FORMATION OF A KEPLERIAN DISK IN THE INFALLING ENVELOPE AROUND L1527 IRS:
TRANSFORMATION FROM INFALLING MOTIONS TO KEPLER MOTIONS

NAGAYOSHI OHASHI1,2, KAZUYA SAIGO3, YUSUKE ASO4, YURI AIKAWA5, SHIN KOYAMATSI6,
MASAHIRO N. MACHIDA6, MASAO SATO7, SANEMICHI Z. TAKAHASHI8, SHIGEHISA TAKAKUWA2,
KENGO TOMIDA9,10, KOHI TOMISAKA11, and HSI-WEI YEN2

1 Subaru Telescope, National Astronomical Observatory of Japan, 650 North A’ohoku Place, Hilo, HI 96720, USA; nohashi@naoj.org
2 Academia Sinica Institute of Astronomy and Astrophysics, PO Box 23-141, Taipei 10617, Taiwan
3 Chile Observatory, National Astronomical Observatory of Japan, Osawa 2-21-1, Mitaka, Tokyo 181-8588, Japan
4 Department of Astronomy, Graduate School of Science, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan
5 Department of Earth and Planetary Sciences, Kobe University, Kobe 657-8501, Japan
6 Department of Earth and Planetary Sciences, Faculty of Sciences, Kyushu University, Fukuoka 812-8581, Japan
7 Joint ALMA Observatory, Ave. Alonso de Cordova 3107, Vitacura, Santiago, Chile
8 Department of Physics, Kyoto University, Oiwake-cho, Kitashirakawa, Sakyo-ku, Kyoto 606-8502, Japan
9 Department of Astronomical Science, Princeton University, Princeton, NJ 08544, USA
10 Department of Physics, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan
11 National Astronomical Observatory of Japan, Osawa 2-21-1, Mitaka, Tokyo 181-8588, Japan

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ABSTRACT

We report Atacama Large Millimeter/submillimeter Array (ALMA) cycle 0 observations of the C18O (J = 2–1), SO (JN = 6s–5s), and the 1.3 mm dust continuum toward L1527 IRS, a class 0 solar-type protostar surrounded by an infalling and rotating envelope. C18O emission shows strong redshifted absorption against the bright continuum emission associated with L1527 IRS, strongly suggesting infall motions in the C18O envelope. The C18O envelope also rotates with a velocity mostly proportional to r−1, where r is the radius, whereas the rotation profile at the innermost radius (∼54 AU) may be shallower than r−1, suggestive of formation of a Keplerian disk around the central protostar of ∼0.3 M⊙ in dynamical mass. SO emission arising from the inner part of the C18O envelope also shows rotation in the same direction as the C18O envelope. The rotation is, however, rigid-body-like, which is very different from the differential rotation shown by C18O. In order to explain the line profiles and the position–velocity (PV) diagrams of C18O and SO observed, simple models composed of an infalling envelope surrounding a Keplerian disk of 54 AU in radius orbiting a star of 0.3 M⊙ are examined. It is found that in order to reproduce characteristic features of the observed line profiles and PV diagrams, the infall velocity in the model has to be smaller than the free-fall velocity yielded by a star of 0.3 M⊙. Possible reasons for the reduced infall velocities are discussed.

Key words: circumstellar matter – stars: individual (L1527 IRS) – stars: low-mass – stars: protostars
Online-only material: color figures

1. INTRODUCTION

Keplerian disks are considered to be universally formed in the course of low-mass star formation and play an essential role in planet formation. In fact, a large fraction of low-mass pre-main-sequence stars, T Tauri stars, are associated with disks (e.g., Beckwith et al. 1990; Andrews & Williams 2005, 2007), and several of these disks are confirmed to have Kepler rotation (e.g., Dutrey et al. 1998; Simon et al. 2000). Its formation process is, however, still poorly understood. In the conventional picture of star formation, a Keplerian disk is formed in a slowly rotating dense molecular core accreting onto a central protostar because of angular momentum conservation of the infalling material (Terebey et al. 1984). On the other hand, recent theoretical simulations suggest that a magnetic field must have a strong impact on the formation of Keplerian disks around protostars (Hennebelle & Ciardi 2009; Machida et al. 2011); in some cases, with a strong magnetic field, Keplerian disks cannot be formed because of the magnetic braking of rotation (Mellon & Li 2008; Li et al. 2011), although there are some controversial issues (Joos et al. 2012; Machida et al. 2014; Krumholz et al. 2013). Although recent observations start showing kinematical evidence for Keplerian disks around low-mass protostars, in particular class I sources (Takakuwa et al. 2012; Yen et al. 2013; Murillo et al. 2013; Harsono et al. 2014; Yen et al. 2014), it is still extremely crucial for us to investigate observationally how Keplerian disks are formed around protostars, particularly those in the earliest evolutionary stage.

