SUPERSONIC JETS AND LOBE MORPHOLOGIES

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1. Introduction

Since the pioneering work by Norman et al. (1982), many numerical studies have been devoted to the analysis of the propagation of a supersonic jet shot into an ambient medium (see Massaglia, Bodo & Ferrari 1995, hereinafter Paper I, and references therein). In spite of these strong efforts many aspects of this problem are still not well understood. This is due to the complexity of the jet-cocoon structure: in fact, the cocoon excites perturbations to the jet flow, which in turn can be amplified by the Kelvin–Helmholtz mechanism and induce a strong activity of the jet's head that affects the cocoon structure. Thus a complex feedback loop mechanism establishes between jet and cocoon which make the dynamics of the interaction very complex.

In addition, when trying a more direct comparison of the results with observations, one must remember that what is observed is an outcome of the distribution of energetic particles and magnetic field and not the bulk of the flowing plasma, and therefore direct comparisons could be misleading. In this paper we focus on the dynamics of the interaction and we describe some properties of the cocoon structure which can be relevant for the observational properties of extragalactic radio sources and have been overlooked in previous studies. We have been able to examine these properties because of the wide exploration of the parameter space especially towards high Mach numbers, typically higher than those discussed in the

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present literature, and because our approach allowed us to follow the jet propagation up to very long times and to keep all parts of the cocoon in the computational domain, whereas the usual approach is limited to follow the jet only for one crossing time of the grid and to lose the back part of the cocoon.

2. Results

We study the dynamics of a supersonic, cylindrical, axisymmetric jet continuously injected into a medium initially at rest. We solve numerically the full set of adiabatic, inviscid fluid equations for mass, momentum, and energy conservation.

The numerical scheme, the grid, the code adopted are discussed in Paper I. In the present calculations we take advantage of the particular setup of Paper I, and we perform the calculation in a reference frame where the jet's head is approximately at rest. Therefore, in the initial configuration, the external medium has a uniform velocity $V_{\rm h} = v_{\rm j}/(1+\sqrt{\nu})$ where $v_{\rm j}$ is the jet velocity in the "laboratory frame" and ν is the ratio of the external to the jet density, and $V_{\rm h}$ is an approximated advance velocity of the jet's head obtained applying momentum conservation in the front region of the jet (see Paper I). This moving frame is adopted in the computations, but afterwards we will discuss the results obtained, translating them back to the reference frame where the external medium is at rest, i.e. to the "laboratory frame". The system of equations was written in non-dimensional form and the boundary conditions have been set as in Paper I.

The numerical scheme adopted is of PPM (Piecewise Parabolic Method) type and is particularly well suited for studying highly supersonic flows with strong shocks (Woodward & Colella 1984).

The dynamics of the interaction of the jet head with the ambient medium and its dependence on M and ν has been extensively discussed in Paper I, where we have explored the plane (ν, M) with $\nu = 3, 10, 30, 100, 300$ and $M = 3, 10, 30, 100, 300, 1000$. We summarize here the main features of this interaction:

a) Jets with high M (≥ 30) and low ν (≤ 30) have higher head velocities. In this case the backflow compression of the jet behind the head yields the formation of strong biconical shocks that transmit the thrust to the head, increasing the ram pressure on the front region; afterwards the compression reflects at the jet axis and a recurrent process leads to recurrent impulsive accelerations of the head.

b) Jets with low M $(M < 30)$, or high M $(M > 30)$ and $\nu > 30$, have lower head velocities. In this case the backflow compression is much weaker and the resulting thrust is not sufficient to accelerate the head.

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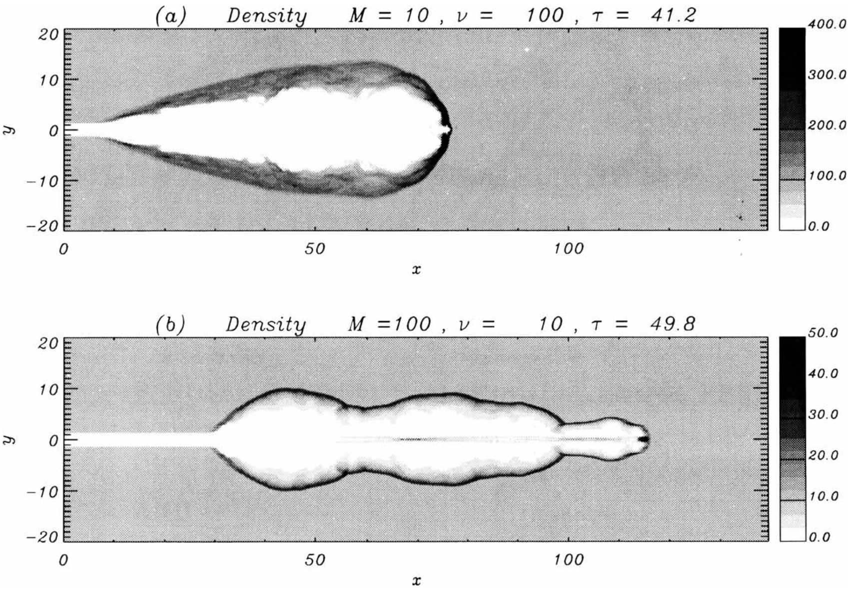

