BENDING THE WAY OF PROTOSTELLAR JETS

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Starting point is the existence of a relative motion between the jet source and the local insterstellar medium.

Combination of source's proper motion and internal motions of the ISM

Typical velocity dispersion of **TTauri** stars $V \sim 1 - 2$ km s^{-1}

Jones & Herbig et al 1979
Hartmann et al 1986

Relative velocity of **Class I** objects $V \leq 2.5$ km s^{-1}
- 4 stars (out of 31) have $V \sim 7$ km s^{-1}

Covey et al ApJ 2006

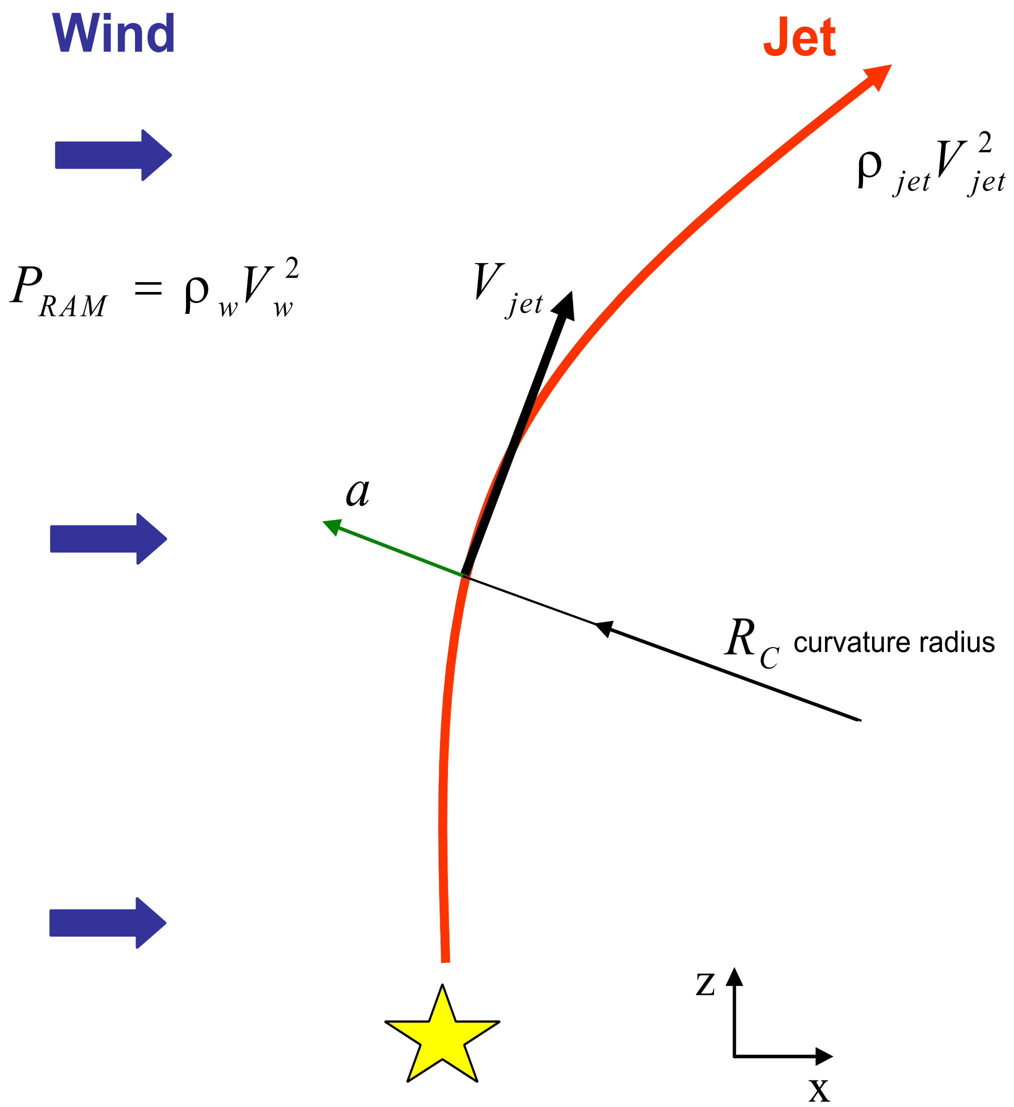
Many cases with faster relative velocities 5 - 20 km s^{-1}

Alcala et al 1997
O'Dell 1994
Bally et al 2000 & 2001
Davis et al. 2008
Goodman et al 2004

Generally relative velocities ~ 1 - 20 km s^{-1} are possible

What are the effects on the outflows?

Relative motion → cross wind on the jet



Wind is generallly not perpendicular to the source

$$(V_{jet})_X \approx V_w$$

$$a \sim 0$$

acceleration

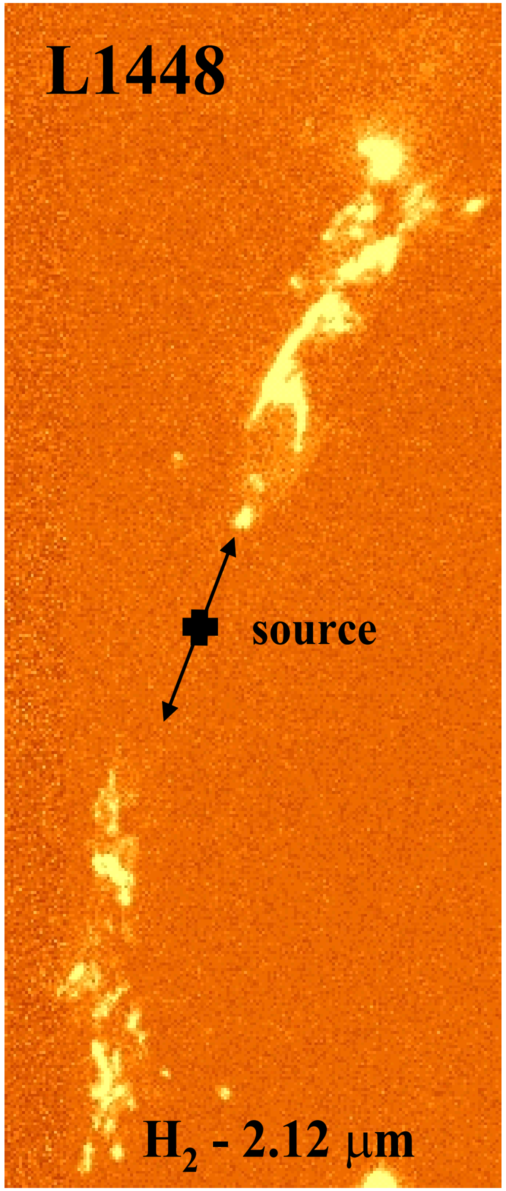
$$a \sim \frac{V_{jet}^2}{R_C}$$

jet-wind interface is Rayleigh-Taylor unstable

- Balsara & Norman 1992 for conditions relevant to extragalactic sources.

- Similar to cloud destruction by winds (e.g. Marcolini et al. 2005)

Curved Protostellar jets



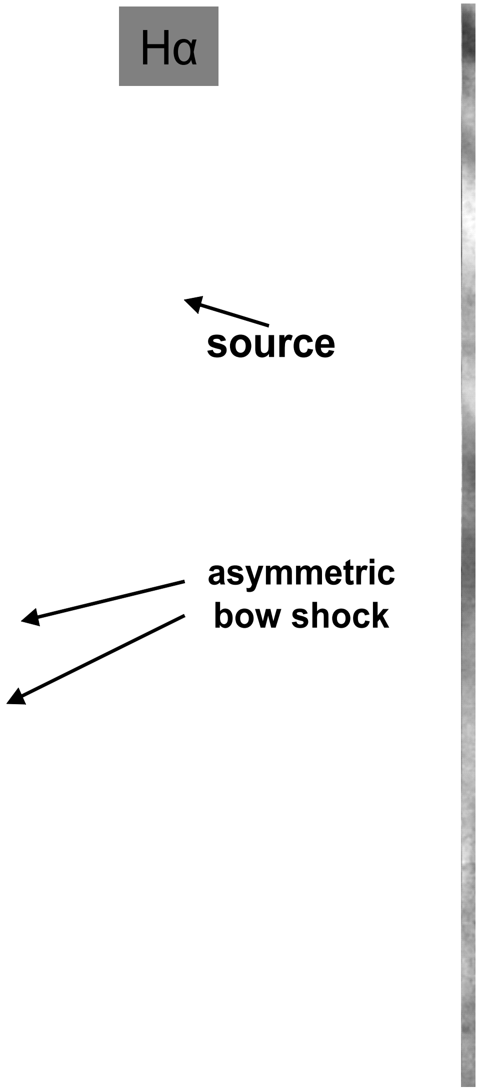
Davis & Smith 1995

Do we see bent protostellar jets?

Can a "wind" (→ relative velocity) curve the jets?

Canto & Raga 1988
Lim & Raga 1998
Masciadri & Raga 2001
Kajdic & Raga 2007

Was the RT instability observed?