L1527 IRS (hereafter L1527), originally found as an infrared point source (IRAS 04368+2557) by the Infrared Astronomical Satellite (IRAS) (Beichman et al. 1986), is located in one of the closest low-mass star-forming regions, the Taurus Molecular Cloud, at a distance of about 140 pc, and has been considered to be in the earliest evolutionary stage (class 0) of star formation. The systemic velocity of L1527 was measured to be ∼5.7 km s−1 from C18O J = 1–0 observations using the Nobeyama 45 m single-dish telescope, whereas it was measured to be ∼5.9 km s−1 from N2H+ (J = 1–0) single-dish observations (Caselli et al. 2002; Tobin et al. 2011). We adopt 5.9 km s−1 for the systemic velocity of the L1527 system in this paper. The first detailed observations of L1527 at a high angular resolution were made by the Nobeyama Millimeter Array (NMA), revealing a flattened, edge-on envelope of 2000 AU in radius, perpendicular to the direction of the molecular outflow ejecting in the east–west direction (Ohashi et al. 1997). More importantly, they have suggested that the flattened envelope has dynamical infalling motions with slow rotation. The mass infalling rate was estimated to be 1 × 10−6 M⊙ yr−1. Follow-up observations
at even higher angular resolutions were carried out by the Submillimeter Array (SMA) in $^{13}$CO ($J = 2–1$) and the Combined Array for Research in Millimeter-wave Astronomy (CARMA) in $^{12}$CO ($J = 2–1$). These observations have revealed that the rotation profile of the infalling envelope follows the negative first power of the radius up to $\sim$140 AU in radius (Yen et al. 2013), whereas the power may become $-0.5$ within a radius of $\sim$140 AU where a Keplerian disk might exist (Tobin et al. 2012). These previous observations, however, had relatively poor sensitivity to study kinematics of the envelope and the possible Keplerian disk more accurately. In this paper, we report Atacama Large Millimeter/submillimeter Array (ALMA) cycle 0 observations of the protostar L1527 in the $^{13}$CO ($J = 2–1$), SO ($J_N = 6–5_A$), and 1.3 mm dust continuum. We note that $^{13}$CO is more likely optically thin and thus a reliable tracer to investigate kinematics of the innermost envelope, where a Keplerian disk would be formed, as compared with $^{12}$CO.

2. OBSERVATIONS

ALMA, having enormously high sensitivity as compared with previous interferometers, was used to observe L1527 in $^{13}$CO 2–1, SO 6$_{3}$$-5_{4}$, and 1.3 mm dust continuum observations on 2012 August 26. The total number of the 12 m antenna was 25, and the total on-source time was $\sim$37 min. The velocity resolution of the line emission was $\sim$0.17 km s$^{-1}$. The maximum baseline was 366 m, providing an angular resolution of $0.96 \times 0.73$ in $^{13}$CO (0.8 in geometrical mean), whereas the minimum baseline was 18 m, setting the maximum detectable size at $\sim9''$ for 30% level detection or $\sim7''$ for 50% level detection. The rms noise levels (1$\sigma$) of $^{13}$CO and SO are 8.0 mJy beam$^{-1}$, corresponding to 0.29 K in brightness temperature, and 9.5 mJy beam$^{-1}$, corresponding to 0.35 K, respectively, with the velocity resolution of 0.17 km s$^{-1}$. The noise level of the continuum map is $\sim$0.3 mJy. All the observation parameters are summarized in Table 1.

3. RESULTS

3.1. The 1.3 mm Continuum Emission

Compact emission of the 1.3 mm continuum having a peak of $\sim$130 mJy beam$^{-1}$ was detected. The peak position measured with a Gaussian fitting is consistent with a previous measurement at high angular resolutions (Tobin et al. 2012; Yen et al. 2013). The continuum emission was barely resolved at the current angular resolution, providing a deconvolved size of $0.64 \times 0.36$ (P.A. $\sim 0.9$), corresponding to $\sim$90 AU $\times$ 50 AU at a distance of 140 pc. Total flux density integrated over the area with more than a 3$\sigma$ level is measured to be $\sim$0.20 Jy. We use the continuum peak position as the protostellar position of L1527 throughout this paper.