Figure 1. **Gray scale image of the density for $M = 10$ and $\nu = 100$ (panel a, 'fat' cocoon), and $M = 100$ and $\nu = 10$ (panel b, 'spearhead' cocoon). This in an example of the two characteristic structures assumed by the cocoon.**

The critical parameter is the inclination of biconical shocks: shocks that have a small inclination angle on the axis are successful in accelerating the jet head.

The cocoon morphology reflects the head's evolution. The two classes of jets listed above lead to two different cocoon morphologies: class a) jets form "spearhead" cocoons (Fig. 1b) while class b) jets lead to "fat" cocoons (Fig. 1a).

The application of the results obtained to extragalactic jets can be performed relating the morphologies emerging from the numerical calculations to those observed mainly in the radio band. A basic question that arises at this point is the following: which physical quantity is most suitable to represent the observed radio brightness distribution? If we assume, as usually done in the literature, the density distribution as an actual tracer of the brightness distribution we can compare the former in Fig. 1a) ($M = 10$, $\nu = 100$) and Fig. 1b) ($M = 100$, $\nu = 10$) with the radio maps of 3C296 and 3C223 (Fig. 2), from Leahy & Perley (1991).

From Fig. 1b) we note that the shock that surrounds the cocoon involves matter of the external ambient. Is this shocked region site of particle acceleration? If the answer is positive we can say that indeed the form of the lobe resembles the density distribution of Fig. 1a), with an elongated structure having the front part protruding from the lobe. Similar morpholo-

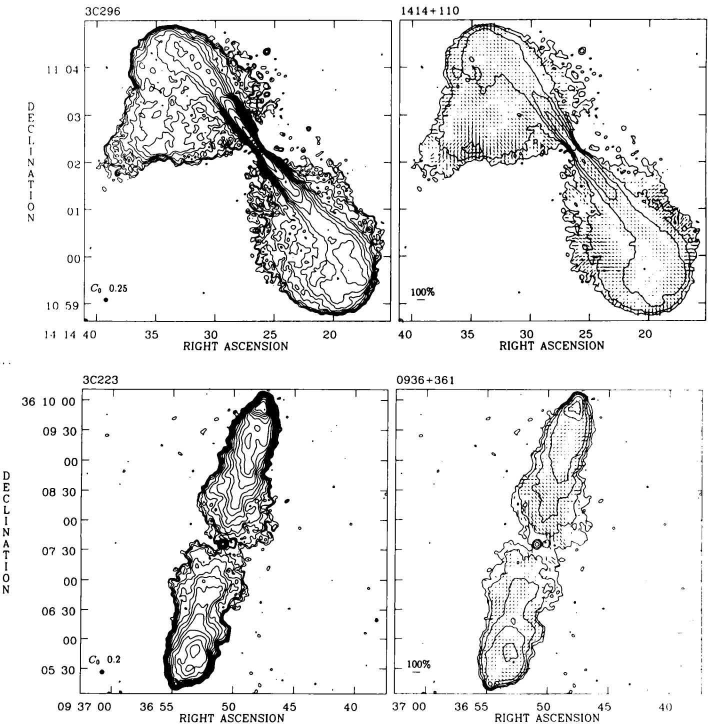

Figure 2. Brightness distribution and polarization map of 3C296 and 3C223

gies can be found in the sample of high luminosity radio sources by Leahy & Perley (1991); a representative example can be 3C223. In this scheme, the jet would be characterized by a high value of the Mach number accompanied by a moderate value of the density ratio. Moreover, the shock that surrounds the cocoon, according to simulations, must have the effect of enhancing the component of the magnetic field along the shock front, resulting in a high polarization at the source edge, with the polarization vector directed normally to the edge itself. This effect is clearly visible in the polarization map of the source mentioned above.

In the case of slow jet, we note from Fig. 1a) that the shock forms only in the front part of the cocoon. An example of this second kind of morphology can be 3C296.

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