Infall motion with rotation of the cluster forming clump GGD12-15

Tomomi Shimoikura(Otsuma Women's University),

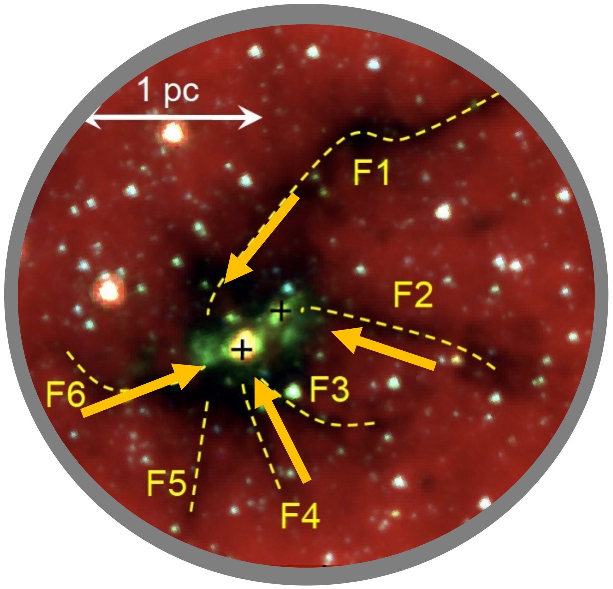
Kazuhito Dobashi(Tokyo Gakugei University),

Naomi Hirano(ASIAA), Fumitaka Nakamura, Tomoya Hirota, Kotomi Taniguchi, Yoshito Shimajiri(NAOJ), Tomoaki Matsumoto(Hosei University)

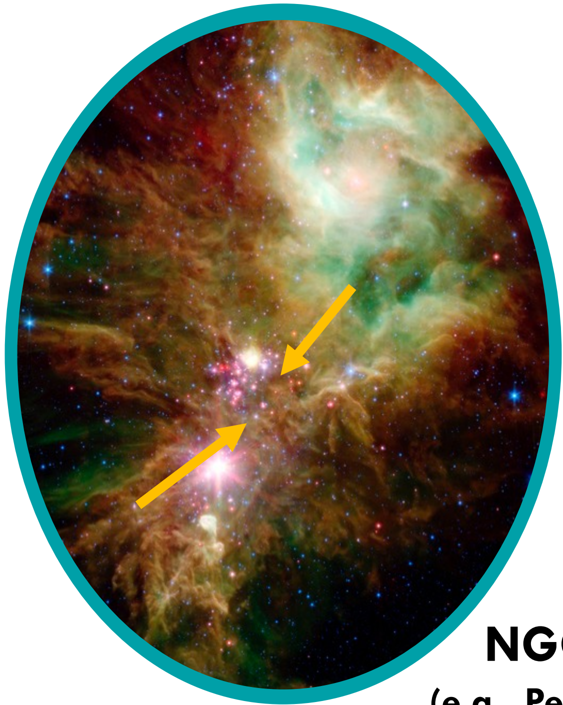
Shimoikura et al. 2022, ApJ, 928, 76

Most stars form in Clusters

The majority of stars in our galaxy are formed in clusters, but it is still unclear how cluster formation is initiated.



SDC335
(Peretto+ 2016)



NGC 2264
(e.g., Peretto+ 2006)

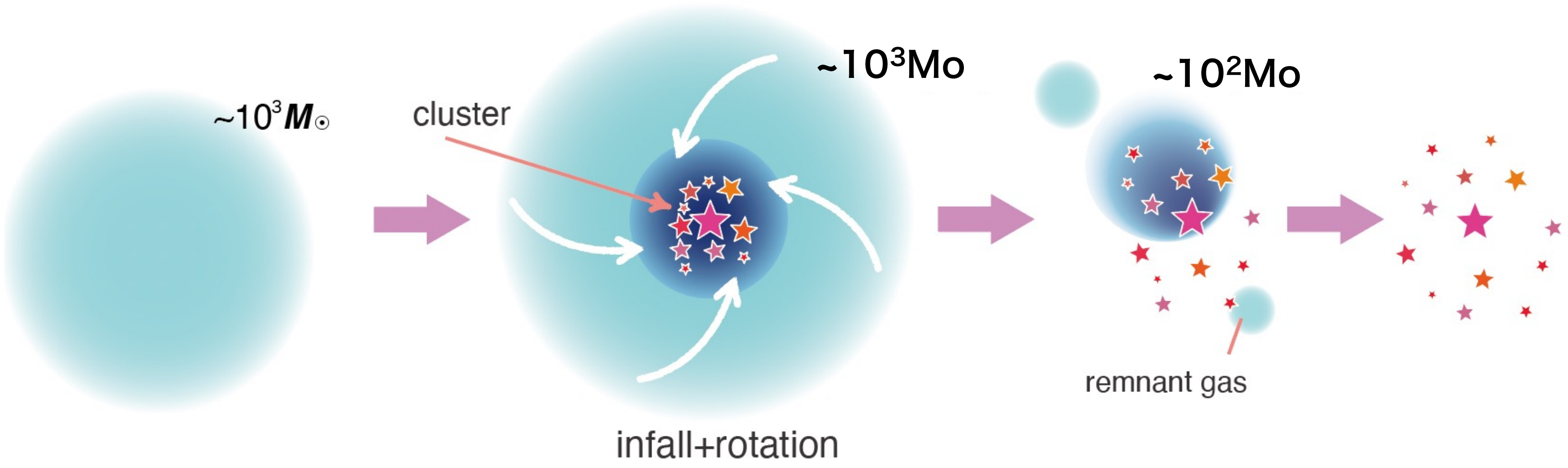
Serpens South
(e.g., Kirk+ 2013)

