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Deceleration of relativistic jets

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Abstract. Recently Massaglia et al. (2016) performed high-resolution three-dimensional simulations of low Mach number jets, showing how turbulence develops and gives rise to a jet structure very similar to that observed in FR-I sources. However these simulations make use of Newtonian dynamics, while observational evidences show that, both in FR-II and in FR-I, the jets at their base (at the parsec scale) are relativistic with very similar Lorentz factors (Giovannini et al. 2001, Celotti & Ghisellini 2008). It is then clear that in FR-I jets a deceleration to sub-relativistic velocities must occur between the inner region and the kpc scale, where they show their typical plume-like, turbulent morphology (Laing & Bridle 2014). Since FR-I jets are less powerful than FR-II, but have similar Lorentz factors, they have to be less dense and therefore more prone to deceleration by the external medium. Rossi et al. (2008) performed numerical simulations of the propagation of relativistic jets with different values of the density ratio between the jet and the ambient medium and showed that, while jets with density ratio between 0.01-0.1 (and power corresponding to FR-II) propagate almost undisturbed, jets with lower values of the density ratio (and power corresponding to FR-I) show evidences of entrainment and deceleration in their external layers. Due to the limitations of computational power, Rossi et al (2008) could follow the jet propagation only up to about 60pc (assuming the jet radius at injection to be about 1pc) and could not see a complete transition to subrelativistic velocities, in fact in their simulations the jet core remained relativistic. With this project our purpose is to extend the work by Rossi et al. (2008), following the jet until it reaches sub-relativistic transonic velocities and therefore to make a connection with the results by Massaglia et al. (2016).

1. Introduction

Extragalactic radio sources are traditionally divided into two morphological classes according to their intrinsic power (Fanaroff & Riley 1974): low luminosity sources (Fanarof-Riley type I, FR-I) are brighter close to the nucleus of the parent galaxy and their jets become dimmer with distance, while high power sources (Fanarof-Riley type II, FR-II) show the maximum brightness in the hot spots at the jet termination. The different morphology is generally accepted as reflecting a difference in how the jet energy is dissipated during propagation in the extragalactic medium, and it produces the observed radiation. In FR-II sources energy and momentum are transported without losses to the jet termination, while in FR-I sources turbulence and entrainment must play an important role in shaping their morphology.

Up to now numerical jet simulations focused on hypersonic jets and succeeded in re-

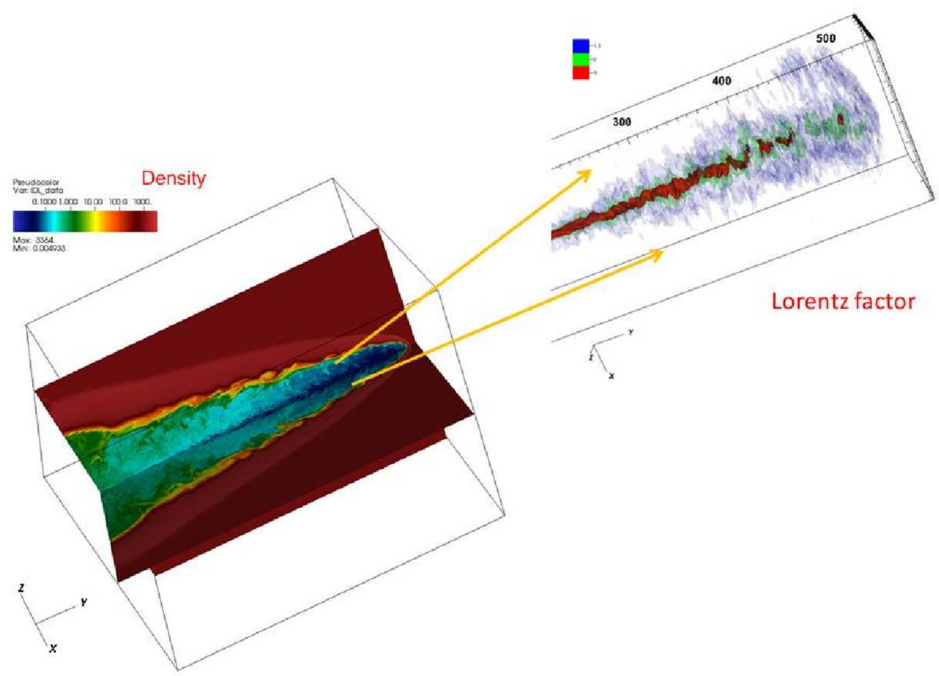

Fig. 1. On the left, cuts of the density distribution on the xy and yz planes, on the right 3D isosurfaces of the Lorentz factor.

