Radio mode feedback: Does relativity matter?

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ABSTRACT
Radio mode feedback, associated with the propagation of powerful outflows in active galaxies, is a crucial ingredient in galaxy evolution. Extragalactic jets are well collimated and relativistic, both in terms of thermodynamics and kinematics. They generate strong shocks in the ambient medium, associated with observed hotspots, and carve cavities that are filled with the shocked jet flow. In this Letter, we compare the pressure evolution in the hotspot and the cavity generated by relativistic and classical jets. Our results show that the classical approach underestimates the cavity pressure by a factor ≥ 2 for a given shocked volume during the whole active phase. The tension between both approaches can only be alleviated by unrealistic jet flow densities or gigantic jet areas in the classical case. As a consequence, the efficiency of a relativistic jet heating the ambient is typically ~ 20% larger compared with a classical jet, and the heated volume is 2 to 10 times larger during the time evolution. This conflict translates into two substantially disparate manners, both spatially and temporal, of heating the ambient medium. These differences are expected to have relevant implications on the star formation rates of the host galaxies and their evolution.

Key words: Galaxies: active — Galaxies: jets — Hydrodynamics — Shock-waves — Relativistic processes — X-rays: galaxies: clusters

1 INTRODUCTION
Radio mode feedback is associated with the evolution of relativistic jets in active galaxies. The way the energy deposited in the ambient medium by these jets contributes to stop cooling flows temporarily and quenches star formation within the host galaxy has been addressed so far from two different assumptions: 1) the cavities triggered by jets are in pressure equilibrium with their environments (see, e.g., McNamara & Nulsen 2007; Fabian 2012, and references therein), and 2) the feedback is mediated by a shock (as suggested by different numerical simulations Zanni et al. 2005; Wagner, Bicknell & Umemura 2012; Perucho et al. 2011, 2014). The results obtained from both points of view are obviously divergent: the former studies typically conclude that heating might take place due to mixing of the hot injected gas with the environment in the wake of a buoyant, hot, and dilute bubble in the pressure gradient of the galaxy or cluster; the latter conclude that the shock driving the cavity expansion plays a fundamental role in heating, transferring a large amount of the injected energy to the shocked ambient gas.

Radio galaxies are classified in terms of their morphology, as FRI or FRII. FRIs are known to be less powerful (Rawlings & Saunders 1991; Ghisellini & Celotti 2001), with a break power between 10^{44} and 10^{45} erg/s. Although it is obvious that jets in FRII sources are surely triggering a bow-shock (e.g., Croston et al. 2011; Stawarz et al. 2014), both observations (Croston et al. 2004; Kraft et al. 2007) and numerical simulations (Perucho & Martí 2007) have shown that young FRI jets can also be surrounded by such shocks, albeit with smaller Mach numbers than those in FRII jets.

Concerning the evolution of radio sources surrounded by shocks, a strong debate still remains. Recent simulations have shown that the efficiency of the energy transfer to the ambient medium, as well as the spatial and temporal scales involved, can be very different for relativistic (both kinematically and thermodynamically) and non-relativistic jets (Perucho et al. 2011, 2014, PMQR14 from now on). At very large spatial and temporal scales, the total amount of energy released to the ambient has to be the same in both, relativistic and non-relativistic jets – as it cannot be expected otherwise based on conservation principles. However, the notable differences during the jet evolution translate into relevant changes in the gas cooling rates with time and position (see, e.g., Zanni et al. 2005; O’Neill & Jones 2010; Gaspari et al. 2012; Cielo et al. 2014; Guo 2016). This conflict in the budget of cold gas fueling the galaxies could lead to dramatic
differences in the star formation rates in the host galaxies and, therefore, in the galactic evolution as a whole.

In Komissarov & Falle (1998), the authors studied the differences on the long-term evolution of relativistic and classical jets and found an essential similarity in the evolution of both types of flow for jets of the same power. Being in broad agreement with their conclusions, in this Letter, we try to quantify the differences on the evolution of the pressure at the hotspot and cavity in terms of the specific values given to the parameters defining the jet power in both classical and relativistic flows (internal energy, density, flow speed and jet section). This is interesting to understand the process of energy transfer to the ambient medium. Throughout this Letter, we will assume an ideal gas equation of state to describe both the jet and the ambient medium plasmas.

