Outflows and Jets: Theory and Observations
Winter term 2008/2009
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Topics today

- Jet launching processes, magnetic field morphology and jet launching observations
- Driving jet and entrained outflow observations
- Outflow entrainment models
- Additional observables to constrain outflow/jet properties
Jet launching from accretion disks

“magnetic accretion-ejection structures” (Ferreira et al. 1995-1997):
1) disk material diffuses across magnetic field lines, 2) is lifted upwards by MHD forces, then
3) couples to the field and 4) becomes accelerated magnetocentrifugally and 5) collimated

Quasi-magnetohydrostatic equilibrium, turbulent magnetic diffusivity:
Lorentz forces:
\[
F_{\phi} = \frac{B_p}{2\pi r} \nabla || I \\
F || = -\frac{B_{\phi}}{2\pi r} \nabla || I \\
F _\perp = B_p j_{\phi} - \frac{B_{\phi}}{2\pi r} \nabla _\perp I
\]

If \( F _\perp \) decreases \( \rightarrow \) gas pressure gradient lifts plasma from disk surface
If \( F || \) increases \( \rightarrow \) radial centrifugal acceleration of plasma
Jet launching

- Large consensus that outflows are likely driven by magneto-centrifugal winds from open magnetic field lines anchored on rotating circumstellar accretion disks.

- Two main competing theories: disk winds $\iff$ X-winds

- Are they launched from a very small area of the disk close to the truncation radius (X-wind), or over larger areas of the disk (disk wind)?
Jet-launching: Disk winds I

- Infalling core pinches magnetic field.
- If poloidal magnetic field component has angle larger 30° from vertical, centrifugal forces can launch matter-loaded wind along field lines from disk surface.
- Wind transports away from 60 to 100% of disk angular momentum.

Recent review: Pudritz et al. 2006
- On larger scales, a strong toroidal magnetic field builds up during collapse.

- At large radii (outside Alfven radius $r_{A}$, the radius where kin. energy equals magn. energy) $B_{\phi}/B_{p}$ much larger than 1
  --> collimation via Lorentz-force $F_{L} \sim j_{z}B_{\phi}$
- The wind is launched magneto-centrifugally from the inner co-rotation radius of the accretion disk (~0.03AU)
Ambipolar diffusion

Girart et al. 2006
Jet rotation in DG Tau

Bacciotti et al. 2002

Testi et al. 2002

Corrotation of disk and jet

Bacciotti et al. 2002
- From toroidal and poloidal velocities, one infer footpoints $r_0$, where gas comes from --> outer $r_0$ for the blue and red wing are about 0.4 and 1.6 AU (lower limits) --> consistent with disk winds
- About 2/3 of the disk angular momentum may be carried away by jet.
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Driving jet and entrained molecular outflow I

Grey: $H_2$
Contours: CO

HH212: Lee et al. 2006
IRAS20126+4104, Lebron et al. 2006
Driving jet and entrained molecular outflow II

HH211, Gueth et al. 1999, Hirano et al. 2006, Palau et al. 2006
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Outflow driving I

- Molecular outflow masses usually much larger than stellar masses
  --> unlikely that outflow-mass directly from star-disk, rather swept-up entrained gas.
- Clump mass correlates with outflow mass.
- Force observed in outflow cannot be explained just by force exerted from central object → other outflow driving and entrainment processes required.

[Graph showing the relationship between outflow mass and clump mass, and another graph showing force vs. luminosity with data from Wu et al. 2004, 2005.]
Outflow driving II

Momentum-driven vs. energy-driven molecular outflows

- In the energy-driven scenario, the jet-energy is conserved in a pressurized bubble that gets released adiabatically as the bubble expands. This would result in large transverse velocities which are not observed --> momentum conservation better!

**Completely radiative shock** → only dense plug at front

**Completely adiabatic shock** → large bow shocks with mainly transverse motions

Both wrong → Hence intermediate solution with highly dissipative shock required → forward motion and bow shock!

→ This can accelerate the ambient gas!

**Masson et al. 1993**
Outflow entrainment models I

Basically 4 outflow entrainment models are discussed in the literature:

Turbulent jet entrainment model
- Working surfaces at the jet boundary layer caused by Kelvin-Helmholtz instabilities form viscous mixing layer.
  --> The mixing layer grows with time and whole outflow gets turbulent.
- Broken power-law of mass-velocity relation is reproduced, but velocity decreases with distance from source.

