Doppler boosting effects on the radiation of relativistic extragalactic jets

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Abstract: The topic of this work will be the study of radio emission of an extragalactic jet by using a relativistic gas simple model. The dynamics will be described using hydrodynamics, i.e. considering a low magnetic field B, and the radiation of the jet will be modeled as synchrotron radiation taking into account Doppler Boosting. Representative parameters and some approximations have been used in order to simplify and easily understand the behavior of the relativistic radio jets.

I. INTRODUCTION

Relativistic jets are collimated outflows of plasma and fields that are formed from accretion processes in compact objects. We can observe the jet phenomenon in Galactic objects such as black holes or neutron stars in binaries, and in extragalactic systems like active galactic nuclei (AGN) or gamma-ray bursts (GRB) [1].

The accretion of matter, with angular momentum and magnetic fields, into the huge gravitational well of a compact object, leads to the formation of an accretion disk [2] and sometimes to two oppositely-directed collimated outflows of particles. It is still not clear how these particles are accelerated, the collimation processes, the origin of their radiation itself, and other fundamental questions like the jet composition [3].

What we know is that the particles must be accelerated locally along the jet, as otherwise expansion losses would lead to very high total power requirements [4]. In our model nevertheless, it is enough to consider that particles are accelerated in the base of the jet with shock waves [5]. Even though we do not enter in the details of the process, the mechanism consists in the particles increasing their energy by crossing the front wave from the unshocked zone to the shocked zone, and vice-versa.

As mentioned, the jet has two opposite directions, although it sometimes appears to be one-sided and Doppler boosted. Scientists interpret this as evidence of bulk relativistic motion of the emitting particles [6].

Our way to get information from jets is through studying their radiation. Astrophysical jets can be highly powerful and often emit radiation over all the electromagnetic spectrum. It is known that in AGN, and particularly in Blazars [**?**], the jets can be studied through their strong non-thermal emission in radio and high energies. In our case, we are interested in the radio emission of AGN jets and in one of the dominant processes: the synchrotron radiation that occurs when a charged particle subjected to a magnetic field radiates as it is accelerated by the Lorentz force [7]. Parsec scales are particularly important as higher energy emission is also expected from those jet regions. Radio emission, however, is interesting since it provides spectral, morphological and temporal information.

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II. PHYSIC MODEL

To characterize AGN jet radio emission we will focus first on the dynamics of jets, and then on their radiation.

A. DYNAMICS

To model AGN jets we use a relativistic hydrodynamic simple model with many approximations in order to get a general idea about how the jet behaves. First of all we have a fluid in stationary flux that moves along a pipeline (jet) in the z direction. The shape of the jet is described by:

$$r = kz^{\alpha}, \tag{1}$$

where r is the radius, k is a constant and α is the power-law index that will determine if the jet is conical ($\alpha = 1$) or parabolic ($\alpha = 0.5$). In the range of distances in which we work we consider a low magnetic field B with a magnetic fraction $\eta_B \ll 1/2$. This allows us to use hydrodynamics instead of magnetohydrodynamics. We also consider that in the fluid there is a population of non-thermal particles, the energy spectrum of which is not Maxwellian and can reach very high energies, and their energy losses by radiation are negligible. The fluid must follow the conservation of mass, energy, and momentum flux, presented in equations (2), (3) and (4), respectively:

$$s\gamma v\rho = C_1, \tag{2}$$

$$s\gamma^2 v\rho c^2 h = C_2, \tag{3}$$

$$s\gamma^2 v^2 \rho h + sP = C_3, \tag{4}$$

where s is the area of the section at z, c is the speed of light, γ is the Lorentz factor, v is the velocity of the particles in the jet, ρ is the density of particles in the fluid rest frame, h is the specific enthalpy, P is the thermal pressure of the fluid, and C_1, C_2 and C_3 are constants. Dividing equations (2) and (3) we can deduce that $h\gamma$ has a constant value along the jet. We assume that the gas suffers adiabatic cooling without losing energy through radiation, just spending energy with work against the walls. Then, the thermal pressure of the fluid evolves as:

$$P\rho^{-\hat{\gamma}} = constant, \tag{5}$$

where $\hat{\gamma}$ is the adiabatic coefficient, which in our case corresponds to 4/3 as the fluid is a relativistic, ideal and monatomic gas. The specific internal energy ϵ follows:

$$\epsilon = \frac{P}{(\hat{\gamma}-1)\rho}. \tag{6}$$

We can write the specific enthalpy as:

$$h = 1 + \frac{\epsilon}{c^2} + \frac{P}{\rho c^2} = 1 + \frac{\hat{\gamma}}{\hat{\gamma}-1}\frac{P}{\rho c^2}, \tag{7}$$