Revealing how mass accumulates from a parent molecular clump to form a massive core is important for our understanding of the formation process of clusters.

How does cluster formation occur ?

We found that some molecular clumps are characterized by a velocity structure representing gravitational contraction with rotation.

formation of massive clump	early stage of cluster formation	advanced stage of cluster formation	final stage of cluster formation



The proposed evolutionary scenario of cluster formation (Shimoikura et al. 2018).

How does cluster formation occur ?

Infall motion with rotation of the clumps
(Shimoikura+ 2018)

cloud-cloud collisions
filament–filament collisions
(e.g., Nakamura+ 2014)

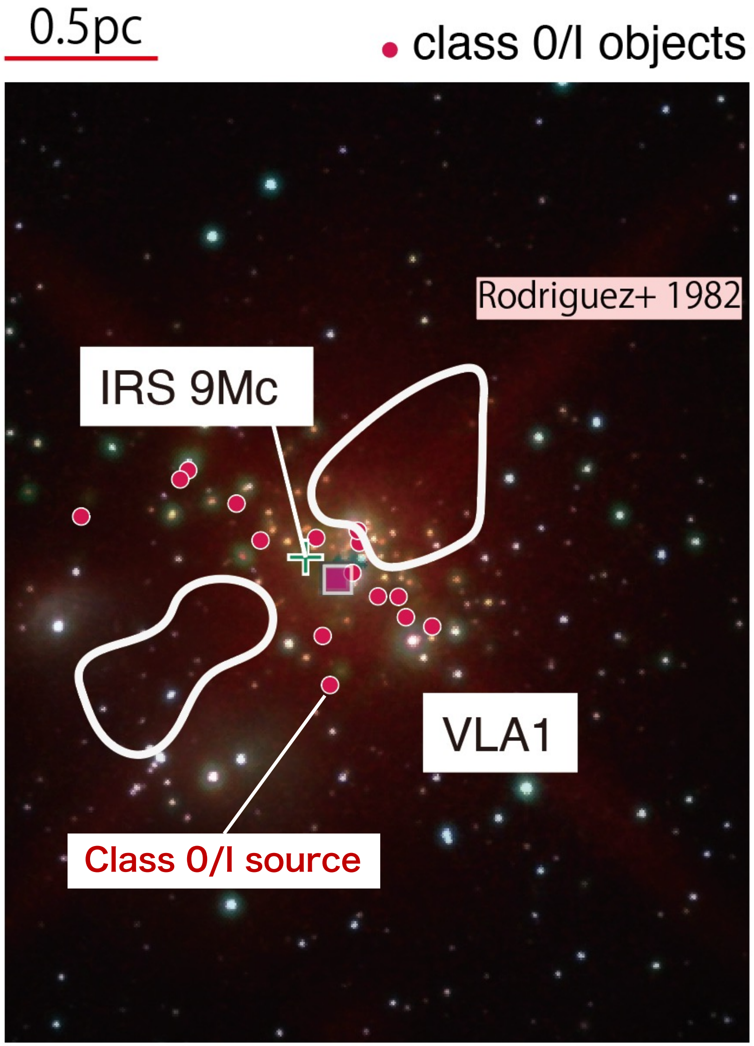
outflows

inflows

Influenced by supernova remnants
(e.g.,Dobashi+ 2019)

To understand the gas kinetics of cluster-forming clumps through molecular spectroscopy, it is necessary to investigate the entire velocity field of cluster-forming clumps.

GGD 12-15



An active star-forming site embedded in the Mon R2 molecular cloud.

- **Distance: 893 pc (Dzib+ 2016)**
- **A compact HII region VLA1 is formed (Gómez+ 2002)**
- **A young cluster (~100 members, ~4 Myr) (e.g., Gutermuth+ 2011).**
- **A bipolar molecular outflow extending about 6’ (e.g.,Rodriguez+ 1982), seems to be driven by the Class 0/I source IRS 9Mc(Sato+ 2008).**

These results indicate that the clump is in a relatively young stage of cluster formation and is forming the cluster very actively.

