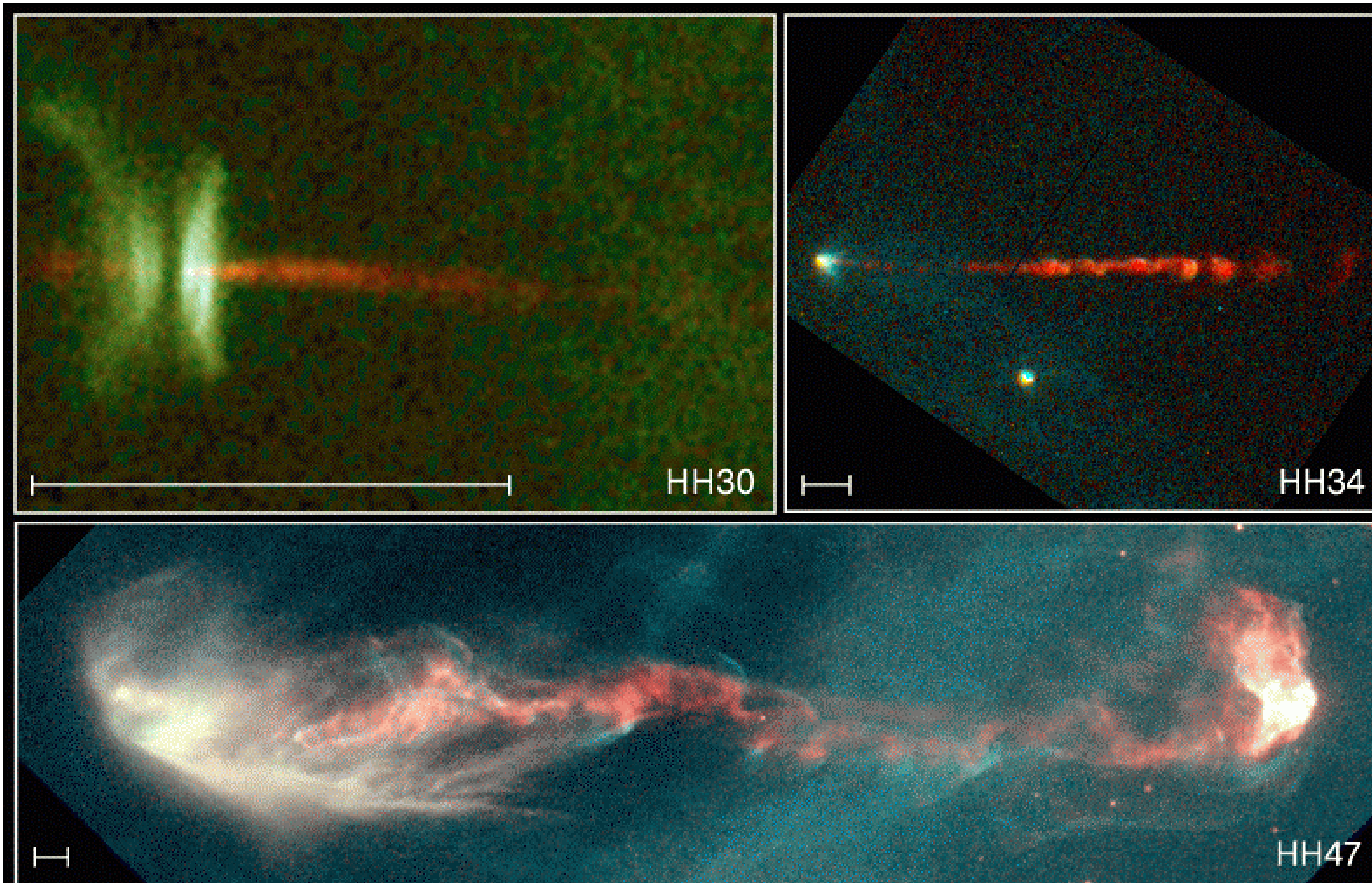
How is the MHD turbulence driven in the dense ISM?

pc-scale outflows?