Before obtaining the state equation of the gas we will consider three different cases:

- $h \gg 1$, $\gamma \simeq 1$. Describes a hot and subsonic gas. If h is much greater than 1 we can approximate equation (7) as:

  $$h \approx \frac{\hat{\gamma}}{\hat{\gamma}-1}\frac{P}{\rho c^2}. \tag{8}$$

  Now we can express equation (2) like:

  $$sv\rho c^2 h \simeq C_2 \simeq C_1 c^2 h \Longrightarrow h \simeq constant.$$

  If h is constant, ρ and P will be constant as well (due to equations (8) and (5)), and then equation (3) can be expressed like:

  $$sv\rho \simeq C_1 \Longrightarrow v \propto s^{-1}. \tag{9}$$

  But this is not possible because the velocity can not decrease if outside the jet there is a low pressure medium. This shows that our approach does not work if the jet is subsonic.

- $h \simeq 1$, $\gamma \gg 1$. These conditions represent those of a cold and supersonic gas where equations (2) and (3) lead to:

  $$s\gamma^2 v\rho c^2 \simeq C_2 \simeq C_1 \gamma c^2 \Longrightarrow \gamma \simeq constant.$$

  If γ is constant, ρ and v will be constants as well. The jet thus does not have enough internal energy to spend in increasing the velocity of the particles.

- $h \gg 1$, $\gamma \gg 1$. This is the case that we will study and shows a hot and supersonic gas, i.e. a relativistic gas, typical in jets not far from their base. These are thus the conditions expected in AGN jets in the spatial scale of interest. We can obtain the state equation using equations (2), (3), (5) and (8). We can also take v as constant, since the Lorentz factor takes large values. Some of the relevant relations between variables are:

  $$\gamma \propto \rho^{-1/3} \propto z^{\alpha}. \tag{10}$$

The initial conditions of our jet model are:

$$\begin{aligned} \gamma_o &= 10 \\ z_o &= 0.1\text{pc} \\ h_o &= 10 \\ C_2 &= 10^{45}\text{erg/s} \end{aligned}$$

These are just representative parameters with illustrative values in order to give an idea of the dynamics of the jet. Where γ_o, z_o, h_o and C_2 are the initial values of the Lorentz factor, the z position and the specific enthalpy, and the jet power. Since we are using the approximation given in equation (8), our maximum z will correspond to $z_{max} = z(h = 1)$.

B. RADIATION

For studying the radiation of the jet we will focus on the apparent luminosity that an observer sees from a given viewing angle θ, at a certain frequency ($L^{obs}_{sync}(\nu)$). For that, we first calculate the luminosity at a given frequency of the jet in the rest frame of the fluid ($L'_{sync}(\nu')$). From now on primed variables will refer to the fluid rest frame.

First of all, we have to take into account that the emitting fluid is moving, so the strength and the frequencies of the emission are altered by the Doppler effect. As observers, we are looking at the jet with a certain viewing angle that also effects our perception.

We observe apparent jet luminosities, related to the corresponding intrinsic quantities in the fluid rest frame, through the Doppler factor [8]:

$$\mathcal{D} = \frac{1}{\gamma(1-\beta\cos\theta)}, \tag{11}$$

where β is the velocity of the jet in units of speed of light. We call Doppler boosting effect when $\mathcal{D}$ is grater than 1 so the observed flux is enhanced. If $\mathcal{D}$ is less than 1, the observed flux is attenuated, which is called Doppler deboosting. A counter jet is always doppler deboosted but for a forward jet it depends on the viewing angle [9].

To convert the luminosity in the fluid frame to the luminosity that the observer sees for a given frequency, we will need a factor $\mathcal{D}^3$. This factor includes the contribution of the solid angle, into which the moving source radiates, changes by $\mathcal{D}^2$, due to aberration, and the effect of the time shortening by a factor $\mathcal{D}$ ($\Delta t' = \mathcal{D}\Delta t^{obs}$). Hence, the relation between luminosities will be:

$$dL'_{sync}(\nu') = \mathcal{D}^3 dL^{obs}_{sync}(\nu). \tag{12}$$

Note that the Lorentz factor is changing along z, and so is doing the Doppler factor. The radiation over all the frequency spectrum would have a factor of $\mathcal{D}^4$: $L^{obs}_{sync} = \mathcal{D}^4 L'_{sync}$ [10].

