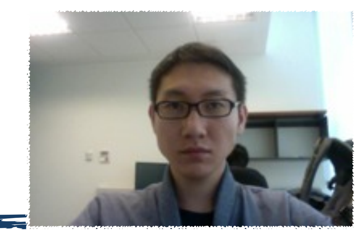
The two-dimensional angular momentum distribution in a protostellar core L1527



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Abstract

We proposed a new analytic method to derive the two-demential angular momentum distribution of a dense core and applied our method to a nearby isolated dense core L1527 in taurus star formation region of 140 pc. A 6'x6' region, correspond to the dense core scale about 0.2pc was mapped, in $C^{18}O$(1-0) with 0.1 km/s resolution toward L1527 with the Nobeyama 45m Telescope. In the integrated intensity map, the emission distribution is concentrated on the protostar. As a result, we derived successfully the changing direction of the angular momentum vector from outside (P.A.= -70 deg) to inside (P.A.= +75 deg). The rotation axis in the inner part is roughly perpendicular to outflow axis but different from outer one which agrees with the velocity gradient identified in the N_2H^+ map by Tobin+2011. These results have demonstrated usefulness of our method and we have confirmed that a dense core kinematics in L1527 cannot be explained by just a simple rigid-rotation axis.

Method ~Two-dimensional angular momentum distribution~

Calculation form from FITS cube data

The angular momentum and the specific angular momentum are defined as $\boldsymbol{J} \equiv \boldsymbol{r}\times\boldsymbol{p} = M\boldsymbol{r}\times\boldsymbol{v}$ and $\boldsymbol{j} \equiv \boldsymbol{J}/\mathrm{M} = \boldsymbol{r}\times\boldsymbol{v}$, respectively. Because the FITS cube data have a spatial two-dimension and a radial velocity information, the observed $\boldsymbol{r}$ and $\boldsymbol{v}$ are expressed as $\boldsymbol{r} = (x, y, 0)$ and $\boldsymbol{v} = (0, 0, V_r)$, respectively. Then, the specific angular momentum obtained by observed data is $\boldsymbol{j} \equiv (j_x, j_y, j_z) = (yV_R, -xV_R, 0) \equiv (\boldsymbol{j}_{obs}, 0)$. Based on these formula, the calculation form from FITS cube data is derived as follow. We calculate the two-dimensional angular momentum in the annular around the protostar masked outflow regions. When the subscripts i, j, k represents RA, Dec., the Velocity axis, respectively, and f_{ijk} represents the pixel value of the cube fits data,

$$\boldsymbol{j}_{obs} = \frac{\boldsymbol{J_{obs}}}{M_{obs}} = \frac{\sum_{i,j\in\mathrm{ring\ w/o\ outflow}} \begin{pmatrix} \sum_k C f_{ijk} y V_R C_V \\ -\sum_k C f_{ijk} x V_R C_V \end{pmatrix}}{\sum_{i,j\in\mathrm{ring\ w/o\ outflow}} \sum_k C f_{ijk}}, \quad (1)$$

whereas C and C_V are conversion factors.

Using this formula, we can derive the radial distribution of direction and magnitude of the specific angular momentum vector.

Test case of simple model data

We applied the above method to the Bonnor-Ebert sphere with the rigid-rotation using LTE radiation transfer to derive the two-dimensional angular momentum distribution. The physical parameters are found in Table 1 and Fig 1. We masked the region within opening angles of 90 deg with perpendicular to the rotational axis in the calculation.

(Model parameters)	
Density	Bonnor-Ebert sphere with T=10K, n_{center}=1E5 (cm^{-3})
Velocity	Rigid Rotation (v_{rot} = 0.05km/s at R=1000AU)
Molecular abundance	1.7E-07 for $C^{18}O$
Dust opacity	0.001768 (cm^2/g)
(Obs. parameters)	
Map size	28000 AU x 28000 AU
Pixel's resolution	100 AU
Inclination	30deg, 60deg and 85deg