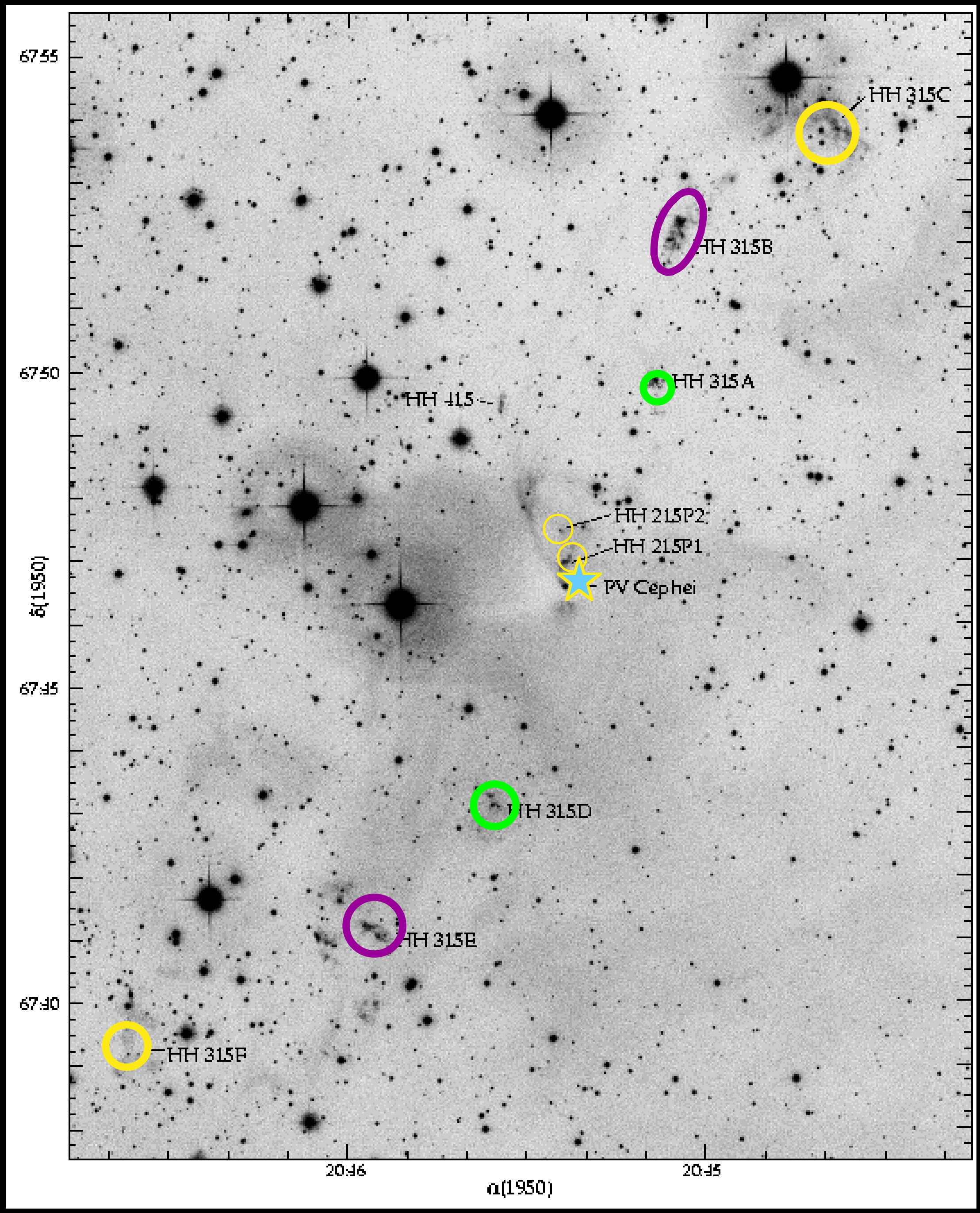
Jets from Young Stars HST • WFPC2

PRC95-24a • ST ScI OPO • June 6, 1995

C. Burrows (ST ScI), J. Hester (AZ State U.), J. Morse (ST ScI), NASA

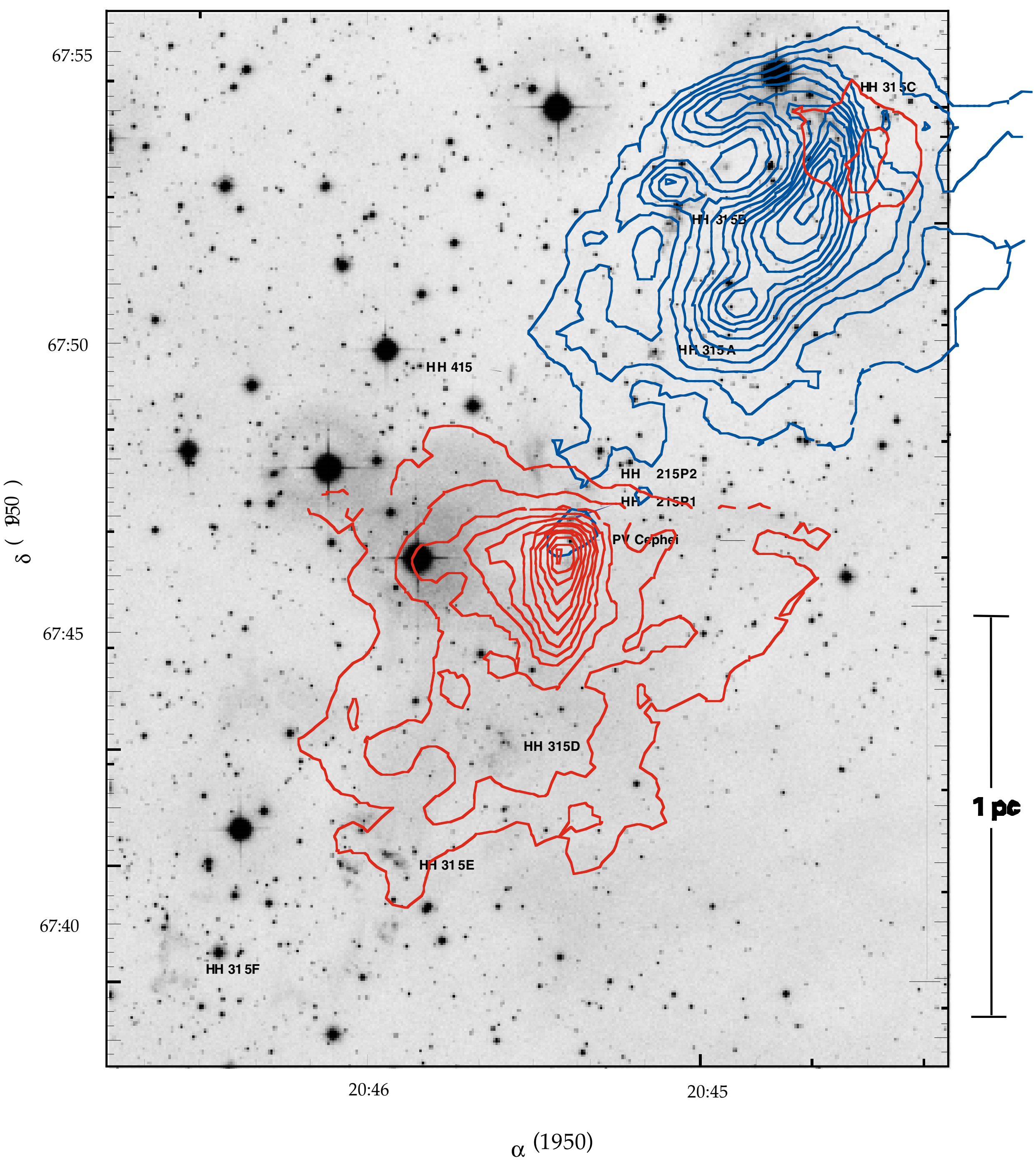
"Giant" Herbig-Haro Flows: PV Ceph

1 pc



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

Driving Turbulence with Outflows

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_{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

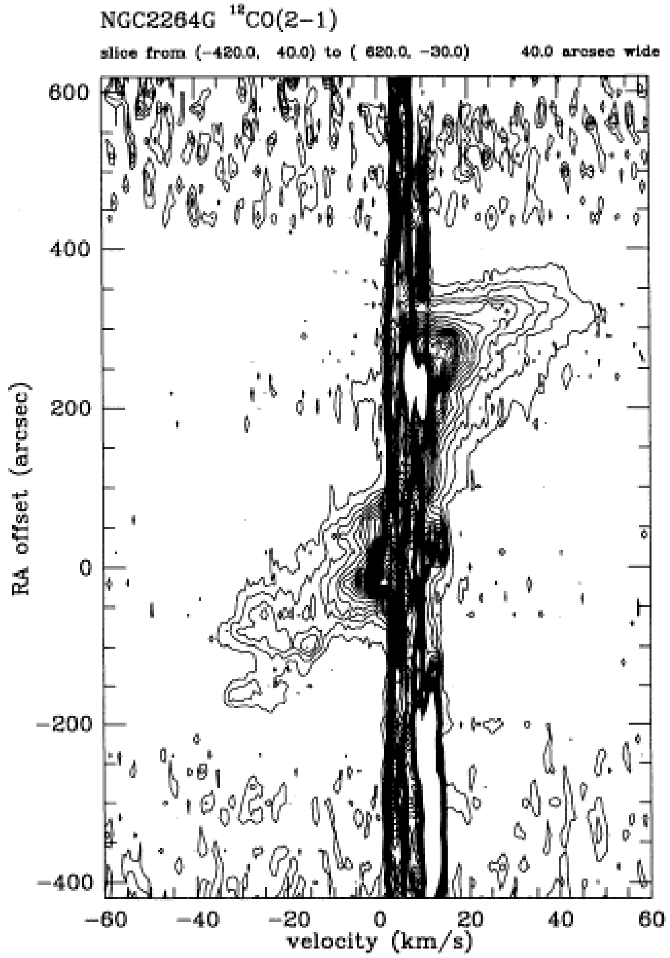


FIG. 4.—The position-velocity map in a 40" wide strip along the major axis of the NGC 2264G outflow. The bipolar velocity field of the outflow is clearly observed. A linear increase in flow velocity with distance from the center of symmetry of the flow appears to characterize the velocity field. Despite the close similarity in both spatial and velocity extent of the outflowing gas, the detailed structure of the velocity fields in the red and blue lobes is strikingly different. The contour intervals are 0.15 K beginning with the 0.1 K contour.

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.

