Driving mechanisms for molecular outflows

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Why are we interested?

- Molecular outflows are significant signatures of star formation
- They may be a useful constraint on jet/outflow launching mechanisms
- They can give us insight into the possibility of outflow-driven turbulence
- Self-regulated star formation ...

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Some fundamental properties

- By definition molecular outflows are poorly collimated
- Tend to be slow moving ($v \sim 10$–$20\,\mathrm{km\,s^{-1}}$)
- Shell-like morphology
- Tend to be cold (hence observed in CO)
- Are thought to be made up of shock-heated material which has had time to cool

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Typical outflows

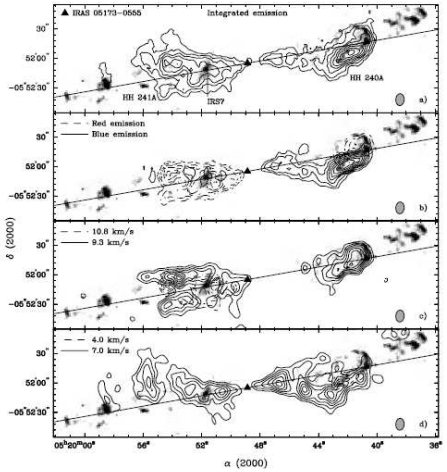

FIG. 3.—CO emission from the HH 240/241 region in the BIMA observations overlaid on a gray-scale H_2 image provided by Davis et al. (1997). The line indicates the major axis of the CO outflow. The triangle marks the position of IRAS 05173−0555. (*a*) The CO emission integrated over the entire line, from 13.13 to 1.70 km s^{-1}. (*b*) The red emission integrated from 13.13 to 9.32 km s^{-1}, and the blue emission integrated from 7.63 to 1.70 km s^{-1}. (*c*) and (*d*) Each shows two channel maps at different velocities. The velocity are given in the upper left corner of each panel. For (*a*) the contours start at 16 Jy beam^{-1} km s^{-1} with a step size of 8 Jy beam^{-1} km s^{-1}. For (*b*), the contours start at 10.0 Jy beam^{-1} km s^{-1} with a step size of 5 Jy beam^{-1} km s^{-1}. For panels (*c*) and (*d*), the contours start at 4.5 Jy beam^{-1} with a step size of 1.8 Jy beam^{-1}. The beam size is 12″.1 × 8″.53.

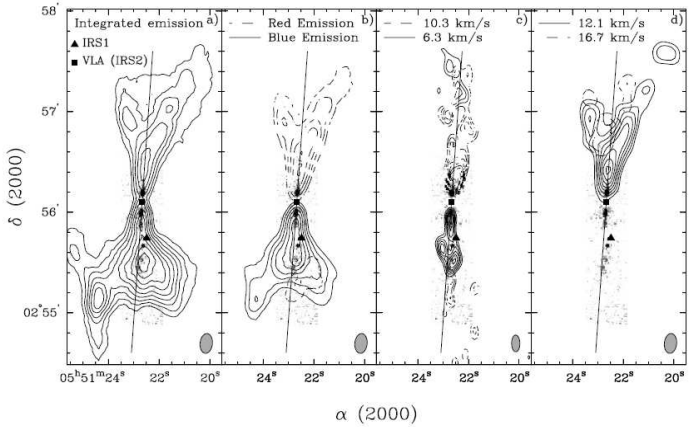

FIG. 1.—CO outflow emission for VLA 05487 in the BIMA observations overlaid on a gray-scale H_2 image provided by Garnavich et al. (1997). The line in each panel indicates the direction of the H_2 jet centered at VLA 05487 (IRS 2). (*a*) The CO emission integrated over the entire line profile, from 0.17 to 17.40 km s^{-1}. (*b*) The red emission (*dashed line*) integrated from 9.32 to 17.40 km s^{-1} and the blue emission (*solid line*) integrated from 8.30 to 0.17 km s^{-1}. (*c*) Channel maps to the red and blue showing the low-velocity outflow emission. (*d*) Two channel maps in the red wing showing how the outflow emission changes with increasing red-shifted velocity. For (*a*) and (*b*), the contours start at 10 Jy beam^{-1} km s^{-1} with a step size of 4 Jy beam^{-1} km s^{-1}. For (*c*), the contours start at 0.6 Jy beam^{-1} with a step size of 0.2 Jy beam^{-1}. For (*d*) the contours start at 1.5 Jy beam^{-1} with a step size of 0.5 Jy beam^{-1}. The beam size is 11″.82 × 7″.28 for (*a*), (*b*), and (*d*), while 9″.97 × 4″.91 for (*c*).

Lee et al (2000)

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PV diagrams

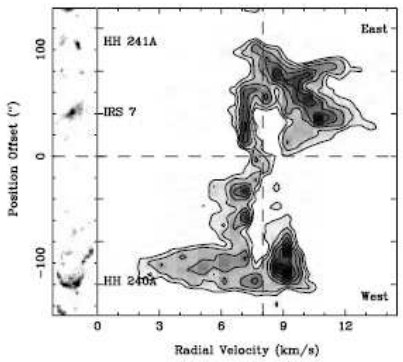

FIG. 8.—PV diagram of the HH 240/241 outflow cut along the major axis, with the H_2 image of the jet along the left side. The vertical dashed line indicates the ambient velocity. The horizontal dashed line indicates the driving source position. Contours start at 2.4 Jy beam^{-1} with a step size of 1.2 Jy beam^{-1}.

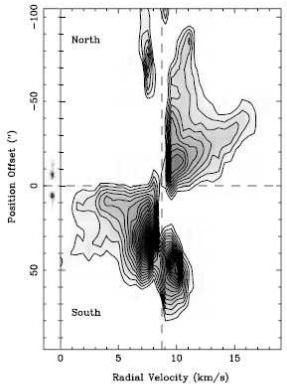

FIG. 6.—PV diagram of the VLA 05487 outflow cut along the jet axis, with the H_2 image of the jet displayed along the left side. Vertical dashed line indicates the ambient velocity. Horizontal dashed line indicates the driving source position. The contours start at 2.5 Jy beam^{-1} with a step size of 1 Jy beam^{-1}. The emission near ambient velocity is resolved out by the interferometer.