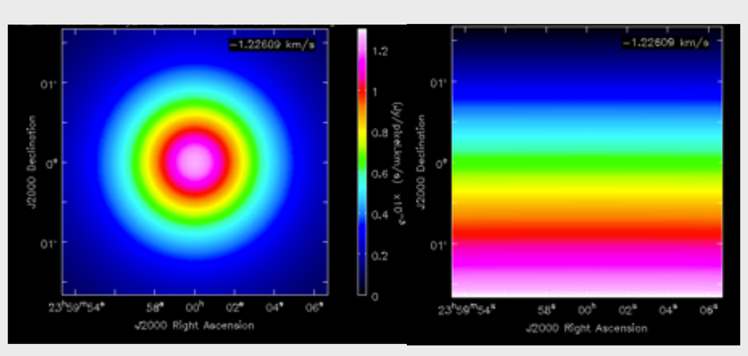

Fig 1: The integrated and 1st moment map of data. 1st moment map(right) of the velocity range is changed by inclination.

Fig 2 shows the result. A gray line denotes the assumed angular momentum distribution (as j(r)=v_{rot} r^2) in the plain perpendicular to the rotation axis, which is usually used in previous researches. Blue, yellow and red lines shows the cases for the different inclinations. Left graph in Fig 2 is without correction of inclination and right graph is with correction of inclination. For the rigid rotation model, a correction of inclination is straightforward (multiplied by 1/sin(i)).

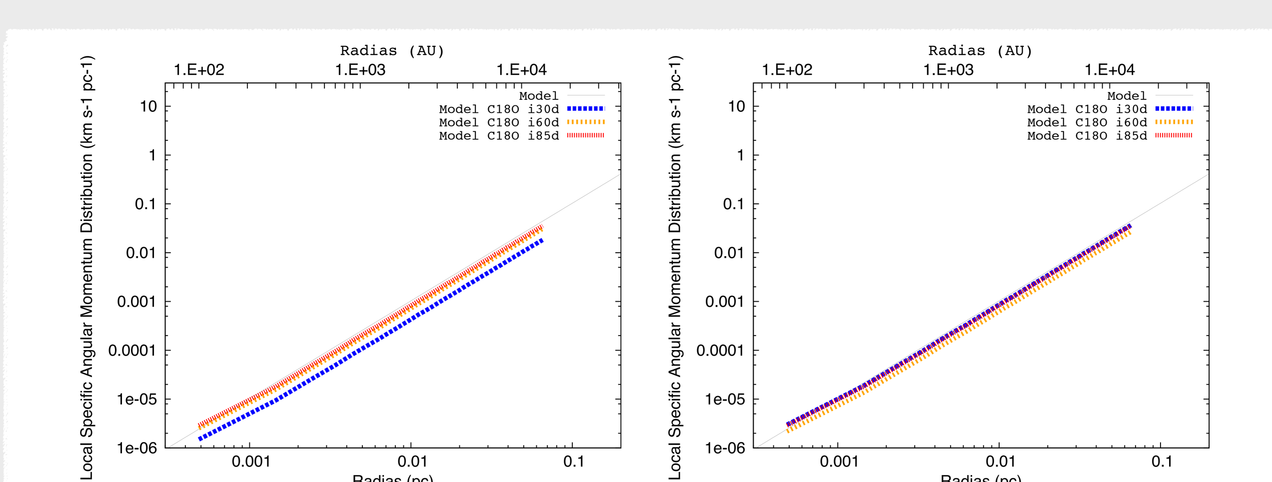

Fig 2: The angular momentum distribution. Left graph is not corrected by inclination and right graph is corrected by inclination.

Even after the inclination correction, the calculated angular momentum are smaller than the assumed angular momentum. This is caused by a averaging effect over angels. In case of the spherical symmetric density and the linear velocity gradient, the averaging effect can be corrected. Observed data usually have asymmetry features that cause an error of typically 20% in the estimate.

Results

Observation

Observation was carried out with the following settings.
- Telescope : NRO45m
- Science terget : a protostellar core L1527 in taurus cloud(140 pc)
- Observation mode : 6'x6' OTF raster mapping (~0.22pc x 0.22pc)
- Observed lines : $C^{18}O$(J=1-0)
- Spatial resolution : about 15" (2100AU)
- Velocity resolution : 0.1 km/s
- Observation date : 2012/3/20-2012/5/25

