Improved Simulations of Magnetic Fields in Star Formation

and the Unplanned Discharge from the First Hydrostatic Core

Terrence Tricco
terrence.tricco@monash.edu
http://users.monash.edu/~tricco

Daniel Price (Monash)
Matthew Bate (Exeter)

MoCA
Monash Centre for Astrophysics
MONASH University
Science

Numerical Method: SPH
(Smoothed Particle Hydrodynamics)

SPH is well suited for astrophysics because:

- Couples with n-body codes
- Strong conservation properties, very stable
- Inherently adaptive, resolution is where the mass is

SPH is well suited for star formation because:

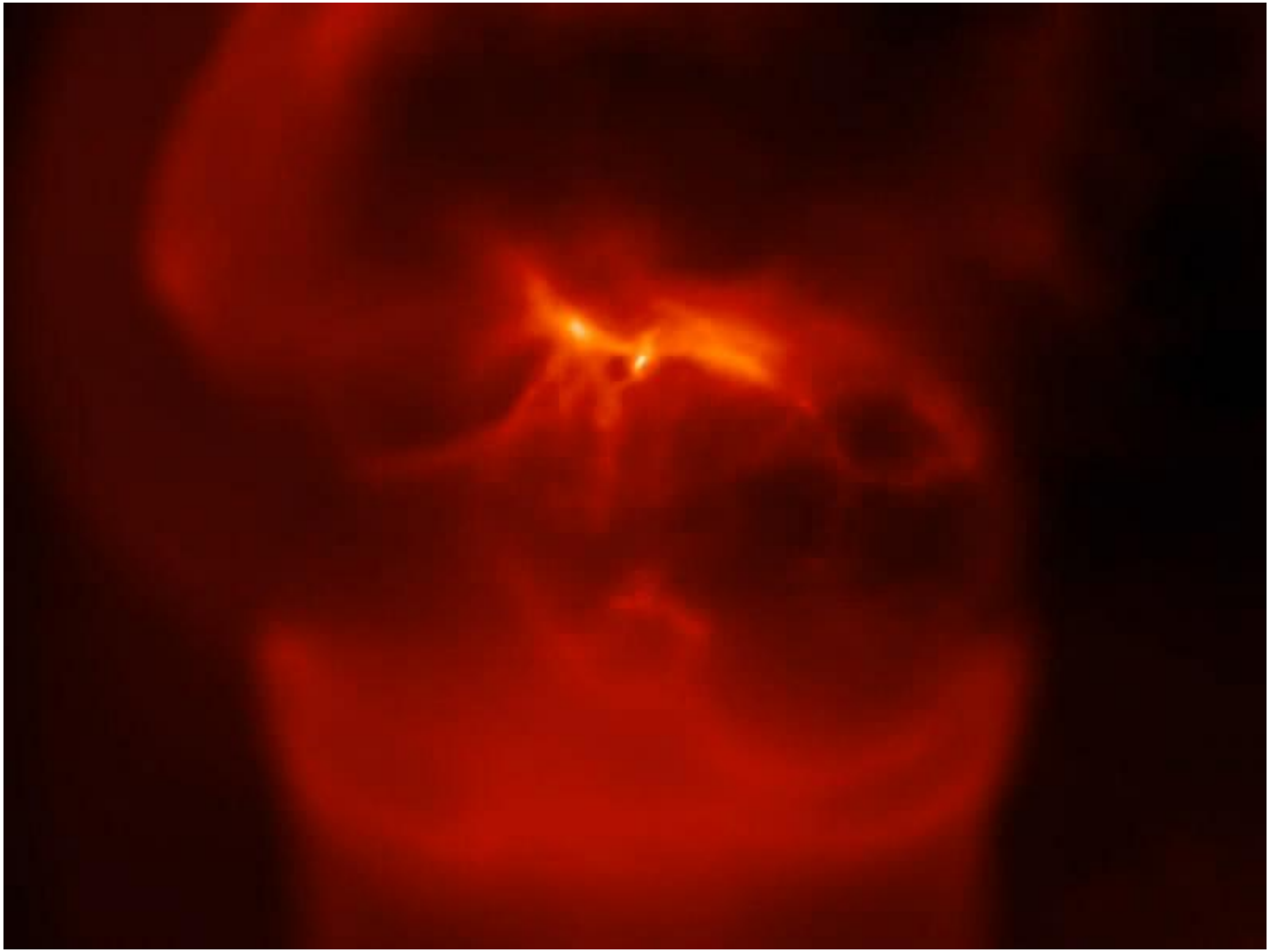
- Range of scales is huge:
  - initial cloud 10^{-18} g/cm^3
  - first hydrostatic core 10^{-13} to 10^{-11} g/cm^3
  - second collapse 10^{-8} to 10^{-1} g/cm^3 (protostellar core)
  - stellar density 1.4 g/cm^3

