A Kinematical Transition from an Infalling Envelope to a Core around the Protostar L1489 IRS

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Motivation:

Protoplanetary disks are important objects for planet formation. However, their formation process is still unclear. Disks form around protostars as mass and angular momentum are transferred from cores. Hence, revealing the gas kinematics around protostars over wide-spatial scales from a disk (~100 au) to a core (~10,000 au) is essential to understand the physical process of disk formation. Some works have investigated the kinematics on 100–1,000 au scales and revealed that infalling envelopes are connected to rotationally supported disks smoothly. However, the kinematics on 1,000–10,000 au scales and the transition from an infalling envelope to a core are still unclear.

What we do:

We have observed the Class I protostar L1489 IRS with Atacama Compact Array (ACA or Morita array) and IRAM 30-meter telescope in $C^{18}O$ 2–1 to investigate the gas kinematics on 1,000–10,000 au scales. We have measured a radial profile of rotational velocity, and constrained infalling velocity from a comparison between kinematic models and observations.

Our findings:

- *The radial profile of the measured rotational velocity shows a break at a radius of ~2,800 au:* the power-law index of the profile changes from ~-1 to ~0.2, suggesting a kinematical transition from an infalling envelope to a core.
- An envelope model with *infalling velocity slower than the free-fall velocity by a factor of 0.4* explains observations better than a free-fall model. Magnetic field could be an origin of such a slow infalling velocity.

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Reference: [1] Ohashi et al. 1997, ApJ, 488, 317–329; [2] Belloche 2013, EAS Pub. Ser., 62, 25; [3] Gaudel et al. 2020, A&A, 637, A92; [4] Lee 2010, ApJ, 725, 712–720; [5] Sai et al. 2020, ApJ, 893, 51; [6] Ulrich 1976, ApJ, 210, 377–391; [7] Aso et al. 2015, ApJ, 812,27; [8] Shu 1977, ApJ, 217, 488–497; [9] Yen et al. 2011, ApJ, 742, 57; [10] Goodman et al. 1993, ApJ, 406, 528–547

Gas Kinematics around Protostars

It is suggested from line observations that protostars are surrounded by three different kinematic structures: a disk rotating at Keplerian velocity on ~100 au scale, an infalling envelope, where material infalls conserving angular momentum, on ~1,000 au scale, and a core rotating like a rigid-body or being turbulent on ~10,000 au scale [1, 2, 3]. Confirming this picture in individual sources is required to understand how material is brought from cores to disks. Recent works probing the kinematics on a 100–1,000 au scales have revealed the transition from a disk to an envelope in tens of protostellar systems [e.g., 4]. However, *the kinematics on 1,000–10,000 au scales and the transition from an envelope to a core are still unclear.*

Protostar L1489 IRS

- $M_* = 1.6\ M_{\rm sun}$ (from the Keplerian rotation), $L_{\rm bol} = 3.5\ L_{\rm sun}$, $T_{\rm bol} = 226$ K
- $v_{\rm sys} = 7.22$ km/s

L1489 IRS is a Class I protostar in the Taurus molecular cloud (d~140 pc). From our previous observations with ALMA, Keplerian rotation of a disk ($v_{\rm rot} \propto r^{-0.5}$) and rotation of an envelope conserving angular momentum ($v_{\rm rot} \propto r^{-1}$) are identified at radii less than 1,000 au [5]. However, rotational and infalling velocity at radii of 1,000–10,000 au are still unknown.

Objective of this work:

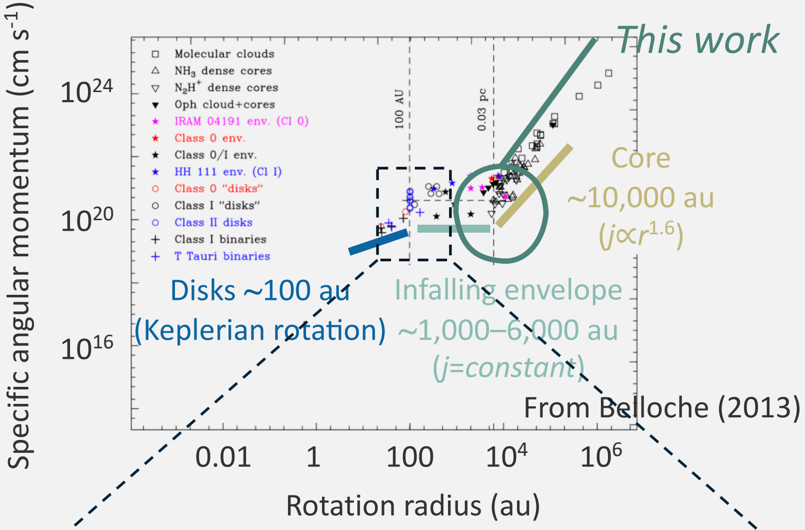
- *To measure rotational and infalling velocity at radii of 1,000–10,000 au*
- *To reveal a kinematical transition from an infalling envelope to a core*

Mapping Observations

We have mapped 2'x2' region around L1489 IRS with ACA and IRAM 30-meter telescope in $C^{18}O$ 2–1. Both data are combined using CASA with a task *feather* and the combined data are analyzed.