2 RELATIVISTIC VERSUS CLASSICAL APPROACH

In this section we obtain analytical expressions for the comparison of the hotspot pressure in relativistic and classical jets. In both cases we assume that the terminal shock is strong, with both, shock speed and post-shock flow speed much smaller than the initial jet speed.

2.1 Classical jet

The jet power for a classical jet is defined as:

\[ P_j = \frac{v_j P_j}{(\gamma_j - 1)\rho_j} + \frac{1}{2} v_j^2 \rho_j A_j. \]  

(1)

where \( \gamma_j \) is the adiabatic exponent of the equation of state describing the jet plasma, \( P_j \) and \( \rho_j \) stand for its pressure and density, respectively, \( v_j \) is the jet flow velocity, and \( A_j \) is the jet cross-section.

In the case of a jet made of cold plasma, the jet power is then simplified to the following expression:

\[ P_j \approx \frac{1}{2} v_j^3 \rho_j A_j. \]  

(2)

The last relevant relation to be considered is the post-shock pressure at the jet head for a strong shock, as derived from the Rankine-Hugoniot jump conditions (Landau & Lifshitz 1959; Scheuer 1974; Kaiser & Alexander 1997):

\[ P_h = \frac{2 \gamma_j P_j}{\gamma_j + 1} M_j^2. \]  

(3)

where \( P_h \) stands for the post-shock pressure at the jet head, and \( M_j \) is the jet Mach number. Comparing Eqs. (2) and (3) we obtain a relation between the jet power and the hotspot pressure:

\[ P_h \approx \frac{4 L_j}{(\gamma_j + 1)v_j A_j}. \]  

(4)

2.2 Relativistic jet

The total jet power for a relativistic jet is defined as:

\[ P_j = \frac{v_j (\gamma_j v_j^2 - c^2) \rho_j v_j A_j}{\Gamma_j}. \]  

(5)

where \( h_j = c^2 + \frac{v_j P_j}{(\gamma_j - 1)\rho_j} \) is the jet specific enthalpy, \( \Gamma_j \) is the jet Lorentz factor, and \( c \) is the speed of light.

If the jet is hot (\( h_j \gg c^2 \)) and has a large Lorentz factor (\( \Gamma_j \gg 1 \)), then:

\[ L_j \approx \frac{v_j P_j}{\gamma_j - 1} \Gamma_j^2 v_j A_j. \]  

(6)

The conservation of momentum flux across the shock is (e.g., Landau & Lifshitz 1959; Martí & Müller 1994):

\[ \rho_j h_j \Gamma_j^2 \frac{v_j^2}{c^2} + P_j = \rho_h h_h \Gamma_h^2 \frac{v_h^2}{c^2} + P_h. \]  

(7)

Now, considering that the jet is both relativistic thermodynamically, \( h_j \gg c^2 \) (i.e., \( P_j/\rho_j \gg c^2 \)), and kinematically (\( \Gamma_j^2 \gg 1 \)), and taking into account that if the shock is strong \( v_h \ll v_j \), the previous expression becomes

\[ P_h \approx \frac{v_j \rho_j h_j}{A_j c^2}. \]  

(8)

Comparing Eqs. (6) and (8), we obtain:

\[ P_h \approx \frac{L_j v_j v_j}{A_j c^2}. \]  

(9)

Let us note that the last expression is also recovered in the case of a cold relativistic jet as far as \( h_j \Gamma_j \gg c^2 \).

2.3 Comparison between the classical and the relativistic approach

For the comparison between the classical and the relativistic approaches, we include subscripts \( c \) and \( r \), respectively.

