Modeling Poynting flux vs. kinetic-energy dominated jets

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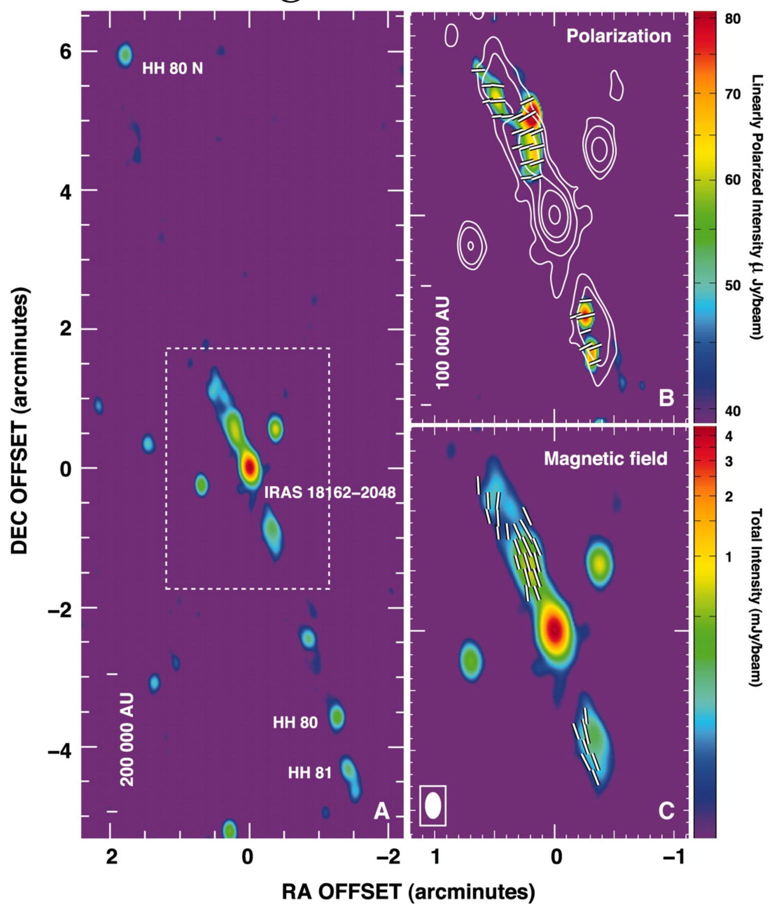
Introduction

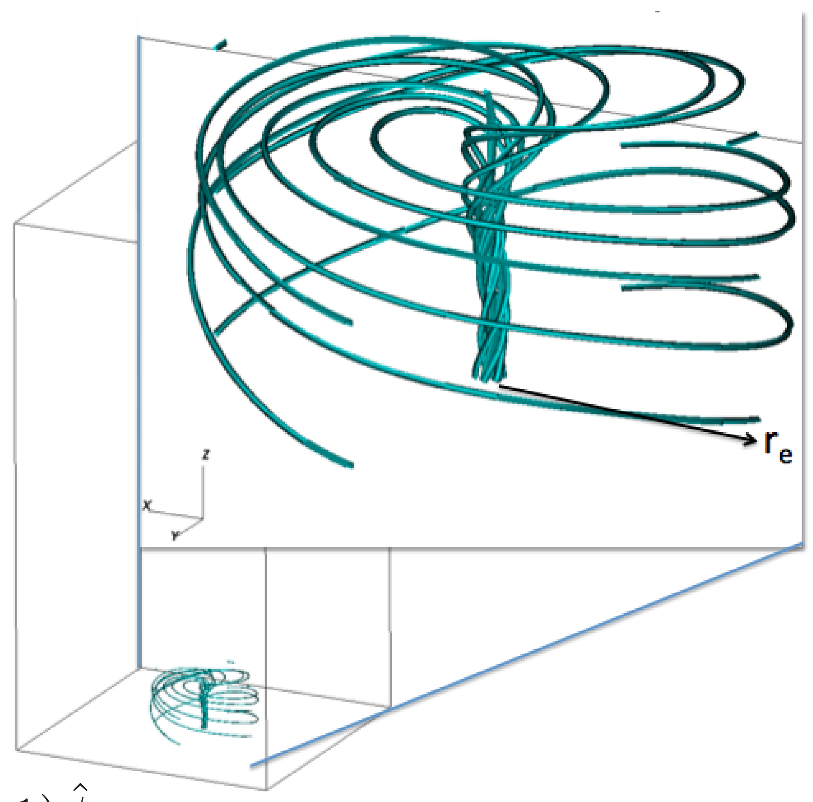
Jets are observed in the vicinities of Protostellar Objects, Young Stellar Objects (YSOs), post-AGB stars, X-ray binaries and active galactic nuclei. Models suggest that jets are launched and collimated by accretion, rotation and magnetic mechanisms in their "central engine" (review [1]). The extent over which the magnetic energy of jets dominates the kinetic energy divides them into (i) magnetocentrifugal jets [2], in which magnetic fields only dominate out to the Alfvén radius, (ii) Poynting flux dominated jets [3,4] (PFD), in which magnetic fields dominate the jet structure. Recent laboratory experiments have produced magnetized jets [5].