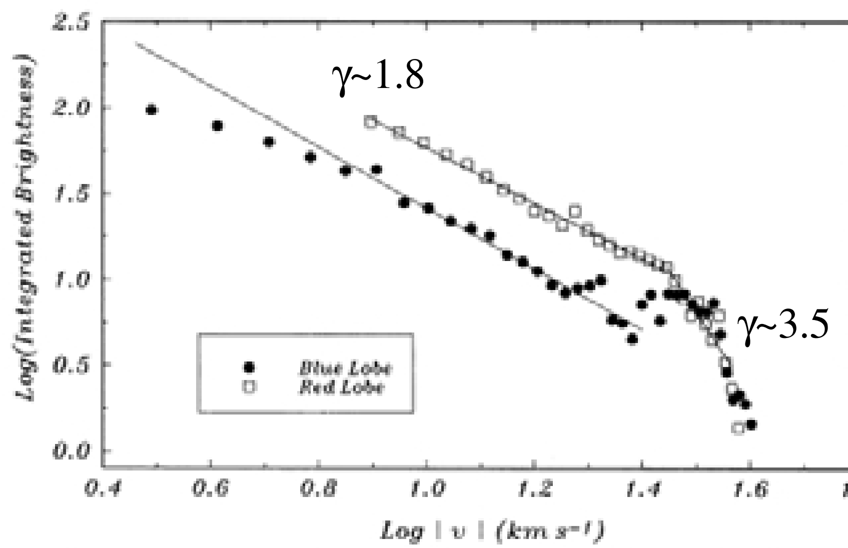


FIG. 2.—Velocity profiles for outflow emission in the red- and blueshifted lobes. This graph shows the sum of the CO integrated intensitie intervals for all positions in each lobe of the outflow as a function of the absolute value of flow velocity. Here the flow velocity is measured with rest velocity of the outflow (i.e., $v = v_{lsr} - v_0$).

Lada, C.J. & Fich, M. 1996, ApJ,.459, 638

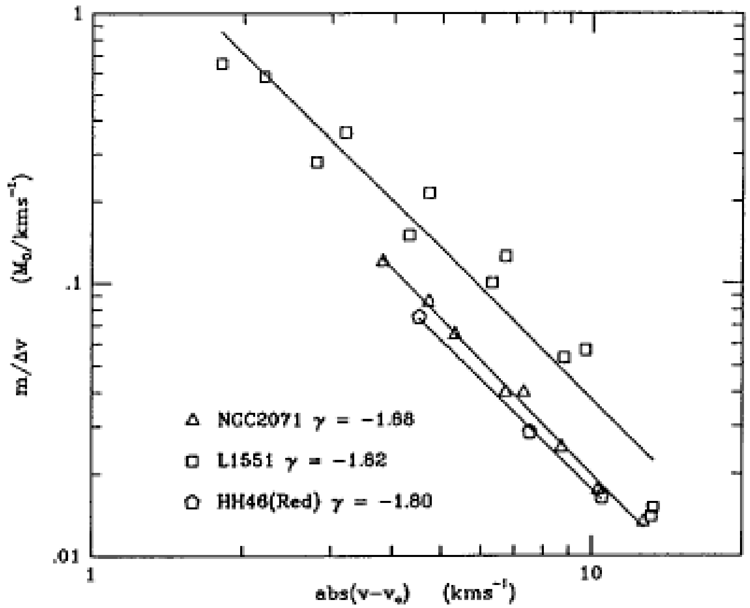


FIG. 2.—Observed mass distributions for three outflows. The vertical scale shows the mass per velocity interval ($M_{\odot}$/km s^{-1}), integrated over each lobe of the outflow, and the horizontal scale shows the absolute value of the velocity offset from the line center (km s^{-1}). The triangles show 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.

PROPERTIES OF SWEPT-UP MOLECULAR OUTFLOWS

COLIN R. MASSON

AND

LAWRENCE M. CHERNIN

THE ASTROPHYSICAL JOURNAL, 387:L47–L50, 1992 March 1

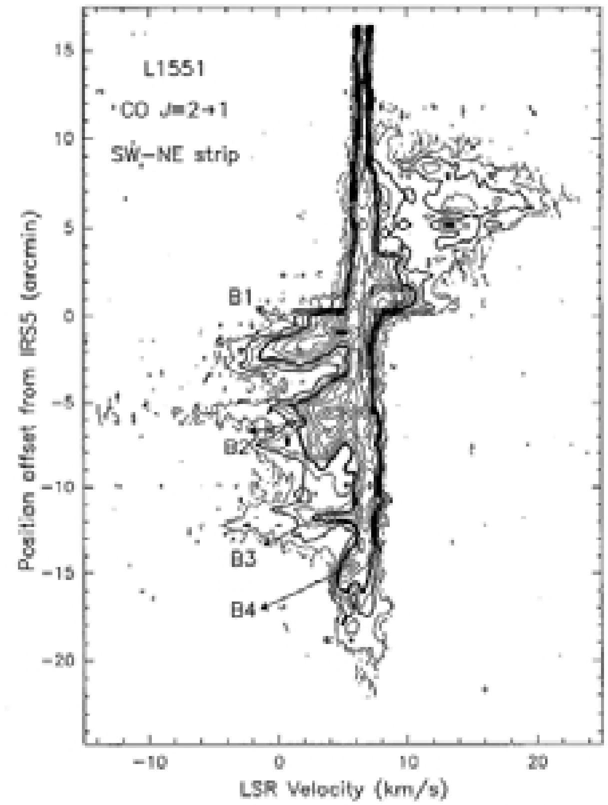


FIG. 1.—Velocity-position diagram along a SW-NE line, i.e., close to the main L1551 outflow axis, in the CO 2→1 line. Position offsets are in arcseconds with respect to IRS 5, which is 04ʰ28ᵐ40ˢ1, 18°01′41″2 (1950.0). Contours are at 1 K (*dash*), 1.5, 3 (*thick*) 4.5, 6 (*thick*), ... etc. B1, B2, B3, and B4 are the high-velocity features discussed in the text.

SUCCESSIVE EJECTION EVENTS IN THE L1551 MOLECULAR OUTFLOW

R. BACHILLER,[1] M. TAFALLA,[1,2] AND J. CERNICHARO[1]

THE ASTROPHYSICAL JOURNAL, 425:L93–L96, 1994 April 20

L1551

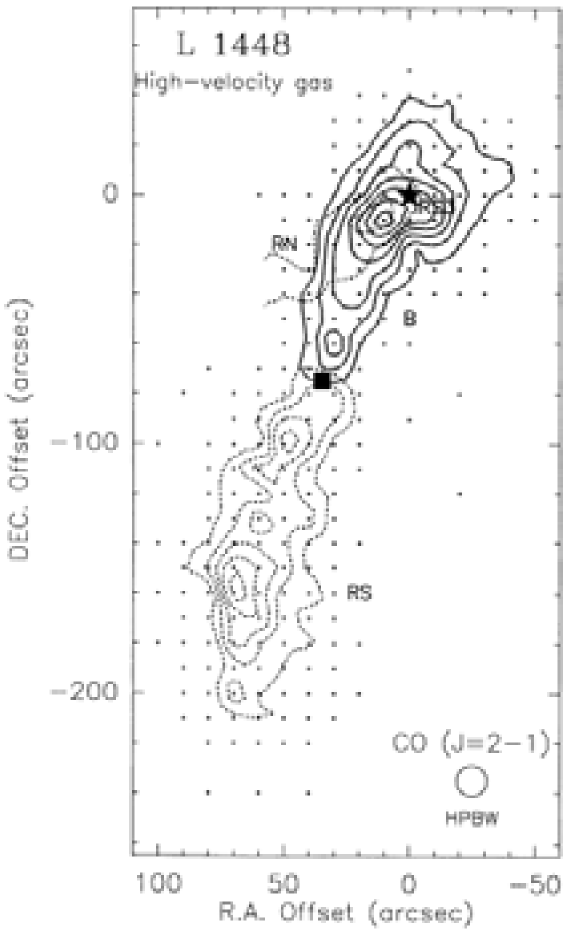


Fig. 8. Map of CO $J = 2 - 1$ intensity integrated in the line wings. The solid contours are for the blueshifted emission (from $-55\,km\,s^{-1}$ to $0\,km\,s^{-1}$) and the dashed contours for the redshifted emission (integrated from $10\,km\,s^{-1}$ to $65\,km\,s^{-1}$). First contour and contour interval are $10\,K\,km\,s^{-1}$. The high-velocity CO emission probably results from the superposition of two different outflows. The main outflow is centered on the position marked by the black square, we predict that at this position must be placed an un-seen young stellar object: the "U-star". The second outflow is probably excited by IRS 3 (see text for details)

