Observational Identification of First Cores: Non-LTE Radiative Transfer Simulation

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1.Introduction

A first core (FC) is a first hydrostatic object formed in the star formation process. Before the FC formation, the cloud core experiences runaway collapse, while Shu-type accretion flow and outflow are appeared after it. FC-formation is one of the most important epochs in star formation. Although more than 40 years have passed since Larson (1969) predicted it from his radiative hydro simulation, this is not confirmed observationally. In this paper we present how the FC is observed with high-density tracer rotational transition of CS.

2.Method

Data: We performed 3D radiative magnetohydro simulation (Tomida + 2010). Figs. 1(a) and (b) represent the structure before the FC formation, in which thermal radiation from dust is the major coolant and the gas temperature is essentially isothermal (runaway collapse). Figs. 1(c) and (d) are snapshots after FC-formation, which show temperature is apparently higher than the interstellar temperature T=10K in the FC and a slow molecular outflow is driven in z-direction around the FC.

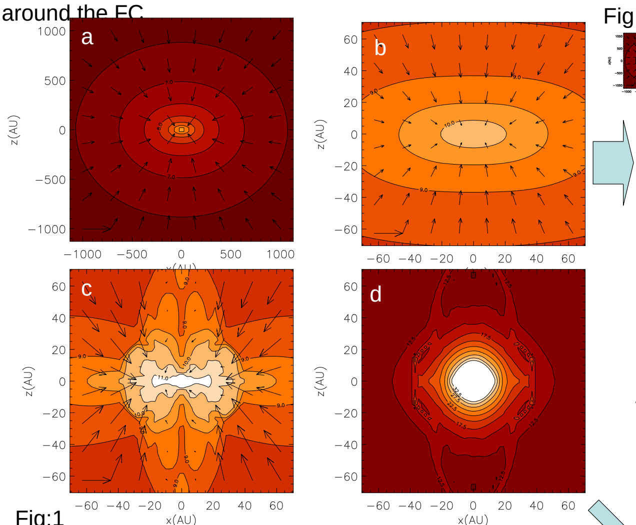


Fig:1

Density structure of prestellar isothermal collapse phase at 2200-AU (a: Level 5) and 140-AU (b: Level 9) scales. The contour levels are H_2 number density n=$10^{6.5}$cm^{-3},10^{7}cm^{-3}, $10^{7.5}$cm^{-3},…. The central density reaches n_c~$10^{10}$$H_2$cm^{-3} at this time. In this phase, gas is essentially isothermal with ~10K, which is not shown in this figure. In (c) we show the density distribution after the first core formation. The kinetic temperature is plotted in (d) with contour levels T=12.5K, 15 K, 17.5 K},…The size of panels (c) and (d) is 140 AUx140 AU (Level 9). The velocity field is shown by arrows. We plot a velocity vector of (v_x,v_z)=(1km s^{-1},0) in the lower-left corner for comparison.

Non-LTE Radiation Transfer (RT): Balance equation for CS rotational levels are solved coupled with radiative transfer eq. iteratively. The Einstein's A and B coefficients and the C coefficients are taken from the Leiden Atomic and Molecular Database LAMDA.

$$n_J \sum_{J'\neq J} R_{JJ'} = \sum_{J'\neq J} n_{J'} R_{J'J} \qquad \text{from } J \quad \text{to } J$$

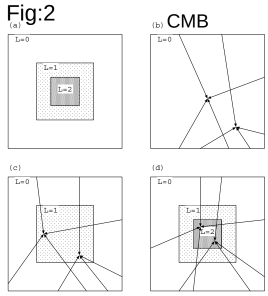
$$R_{JJ'} = \begin{cases} A_{JJ'} + B_{JJ'}\bar{J}_{JJ'} + nC_{JJ'} & \text{for } J > J' \\ B_{JJ'}\bar{J}_{JJ'} + nC_{JJ'} & \text{for } J < J' \end{cases}$$

Specific intensity J is calculated by solving radiative transfer equation for radiation intensity I by Monte Carlo method.

Nested Grid Hierarchy:
Since we need higher spatial resolution around the FC, we adopted nested grid hierarchy (Fig2a).

We solve non-LTE RT by following procedure:
(1) Solve L=0 (coarsest grid) with the CMB outward boundary (Fig2b).

