Modeling accretion-ejection processes in magnetized young star environments

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Outline

• Young Stellar Objects:
  Observational clues and puzzles

• Magnetohydrodynamic modeling
  ⇒ launching jets from accretion disks
  ⇒ wind-jet interactions
  ⇒ near-star accretion processes

• Outlook: bringing all scales together
Astrophysical Jets: YSO

- Forming stars: T-Tauri with mass $M_* \leq M_\odot$
  $\Rightarrow$ bipolar jets, velocities up to 400 km/s
- accretion disk play role in launching process:
  $\Rightarrow$ proportionality between jet/disk luminosity
Astrophysical Jets

- astrophysical jets: ubiquitous in presence of accretion disks
  ⇒ Young Stellar Objects (YSO)
  ⇒ compact objects in binaries
  ⇒ Active Galactic Nuclei (AGN)

- collimated, reach high velocities (up to $c$)
  ⇒ mass source of the jet?
  ⇒ how to collimate and keep collimated?
  ⇒ how to launch and accelerate mass in jet?
MagnetoHydroDynamics

- Conserve MASS, MOMENTUM, ENERGY, MAGNETIC FLUX $\Rightarrow$ 8 non-linear PDE
  $\Rightarrow \nabla \cdot \mathbf{B} = 0$: no magnetic monopoles
- 7 wavespeeds entropy, $\pm$ slow, $\pm$ Alfvén, $\pm$ fast [anisotropic!]

MHD waves animation
Magnetic Accretion-Ejection structure

- key ingredients are: presence of accretion disk + \( B \) ⇒ observed versus ‘artist impression’ (for AGN)

- perform axially symmetric 2.5D MHD simulations
  ⇒ disk with initial vertical $B$: self-consistently forms collimated jet
  ⇒ 15% of accreted mass persistently ejected
**MAES**

- mechanism for jet launch and acceleration
  - mass source: accretion disk
  - collimation and acceleration of jet: \( B \)
- identical for YSO, compact objects, AGN:
  - MAES model relies on its gravitational influence on disk material
  - does not require specific disk/magnetosphere interaction
  - object (plus magnetosphere or event horizon): point source
  - consistent with observed jet radii at ‘origin’
MAES: Streamlines

- in jet launch region: accretion and ejection

⇒ resistive disk treatment allows accretion

⇒ accretion rate as BC: mimics outer regions
MAES: persistent launch

- spatio-temporal resistivity only in disk
  - accretion flow slips across vertical $B$
  - region above disk: ideal MHD (frozen-in)
- jet launch, once initiated, persists:
  - material ejected from disk: 15 % of $\dot{M}_A$
MAES: hollow jets

- since jet launched from disk: hollow jet
  \[ \Rightarrow \text{reaches super-fast magnetosonic speeds: accelerated while ejected} \]
MAES: Force analysis

- Jet ejection mechanism: axial force analysis

⇒ thermal pressure gradient lifts matter
⇒ magnetic torque brakes in disk, spins up jet
MAES: Angular Momentum

- Angular Momentum: channeled by \( B \)
  - \( \Rightarrow \) in disk: magnetic torque brakes azimuthally
  - \( \Rightarrow \) gravity wins from centrifugal: accretion
  - \( \Rightarrow \) AM flux parallel to poloidal flow/\( B_p \)
- torque \( (J \times B)_\varphi \) changes sign at disk surface:
  - \( \Rightarrow \) magnetocentrifugal acceleration of jet
- starts and stays collimated by magnetic hoop force
  - \( \Rightarrow B_\varphi \) created by rotating disk
MAES Jet extent

- radial extension of jet launching region
  \[ \Rightarrow \text{equipartition field region} \]
  \[ \Rightarrow \text{sufficiently bent poloidal } B(\text{cold jet}) \]
MAES Energetics

- Jet energetics
  - disk material heats: compression & Ohmic
  - hot jet emerges
- jet luminosity $\propto$ energy liberated by accretion $GM_\ast \dot{M}_A/2R_I$
MAES Summary

Escaping accretion

• mechanism for launch
  ⇒ magnetic torque brakes disk material azimuthally and spins up jet matter
  ⇒ mass source for jet: disk
  ⇒ $B$ collimates, accelerates
  ⇒ Jet formation animation

