From Atoms to Stars

— Tracing the Formation of Molecular Clouds, Supercritical Cores, and Super-Jeans Cores

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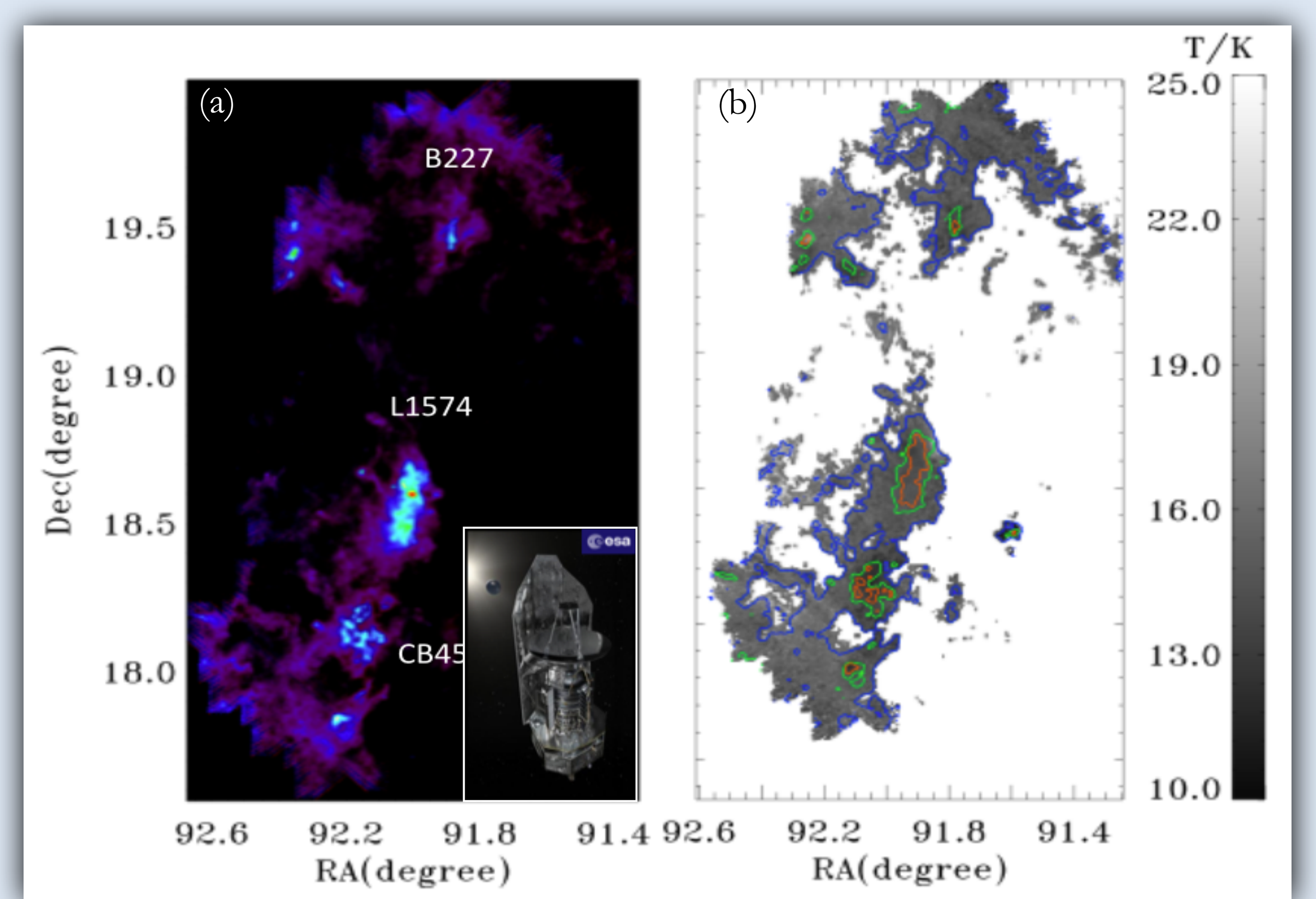
ABSTRACT

We present three projects aiming to trace key stages of dense core formation and evolution. First, we combine the HI Narrow Self Absorption (HINSA: Li & Goldsmith 2003) technique with Herschel imaging and 2MASS extinctions to discover on-going molecular cloud formation in isolated dark clouds. Second, high resolution combined VLA+GBT ammonia maps of Orion molecular clouds are analyzed together with dust continuum to reveal likely super-critical core candidates. Third, CARMA N_2H^+, HCO^+, and 3mm continuum images show two extremely dense cores ($n \sim 10^9$ cm^{-3}) which are in super-Jeans state and likely accreting mass.

