High-Resolution Studies of the Multiple Cores Systems toward Cluster Forming Regions

H. Saito[1], M. Saito[1], Y. Yonekura[2], F. Nakamura[3]
(saito@nro.nao.ac.jp)

1. National Astronomical Observatory of Japan
2. Osaka Prefecture University
3. Niigata University

Abstract

We present the results of $C^{18}O$ observations by Nobeyma Millimeter Array toward dense clumps with radii of ~ 0.3 pc in nine cluster-forming regions including massive (proto)stars. We identified 199 cores, whose radius, line width, and mass range from 0.02 to 0.11 pc, from 0.43 to 3.33 km/s, and from 0.5 to 54.1 $M_\odot$, respectively. Many cores with various line widths exist in one clump, and the index of the line width-radius relation differs from core to core in the clump. This indicates that the degree of dissipation of the turbulent motion varies for each core in one clump. Although the mass of these cores increases with the line width, most cores are gravitationally bound by the external pressure. In addition, the line width and the external pressure of the cores tend to decrease with distance from the center of the clump, and these dependences may be cause of the H_2 density structure of the clump that affect the physical properties of cores. Thus, we suggest that the cluster is formed in the clump through the formation of such multiple cores, which would have strong relations between the physical parameters of the cores and the H_2 density structure and the turbulent motion of the clump.

Introduction

- Most stars in the galactic disk are formed in dense molecular gas within GMCs as members of cluster (e.g., Lada & Lada 2003).
- The clusters consist of various masses of stars and most massive stars exist at the centers of clusters (e.g., Raboud & Mermilliod 1998).
- The clusters are formed in gas systems with a size scale of a cluster (~ 0.3 pc) in GMCs (e.g., Saito et al. 2007) and these systems called "clumps".
- A few compact gas systems, have a size scale of ~ 0.03 pc similar to typical cores in low-mass star-forming regions (LMSFRs) were discovered by interferometeric observations toward cluster forming regions.
- Generally, one or a few stars form would from a core (including a hot core) even in cluster-forming regions (e.g., van der Tak et al. 2005). Hence, it is necessary for many cores to form in one clump in order to form a cluster with a large number of stars.
- We carried out molecular line observations in order to detect cores in the clump and to reveal the physical relations between the cores and the clump.

Targets

- We must select targets at a similar evolutional stage, at a similar distance, and with a similar bolometric luminosity in order to compare details of the physical conditions of the dense gas to the characteristics of the clusters.
- We slected 14 objects from the large clumps with a size of 1.0 pc identified by previous observations (e.g., Zinchenko et al. 1998).
- These objects have a IRAS source with a luminosity of ~ 10^4 $L_\odot$ and a distance of ~ 3 kpc, and the indicators of young massive stellar object and NIR clusters.
- We observed 9 of them where physical parameters of dense clumps are already derived by single dish observations with a resolution of ~ 15" (Saito et al. 2007).
- Our targets:
  IRAS 02461+6147 (AFGL 5085), IRAS 03035+5819 (AFGL 437)
  IRAS 05375+3540 (AFGL 5162; S235A/B), IRAS 06056+2131 (AFGL 6366s; S247)
  IRAS 06058+2138 (AFGL 5180; S247), IRAS 06061+2151 (AFGL 5182; S247)
  IRAS 06117+1350 (AFGL 902; S269), IRAS 19442+2427 (AFGL 2454; S87)
  IRAS 19446+2505 (AFGL 2455; S88B)

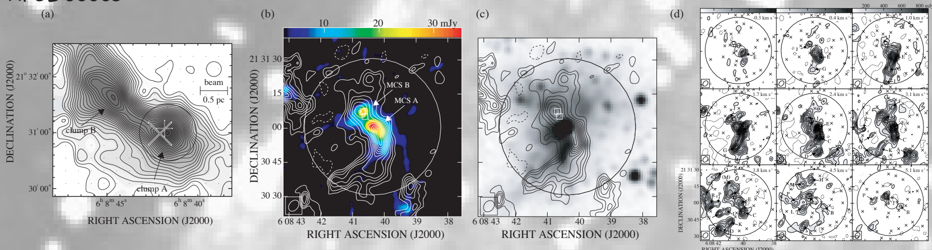
Observation

Nobeyama milimeter Array (NMA)

