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A Substellar-Mass Protostar and its Outflow of IRAS 15398-3359 Revealed by Subarcsecond-Resolution Observations of H_2CO and CCH

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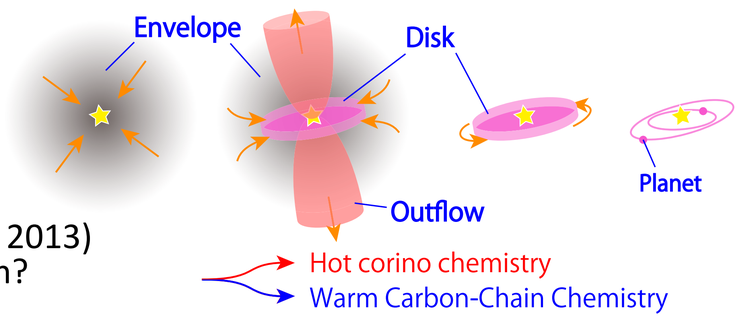
1. Abstract

Subarcsecond (0".5) images of H_2CO and CCH line emission have been obtained in the 0.8 mm band toward the low-mass protostar IRAS 15398-3359 in the Lupus 1 molecular cloud as one of the Cycle 0 projects of ALMA. We have detected a compact component concentrated in the vicinity of the protostar and a well-collimated outflow cavity extending along the northeast-southwest axis. The inclination angle of the outflow is found to be about 20°, or almost edge-on, based on the kinematic structure of the outflow cavity. The centrally concentrated component is interpreted by use of a model of the infalling rotating envelope with the estimated inclination angle, and the mass of the protostar is estimated to be less than 0.09 M_{sun}. Although IRAS 15398-3359 and L1527 are both the warm-carbon-chain chemistry sources, their physical properties in the vicinity of the protostar are found to be much different from each other.

2. Background

Disks
- When and how is a disk formed?

Chemical Diversity
- HCC vs WCCC (Sakai & Yamamoto 2013)
- Origin and evolution?



Prior Research: L1527
- WCCC source (Sakai et al. 2008)
- Kinematic structure in the envelope was resolved (Sakai et al. 2014a, 2014b).
  - Model of an infalling rotating envelope (Particles cannot fall into the inside of the centrifugal barrier.)
  - PV diagram of CCH is well reproduced (Sakai et al. 2014b).
  - Radius of the centrifugal barrier is determined.

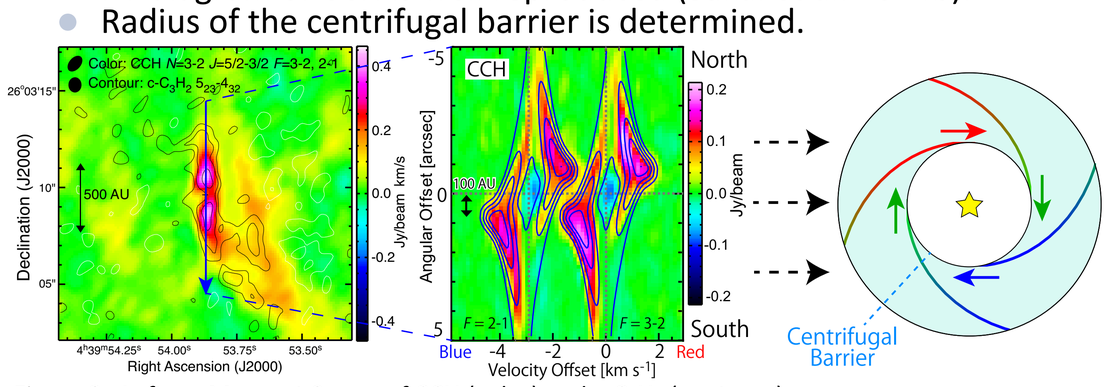


Figure 2. Left: Moment 0 map of CCH (color) and c-C_3H_2 (contours).
Center: PV diagram along the envelope axis of CCH (color) and the model results (contours).
Right: Model of an infalling rotating envelope.