Along the jet, the total internal energy density u evolves and a fraction η_{NT} of this energy is the non-thermal internal energy density u_{NT}. Furthermore, we assume the energy distribution density of the non-thermal particle population n' is proportional to $E'^{-\delta}$ (δ is the energy spectral index that for many sources is $2 < \delta < 3$ [11]; in this model we will use $\delta = 2$):

$$n'(E') = \frac{u_{NT}E'^{-2}}{10} = \frac{u\eta_{NT}E'^{-2}}{10}. \tag{13}$$

Moreover, the total pressure of the gas has two components, the thermal (+ non-thermal) and the magnetic pressure, related to each other through the magnetic fraction η_B:

$$P_{total} = P_{mag} + P,$$
$$P_{mag} = \frac{B'^2}{8\pi} = \eta_B P_{total}. \tag{14}$$

We consider that the particles in the jet emit isotropic radiation. The power synchrotron radiation per particle is:

$$|\dot{E}'| \simeq a_s B'^2 E'^2, \tag{15}$$

where $a_s \simeq 1.6\times10^{-3}$ in cgs. Then, the spectral emissivity for an ensemble of particles is:

$$\dot{\varepsilon}'_{sync}(\nu') \simeq n'(E')\dot{E}'\frac{dE'}{d\nu'}, \tag{16}$$

with the frequency ν' in the fluid frame as:

$$\nu' = 0.3c_s B' E'^2 \Longrightarrow \frac{dE'}{d\nu'} = \frac{1}{2\sqrt{0.3c_s B'\nu'}}, \tag{17}$$

where $c_s \simeq 6.27\times10^{18}$ in cgs.

The luminosity in the fluid frame corresponds to:

$$L'_{sync}(\nu') = \int_{z_o}^{z_{h=1}} s\dot{\varepsilon}'_{sync}(\nu')dz', \tag{18}$$

and, using equation (12):

$$L^{obs}_{sync}(\nu) = \int_{z_o}^{z_{h=1}} \mathcal{D}^3 s\dot{\varepsilon}'_{sync}(\nu')dz'. \tag{19}$$

Notice that we keep our variables primed as the photons have been emitted in the fluid frame. This also means that $dz' = dz/\gamma$.

With equations (11), (14), (15), (16), (17), and knowing that $s = \pi k^2 z^{2\alpha}$, we finally obtain:

$$L^{obs}_{sync}(\nu) \approx 1.30\frac{a_s k^2 \pi^{7/4}\eta_{NT}}{\sqrt{c_s}}(\frac{\eta_B}{1-\eta_B})^{3/4} \times \int_{z_o}^{z_{h=1}} \frac{\mathcal{D}^{7/2}P^{7/4}z^{2\alpha}}{\gamma\nu^{1/2}}dz. \tag{20}$$

This integral will be solved for a $\nu = 5$GHz by numeric methods in the next section.

III. RESULTS

For obtaining the behavior of the different variables we have written a program that follows the relations of equation (10), starting with the initial conditions. The results are presented for $\alpha = 1$ and $\alpha = 0.5$.

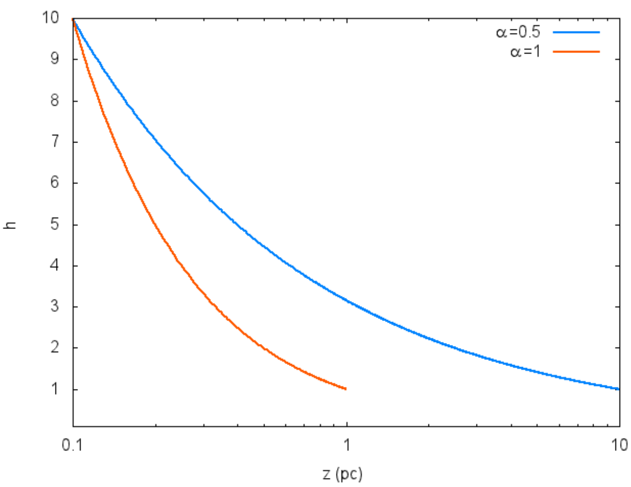

FIG. 1: Specific enthalpy along the z direction calculated using the initial conditions. At h=1 calculus stops as our approximation in equation 8 is far from correct. Two cases are represented; conical (orange) and parabolic jet (blue).

First, in figure (1) we can see how h decreases whit z. For $\alpha = 1$ the specific enthalpy decreases faster. It has sense since if the area section raises faster the jet will also cool faster. Notice that for $\alpha = 1$ the curve stops at $z \approx 1$, which is when h=1.