3.2. $^{13}$CO Emission

$^{13}$CO 2–1 was detected at more than a 6$\sigma$ level from $V_{LSR} = 3.1$ km s$^{-1}$ (or $-2.7$ km s$^{-1}$ in $\Delta V$ with respect to the systemic velocity of $5.9$ km s$^{-1}$) to $8.5$ km s$^{-1}$ ($\Delta V = 2.6$ km s$^{-1}$ in LSR velocity, except for $V_{LSR} = 6.0$ km s$^{-1}$ where $^{13}$CO shows absorption. The $^{13}$CO 2–1 line profile at the position of the central protostar is shown in Figure 1(a).

As was mentioned above, the $^{13}$CO 2–1 emission shows a very strong, negative dip at $V_{LSR} = 6.0$ km s$^{-1}$ and 6.1 km s$^{-1}$, which are slightly redshifted as compared with the systemic velocity of 5.9 km s$^{-1}$. The negative dip reaches $\sim-2.5$ K, corresponding to $\sim9\sigma$, and should mostly be produced by absorption because ALMA cannot make such a negative dip when filtering out extended structures. The position and size of the negative dip seen in the channel map are basically the same as those of the continuum emission, strongly suggesting that the negative dip is absorption against the continuum emission. Such a negative redshifted absorption, or the so-called inverse P-Cygni profile, is naturally explained by infall motions, as previous studies also interpreted. The intensity-weighted mean velocity (i.e., moment 1) map shows a clear velocity gradient from the north (blueshifted) to the south (redshifted), in the same direction of the elongation of the flattened structure.

The moment 0 map of $^{13}$CO 2–1 integrated over $V_{LSR}$ between 3.1 km s$^{-1}$ and 8.5 km s$^{-1}$ shows a flattened structure elongated in the north–south direction (Figure 2(a)). This flattened structure, which is consistent with those previously observed in L1527 (Osahi et al. 1997; Tobin et al. 2012; Yen et al. 2013), is basically the envelope surrounding L1527 IRS, as the previous studies also interpreted. The intensity-weighted mean velocity (i.e., moment 1) map shows a clear velocity gradient from the south (blueshifted) to the north (redshifted), in the same direction of the elongation of the flattened structure.

This velocity gradient, which has been also detected in previous observations (Ohashi et al. 1997; Tobin et al. 2012; Yen et al. 2013), is naturally considered to be due to rotation of the flattened structure. The position–velocity (PV) diagram cutting

### Table 1

| Interferometer and date | SO 6$_{3}$$-5_{4}$ | C$^{18}$O 2–1 | Continuum |
|-------------------------|-------------------|---------------|-----------|
| Target                  | L1527             |               |           |
| Coordinate center       | R.A. (J2000) = 4$^d$39$^m$53$^{s}.0000$ |               |           |
|                         | Decl. (J2000) = 26$^d$03$^m$10$^{s}$.0000 |               |           |
| Frequency               | 219.9494 GHz      | 219.5603 GHz  | 225.4336 GHz |
| Primary beam            | 28$^{\prime}\!6$  | 28$^{\prime}\!6$ | 27$^{\prime}\!9$ |
| Projected baseline length | 18.0 – 372.5 m |               |           |
| Synthesized beam (P.A.) | 0.96 $\times$ 0.73 (+10$^{\prime}$) | 0.96 $\times$ 0.73 (+11$^{\prime}$) | 0.93 $\times$ 0.70 (+12$^{\prime}$) |
| Velocity resolution     | 0.17 km s$^{-1}$  | 0.17 km s$^{-1}$ | 94 MHz |
| Noise level (no emission) | 8.0 mJy beam$^{-1}$ | 6.6 mJy beam$^{-1}$ | 0.53 mJy beam$^{-1}$ |
| Noise level (detected channel) | 9.5 mJy beam$^{-1}$ | 8.0 mJy beam$^{-1}$ | ... |
| Passband calibrator     | J0522–364         |               |           |
| Flux calibrator         | Callisto          |               |           |
| Gain calibrator         | J0510+180         |               |           |
Figure 1. Line profiles of C$^{18}$O 2–1 and SO 6$_{5}$–5$_{4}$ obtained at the central star position within an area of 0′.75 × 0′.75. The vertical dashed line in each panel shows the systemic velocity of 5.9 km s$^{-1}$. Observed line profiles are shown in black lines, whereas those calculated by models are shown in red lines. C$^{18}$O line profiles are presented in panels (a) and (c), whereas SO line profiles are presented in panels (b) and (d).