3. Observation

IRAS 15398-3359
- Lupus 1 molecular cloud, D = 155 pc, (α_{2000}, δ_{2000}) = ($15^h43^m02^s.3$, -34°09'07".5)
- Low-mass Class 0, warm carbon-chain chemistry source (Sakai et al. 2009)

ALMA Cycle 0
- Date: Dec. 31, 2012, On-Source Time: 27 min (set 1), 21 min (set 2)
- Band 7 set 1: LSB 351 GHz, 363 GHz, set 2: LSB 338 GHz, 350 GHz
- Bandwidth: 469 MHz, Frequency resolution: 122 kHz (~ 0.1 km/s), T_{sys}: 120 ~ 300 K

Figure 1. Antennas of ALMA

Line
- CCH (N=4-3, J=7/2-5/2, F=4-3 & 3-2; F_2, ...)
- H_2CO (5_{05}-4_{04}, 5_{15}-4_{14}, 5_{24}-4_{23})
- CH_3OH ($J_K = 7_0$-6_0 A^+, ...)

High resolution ~ 100 AU

Beam size
- CCH F_2: 0".70 x 0".46 (PA = 72°)
- H_2CO (5_{15}-4_{14}): 0".60 x 0".44 (PA = 46°)

4. Distribution

- Outflow features
  - Well collimated
  - NE: Redshifted
  - SW: Blueshifted
- Compact component
  - Centrally concentrated → Envelope or disk?
  - H_2CO: Single-peaked
  - CCH: More flattened

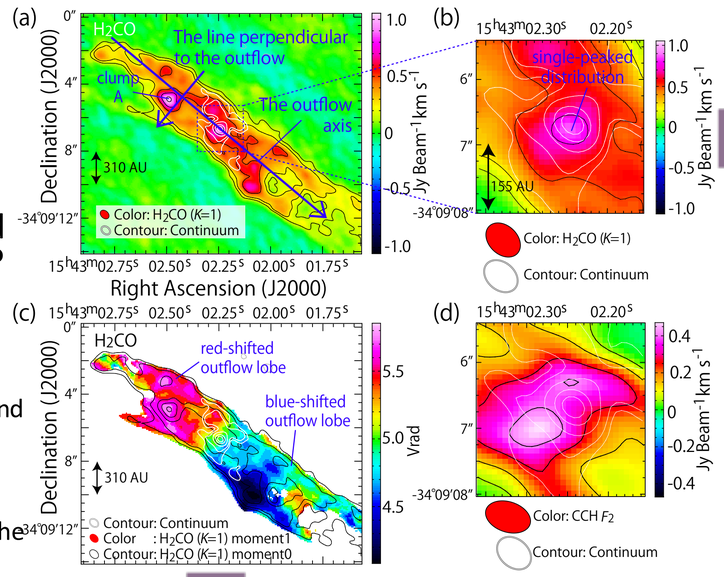


Figure 3.
(a) Moment 0 map of H_2CO (color) and the continuum (white contours).
(b) A zoom of the central part of (a).
(c) Moment 1 map of H_2CO.
(d) A zoom of the central part of the moment 0 map of CCH.

5. Outflow

- PV diagrams of the outflow along 2 axes shown in Fig. 3a
  - Accelerated component along the outflow
  - Elliptic feature across the outflow
- Inclination angle is estimated to be 20° ± 10°.
  - Edge-on: Previously reported to be 'pole-on'.
    - 50° by Yıldız et al. 2013, 75° by van Kempen et al. 2009
- Opening angle is much smaller than the L1527 case (C ~ 0.05).
- Parameters: i = 20°, V_0 = 0.38, C = 0.8

Outflow cavity is resolved.