Fig:2



(2) Solve L=1 (Fig2c). Generate rays passing L=1 grid. Integrate radiative transfer equation along the rays for the part covered by L=0 grid but outside L=1 grid. Record the intensity at the outer boundary of L=1. Then, by iteration, obtain the equilibrium solution for L=1 grid.
(3) Solve L=2 (Fig2d) as the same as L=1 grid.

3. Result

Before vs after the FC formation

Fig:3

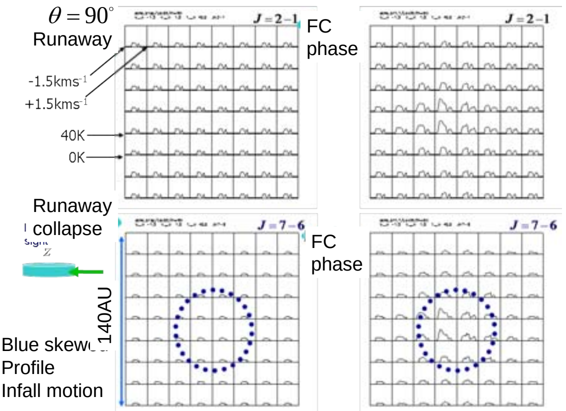


Fig:3 Difference between prestellar and FC phase spectra:
(1) FC phase is much brighter than the prestellar phase.
(2) Blue skewed profile becomes significant in the FC phase.

Fig:4

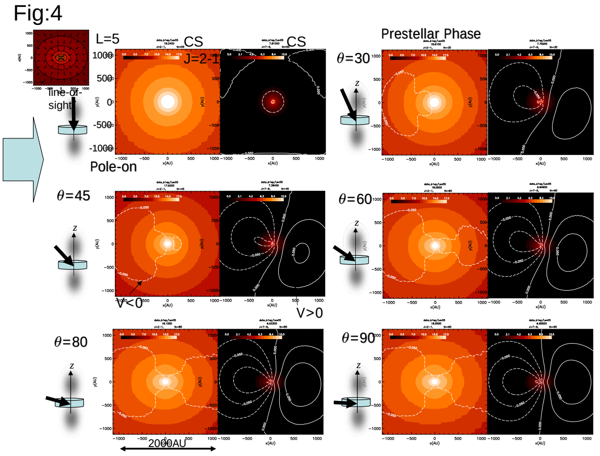


Fig.4: Prestellar Phase = Runaway Collapse:
(1) In 2000AU scale the cloud contract spherically.
(2) Rotation is not traced so apparently.

Fig:5

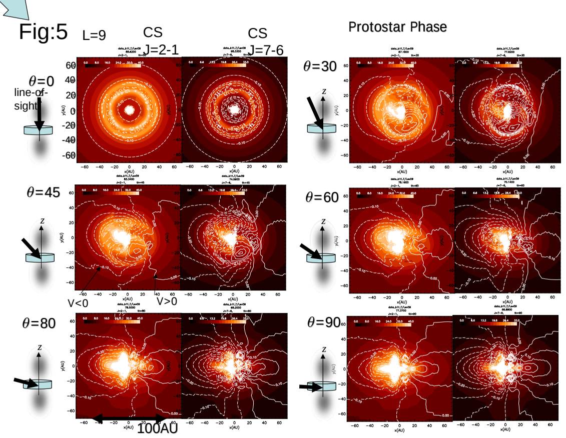
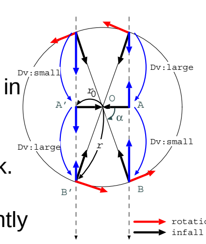


Fig.5: FC Phase = Rotating and Contracting Disk and Outflow:
(1) θ<30deg the outflow is observed with negative velocity.
(2) At θ=30deg, a bar-like structure appears in the negative velocity.
(3) At θ~60deg, positive-velocity structure connects with the receding side of the disk.
(4) θ>80deg, rotation motion is observed. However, the approaching side is apparently brighter than the receding side, which indicates the gas forms a rotating and contracting disk.



4. Conclusion

A FC disk is clearly observed in high-density tracer molecule CS. FC disk indicates both rotation and contraction, which is not appeared in prestellar stage. After the second core is formed the disk seems to be observed much brighter than FC.