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

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A first core is a first hydrostatic object formed in the course of dynamical contraction of a molecular cloud core. Since the inflow pattern changes drastically before and after the first core formation, it is regarded as a milestone in the star formation process. Although the first core was predicted by Larson in 1969[1], this has not been confirmed by observation yet. In order to identify the first core from a mapping observation, the features expected for the first core are studied for CS rotation transitions at radio wavelengths[3]. The non-LTE radiation transfer is calculated for the results of radiation magnetohydrodynamical simulations of the contraction of the magnetized molecular cloud core in rotation [2]. Figure 1 indicates the structure at the age of $\tau = 6.45 \times 10^2$yr after the first core formation.

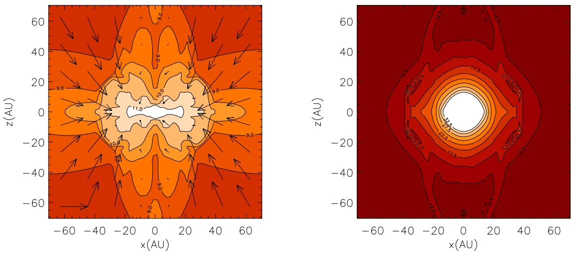

Figure 1: Density and velocity (left) and temperature (right) distributions. In this 140-AU scale map shows that a first core forms $r < 30$AU and an outflow is ejected vertically. Inflowing gas is essentially isothermal with a temperature of $T \simeq 10$K, while the first core has higher temperature.

We use the Monte-Carlo method to solve the non-LTE radiation transfer in a nested grid hierarchy. Balance equation between radiative excitaion, induced emission, spontaneous deexcitaion, collisional excitation and deexcitation is solved, coupled with the radiation transfer equation. Denoting the number density of the J level (energy level $E(J)$) as n_J, we can write the balance equation as $n_J \sum_{J' \neq J} R_{JJ'} = \sum_{J' \neq J} n_{J'} R_{J'J} \quad (J = 0, 1, \cdots, J_{\max})$, where $R_{JJ'}$ represents the transition probability from J to J' as

$$R_{JJ'} \begin{cases} = A_{JJ'} + B_{JJ'} \mathcal{J}_{\nu JJ'} + n C_{JJ'} & \text{for } J > J', \\ = B_{JJ'} \mathcal{J}_{\nu JJ'} + n C_{JJ'} & \text{for } J < J', \end{cases}$$

where $A_{JJ'}$ and $B_{JJ'}$ represent Einstein's coefficients, the former being the coefficient for spontaneous emission and the latter the coefficient for absorption ($J < J'$) and induced emission ($J > J'$). $C_{JJ'}$ is the collisional transition rate from J to J' for collisions with H_2 molecules whose density is denoted by n. The average intensity of radiation with a frequency of $\nu = [E(J') - E(J)]/h$ is written as $\mathcal{J}_{\nu JJ'}$, where h is the Plank constant.

In the first core phase, an outflow arises from the vicinity of the first core due to the twisted magnetic field amplified by the rotation motion of the contracting gas disk.

The disk and outflow system has several characteristic observational features (Fig. 2): (i) relatively opaque lines indicate asymmetry in the emission lines in which the blue side is stronger than the red side (an infall signature of the envelope); (ii) in the edge-on view, the disk has a signature of simultaneous rotation and infall, i.e., the integrated intensity of the approaching side is brighter than that of the receding side and the gradient in the intensity-weighted velocity is larger in the approaching side; (iii) the observed outflow indicates rotation around the rotation axis. The size of the outflow gives the approximate age after the first core is formed, since the outflow is not expected for the earlier runaway isothermal collapse phase

The reason why the mirror symmetry is broken in the rotating infall disk is understood as follows. This assymmetry arises due to the self-absorption. Since the temperature decreases outwardly, the emission from the portion near the tangential point is absorbed by foreground rotating inflow gas. In this configuration, velocity difference between gases which contribute emission and absorption is larger for approating side rather than receding side of rotation.

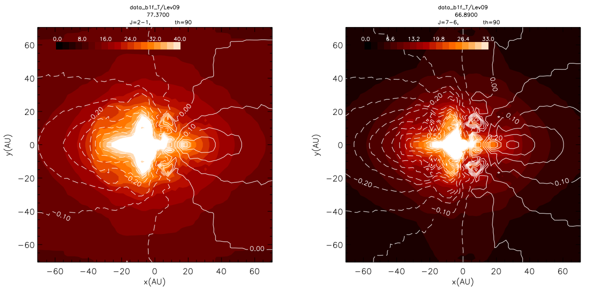

Figure 2: Expected distribution of the integrated intensity of the CS $J = 2-1$ (left) and $J = 7-6$ (right) emissions. The integrated intensities are shown with false color and intensity-weighted mean velocity (first moment) is shown in white contour lines. This shows the edge-on view.

References

[1] Larson, R. B. 1969, MNRAS, 145, 271

[2] Tomida, K., Tomisaka, K., Matsumoto, T., Ohsuga, K., Machida, M.N., & Saigo, K., 2010, ApJ, **714**, L58

[3] Tomisaka, K. & Tomida, K.: 2011, PASJ, **63**, 1151