Open questions: What is the relation between the main observable features (length, velocity, cocoon geometry, etc.) of PFD jets and their power (this is known for kinetic-energy dominated (magnetocentrifugal) jets)? What is the effect of cooling and rotation on PFD jets? The image below is from [8].



Model

We use the Adaptive Mesh Refinement (AMR) code *AstroBEAR2.0* [6] to solve the equations of radiative-MHD in 3D. The domain: $|x|, |y| \leq 160$ AU and $0 \leq z \leq 400$ AU, $64 \times 64 \times 80$ cells plus 2 AMR levels; resolution of 1.25 AU.



Initial conditions:
- Static molecular gas
- Ideal gas eqn. of state ($\gamma = 5/3$)
- $n = 100\,\mathrm{cm}^{-3}$; $T = 10000\,\mathrm{K}$

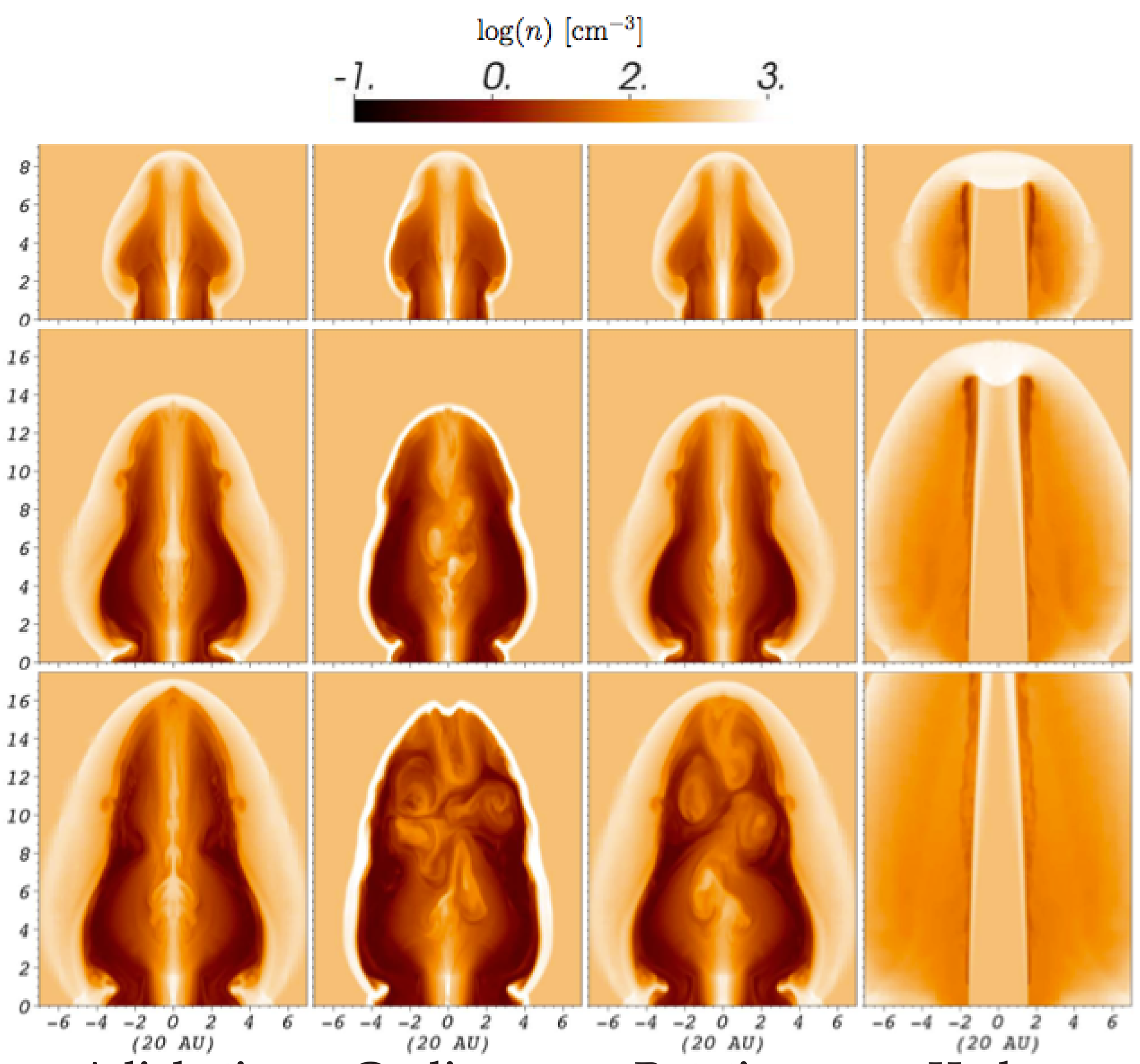
- $$\mathbf{A}(r,z) = \begin{cases} \frac{r}{4}(cos(2\,r)+1)(cos(2\,z)+1)\hat{\phi}+ & \\ \frac{\alpha}{8}(cos(2\,r)+1)(cos(2\,z)+1)\hat{k}, & \text{for } r,z < r_e; \\ 0, & \text{for } r,z \geq r_e, \end{cases}$$
- $r_e \sim 30$ AU; $\alpha = 40$ ($=800$ AU); $\beta < 1$ for $r, z < r_e$.

