Long-term Relativistic Jet Propagation and Dynamics

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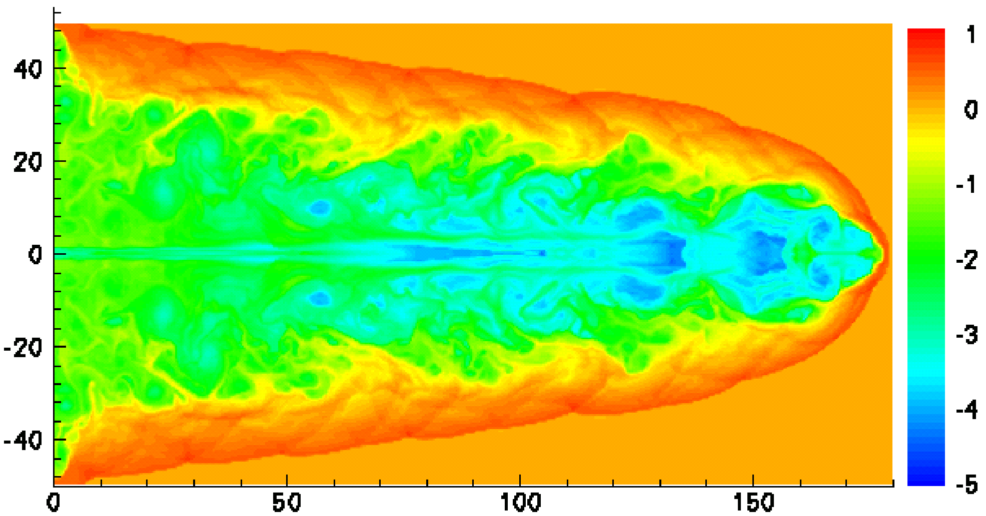
<u>OUTLINE</u>

Introduction
- AGN Jet observation, theory, & simulation

Numerical 2D/3D
- propagation efficiency
- flow structure
- emissivity

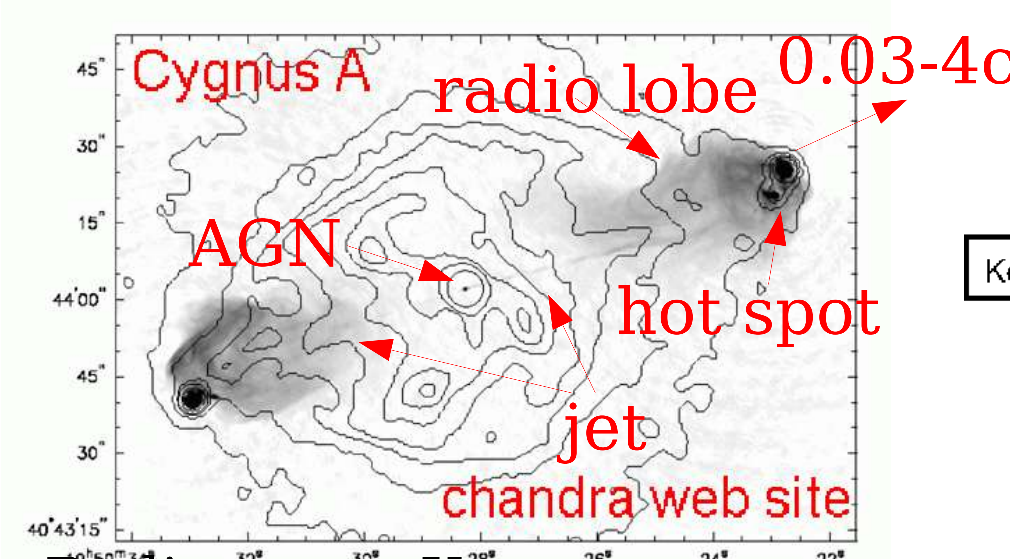
Conclusion



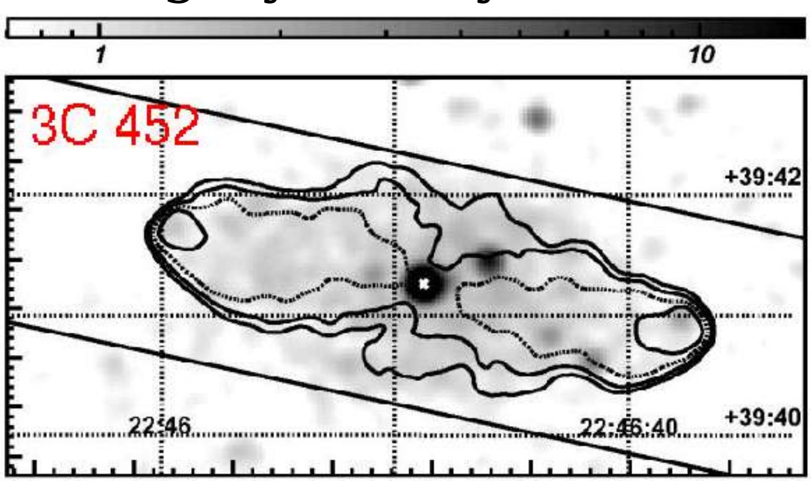
Ultra Relativistic Jets in Astrophysics :
Observations, Theory and Simulations
Banff, Alberta, Canada July 11-15, 2005

Mizuta et al. ApJ 606, 804 (2005)

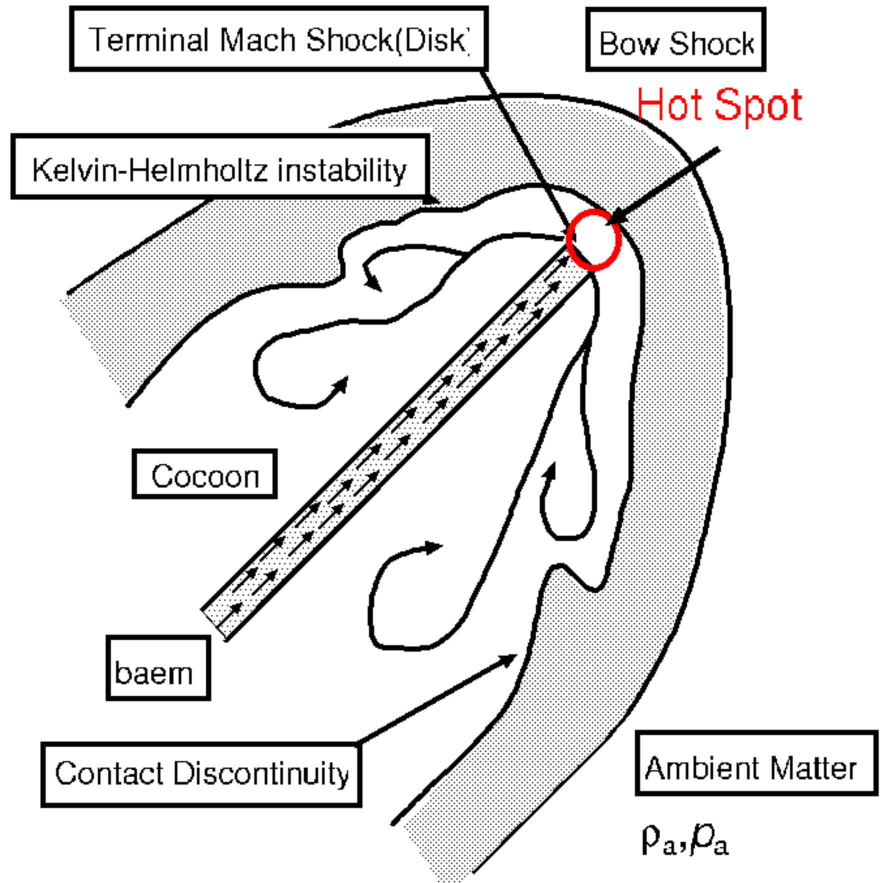
Observation and Dynamics of AGN Jets



Radio gray, X-ray contour



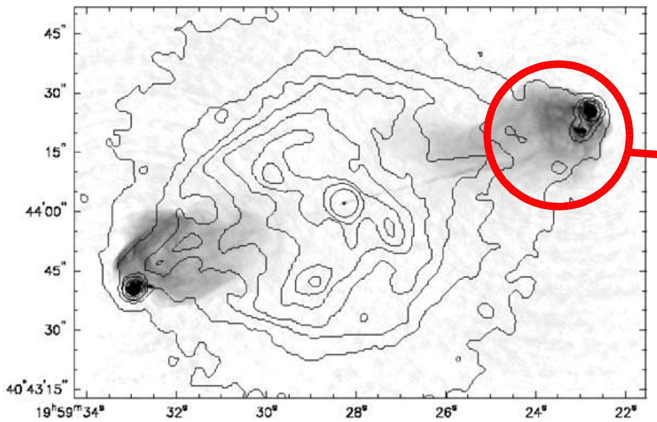
(Isobe et al '02)