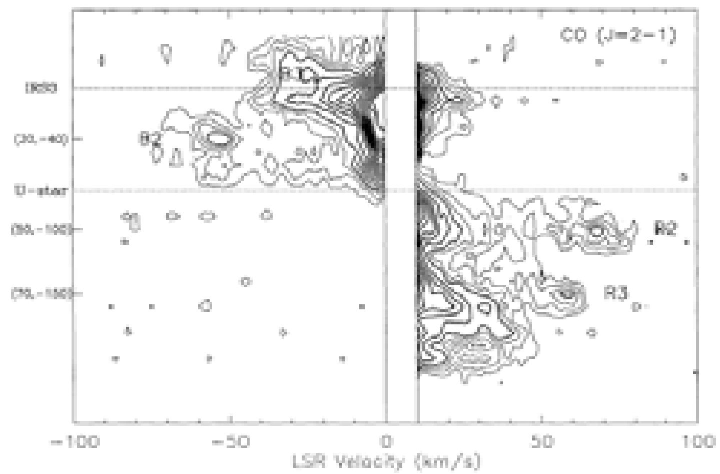


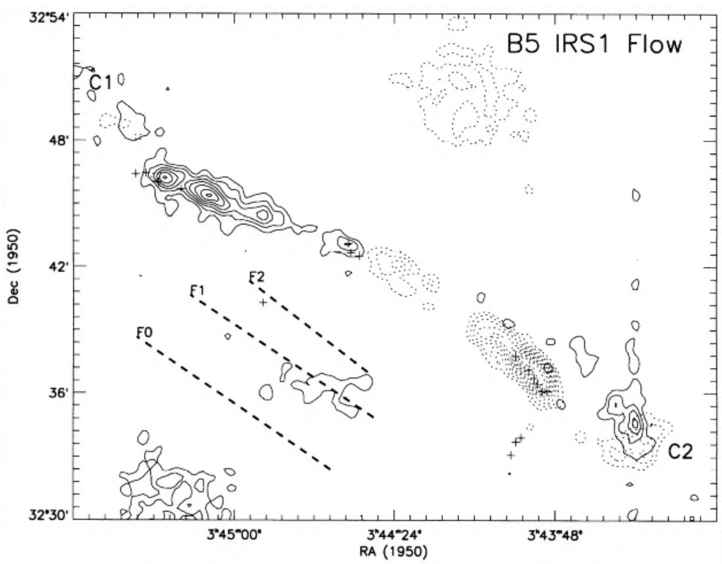
Fig. 10. Velocity-position diagram along a line passing through the U-star position, IRS 3 and several high-velocity bullets. This line is close to the main outflow axis. The IRS 3 and U-star positions are indicated by dashed horizontal lines; some other positions, where CO bullets are seen, are indicated in the left axis (offsets with respect to IRS 3 are in arcsec). The emission in the velocity interval 0–10 $km\,s^{-1}$ is dominated by the ambient cloud, and the contours in this zone have not been displayed for clarity. Several molecular bullets at high-velocities are clearly seen (B2, R2, R3). Note also the deceleration of the high-velocity gas from the U-star position. Light contours are at 0.2, 0.4 and 0.6 K, solid contours are at 0.8, 1.2, 1.6 K, ... etc

Astron. Astrophys. 231, 174–186 (1990)

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

R. Bachiller[1], J. Cernicharo[1,2], J. Martín-Pintado[1], M. Tafalla[1,★], and B. Lazareff[3]

L1448



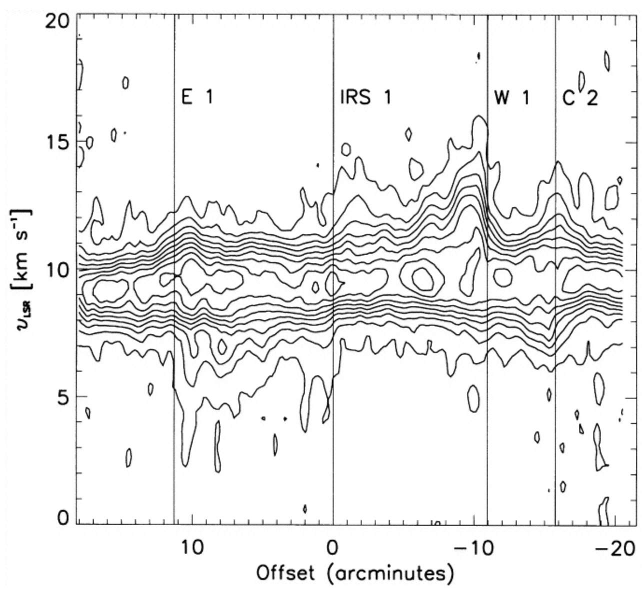


FIG. 10.Northeast lobe of the IRS 1 flow. (a) Area-integrated spectrum of region R2 in 12CO J = 2 1 (solid line), 12CO J = 10 (dotted line), and 13CO J = 10 (dashed line). (b) Fit to the ratio of optical depths R12/13 = (12CO J = 10)/(13CO J = 10), integrated over the region. Valid points kept for the 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 v-. 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).

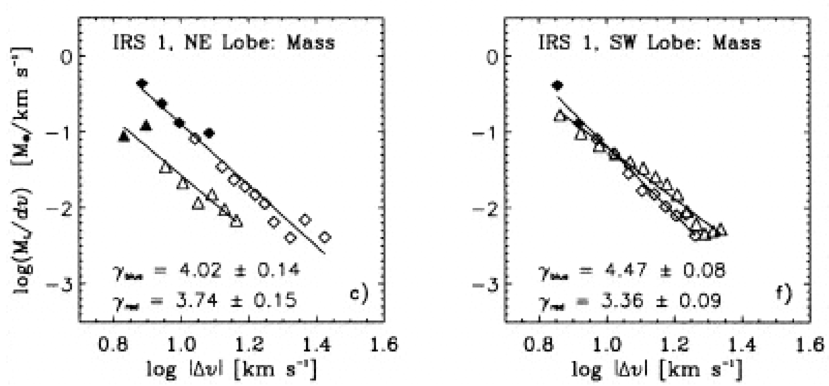
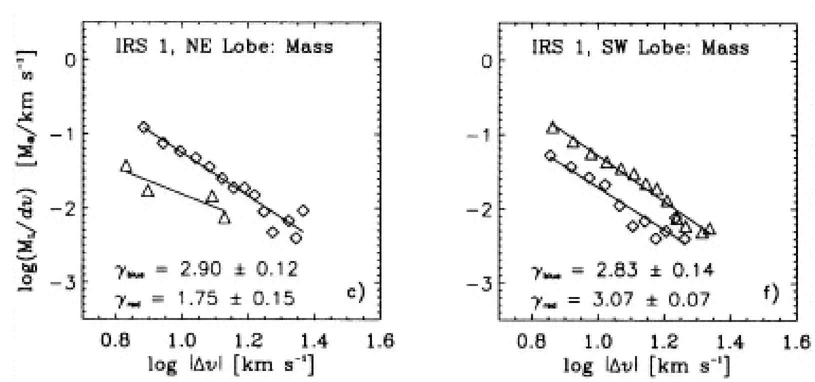