Bally & Reipurth 2001

Basic estimates of the RT growth rate

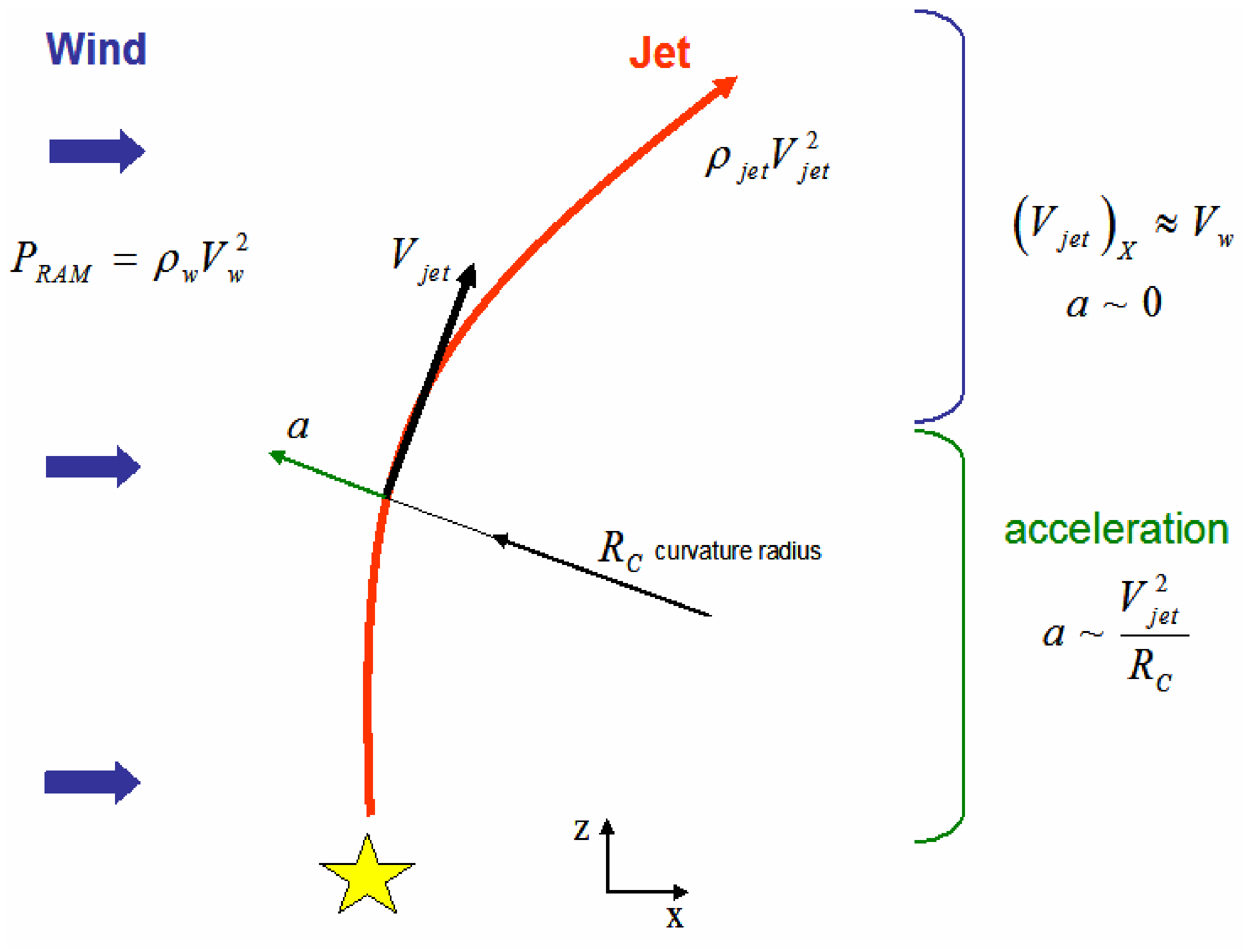
$$\omega_{RTI}\tau_a \sim 2.5\sqrt{A\frac{V_{wind}}{c_s}}\left(\frac{\rho_{jet}}{\rho_{wind}}\right)^{1/4}$$

$\omega_{RTI}\tau_a < 1$ RT has no time to grow

$\omega_{RTI}\tau_a \geq 1$ RT has time to grow

Nominal values:

- $V_{jet} \sim 100$ km s^{-1}
- $r_{jet} \sim 50$ AU
- $V_{wind} \sim 1-10$ km s^{-1}
- $c_s \sim 10$ km s^{-1}
- $\frac{\rho_{jet}}{\rho_{wind}} \sim 10$
- $A \sim 1$



$$\omega_{RTI}\tau_a \sim 1.4 - 4.4$$

Simulate fast wind case to show a well developed RT

Simulations of curved jets

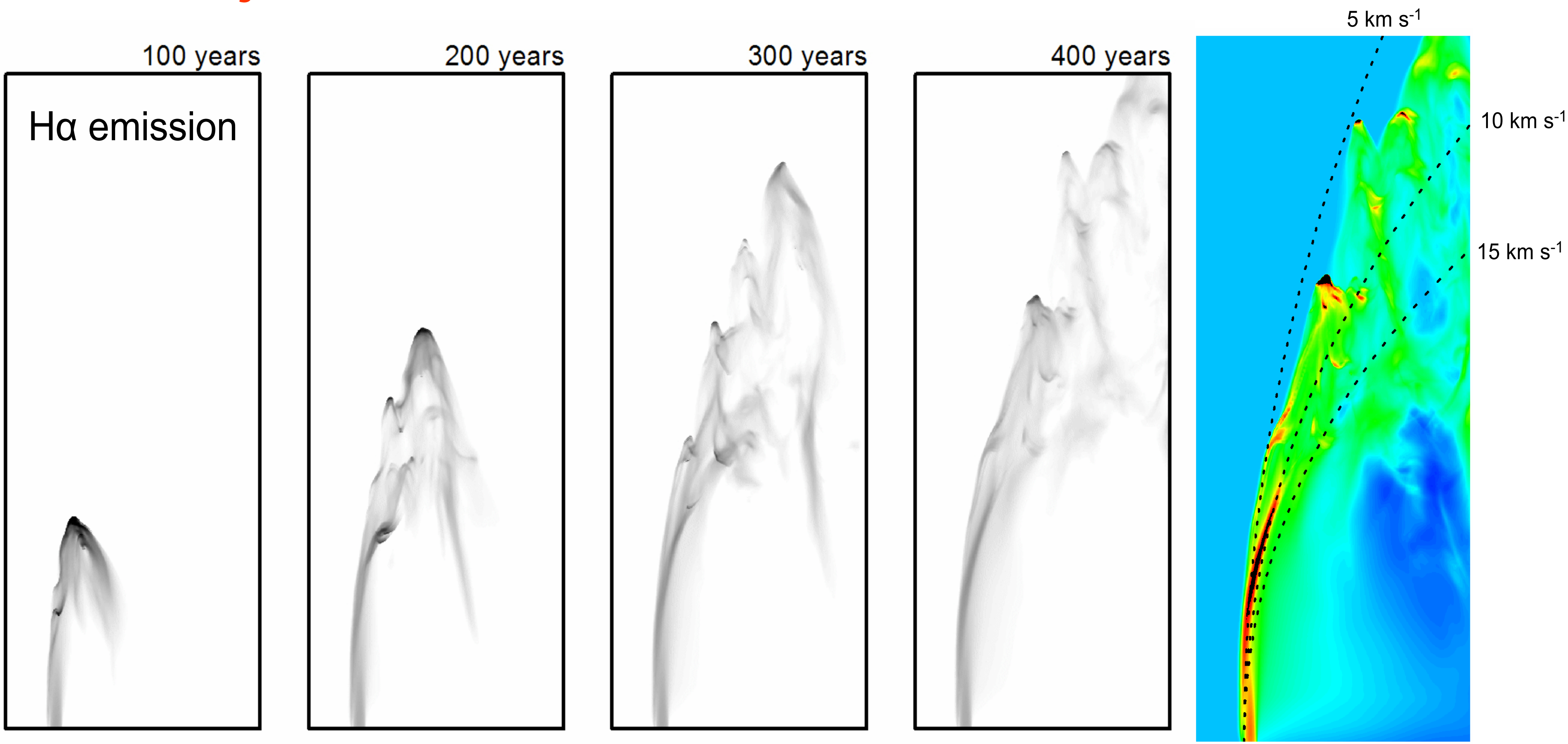
Nominal values for the simulations

$v_{jet} = 100$ km/s ; $n_{jet} = 1000$ cm^{-3}

$v_{wind} = 25$ km/s ; $n_{wind} = 100$ cm^{-3}

animation

Uniform jet and wind

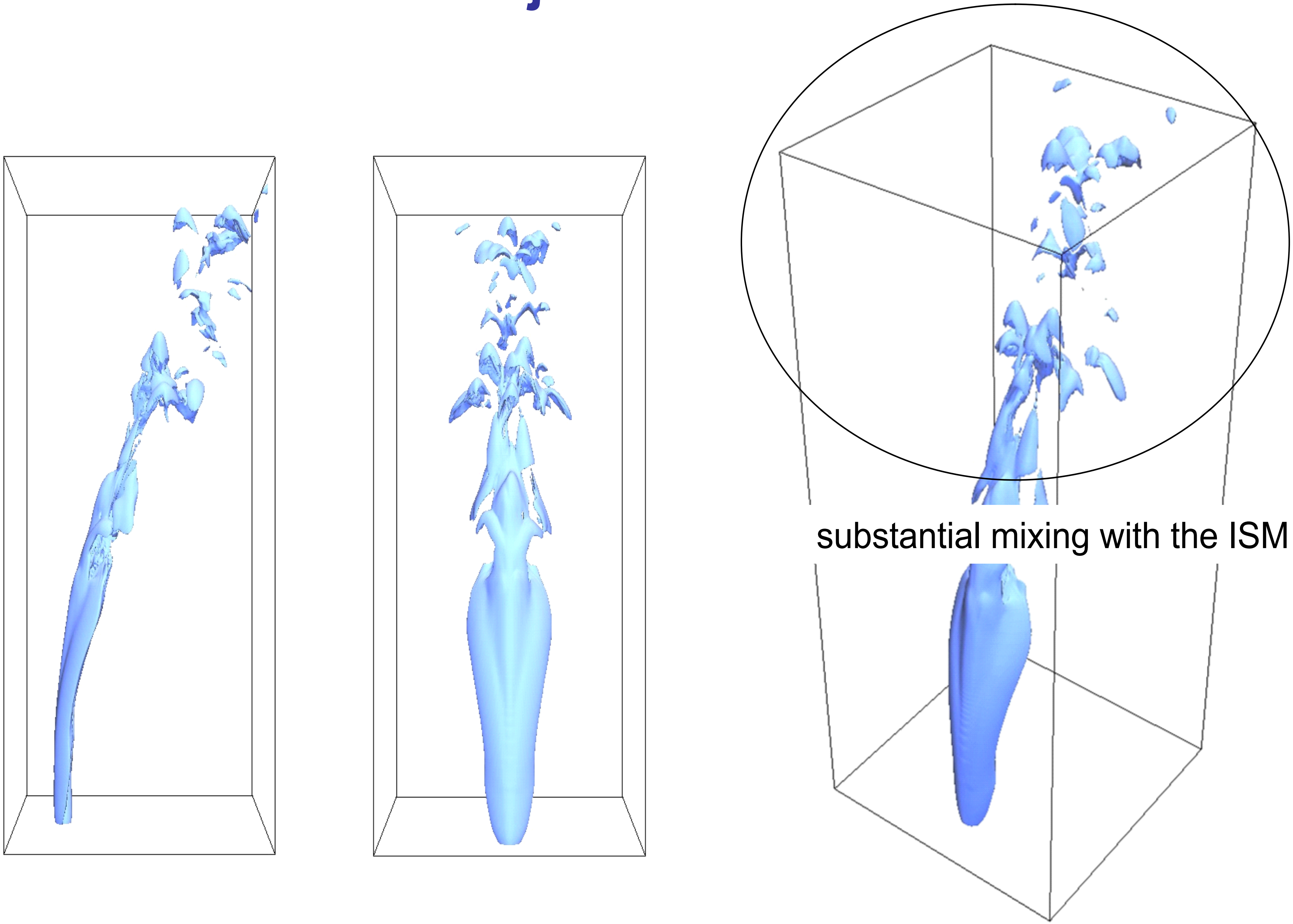


domain 2004x2004x4864 AU (resolution: 4 AU)