Isolated dark clouds exhibit the transition from HI to H_2

-Zuo et al. 2014, in prep.



(a) The RGB image of Herschel comprised of three SPIRE band at 250 μm (blue), 350 μm (green), and 500 μm (red).
(b) Temperature distribution (10 to 25 K) of the three dark clouds overlaid with dust emission at 350 micron (blue: 0.03 Jy, green: 0.15 Jy, red: 0.27 Jy). (c) The HI absorption correlated with ^{13}CO emission for three clouds. The circled regions of dust emission image corresponded with the spectrum of the clouds respectively.

◇Projects

- Herschel OT1 Program – Isolated Dark Clouds with Signs of On Going H_2 Formation (PI: Di Li)
- Arecibo Project – Reveal the Transition from Atomic to Molecular ISM (PI: Di Li Student PI: Pei Zuo)
- FCRAO Project – CO Emission of Dark Clouds

◇HI Narrow Self-Absorption (HINSA)

HINSA traces the cold atomic hydrogen which are cooled through collisions with molecular hydrogen and can be used for measuring the evolutionary state of clouds in terms of H_2 formation (Li & Goldsmith 2003; Goldsmith & Li 2005). The measured abundance of [HI]/[H_2] can be modeled in terms of the H_2 formation timescale based on

$$R_{H_2} = \frac{1}{2} S_{HI} \varepsilon_{H_2} n_{HI} \langle v_{HI} \rangle \sigma_{gr} n_{gr}$$