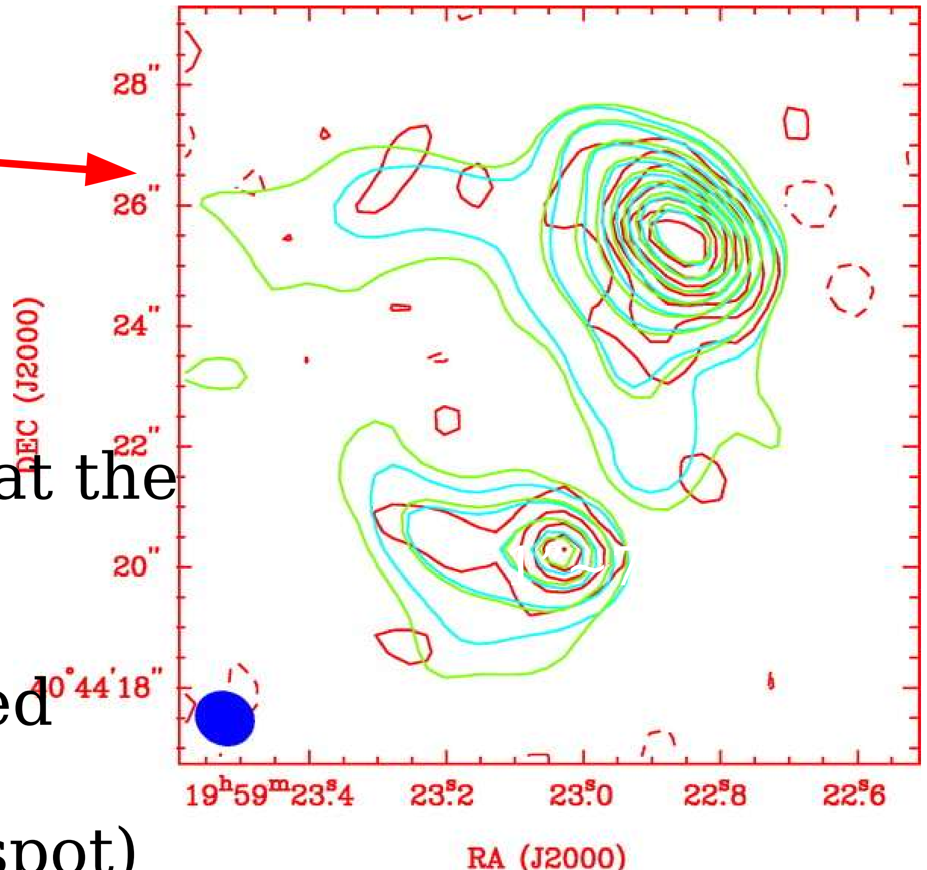


A schematics of the head of the jet.

Non-thermal emission is observed (AGN, knot, hot spot, and radio lobe).The dynamics is controlled by the thermal gas. Most of them are hidden.

Secondary hot spot





hot spot = Bright region at the head of the jet

two hot spots are observed in one side in many jets (primary, secondary hot spot)

How is the structure formed ?
Which hot spot is the terminal of the jet ?
Priminary or secondary hot spot ?

Cygnus A (radio230Ghz)

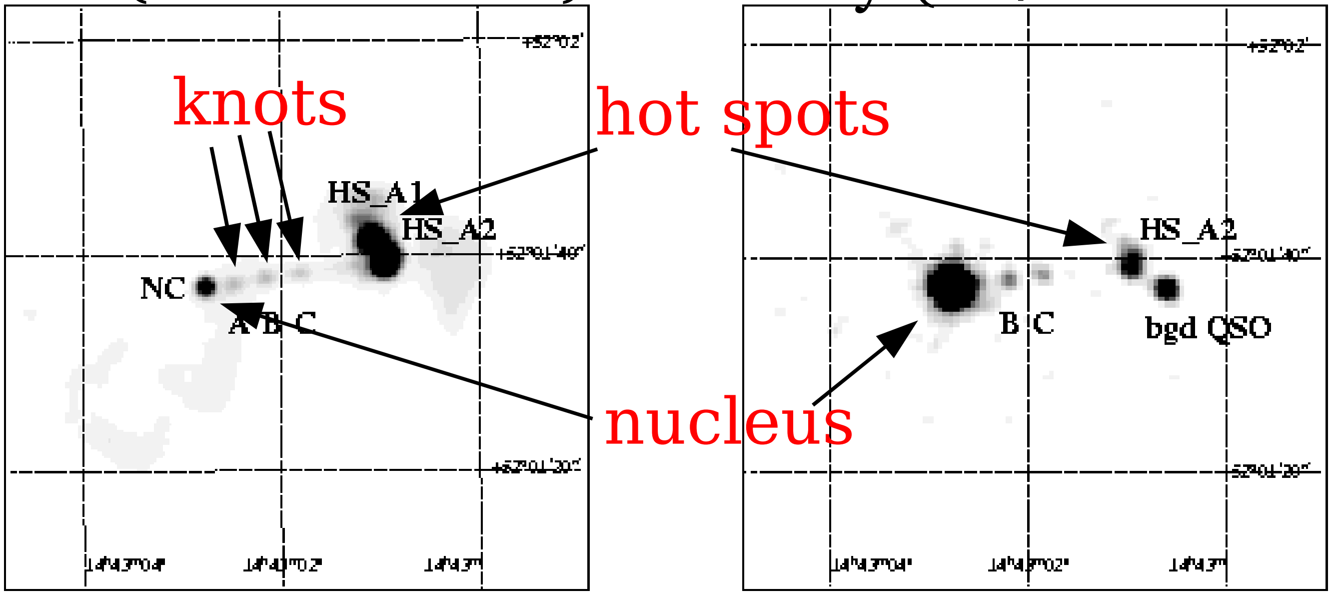
Wright et al.

ApJ 614, 115(2004)

Knots in large scale

3C303 (z=0.141) a few tens kpc jet

radio (1.5GHz : VLA)　　X-ray (0.4-8keV: *Chandra*)



Kataoka et al. A&A, **399**, 91 (2003)

Fig. 1. (a) Radio image of 3C 303. The grey scale is a 1.5 GHz VLA image (Leahy & Perley 1991; actually taken from Leahy, Bridle & Strom 1998). The resolution is 1.2 arcsec and black represents 20 mJy beam^{-1}. NC denotes the nucleus; A, B and C the jet knots; and HS_A1 and HS_A2 the hotspot components. (b) X-ray image of 3C 303 in the 0.4–8 keV band (ACIS-S onboard *Chandra*). The image is smoothed with a $\sigma = 0.5$ arcsec Gaussian. B and C denotes the jet knots, and HS_A2 the hotspot component A_2.

Non thermal emission

What is the origin of non-thermal particles ?

