Discovery of the rotating molecular outflow and disk in the Class-0/I protostar [BHB2007]#11 in Pipe

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1. Introduction

The loss of angular momentum is inevitable in star formation processes, and the transportation of angular momentum by a molecular flow is widely thought to be one of the important processes. The rotation of the outflows/jets are, however, detected in few cases and it is not unclear how much angular momentum is ejected by the molecular flows and where the angular momenta are subtracted by the molecular flows.

2. Target - [BHB2007] #11

- In the Barnard 59 region (SFR~20 % ; Brooke et al. 2007)
- Distance = 130 +13/-20 pc ; Lombardi et al. 2006
- Class-0/I source ; Brooke et al. 2007
- **Molecular outflow axis is almost on the plane of the sky**
  - **Good target for revealing envelope, disk, and outflow rotation**

ASTE CO(3-2) map

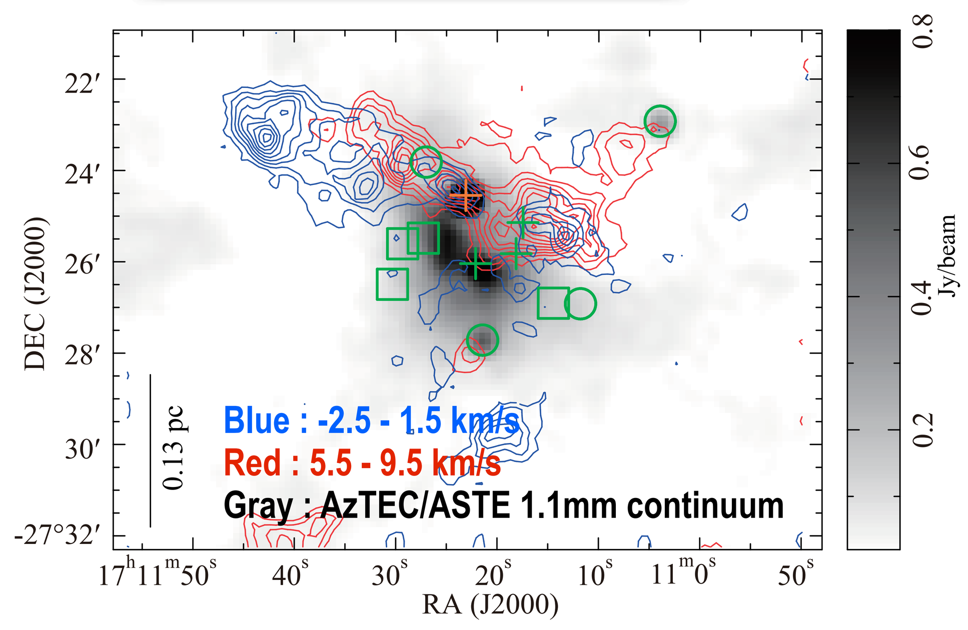


Fig. 1
Contours : 3,5,6,...×σ (1σ = 0.3 K(T_A^*))
Crosses : Class-0/I
Circles : Flat
Boxes : Class-II (Forbrich et al. 2009)

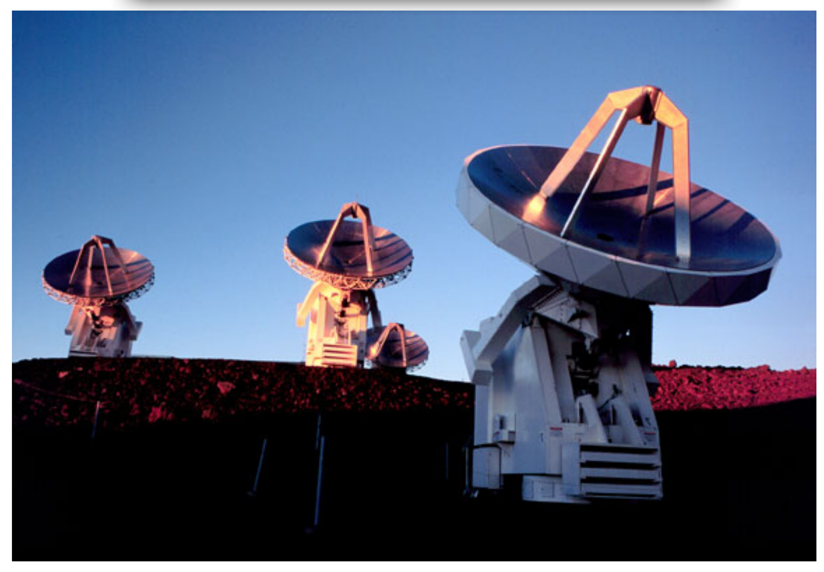
Hara et al. (2013)

