## Outflows and Jets: Theory and Observations
### Summer term 2011
Henrik Beuther & Christian Fendt

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Topics today

- Jet launching processes, magnetic field morphology and jet launching observations

- Outflow entrainment models

- Additional observables to constrain outflow/jet properties
Outflows & Jets: Theory & Observations

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
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.

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

- At large radii (outside Alfven radius $r_{A,\nu}$, the radius where kin. energy equals magn. energy) $B_\phi/B_p$ much larger than 1
  $\rightarrow$ collimation via Lorentz-force $F_L \sim j_z B_\phi$

Banerjee & Pudritz 2006
- 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-launching points and angular momenta

- From toroidal and poloidal velocities, one infers 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

HH211, Gueth et al. 1999, Hirano et al. 2006, Palau et al. 2006
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 core mass](Image1)

![Graph showing the relationship between force and luminosity](Image2)

*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 shocks 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 entraining molecular gas.
  → 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 → opposite to observations

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

Raga et al. 1993
Outflow entrainment models

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   - Working surfaces at the jet boundary layer caused by Kelvin-Helmholtz instabilities form viscous mixing layer.
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2. **Jet-bow shock model**
   - As jet impact on ambient gas, bow shocks are formed at head of jet. High pressure gas is ejected sideways, creating a broader bow shock entraining the ambient gas. Episodic ejection produces chains of knots and shocks.
   - Numerical modeling reproduce many observables, e.g. Hubble-law.

Gueth et al. 1999
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.
3-dimensional hydrodynamic simulations, including H, C and O chemistry and cooling of the gas, this is a pulsed jet.
Jet simulations II: small precession

\[
P_5 \quad \text{H}_2 \ 1 \rightarrow 0 \quad S(1) \quad t = 0 \text{ yr}
\]

\[
P_5 \quad \text{CO} \ 0 \rightarrow 0 \quad R(1) \quad t = 0 \text{ yr}
\]

Rosen & Smith 2004
Jet simulations III, large precession

P20 \( \text{H}_2 \ 1 \rightarrow 0 \ \text{S}(1) \ t = 0 \ \text{yr} \)

P20 \( \text{CO} \ 0 \rightarrow 0 \ \text{R}(1) \ t = 0 \ \text{yr} \)

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 collimations degree) blows into ambient gas forming a swept-up shell. Different degrees of collimation can be explained by different density structures of the ambient gas.
- Attractive models for older and low collimated outflows.

Circulation model
- Molecular gas is not entrained by an 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 models were proposed to explain also massive outflows because it was originally considered difficult to entrain that large amounts of gas.
- Maybe not necessary today anymore ...

Shu et al. 1991
Outflow entrainment models II

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# Outflow entrainment models III

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<tr>
<td>Turbulent Jet</td>
<td><img src="image1" alt="Diagram" /></td>
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<td>Jet Bow Shock</td>
<td><img src="image2" alt="Diagram" /></td>
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<td>Wide-angle Wind</td>
<td><img src="image3" alt="Diagram" /></td>
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<tr>
<td>Circulation</td>
<td><img src="image4" alt="Diagram" /></td>
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*Assuming an underlying density distribution of $r^{-1}$ to $r^{-2}$.*

Arce et al. 2002
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Collimation and pv-structure

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

Lee et al. 2001
Episodic ejection events and bullets

Moriarty-Schieven et al. 1988

L1551

-9 to 6 km s⁻¹

0 to 23 km s⁻¹

Moriarty-Schieven et al. 1988
Episodic ejection events and bullets

Cut along the jet-axis

Bachiller et al. 1994
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.
Highest velocity molecular gas

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

AFGL2591, van der Tak et al. 1999
Summary

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

- Outside the Alfven 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 us to constrain the models.
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