Motivated these observations
2D & 3D calculations have been done to see

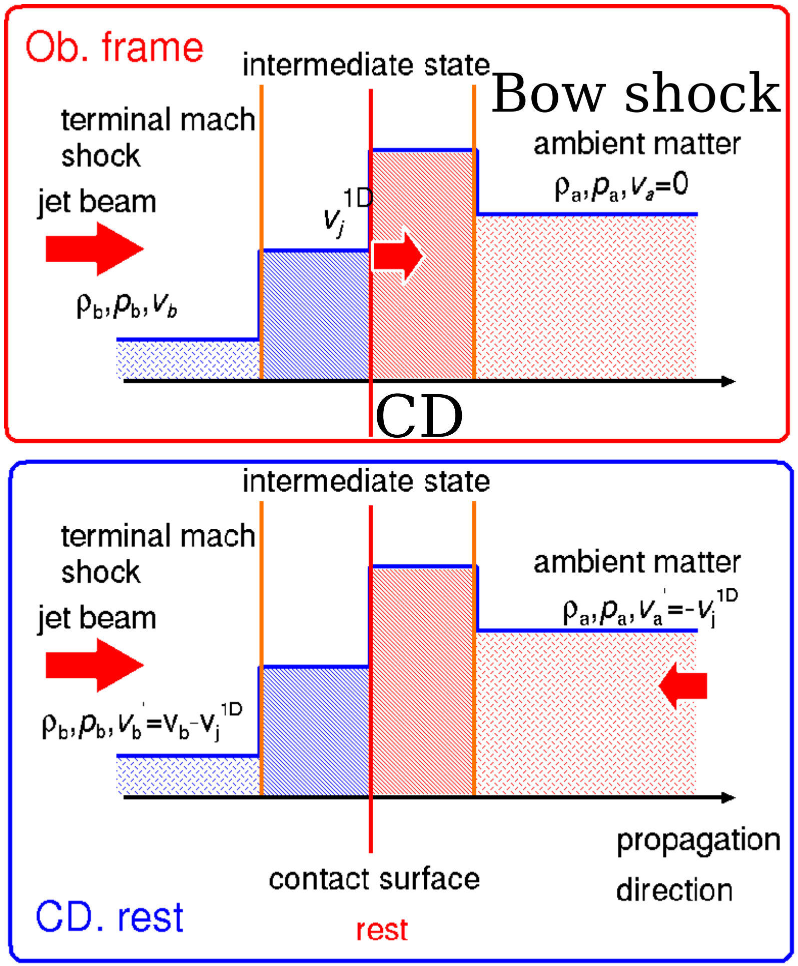
How the jet keeps collimated structure

Propagation velocity
---age of jet itself and life of AGN

Outer Shape
--- comparison with X-ray observation

Emissivity (radio lobe, knots, hot spots)
--- how extended the lobe is,
test for particle acceleration theory

1D theoretical estimate of propagation velocity by Norman (1982), Marti et al.(1997)



Propagation velocity (v_j)
< Beam velocity (v_b)

$$v_j < v_b$$

momentum balance

$$\rho_a h_a \Gamma_j^2 \Gamma_b (v_b - v_j^{1D})^2 + p_b = \rho_a h_a \Gamma_j^2 (-v_j^{1D})^2 + p_a$$

$$v_j^{1D} = \frac{\sqrt{\eta_R^*}}{1+\sqrt{\eta_R^*}} v_b$$

where $\eta_R^* = \Gamma_b^2 \cdot (\rho_b/\rho_a)$ for cold beam

Norman 1982,
Marti et al. 1997,
Mizuta et al. 2004

Basic Equations

Axisynmmetric Special Relativistic Hydrodynamic Equation

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

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

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

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

EOS

$p = (\gamma - 1)\rho\epsilon$ γ =5/3 const

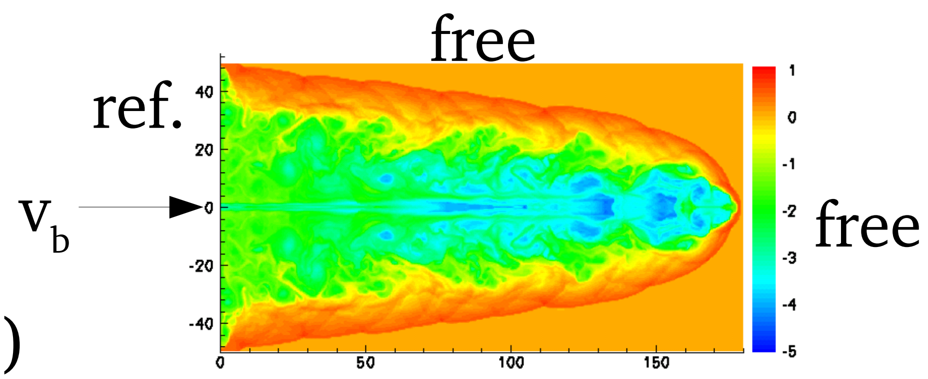
ρ density
p pressure
v_i velocity component
$\Gamma = (1\text{-}v^2)^{-1/2}$
Lorentz factor
ε specific internal energy
$h=1+\varepsilon+p/\rho$
specific enthalpy
γ adiabatic index

Numerical Condition

Three models are studied.

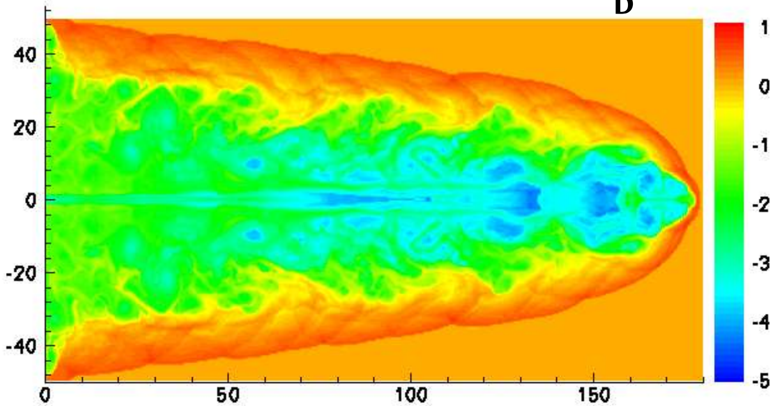
	JB02	JB03	JB04
$\eta \equiv \rho_b/\rho_a$	1.28×10^{-3}	3.76×10^{-3}	9.15×10^{-3}
$M_b \equiv v_b/c_b$	6.0	6.0	6.0
ϵ_b	2.55×10^{-2}	2.55×10^{-2}	2.55×10^{-2}
γ	5/3	5/3	5/3
$K \equiv p_b/p_a$	10	33	100
$\Gamma_b(v_b)$	7.1(0.99)	7.1(0.99)	7.1(0.99)
v_j^{1D}	0.2	0.3	0.4
expiration time $R_b/(c)$	1800	1200	600

500x1800 grid points
$=50R_b \times 180R_b$
10 grid points / R_b
(injected beam radius)

