# Numerical Study of AGN Jet Propagation with Two Dimensional Relativistic Hydrodynamic Code

AKIRA MIZUTA, SHOICHI YAMADA, AND HIDEAKI TAKABE

Institute of Laser Engineering of Osaka University, Suita Osaka 565-0871, Japan

E-mail: amizuta@ile.osaka-u.ac.jp, syamada@ile.osaka-u.ac.jp and takabe@ile.osaka-u.ac.jp

## ABSTRACT

We investigate the morphology of Active Galactic Nuclei(AGN) jets. AGN jets propagate over kpc ∼ Mpc and their beam velocities are close to the speed of light. The reason why many jets propagate over so long a distance and sustain a very collimated structure is not well understood. It is argued taht some dimensionless parameters, the density and the pressure ratio of the jet beam and the ambient gas, the Mach number of the beam, and relative speed of the beam compared to the speed of light, are very useful to understand the morphology of jets namely, bow shocks, cocoons, nodes etc. The role of each parameters has been studied by numerical simulations. But more research is necessary to understand it systematically. We have developed 2D relativistic hydrodynamic code to analyze relativistic jets. We pay attention to the propagation velocity which is derived from 1D momentum balance in the frame of the working surface. We show some of our models and discuss the dependence of the morphology of jets on the parameter.

Key Words : AGN: jets – hydrodynamics – methods: numerical – relativity

## I. INTRODUCTION

Active Galactic Nuclei(AGN) jets are one of the largest scale phenomena in the space (for example Carilli & Barthel 1996). The jet is ejected form accretion disk that surrounds AGN and propagates over a long distance in the ambient medium. There are two shocks at the head of the jet. One is a bow shock which accelerates ambient matter. The other is a terminal mach shock at which the beam ends. The matter which crosses the terminal mach shock extends to the radial direction and envelops the beam, thus the cocoon structure is made. In the cocoon, there is Kelvin-Helmholtz instability at the contact discontinuity between the ambient matter and the jet.

For last thirty years analytical studies and numerical simulations of jets have been performed to understand the morphology of the jet. Blandford & Rees (1974) and Scheuer (1974) discussed the structure of the jet with the beam model. One of the early numerical results is shown by Norman et al. (1982). Although it was a non-relativistic simulation, they showed main features of jets, two shocks at the head of jet and a cocoon. The difficulty of numerical relativistic hydrodynamics made it delayed to investigate the relativistic effect for the morphology of the jet. In this decade, some stable codes for the ultra-relativistic regime have been developed (Eulderink & Mellema 1994; Duncan, G. C. & Hughes, P. A. 1994; Font et al. 1994; Koide, Nishikawa & Mutel 1996; Aloy et al. 1999a).

Martí et al. (1997) and Aloy et al. (1999b) performed long simulations to investigate the morphology of the jets with 2D and 3D relativistic hydrodynamic codes. Relativistic magnetized jets were shown by Komissarov (1999). These papers verify that the morphology of jets depends on such dimensionless parameters as the density ratio of the beam and the ambient gas ($\eta \equiv \rho_b/\rho_a$), relative speed of the beam compared to the speed of light ($v_b/c$), and the Mach number of the beam ($M_b = v_b/c_{s,b}$). In most of these simulations a so-called pressure matched jet is assumed, namely the pressure ratio $K \equiv p_b/p_a = 1$. Recently Scheck (2000) has demonstrated that the propagation velocity $v_j^{1D}$ which is derived from 1D momentum balance in the frame of the working surface is very useful for understanding the propagation of the jet into the ambient medium. He fixed $v_j^{1D} = 0.2$ in his models. In this paper, we also pay our attention to the parameter and discuss the morphology and dynamics of the three jet models fixing $v_j^{1D} \sim 0.36$.

## II. BASIC EQUATIONS

If the beam velocity is very large $v_b \sim 1$ the relativistic effect is very important for the morphology of jets. Here we take the unit that the velocity of light is unity. Relativistic hydrodynamic equations have to be solved;

$$\frac{\partial(\rho W)}{\partial t} + \frac{1}{r}\frac{\partial(r\rho W v_r)}{\partial r} + \frac{\partial(\rho W v_z)}{\partial z} = 0, \quad (1)$$

$$\frac{\partial(\rho h W^2 v_r)}{\partial t} + \frac{1}{r}\frac{\partial r(\rho h W v_r^2 + p)}{\partial r} + \frac{\partial(\rho h W^2 v_r v_z)}{\partial z}$$
$$= \frac{p}{r}, \quad (2)$$

$$\frac{\partial(\rho h W^2 v_z)}{\partial t} + \frac{1}{r}\frac{\partial(r\rho h W^2 v_r v_z)}{\partial r} + \frac{\partial(\rho h W^2 v_z^2 + p)}{\partial z}$$
$$= 0, \quad (3)$$

