Into the void: Simulating magnetic outflows from young disks at launching and observational length scales

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Motivation

Jets and outflows are observed in AGN, around brown dwarfs, and everywhere in between.

Although there has been substantial discussion in the literature regarding the launching and collimation of protostellar jets, simulations which resolve the launching region (<1 AU) have not previously extended to large length scales (>1000 AU).

Herein, we present simulations of protostellar jets that self-consistently include both the launching mechanism & the larger observable length scales.

Method: AZEuS

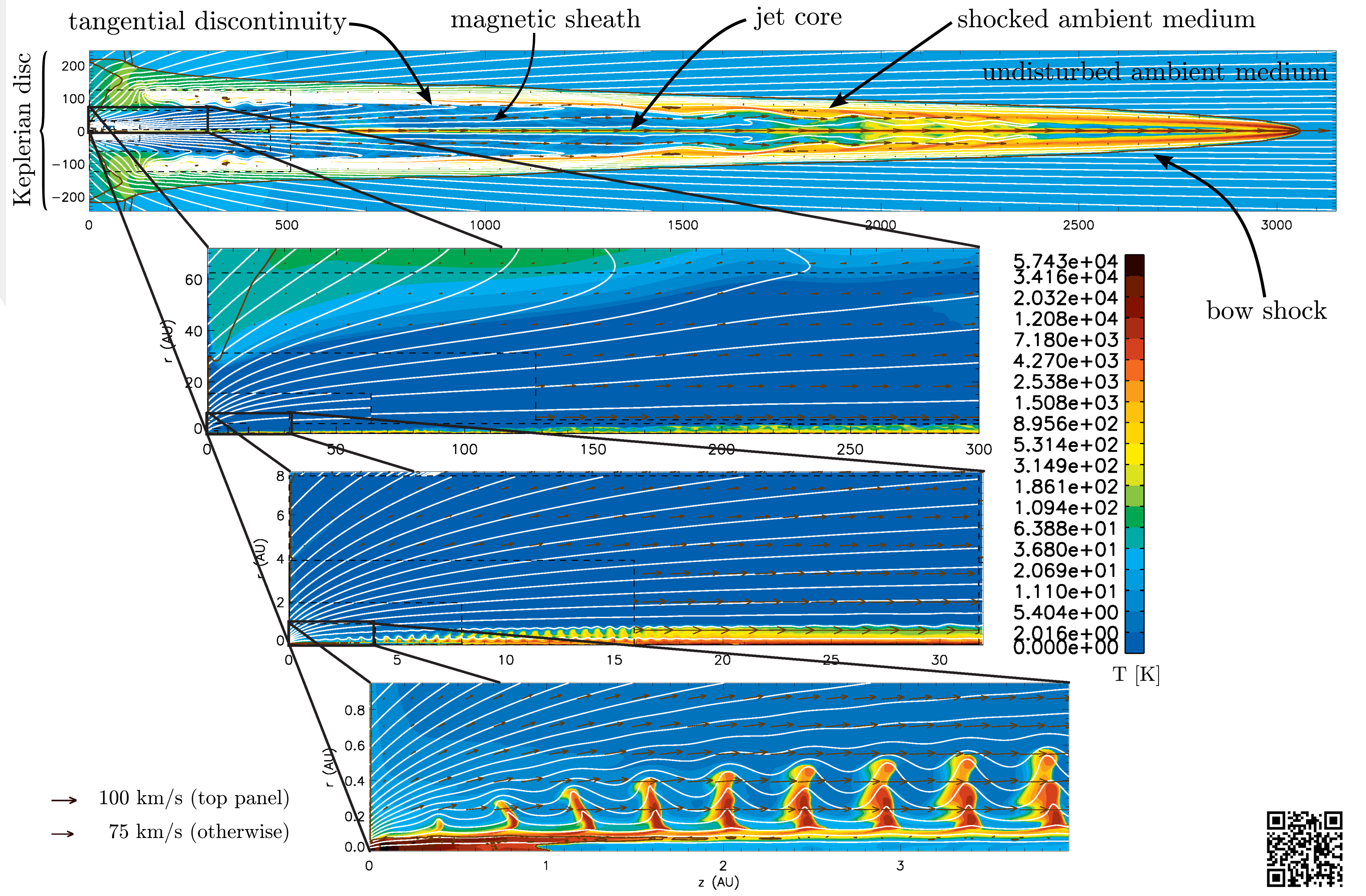
⇒ *ZEUS-3D* + adaptive mesh refinement

- Ramsey, Clarke, & Men'shchikov (ApJS, 199, 13, 2012).
- `http://www.ica.smu.ca/azeus/`

Initial conditions

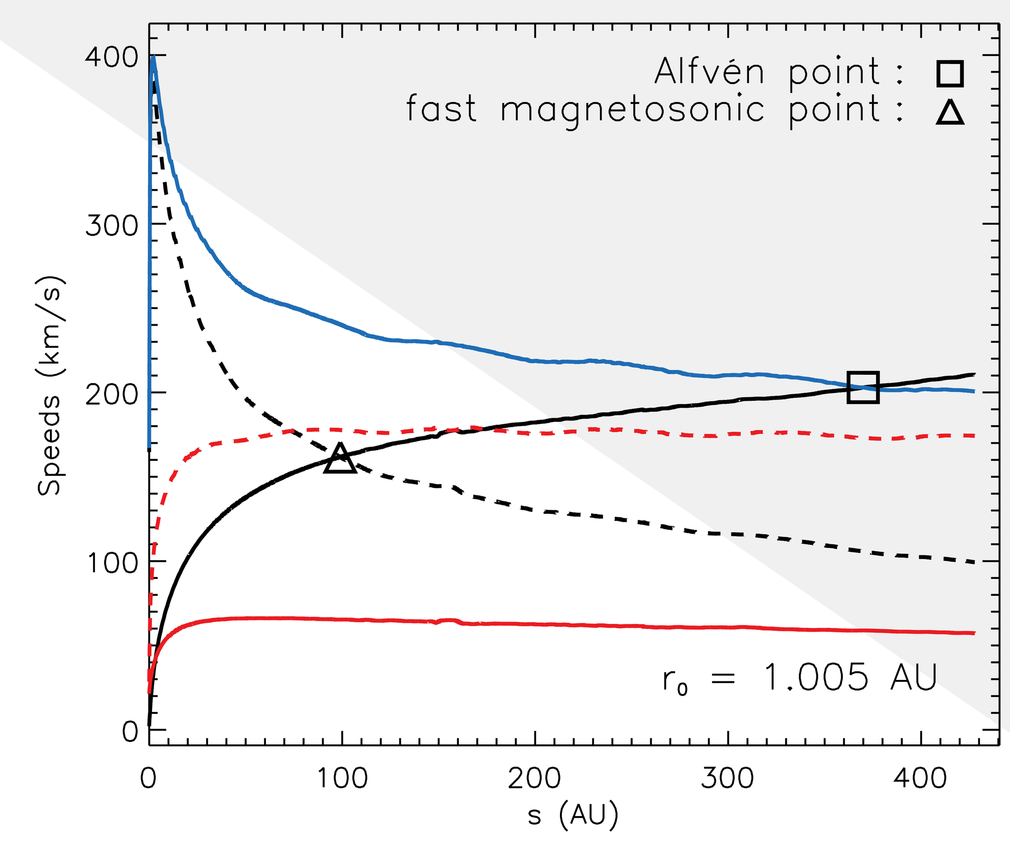
- 2.5-D cylindrical coords.; ideal MHD; hydrostatic atmosphere; force-free magnetic field.
- $v_{\rm inflow}$, $p_{\rm gas}$, ρ specified in an initially Keplerian disc; other boundary conditions evolve with time.
- Domain: $4050\,{\rm AU} \times 250\,{\rm AU}$; 9 levels of AMR; $\Delta x_{\rm min} = 0.00625\,{\rm AU}$.
- Simulations: $B_{\rm i} = 200, 100, 63.2, 40, 20, 10, 5\,{\rm G}$ $(\beta_{\rm i} = 0.1, 0.4, 1.0, 2.5, 10, 40, 160)$.