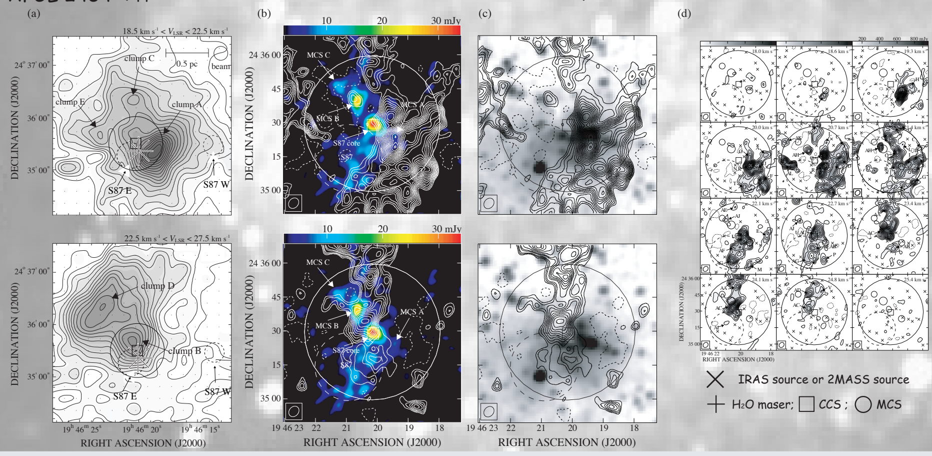
1. Obs. term : From Nov. in 2002 to Apr. in 2003
2. Obs. Line : $C^{18}O$ (J=1-0) (109.782 GHz)
3. Receiver : S100
4. Back End :UWBC & FX
5. Ch. resolution : 31.25 kHz (~ 0.1 km/s)
6. Configuration : D & C
7. Synthesized beam : ~ 4" - 5"

Observational Results (Examples: AFGL 6636s & AFGL 2454)

AFGL 6636s



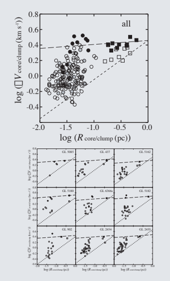
AFGL 2454 (upper : Vlsr = 18.5 - 22.5 km/s; lower : Vlsr = 22.5 - 27.5 km/s)



- (a) The distribution of $C^{18}O$ clumps which are taken from Saito et al. (2007), IRAS sources, H_2O masers, HII regions, and the primary beam area of NMA observation. (b) The intensity distribution by NMA is compared with the 100 GHz continuum image, (c) The $C^{18}O$ distribution is overlaid on the 2MASS Ks-band image. (d) The distribution of $C^{18}O$ cores, centimeter continuum sources (CCSs), milimeter continuum sources (MCSs),
- We have identified 199 cores from NMA images toward 9 cluster-forming regions. The radius, line width, and mass of these cores range from 0.02 to 0.11 pc, from 0.43 to 3.33 km/s, and from 0.5 to 54.1 $M_\odot$, respectively. Next, We compared these cores with 2MASS sources, MCSs, and CCSs as indicators YSOs, and we identified 38 star-forming cores (core with SF) including 11 massive star-forming cores (core with MSF).

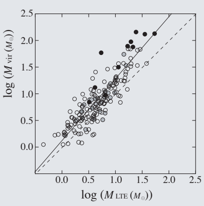
Core Conditions and the physical relations

Line Width - Radius Relation



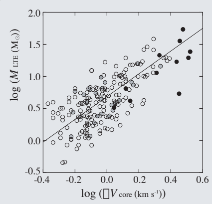
- Figures show the relation between line width and the radius of the cores and the clumps (black : with MSF ; grey : with SF).
- Although the line width of the clumps is in a narrow range of 1.5 - 3.2 km/s, the line width of the cores is in a much wider range of 0.43 - 3.33 km/s. Such a feature is seen even in the individual regions.
- This relation does not follow a single power-law relation. Almost all cores and clumps are in the area between the dashed line (ndex ~ 0.05) and the broken line (index ~ 0.5), and the index of this relation differs from core to core.
- This result indicates that the degree of the dissipation of the turbulent motion varies even in one clump.

LTE mass - Virial mass Relation



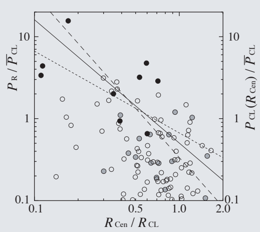
- Figure shows a correlation between the LTE mass and the virial mass for cores. Most of the cores have a larger virial mass than the LTE mass.
- The coefficient of this relation is close to unity, indicating that in the virial equation, the difference in the gravitational and kinetic energy terms is almost proportional to the gravitational energy term.
- In order to strike a good balance between this difference and the external pressure and for more massive cores to achieve the equilibrium state, the external pressure on the surface of cores must be larger.