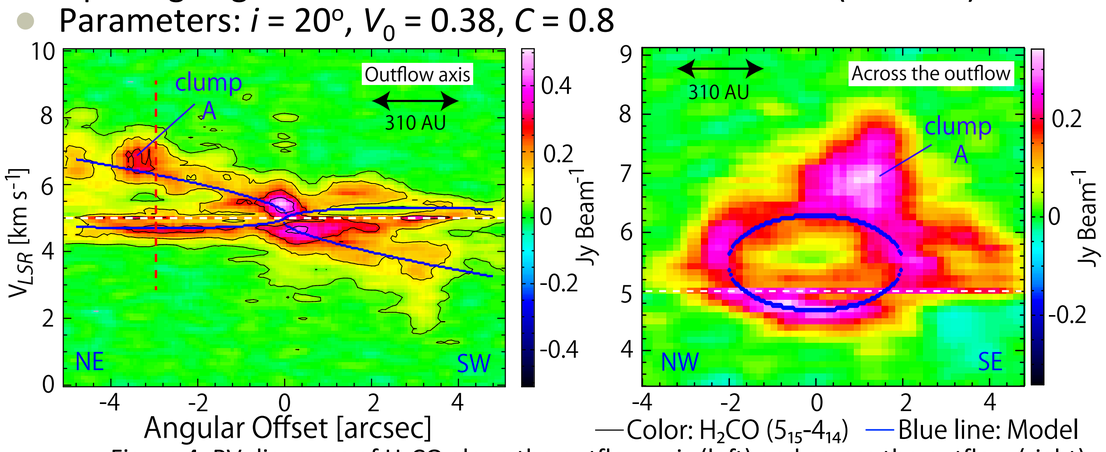
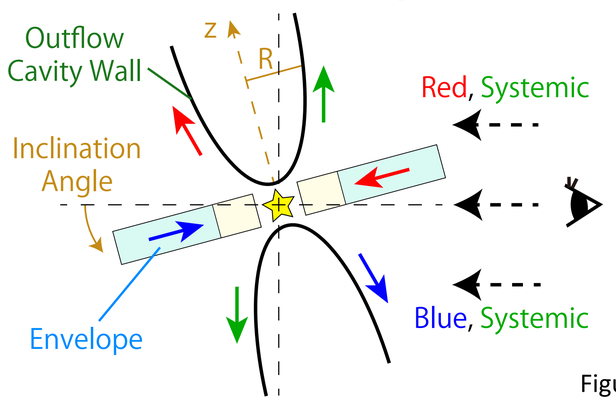


Figure 4. PV diagrams of H_2CO along the outflow axis (left) and across the outflow (right).



Standard Parabolic Model (Lee et al. 2000)

$$z = C R^2$$
$$V_R = V_0 \frac{R}{R_0}$$
$$V_z = V_0 \frac{z}{z_0}$$

C: Shape (arcsec^{-1})
V_0: Velocity (km s^{-1})
$R_0 = z_0$ = 1 arcsec

- Accelerating
- Not spiraling
- Expanding

Figure 5. Velocity field along the outflow axis.

6. Envelope

- PV diagrams of H_2CO
  - Centrally concentrated component
  - Small velocity shifts (~ ± 1 km s^{-1})
    - → Low protostellar mass
    - → Marginal rotation
  - High-velocity component
    - → Hint of a Keplerian disk?
- Parameters:
  - M = 0.02 M_{sun} (L1527: 0.18 M_{sun})
  - r_{CB} = 30 AU (L1527: 100 AU)
  - R_{ext} = 240 AU