Results of Observation

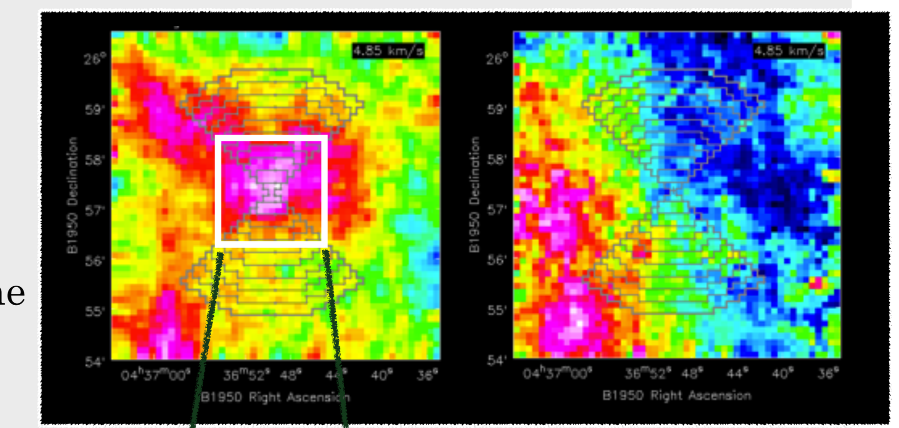

Fig 4 shows the integrated intensity and the 1st moment map of $C^{18}O$ in L1527. In the integrated intensity map, the emission distribution is concentrated on the protostar.
Achieved sensitivity (1 sigma) :
~0.1K with 0.1 km/s [Ta*] for $C^{18}O$

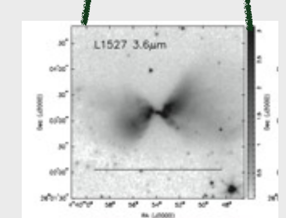

Fig 4: (left) The integrated map of C18O in L1527. (right) The 1st moment map of C18O in L1527. Gray lines are the calculated regions of the two-dimensional angular momentum distribution.

Fig 5: Spitzer3.6μm image in L1527 (Tobin+2010)

Two-dimensional angular momentum distribution in L1527

We masked the region within opening angles of 90 deg with perpendicular to the outflow axis in the calculation (cf, Fig 5, Tobin+2010). Fig 6 and 7 show the results of the two-dimensional angular momentum distribution. You can cee the change in the angular momentum vector from the inner to outer core. The angular momentum vector dramatically changes at about 0.02 pc.

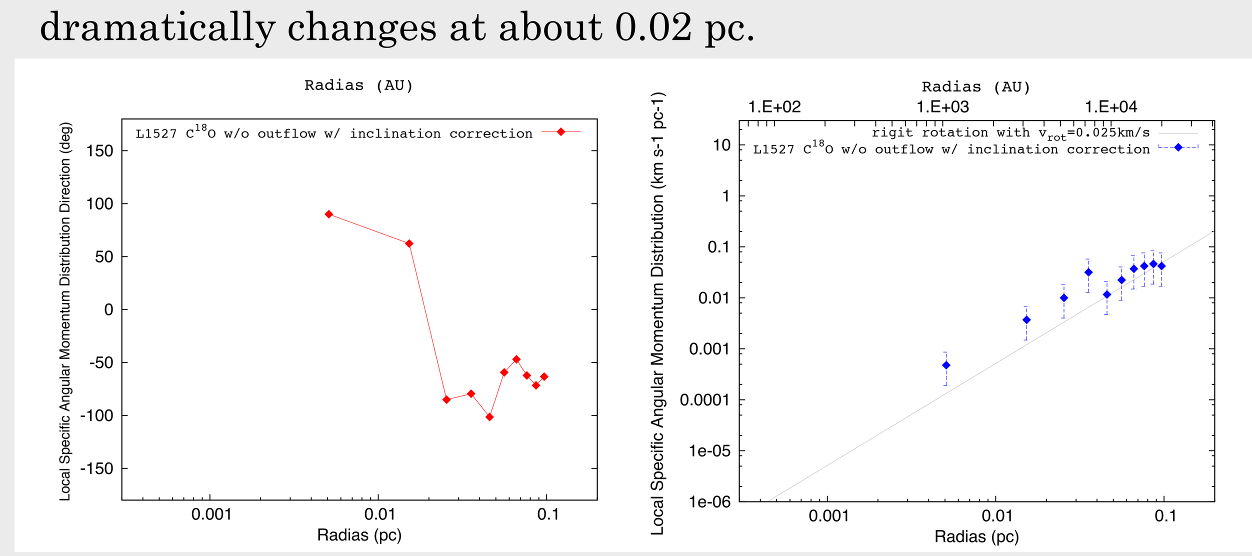

Fig 6: (left) The radial distribution of the direction of rotation vector.

