different distances from the jet base. For $\theta = 0°$, more radiation comes from the outermost regions of the jet, the fastest ones, due to Doppler boosting. For $\theta = 90°$, most of the radiation comes from the areas close to the base, since the radiation is less beamed further and suffers therefore less Doppler de-boosting in this slower region. These effects would strongly affect the aspect of jets as seen by the observer if enough resolution were available to distinguish the regions under study. It is remarkable that overall, small θ-values imply jet apparent luminosities many orders of magnitude larger than those of jets with large θ-values but otherwise the same intrinsic jet properties. This is consistent with the fact that jets observed off-axis can be only detected in the local universe.

Acknowledgments

To conclude with this work, I would like to be grateful first to my advisor Valentí Bosch-Ramon because of his effort in helping myself to push through with this, in addition to have guided me in the best way. Also, to my friends, who have encouraged me in moments I really needed, who have helped me to continue and to never give up. Furthermore, I would like to thank my family, because they have supported me in these days in which the things were not working as well as they should, and finally, to the UB and all the professors that I have had, because the years I have lived in this university will be magical memories for me, due to the fact that they have turned around many of my visions and have made me learn to touch with my feet the ground.

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