Observations

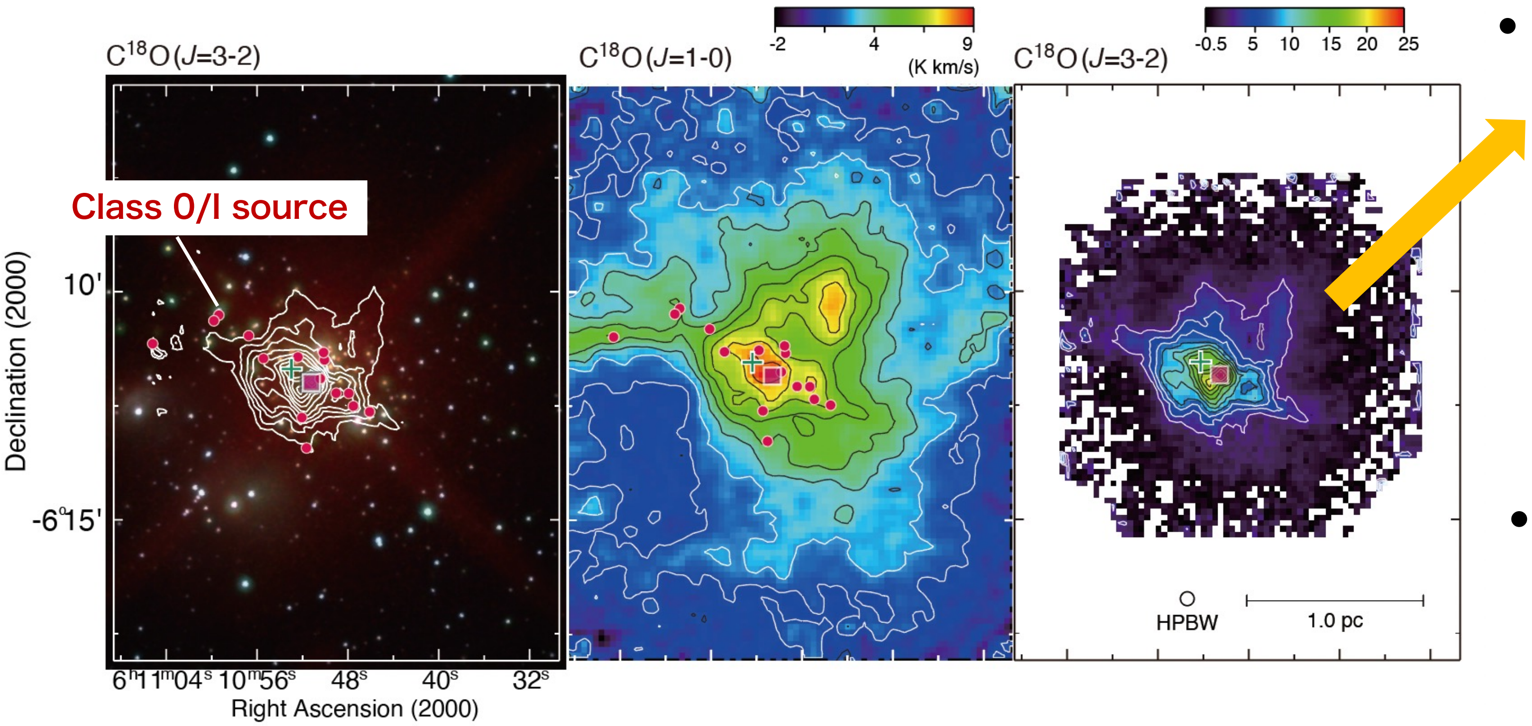
To investigate the molecular gas kinematics in the clump, we observed the region with various molecular emission lines.

- **Molecular Lines**
  - $C^{18}O(J=3\text{-}2)$: 329.33 GHz
  - $C^{18}O(J=1\text{-}0)$: 109.78 GHz
  - $^{12}CO(J=1\text{-}0)$: 115.27 GHz
- **Map resolution: ~15"**
- **Velocity resolution: 0.1 km/s**

Other observational molecular lines

$^{13}CO(J=1\text{-}0)$, $N_2H^+(J=1\text{-}0)$, $HC_3N(J=10\text{-}9)$, $CCS(J_N=8_7\text{-}7_6)$