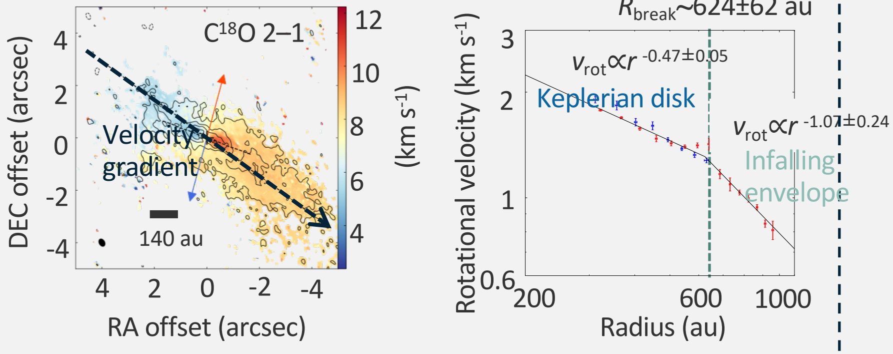
Summary of the combined data
- Beam size: 7.7''x6.4'' (-85°) (~1,000 au resolution)
- Δv: 0.17 km/s
- Rms: 0.11 Jy/beam

Radial distribution of specific angular momentum



From Belloche (2013)

Previous work (see Sai et al. 2020)

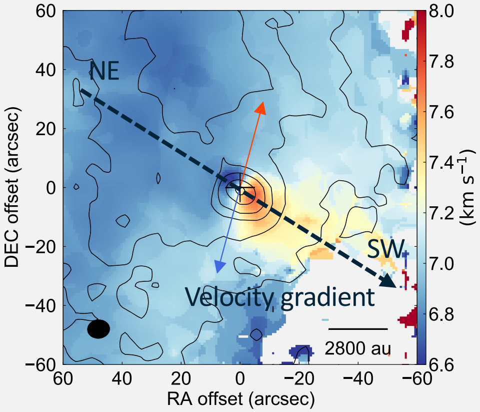


- Velocity gradient due to rotation (in a direction perpendicular to the outflow) was seen.
- Rotational velocity was measured at radii of 300–1,000 au from the velocity gradient.

Observational Results & Mesurement of Rotational Velocity

The $C^{18}O$ 2–1 emission shows a velocity gradient likely due to rotation. Hence, we have measured the rotational velocity.

Moment 0/I maps



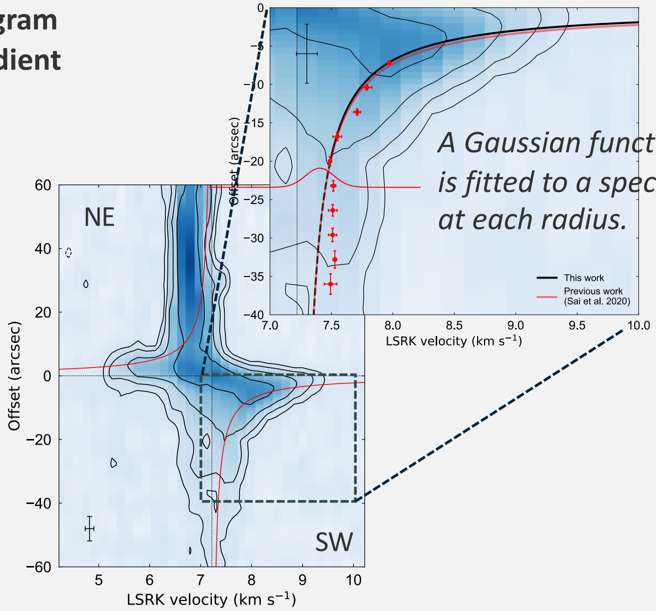
Contour: integrated intensity
Color: intensity weighted mean velocity
Red & blue arrows: direction of the outflow

The $C^{18}O$ 2–1 emission shows the following features:

- Intensity peak at the protostellar position
- Velocity gradient in the same direction as that of the disk rotation
- Second peak at the northeast side

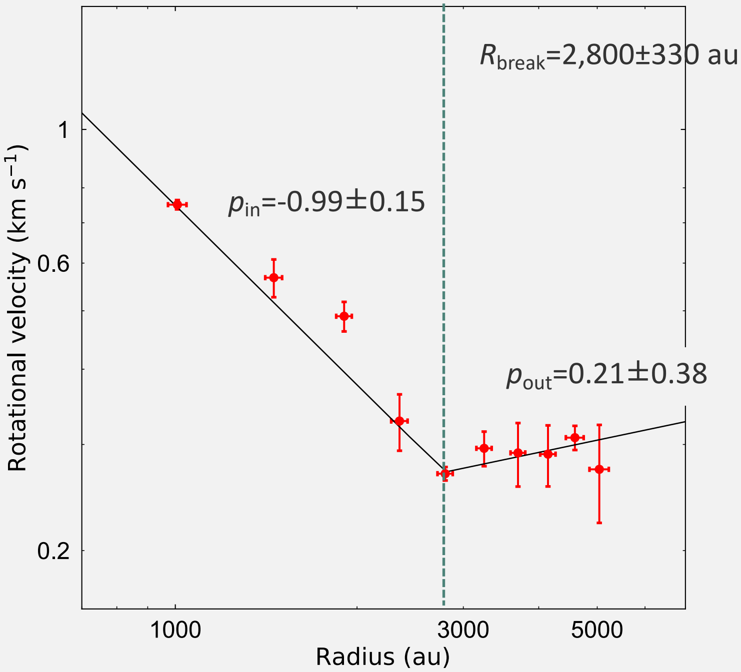
Position-velocity (PV) diagram cut along the velocity gradient