Lee et al (2000)

- Some outflows exhibit “spurs” in their PV diagrams
- Others appear to exhibit more oval features

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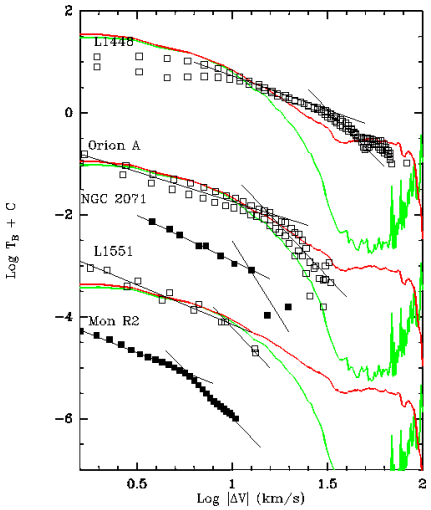
Line profiles



Tafalla & Bachiller (1999), Downes & Cabrit (2003)

- One of the most robust observations is that of a broken power-law dependence of *intensity* on velocity in the line wings

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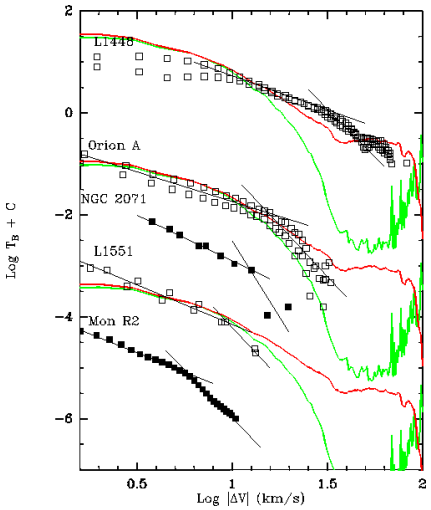
Line profiles



Tafalla & Bachiller (1999) & Downes & Cabrit (2003)

- The exponent lies in the range -1.5–-3 at low velocities, but ≤ -5 at higher velocities

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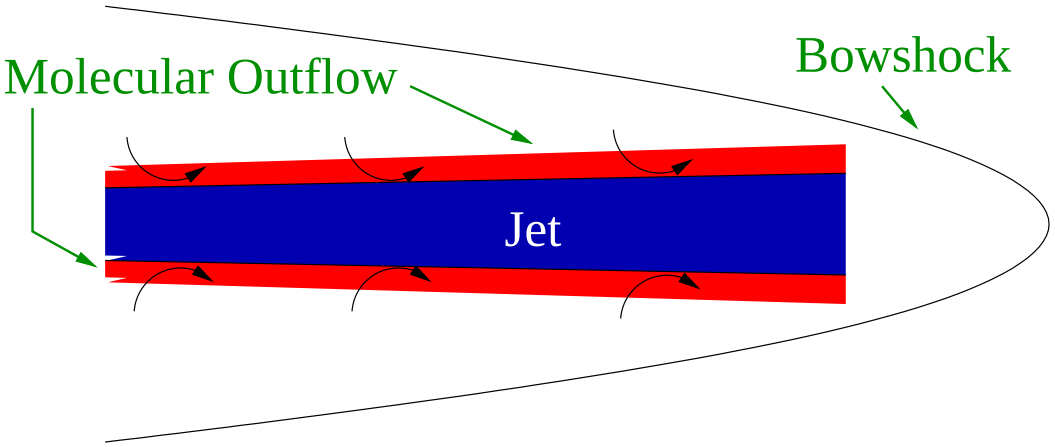
Models

Steady-state entrainment



Canto & Raga (1991); Stahler (1994) ...

- Relies on fluid instabilities to entrain material along the length of the underlying jet
- Will give rise to the “spurs” seen in PV diagrams

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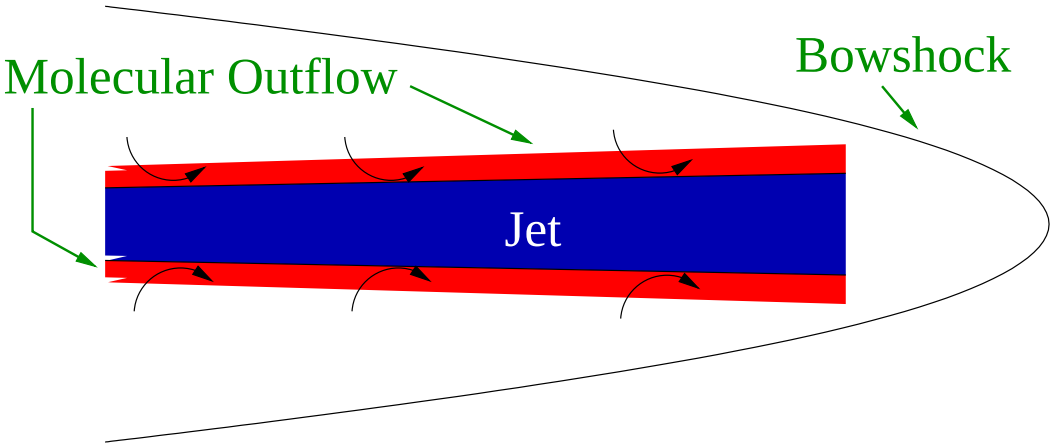
Steady-state entrainment



Canto & Raga (1991); Stahler (1994) ...

- Need an appropriate instability (none appear to exist)
- Jet would need to transfer up to $\sim$ 50% of its momentum without itself decollimating

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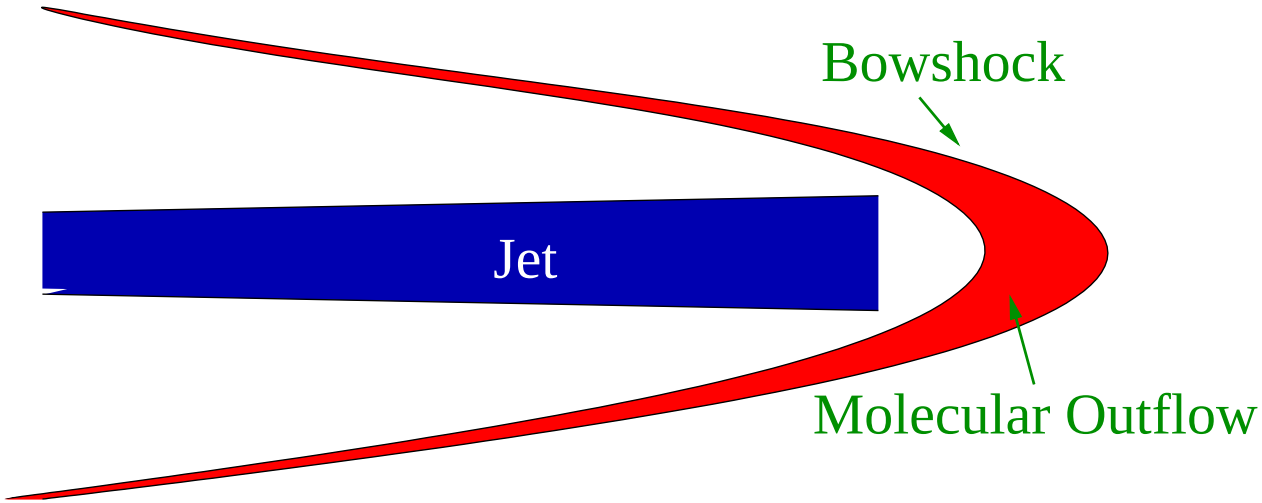
Jet-driven outflows



De Young (1986), Raga & Cabrit (1993), ...

- The jet drives a bowshock into the ambient medium.
- The bowshock is considered to be the molecular outflow.