Magnetic Fields in SPH

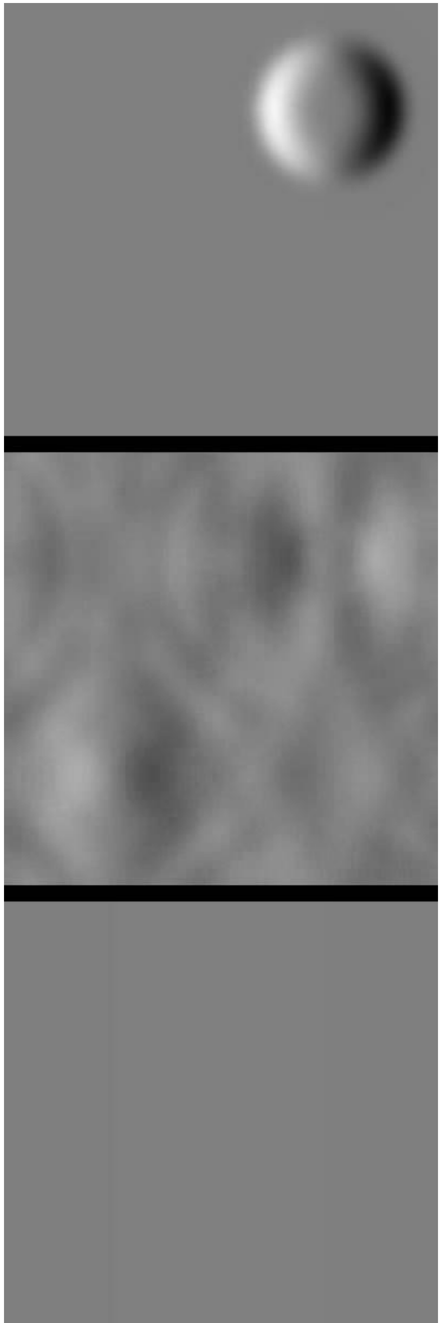
Most important criterion:

$$\boxed{\nabla \cdot \mathbf{B} = 0}$$

- Real fields have no divergence, so we want our representation of the field to be realistic,
- If large divergence is present, can cause numerical artifacts and stability issues.



- Collapse of a magnetised molecular cloud core (edge on view)
- Strong central divergence of the magnetic field causes the gas and surrounding accretion disc to explode outwards



Hyperbolic/Parabolic Divergence Cleaning

- Add new scalar field coupled to magnetic field

$$\left(\frac{\mathrm{d}\mathbf{B}}{\mathrm{d}t}\right)_{\psi} = -\nabla\psi$$

$$\frac{\mathrm{d}\psi}{\mathrm{d}t} = -c_h^2 \nabla \cdot \mathbf{B} - \frac{\psi}{\tau}$$

- Produces damped “divergence waves” through the magnetic field

$$\frac{\partial^2(\nabla \cdot \mathbf{B})}{\partial t^2} - c_h^2 \nabla^2 (\nabla \cdot \mathbf{B}) + \frac{1}{\tau}\frac{\partial(\nabla \cdot \mathbf{B})}{\partial t} = 0$$