and

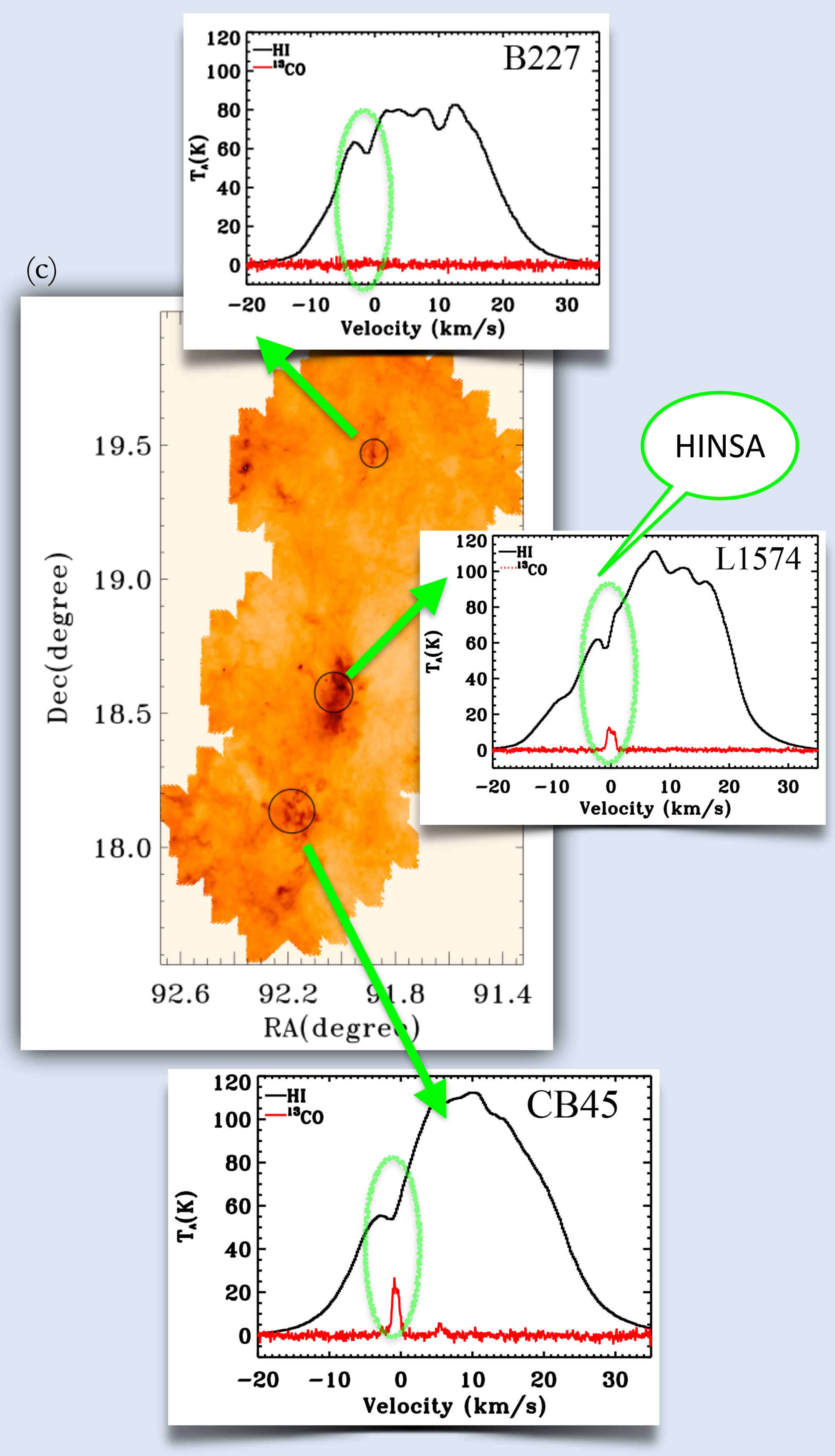
$$\frac{N(HINSA)}{cm^{-2}} = 1.95\times10^{18}\tau_0 \frac{\Delta V}{km\cdot s^{-1}} \frac{T_k}{K}$$

We selected three isolated dark clouds based on the intriguing morphology of displacement between CO, 2MASS extinction, and cold atomic gas. We obtained dust temperatures and column density based on SED fitting of Herschel data normalized by 2MASS extinction, HI abundance based on HINSA, CO column density based on ^{13}CO.

◇Results

Three isolated dark clouds B227, L1574, and CB45 are at different stages of evolution.