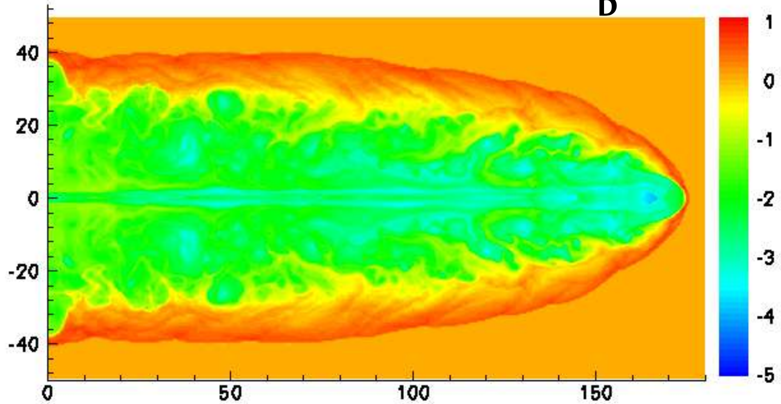


Rest mass density contours at the end of simulations

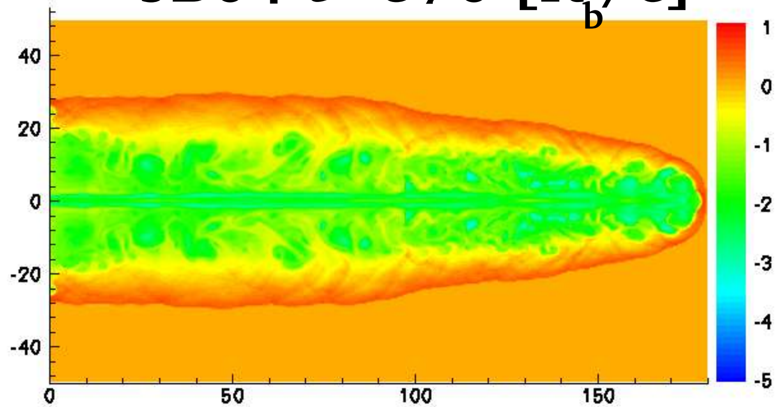
JB02 t=1770 [R_b/c]



JB03 t=1140 [R_b/c]



JB04 t=570 [R_b/c]

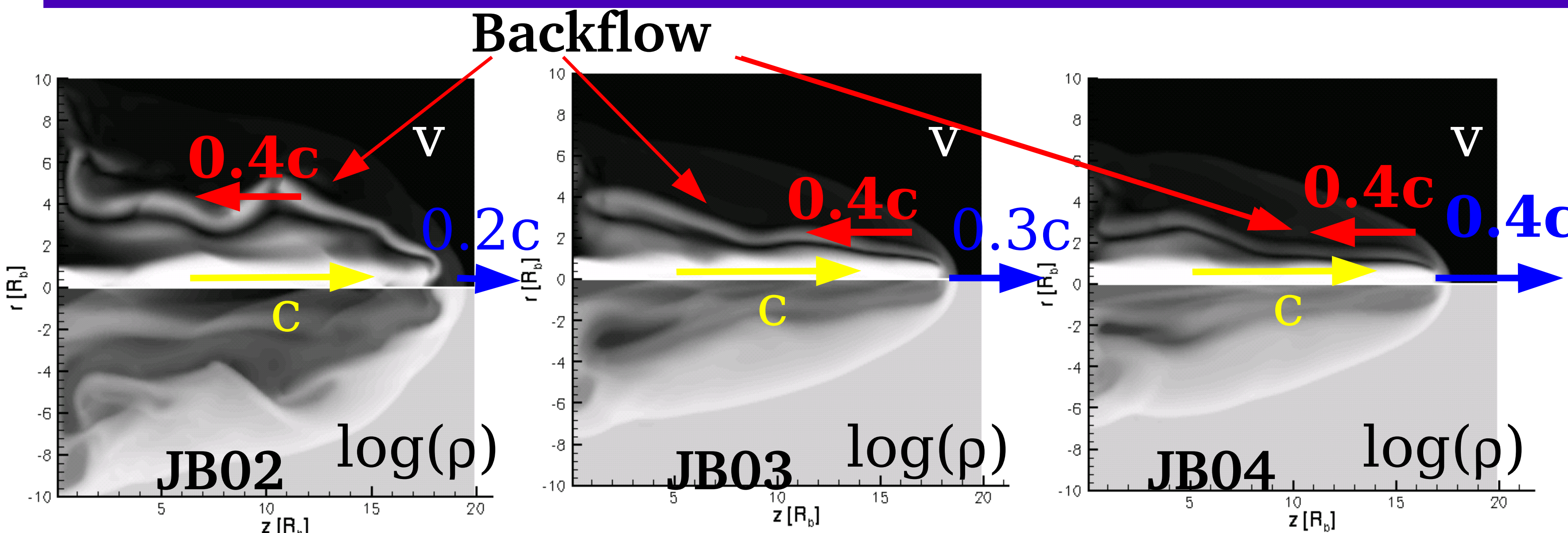


Slower jet
- Cone like outer shape like Cygnus A

Faster jet
- Cylinder like outer shape like 3C452

Is this difference due to the difference of v_j^{1D}?

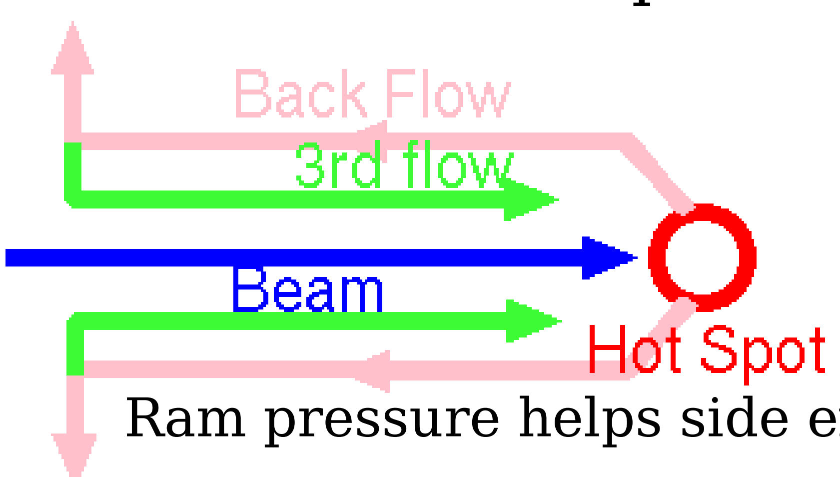
Back flows from the hot spot affect the dynamics and outer shape of the jets

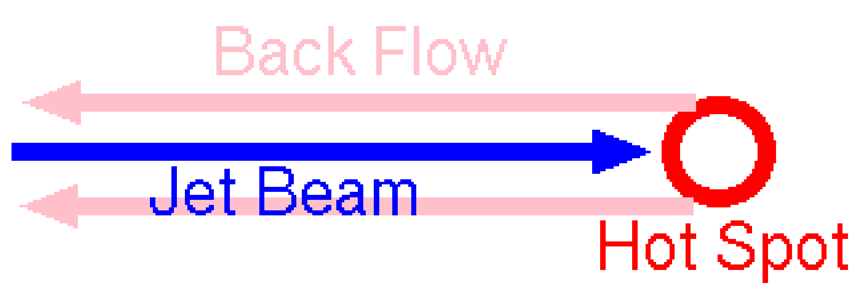


Very early phase of the simulation

Slower head speed

Faster head speed





Ram pressure helps side expansion

The dynamics in the early phase can be tested by the observation of Compact Symmetric Objects (CSO)