Spatial distribution of the molecular emission lines

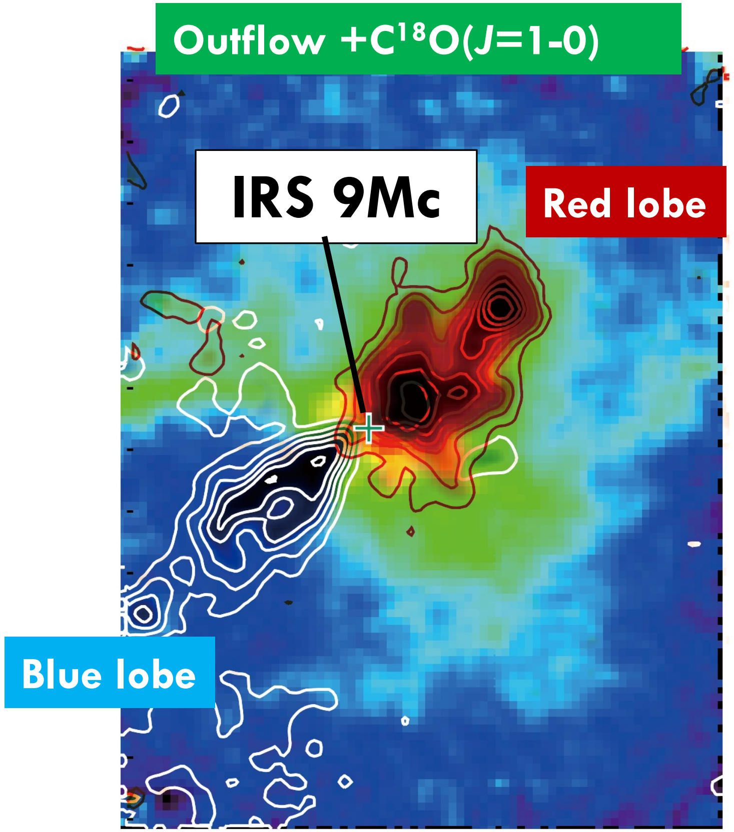


- **Physical properties of the clump:**
  - $R \sim 1.3$ pc
  - $T_{ex} \sim 40$ K
  - $M \sim 3000\ M_{\odot}$
  - $\Delta V \sim 2.5\ \mathrm{km\ s^{-1}}$

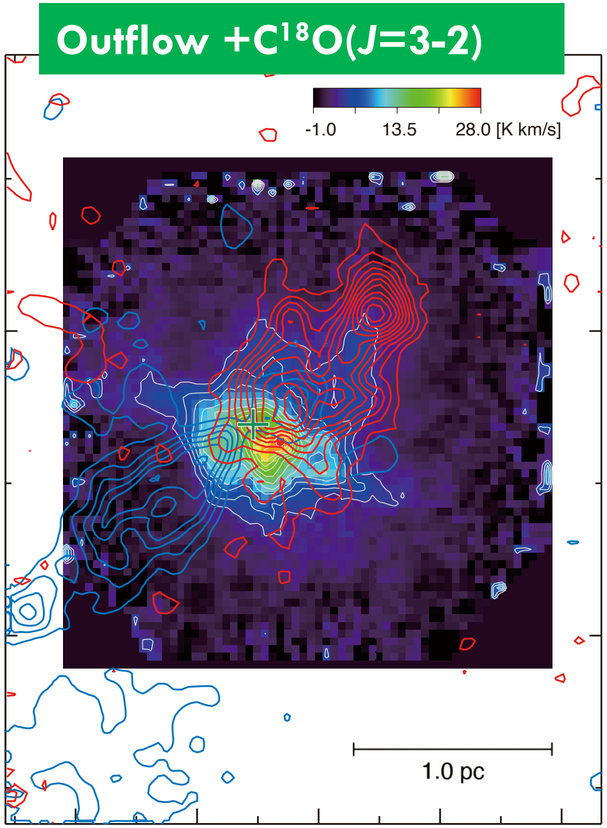
- **Physical properties of the core:**
  - $R \sim 0.3$ pc
  - $M \sim 500\ M_{\odot}$
  - $\Delta V \sim 2.0\ \mathrm{km\ s^{-1}}$

The cluster extends from northeast to southwest, and the Class 0/I objects are located along the structure.

Search for Outflow



color:C^{18}O(J=1-0)