Fig 7: (right) The radial distribution of the angular momentum magnitude. A gray line shows the rigid-rotation case with 0.025 km/s at 1000AU (Ohashi+1997) and the error bars are estimated by 20% of averaging effect and the dispersion of rotational axes.

Our method has a disadvantage that errors occur in calculating the angular momentum vector if the region of calculation is asymmetric respect to X and Y axes. Figure 8 shows angular momentum vectors at different opening angles and the angle jump is seen in all cases. The dominant errors in angular momentum amplitude come from averaging effects and inaccurate correction for inclinations. It is not straightforward to estimate the inclination if the outflow axis changes as mentioned above. The angular momentum magnitude is roughly proportional to the square of the radius. Error bars in Fig. 7 include errors in inclination correction caused by scatter of the angular momentum vector angles.

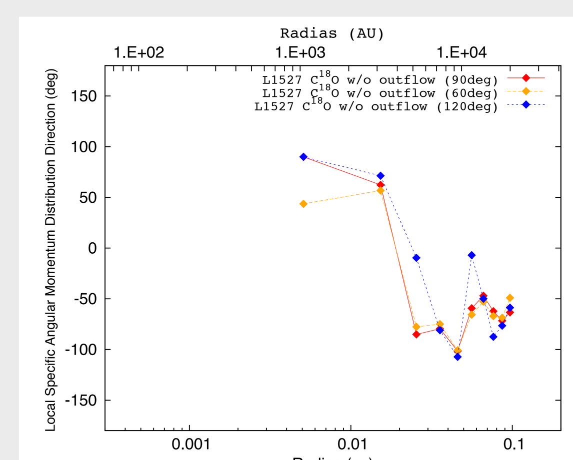

Fig 8: The radial distribution of the direction of rotation vector with different calculated regions (masked opening angle of 60deg, 90deg and 120 deg).

In the past, there are two approaches to investigate the rotation in cores. One is a classical method, which is conducted by the linear or planar fitting of the velocity gradient, such as Goodman+1993, Ohashi+1997, and Caselli+2002. The other is analyzing P-V diagram, which can derive whether rigid-rotation or differential rotation (Belloch+2002). We, however, could not obtain the radial dependence of the rotation axis in those methods. Such exception is Tobin+2011, who indicated the difference of the directions of the velocity gradient between large- and small-scale. In theory, the rotation axes are changing in the evolution depending on the initial angular momentum and the magnetic field strength (Matsumoto+2003). Among those situations, we derived successfully the change in the angular momentum vector from the inner to outer core of L1527. The inner rotational vector's direction is especially connected to the rotation axis of the inner disk (Tobin+2012). Thus, we have confirmed a dense core L1527 cannot be explained by just a single rotation axis. We also applied our method to an isolated dense core B335. In the B335 core, the direction of rotational vector is almost constant over all scales in parallel to the outflow direction. There are difference situations between L1527 and B335, and we speculate that the origin of these dense cores is different. Furthermore the change in direction of the rotational axis naturally explains existence of YSOs whose outflow axis seems to change (Teixeira +2008). Previously such objects can be explained in terms of precession, but there will be certain cases that the outflow axis changes by accreting material from outer core with a different rotation axis from the inner one.

Therefore, it is important to analyze the two dimensional specific angular momentum distributions and our newly proposed method is useful.

Reference;

Belloch et al. 2002, A&A ,393, 927, Caselli et al. 2002, ApJ, 572, 238, Goodman et al. 1993, ApJ, 406, 528, Kiyokane et al. 2012 in the 1st year of ALMA conference, Kurono et al. 2013, ApJ, 765, 85, Matsumoto et al. 2003, ApJ, 595, 913, Ohashi et al. 1997, ApJ, 488, 317, Teixeira et al. 2008, MNRAS, 384, 71, Tobin et al. 2011, ApJ, 740, 45, Tobin et al. 2012, Nature, 492, 83