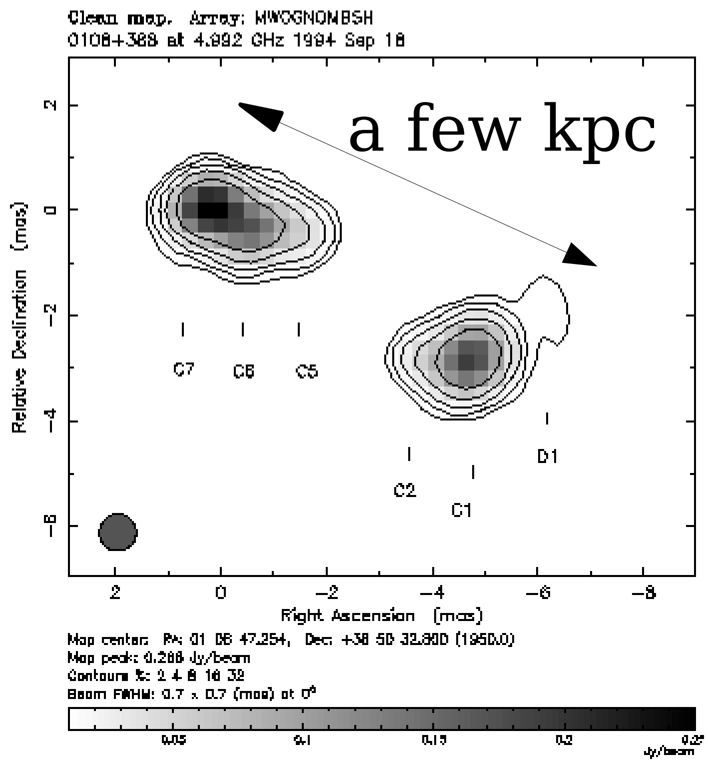


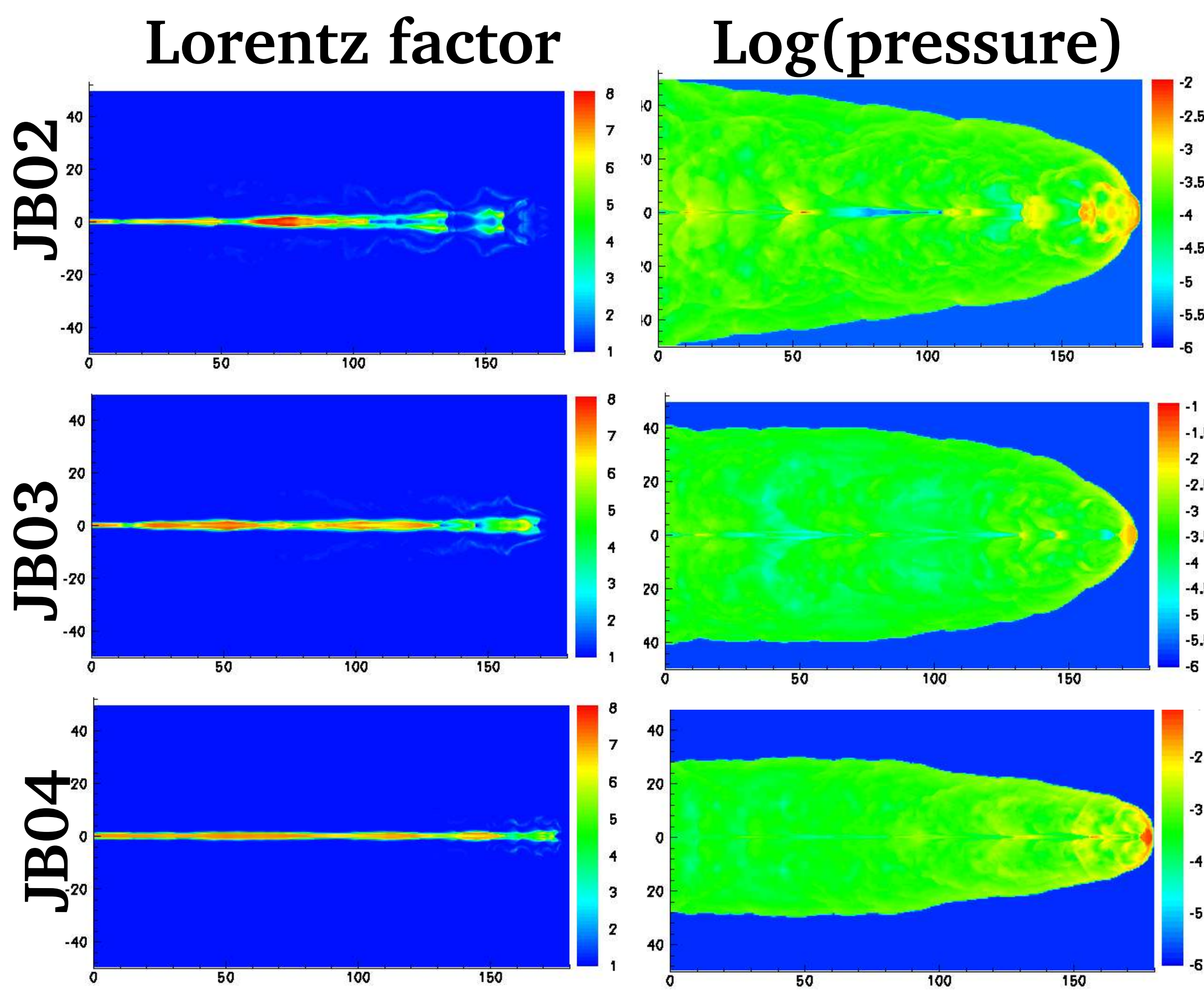
Fig. 1. Third epoch image of 0108+388 with the positions of components identified in gaussian modelfitting indicated. Rms noise=0.88 mJy beam^{-1}.

Compact symmetric Objects (CSOs)
====> young AGN jet ?

a few tens CSOs
"two sided" hot spots and lobes
d ~ a few kpc
expansion velocity ~0.1-0.5c
age ----- a few ky

Separation of outer components
at a rate of 0.197+0.026 *c*
Owsianic et al. A&A **336** L37 (1998)

Collimation of the Jets (1)

