How is the MHD turbulence driven in the dense ISM?

pc-scale outflows?
"Giant" Herbig-Haro Flows: PV Ceph

Reipurth, Bally & Devine 1997
Giant HH Flow in PV Ceph

$^{12}$CO (2-1) OTF
Map from NRAO 12-m

Red: 3.0 to 6.9 km s$^{-1}$
Blue: -3.5 to 0.4 km s$^{-1}$

Arce & Goodman 2001
Studies in Héctor Arce’s Ph.D. Thesis (Harvard, 2001; see Arce & Goodman 2001 a,b,c,d) show:

- HH 300 outflow has ~enough power (~0.5 \(L_{\text{sun}}\) at a 1-pc scale) to drive turbulence in its region of Taurus (using estimates based on Gammie & Ostriker 1996)
- Many outflows show clear evidence for “episodicity” and this may effect coupling of outflow energy to cloud
- Episodicity may also explain steep mass-velocity relations, and odd-looking p-v diagrams
- Outflow sources move through the ISM (e.g. PV-Ceph)
NGC 2264G

profile. These observations show that the variation of flow emission and mass with velocity is not self-similar at all flow velocities. Similar departures from single power-law shapes have also been observed at high velocities in the profiles of the Orion A (Kuiper et al. 1981), L1448, and Mon R2 (Tafalla 1993) outflows. Moreover, in these flows the slopes of the profiles beyond the spectral break are quite similar (i.e., $\gamma \sim -3.5$) to that reported here. Tafalla (1993) has also presented evidence that suggests that spectral breaks may be present in the Orion B, NGC 2071 and L1551 outflows at high flow velocities.

$\gamma \sim 1.8$

$\gamma \sim 3.5$

Fig. 2.—Observed mass distributions for three outflows. The vertical scale shows the mass per velocity interval ($M_\odot/(km\ s^{-1})$, integrated over each lobe of the outflow, and the horizontal scale shows the absolute value of the velocity offset from the line center (km s$^{-1}$). The triangles show data for NGC 2071, the squares show L1551, and the pentagons show the red lobe of HH 46-47. The lines show power-law fits to the data.

**SUCCESSIVE EJECTION EVENTS IN THE L1551 MOLECULAR OUTFLOW**

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High-velocity molecular bullets in a fast bipolar outflow near L 1448/IRS 3

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FIG. 10. Northeast lobe of the IRS 1 flow. (a) Area-integrated spectrum of region R2 in 12CO J = 2
1 (solid line), 12CO J = 10 (dotted line), and 13CO J = 10 (dashed line). (b) Fit to the ratio of
optical depths R12/13 = (12CO J = 10)/(13CO J = 10), integrated over the region. Valid points
kept for the fit are those with ratios with both intensities above twice the rms noise and for
velocities outside the turbulent line core (diamonds). Invalid points not meeting those criteria are
indicated by a cross. The second-order polynomial fit to the valid points is shown as a solid curve.
The dashed line is the result of fitting a parabola to the entire cloud in region R1. Vertical dashed
lines outline the turbulent line core (cloud vLSR ± 0.75 km s⁻¹). (c) Luminosity mass vs.
inclination-corrected velocity from center of the flow. Lines show fits to the power law ML
⁻γ. Points for the blueshifted lobe are indicated by diamonds; the redshifted lobe points by
triangles. Filled symbols denote masses calculated directly from 13CO J = 10; open symbols denote
masses calculated from the fit of the optical depth ratio. (d, e, and f) Same as (a), (b), and (c)
except that they are for the southwest lobe of the IRS 1 flow (region R3).

FIG. 11. Northeast lobe of the IRS 1 flow with the ambient cloud subtracted out. (a) Area-integrated 12CO J = 21 emission in region R2 (thin line); same emission with the ambient
cloud (defined by region R4) subtracted out (thick line). (b and c) Same as for Fig. 10. (d, e, and
f) Same as (a), (b), and (c) except that they are for the southwest lobe of the IRS 1 flow (region
R3 in Fig. 9) with the ambient cloud (region R5 in Fig. 9) subtracted out.
Sample outflow position-velocity diagrams

Lada & Fich 1996

Bachiller, Tafalla & Cernicharo 1994

Yu Billawala & Bally 1999

Bachiller et al. 1990
Outflow position-velocity diagrams

Behavior

“Hubble” Wedges

Example

Velocity

Single or Dominant “Hubble” Flow

Position

z (distance from source) [pc]
Variations in Burst History...

- e.g. NGC2264: Single or Dominant “Hubble” Flow
- e.g. L1448: Sorted “Hubble” Wedges
- e.g. B5, HH300: Random “Hubble” Wedges

Position

Velocity
Mass-Velocity & Position-Velocity Relations in Episodic Outflows

Power-law Slope of Sum = -2.7
Slope of Each Outburst = -2

A,B,C... for constant $v_{\text{max}}$
a,b,c... for varying $v_{\text{max}}$
(alphabetical=chronological)

Arce & Goodman 2001
Time-Ordering of p-v Diagrams?
Episodic ejections from precessing or wobbling moving source

Required motion of 0.25 pc (e.g. 2 km s$^{-1}$ for 125,000 yr or 10 km s$^{-1}$ for 25,000 yr)

Arce & Goodman 2001
Even leaves a trail?

Arce & Goodman 2001

Cloud $V_{LSR} = 1.68$ km/sec starting contour= 1.5 K km/sec contour steps= 1 K km/sec
Outflows Driving Turbulence

- What you see (now) is not the whole story.
  - Outflows seem to have a complex time-history.
  - Sources may travel.

Questions Raised:
- Is true net momentum/energy input is still measurable from observations?
- Do simulations need to include time history, or is “net” enough?
- How do we find all the flows?