Evolution: Continuous central injection of magnetic or kinetic energy.

Simulations:
- *Magnetic towers*: adiabatic; optically thin cooling [7]; Keplertian rotation
- *Hydrodynamical jet* with the same time average propagation speed and energy flux than the adiabatic magnetic tower.

Structure and evolution

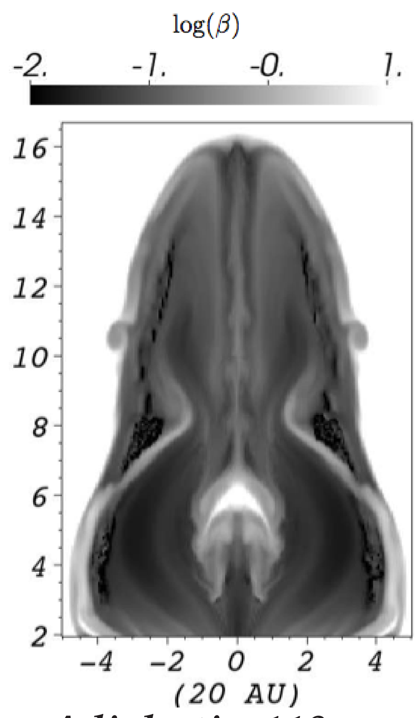
Magnetic pressure pushes field lines and plasma up, forming magnetic cavities with low density. The adiabatic case is the most stable. Towers decelerate relative to the hydro jet; magnetic energy pressure produces axial but also radial expansion. Towers' jets (cores) are thin and unstable, whereas the hydro jet beam is thicker, smoother and stable.



Time= {42, 84, 118} yr, from top to bottom.

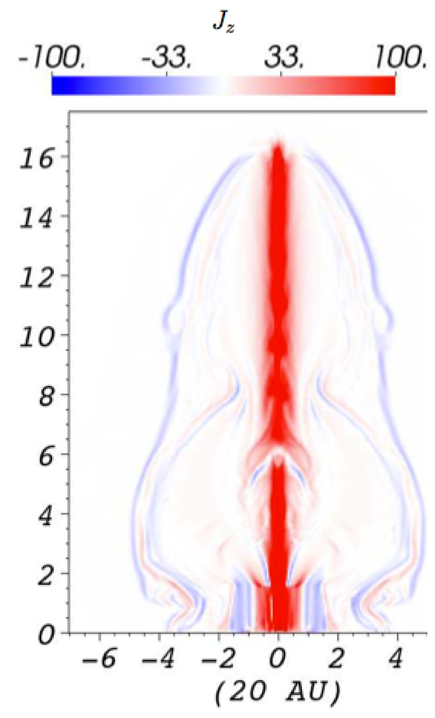
Forces and current density

Magnetic pressure dominates over thermal. Towers' jets (cores) are confined by the magnetic hoop stress from surrounding field lines. The cavity is collimated by external thermal pressure.