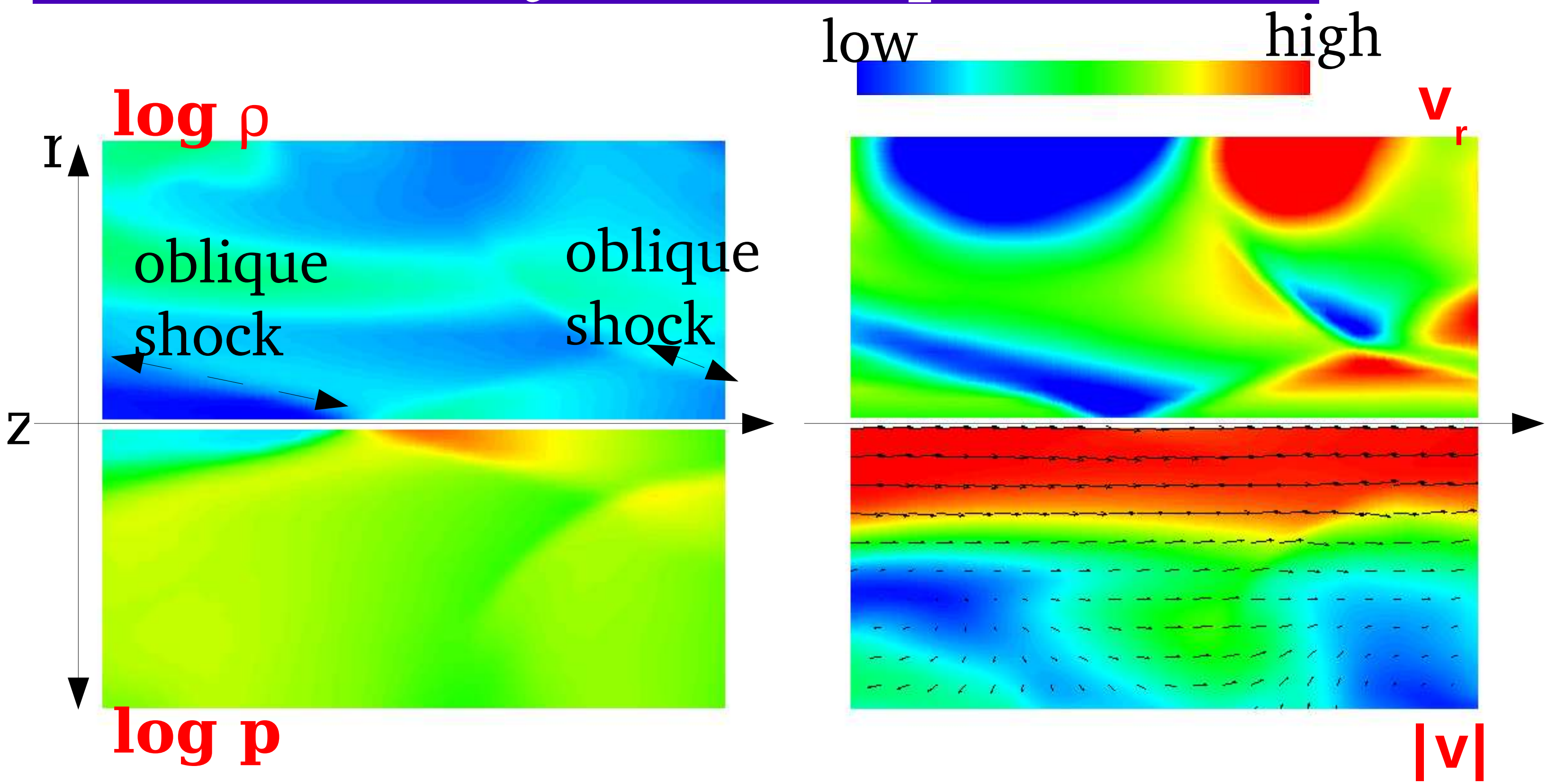


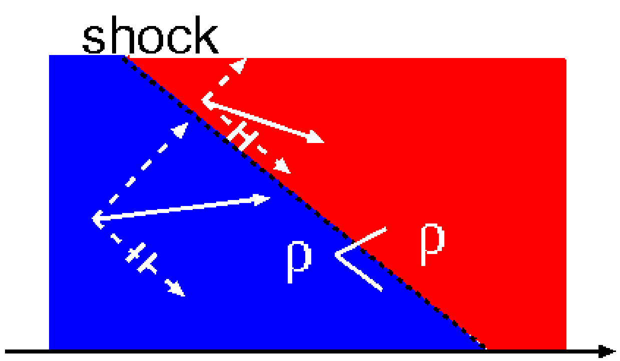
The pressure inside the bow shock is almost uniform except some high pressure region along th axis.

The half opening angle ~ 6^{o}.

High pressure region may corresponds to knots in the jet.

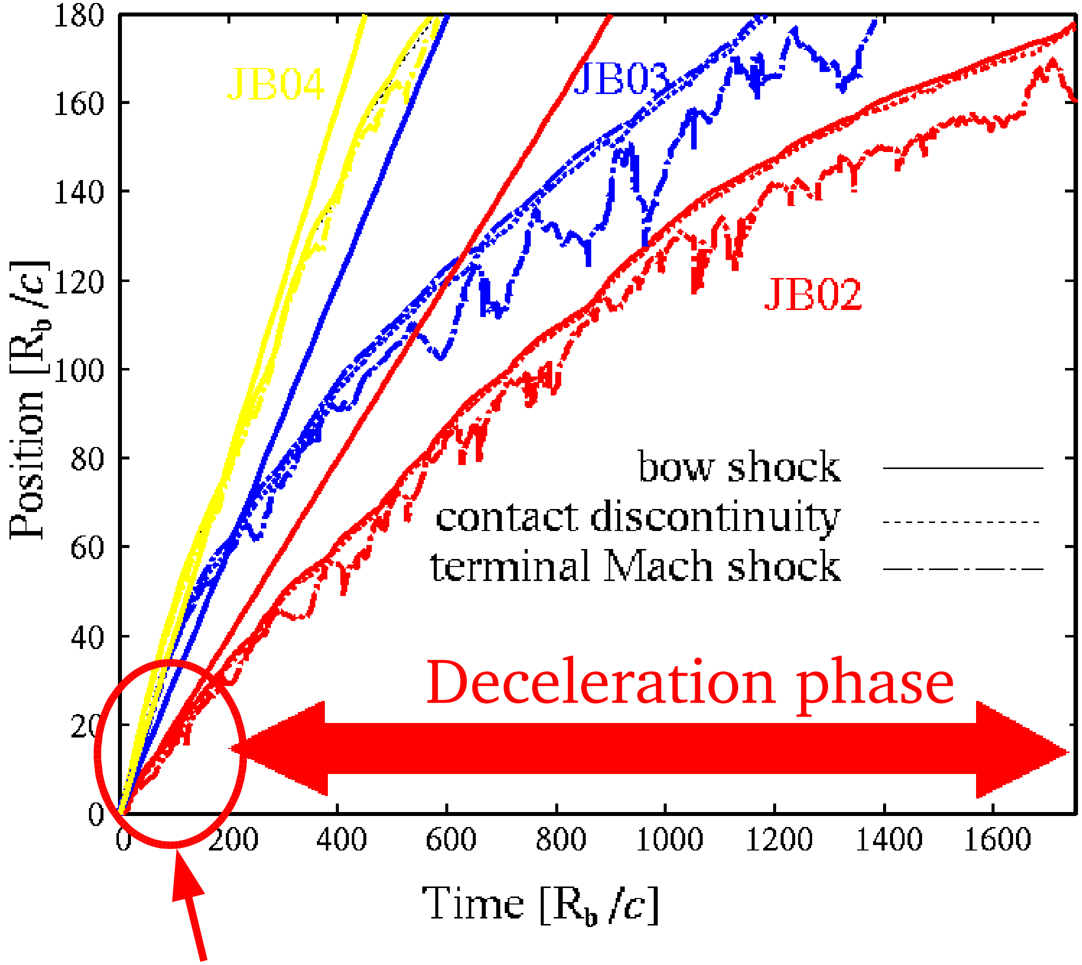
Collimation of jet (2): reconfine mechanism by the oblique shock





The radial component of the velocity decreases when the flow pass the oblique shock (Muller 1997).

Propagation of Jets : the head of the jet decelerates



Follows 1D estimation

In the early phase, the propagation velocity follows 1D theoretical estimation.