Jet path from analytical model by Canto & Raga 1995

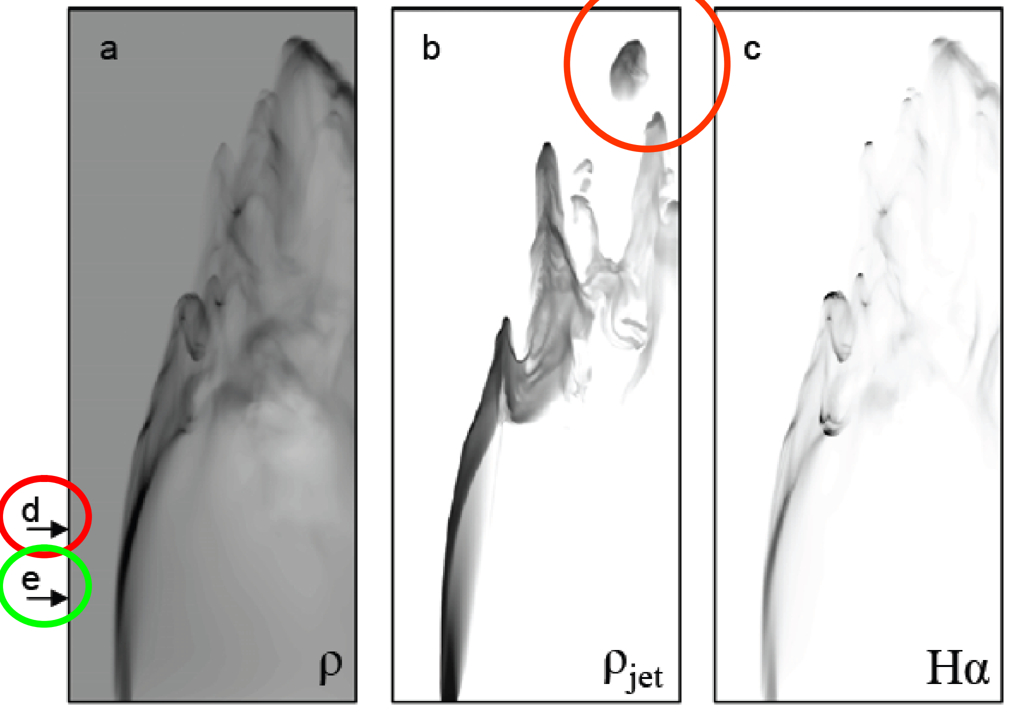
Ciardi et al. 2008

Simulations of curved jets - 3D views



Rayleigh-Taylor instability in curved jets

NON-ROTATING

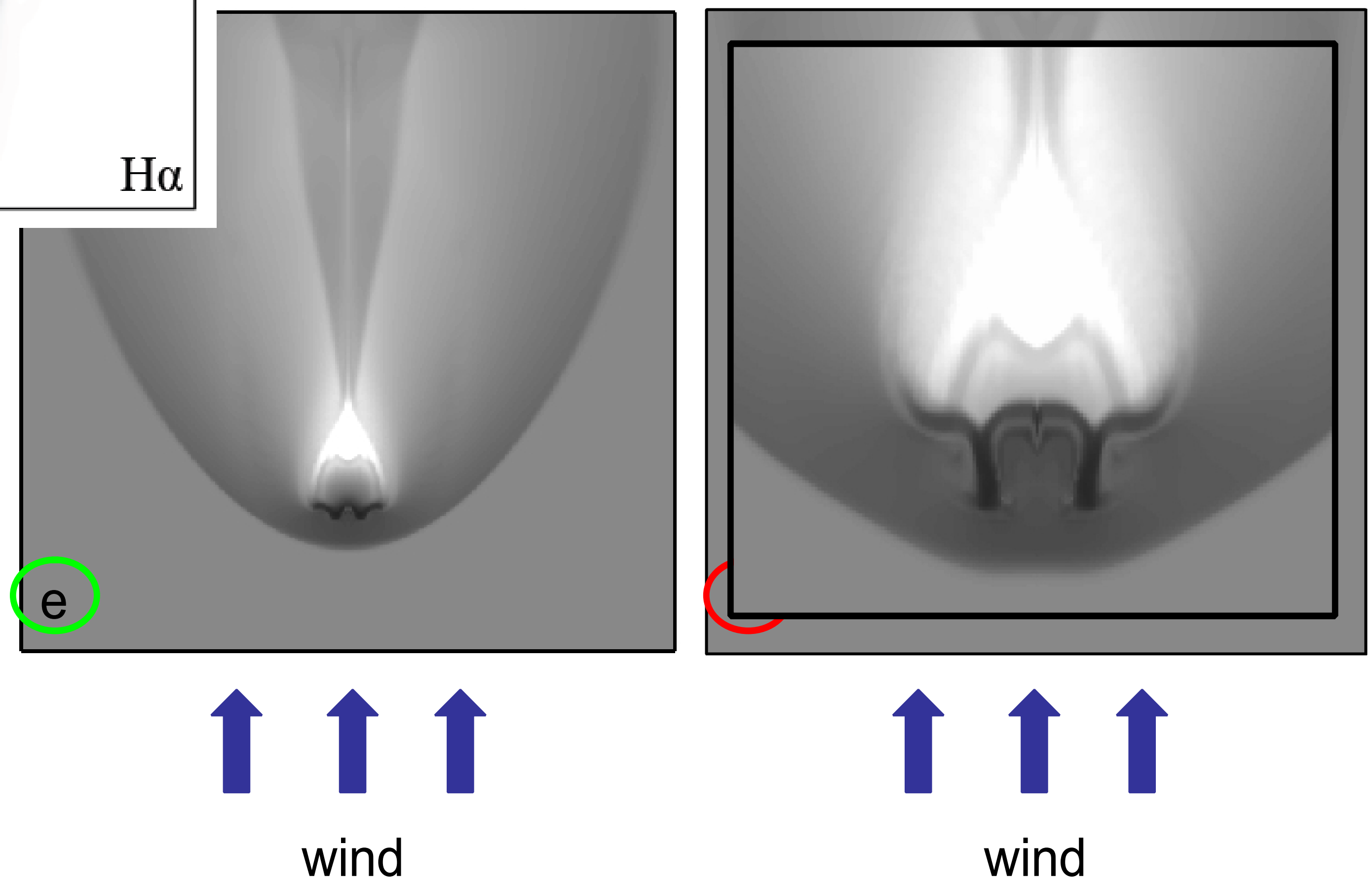


For the simulated jets

$$\tau_{RTI} \leq \tau_a \sim 150 \text{ years}$$

and RTI should have time to develop.

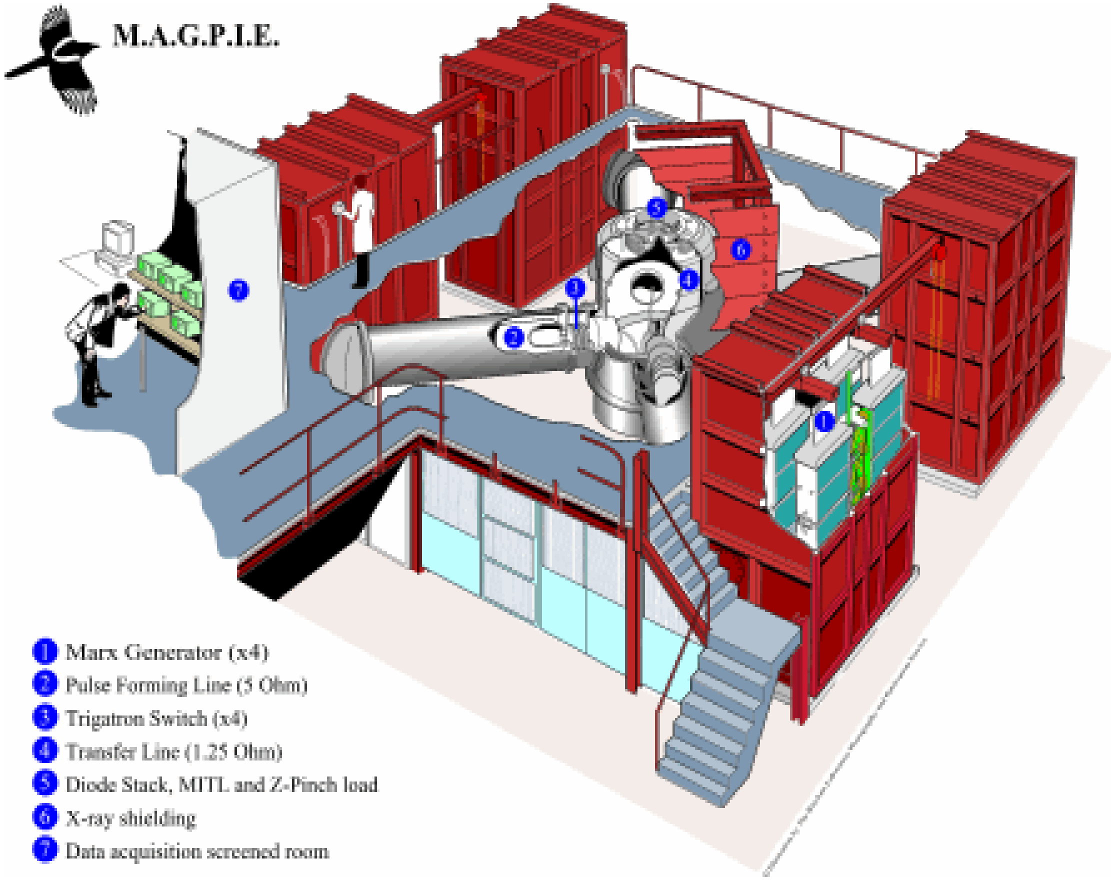
Slices in x-y plane showing atomic number density at points e and d of the flow.



Jet is disrupted by the RT.

WELL, THESE ARE SIMULATIONS.
BUT DOES IT REALLY HAPPEN?