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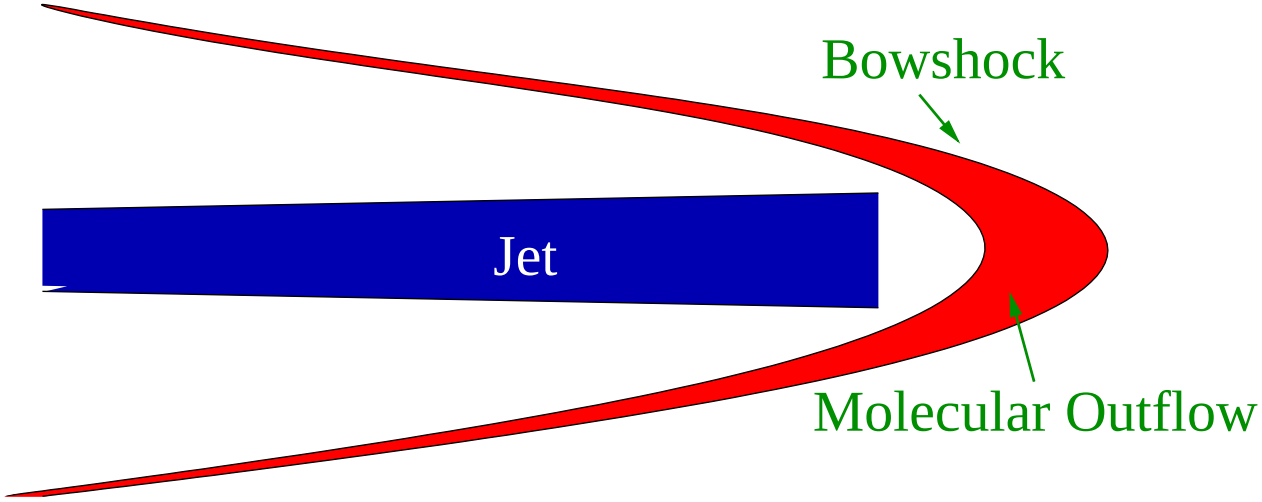
Jet-driven outflows



De Young (1986), Raga & Cabrit (1993), ...

- This material will be cool and much less well-collimated than the jet itself.
- Dissociation of molecules?

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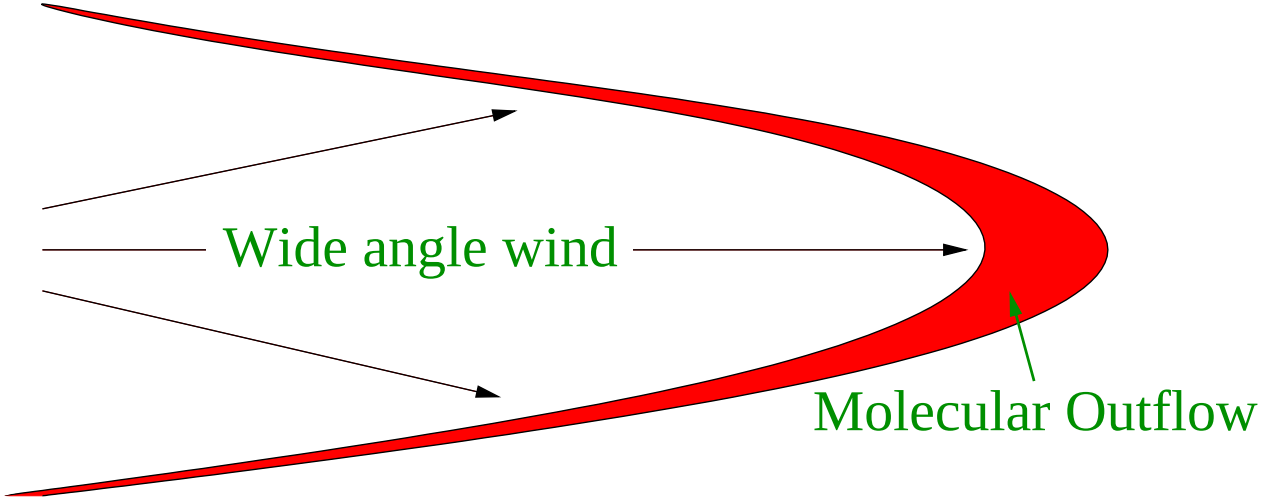
Wind-driven outflows



Shu et al (1991, 1995, ...), ...

- A wide-angled wind snow-ploughs into the ambient medium.
- The resulting dense shell is regarded as the molecular outflow.

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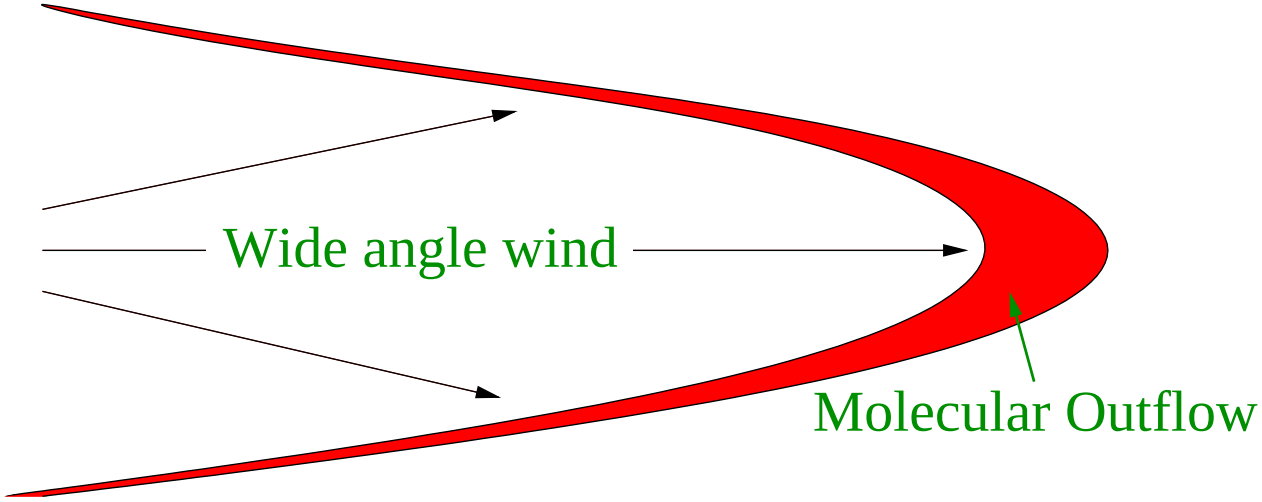
Wind-driven outflows



Shu et al (1991, 1995, ...), ...

- *As modeled so far, a* $\frac{1}{r^2}$ *profile for the ambient medium is an intrinsic part of this model* (cf J. Bally's talk)
- Dissociation of molecules?