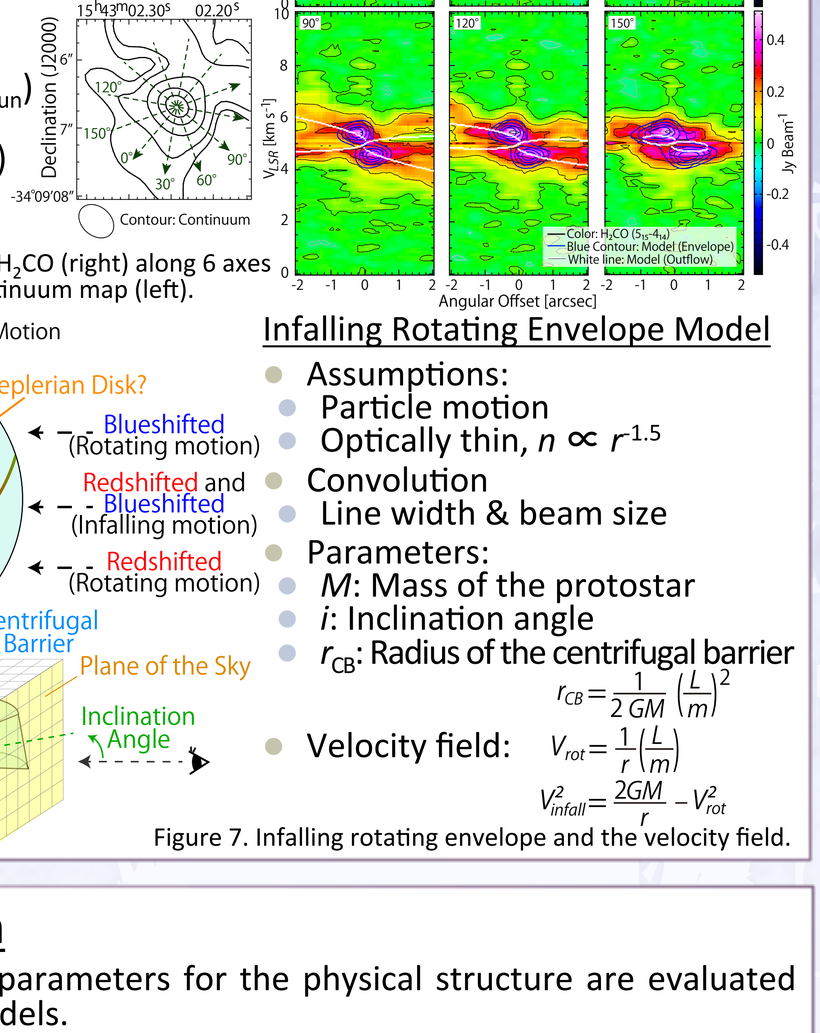
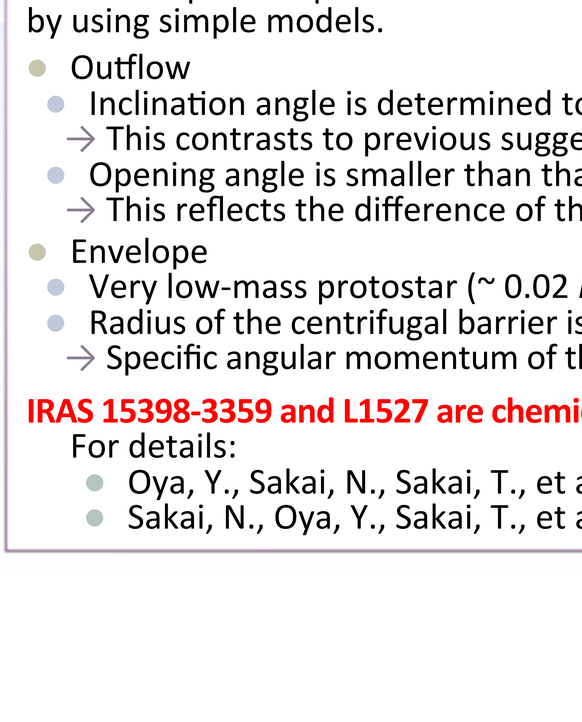


Figure 6. →
6 PV diagrams of H_2CO (right) along 6 axes shown in the continuum map (left).



Infalling Rotating Envelope Model

- Assumptions:
  - Particle motion
  - Optically thin, $n \propto r^{-1.5}$
- Convolution
  - Line width & beam size
- Parameters:
  - M: Mass of the protostar
  - i: Inclination angle
  - r_{CB}: Radius of the centrifugal barrier

$$r_{CB} = \frac{1}{2}\frac{1}{GM}\left(\frac{L}{m}\right)^2$$

- Velocity field:

$$V_{rot} = \frac{1}{r}\left(\frac{L}{m}\right)$$
$$V_{infall}^2 = \frac{2GM}{r} - V_{rot}^2$$

Figure 7. Infalling rotating envelope and the velocity field.

7. Discussion

Several important parameters for the physical structure are evaluated by using simple models.

- Outflow
  - Inclination angle is determined to be around 20° (edge-on).
    - → This contrasts to previous suggestions of a more pole-on geomety.
  - Opening angle is smaller than that the L1527 case (collimated).
    - → This reflects the difference of the dynamical ages of the outflows.
- Envelope
  - Very low-mass protostar (~ 0.02 M_{sun}, at least < 0.09 M_{sun})
  - Radius of the centrifugal barrier is much smaller than the L1527 case.
    - → Specific angular momentum of the gas is small (almost free-fall).

IRAS 15398-3359 and L1527 are chemically similar, but physically different.

For details:
- Oya, Y., Sakai, N., Sakai, T., et al., 2014, ApJ, 795, 152
- Sakai, N., Oya, Y., Sakai, T., et al., 2014, ApJL, 791, L38