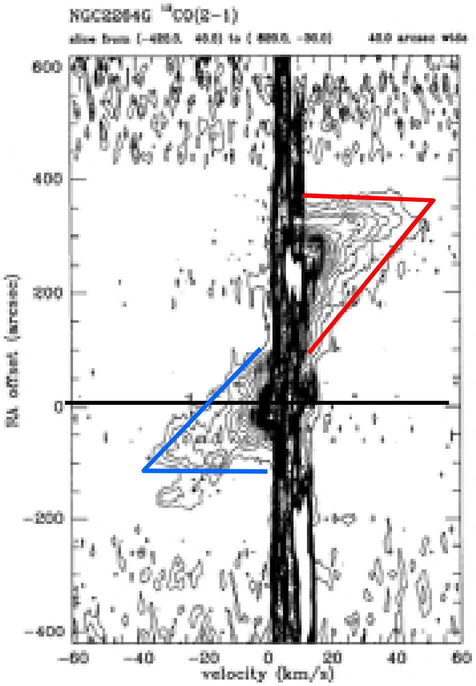
FIG. 11.Northeast lobe of the IRS 1 flow with the ambient cloud subtracted out. (a) Area-integrated 12CO J = 21 emission in region R2 (thin line); same emission with the ambient cloud (defined by region R4) subtracted out (thick line). (b and c) Same as for Fig. 10. (d, e, and f) Same as (a), (b), and (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.



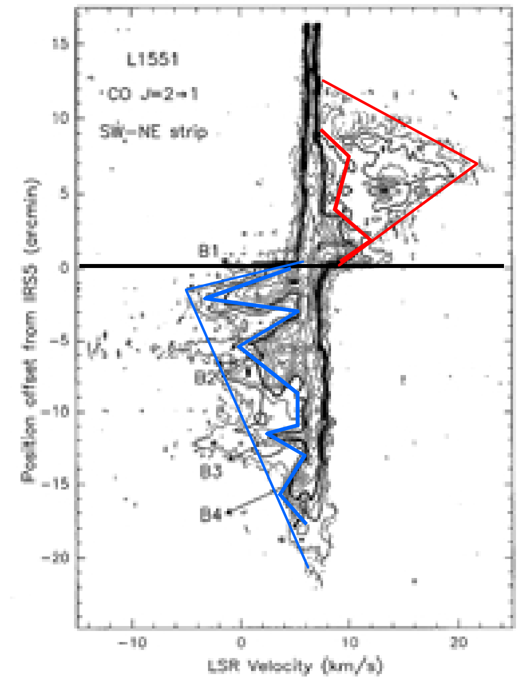
Yu, Billawala, Bally, 1999

B5

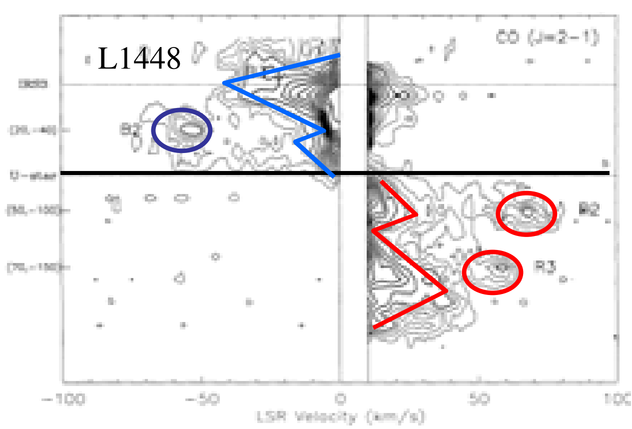
Sample outflow position-velocity diagrams