Testing astrophysical models using laboratory experiments



Currents ~ Mega Ampere

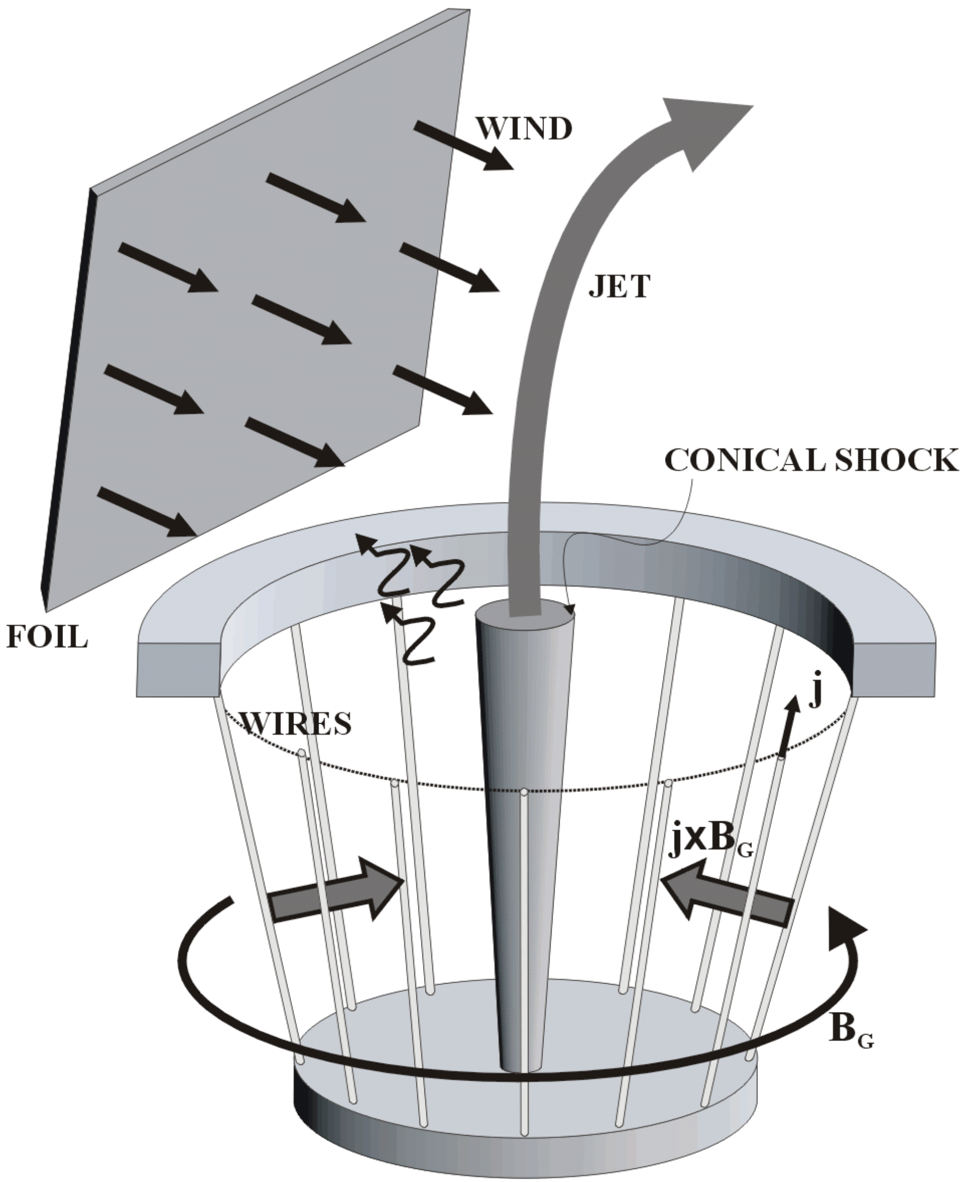
Pulse duration of 240 ns

Energy ~ 300 kJ

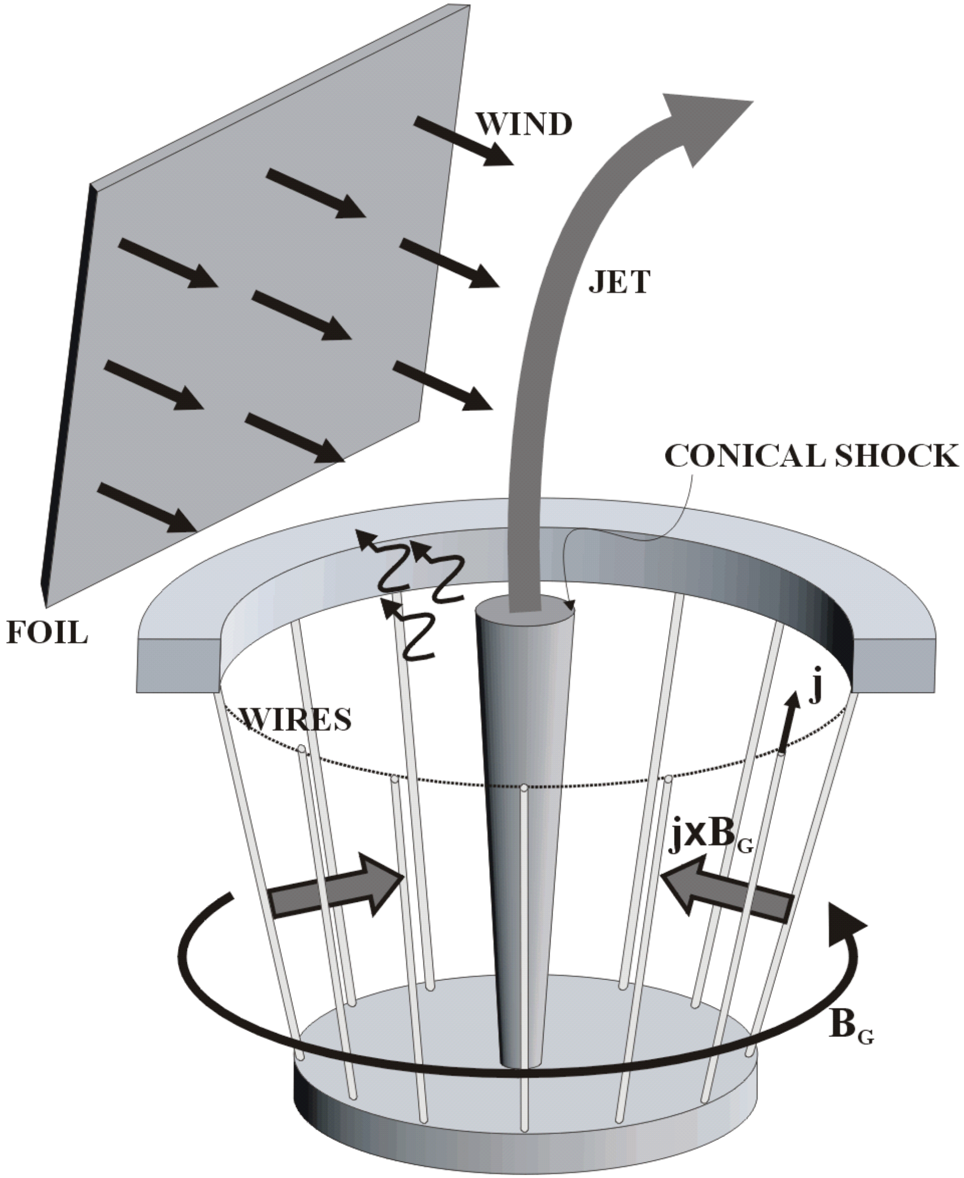
Characteristic powers ~ Tera Watts

Plasma volume ~ cubic centimetre

Testing astrophysical models using laboratory experiments



Testing astrophysical models using laboratory experiments

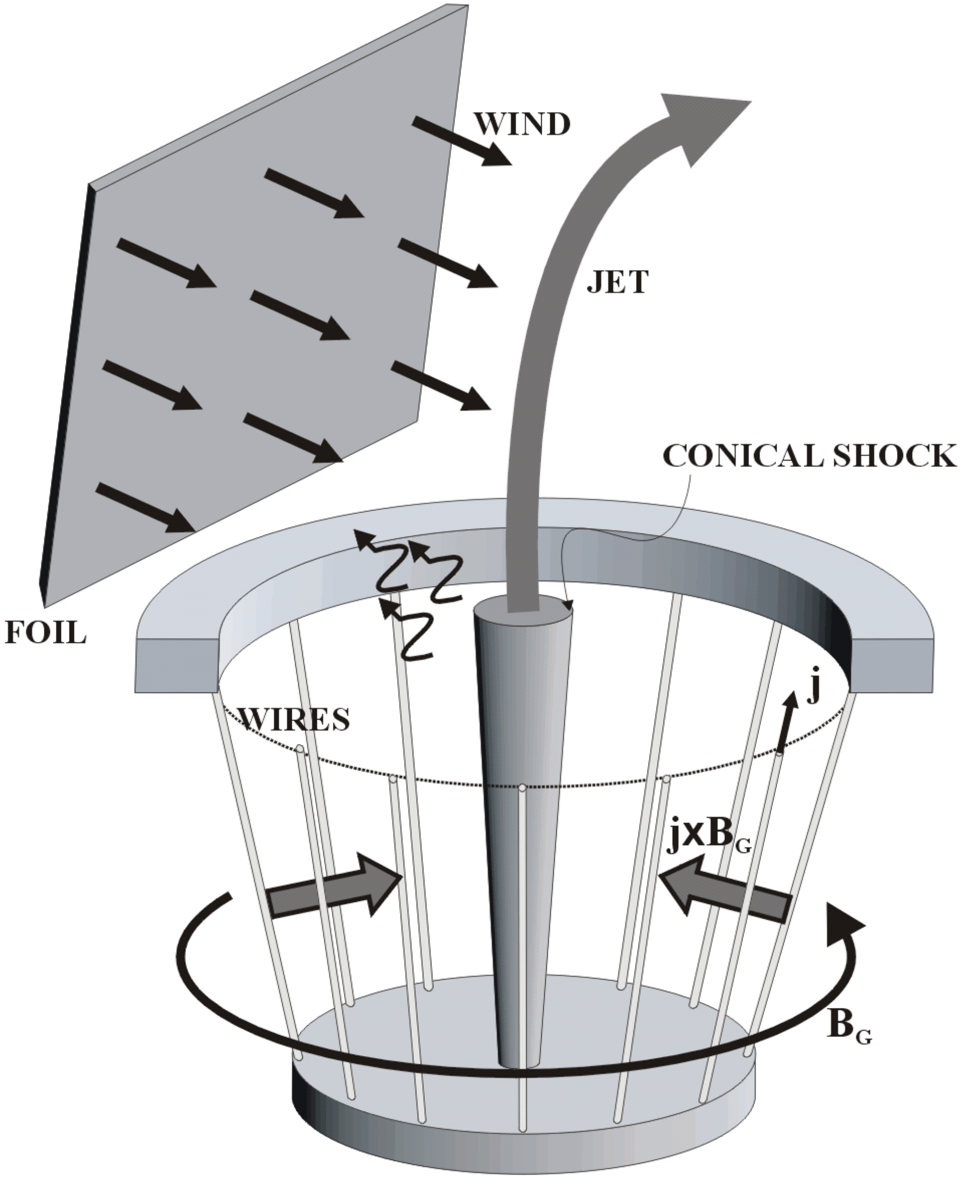


Typical jet and wind parameters:

$$V_{jet} = 100 - 200 \text{ km s}^{-1} \qquad n_{jet} = 10^{18} - 10^{20} \text{ cm}^{-3}$$

$$V_{wind} = 30 - 50 \text{ km s}^{-1} \qquad n_{wind} = 10^{18} - 10^{19} \text{ cm}^{-3}$$