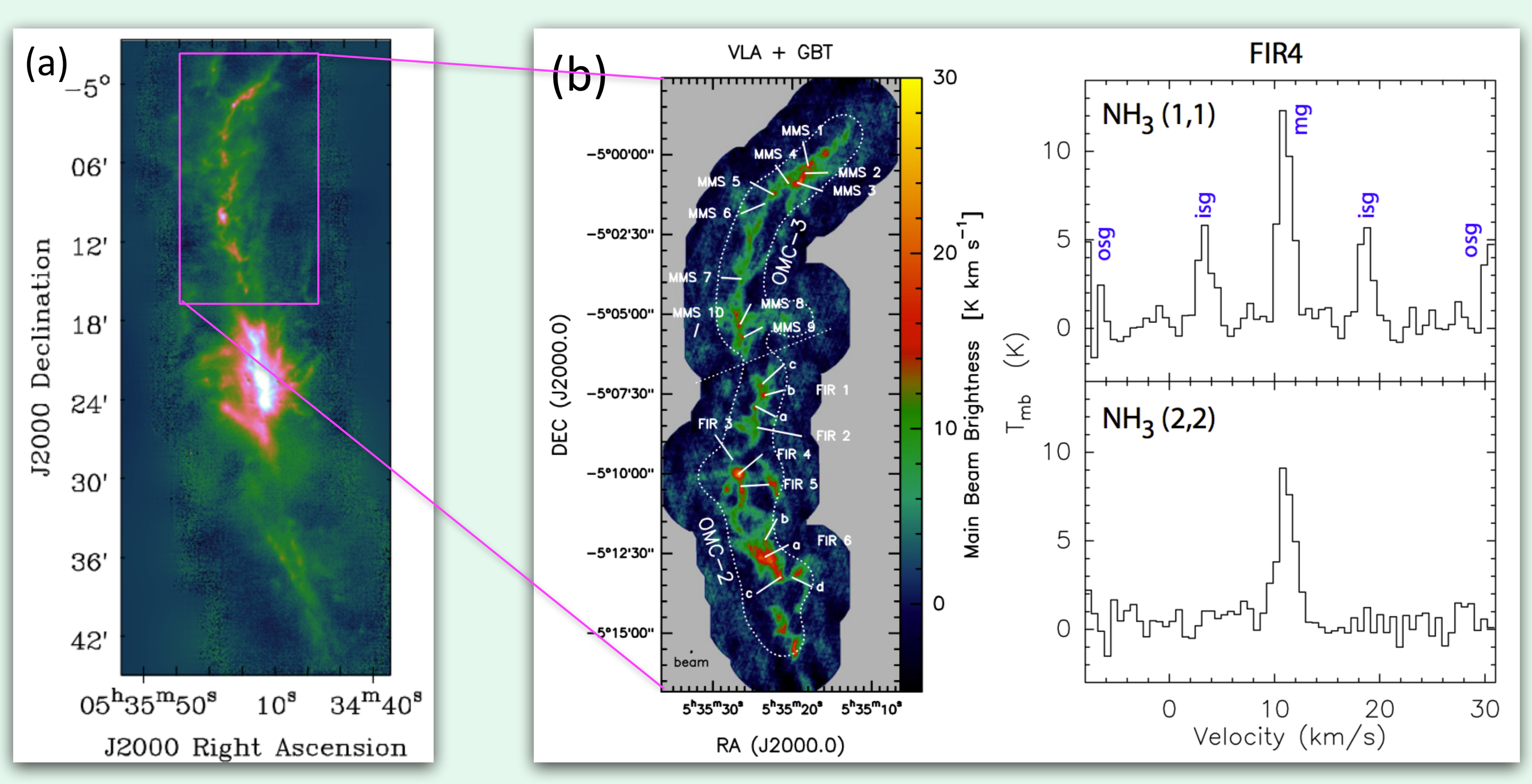
- B227: Strong HINSA, no ^{13}CO emission, weak dust indicating early core formation stage with ongoing H_2 formation.
- CB45: The dust emission is stronger, the strongest ^{13}CO emission indicating middle stage with abundant CO.
- L1574: The strongest dust emission, the weaker ^{13}CO emission, and lower HINSA abundance suggesting further evolution with possibly the onset of CO depletion.

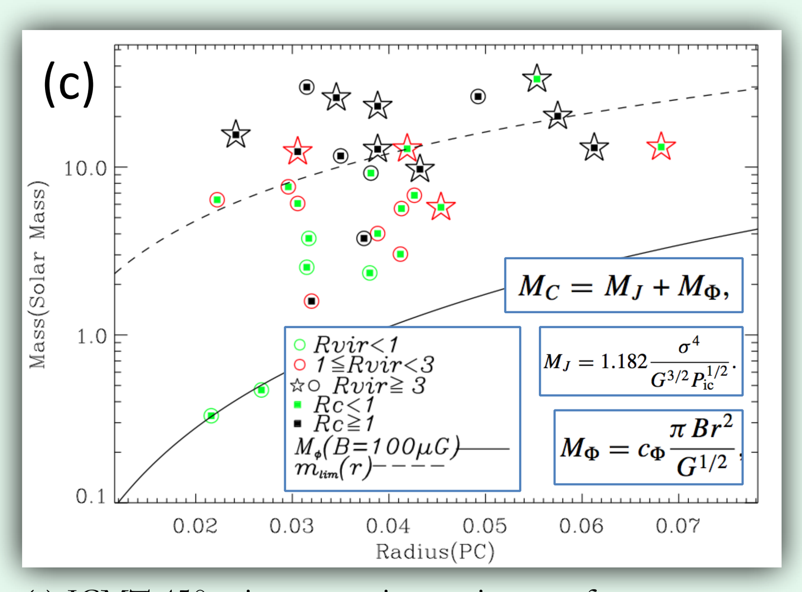


(c) Dust emission at 250 μm overlaid with corresponding HINSA and ^{13}CO emission at three typical positions which is amplified for 10 times.