Stable Formulation

- Define energy of ψ field

$$e_\psi \equiv \frac{\psi^2}{\mu_0 \rho c_h^2}$$

- Include as part of system Lagrangian

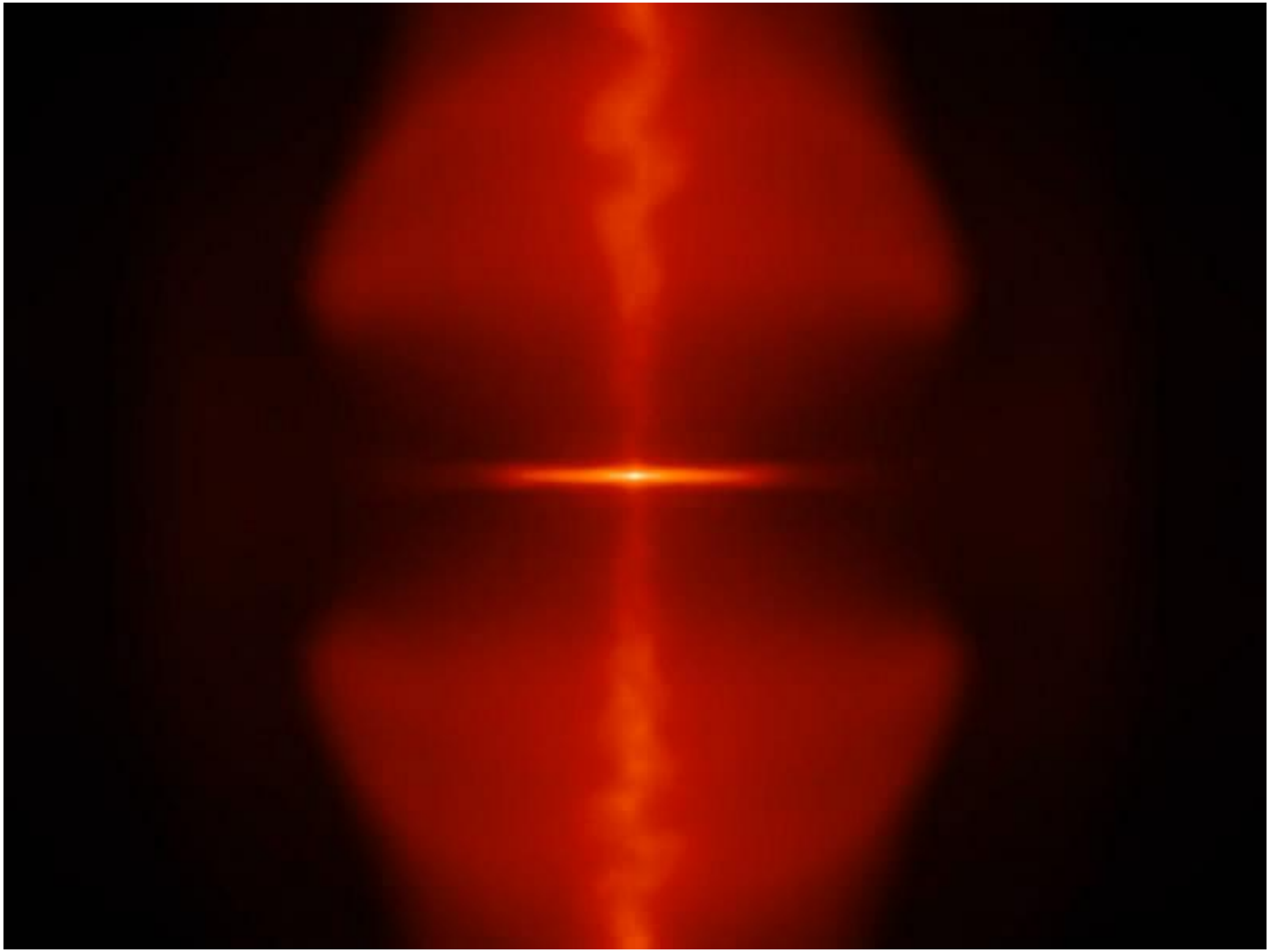
$$L = \int \left(\tfrac{1}{2}\rho \mathbf{v}^2 - \rho u - \frac{\mathbf{B}^2}{2\mu_0} - \frac{\psi^2}{2\mu_0 c_h^2} \right) \mathrm{d}V$$

- Retains the conservation properties of SPH, solves a lot of stability issues
- Requires matching SPH operators for $\nabla\psi$ and $\nabla \cdot \mathrm{B}$