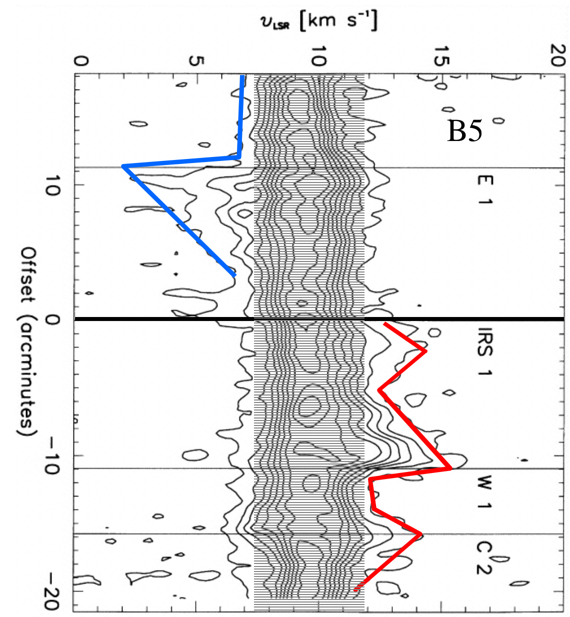
Lada & Fich 1996



Bachiller, Tafalla & Cernicharo 1994

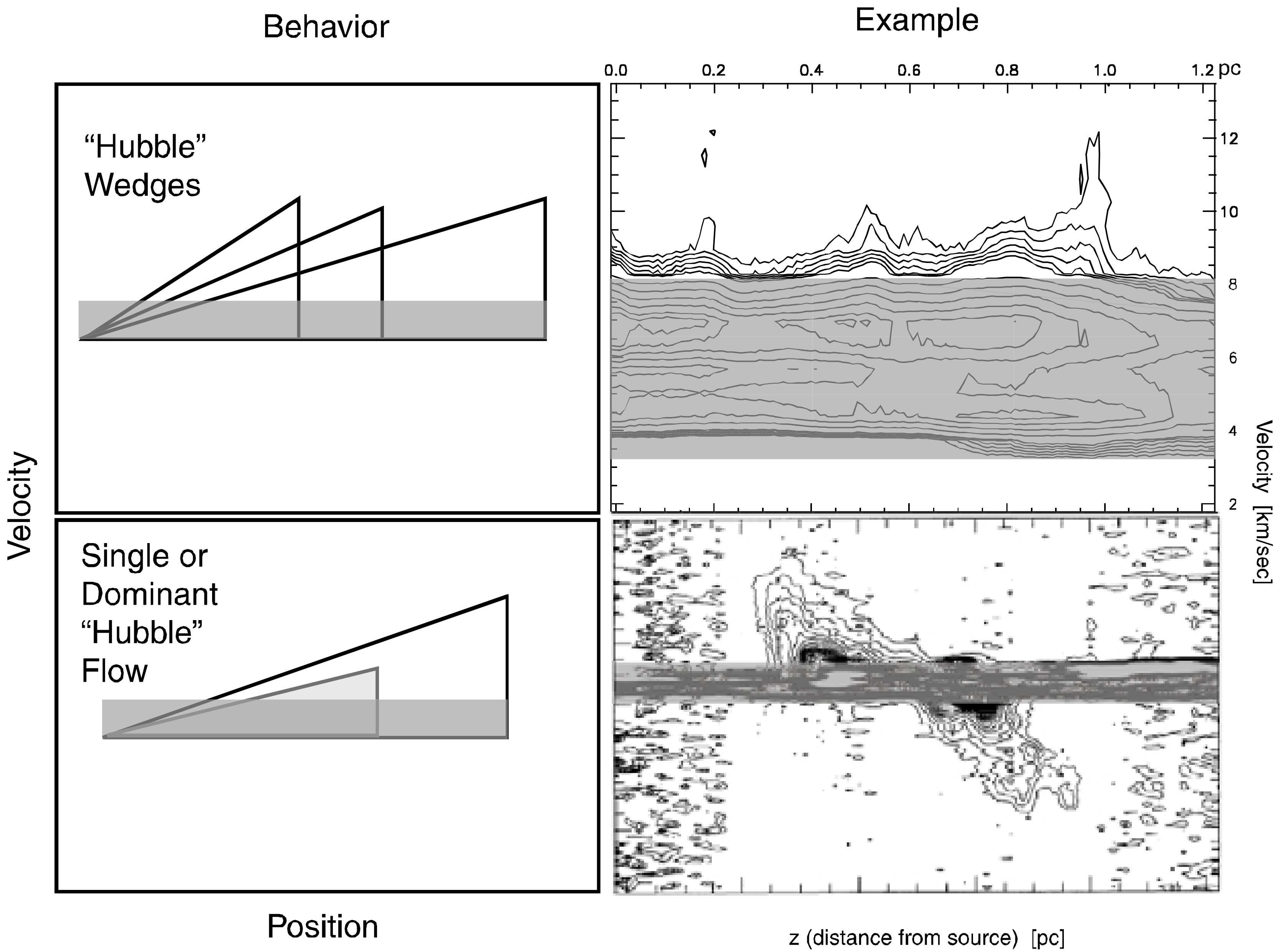


Bachiller et al. 1990



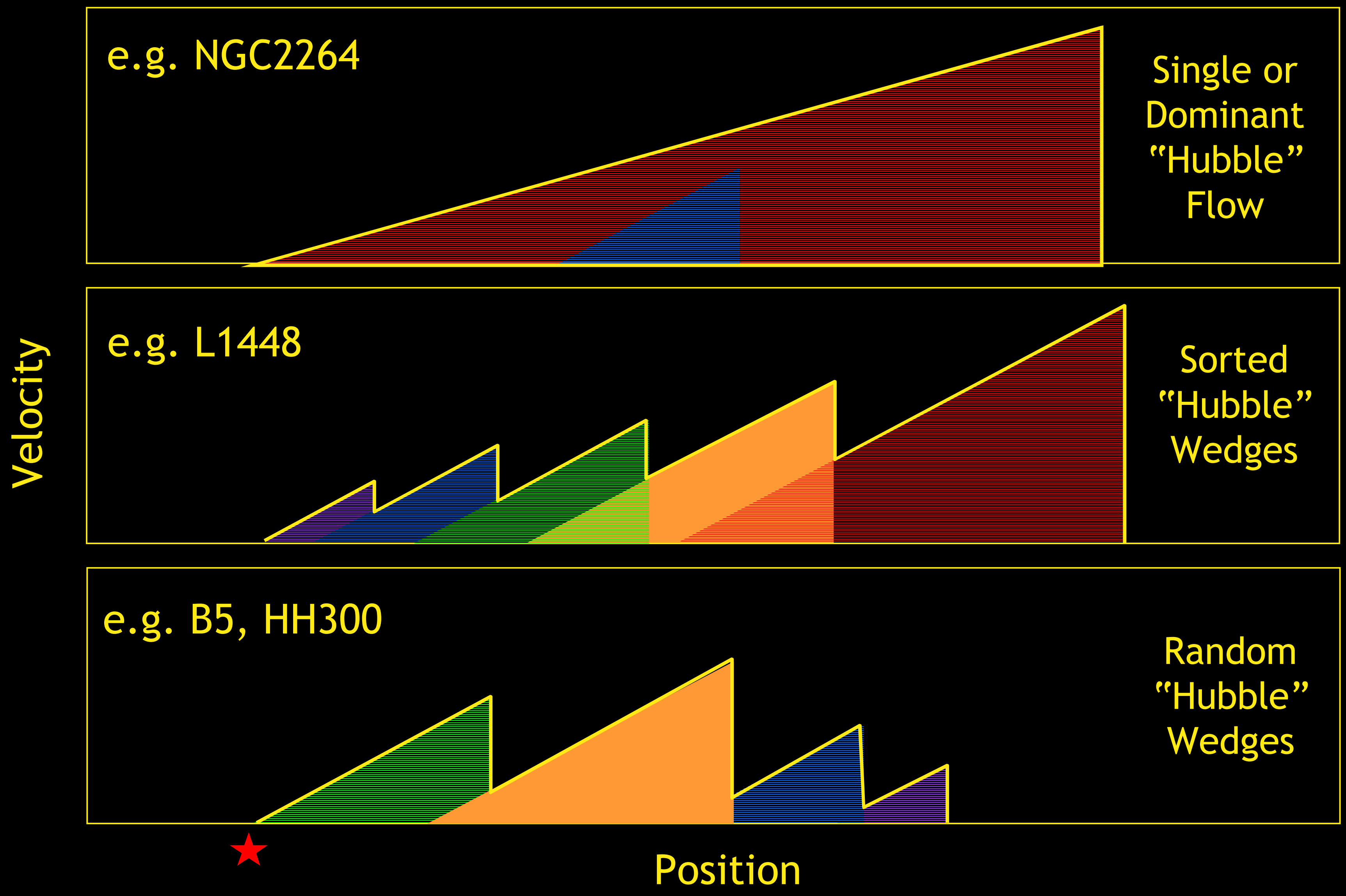
Yu Billawala & Bally 1999

Outflow position-velocity diagrams