The Super-Critical Starless Core Candidates -VLA + GBT NH_3 Maps

- Li et al. 2013, ApJL, 768, L5





(a) JCMT 450 micron continuum image of the OMC. (John stone et al. 1999);
(b) Integrated NH_3 (1,1) image of the OMC-2, 3 region; NH_3 (1,1) (2,2) spectra towards FIR4.
(c) The core mass–size relationship for the identified Orion cores. Solid line: mass supported by a steady magnetic field of 0.1 mG. Dashed line: upper limit of total pressure support from thermal and turbulent motion.

Observation:

We mapped the quiescent regions in the Orion Molecular Cloud (OMC) in VLA NH_3 (1,1) (2,2)

→ accurate T_{kin} and ΔV measurements.

Results:

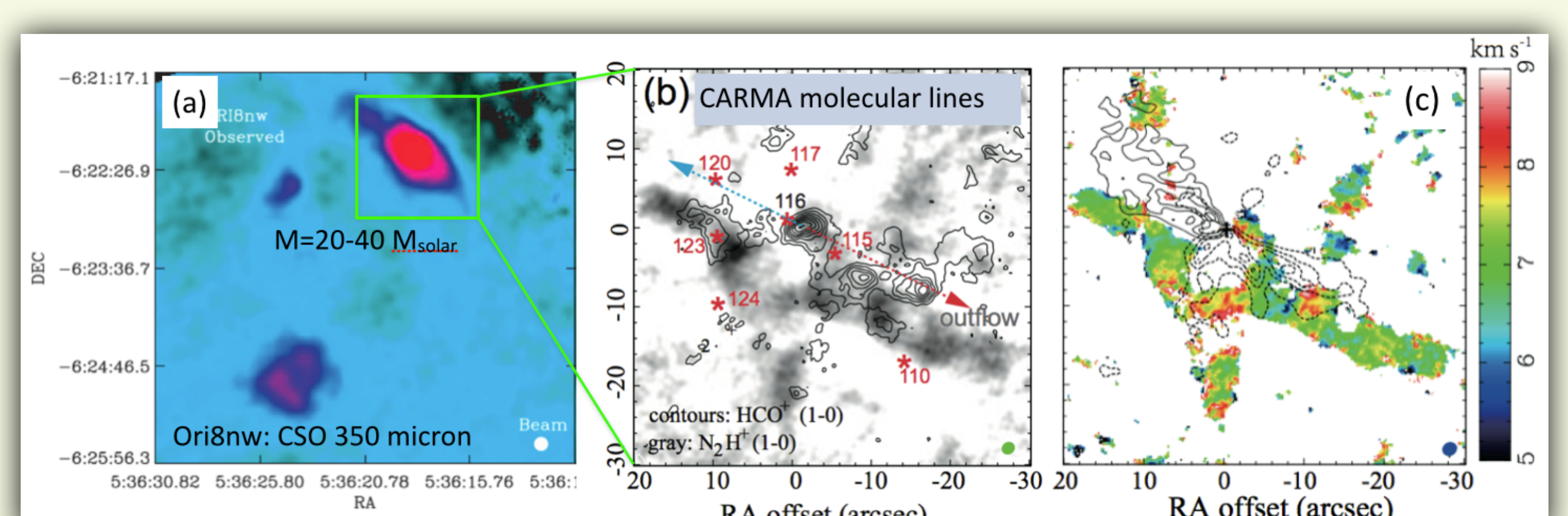
- 30 cores identified in OMC-2, 3
  ⟨M⟩=11 M_{solar}, ⟨r⟩=0.039 pc, ⟨T_{kin}⟩=17 K, ⟨R_{vir}⟩=M_{gas}/M_{vir}=3.9 (virial parameter) ⟨R_c⟩=1.5 (critical mass ratio)
- 14 cores have R_c>1. Some cores supercritical for E_p/E_k energy ratios, with uncertainties considered.