Mass - Line Width Relation



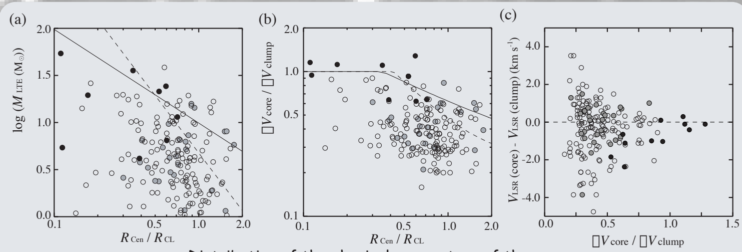
- Figure shows that the line width of the cores increase with the LTE mass. From this tendency, dense gas with a large motion in a clump seems to be necessary in order for massive cores to form.
- The coefficient of this relation is ~ 1.8, and this coefficient does not contradict the results of the LTE - virial mass relation.
- This relation indicates that the average H_2 density of the cores would increase with the line width of the cores because the range of the radius of the cores is small.

Distribution of the cores in the clump



Distribution of the external pressure of the cores

- Figure shows the required pressure of cores, P_r, plotted against the distance, R_{cen}, from the center of the clump. Here, P_r and R_{cen} are normalized to the average clump pressure and the radius of the clump, respectively.
- The cores with large P_r concentrate in the center of the clump. Thus, the nearer the core are to the center of the clump, the higher the external pressure on the surface is expected to become.
- When the H_2 density structure of the clump follows $n(H_2)_{clump}$ ~ $R_{cen}^{-□}$, the pressure in the clump, P_{cl}, is estimated as a function of R_{cen} by P_{cl} ~ (1-□/3) $(R_{cen})^{-□}$: □= 1 (dotted), 1.5 (solid), and 2 (dashed).
- These curves a re similar to the upper envelope of this plot, and this indicates that almost all core would be gravitationally bound by the external pressure if the H_2 density structure in the clump has a relation of ~ $R_{cen}^{-□}$.



Distribution of the physical parameters of the cores

- Figure (a) shows the mass of cores plotted against the distance, R_{cen}, from the center of clump. The upper envelope of the core mass would gradually decrease with distance. The solid and dashed lines indicate the mass-distance relations with □= 1.0 and 2.0 if the H_2 density of the cores is in proportion to the H_2 density in the clump, that has a density structure of ~ $R_{cen}^{-□}$. The distribution of the upper envelope of the core mass is similar to the relations epressed by these lines. Thus, the distribution of the core mass would be controlled by the H_2 density structure in the clump.
- Figure (b) shows the ratio of the line width for the cores and the clump plotted against the distance. The starless cores with a high line width ratio (> 0.7) are concentrated in the center of the clump, and the upper envelope of this ratio would gradually decrease with distance. The solid and dashed lines indicate the ratio of the maximum line width of the core to that of the clump with □= 1.0 and 2.0 if the mass-distance relation is same as in Figure (a). The distribution of the upper envelope of the line width ratio is similar to the relations epressed by the two lines. Thus, the spatial distribution of the internal kinetic motion of the cores also would be controlled by the H_2 density structure in the clump.
- Figure (c) shows the difference in the radial velocity of the core and the clump plotted against the ratio of the line width ratio for cores and the clump. Altough the cores width a large line width ratio have a radial velocity similar to that of the clump, the difference in the radial velocity of the cores with a smaller line width ratio is distributed over a wide range. The cores with a large line width hardly move in the clump and the cores with a narrow line width move around in the clump. We suggest that cores with a narrow line width are formed in the low external pressure region of the clump by converting the internal kinetic energy of the gas to the energy of relative motion of cores.

- From these disscussions, we suggest that the central region of the clump, which has a density structure of ~ $R_{cen}^{-□}$, is the environment where cores with large internal kinetic motion and high average H_2 density are easily formed and that internal kitetic motion and average H_2 density of the formed cores are expected to decrease as the separation between the formed region and center of the clump becomes longer.
- According to the result that the mass of the formed star would depend on the H_2 density and turbulent motion of the core, the mass of the formed star decreases with the distance from the center of the clump. Therefore, we suggest that there is a close relation the spatial distribution of the mass of the stars in the cluster formed in the clump and the H_2 density structure of the clump. Thus, the physical characteristics of the cluster would depend on the H_2 density structure, internal kinetic motion, and the mechanism of the core formation in the clump.