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Jet-driven outflows

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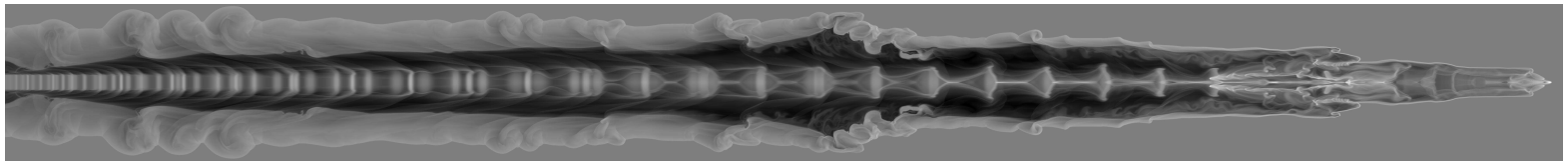
Morphology



Keegan & Downes (2005)

- Molecular outflow is less well-collimated than the underlying jet.
- It has a shell-like morphology, enclosing a low-density region (the jet cocoon).

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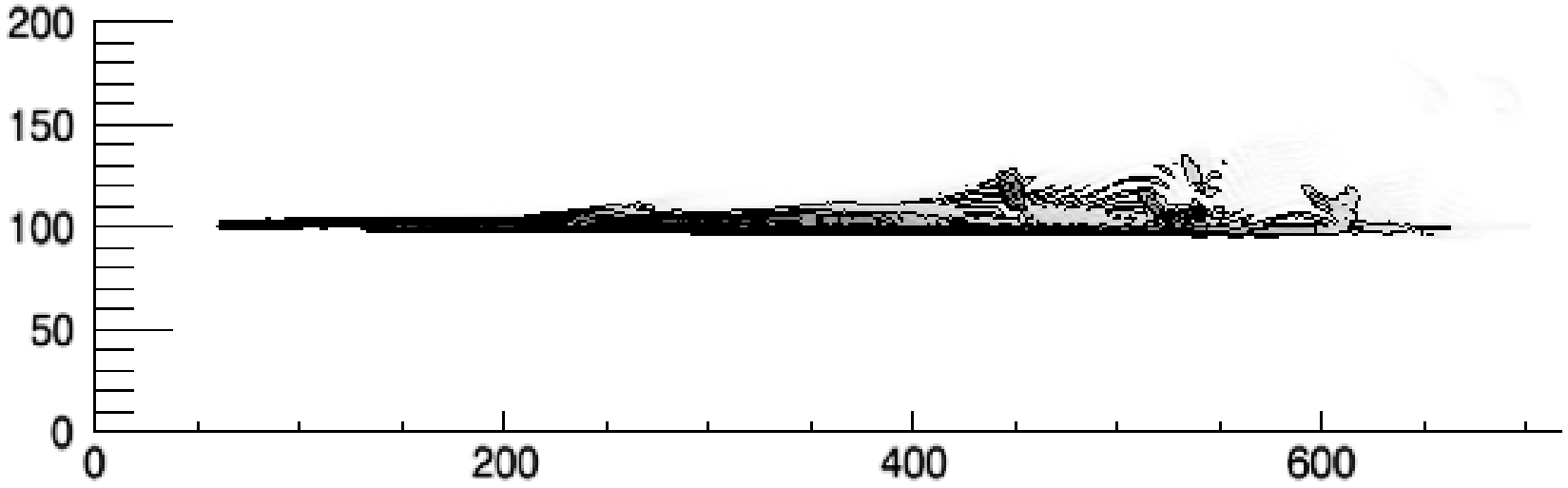
PV diagrams



PV diagram for a young, radiative jet with $i = 30^{\circ}$

- Spurs seen in PV diagrams.

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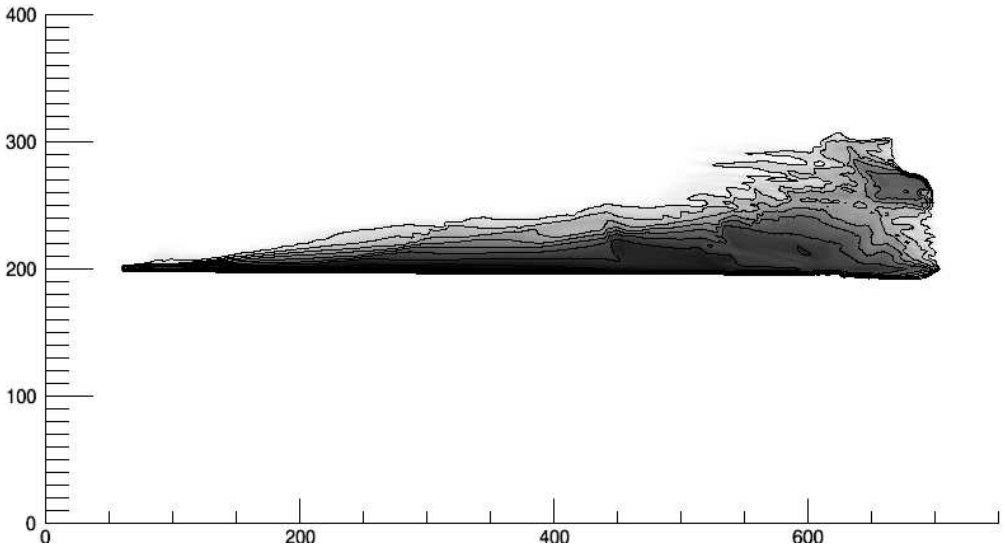
PV diagrams



PV diagram for a young, radiative jet with $i = 30^\circ$ - integrated over the whole flow

- Clear spurs seen in PV diagrams.

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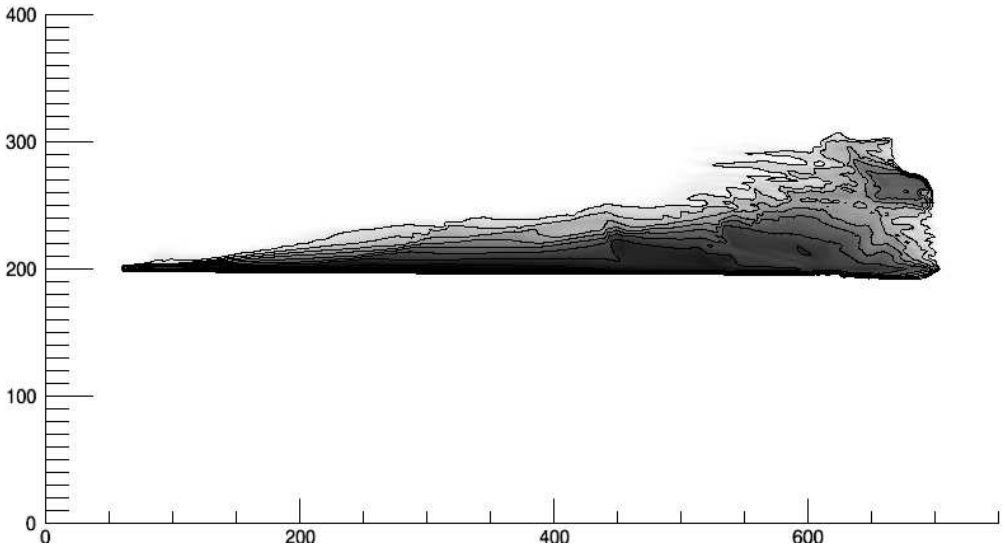
PV diagrams



PV diagram for a young, radiative jet with $i = 30^\circ$

- Result directly from the topology of the bowshock itself.