Results

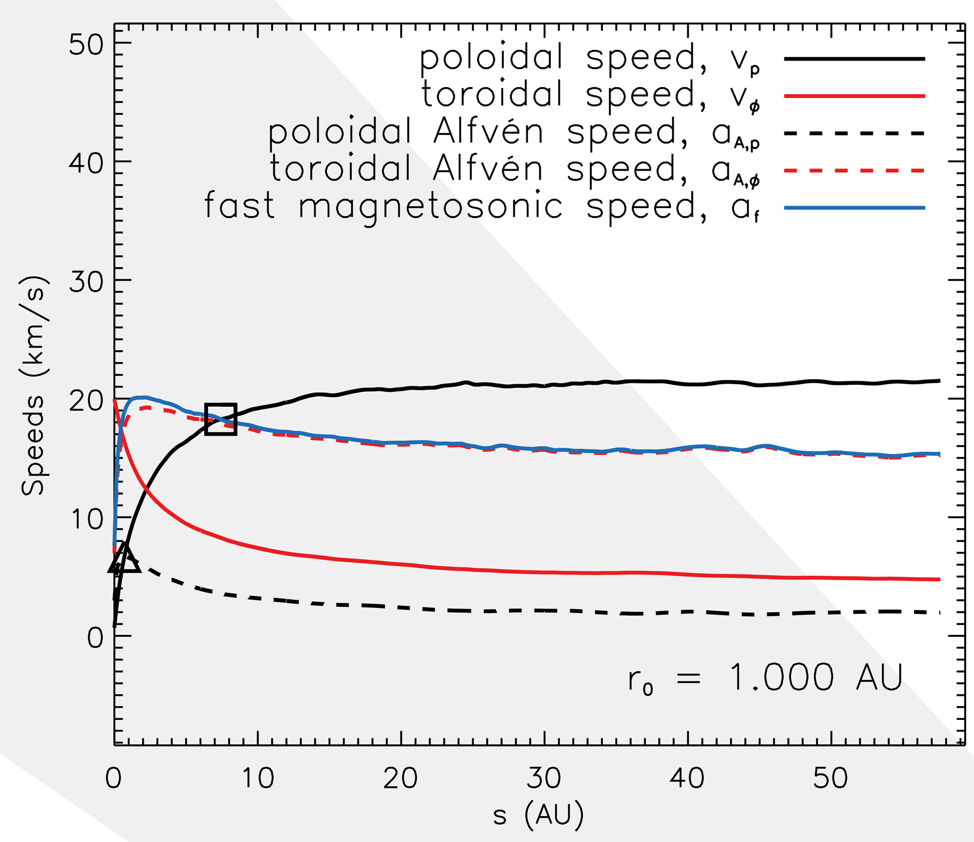


A $B_{\rm i} = 20\,{\rm G}$ ($\beta_{\rm i} = 10$) jet at $t = 100$ yr. Temp. is shown in colour, mag. field lines in white, velocity vectors & the slow magnetosonic surface in black. For movies, see: `www.ica.smu.ca/zeus3d/rc10/`