2.3.1 Jet power and jet cross-section

Since we are interested in comparing jets with the same power, according to Eqs. (2) and (5), the parameters defining both models shall verify

\[ \frac{1}{2} \rho_{j,c} A_{j,c} v_{j,c}^3 \approx h_{j,r} \Gamma_{j,r}^2 \rho_{j,r} v_{j,r} A_{j,r}. \]  

(10)

or, equivalently,

\[ \frac{A_{j,c}}{A_{j,r}} \approx \frac{4 v_{j,c}}{v_{j,r}} \frac{\rho_{j,c}}{\rho_{j,r}} \frac{h_{j,c} \Gamma_{j,c}^2}{h_{j,r} \Gamma_{j,r}^2}. \]  

(11)

A number of comments about this expression are relevant for our discussion: 1) \( v_{j,r} \approx c \), 2) a jet velocity of \( \approx 0.3c \) is in the limit of consistency with the non-relativistic dynamics as the relativistic effects in the conservation of mass, momentum and energy are in the range 5 – 10%, 3) we assume \( \rho_{j,c} \approx \rho_{j,r} \). Therefore, the first three terms in parentheses are of order unity. This, together with the fact that the last term can be much larger than one in the case of a hot, relativistic jet, leads to the well known result that a classical jet needs a section at least two orders of magnitude larger than a relativistic jet of the same power.
2.3.2 Hotspot pressure

The difference in the jet cross-sections of classical and relativistic jet models of the same power has implications in the ratio of hotspot pressures. From Eqs. 4 and 9 we have

$$\frac{P_{h,c}}{P_{h,r}} \sim (\gamma_{j,c} + 1) \frac{v_{j,c}^2}{v_{j,r}^2} A_{j,c} A_{j,r}$$

(12)

or, substituting the cross section ratio from Eq. 11,

$$\frac{P_{h,c}}{P_{h,r}} \sim 7 \times 10^{-2} \left( \frac{\rho_{j,c}}{\rho_{j,r}} \right)^2 \left( \frac{c}{v_{j,c}} \right)^2 \left( \frac{0.3c}{v_{j,c}} \right)^2 \left( \frac{c^2}{\Gamma_{j,r}^2} \right)$$

(13)

(where we have used $\gamma_{j,c} = 5/3$, as corresponding to a cold jet). Again the fact that the first three terms in parentheses are of order unity and the last one can be significantly smaller than one, leads to hotspot pressures of classical jets much smaller than those of relativistic jets of the same power. If the relativistic jet power was recovered by only increasing the jet rest-mass density, a classical jet would need $\rho_{j,c} \sim 10^2 \rho_{j,r}$ to obtain the same post-shock pressure as a mildly relativistic jet with $h_{j,r} \sim 2c^2 - 10c^2$, $\Gamma_{j,r} = 5 - 10$.

3 RESULTS

3.1 Cavity pressure

The transfer of energy to the ambient medium in powerful radio sources is driven by a strong shock that heats and accelerates the ambient gas as it advances. The strength of this shock depends on the evolution of the pressure in the cavity, $P_{cav}$, along time. Owing to the large value of the sound speed in this region, this pressure is very similar throughout the whole shocked volume (e.g., PMQR14).

Since the cavity is inflated with expanding plasma flowing from the hotspot, it is reasonable to expect that both cavity and hotspot pressures are linked. The model presented in Kaiser & Alexander (1997) for pressure confined jets leads to $P_{cav} \propto J_0$, and a self-similar evolution of the source expansion at large times. The model was confirmed by numerical simulations of classical and relativistic cold jets propagating in a uniform ambient medium by Komissarov & Falle (1998). However it is expected that effects coming from the internal energy content of the jets, or the propagation through stratified media result in a more complex evolution. Indeed, the hotspot evolution depends on the dynamics at the jet head and, in particular, on the changes of the jet section close to the head. In any case, we do expect two effects. First, that the link between the hotspot and the cavity remains. Second, that the systematic difference found analytically at early stages between the hotspot pressures in both, the classical and relativistic approaches, produces qualitative differences in the process of expansion of the cavity and, in particular, in the efficiency of the heating of the ISM and IGM.

3.2 Comparison with numerical simulations

One way to estimate the efficiency of the heating is by comparing the strength of the shocks in both classical and relativistic models with the maximum shock strength achievable for a jet of a given power which in turn is related to the quantity

$$P_{cav,m} = \frac{L_j t}{V_{cav}}$$

(14)

where $t$ is the age of the jet and $V_{cav}$, the cavity volume. This expression represents the (maximum) pressure in the cavity assuming that all the injected energy is transferred to it and participates in driving the shock (Begelman & Cioffi 1989).