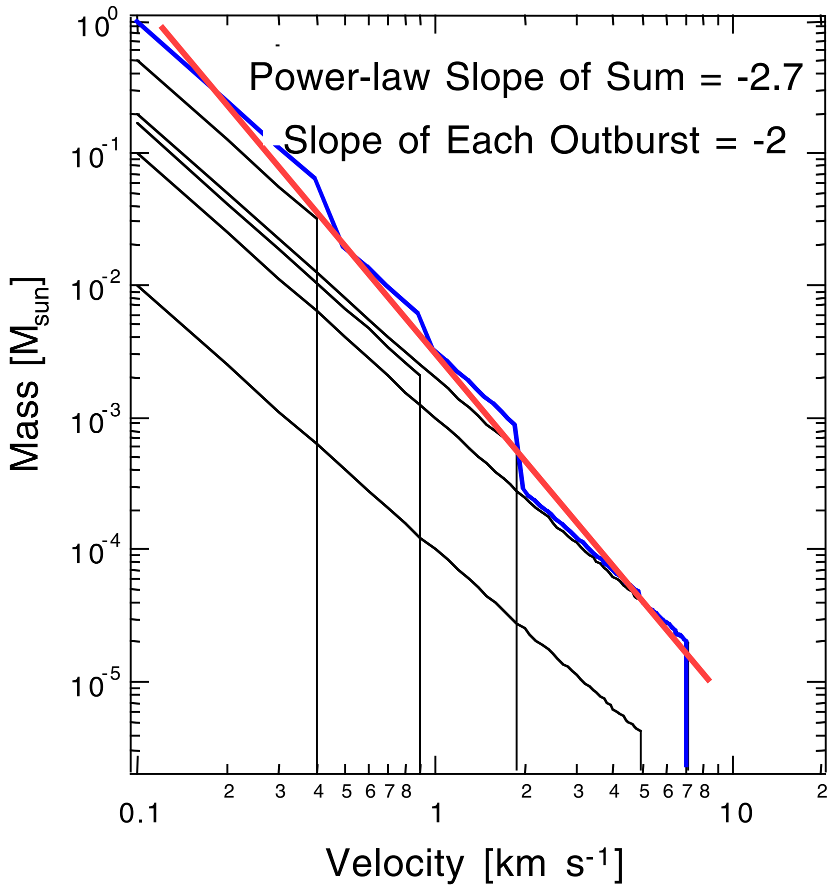


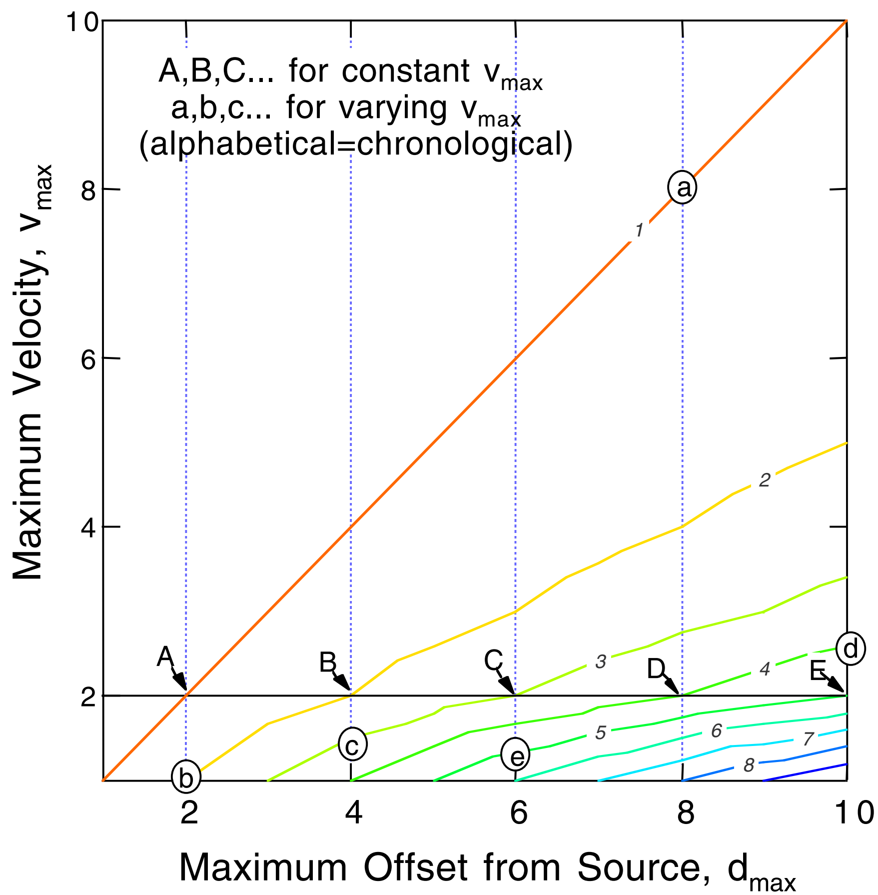
Arce & Goodman 2001

Variations in Burst History…



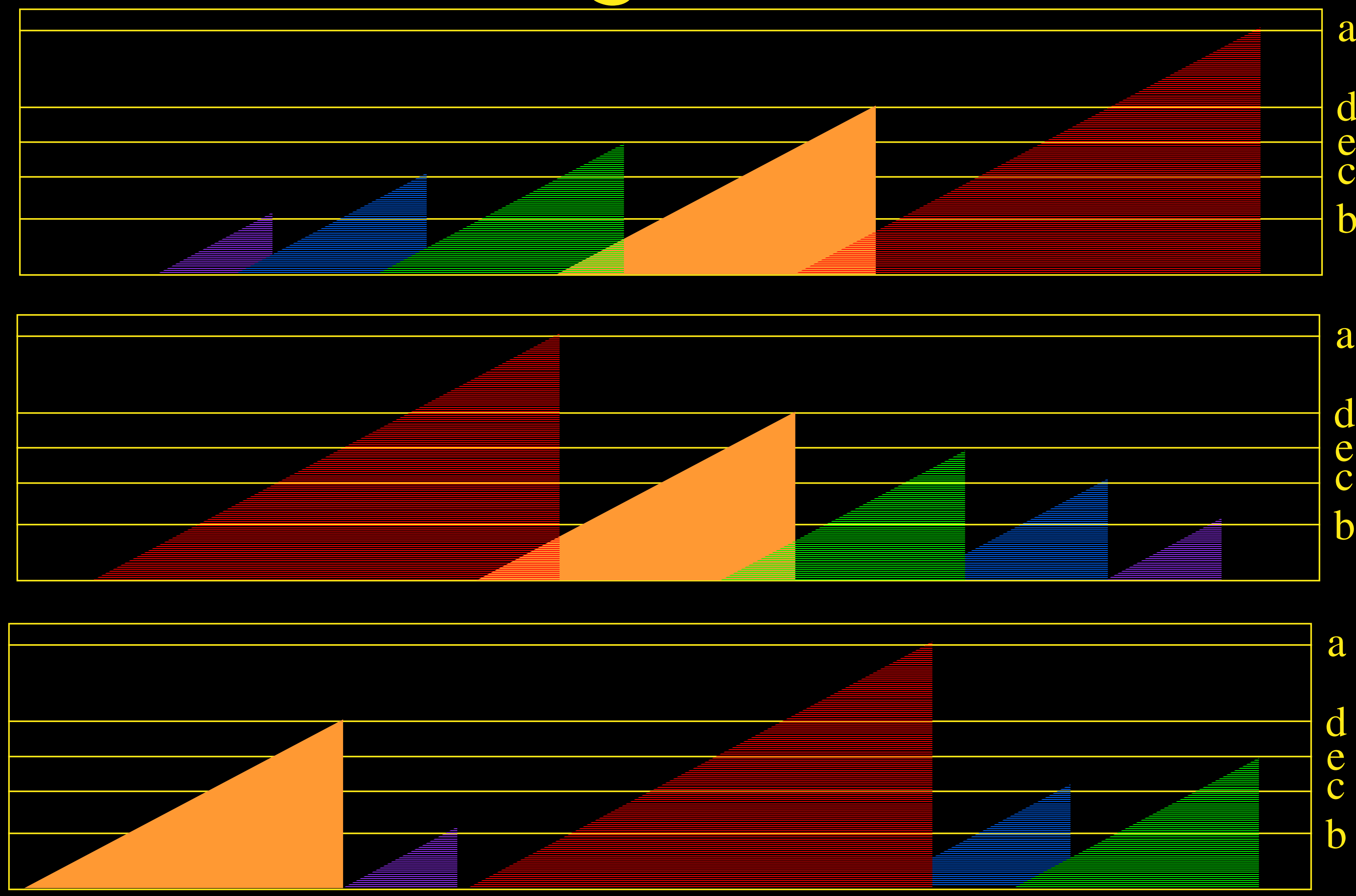
Mass-Velocity & Position-Velocity Relations in Episodic Outflows