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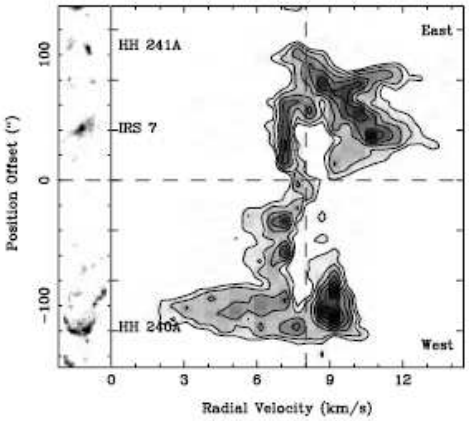
PV diagrams



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Lee et al 2000

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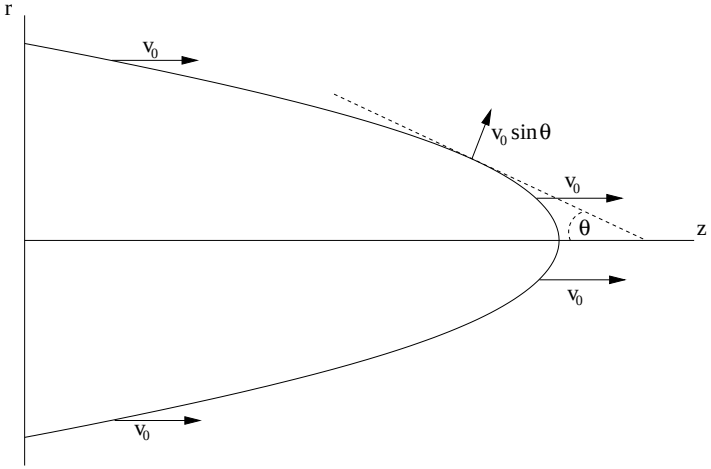
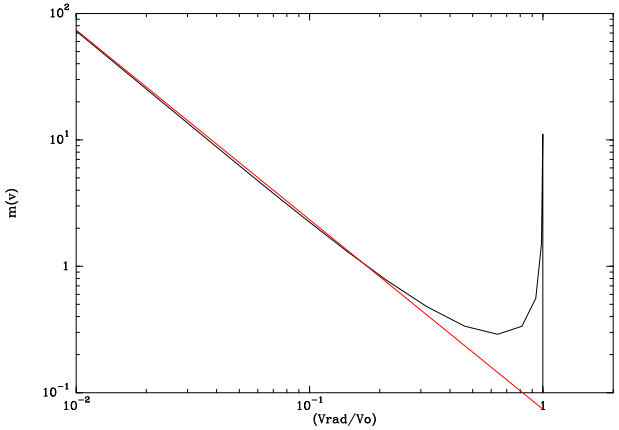
Line profiles





Smith, Suttner & Yorke (1997), Downes & Ray (1999), Downes & Cabrit (2003)

- Jet-driven outflows give very good matches to the observed line profiles

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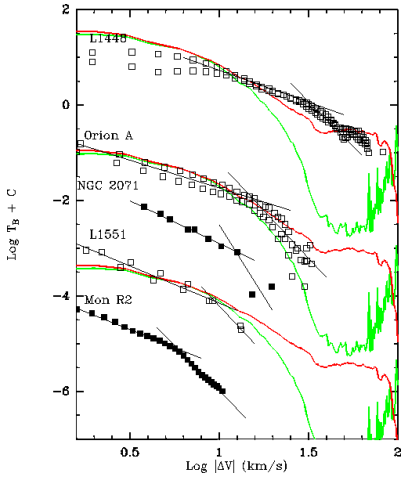
Line profiles



Tafalla & Bachiller (1999), Downes & Cabrit (2003)

- Get broken power-law behaviour
- Results from dissociation speed of CO rather than any kinematic properties (e.g. Zhang & Zheng 1997)

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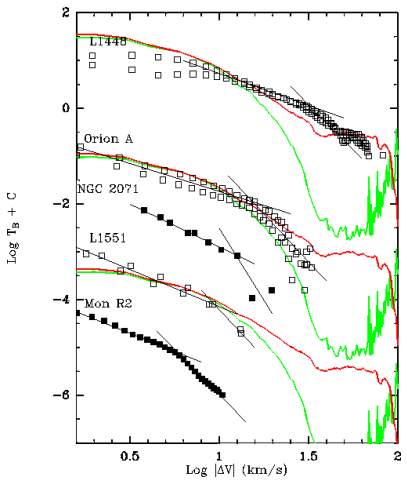

Tafalla & Bachiller (1999), Downes & Cabrit (2003)

- Slope at low velocities determined by shape of the bowshock

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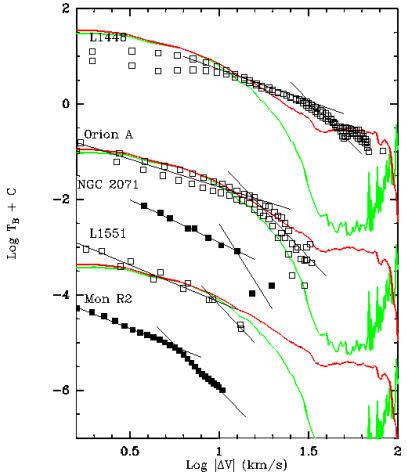
Line profiles



Tafalla & Bachiller (1999), Downes & Cabrit (2003)

- Slope at high velocities determined by both bowshock topology and temperature dependence of emissivity.

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Momentum budgets & timescales

- Bowshocks dissociate molecules
- Can they really accelerate enough molecules to make up molecular outflows? (Downes & Ray 1999)

Yes:

- Dissociation occurs only near the head of the shock, but most mass & momentum is in the wings
- The timescales estimated for Class 0 outflows are, in some cases, likely to be an order of magnitude too high
  $\longrightarrow$ need a higher momentum deposition rate than previously thought (Downes & Cabrit 2007)

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Wind-driven outflows

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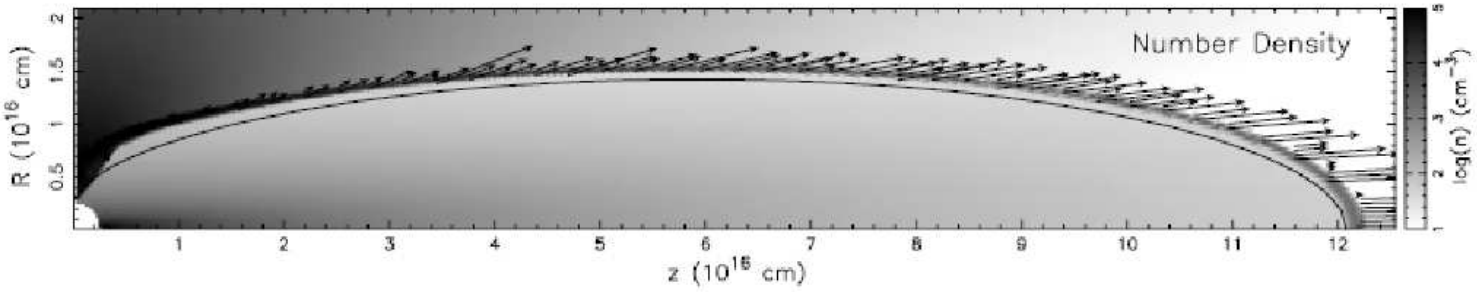
Morphology