Testing astrophysical models using laboratory experiments



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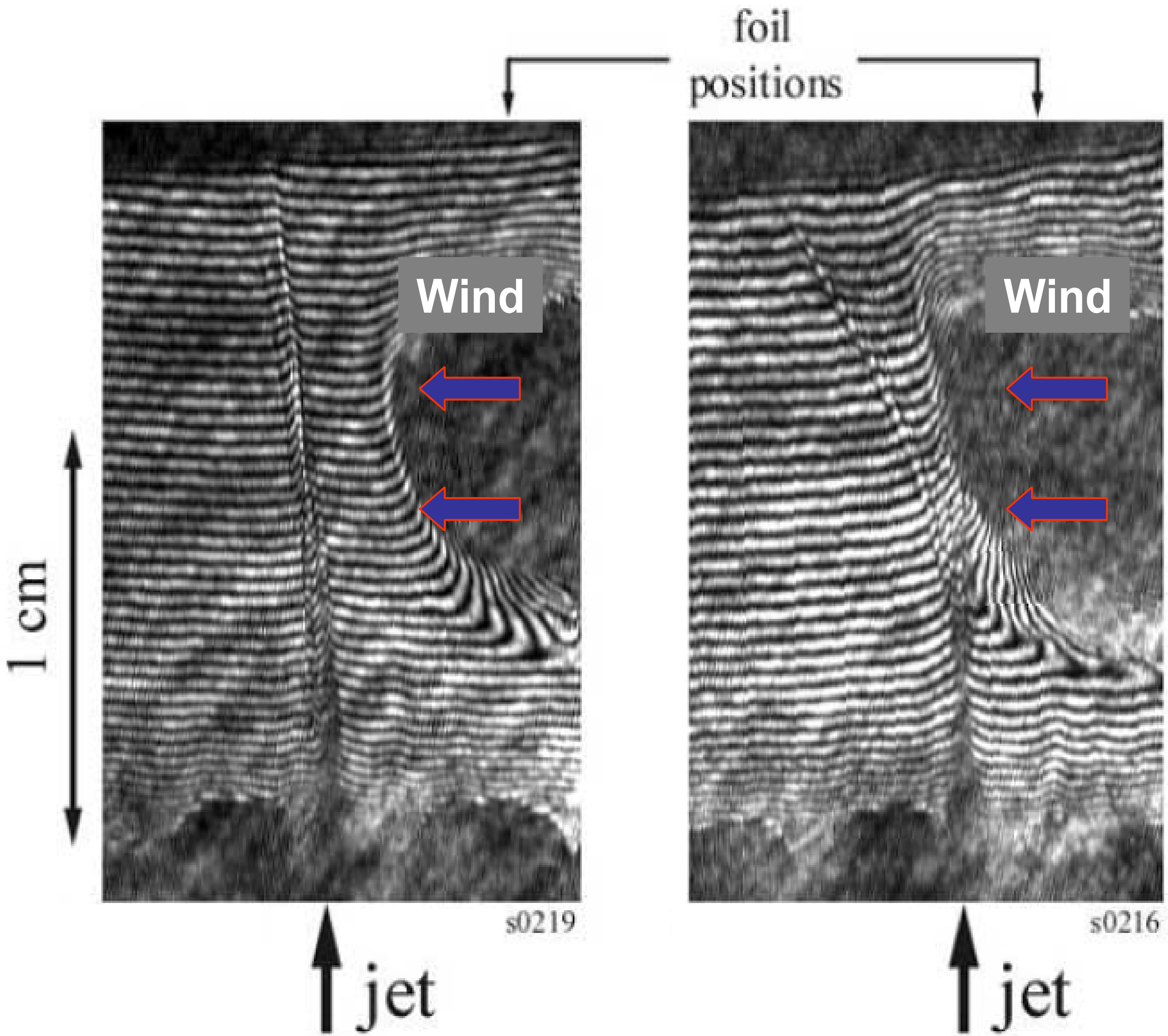
The jets are *radiatively cooled* and :

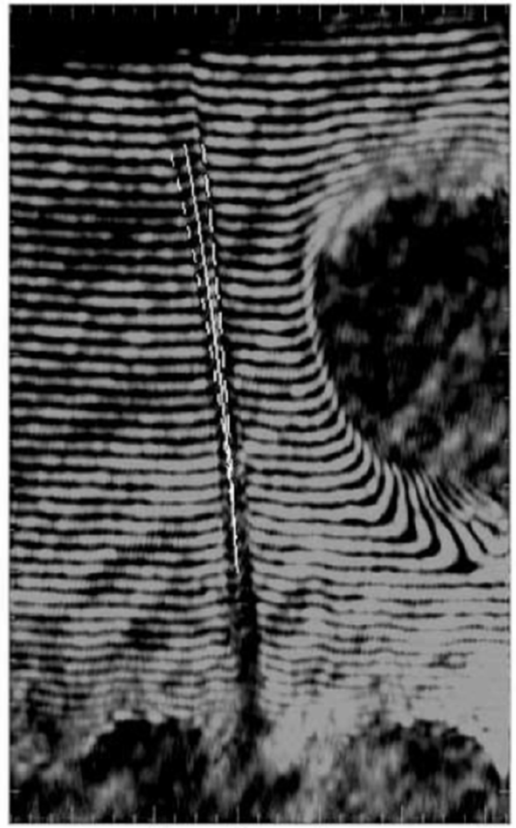
$$\text{Mach} > 20 \qquad \text{Re} > 10^4 \qquad \text{Pe} > 50 - 100$$

Ratios: $$\frac{V_{jet}}{V_{wind}} = 2 - 6 \qquad \frac{n_{jet}}{n_{wind}} = 0.1 - 100$$

Laboratory jets are scaled-down, astrophysically relevant flows in a regime of interest to HH jets.