In figure (2) we can see how the Lorentz factor increases with z. Comparing the two values of α is evident that in the conical shape γ grows faster. The maximum

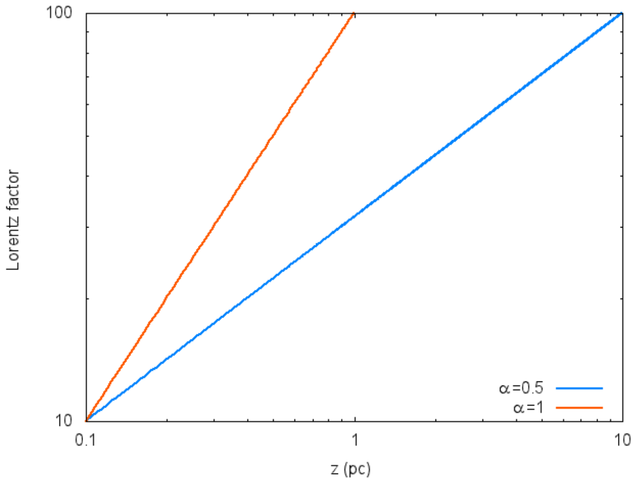

FIG. 2: Lorentz factor along the z direction. There are conical (orange) and parabolic shape (blue) jets shown.

value is reached at $\gamma = 100$, which is consistent with $h\gamma = h_o\gamma_o = 100$.

The density (figure 3) and the pressure also drop while increasing z. The area section is growing and the velocity of the particles is doing it as well. Therefore, the density (and the pressure) must decrease.

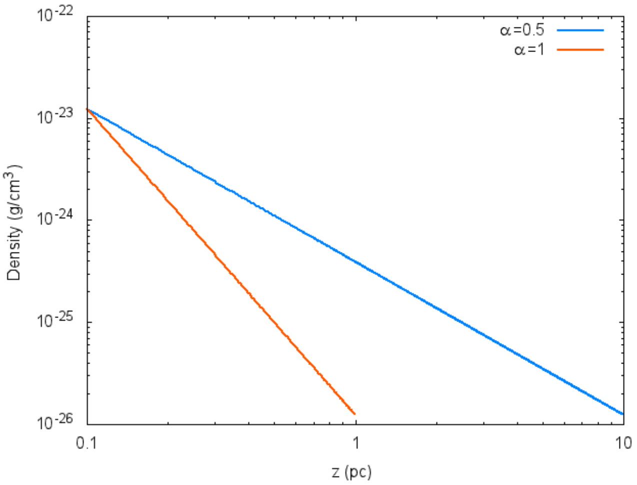

FIG. 3: Density along the z direction. There are conical (orange) and parabolic shape (blue).

We have calculated the apparent luminosity in the observer frame depending on the viewing angle (figure (4)). We can see that for small angles the luminosity is very high, achieving $\simeq 500$ mJy (for $\alpha = 0.5$ at 500 Mpc of distance) and it rapidly decreases as the observer moves away angularly from the jet axes.

The Doppler factor for different z has been calculated in order to obtain where the jet emission starts to be deboosted. From $\theta = 0$ rad to $\theta_d \approx 0.44$ rad the observed jet emission is enhanced compared with the corresponding

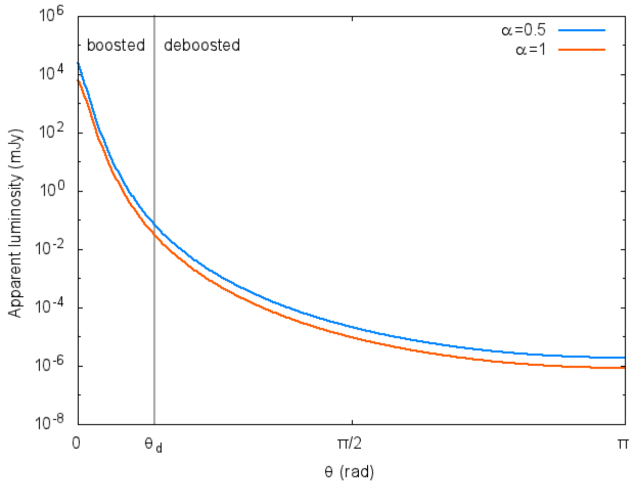

FIG. 4: Apparent luminosity at the observer's frame depending on the viewing angle using the variables from the hydrodynamic model. The units are milijansky at a distance of 500 Mpc. Conical (orange) and parabolic shape (blue) are represented. Grey line shows the limit angle, θ_d, where the jet starts to be deboosted.

value at the fluid frame and, for the rest of angles, it is attenuated.

Note that varying the η_{NT} (not presented here) the apparent luminosity in the observer frame changes proportionally.