The driving mechanism



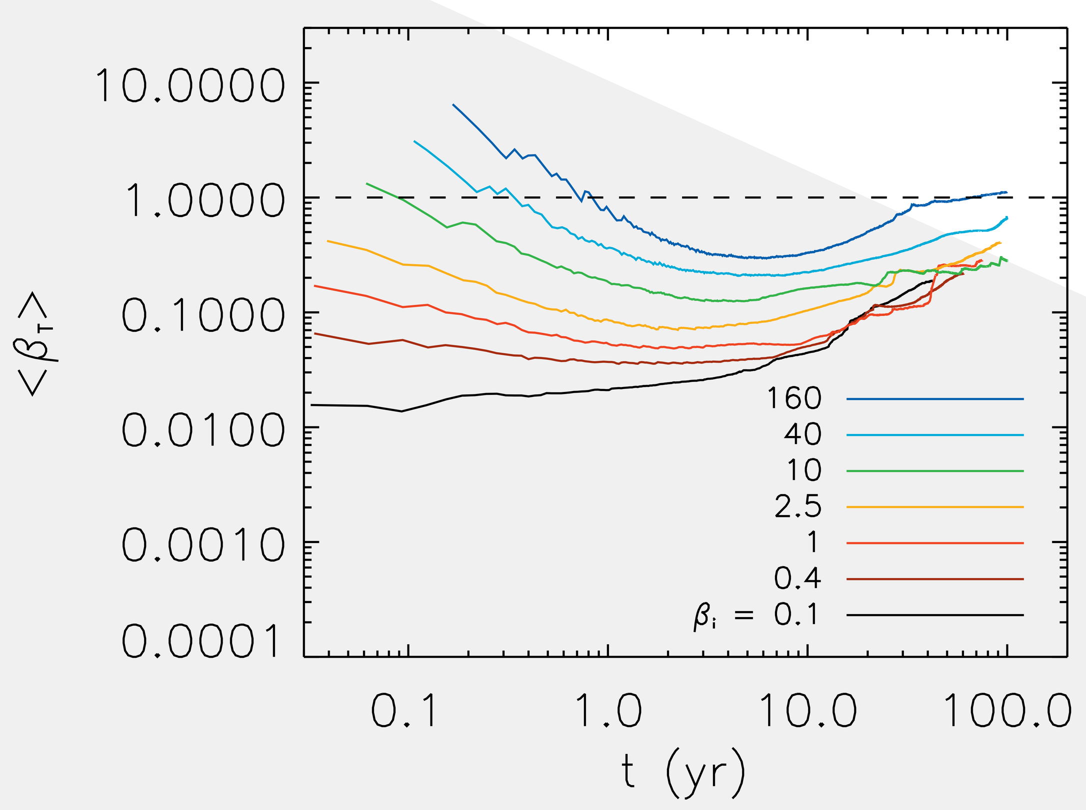
$B_{\rm i} = 200$ G ($\beta_{\rm i} = 0.1$)



$B_{\rm i} = 5$ G ($\beta_{\rm i} = 160$)