Tricco, Price, J. Comp. Phys. accepted

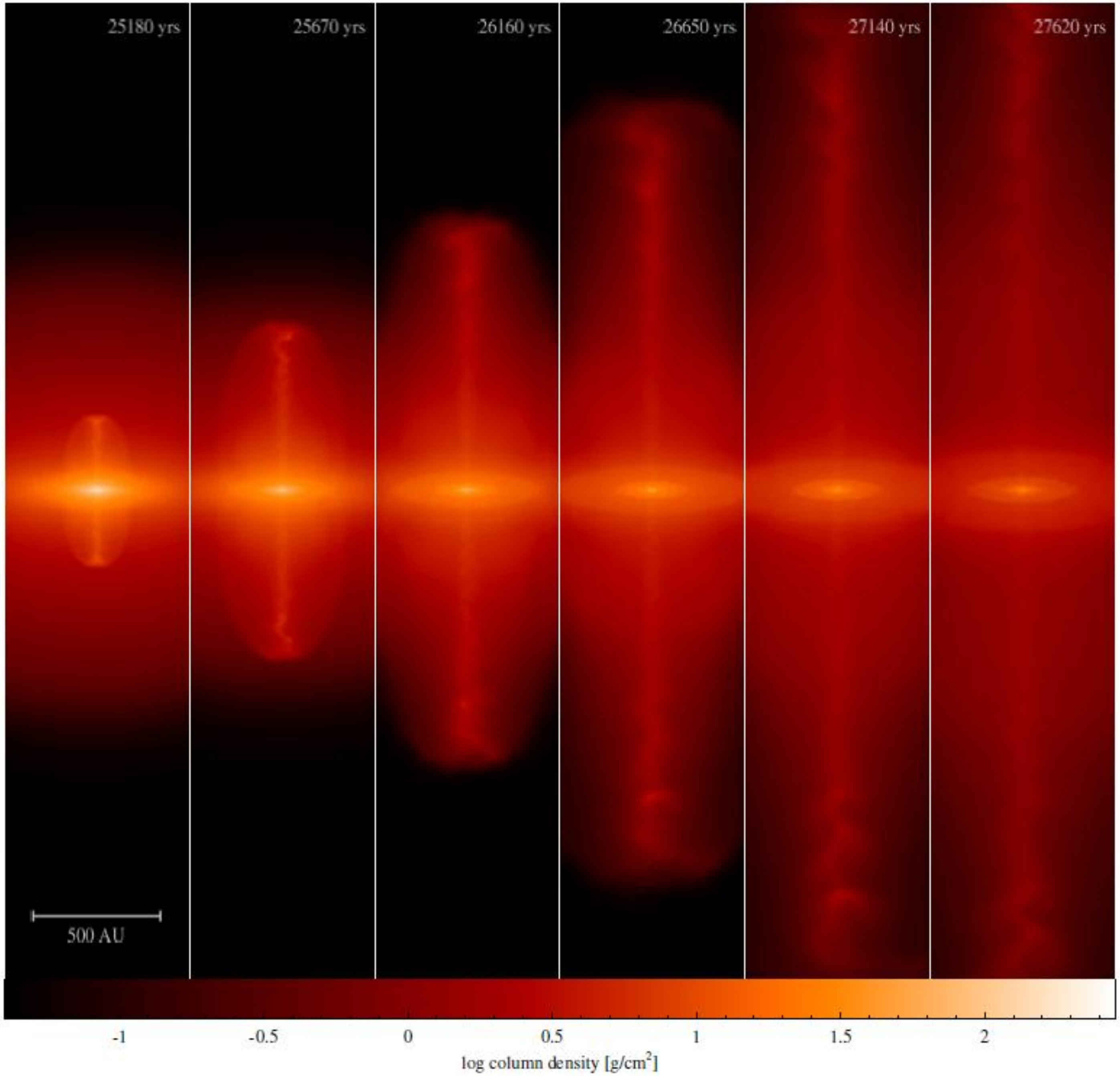
Low Mass Star Formation

- 0.5 - ~few solar mass
- Form in cold molecular clouds
- Isothermal collapse initially
- As density increases, becomes optically thick, starts to heat
  - Forms **first hydrostatic core**
  - 5-10 AU radius
  - Short lived, ~few thousand years
- At 2000 K, H_2disassociates leading to second isothermal collapse to form protostellar core