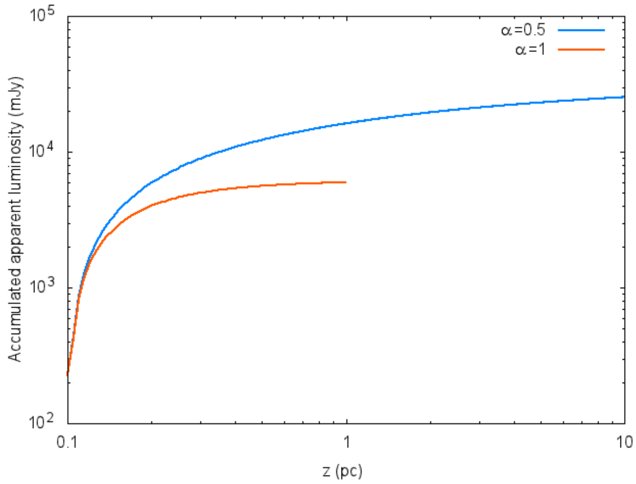

FIG. 5: Accumulated apparent luminosity at 5 GHz of the jet in the observer frame at $\theta = 0$ rad. Each point shows the radiation contribution of the jet from z_o to z. Conical (orange) and parabolic shape (blue) jets are represented.

It is also interesting to know the apparent luminosity contribution of every part of the jet. Figures (5) and (6) presents the accumulated luminosity at every z (from z_o to z) at $\theta = 0$ rad and $\theta = \pi/2$ rad, respectively. It is clear that the base of the jet is where the amount of radio emission at 5 GHz is higher. The shapes of the curves are similar but the radiation at $\theta = \pi/2$ rad converges much closer to the jet base. For different α the behavior is as expected since the luminosity for the parabolic shape is higher.

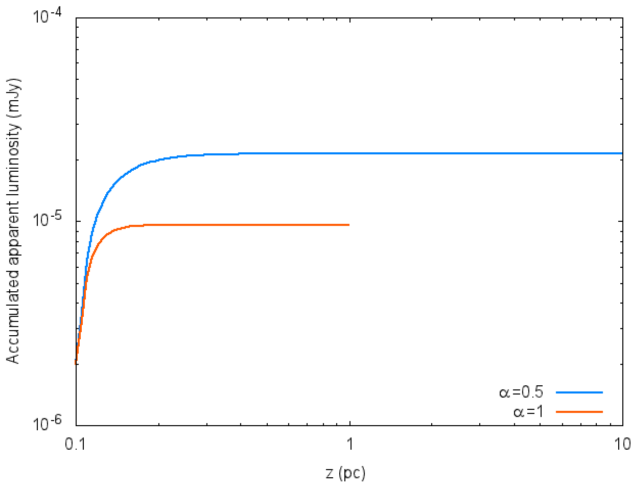

FIG. 6: Accumulated apparent luminosity at 5 GHz of the jet in the observer frame at $\theta = \pi$rad. Each point shows the radiation contribution of the jet from z_o to z. Conical (orange) and parabolic shape (blue) jets are represented.

IV. CONCLUSIONS

Our model is consistent with the hydrodynamics for a jet formed by a hot, supersonic and relativistic ideal gas.

From the results we can extract that along the jet the specific enthalpy is being spent in raising the Lorentz factor. The pressure and the density drop along the jet. The mass, momentum and energy flux must be constant, if the surface and velocity are increasing, the density and the pressure must decrease.

For $\alpha = 1$ the jet is more efficient transferring the internal energy into kinetic energy. To describe the conical jet away from 1-10 pc in our models does not make sense because there is where h=1, which means that the jet is already cold and does not have more thermal energy to transform into kinetic energy. At $h < 1$ we would also get into conflict with equation (8) [**?**]. Moreover, the parabolic shape shows more apparent luminosity for all the viewing angles. The apparent radio radiation contribution of the jet base is also more dominant in all the parts of the jet for $\alpha = 0.5$.

It is also clear that the luminosity in the observer frame strongly depends on the viewing angle. The jet is heavily beamed presenting the highest value for $\theta = 0$ rad. Therefore, only the jets aligned with the line of sight will be bright enough to be observed at very large distances.

The major apparent radio flux increase is coming from the base of the jet, where the particles suffer a higher acceleration due to the gradient in the thermal pressure, but h is still well above 1.

Finally, from $\theta_d \approx 0.44$ rad the forward jet starts to be deboosted and radiation becomes so weak that it can only be detected in nearby objects. If we look at a jet from the back there is almost no luminosity showed. This phenomenon is the typical explanation for one-sided jets.

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[12] Blazar is a very compact quasar powered by supermassive black holes in the center of an active galaxy.
[13] In fact, the validity of our approach starts to fail for h values of a few.