Inward Motions in (Starless) Dense Molecular Cores

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Workshop on Dense Cores, July 27-30, 2014
Nearby (Low-mass) Dense Cores

- Locally density-enhanced regions in the dark clouds

- “The simplest and earliest star-forming sites” giving initial conditions of low-mass star formation

- Pioneering studies by Myers and his collaborators (1983, 1989) using the optical inspection of the Palomar plates and molecular (especially NH$_3$) observations

\[ L \sim 0.1 \text{ pc}, \quad \text{Mass} \sim \text{a few } M_\odot, \quad T \sim 10 \text{ K}, \quad <\rho> \sim \text{a few } 10^4 \text{ cm}^{-3} \]
Starless, Pre-stellar, and Proto-stellar Cores

- “Starless” if they have no embedded protostars \[L_{\text{int}} \geq 4 \times 10^{-3}(d/1\text{40 pc})^2 L_\odot\] or no associated T-Tauri stars (Lee & Myers 1999, Dunham et al. 2008)

- “Pre-stellar” if gravitationally bound
  - Give best initial conditions of dense gas prior to low-mass star formation
  - higher densities of $10^5$-$6$ cm$^{-3}$, likely to show inward motions
Why Inward motions in starless (pre-stellar) cores?

• A direct sign of physical progress toward star formation

• Not yet clear what the exact origin of the inward motions would be?

• Need a systematic study on inward motions in starless cores
The start: A Catalog of Dense Cores


- 306 starless cores and 94 protostellar cores (with IRAS point sources)

- 75–85% of the starless cores remain “starless” after Spitzer (Dunham + 2008)
A Signature of Inward Motions in Starless Cores


Optically thick high density tracers: HCN 1-0, CS 2-1, 3-2, HCO+, H2CO lines

Optically thin tracers: rare isotopologue lines such as H13CO+, C34S lines, or N2H+ line

Courtesy by J. William
Infall Asymmetry in a Starless Core

- First found L1544 by Tafalla et al. (1998)

Its extended inward motions were inconsistent with that expected from “inside-out” collapse of a singular isothermal sphere (F. Shu 1979)
A Search for Infall Asymmetry in Starless Cores I.

- Single pointing surveys of 220 starless cores in CS 2-1 and N2H+ 1-0 lines (Lee, Myers, & Tafalla 1999).

→ 66 sources were detected in both CS and N2H+
→ 16 starless cores with inward motions
A Search for Infall Asymmetry in Starless Cores II.

-Detection of 66 starless cores in CS 3-2 and N2H+ 1-0 lines from ARO 12m (Lee, Myers, & Pudlume 2004).

→ 17 starless cores with inward motions
A Search for Infall Asymmetry in Starless Cores III

- Detection of 48 starless cores in HCN and N2H+ 1-0 lines from TRAO 14m (Sohn, et al. 2007).

16 starless cores with inward motions
Quantifying the Spectral Line Asymmetry

\[ \delta V = \frac{(V_{\text{thick}} - V_{\text{thin}})}{\Delta V_{\text{thin}}} \]

\( \delta V < 0 \) : blue asymmetry
\( \delta V > 0 \) : red asymmetry

(Mardones et al. 1997).
Statistics on Spectral Asymmetry in Central Region of Starless Cores


Dominance of blue sources over red sources, suggesting that inward motions are a dominant feature of starless cores.

The central region of a dense core very likely has inward motions.
A Search for Infall Asymmetry in Starless Cores IV: Mapping

- Mapping survey of 53 starless cores in CS 2-1 and N2H+ 1-0 lines (Lee, Myers, & Tafalla 2001).

→ 19 starless cores with extended (typically 0.05 – 0.15 pc) inward motions
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Extended Infall Asymmetry in Starless Cores

L694-2 (Lee, Myers, & Tafalla 2001)

Extended inward motions are a common feature in starless cores!
Velocity Structures of inward motions in starless cores

- By comparing asymmetric profiles in CS 2-1 and 3-2 lines for starless cores (Lee, Myers, & Plume 2004)

→ $V_{\text{in}}(3-2) > V_{\text{in}}(2-1)$ for 10 cores (0.07 km s$^{-1}$ vs. 0.04 km s$^{-1}$), suggesting more dense, inner gas moves faster than less dense, outer gas in these cores.
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Velocity Structures of inward motions in starless cores

- N2H+ line interferometric observations of L1544 and L694-2 (Williams, Lee, & Myers 2006)

→ Inward velocity increases with smaller projected radii
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Physical Origin of inward motions in starless cores?

- Ambipolar diffusion of relatively low magnetic strength, e.g., $10 \mu G$ (Ciolek and Basu 2000)

- Turbulent dissipation (e.g., Myers and Zweibel 2001)

- Conversing turbulent flows (Ballesteros-Paredes et al. 1999)

- The pressure-free, gravitational collapse of non-singular, centrally concentrated gas configurations (Myers 2005)

“Any of these processes that can provide a sufficiently centrally condensed structure with relatively low velocity dispersion may be viable.”
Red Asymmetry Profiles

Expanding?