producing the characteristics of FR-II sources. Recently Massaglia et al. (2016) performed high-resolution three-dimensional simulations of low Mach number jets, showing how turbulence develops and gives rise to a jet structure very similar to that observed in FR-I sources. However these simulations make use of Newtonian dynamics, while observational evidences show that, both in FR-II and in FR-I, the jets at their base (at the parsec scale) are relativistic with very similar Lorentz factors (Giovannini et al. 2001, Celotti & Ghisellini 2008).

It is then clear that in FR-I jets a deceleration to sub-relativistic velocities must occur between the inner region and the kpc scale, where they show their typical plume-like, turbulent morphology (Laing & Bridle 2014). Since FR-I jets are less powerful than FR-II, but have similar Lorentz factors, they have to be less dense and therefore more prone to deceleration by the external medium. Rossi et al. (2008) performed numerical simulations of the propagation of relativistic jets with diferent values of the density ratio between the jet and the ambient medium and showed that, while jets with density ratio between 0.01-0.1 (and power corresponding to FR-II) propagate almost undisturbed, jets with lower values of the density ratio (and power corresponding to FR-I) show evidences of entrainment and deceleration in their external layers. Due to the limitations of computational power, Rossi et al (2008) could follow the jet propagation only up to about 60pc (assuming the jet radius at injection to be about 1pc) and could not see a com-