Adiabatic, 118 yr

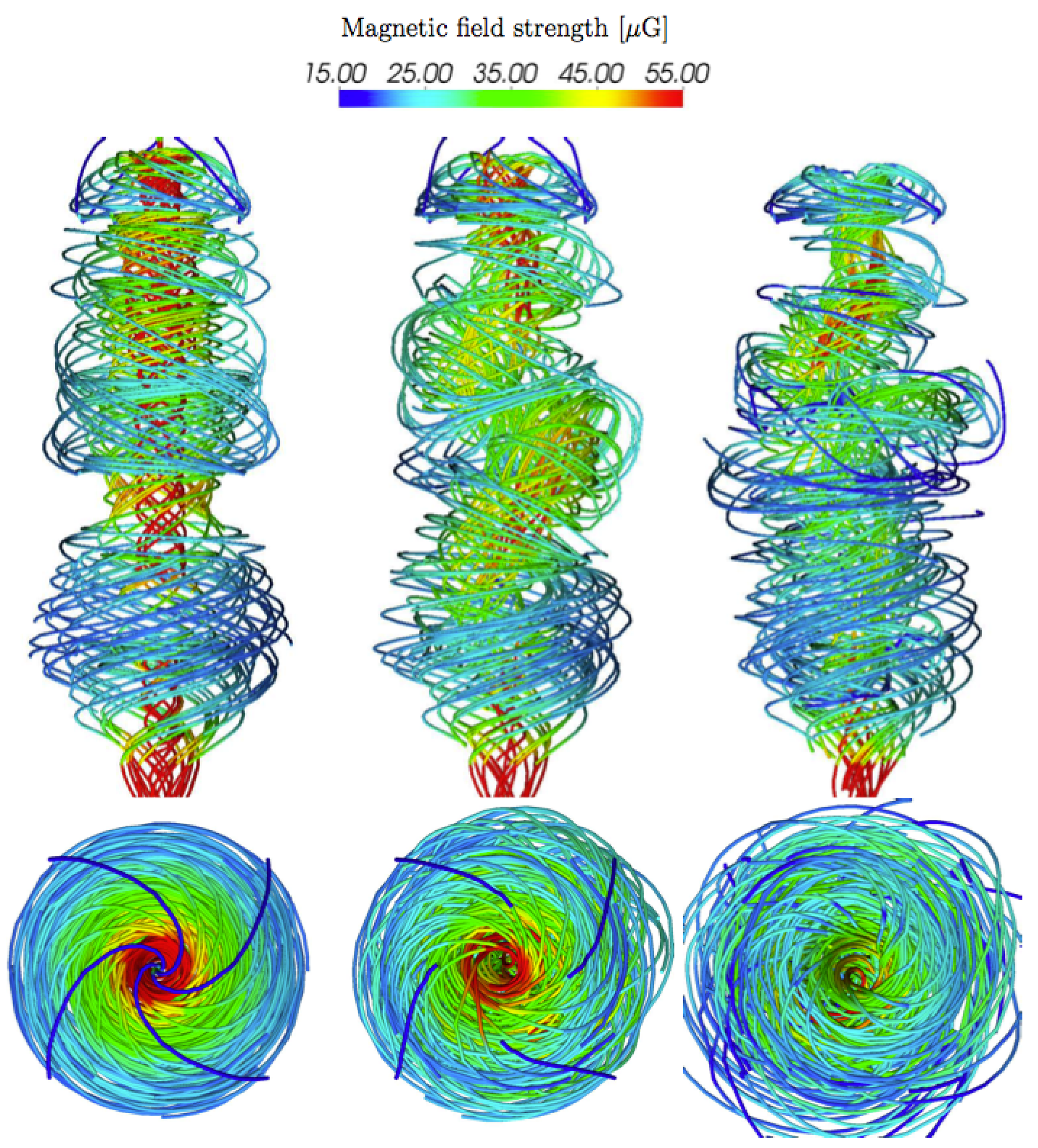
Towers' jets carry a high axial current density. There is a current-free region about the jets. The main return current goes along the cavity's outer contact discontinuity.



