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Infall Signatures of Dense Cores in the Perseus Molecular Cloud

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Abstract: Molecules that trace high density gas (~10^4 cm^{-3}) are useful probes of dense core kinematics where star formation takes place. Blue (red) asymmetries in optically-thick emission profiles are commonly used indicators of core collapse (expansion). We analyze observations of HCO^+ (3-2) and N_2D^+ (3-2) rotational transitions toward 91 dense cores in the Perseus molecular cloud using the James Clerk Maxwell Telescope. While N_2D^+ is optically-thin and traces the systemic velocity of the cores, HCO^+ is often optically-thick and probes core kinematics. We detect significant HCO^+ line asymmetries toward 20 cores using a dimensionless asymmetry parameter (δ_v) and detect contraction (expansion) speeds (V_{in}) toward 22 cores using HILL5, an analytic infall model. Comparing the tracers of core infall, we find that line asymmetries are a good tracer of core infall when the optically-thin emission is aligned with the model-derived systemic velocity, or the line profile center.

HCO^+ (3-2) and N_2D^+ (3-2) Observations

The 91 dense cores in the Perseus molecular cloud observed in the HCO^+ (3-2) and N_2D^+ (3-2) rotational transitions are predominantly located in clustered regions, seen in the 1.1 mm continuum images in Figure 1 (Enoch et al. 2006).