Curved laboratory jets - 1



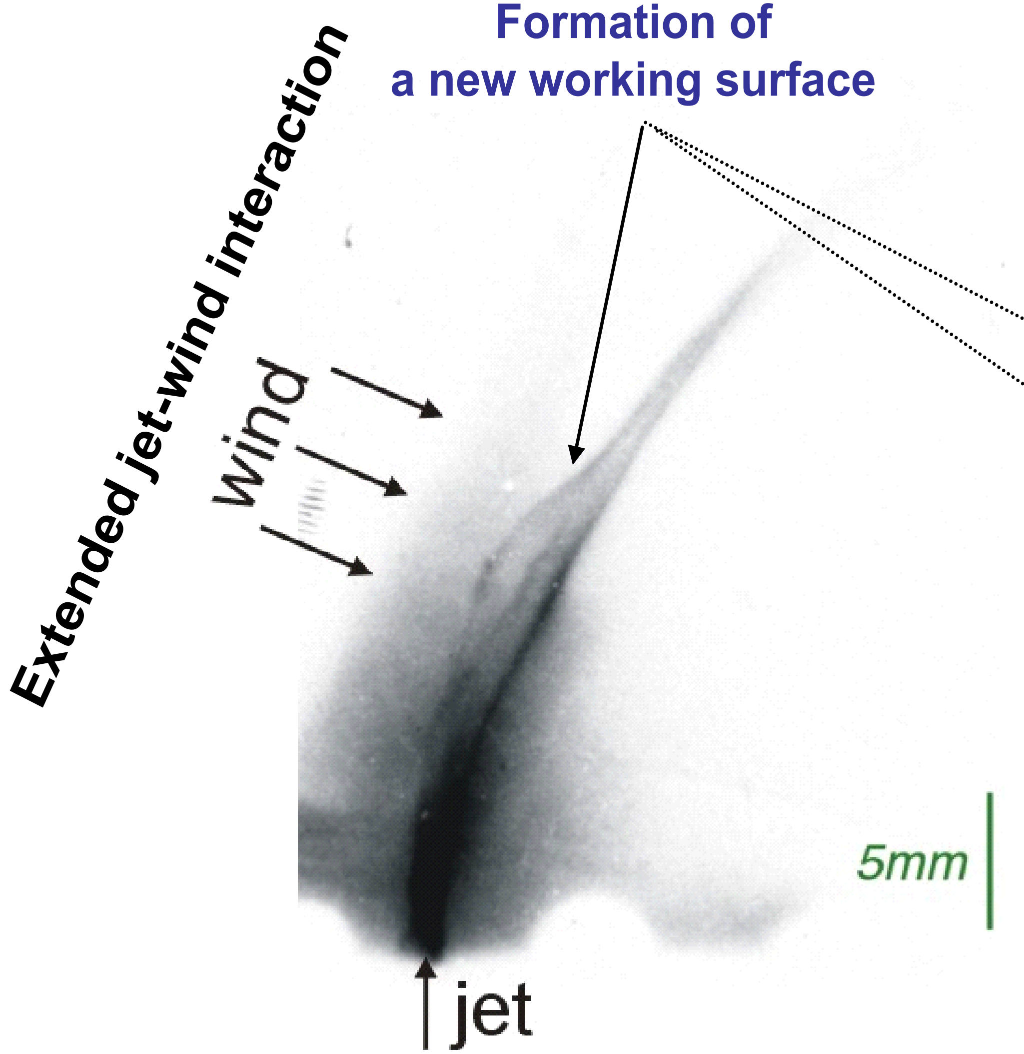


Jet path from analytical model by Canto & Raga 1995

Lebedev et al. 2004

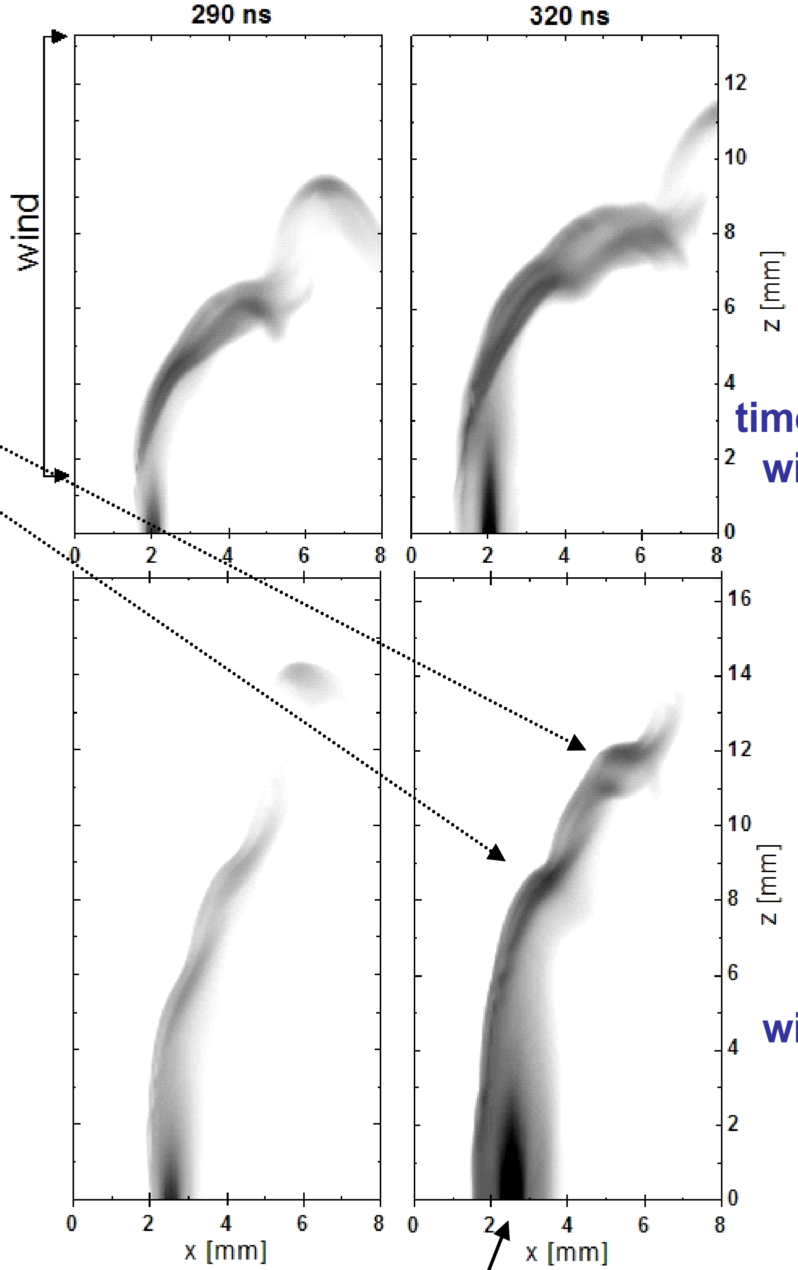
Hypersonic jets can be really curved by a wind.

Curved laboratory jets - 2



Experimental XUV image

Simulated XUV emission



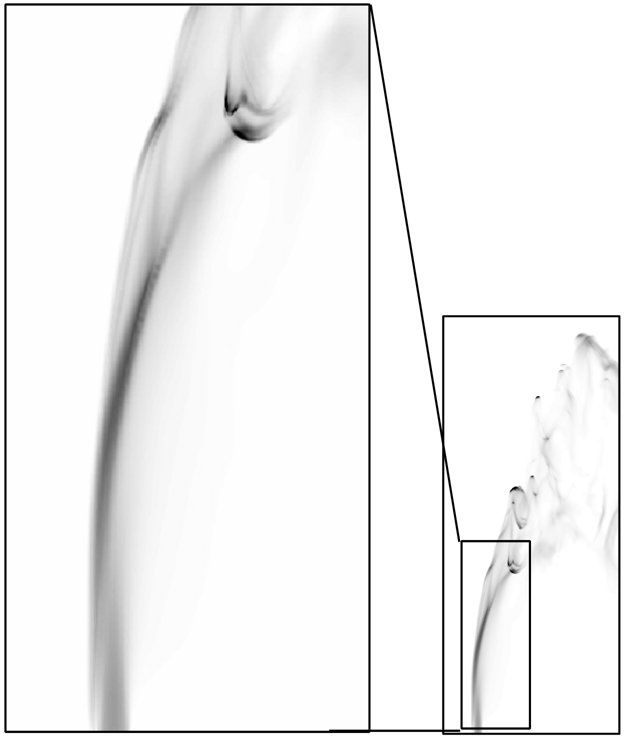
Jet fluxes taken from 2D axisymmetric resistive MHD simulations of conical arrays

Ciardi et al. 2008

We can bend it, but can we break it?

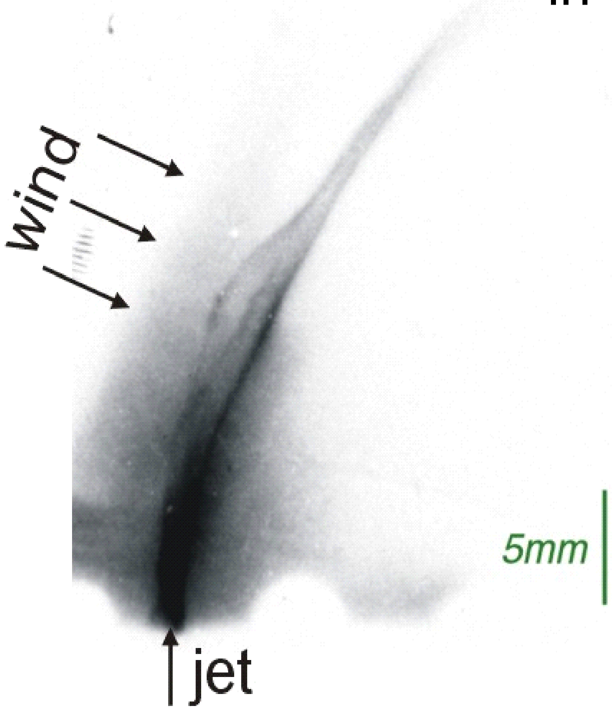
Formation of new working surfaces suggest the RT instability may be growing.

With the RTI emission shifts to the inside of the jet



simulated protostellar jet

Are we seeing the RTI in the laboratory jet?

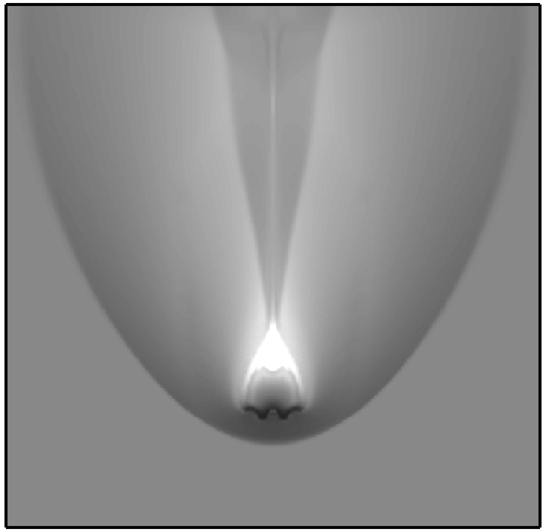


Growth time for the laboratory jet:

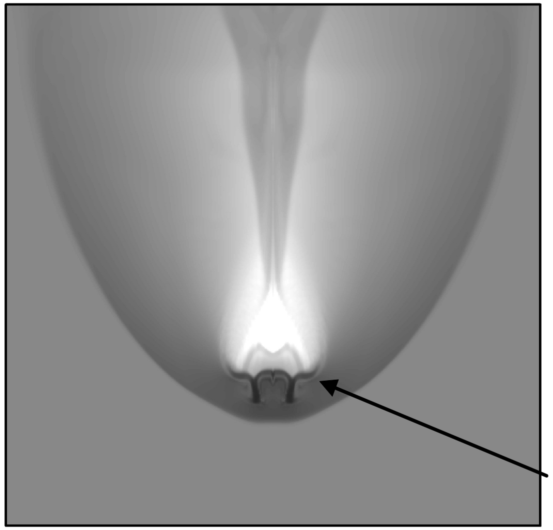
$$\tau_{RTI} \sim 150 \text{ ns} \sim \text{experimental time}$$

Need experiments with even longer interaction times

Mitigating the RT instability: rotating curved jets

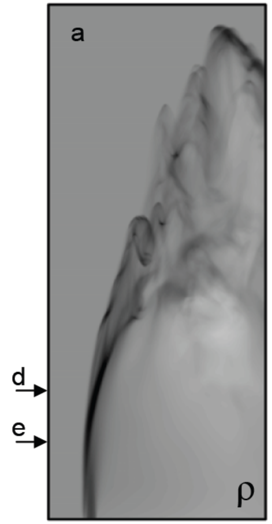


non-rotating

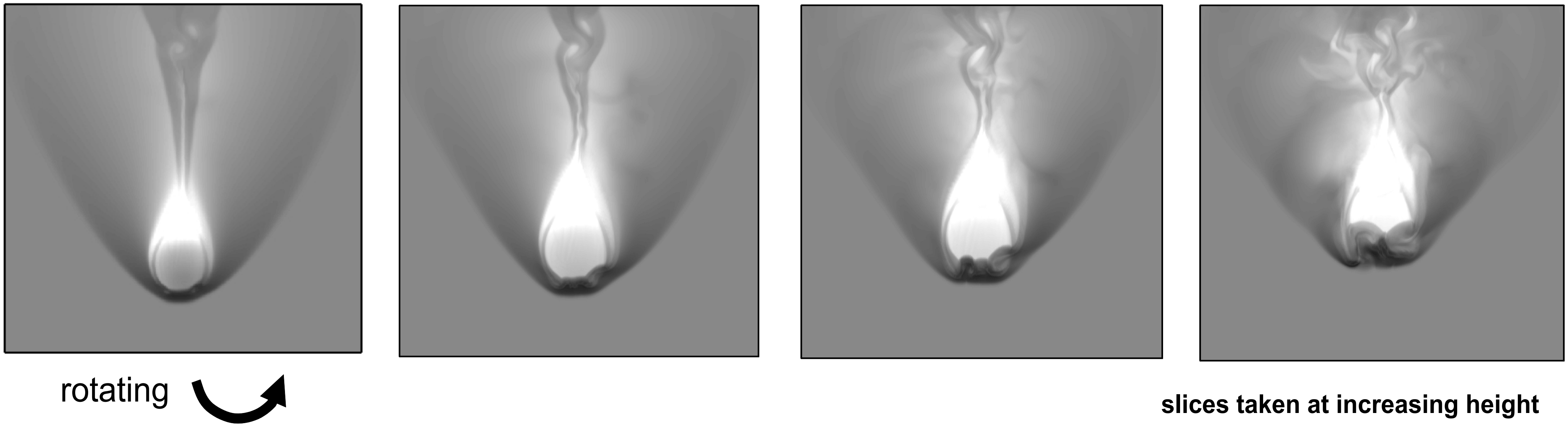


RT should be sheared by rotation.