3. Observations

Submillimeter Array

- Telescope : Submillimeter Array
- Observation date : 2012.2.29
- Array configuration : Extended (5 ant , baseline = 21-110 kλ)

Fig. 2



Line/ Wavelength	1.3 mm dust continuum	^{12}CO(2-1) (230.538 GHz)	^{13}CO(2-1) (220.399 GHz)	C^{18}O(2-1) (219.560 GHz)
Effective beam size	2″.2×1″.1 (-12°)	2″.3×1″.1 (-13°)	2″.2×1″.2 (-11°)	2″.2×1″.2 (-11°)
Typical rms	12 mJy/beam	0.18 Jy/beam @dV=0.53 km/s	0.15 Jy/beam @dV=0.53 km/s	0.15 Jy/beam @dV=0.53 km/s

4. Results

SMA maps

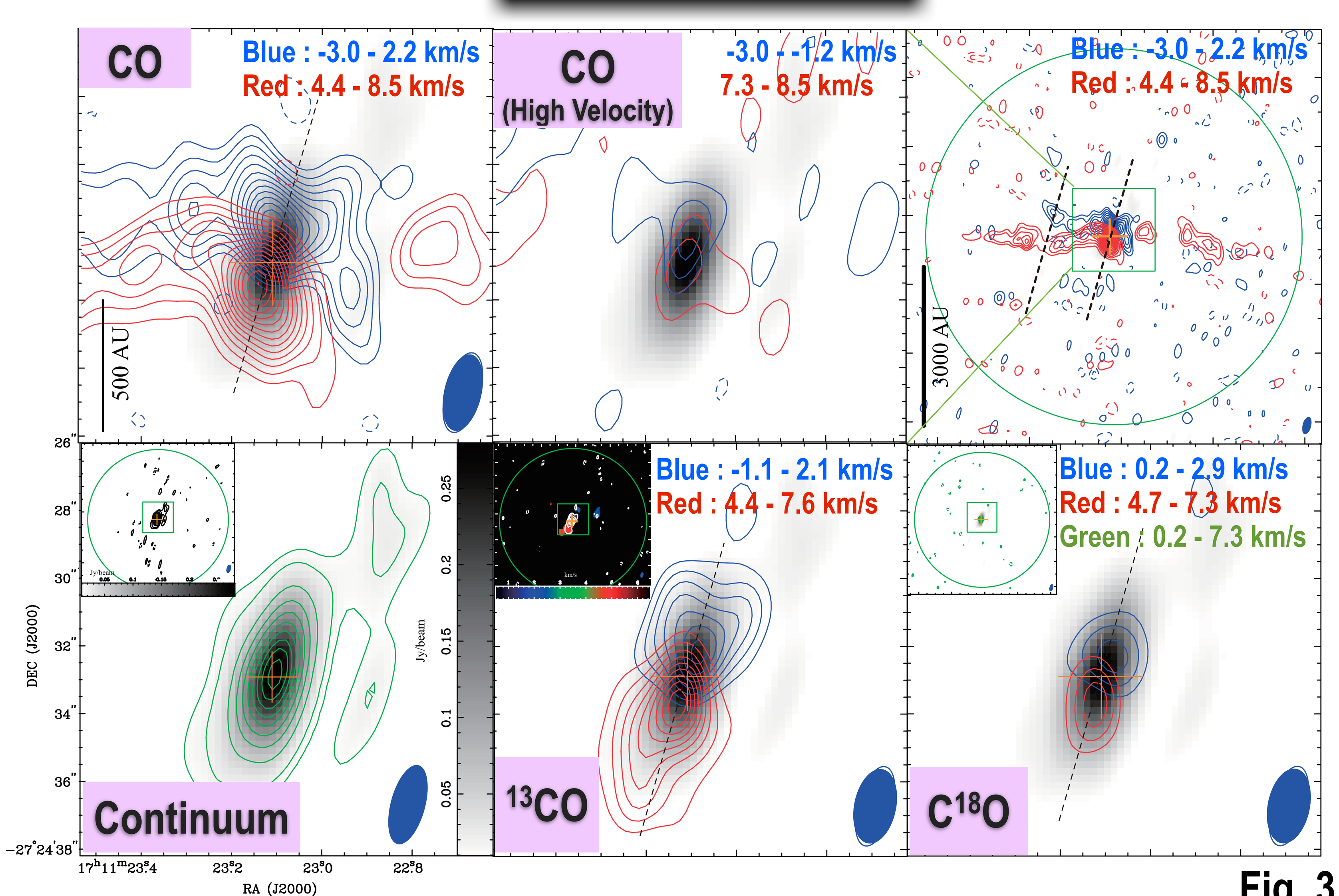


Fig. 3

Contours
CO : 3, 4.5, 6,..×σ (1σ = 0.4 Jy/beam km/s)
CO (high velocity) : 3, 4.5, 6,...×σ (1σ = 0,3 Jy/beam km/s)
continuum : 3, 6, 16,...×σ (1σ = 3.2 mJy/beam)
^{13}CO : 3, 6, 9,...×σ (1σ = 0.34 Jy/beam km/s)
C^{18}O :
Green contours 3, 4.5, 6,...×σ (1σ = 0.34 Jy/beam km/s)
Other contours 3, 4.5, 6,... ×σ (1σ = 0.21 Jy/beam km/s)
Continuum : 3, 6, 10, ... ×σ (1σ = 3.2 mJy/beam)

Symbols in Figures
Crosses : The peak position of the continuum condensation
Boxes : The area of the figures at top-right corners
Circles : SMA FoV
Dashed lines : Cut lines of Fig. 4

- Velocity Gradient which is perpendicular to the outflow axis (Fig. 1) is observed in CO, ^{13}CO, and C^{18}O lines.
  - The envelope / disk rotation (see also below PV diagrams)
- Although ^{13}CO and C^{18}O structures are elongated NW-SE direction, only CO distribution is oriented SE-NW direction.
  - **CO traces the molecular outflow.**
- The velocity gradient is also detected in CO outflow lobe.
  The direction of the velocity gradient is consistent with that of the center.
  - **The molecular outflow is rotating ?**