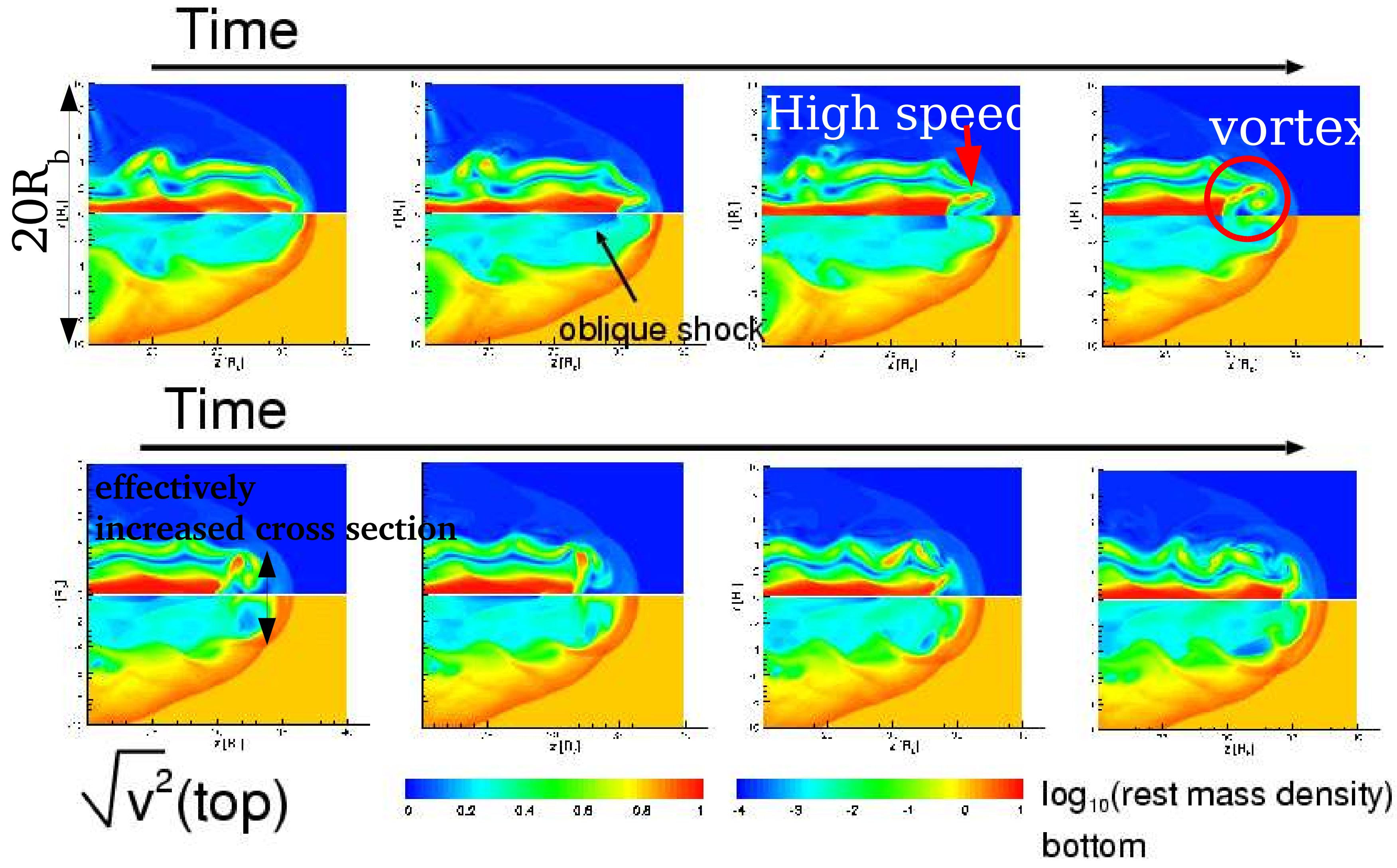
Deceleration phase observed in all cases.

The jet with small v_j^{1D} effectively decelerates.

The position of the terminal Mach shock oscillates in time.

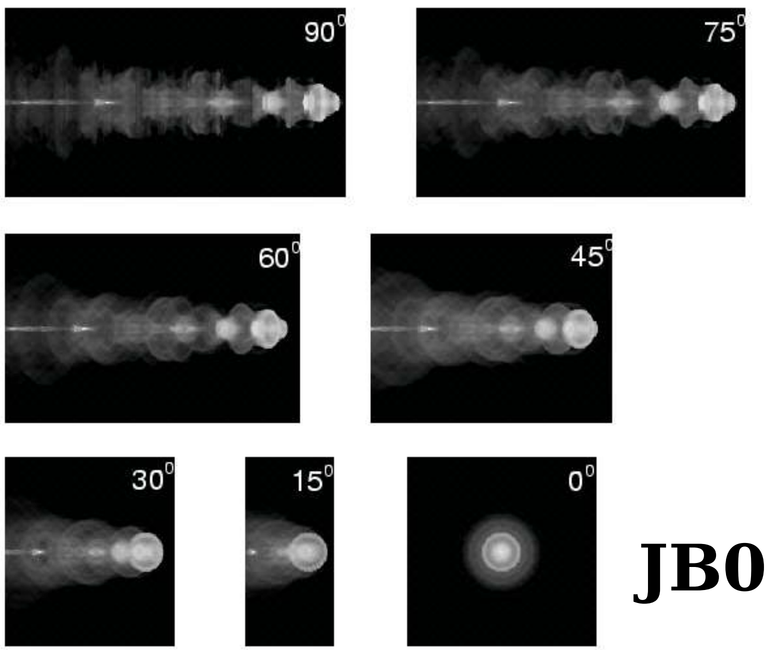
Why decelerating ?

formation and separation of vortices

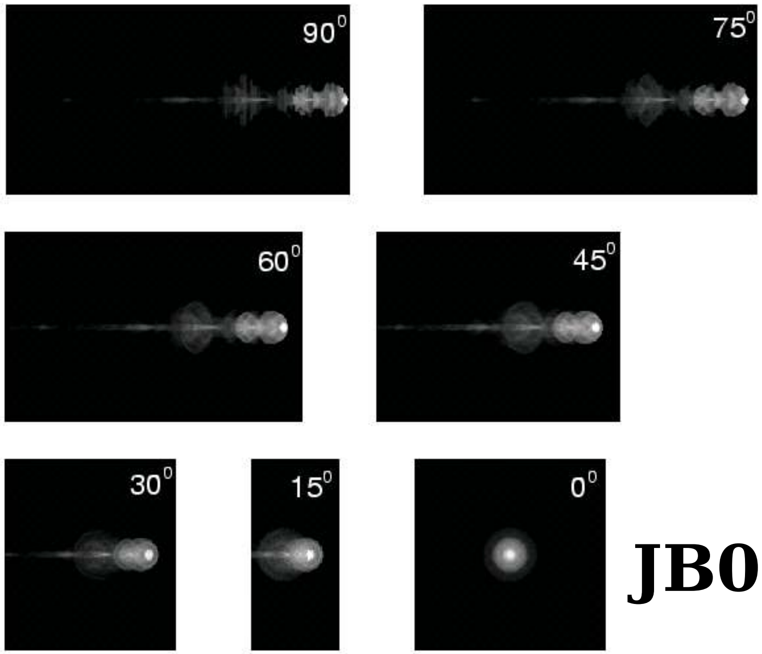


The gas through an oblique shock at the end of the jet becomes a fast flow of back flows

Synchrotron map



JB02



JB04

Extended emissivity

localized emissivity

Synchrotron emissivity : Power $\propto fpB^{1+\alpha}$
(f:fraction of beam gas, p:pressure,
B: magnetic field)
$P \sim B^2$ (equipartition), $\alpha = 0.6$

2D Simulations Summary

We performed long-term numerical simulations of very light relativistic jet propagation.

- We found the exsistence of “third flow” which affects the outer shape, dynamics, and morphlogy of jets, although the appearance depends on the boundary condition.

- The deceleration phase commonly occurs. Especially, the lighter jet strongly decelerates.
    - 0.2c is a critical propagation velocity
        - extended outer shape (Cygnus A)
        - cylinder like outer shape (3C 452)

2D Simulations Summary cont.

- During deceleration phase, the formation and separation of vortices occurs repeatedly.

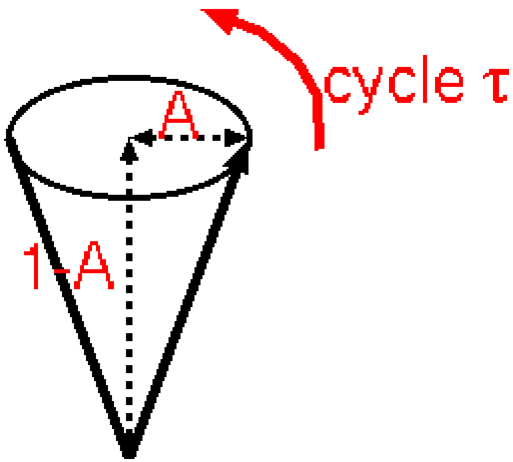
When a vortex grows, the head of the jet decelerates effectively due to increasing cross section to the jet beam.