Jet-bow shock model
- As jet impact on ambient gas, bow shock is formed at head of jet. High pressure gas is ejected sideways, entraining the ambient gas. Episodic ejection produces chains of knots and shocks.
- Numerical modeling reproduce many observables, e.g. Hubble-law.

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Raga et al. 1993
Gueth et al. 1999

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Gueth et al. 1999

Raga et al. 1993
The case of the HH34 bow shock

In the jet-frame, after subtracting the velocity of the mean axial flow, the knots are following the sides of the bow shock.
Jet simulations I

3-dimensional hydrodynamic simulations, including H, C and O chemistry and cooling of the gas, this is a pulsed jet.

Rosen & Smith 2004
Jet simulations II: small precession

P5 $H_2 1\rightarrow 0 \ S(1) \ t = 0 \ yr$

P5 $CO \ 0\rightarrow 0 \ R(1) \ t = 0 \ yr$

Rosen & Smith 2004
Jet simulations III, large precession

\[ P_{20} \quad \text{H}_2 \ 1 \rightarrow 0 \quad S(1) \quad t = 0 \text{ yr} \]

\[ P_{20} \quad \text{CO} \ 0 \rightarrow 0 \quad R(1) \quad t = 0 \text{ yr} \]

Rosen & Smith 2004
Outflow entrainment models II

Wide-angle wind model
- A wide-angle wind (a disk-wind from larger disk radii resulting naturally in lower velocities and lower collimation) blows into ambient gas forming a swept-up shell. Different degrees of collimation can be explained by different density structures.
- Attractive models for older and low collimated outflows.

Circulation model
- Molecular gas is not entrained by underlying jet or wind, but it is rather infalling gas that was deflected from the central protostar in a region of high MHD pressure.
- This model was proposed to explain massive outflows because it was originally considered difficult to entrain that large amounts of gas.
Maybe not necessary today anymore ...

Fiege & Henriksen 1996
Shu et al. 1991
### Outflow entrainment models III

#### Molecular outflow properties predicted by different models

<table>
<thead>
<tr>
<th>Model</th>
<th>Wind</th>
<th>Morphology</th>
<th>Velocity</th>
<th>Temperature</th>
<th>Momentum $^a$</th>
</tr>
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<tbody>
<tr>
<td>Turbulent Jet</td>
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<tr>
<td>Wide-angle Wind</td>
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$^a$ Assuming an underlying density distribution of $r^{-1}$ to $r^{-2}$.

Arce et al. 2002
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HH212: consistent with jet-driving
- pv-structure of jet- and wind-driven models very different.
- Often Hubble-law observed --> increasing velocity with increasing dist. from protostar
- Hubble-law maybe explained by: (a) decreasing grav. potential with distance to star
  (for central jet), (b) decreasing density gradient and hence pressure with distance
  from star (for larger-scale outflow), (c) continuous (or episodic) driving of the jet in
  a non-ballistic fashion that energy constantly gets induced in jet.

VLA0548: consistent with wind-driving
Episodic ejection events and bullets

Bachiller et al. 1994

Cut along the jet-axis
The mass-velocity relation usually displays a power-law. In the jet-entrainment model this can be explained by the successively larger annuli of the lower-velocity, entrained outer gas layers. Different power-laws and power-law breaks have been observed. This can be attributed to varying inclination angles and also periodicity.
Episodic ejection events II

Arce et al. 2001
Outflow precession and periodicity

Bachiller et al. 2001
Highest velocity molecular gas

NGC6334I, Leurini et al. 2006, T>50K

AFGL2591, van der Tak et al. 1999
Jet sizes

- Class 0: <0.8pc
- Class I: <0.6pc
- Class II: <0.25pc

Stanke 2003
Summary

- Protostellar jets are launched magnetohydrodynamically from the disk and then accelerated magneto-centrifugally.

- Outside the Alfvén radius $r_A$ (kin. energy equals magn. energy) $B_\phi$ dominates and collimation happens via Lorentz-force.

- Jet-launching discussed as disk-wind or X-wind. Observations support disk-wind scenario (although X-wind can be considered as special case of disk-wind at the inner disk-truncation radius).

- Various outflow-entrainment models, jet-entrainment and wide-angle wind are likely the two most reasonable mechanisms.

- Outflows/jets are likely episodic.

- Observational tools like pv-diagrams, mv-diagrams and various different jet/outflow tracers allow to constrain the models.