Lee et al (2001)

- Isothermal wide angle wind with $v \sim \cos\theta$, $\rho \sim \frac{1}{(r\sin\theta)^2}$
- Shell-like morphology, surrounding a low density region

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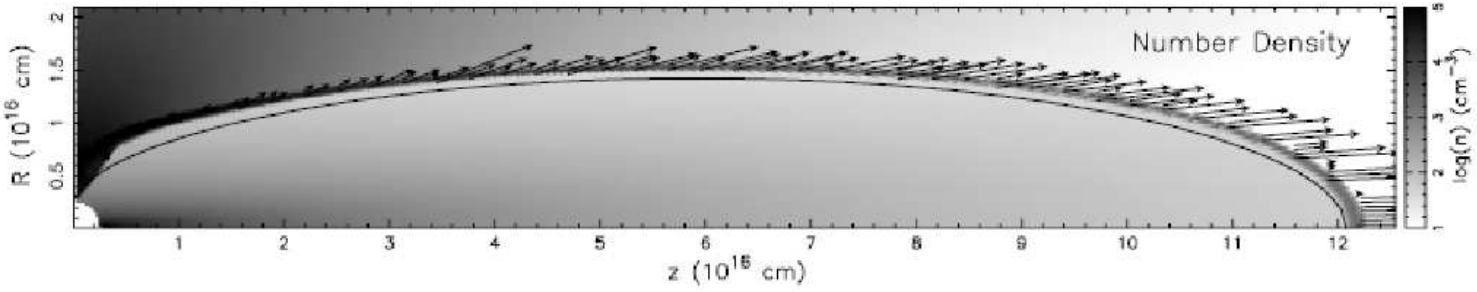
Morphology



Lee et al (2001)

- Can have very low length-to-width ratios

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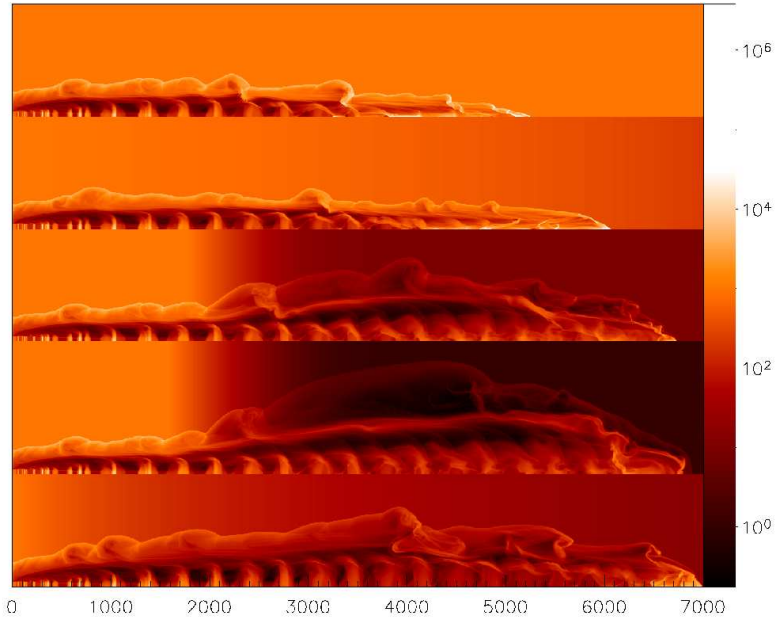
Morphology - back to jets ...



Corkery & Downes (2008, in prep)

- Assumption of $\frac{1}{r^2}$ helps the length-to-width issue for jets too ...

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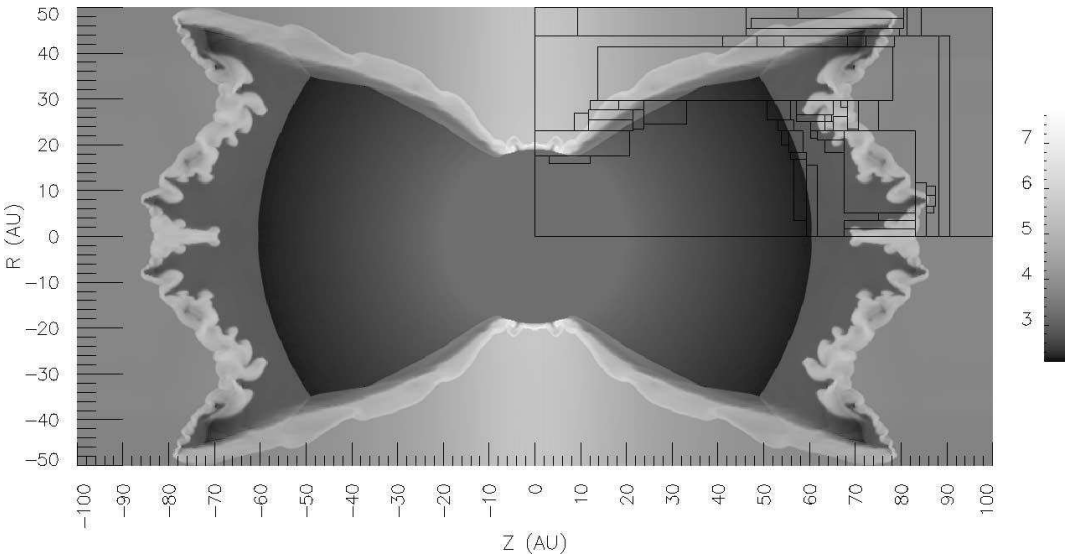
Morphology - back to winds ...



Cunningham et al (2005)

- Things change when we go to non-isothermal winds though ....

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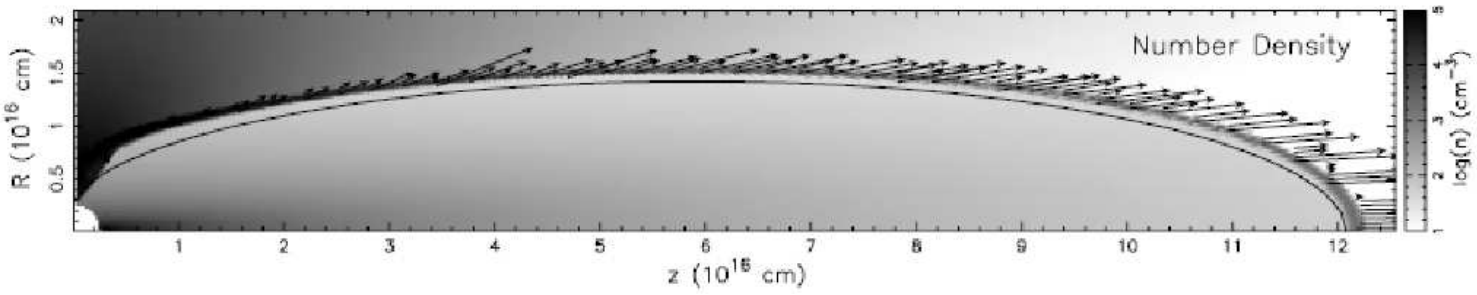
PV diagrams



Lee et al (2001)

- But let's suppose anyway ...