In the following we compare the time evolution of a set of numerical simulations of classical and relativistic jet models of the same power, paying attention to (i) the ratio $P_{cav}/P_{cav,m}$, (ii) the volume swept by the shock in the different simulations, and (iii) the efficiency in the energy transfer to the ambient medium.

The set of models is composed by a classical jet (J46n), a relativistic cold jet (J46c), and a relativistic hot jet (J46h). All with a power of $10^{39}$ erg/s. Models J46c and J46n were already discussed in PMQR14 (J46c being J46 in that work), and J46h is new. We display the relevant parameters of the jets in Table 1. The rest-mass density of models J46c and J46n is the same, but the jet radius of J46n was increased. The rest-mass density of the hot model was reduced by a factor of 10 to obtain an equivalent jet power. Both relativistic jets have a Lorentz factor $\Gamma_j = 5.6$.

Models J46c and J46h propagate at an almost constant speed up to $t = 2$ Myr when they suffer an abrupt deceleration indicating the transition from the one-dimensional (1D) propagation phase to the two-dimensional (2D) propagation phase (see, e.g., Scheck et al. 2002; Perucho et al. 2011). On the contrary, model J46n stays in the 1D phase along the whole simulation. During the 1D phase of the relativistic models, the ratio $P_{h,c}/P_{h,r}$ is much smaller than one ($\approx 0.08$), as anticipated by Eq. (13). Beyond this phase, the hotspot pressures of the relativistic jets drop below the pressure corresponding to the classical model and decrease steadily along the evolution. The behaviour of the hotspot pressure is associated with the change in the jet cross-section at the hotspot (see Eqs. 4 and 9, and Fig. 5 in PMQR14) which in turn depends on the conversion of kinetic energy to internal energy along the jet (much larger in the relativistic models).

Regarding the relation between $P_h$ and $P_{cav}$, we have applied $\chi$-squared fits to the values obtained for each simulation and found that $P_{cav} \propto P_h^a$, with $a$ in the range 0.35-0.55, depending on the simulation. The small dispersion in the exponent of the power law indicates that the physical processes linking the evolution of the hotspot and cavity pressure are essentially the same for both classical and relativistic jets.

Figure 1 (top panel) shows the evolution of the ratio of

| Model | $v_j$ (c) | $\rho_j$ (g/cm$^3$) | $h_j$ (c$^2$) | $R_j$ (pc) |
|-------|------------|-----------------|-------------|-----------|
| J46c  | 0.984      | 8.3 $\times$ 10$^{-29}$ | 1.0         | 100       |
| J46h  | 0.984      | 8.3 $\times$ 10$^{-29}$ | 8.0         | 100       |
| J46n  | 0.3        | 8.3 $\times$ 10$^{-29}$ | 1.0         | 3 $\times$ 10$^9$ |
the cavity pressure, $P_{\text{cav}}$, over the maximum cavity pressure as defined by Eq. (14), for the three numerical simulations. Both relativistic models show a similar ratio $P_{\text{cav}}/P_{\text{cav,m}}$ ($\approx 0.4$) that doubles the corresponding to the classical model ($\leq 0.2$). The difference in the pressure ratios starts right from the beginning extending through both the 1D and the 2D propagation phases of the relativistic jets. The bottom panel of Fig. 1 shows the volume of the region processed by the shock. The faster propagation of the relativistic jets during their 1D phase and the drop of the hotspot pressure in the relativistic models in the long term evolution translates into larger ambient volumes affected by the shock (a factor 12 at the end of the 1D phase; a factor 2 at $t = 16$ Myr).

Figure 2 shows the fraction of the injected energy invested in different channels as a function of time for J46c and J46n. The energy transfer efficiency to the ambient medium is higher in the case of the relativistic jet. The difference in the amount of kinetic energy kept by the jet particles in the two cases explains the difference in $P_{\text{cav}}/P_{\text{cav,m}}$ between the two the classical and the relativistic models. It is also important to note that: 1) the internal energy of the shocked ambient medium takes the larger amount of the injected energy in both cases ($\approx 70\%$ of the injected energy in the relativistic case; $\approx 50\%$ in the classical case), and 2) the total amount of energy transferred to the ambient medium (internal plus kinetic) is up to a 20% larger in the relativistic case at any time.