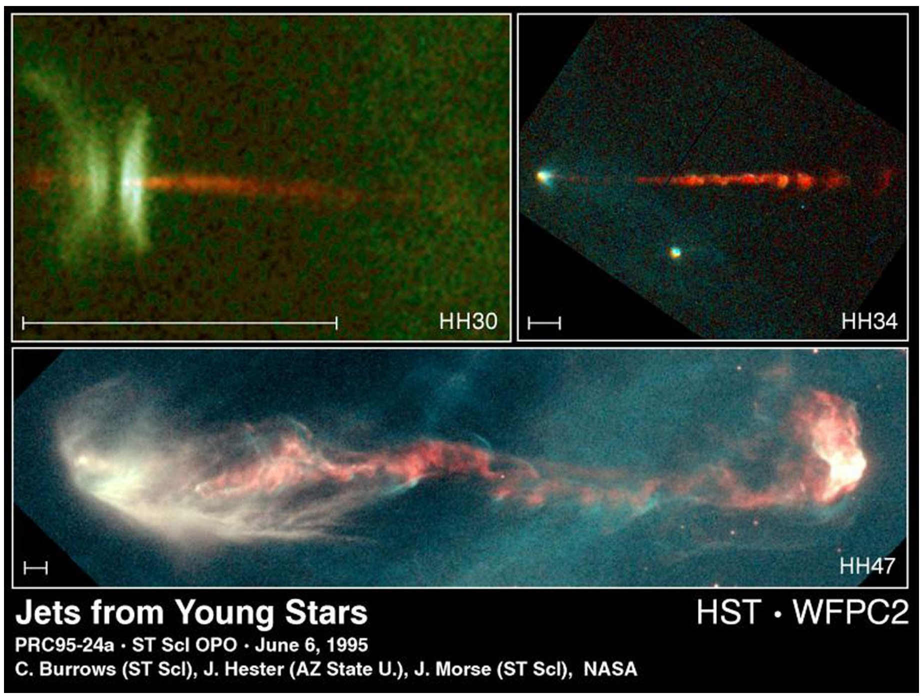


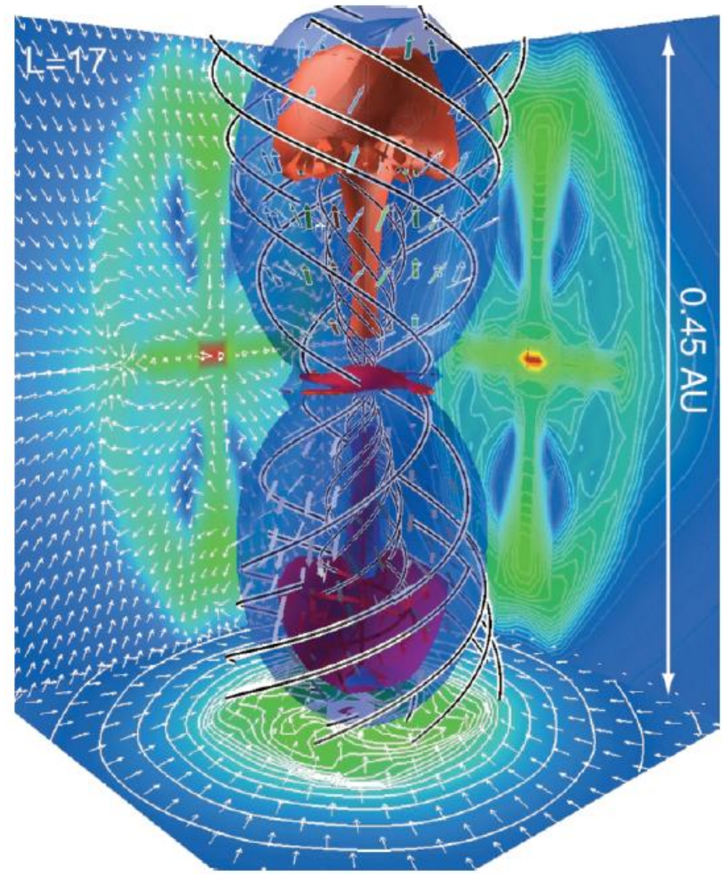
- Collapse of a magnetised molecular cloud core (edge on view)
- With divergence cleaning, collapse remains stable
- Emergence of magnetically propelled jet

Price, Tricco, Bate, MNRAS (2012)

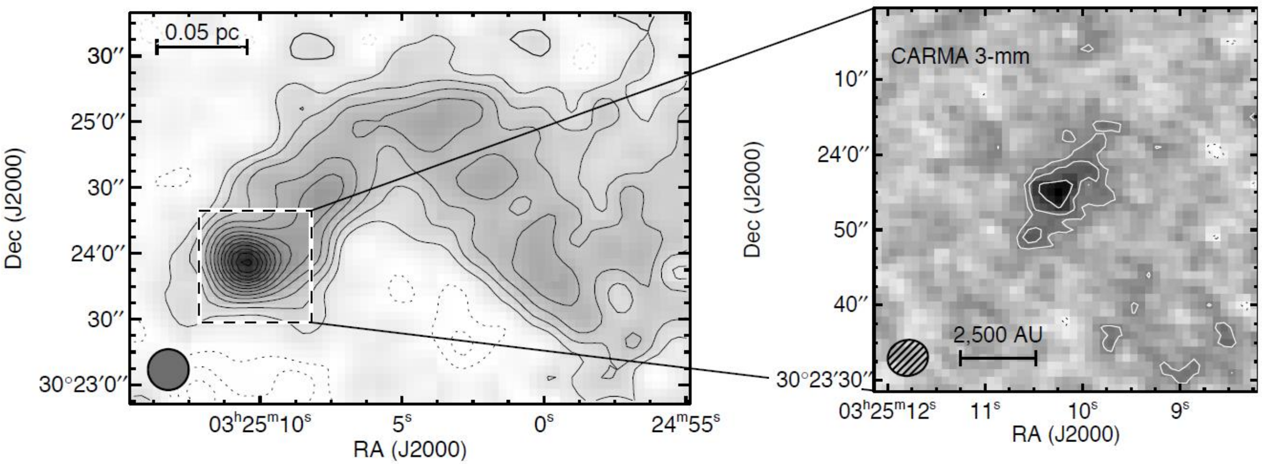

25180 yrs
25670 yrs
26160 yrs
26650 yrs
27140 yrs
27620 yrs
500 AU
-1
-0.5
0
0.5
1
1.5
2
log column density [g/cm^2]

- Jets from protostellar cores well observed and simulated
- Both wide and low angle (10° / 45°)
- High velocity (50-500 km/s)