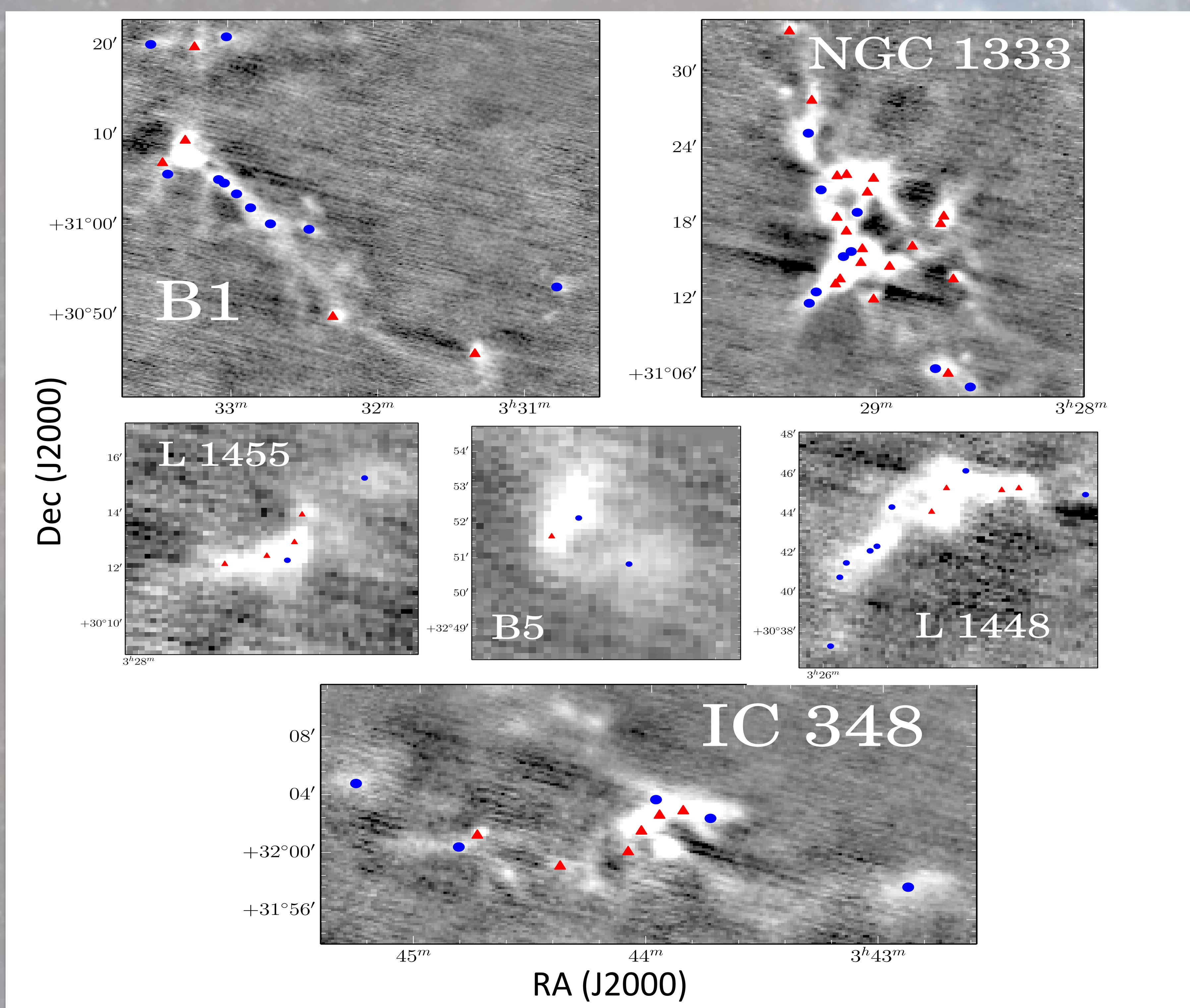

Figure 1. 1.1 mm continuum images of well known sub-regions within the Perseus molecular cloud taken with Bolocam on the Caltech Submillimeter Observatory 10 m telescope (Enoch et al. 2006). Overlaid are circles (blue) and triangles (red) that indicate core pointings toward starless and protostellar dense cores, respectively.

Detection Rates and Core Infall Velocities

Protostellar cores:

- had a higher HCO^+ detection rate
  - 41/43 (95%) protostellar cores
  - 31/48 (65%) starless cores,
- were more likely to exhibit asymmetries
  - 12/20 (60%) protostellar cores
  - 8/20 (40%) starless cores,
- and were more likely to be fit with HILL5
  - 15/22 (68%) protostellar
  - 7/22 (32%) starless

Infall speeds:

- ranged from subsonic (0.03 kms^{-1}) to supersonic (0.4 kms^{-1}) where supersonic infall likely traces global rather than core infall
- were often much less than their free-fall speeds

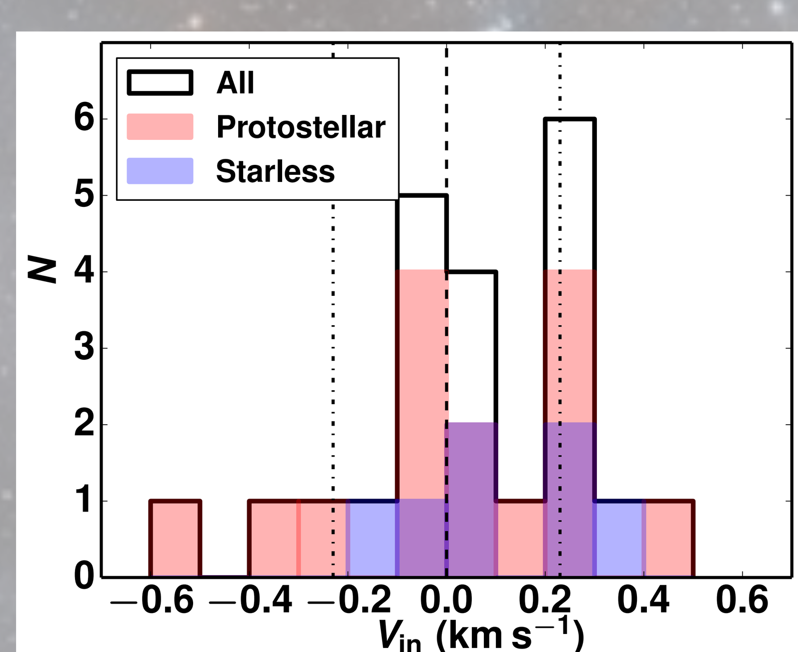

Figure 4. Histograms of V_{in} values of the dense cores modeled with the analytic HILL5 model. Note that V_{in} < 0 implies outward motion. The dashed lines indicate the approximate sound speed of the molecular gas assuming a gas kinetic temperature of 11 K (Rosolowsky et al. 2008).