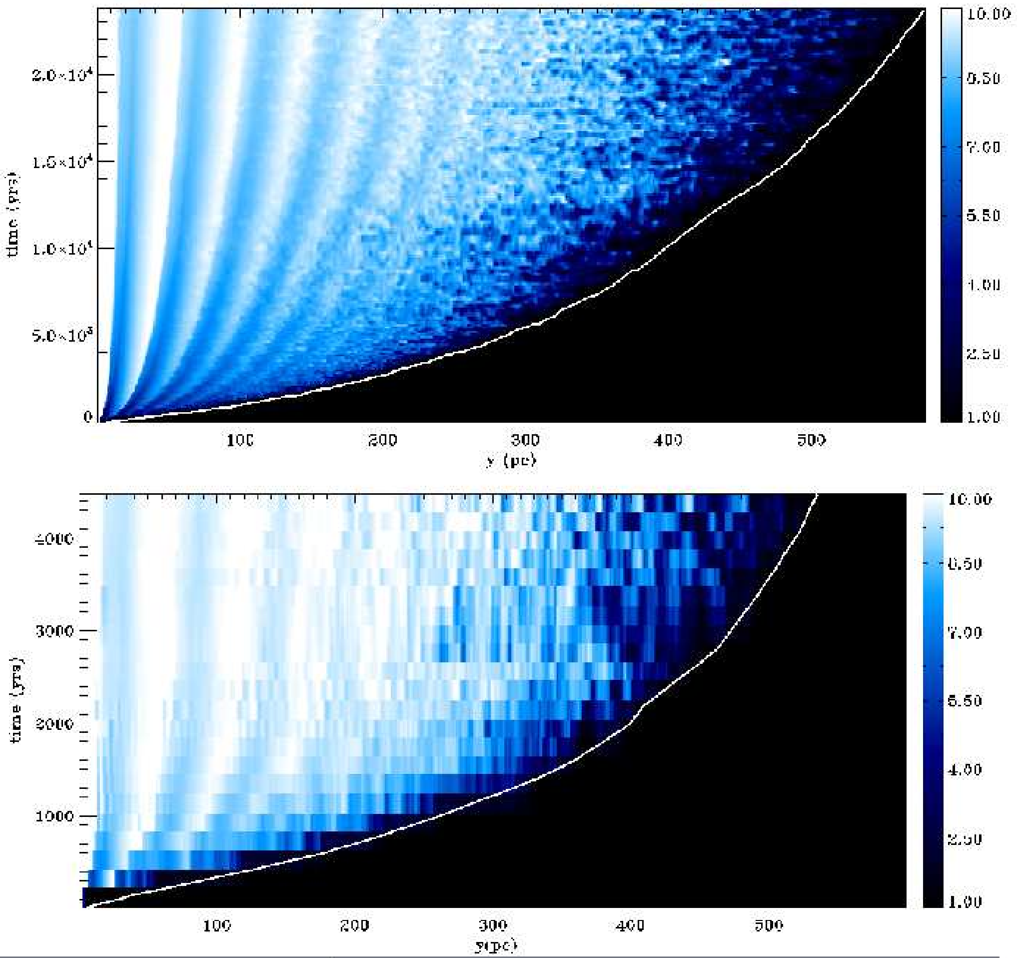

Fig. 2. Maximum Lorentz factor (given by the color scale) for each y and time. The position of the jet head as a function of time is also overplotted.

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2. Numerical setup

Numerical simulations have been carried out by solving the relativistic equations of conservation for the particle number and for the energy-momentum, with the PLUTO code (Mignone et al. 2007). Simulations were carried out on a Cartesian domain with coordinates in the range $x \in [-L_x/_2, Lx/2], y \in [0, L_y]$ and $z \in [-L_z/2, L_z/2]$ (lengths are expressed in units of the jet radius, where the jet radius is assumed to be 1pc, y is the direction of propagation). We take $L_y = 600$, while L_x and L_z depend on the particular simulation. Since we consider scales below 1kpc, we are still inside the galactic core and we can assume an ambient medium with constant density. The boundary conditions are outflows on all boundaries except the injection boundary at y = 0, where outside the unit circle we impose reflecting boundary conditions, while inside we inject a cylindrical flow characterized by the density and pressure ratios η and K with the ambient medium and the Lorentz factor γ. We analysed three cases, all of them have $\gamma = 10$, case A has $\eta = 10^{-4}$ and $K = 1$, case B has $\eta = 10^{-4}$ and $K = 10$ and case C has $\eta = 10^{3}$ and $K = 1$.

3. Results

In Fig. 1 we show cuts of the density distribution on the two planes (xy) and (yz) together with 3D isosurfaces of the Lorentz factor in the front part of the jet, for case A, when the jet head has reached about 550 jet radii. The Lorentz factor image shows that, starting from about 370 jet radii, the relativistic core of the jet is fragmented. from this point onward, most of the material flows at mildly relativistic velocities, with Lorentz factor between 1.5 and 2, with small highly relativistic blobs with Lorentz factor larger than 5. In Fig. 2 we display the distribution of the maximum value of the Lorentz factor (given by the color scale) found for each y and for each time. We overplot also the position of the jet head as a function of time. Notice that the times for case C are much shorter than those for case A. The propagation velocity of the higher density jet (case C) is much higher than that of the lower density jet (case A), then the jet in case C reaches the same distance as case A in a much shorter time. In both cases we observe a deceleration of the jet head velocity due to entrainment of the external material, in case A however the terminal velocity is much lower than that in case C. From the distribution of the maximum of the Lorentz factor, we can see the presence of shocks in the first part of the jet, the shocks are generated by the overpressured cocoon and produce a deceleration that is more evident in case A. The strength of the shocks and the subsequent deceleration decrease with time, as the cocoon pressure also decreases. In both cases, the jet becomes then more fragmented, with low velocity material mixed with highly relativistic fragments. In case C, however the high velocity fragments are present much closer to the jet head, while in case A, close to the jet head, the velocities appear to be subrelativistic. Outside the core radius the external density starts decreasing and the effect of entrainment is less effective, therefore, if a deceleration has not yet occurred at distances smaller than about 1 kpc, it is very difficult that it could occur at larger distances. Our results show that the deceleration for the jet with $\eta = 10^{-3}$ is substantial and the jet material moves mostly at subrelativistic velocities at a distance of about 500pc, this is not true for the case of higher density or of the same density but with higher pressure (case B). The results have been obtained thanks to the time allocation through the INAF-CINECA MoU that has allowed to perform these simulations that are computationally very demanding and that necessarily require High Performance Computing resources. These results have been presented in Rossi et al. (2020).

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