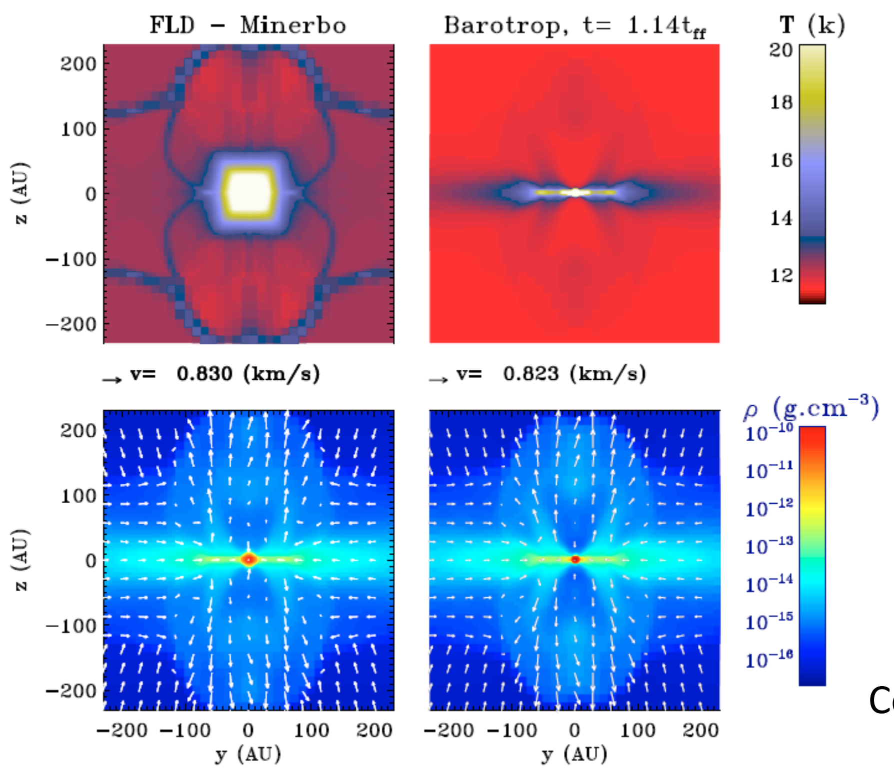




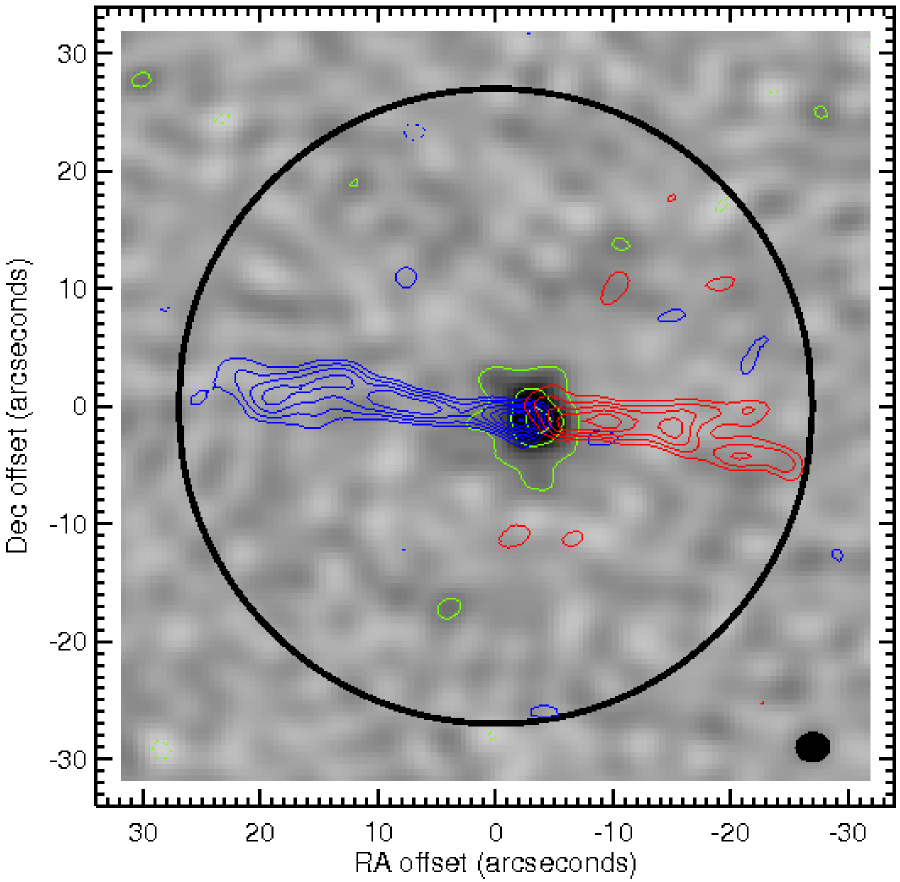
Machida, Inutsuka, Matsumoto (2006)