Line Asymmetries and the Analytic Infall Model

Isolated spherical cores undergoing collapse

- produce red-shifted self-absorption
- results in classic blue asymmetries
- is caused by the combination of radial motion
- and high optical depth. (Leung & Brown 1977)

We used a dimensionless asymmetry parameter,

$$\delta_v = \frac{V_{thick} - V_{thin}}{\Delta v_{thin}}, \qquad (1)$$

defined by Mardones et al. (1997) to quantify HCO^+ asymmetries toward 20 cores

- $\delta_v < 0$ indicates collapse
- $\delta_v > 0$ indicates expansion/outflow

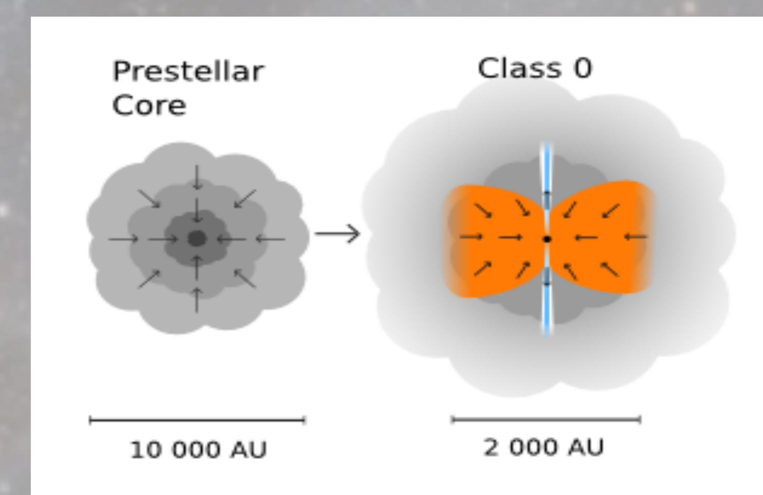

Figure 2. A cartoon representation of a prestellar core (left) collapsing to form a Class 0 protostar with its signature outflows shown (right). Adapted from Persson (2013).

The analytic HILL5 model of a collapsing core used to model infall velocities (V_{in}) toward 22 cores assumes:

- two slabs of gas moving toward or away from each other at a constant speed
- the excitation temperature follows a linear relationship with optical depth