PV diagrams

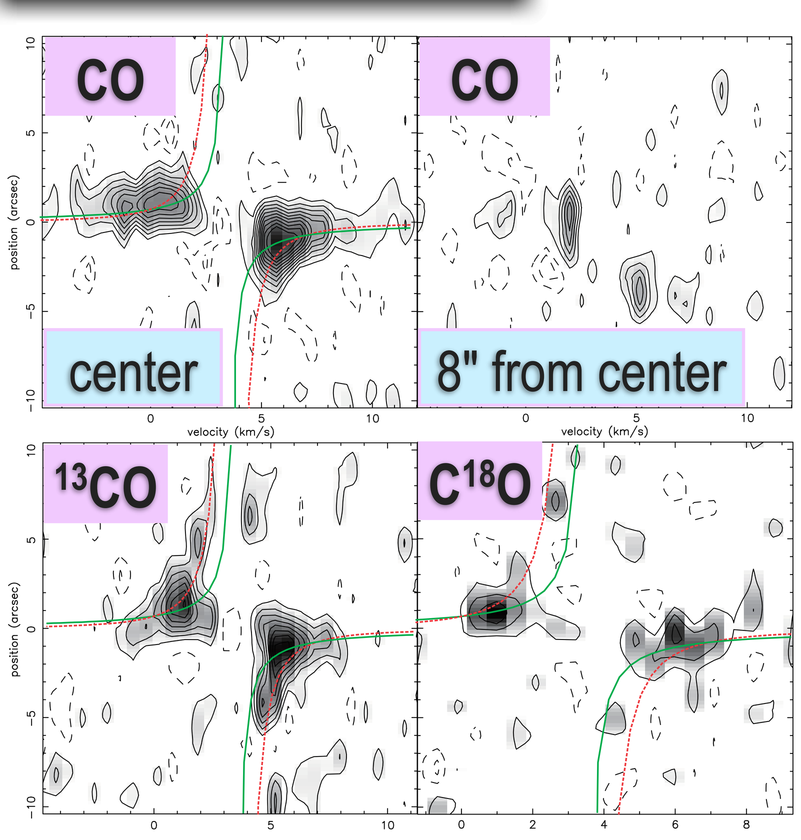


Fig. 4

Contours
CO : 1.5, 3, 4.5, ...×σ (1σ = 0.19 Jy/beam)
^{13}CO : 1.5, 3, 4.5, ...×σ (1σ = 0.15 Jy/beam)
C^{18}O : 1.5, 3, 4.5, ...×σ (1σ = 0.15 Jy/beam)

Symbols in Figures
Crosses : The peak position of the continuum condensation
Boxes : The area of the figures at top-right corners
Circles : SMA FoV
Dashed lines : Cut lines of Fig. 4
Fig.4
Green curves : Rotation with the conserved angular momentum (1.6×10-3 km/s pc)
Red curves : Keplerian rotation curve (central stellar mass = 1.3 M_{sun})