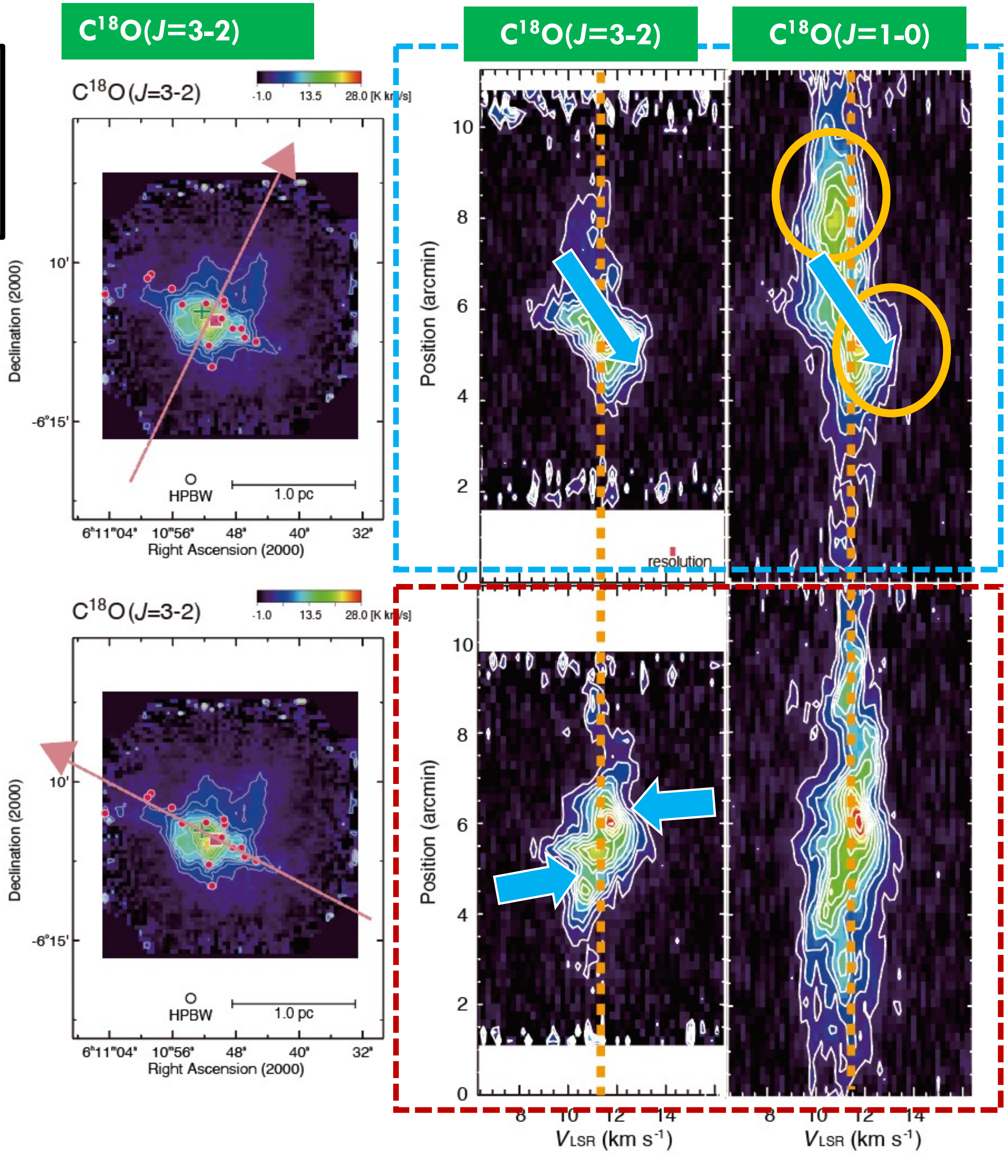
color:C^{18}O(J=3-2)

We found the outflow consists of blueshifted and redshifted lobes that extend over ~1 pc covering the entire clump, with an estimated mass of 11.7 Mo and 10.6 Mo for the blue and red lobes, respectively.

Velocity Structure

PV diagram taken along the minor axis of the clump

PV diagram taken along the major axis of the clump



- **There is a velocity gradient.**
- **There are two well-defined peaks.**

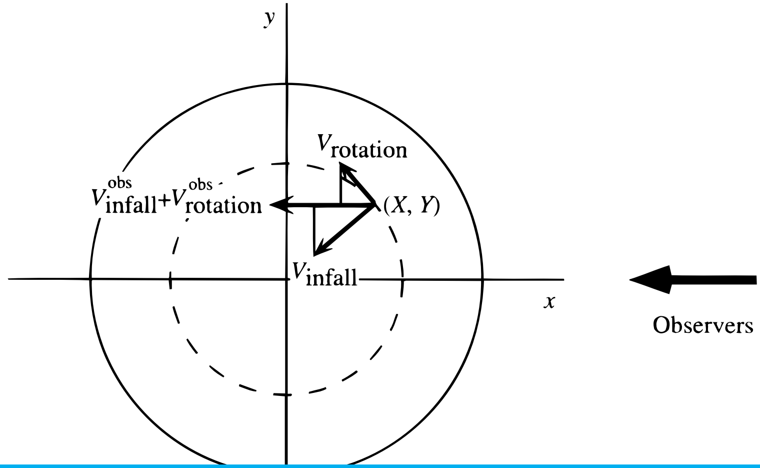
The feature is very similar to those observed in the envelope of low-mass YSOs.