(A color version of this figure is available in the online journal.)

Figure 2. Integrated intensity (moment 0) shown in contours and intensity-weighted mean velocity (moment 1) maps shown in color of C$^{18}$O 2–1 (left-hand side) and SO 6$_{5}$–5$_{4}$ (right-hand side). Contours are drawn from 3σ to 15σ in steps of 3σ and in steps of 5σ for more than 15σ. The cross and the blue ellipse at the bottom right corner in each panel show the position of the central protostar L1527 IRS and the synthesized beam.

(A color version of this figure is available in the online journal.)

The total integrated intensity of C$^{18}$O is measured to be 2.7 Jy km s$^{-1}$, from which the total H$_2$ gas mass of the C$^{18}$O envelope is estimated to be 1.1 × 10$^{-3}$ $M_\odot$, on the assumption

through the line perpendicular to the rotation axis (Figure 3(a)) clearly demonstrates that the rotation is differential with a larger angular velocity at a smaller radius.
that the line is optically thin, the C$^{18}$O excitation temperature is 10 K, and the relative abundance of C$^{18}$O is $3 \times 10^{-7}$. Because the excitation temperature assumed here would be a lower limit to the actual value, the total H$_2$ mass estimated should be considered as an upper limit to the actual gas mass.

In summary, the C$^{18}$O emission traces a flattened envelope having both infall and rotation motions. Details of the kinematics will be discussed in Section 4.

### 3.3. SO Emission

In addition to C$^{18}$O 2–1 emission, SO emission was significantly detected in the velocity range of 4.0–7.7 km s$^{-1}$ in the LSR velocity at more than the 6σ level. The line profile of SO measured at the position of the central protostar, shown in Figure 1(b), has a single peak at a velocity close to the systemic velocity, which is quite different from the C$^{18}$O profile having

![Figure 3. Position–velocity (PV) diagrams along the line from the north to south passing through the position of the central star. Left-hand panels show diagrams of C$^{18}$O, whereas right-hand panels show those of SO. Diagrams obtained from the observations are shown in black or white contours, whereas diagrams calculated from models are shown in color. The solid contours are drawn from +3σ with a 3σ step, whereas the dotted contours are drawn in the same way but from −3σ. The vertical and horizontal dashed lines in each panel show the systemic velocity and the position of the central star, respectively. (a) Diagram obtained from the observations. Blue and red marks show representative data points in the diagram. (b) Diagram obtained from the observations. (c) Model diagram obtained from Model 1 compared with the observed diagram shown in panel (a). (d) Model diagram obtained from Model 1 compared with the observed diagram shown in panel (b). (e) Same as panel (c), but model diagram is obtained from Model 2. (f) Same as panel (d), but the model diagram is obtained from Model 2.](image-url)
a deep absorption feature at a velocity close to the systemic velocity. The map of SO integrated over $V_{LSR}$ between 4.0 km s$^{-1}$ and 7.7 km s$^{-1}$ shows a compact structure located in the inner region of the C$^{18}$O flattened envelope (Figure 2(b)). The deconvolved size of the SO emission was measured to be $1.4'' 	imes 0.68''$, corresponding to 200 AU × 95 AU, with a Gaussian fitting to the moment 0 map.

The moment 1 map of SO shows a clear velocity gradient in the north–south direction, where the C$^{18}$O emission also has a similar velocity gradient. Because the north–south velocity gradient of the C$^{18}$O emission is due to rotation, it is naturally considered that the north–south velocity gradient of the SO emission is also due to rotation. However, the PV diagram of the SO emission along the north–south direction, presented in Figure 3(b), shows velocity structures that are quite different from those seen in the C$^{18}$O PV diagram shown in Figure 3(a); between $-$1 km s$^{-1}$ and $-$1 km s$^{-1}$ in the relative velocity (or between $-$5 km s$^{-1}$ and $-$7 km s$^{-1}$ in the LSR velocity), the velocity changes almost linearly as a function of the position, as shown in the green line in Figure 3(b). In addition to the component showing a linear velocity gradient, there would be additional components at higher velocities than $-$1 km s$^{-1}$ in the relative velocity close to the central star.