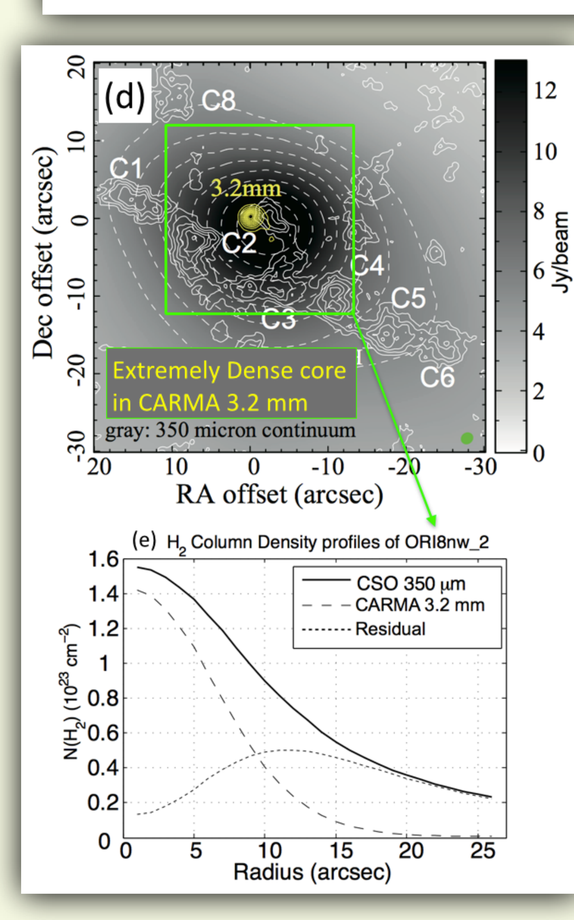
Conclusion:

- **Thermal and non-thermal gas motions alone cannot prevent collapse.** Strong B-field of B>0.5 mG needed to render them subcritical (if exists).
- Orion dense cores are much more tightly bound than the Gould Belt cores.
- The newly discovered super-critical candidates are good targets for ALMA.

Extremely Dense and Likely Super-Jeans Cores - CARMA Maps

- Ren, Li, & Chapman 2014, ApJ in Press, astro-ph:1404.7413





(a) CSO/SHARC-II 350 μm continuum image of ORI8nw_2. (Li et al. 2007);
(b) Integrated N_2H^+ and HCO^+ images which reveal the internal gas distribution of the 350 μm core;
(c) The velocity field of the N_2H^+ and its coherence with the CO outflow (contours);
(d) The location 3.2 mm continuum core within the 350 μm core;
(e) The column density averaged at each radius for the 3.2 mm core, 350 μm core, and the residual of the two which exhibits the flat envelope.

Source Selection:

Ori8nw_2: the largest R_c among the sample of Li et al. (2007, 2013)

CARMA Observation:

3.2 mm continuum, N_2H^+ and HCO^+ (1-0) at 1.5" resolution.

Results:

Plausible fragmentation in N_2H^+ clumps (Fig 3b,c)

The core is extremely centrally concentrated (Fig. 3d, e) the gas density **reaches $n(H_2)=1.6\times10^9$ cm^{-3}**

Outflow shaping the gas structure (Fig. 3c).

Implication:

plausible fragmentation halted the high-mass star formation:

(T=30 K, n=10^7 cm^{-3}, B=1 mG) ⟹ λ_{Jeans}=5" comparable to the N2H+ clump size.

To halt fragmentation:

[1] The B-field should be stronger (>5 mG) and closely coupled with the gas to resist the self-gravity, or

[2] The temperature increases so that the thermal pressure becomes more important.

The central dense core property:

[1] Absence of IR sources ⟹ likely pre-stellar stage.

[2] **Super-Jeans state.** Its internal fragmentation and collapse are desirable for ALMA observation.

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