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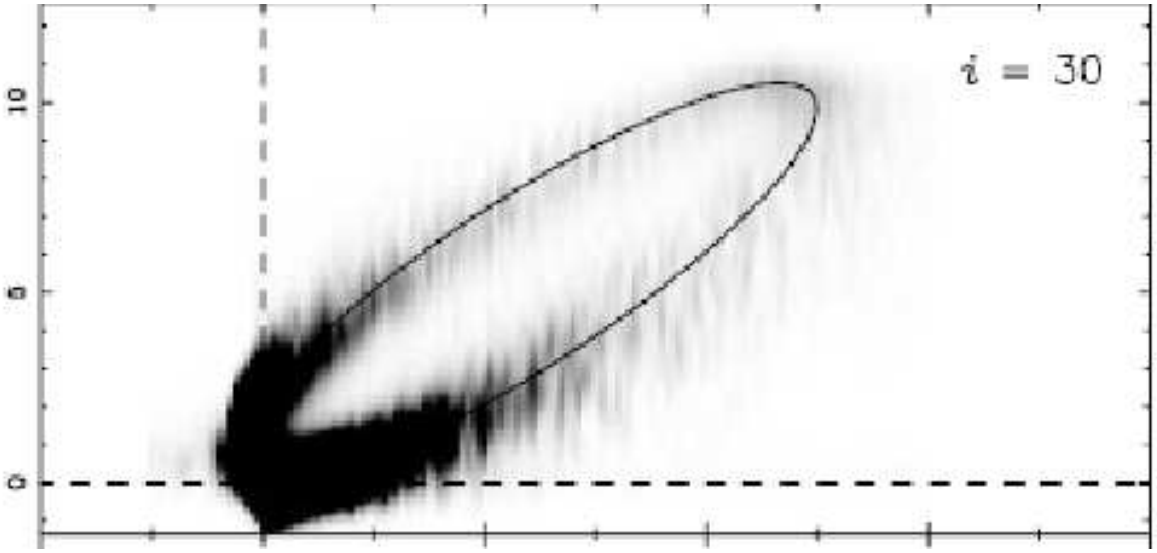
PV diagrams



- Tend not to generate spurs, but can generate parabolic/oval features (Lee et al 2000, 2001, 2002; Sheng et al 2006; Sheng 2007)

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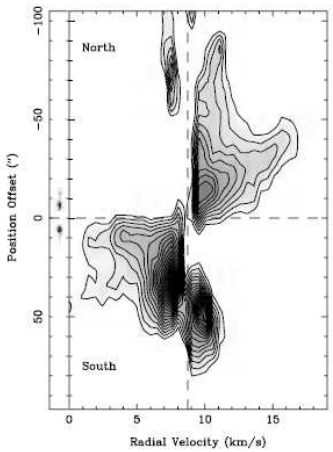
PV diagrams



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Lee et al 2000

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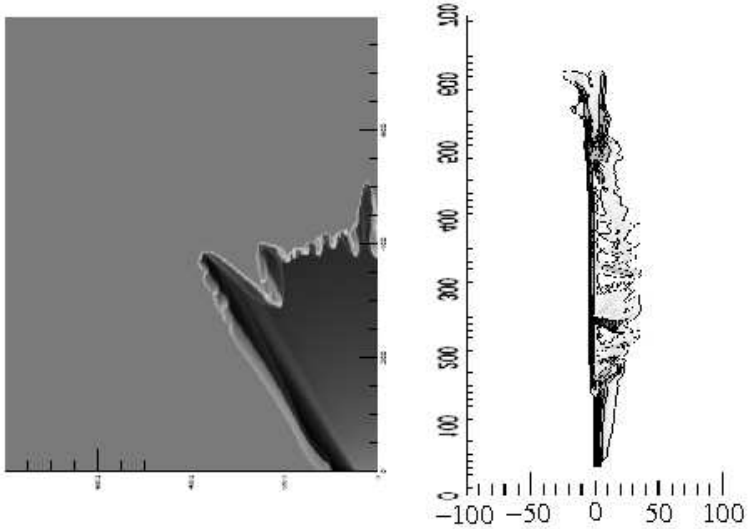

- This from a similarly aged non-isothermal wide angle wind into a uniform medium ...

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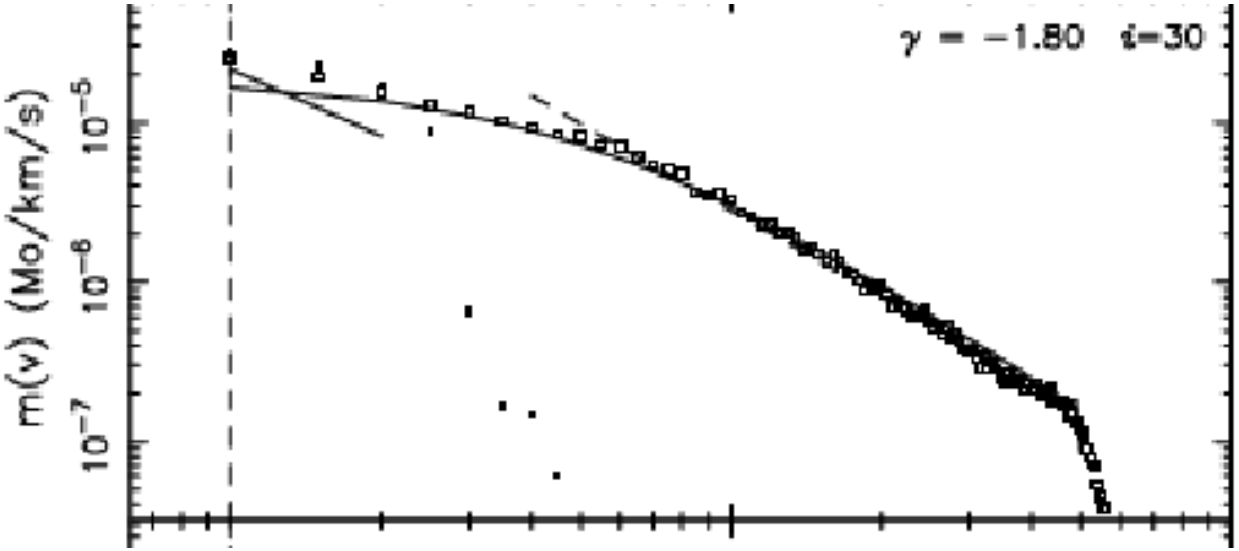
Line profiles