the systemic velocity of the clump

Infall motion with rotation

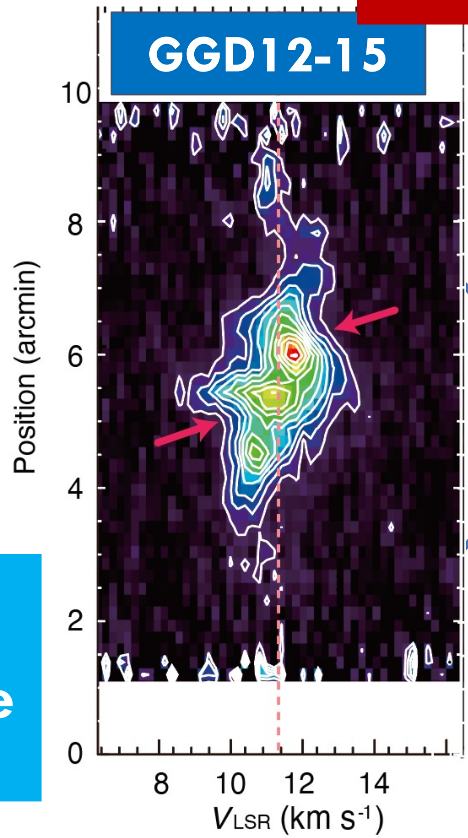
Early stages of cluster-forming clumps → scaled-up version of single protostellar envelope with infall + rotation

A low-mass protostar

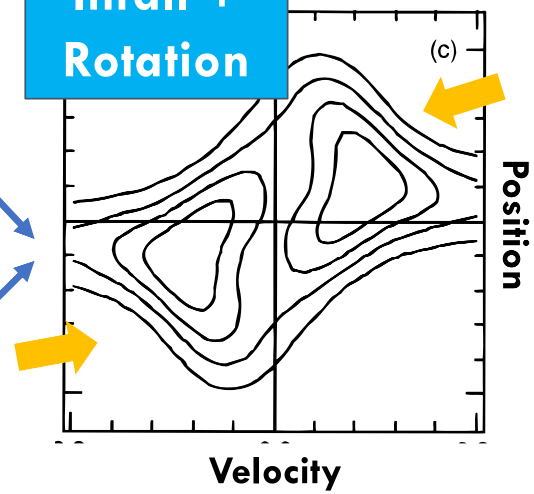


The double-peaked feature for the low-mass YSOs has been interpreted as an infalling envelope with rotation.

GGD12-15



Infall + Rotation

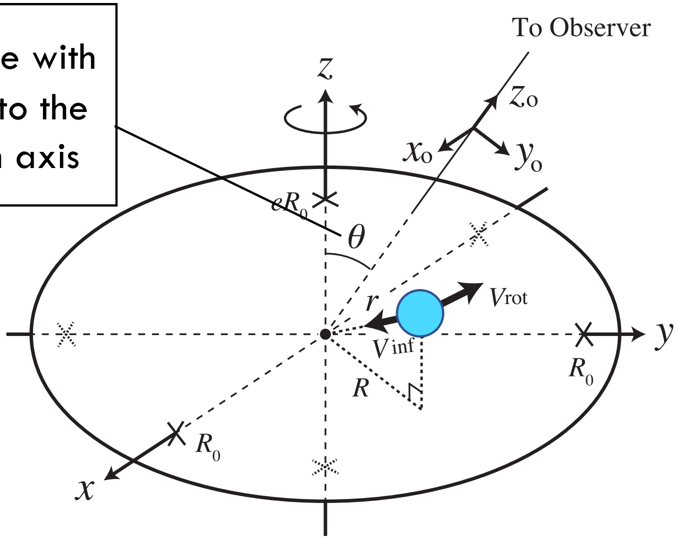


(IRAS 04368+2557, Ohashi+ 1997)

Oblate Clump Model

We made a simple model of an oblate clump with an ellipticity e_0 that is gravitationally collapsing with rotation and formulated the infall velocity V_{inf}, rotational velocity V_{rot}, and density distributions as a function of distance to the center of the clump.