$$\frac{\partial(\rho h W^2 - p)}{\partial t} + \frac{1}{r}\frac{\partial(r\rho h W^2 v_r)}{\partial r} + \frac{\partial(\rho h W^2 v_z)}{\partial z} = 0, \quad (4)$$

where, $\rho, p, v_r, v_z, W, \epsilon$, and $h$ are the rest mass density, pressure, velocity components of $r-, z-$ directions, Lorentz factor ($\equiv (1-v^2)^{-1/2}$), specific internal energy and specific enthalpy ($\equiv 1 + \epsilon + p/\rho$), respectively. Here the axisymmetry is assumed. The equations (1)-(4) are not closed until the equation of state is provided. In this paper we assume the gas is ideal;

$$p = \rho\epsilon(\gamma - 1), \quad (5)$$

where $\gamma$ is a specific heat. From these equations the sound speed $c_s$ is defined as

$$hc_s^2 \equiv \left(\frac{\partial p}{\partial \rho}\right)_\epsilon + \frac{p}{\rho^2}\left(\frac{\partial p}{\partial \epsilon}\right)_\rho = \frac{\gamma p}{\rho}. \quad (6)$$

## III.  THEORY

In this field, 1D analysis has been used to estimate the propagation velocity of the jet. The definition of the propagation velocity $v_j$ is the velocity of the working surface which is contant discontinuity at the head of the jet in the frame where the ambient gas is rest. In general the propagation velocity is less than that of the beam, because of the conversion of the large kinematic energy of the beam to the thermal energy in the hot spot. Assuming the momentum balance between the beam and the ambient gas in the fame of the working surface, we have

$$\rho_b h_b W_j^2 W_b^2 (v_b - v_j^{1D})^2 + p_b$$
$$= \rho_a h_a W_j^2 (-v_j^{1D})^2 + p_a. \quad (7)$$

This equation leads to,

$$v_j^{1D}$$
$$= \frac{\eta_R^* v_b - \sqrt{\eta_R^* v_b^2 - (\eta_R^* - 1)(K-1)c_{s,a}^2/(\gamma W_j^2)}}{\eta_R^* - 1}, \quad (8)$$

$$\text{where } \eta_R^* \equiv \eta_R W_b^2, \quad \eta_R \equiv \frac{\rho_b h_b}{\rho_a h_a}. \quad (9)$$

In general the sound speed of interstellar matter is much smaller than the velocity of the beam; ($c_{s,a} \ll v_b$) so we can neglect the term which includes $K$ As a result, Eq.(8) reduces to

$$v_j^{1D} = \frac{\sqrt{\eta_R^*}}{1 + \sqrt{\eta_R^*}}v_b. \quad (10)$$

This is identical to the equation derived by Martí et al. (1997) for the pressure-matched jet ($K = 1$). Of course, this estimate does not include multidimensional effect, so the actual propagation velocity is less than $v_j^{1D}$. Scheck (2000) showed that the actual propagation velocity is almost the same in his models with a fixed $v_j^{1D} = 0.2$, in spite of the large differnce of the specific internal energy of the beam among the models.

## IV.  NUMERICAL SIMULATION

We solve relativistic hydrodynamic equations Eq.(1-5) with our 2D relativistic hydrodynamic code numerically. The code is based on an approximate Riemann solver for relativistic flows. The numerical flux is derived from Marquina's flux formula (Donat & Marquina 1996, Donat et al 1998). The code is of second order accuracy spatically using MUSCL method (van Leer 1977,1979) and of first order temporally.

We use 2D cylindrical computational grid (300 × 1200 = 30$R_b$ × 120$R_b$) and put stationary ambient gas initially. The relativistic beam flow ($v_b = 0.99$) is injected continuously from one side of computational region; near the symmetrical axis (10 grid points). The boundary condition for the other boundaries is free.

We calculated three models (Table 1), in which the propagation velocity is fixed to be $\sim 0.37$. The beam A is a very cold beam, namely, the most energy of the beam is kinematic energy. On the contrary, the beam B and C are hot beams, taht is, the temperature of the beam is relativistic(B) or ultra-relativistic(C).

## V.  RESULTS AND DISCUSSION

Figure 1 shows snapshots of rest mass density for three models at $t = 405[R_b/c]$. The beam of model A remains very collimated and we can see a fine node structure in the beam. This node structure is a common feature for cold jets. On the contrary, for hot beams (B and C), there is less structure seen in the beam. In the case of hot beam, since the thermal energy of the beam is very large, it tends to expand transversally and the shape of the bow shock becoms less acute. It is more difficult to develop the internal shock in the hot beam than in the cold one.

Very complex vortexes are seen in all cocoons. This originates form the Kelvin-Helmholtz instability between the matter which crossed the Mach disk and the ambient matter that is accelerated by the bow shock.