MHD jet launching models and observations indicated jet rotation is there.



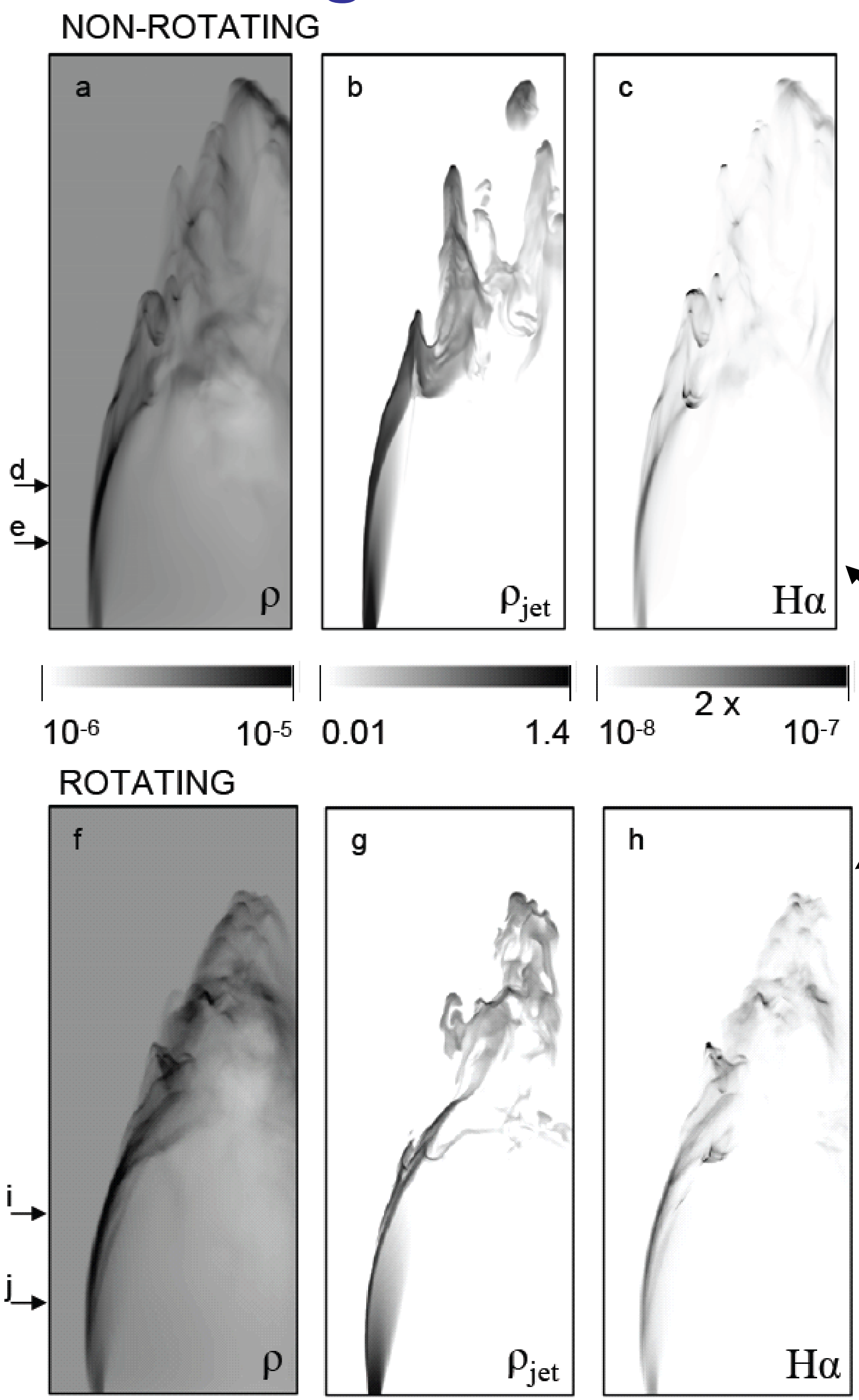
Solid body, subsonic jet rotation.



rotating

slices taken at increasing height

Rotating and non-rotating curved jets



Rotation shears the RTI modes.

Emission is confined to the upwind side.

Jet body disrupted by combined RT and KH.

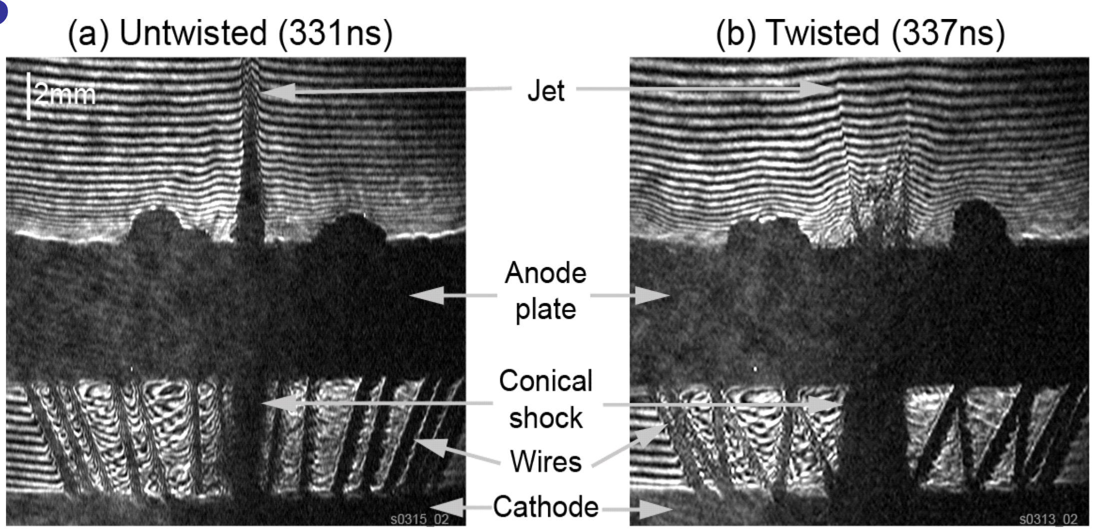
Rotating "laminar" jet propagates further.

There may be an observational way of discriminating between those two.

We can test the prediction of the effects of rotation in the laboratory.

Rotating laboratory jets

Twisted conical arrays produce rotating laboratory jets.