L429-1

\[ \Delta \delta \quad (\ '') \]

\[ \Delta \alpha \quad (\ '') \]

\[ 0.1\text{pc} \]

\( T_s \quad (\) km/s\)

e.g.,
L134A, L429-1, CB246
(Lee et al. 2001)
&
FeSt1-457
(Auguti + 2007)
Red and Blue Asymmetry Profiles?

(Lee et al. 2001)

(Lada et al. 2003)
The Red Asymmetry or the Mixture Profiles?

-Oscillating motions of some specific mode in gaseous outer layers of the cores may explain “the red profiles” and “the complicated mixture of blue and red asymmetric profiles” (e.g., Lada et al. 2003, Broderick & Keto 2010)

- E.g., L429-1 in l=1, m=1 mode, L1512 in l=2, m=1 mode, B68 in l=2, m=2 mode

False-color intensity maps of the real part of a series of low-order spherical harmonics (Lada et al. 2003)
Remaining Questions on Internal Motions in Starless Cores (Lee & Myers 2011)

- How likely is it for a core to have motions dominated by infall, expansion, oscillation, or no obvious pattern?

- Which physical parameters are significant and how do they relate to the observed internal motions?

- Do the patterns of the internal motions in starless cores reflect any evolutionary status of the cores toward the star formation?

- Would some environmental conditions affect their internal motions in starless cores?
Spectral Line Data

● Single Pointing Data:
  - 66 cores in CS 2-1 & N2H+ 1-0 from Haystack 37m (Lee et al. 1999)
  - 66 cores in CS 3-2 & N2H+ 1-0 from ARO 12m (Lee et al. 2004)
  - 48 cores in HCN 1-0 & N2H+ 1-0 from TRAO 14m (Sohn et al. 2007)

● Mapping Data
  - 34 cores in CS 2-1 & N2H+ 1-0 from FCRAO 14m (Lee + 2001)
Internal Motions in Starless Cores

How is it likely for a core to show infall asymmetry at any place when one looks at the dense core?

- Dominance of blue profiles over the cores
  (bright N2H+ cores are likely to have inward gaseous motions.)
δV Distribution with Gas Column Density

- Which physical parameters are significant and how do they relate to the observed internal motions?

The cores with stronger N2H+ emission tend to have their profiles more blue-skewed.
Positions with high column density are more likely contracting.
$\delta V$ Distribution with the Distance from Peak Gas Column Density

$\delta V$ tends to be more negative at inner region and also still negative even at large radii.
Classification of the Cores According to Their Internal Motions

By two parameters, \( E \equiv (N_- - N_+)/N_{\text{tot}} \) and \( P \) values

- **Contracting Cores** \((E \geq 0.10 \text{ and } P \leq 0.1)\) showing significant overabundance of blue profiles: 19
- **Oscillating Cores** \((E \sim 0 \text{ with a large spread in } dV \text{ distribution})\) where blue and red profiles are observed in a comparable number: 3
- **Expanding Cores** \((E \geq -0.15 \text{ and } P \sim 0)\) showing significant overabundance of red profiles: 3
- **Static Cores** \((E \sim 0.0 \text{ with a small spread in } dV \text{ distribution})\) showing their CS profiles similar to a single Gaussian form: 8
Inward motions are occurring in most regions of the contracting cores, with predominance of these motions in their inner regions.
δV Distribution with Peak Gas Column Density

Contracting cores are far more numerous for bright cores and over certain column density ($\sim 6 \times 10^{21} \text{ cm}^{-2}$) there are only contracting cores!

Interestingly, similar to a column density threshold for prestellar cores ($\sim 7 \times 10^{21} \text{ cm}^{-2}$) above which interstellar filaments are gravitationally unstable and fragment into self-gravitating cores (Andre et al. 2013) (C.F. Heiderman + 2010, Lada + 2010)
Implication of Evolution of Starless Cores

N(N2H+) increases with other evolutionary indicators including N(N2D+), N(N2D+)/N(N2H+), and CO depletion factor (Crapsi et al. 2005).

In terms of increasing column density, starless cores in different internal motions may reflect their different status of evolution.
Summary

1. Blue profiles are dominant in starless cores, implying that inward motions are prevalent in starless cores.

2. These profiles are found to be more abundant and their asymmetry is bluer at the positions of the core with stronger N2H+ (or higher column density), indicating that positions with high column density in the core are more likely contracting.

3. Inward motions in contracting cores are occurring along most lines of sight, with predominance of those motions near the density peak region of the cores.
4. Starless cores can be classified to have four types of motions, Contracting (19), oscillating (3), expanding (3), and static motions (8). This classification may indicate a sequence of core evolution in the sense that column density increases from static to contracting cores (c.f. Stahler & Yen 2009).

As starless cores become denser through their oscillating from static motions and reach over some critical value of column density (~$6 \times 10^{21} \text{ cm}^{-2}$), they are more likely to contract.