Figure 2 shows the time evolution of the position of the working surface for each model. Although the jet of model A propagates farther out than other models, the slope in asimptotic region is constant for all models. This means taht the steady propagation velocity is almost the same for all models, $v \sim 0.2$.

Table 1.  Conditions for beam and initial ambient matter for three models

|         | A | B | C |
|---------|------|------|------|
| $\eta$    | $6.6 \times 10^{-3}$ | $3 \times 10^{-3}$ | $1.2 \times 10^{-4}$ |
| $M_b$   | 6.0 | 1.6 | 1.73 |
| $\epsilon_b$ | $2.5 \times 10^{-2}$ | 0.8 | 42 |
| $\gamma$  | 5/3 | 5/3 | 4/3 |
| $K$     | 10 | 100 | 100 |
| $v_b$   | 0.99 | 0.99 | 0.99 |

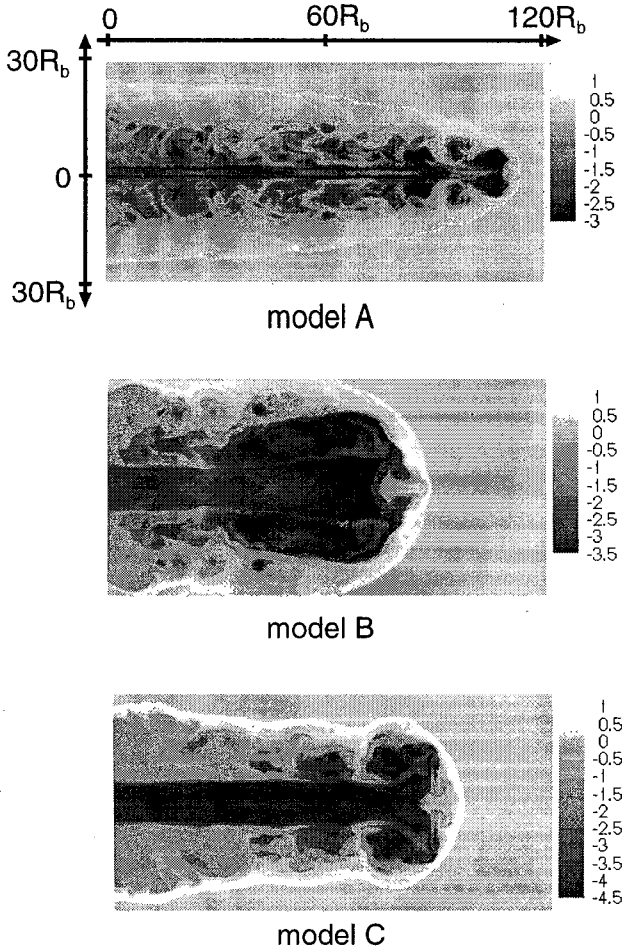**model A**



**model B**



**model C**

**Fig. 1.**— Log scale rest mass density contours, model A(top), model B(middle) and model C (bottom). The time of all snapshots is $t = 405[R_b/(c)]$.



**Fig. 2.**— The time dependence of the position of the working surface, 1D theoretical line (solid), model A (broken line), model B (dash-dotted line) and model C(dotted line).

## VI.  SUMMARY

Three relativistic jets are studied in this paper. The propagation velocity that is derived from 1D momentum balance is fixed, For all models the calcurated propagation velocity is less than the velocity $v_j^{1D}$, but all of them are almost equal to each other. Althouh the stedy propagation velocity of the jet is smaller than $v_j^{1D}$, the parameter $v_j^{1D}$ has important role for the propagation of jet. More systematical numerical and analytical study is necessary to answer the problem that what is the parameter that decides actual propagation velocity and to clear the role of the propagation velocity for the morphlogy and dynamics of jets. And we have to study higher relativistic regime in the future.

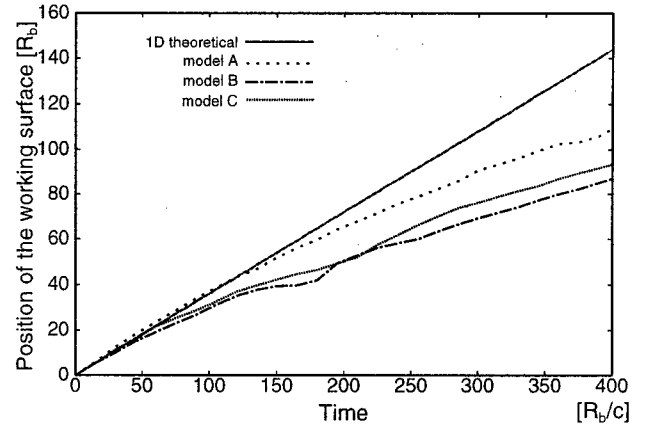This work was carried out on NEC SX5, Cybermedia Center Osaka Univ.

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