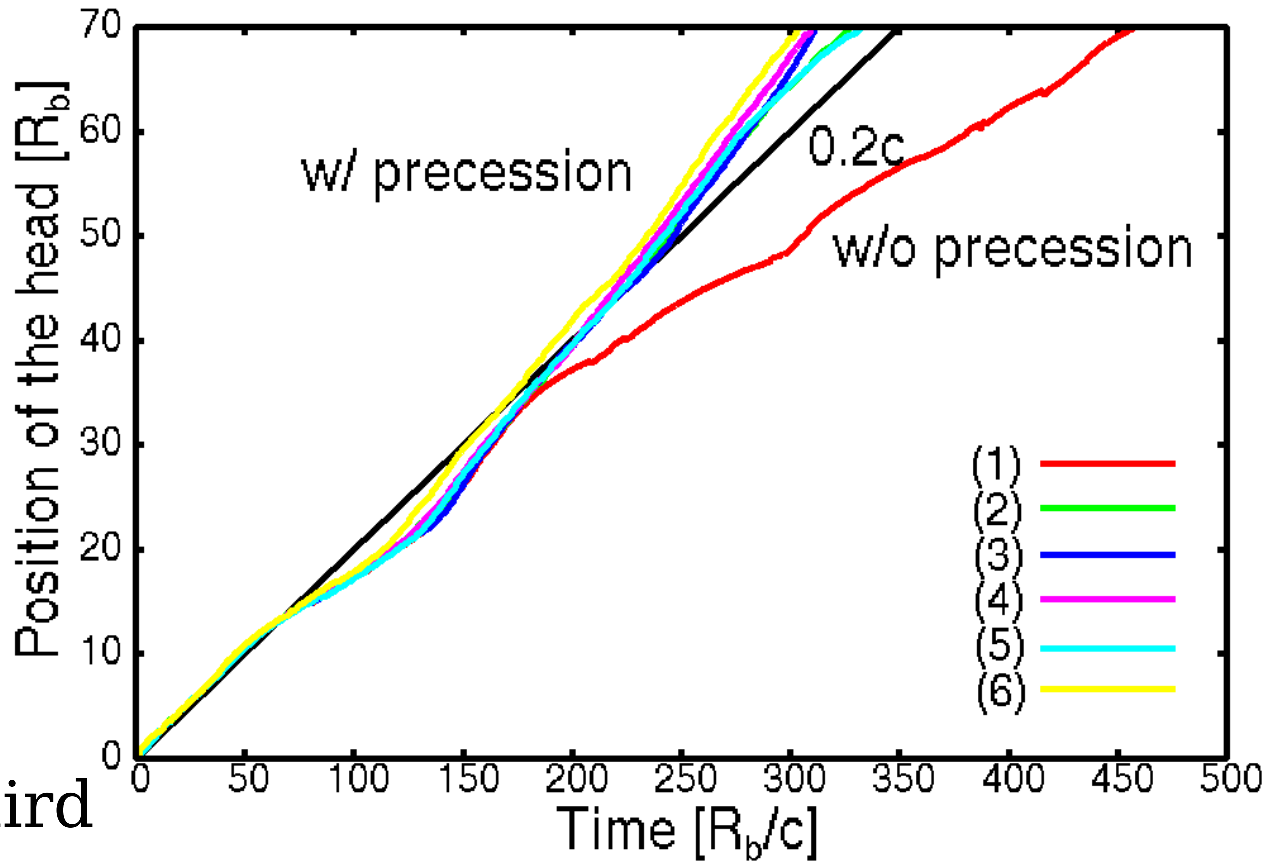
Vortex separation ==> secondary hot spot ?

- The jet which has a number of vortices shows extended emissivity.

How do these results in the case of the jets with some precession ? ==>3D simulations

No deceleration phase was observed

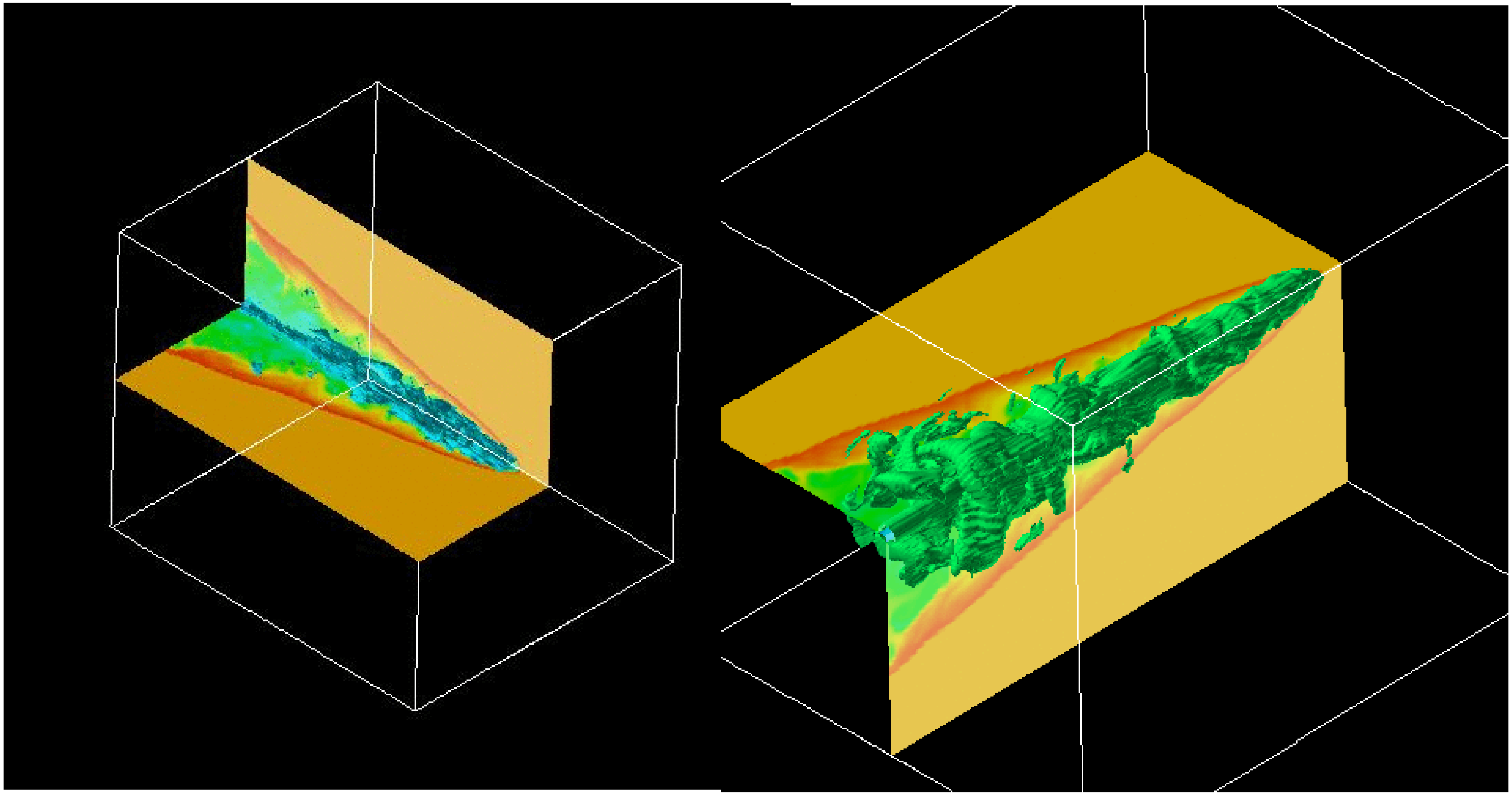




A lack of the third flow, the jets do not decelerate.

(1) A=0.0 τ=---
(2) A=5E-2, τ=1.5
(3) A=1E-2, τ=1.5
(4) A=1.E-2, τ=3.0
(5) A=7.5E-2, τ=1.5
(6) A=1E-2, τ=5.0

The "back flow" also has an angular momentum in large scale



Summary (3D simulations)

- The largest scale 3D calculations have just begun.
- The jets with some precession do not have deceleration phase in current propagation distance for wihch axicymmetric jet begins to decelerate.
- The back flow has helical structure since injected jet has some preseccion.
- Wide range of the parameter sapce and laeger computational domain are necessary for the next step.

Thank you for your attention.