A recent paper by Weinberger et al. (2017), following a classical approach, but including a contribution to pressure by cosmic rays and magnetic field finds an increase in the efficiency of the heating of the ambient medium. This result also shows that a contribution different to kinetic energy (mainly in the form of heat-pressure) to the amount of energy flux injected by the jet increases the efficiency of heating.

In another recent paper, English et al. (2016) have performed a series of simulations of relativistic (magnetized and unmagnetized) jets covering a range in jet powers and velocities (from non-relativistic, $v_j \approx 0.25c$, to mildly-relativistic, $\Gamma_j \approx 3.2$). As discussed by the authors, the lack of bright hotspots at the end of the lobes, in clear contrast with the observations of powerful radio sources, tends to be alleviated by reducing the jet cross section (unrealistically large in the original simulations). This result underpins the line of argument of this Letter.

Our results also suggest that the analytical models that use the classical approach (e.g., Kaiser & Alexander 1997, and all derived models), could underestimate the cavity/lobe pressure created by relativistic jets, if the hotspot pressure is underestimated by using wide jet radii. Nevertheless, radiative models that deal with radio-source brightness evolution and use the cavity pressure to compute it, either assume jet parameters that imply small jet radii (e.g., Kaiser, Dennett-Thorpe & Alexander 1997; Kaiser & Best 2007), or compute $P_h$ from the observed size of hotspots (e.g., Barai & Wiita 2007), which alleviates this effect.
3.3 Caveats

The relation between the hotspot pressures in classical and relativistic jets was obtained under the assumption that the terminal shocks are strong (see Sec. 2). This is justified by the existence of the hotspots in powerful radio sources that implies a substantial conversion of kinetic to internal energy at the shock. Moreover, the resulting expression, Eq. (13), was only used to connect both pressures along the so-called 1D propagation phase of the relativistic jets, where the assumption of the terminal shock being strong is more robust.

We have also neglected the dynamical role of magnetic fields in this analysis. Magnetic field has been proposed to be slightly below or close to equipartition (with the jet internal energy) along the jet and at the radio lobes, which would make it dynamically relevant at these scales (see Hardcastle 2015, and references therein). In case of equipartition, the magnetic field represents a contribution to pressure in Eq. (6) (see also, e.g., English et al. 2016; Weinberger et al. 2017). Therefore, we conclude that a dynamical role of the magnetic field does not change the conclusions derived in this work regarding the difference between the efficiency of heating by relativistic jets, as compared to classical ones.

4 CONCLUSIONS

We conclude in this Letter the following key results:

- The pressures in the hotspot and the cavity of the relativistic jets are always significantly larger than in their classical counterparts. To sort out this discrepancy would require: i) hugely increase the jet rest-mass density with respect to that of relativistic jets, or ii) increase unrealistically the jet radius. Both solutions would imply huge mass-fluxes in conflict with current formation and acceleration mechanisms for jets, which propagate at relativistic speeds at parsec-scales.

- The relativistic jets carve cavities whose volumes are $10^2 - 10^3$ times larger than those of a relativistic jet with $h_{j,r} = 2c^2 - 10c^2$, $\Gamma_{j,r} = 5 - 10$.

- The relativistic jets carve cavities whose volumes are 2 to 10 times larger than the classical jets. This has a direct implication on the amount of heated gas.

- The heating efficiency of the relativistic jets is $\approx 20\%$ higher – during the whole time evolution – compared with the classical jets.

- As a consequence of previous results, the gas cooling rate in the cavity must strongly vary with position and time between both approaches, due to the different heating rates and energy deposition volumes. This should have a direct implication on the star formation rates of the host galaxies, and affect the subsequent galaxy evolution.

To wrap this Letter up, we would like to stress that a relativistic approach is a crucial ingredient for the study of radio mode feedback that cannot be obviated in a consistent description of the galaxy evolution.

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