5. Rotation of the Molecular Outflow and Disk ?

Peak Position vs Velocity plot

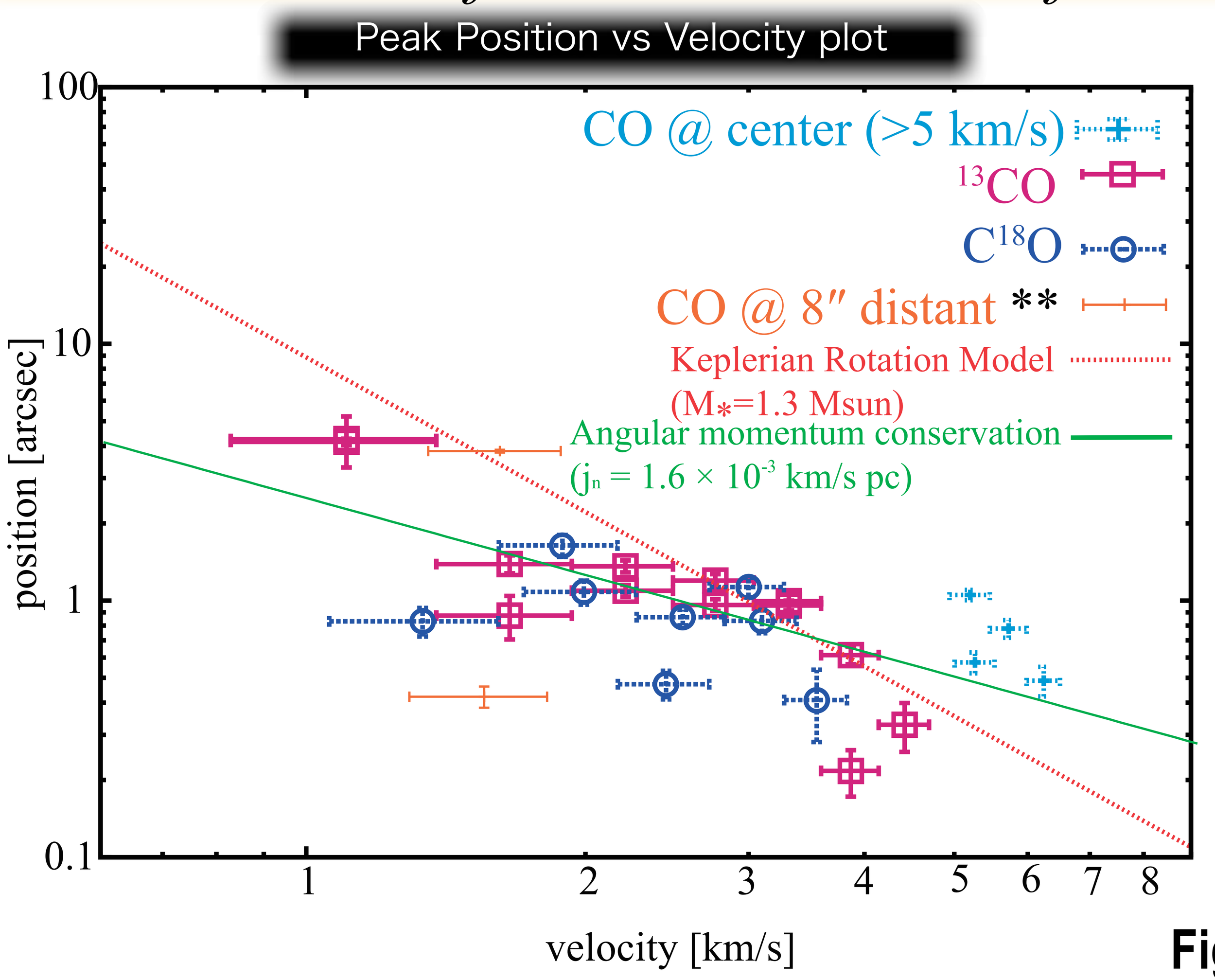


Fig. 5

** The outflow axis is considered to be 15° (the same angle with the dust continuum elongation) and the center velocity is assumed to be the same with the systemic velocity.

- Power-law index of radial rotation profile seems to change at ~ 1″.
  - **The formation of the Keplerian disk ?**
- Specific angular momentum which is estimated from CO emission is as large as those of the ^{13}CO and C^{18}O emissions, and calculated to be (2.1 +/- 0.5) ×10^{-3} km/s pc. **This value is conserved from the center to the edge of the outflow lobe.**
- Why such a large specific angular momentum is generated in the molecular outflow ?

Interpretation of the outflow rotation

1. Explanation by the disk-wind model ?

The molecular flows are expected to be launched by the magneto-centrifugal force and the angular momentum of the launching point is considered to be conserved (Launhardt et al. 2009). The outflow angular momentum of B59#11 is as large as that of the envelope, and the outflow is expected to be launched from the edge of the disk. The outflow velocity is, however, predicted to be approximated by the Kepler speed of the launchig point (e.g. Tomisaka et al. 1998). The Kepler speed at the edge of the disk in B59#11 is expected to be ~3 km/s and such a low velocity flow will not be observed since the outflow axis in B59#11 is lies almost in the plane of the sky.

2. The envelope gas with the large angular momentum is entrained ?

The angular momentum is conserved from the envelope to the outflow lobe (Fig. 5). This result suggests that the envelope gas is entrained and as a result, the outflow lobe has large specific angular momentum. The mass ejection rate of the molecular outflow is 1.5×10^{-7} M_{sun}/yr *** km/s M_{sun} and this result suggests that the molecular outflow play an essential role to extract the angular momentum from the envelope.

*** Assuming that Tex = 30 K, inclination angle = 75 deg, and X[CO] = 10^{-4}.

It is revealed that both of the molecular outflow and the envelope in [BHB2007]#11 has large specific angular momenta. It is the first source in which is the Keplerian disk and the outflow rotation are detected at the same time and a good target for ALMA to reveal the envelope, outflow, and disk connection.

* ASTE : Atacama Submillimeter Telescope Experiment, SMA : Submillimeter Arrray, ALMA : Atacama Large Millimeter/Submillimeter Array