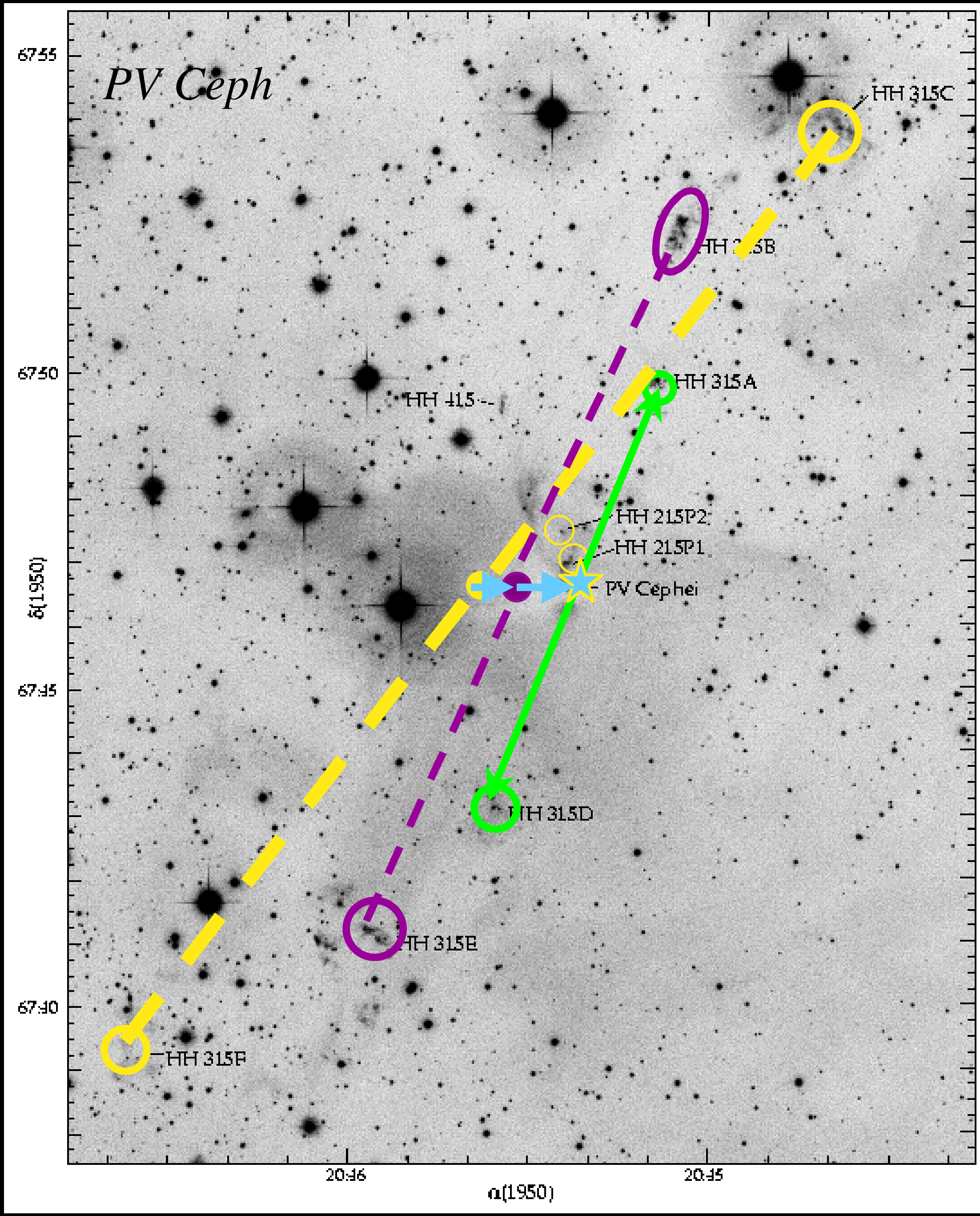
Arce & Goodman 2001

Time-Ordering of p-v Diagrams?



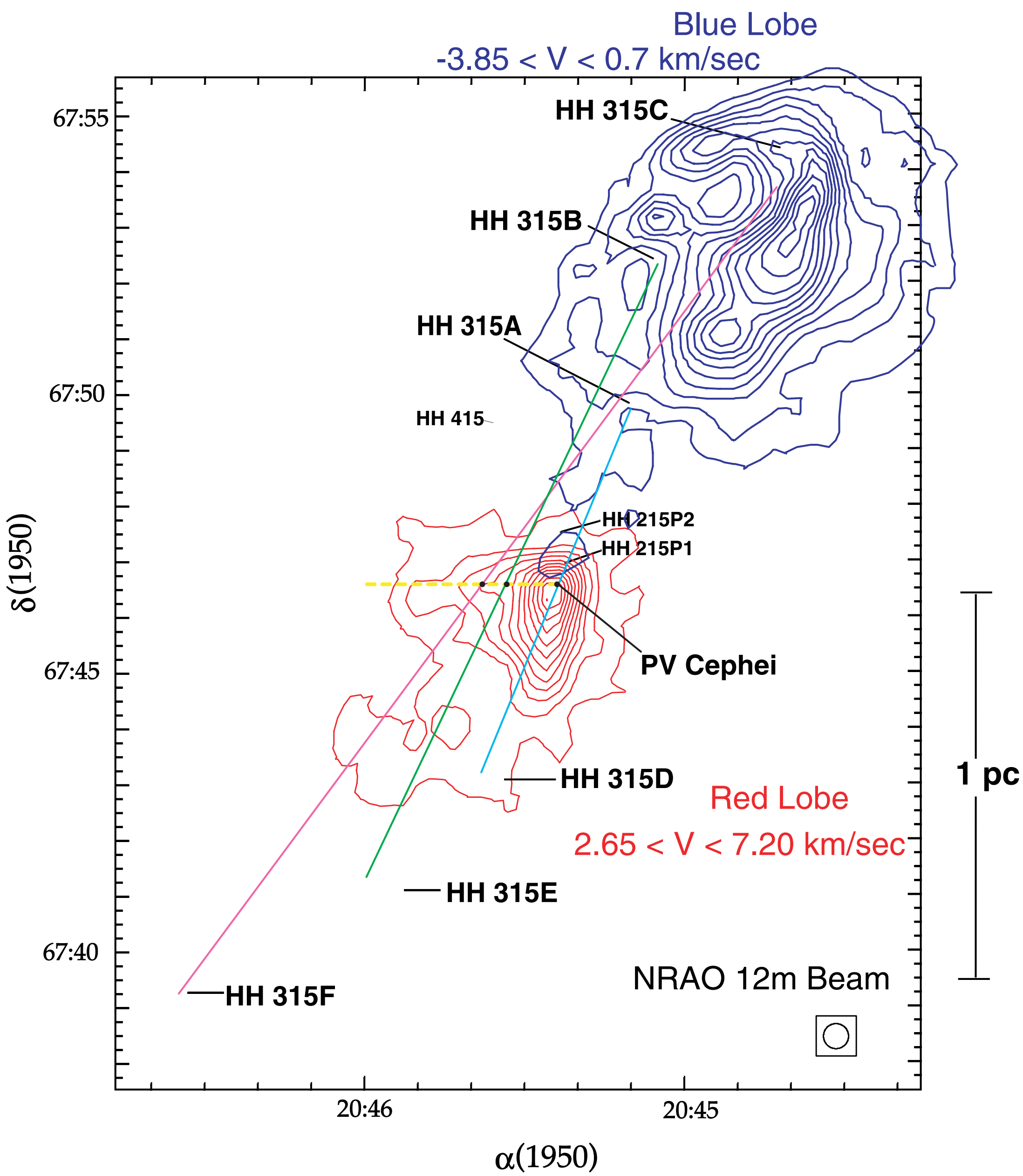
Episodic ejections from precessing or wobbling *moving* source

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?