Adiabatic, 118 yr

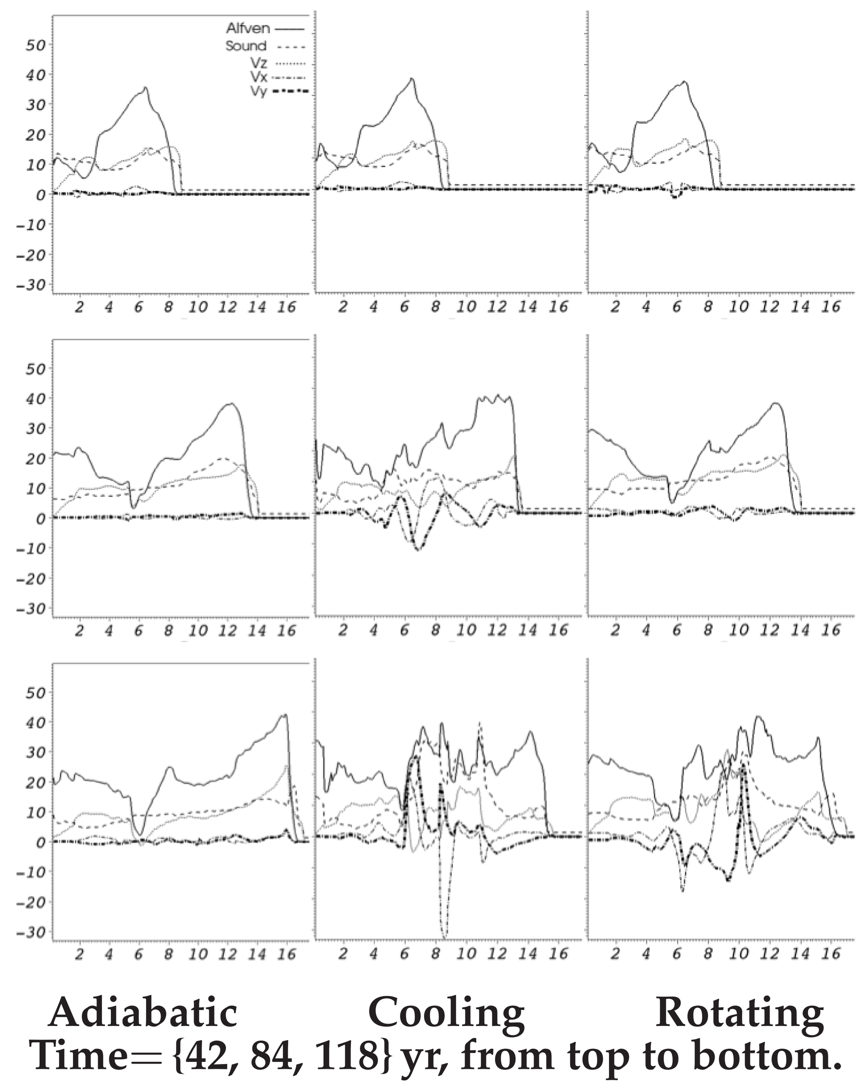
Field geometry and stability

The jets' field lines are parallel to $r = 0$ and surrounded by toroidal lines (red). There is another exterior helical component of lines. The injected magnetic energy keeps a non-force-free configuration at base; "new" lines push "old" ones upwards. Independently, cooling and rotation amplify current-driven perturbations. We see pinch (m= 0) and kink ($m = 1$) modes. The Figure's time is 118 yr.



Jet velocity field, shocks and wave fronts

v_x, v_y, $v_z (= v_{jet})$, the sound and the Alfvén speed of the towers at $r = 0$. Early, jets are sub-Alfvénic and trans-sonic. Fast-forward MHD (FF) and hydrodynamic shocks are formed ahead of the jets' head. FF shocks steepen in time. Hydrodynamic shocks are quickly affected by cooling. The adiabatic and rotating cases show high beta regions between the reverse and the forward slow-modes of compressive MHD waves. Late, the cooling and rotating jets show fast, azimuthal, sub-Alfvénic velocities in their central beam part.



Time= {42, 84, 118} yr, from top to bottom.

Conclusions

- PFD jet beams are lighter, slower and less stable than kinetic-energy dominated ones. We predict characteristic emission distributions for each of these.
- Current-driven perturbations in PFD jets are amplified by both cooling, firstly, and base rotation, secondly: shocks and thermal pressure support are weakened by cooling. Total pressure balance at the jets' base is affected by rotation.
- Our models agree well with [3,4,5,8].

References

[1] Pudritz, R. E., et al., 2007, Protostars and Planets V, 277; **[2]** Blandford, R. D., & Payne, D. G. 1982, MNRAS, 199, 883; **[3]** Lynden-Bell, D. 1996, MNRAS, 279, 389; **[4]** Nakamura, M., & Meier, D. L. 2004, ApJ, 617, 123; **[5]** Lebedev, S. V., et al. 2005, MNRAS, 361, 97; **[6]** Cunningham A. J. et al., 2009, ApJS, 182, 519 (https://clover.pas.rochester.edu/trac/astrobear/wiki/WikiStart); **[7]** Dalgarno A., McCray R. A. 1972, ARA&A, 10, 375; **[8]** Carrasco-González, C. et al., 2010, Science, 330, 1209

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