The angle with respect to the rotation axis



The distance from the center of the clump

$$r = \sqrt{x^2 + y^2 + \left(\frac{z}{e_0}\right)^2}$$

The distance from the rotation axis

$$R = \sqrt{x^2 + y^2}$$

density

$$\rho(r) = \rho_0 \left[1 + \left(\frac{r}{R_\mathrm{d}}\right)^2\right]^{-\frac{\alpha}{2}} \qquad (\alpha = 1.5)$$

for the free-falling clump at r>>Rd

infall velocity

$$V_{\mathrm{inf}}(r) = V_{\mathrm{inf}}^0 \left(\frac{r}{R_\mathrm{v}}\right)\left[1 + \left(\frac{r}{R_\mathrm{v}}\right)^2\right]^{-\frac{1+\beta}{2}} \qquad (\beta = 0.5)$$

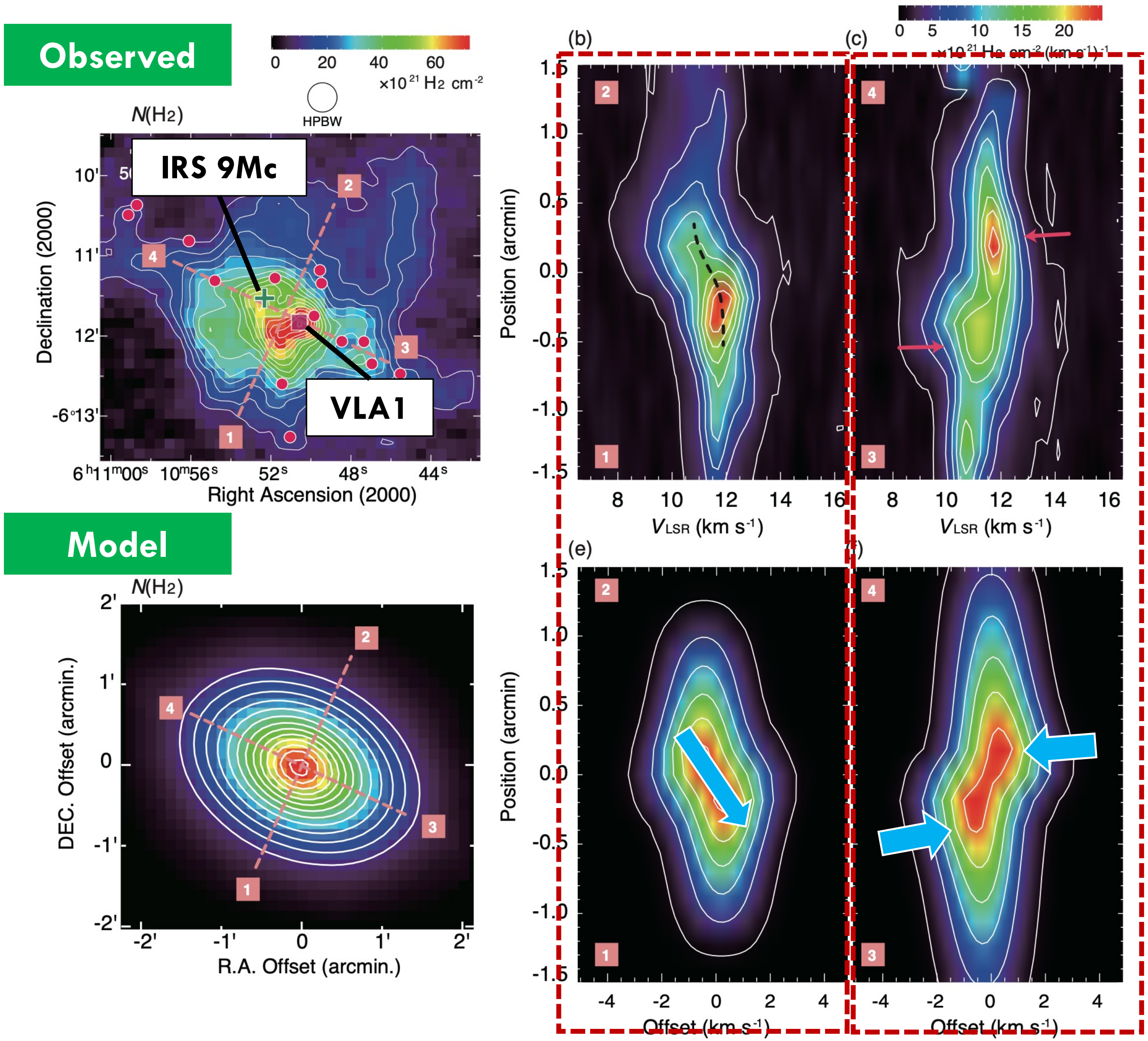
for conservation of energy at r>>Rv

rotation velocity

$$V_{\mathrm{rot}}(R) = V_{\mathrm{rot}}^0 \left(\frac{R}{R_\mathrm{v}}\right)\left[1 + \left(\frac{R}{R_\mathrm{v}}\right)^2\right]^{-\frac{1+\gamma}{2}} \qquad (\gamma = 1)$$