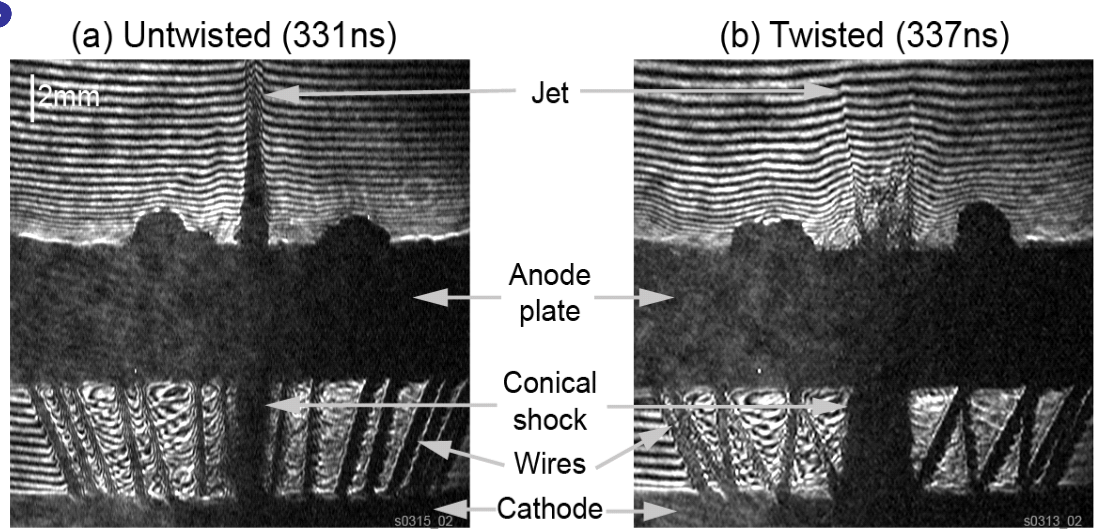
Ampleford et al Phys. Rev. Lett. 2008

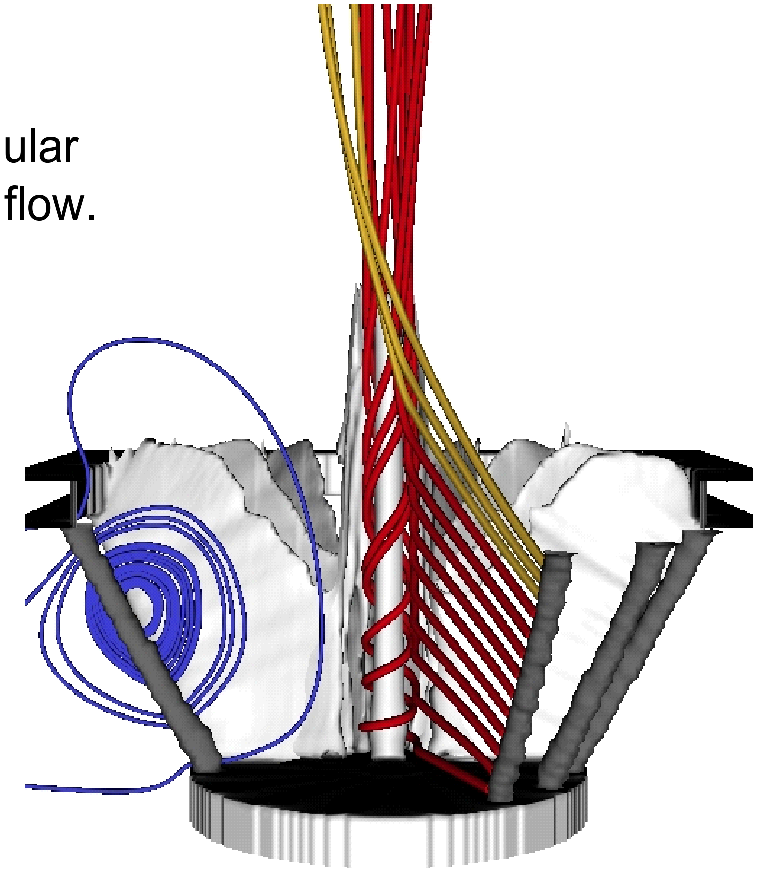
Rotating laboratory jets

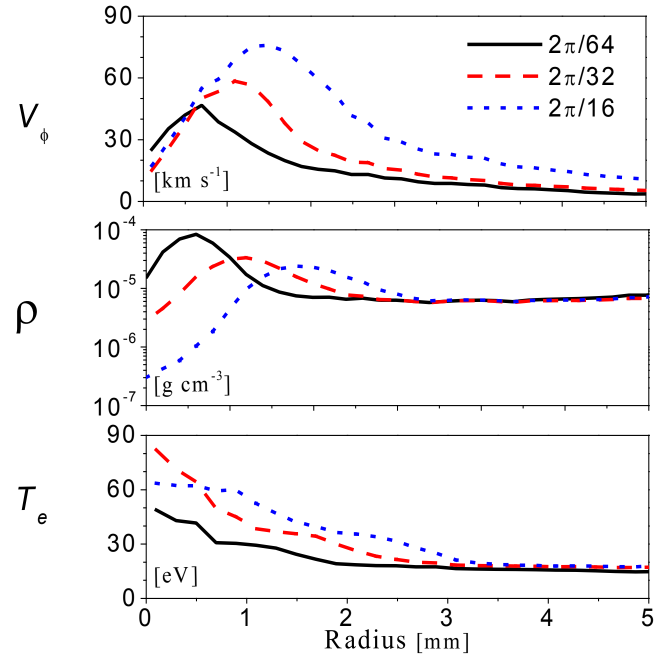
Twisted conical arrays produce rotating laboratory jets.

Measured rotation velocity ~ 10-20 % of axial velocity

Control over the level of angular momentum introduced in the flow.
- Proof-of-principle -



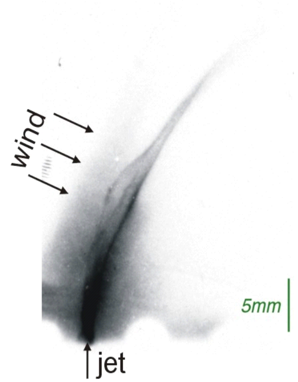


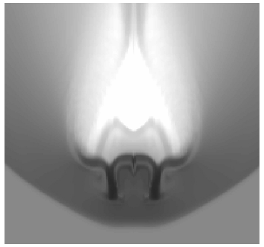


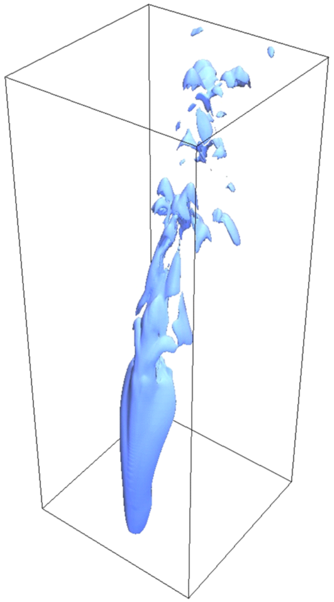
Ampleford et al Phys. Rev. Lett. 2008

Summary

Jets can be curved by a wind
→ experimental confirmation







Curved protostellar jets are unstable to RT
→ development of RT produces "clumpy" jets
→ uniform, steady jet and wind → NO ejection variability

RT instability can be mitigated by rotation
→ it can be tested in the laboratory using rotating jets
→ could give a signature of rotation

Starting point is the existence of a relative motion between the jet source (protostar or TTauri) and the local Insterstellar Medium.

Combination of source's proper motion and internal motions of the ISM

Relative radial velocity of protostars with respect to the local ISM gas:
- Relative velocity of **Class I** objects $V \leq 2.5$ km s^{-1}
- 4 stars (out of 31) have $V \sim 7$ km s^{-1}

Covey et al ApJ 2006

Typical radial dispersion of **TTauri** stars $V \sim 1 - 2$ km s^{-1}

Jones & Herbig et al 1979
Hartmann et al 1986

TTauri stars observed far from molecular clouds imply $V \sim 6$ km s^{-1}

Alcala et al 1997

Widespread outlfow from the Orion Nebula core, speed ~ 20 km s^{-1}.

O'Dell 1994; Bally et al 2000

In NGC 1333 & Perseus star motion relative to ISM ~ 10 km s^{-1}

Bally et al 2001; Davis et al 2008

Parsec scale flow from PV Cep associated with a star V ~ 20 km/s

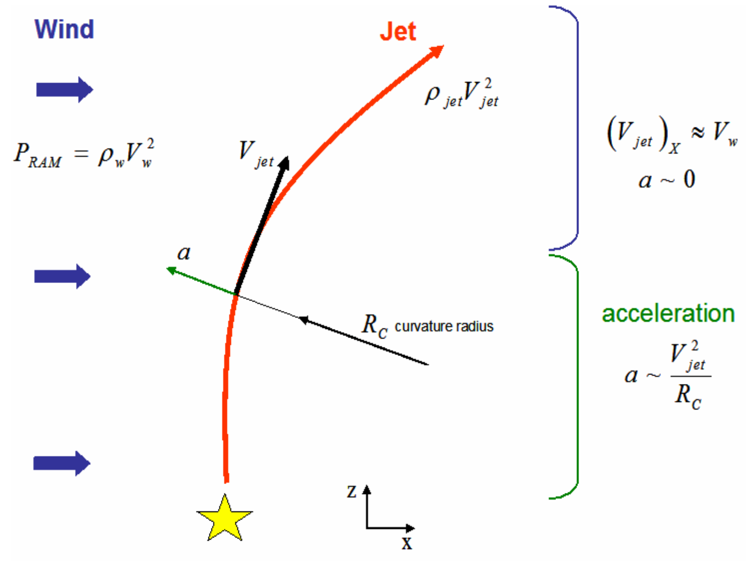
Goodman et al. 2004

Basic estimates

Analytical model for an isothermal jet (and no shocks) gives for radius of curvature (Canto & Raga 1995):

$$R_C = \frac{r_{jet} V_{jet}}{c_s} \left(\frac{\rho_{jet} V_{jet}^2}{\rho_{wind} V_{wind}^2} \right)^{1/2}$$

Time jet is accelerated: $\tau_a = \frac{r_{jet}}{c_s} \sqrt{\frac{\rho_{jet}}{\rho_{wind}}}$



RT growth rate (incompressible): $\omega_{RTI} \approx 2.5 A^{1/2} \left(\frac{\rho_w}{\rho_j} \right)^{1/4} \frac{(c_s V_w)^{1/2}}{r_j}$

Nominal values:

$V_{jet} \sim 100$ km s^{-1}

$r_{jet} \sim 50$ AU

$V_{wind} \sim 1 - 10$ km s^{-1}

$c_s \sim 10$ km s^{-1}

$\frac{\rho_{jet}}{\rho_{wind}} \sim 10$

$A \sim 1$

$$\omega_{RTI} \tau_a \sim 2.5 \sqrt{A \frac{V_{wind}}{c_s}} \left(\frac{\rho_{jet}}{\rho_{wind}} \right)^{1/4}$$

$\omega_{RTI} \tau_a < 1$ RT has no time to grow

$\omega_{RTI} \tau_a \geq 1$ RT has time to grow

$\omega_{RTI} \tau_a \sim 1.4 - 4.4$ Fast wind case RT should be well developed

Summary

Jets can be curved by a wind → experimental confirmation

Development of RT instability in curved HH jets produces "knotty" jets
→ starting with a uniform jet and wind

RT instability is mitigated by rotation
→ It can be tested in the laboratory using rotating jets

Need to use more "appropriate" rotation profiles
Supersonic rotation (close to source) → subsonic rotation (far from source)

Difficult to model jets with small curvature, which should be the most common.
→ synthetic observations

GORGON: 3D resistive MHD

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

$$\frac{\partial}{\partial t}(\rho \mathbf{v}) + \nabla \cdot (\rho \mathbf{v}\mathbf{v}) = -\nabla (p_i + p_e) + \mathbf{j} \times \mathbf{B}$$

$$\frac{\partial \varepsilon_i}{\partial t} + \nabla \cdot (\varepsilon_i \mathbf{v}) = -p_i \nabla \cdot \mathbf{v} - \nabla \cdot \mathbf{q}_i + \Delta_{ie}$$

$$\frac{\partial \varepsilon_e}{\partial t} + \nabla \cdot (\varepsilon_e \mathbf{v}) = -p_e \nabla \cdot \mathbf{v} - \nabla \cdot \mathbf{q}_e + \eta |\mathbf{j}|^2 - \Lambda + \Delta_{ei}$$

$$\mathbf{B} = \nabla \times \mathbf{A} \qquad \mathbf{E} = -\frac{\partial \mathbf{A}}{\partial t} = \eta \mathbf{j} - \mathbf{v} \times \mathbf{B}$$

$$\frac{\partial^2 \mathbf{A}}{\partial t^2} = -c^2 \nabla \times \nabla \times \mathbf{A} - \frac{\mu_0 c^2}{\eta} \frac{\partial \mathbf{A}}{\partial t} + \frac{\mu_0 c^2}{\eta} \mathbf{v} \times \nabla \times \mathbf{A}$$

Specifically designed for z-pinch simulations where initially > 90% of the computational domain is vacuum.

Single Fluid
Two Temperatures - energy coupling -
Heat conduction
Optically-thin radiation losses (f-f, f-b and b-b)
Braginskii-like transport coefficients

Average ion Thomas-Fermi model → LTE ionization

For the astrophysical simulations: $$\frac{\partial n_{HI}}{\partial t} + \nabla \cdot (n_{HI} \mathbf{v}) = n_e n_{HII} \alpha(T) - n_e n_{HI} C(T) \qquad \frac{n_{OII}}{n_{OI}} \approx \frac{n_{HII}}{n_{HI}}$$

COOLING FUNCTION: collisional excitation, collisional ionization and radiative recombination of hydrogen, and the collisional excitation of O I and O II. CORONAL COOLING > 15000 K