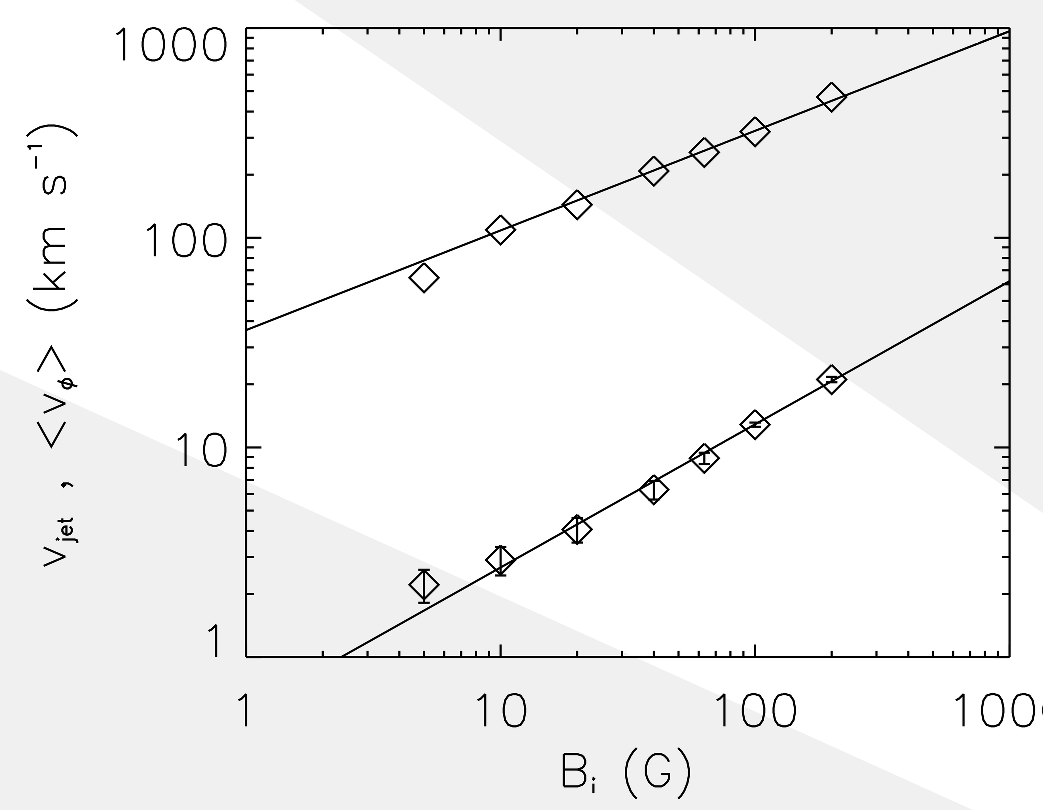
- Magnetocentrifugal launching (Blandford & Payne, 1982) is only efficient up to the Alfvén point ($v_{\rm p} = a_{\rm A,p}$).
- For strong fields, $B_{\rm p} \propto a_{\rm A,p}$ dominates, and the magnetocentrifugal mechanism provides ∼80% of the acceleration (left panel).
- For weak fields, only ∼37% of the acceleration occurs before the Alfvén point (right panel). Instead, $B_\phi \propto a_{{\rm A},\phi}$ dominates, and the majority of acceleration is provided by ∇B_ϕ^2 (a "magnetic tower"; Lynden-Bell, 1996, MNRAS, 279, 389).
- In order to explain the entire acceleration of the jet, *both* mechanisms must be invoked in *both* strong and weak field cases.
- The relative importance of each mechanism is characterised by the ratio of mag. forces parallel and perpendicular to a field line: $F_\parallel / F_\phi = -B_\phi / B_{\rm p}$ (Zanni *et al.*, 2007, A&A, 469, 811).

Towards equipartition



- For weaker initial fields, generation of B_ϕ drives $\langle\beta_T\rangle = 2\langle p\rangle / \langle B\rangle^2$ downward, resulting in magnetically dominated jets. Jets with strong initial fields are magnetically dominated to begin with.
- Over time, all simulations tend to equipartition ($\langle\beta_T\rangle \sim 1$) regardless of initial field strength (*e.g.*, $\beta_{\rm i} = 160$ reaches $\langle\beta_T\rangle \simeq 1$ at $t \simeq 60\,{\rm yr}$).

Direct observables



Correlations between field strength and jet advance speed, avg. jet rotational speed are observed:

$$v_{\rm jet} \propto B_{\rm i}^{0.47\pm0.01};\ \langle v_\phi\rangle \propto B_{\rm i}^{0.66\pm0.01}$$

Characteristic observational values:

proper motion	$100 - 500$ km s^{-1}
rotational speed	$(5-25) \pm 5$ km s^{-1}

Conclusions

- Two physical mechanisms, working in concert, launch and accelerate the jets presented here.
- Jets require a magnetically-dominated environment for launching, but asymptote towards magnetic equipartition ($\langle\beta_T\rangle \sim 1$).
- Regardless of the initial field strength, conditions develop such that a jet is (eventually) always launched.
- Outflows launched magnetically from discs are capable, by themselves, of producing realistic protostellar jets.

References

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