Rotational velocity is measured on the southwest side, where there is less contamination of the second component on the northeast side.



A Gaussian function is fitted to a spectrum at each radius.

Radial profile of the measured velocity



Radial profile of the measured rotational velocity shows a break at r~2,800 au.

Fitting a double power-law function

$$V_{\rm rot} = \begin{cases} V_{\rm break}\left(\frac{r}{R_{\rm break}}\right)^{p_{\rm in}} & (r \le R_{\rm break}) \\ V_{\rm break}\left(\frac{r}{R_{\rm break}}\right)^{p_{\rm out}} & (r > R_{\rm break}) \end{cases}$$

Fitting results:

- Power-law index is ~-1 at r<2,800 au, which can be interpreted as rotation of an envelope conserving angular momentum ($v \propto j/r$).
- Velocity increases with radius at r>2,800 au.

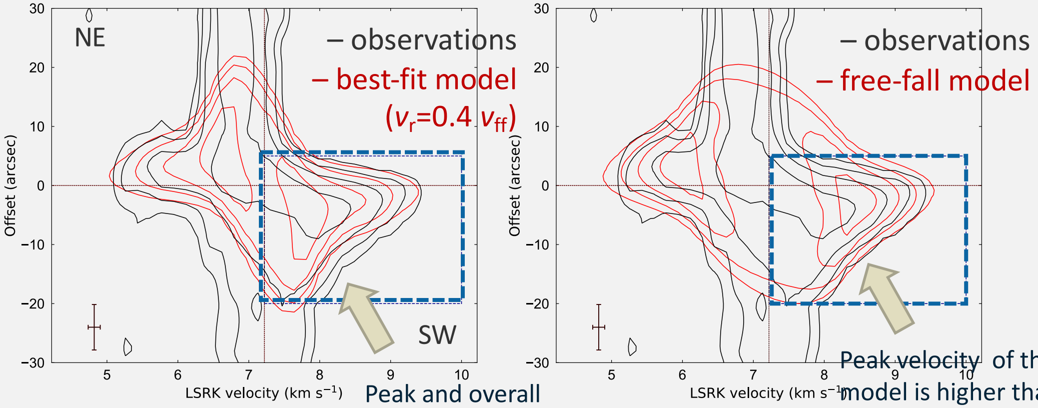
Infalling Velocity

We have constructed a disk and spherical envelope model adopting density and velocity field used in our previous work for a disk and those suggested by Ulrich (1976) for an envelope [5, 6]. To explore the best infalling velocity, we introduced a parameter *α* as follows:

$$v_r(r,\theta) = -\underline{\alpha}\left(\frac{GM_*}{r}\right)^{0.5}\left(1+\frac{\cos\theta}{\cos\theta_0}\right)^{0.5}$$

, where *0<α<1* and *α=1* means free-fall.

We found that *an envelope model with α=0.4 reproduces observations better than a model with α=1.* Magnetic field is one possible cause of the slow infalling velocity. The strength of the required magnetic field is estimated to be ~0.01–0.1 mG from equation of motion and *α*=0.4 [7].



Peak and overall shape show good agreement

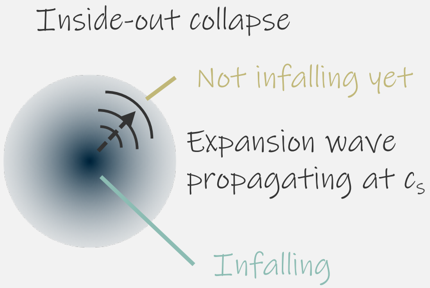
Peak velocity of the model is higher than that of observations

Radial Distribution of Specific Angular Momentum

Radial profile of specific angular momentum is calculated from the measured rotational profile and compared to a simple model calculation.

Model calculation of angular momentum transfer based on the Inside-out collapse [8, 9]

- We assume angular specific momentum distribution in an initial core follows $j \propto r^{1.6}$ as suggested from observations of dense cores [10].
- Expansion wave propagates at sound speed (0.2 km/s) from inside to outside.
- Material inside the front of the expansion wave infalls.



Our calculation suggests the following:

- *Larger initial angular momentum is prefered to explain the radial profile of the measured specific angular momentum.*
- Expected *j*-profile at the age of 1.5x10^5 yr, which is comparable to the lifetime of Class I protostars, matches the measured profile in L1489 IRS.

Radial profile of specific angular momentum *j*