for conservation of angular momentum at R>>Rv

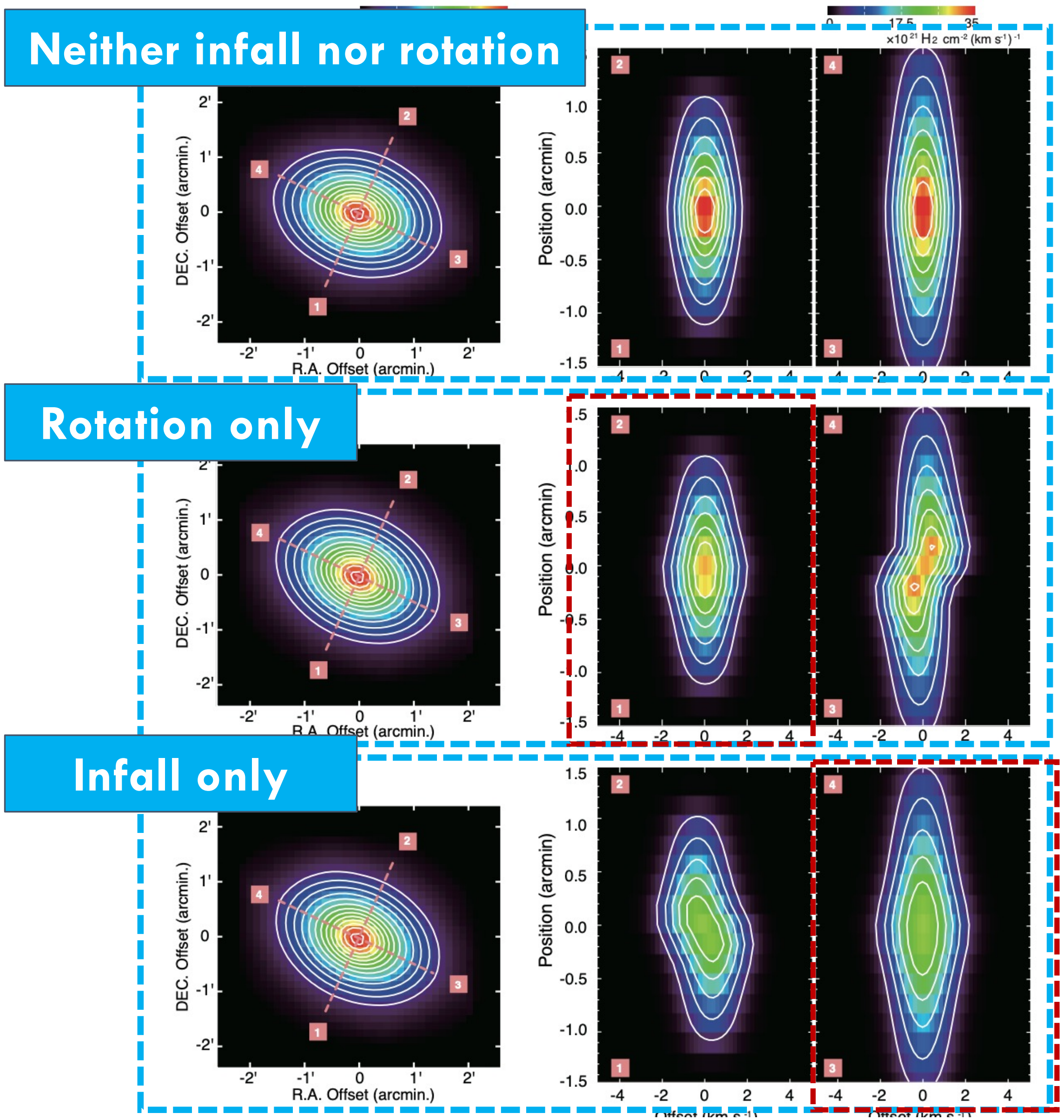
: ρ_0, V_{inf}^0, V_{rot}^0, R_d, and R_v are constants



Results

- The mass infall rate :~$1.6*10^{-3}$ $M_{\odot}$ yr^{-1} at the clump radius 0.5 pc.
- The mass loss rate by the outflow: ~$5*10^{-4}$ $M_{\odot}$ yr^{-1}.

⇨one third of the infalling mass is ejected by the outflow, which is consistent with a theoretical prediction (e.g., Nakamura & Li 2014).



The two features observed in the PV diagrams can be reproduced only when the clump has both of infall motion and rotation at the same time.

These results strongly imply that the GGD 12-15 clump is collapsing with rotation.

Conclusion

- Two significant features appear in PV diagrams of the observed emission lines.
  - the two well-defined peaks seen in the PV diagram taken along the major axis of the clump.
  - a velocity gradient seen in the PV diagram taken along the minor axis of the clump.
- We made a simple model of an oblate clump that gravitationally collapsing with rotation, and formulated the infall velocity, rotational velocity, and density distributions as a function of distance to the center of the clump.
- The two features in the PV diagrams can be reproduced only when infalling and rotational motions are present, implying that the GGD 12-15 clump is collapsing with rotation.