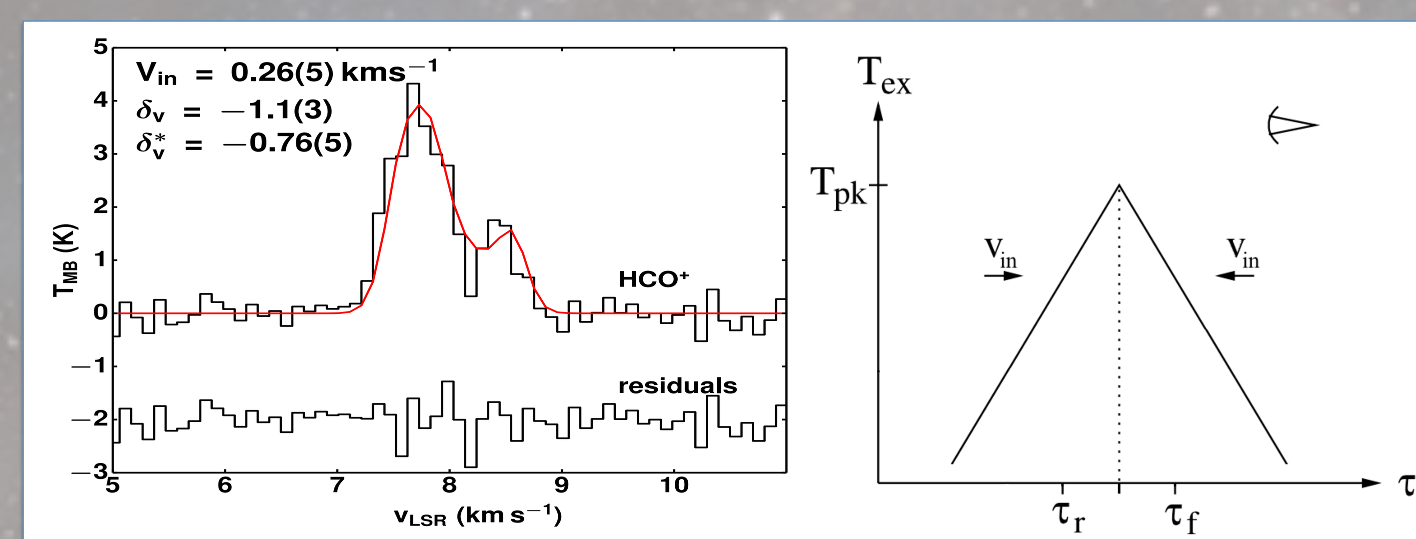

Figure 3. Left: An HCO+ profile (top) toward core B87 overlaid with the HILL5 model (red) and the resulting residuals shown below. Right: A Graphical representation of the HILL5 model. Adapted from De Vries et al. (2005).

Comparison of Infall Tracers

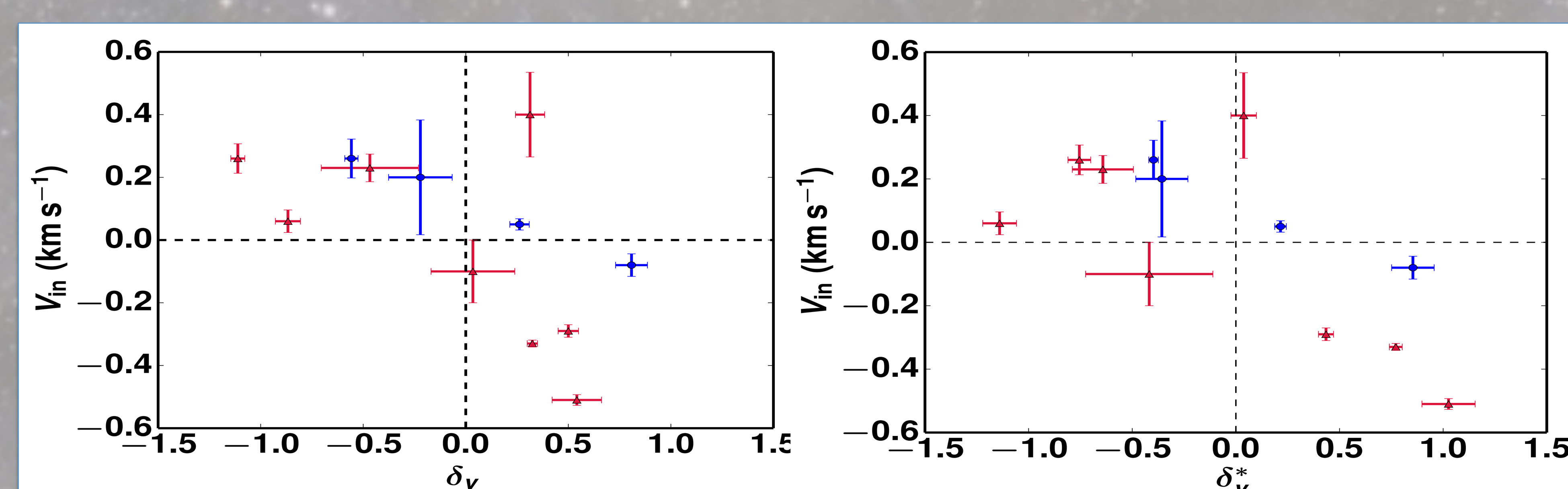

Figure 5. Left: Modeled infall velocities (V_{in}) versus the asymmetry parameter (δ_v). The Pearson correlation coefficient between these two parameters is -0.59. In both plots, starless and protostellar cores are indicated with circles (blue) and triangles (red), respectively. Right: Modeled infall velocities (V_{in}) versus the modified asymmetry parameter (δ_v^*) where V_{thin} in Equation (1) is replaced by the model-derived systemic velocity. The Pearson correlation coefficient between these two parameters is -0.69.

References:
Campbell et al. 2016, in press • De Vries et al. 2005, ApJ, 620, 800 • Enoch et al. 2006, ApJ, 638, 293 • Leung & Brown 1977, ApJ, 214, L73 • Mardones et al. 1997, ApJ, 489, 719 • Persson 2013 • Rosolowsky et al. 2008 ApJS, 175, 509