Pineda et al, ApJ, (2011)

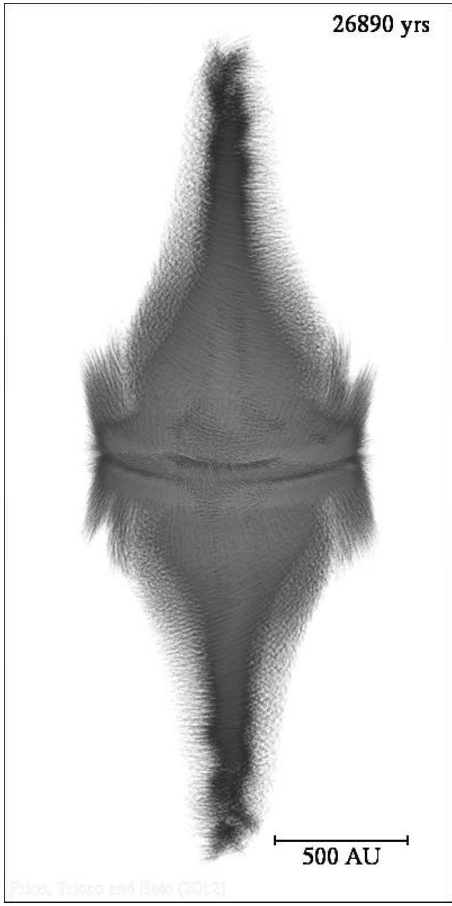


Commercon et al, A&A, (2010)

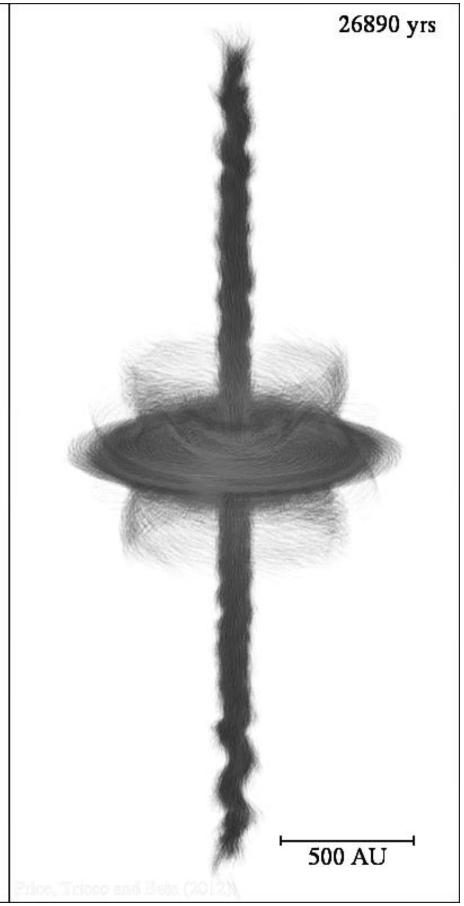


“Detection of a Bipolar Molecular Outflow Driven by a Candidate First Hydrostatic Core”
Dunham et al (2011)

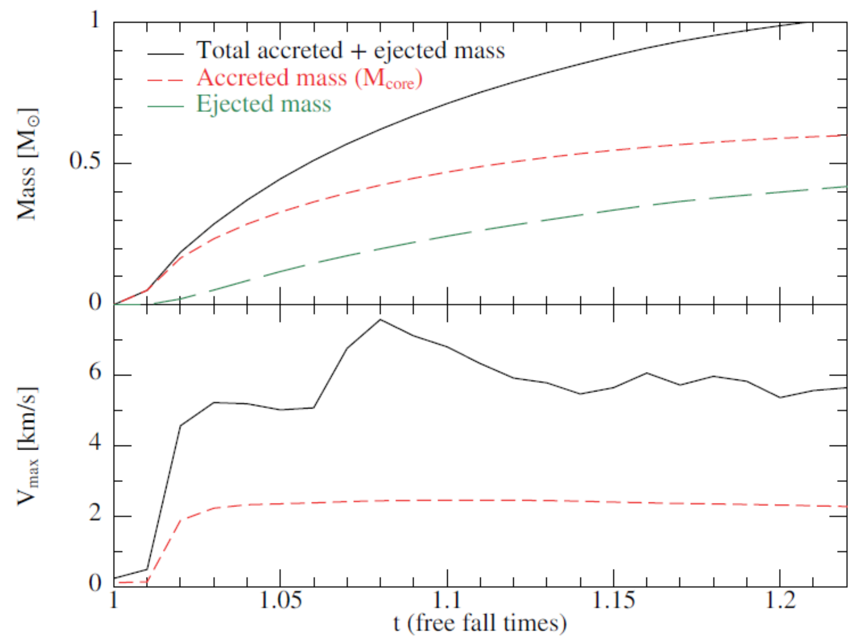
- Slow velocity, 2.9 km/s
- Highly collimated, ~8° opening angle