• accretor can be very different
  ⇒ YSO, compact object, AGN
Jet launching: improving the models

- Numerical ‘proof of principle’ (2.5D VAC code simulations)
- MAES model explains
  ⇒ how jets are launched and accelerated
  ⇒ why start and remain collimated
  ⇒ underluminous disks and hot jets
- Recent improvements:
  ⇒ higher resolution (grid-adaptive) studies
    ⇒ including stellar outflows, viscosity in the disk

- FLASH code (with AMR); emphasize role of anomalous resistivity prescription
Two-component outflows

  ⇒ disk ‘turbulence’ by enhanced visco-resistive $\alpha$-prescription
  ⇒ MHD Poynting flux of disc-jet: removes most AM from thin disc
  ⇒ $B_\phi$ zero to $\beta \sim 1$ in disc scale height ⇒ effective magnetic torque
- wind region: hot corona (turbulent heating near axis)
  ⇒ numerical trick: sink (0.1 AU) → mass source along polar axis
Two-component outflows

- collimation differs for wind versus jet
  - wind region forces: thermal + Lorentz (pinch)
  - in turn collimated by disc-driven jet
- all axisymmetric, aimed at stationary endstates, unanswered:
  - 3D jet stability and termination
  - multi-component jets: interface dynamics?
  - near star accretion dynamics
Near-star accretion

  - axisymmetric studies of ‘stationary’ accretion on magnetized stars
  - relevant for T-Tauri stars with kG (aligned) dipole fields
  - funnel flows connect disk to star, AM transport by magnetic torque
  - meanwhile progressed to 3D unaligned dipoles

  - VAC simulations, using resistive disk and 2.5D
  - Funnel flows are robust features, even down to 140 G fields
  - However, realistic $\dot{M} \sim 10^{-8} M_\odot yr^{-1}$: need kG fields!
Bessolaz et al.

- uses split into static dipole and solve for \( \mathbf{B}_1 \) (Tanaka 1994)
- Temporal evolution and grid:
Bessolaz et al.

- Aim of the study: relative position of truncation radius $r_t$, corotation radius $r_{co}$, equipartition between poloidal magnetic pressure and disc poloidal ram $r_{bf}$, disc thermal pressure
  
  $\Rightarrow$ Analytic criterion for a-priori determination of steady funnels
  
  $$\beta \sim 1, \quad and \quad m_s = \frac{u_r}{C_s} \approx 1$$
  
  $\Rightarrow$ express truncation radius (where accretion halts) in basic parameters
  
  $$\frac{r_t}{R_*} \sim 2 \left(m_s\right)^{2/7} B_*^{4/7} \dot{M}_a^{-2/7} M_*^{-1/7} R_*^{5/7}$$
  
- for realistic CTTS values: truncation radius smaller than co-rotation
  
  $\Rightarrow$ CTTS must always spin-up due to star-disc interaction!
  
  $\Rightarrow$ unless other processes effective (stellar and disc jets again...)
Bessolaz et al.

- forces in funnel flow: first pressure gradient
  \[ \Rightarrow \] eventually gravity wins, free-fall velocity (surface at \( s \sim 1.2 \))
Outlook I

- Model lacks as yet
  - stellar outflows, disc outflows (X-winds?)
  - all models treat disc with anomalous transport prescriptions
  - source of turbulence? MRI? Still compatible with large-scale field?
- near-Keplerian, thin disks versus strongly magnetized, thick disks
  - guaranteed many, different instabilities at play in real disks
  - e.g. Convective Continuum Instability (Blokland et al, A&A 467, 21, 2007)
- 3D effects, stability of (multi-component) outflows?
  - twisted fields → kink instabilities
  - shear flow interfaces: Kelvin-Helmholtz
Outlook II

- stability issue also for relativistic jets (AGN)
  ⇒ Meliani & Keppens, *arXiv:0709.3838*
  ⇒ cross-cut in fast inner, slow outer jet, AMR simulation
  ⇒ different launch mechanism → different rotation profile
  ⇒ interacting body-surface KH, Rayleigh-Taylor (centrifugal force)