- Broken power-law is not so apparent, but does appear with low inclination angles (Lee et al 2001)

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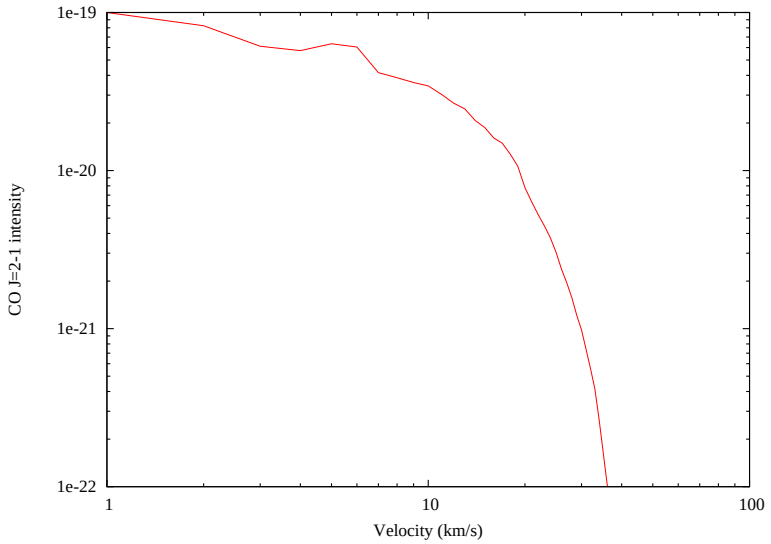
Line profiles



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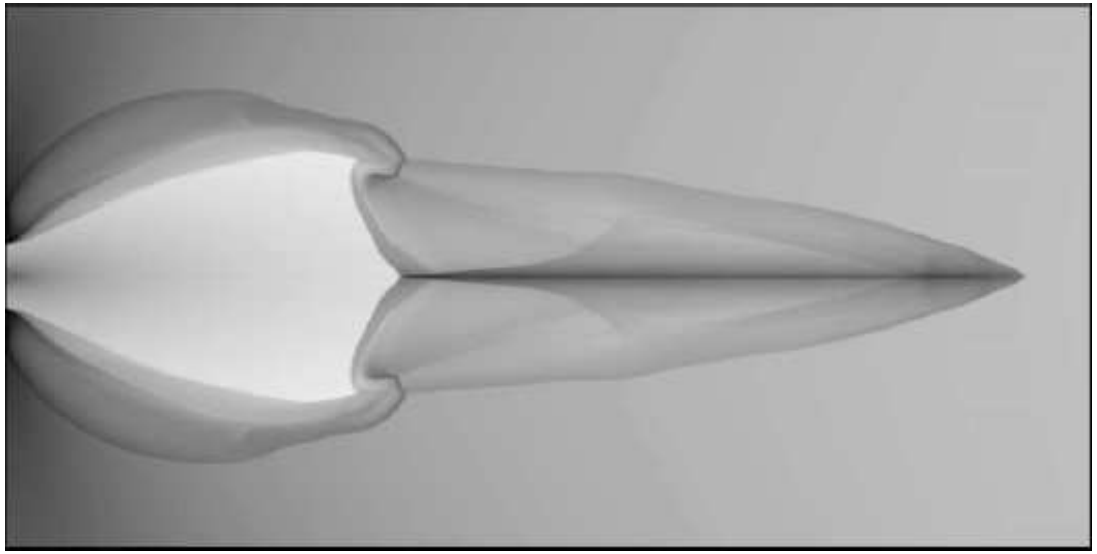
More physics ...



Cunningham et al 03

- Rotating, magnetized wide angle wind ....
- Radically different morphology ...

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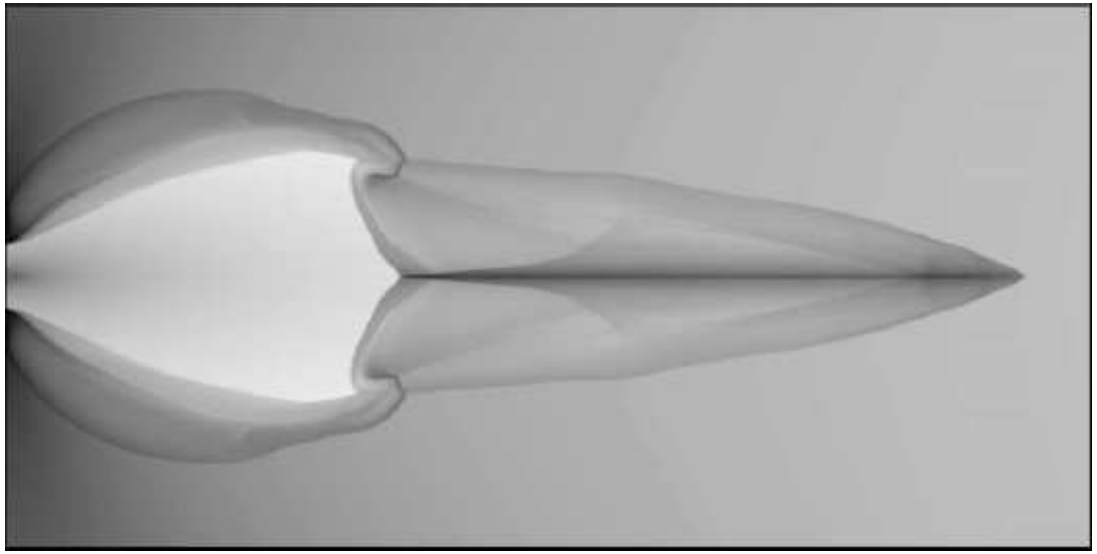
More physics ...



Cunningham et al 03

- Rotating, magnetized wide angle wind ....
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Jet vs. Wind models

Jet model:

- reproduces the morphology of many outflows (perhaps all if episodicity is introduced)
- reproduces PV diagrams of many outflows
- is very successful at producing the required line profiles

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Jet vs. Wind models

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- reproduces PV diagrams of many outflows
- is very successful at producing the required line profiles

Jet vs. Wind models

Wind model:

- can reproduce the morphology of many outflows
- reproduces PV diagrams of many outflows
- reproduces required line profiles (?)
- has not yet been used to produce synthetic observations
- appears to require a $\frac{1}{r^2}$ ambient density profile
- may require an unphysical assumption of isothermality

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Jet vs. Wind models

Wind model:

- can reproduce the morphology of many outflows
- reproduces PV diagrams of many outflows
- reproduces required line profiles (?)
- has not yet been used to produce synthetic observations
- appears to require a $\frac{1}{r^2}$ ambient density profile
- may require an unphysical assumption of isothermality

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Conclusions

- There are still two viable models ...
- The jet-driven model works well – good line profiles, PV diagrams (some concern still about morphology)
- The wind-driven model appears not to have been seriously tested yet
- Need much more detailed work to be done on the wind-driven model
- And a little bit more on the jet-driven one ...

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