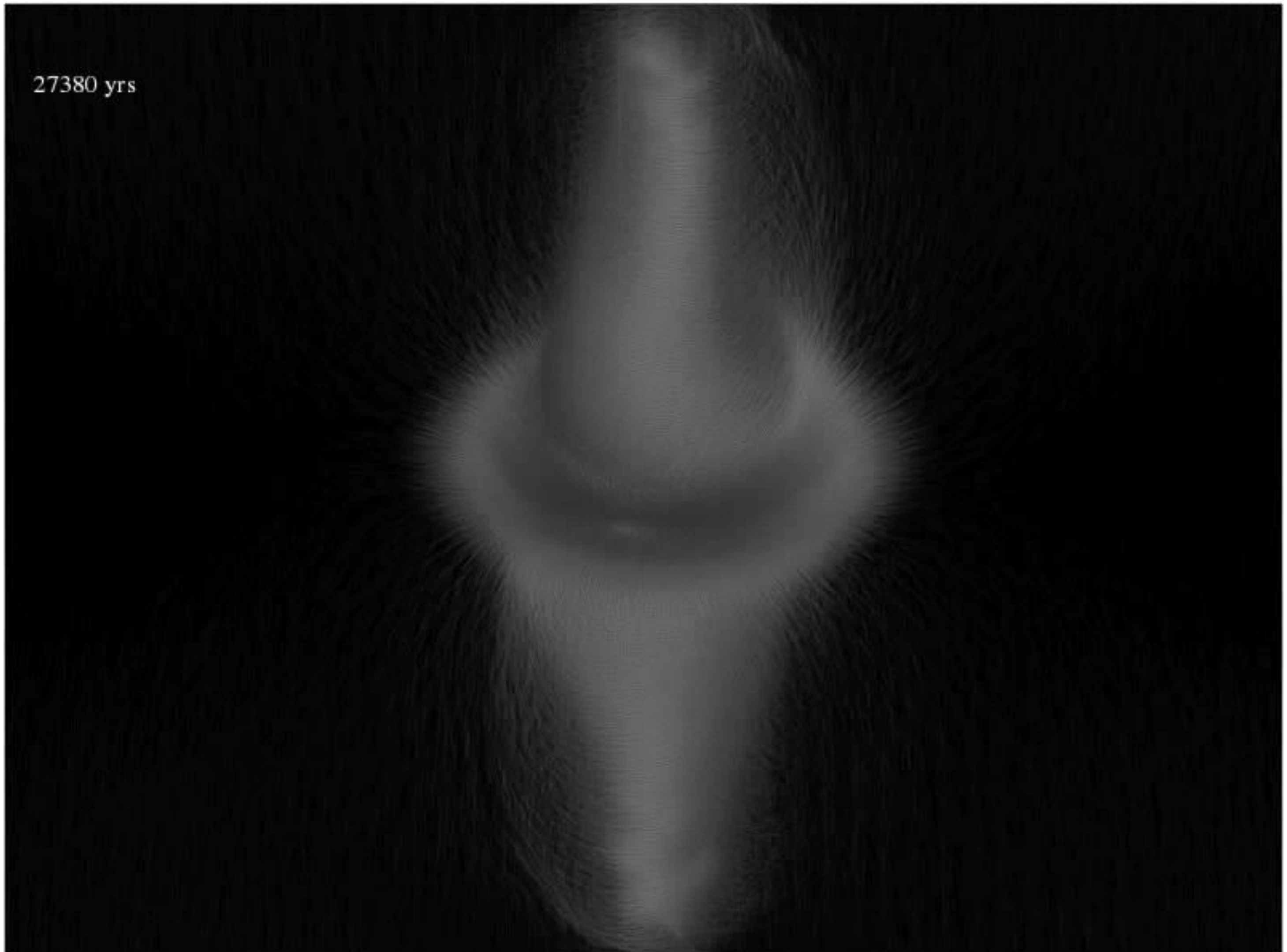


Magnetic Field



Magnetic Current





- Evolution of magnetic field lines during collapse

Price, Tricco, Bate, MNRAS (2012)

Conclusions

- Treatment of magnetic fields in SPMHD has been greatly improved.

- Possible to produce low angle jets from the first hydrostatic core.