Because the SO emission is spatially compact as compared with the C$^{18}$O emission, it would be naturally considered that the SO emission arises from the inside of the C$^{18}$O flattened envelope. The fact that the kinematical nature of the SO emission shown in its line profile and PV diagram is quite different from that of the C$^{18}$O emission may suggest that the SO emission traces some particular regions within the C$^{18}$O envelope. The nature of the SO emission will be discussed in Section 4.2.

4. DISCUSSIONS

4.1. Rotation of the C$^{18}$O Flattened Envelope and Possible Formation of a Keplerian Disk

As was discussed in the previous section, the C$^{18}$O flattened envelope shows a clear velocity gradient along the direction of the elongation, which can be interpreted as rotation. The PV diagram in Figure 3(a) shows that the rotation is differential, having higher rotation velocities as the position gets closer to the central star. In order to understand the nature of the rotation, the power-law dependence of the rotation profile derived from the PV diagram is investigated in detail in this subsection.

The method to examine the power-law dependence of the rotation profile is the same as that described in Yen et al. (2013); whereas Yen et al. used another PV diagram covering larger-scale structures to measure rotation velocities at larger radii $\gtrsim$500 AU, we do not use it. The PV diagram shows its data points measured on the diagram, and these data points are plotted with logarithmic scale in Figure 4(a). For a comparison purpose, previous measurements of the SMA observations (Yen et al. 2013) were also plotted together. From the comparison it is found that the ALMA and SMA measurements at radius more than 100 AU show similar slopes, although the ALMA measurements provide higher rotation velocities than the SMA measurements. Rotation velocities measured by ALMA at smaller radii ($\lesssim$100 AU) are symmetric between blueshifted and redshifted velocities, whereas those measured at larger radii ($\gtrsim$100 AU) are not symmetric with respect to the systemic velocity, suggesting a potential problem of the measurements at larger radii, where ALMA filters out larger-scale structures (see more details below). For smaller radii, the systemic velocity of 5.9 km s$^{-1}$ seems to be quite reasonable even though it was measured by single-dish observations.

A least-square fitting, using a power law ($\propto r^\alpha$), to all the data points, including both SMA and ALMA measurements, is performed, finding that the overall rotation profile can be fitted with a power law having an index of $\sim$−0.7. This value is larger than that measured by SMA on similar scales. However, 50% of emission arising from the structures having a $\sim$1000 AU scale (500 AU in radius) is missed in our current ALMA measurements (see Section 2), and as a result, a missing flux is larger for emission at lower rotation velocities on larger scales. In such a situation, rotation velocities on larger scales are overestimated. For this reason, we focus on the measurements.
at radii less than 100 AU, shown in Figure 4(b), in the following discussions.

Another least-square fitting is performed to the ALMA data measured within 100 AU in radius, finding that the rotation profile at the radius less than 100 AU can be fitted with a power law having an index of ~−1, as shown in the dashed line in Figure 4(b). The sum of the squared residuals, \( \sum (\log V_{\text{obs}} - \log V_{\text{model}})^2/n \), where \( n \) is degrees of freedom, is \( 2.6 \times 10^{-4} \). As was shown by Yen et al. (2013), the power law of the rotation profile at radius larger than 100 AU is also ~−1, suggesting that a similar rotation profile seems to continue even beyond a radius of 100 AU. Tobin et al. (2012) showed that the power law of the rotation around L1527 is ~−0.5 at radius less than 100 AU, i.e., Keplerian rotation, which is inconsistent with our result. For comparison purpose, the rotation curve obtained by Tobin et al. (2012) based on the best fit to their measurements is also shown in Figure 4(b) in the dotted line, apparently demonstrating that their rotation curve is inconsistent with ours. Because Tobin et al. (2012) have assumed Kepler rotation in their fitting, it is not clear whether or not their data can be explained better by a rotation curve with a power-law index of ~−1. These results suggest that the rotation of the flattened envelope around L1527 can be explained as a case where angular momentum is conserved most probably because the material in the envelope is still infalling.

A very close inspection of the ALMA measurements shown in Figure 4(b) found that the rotation profile could become slightly shallower at the innermost rotation radius. In order for us to investigate this possibility, the measured data points within 100 AU are fitted with two power laws having a break at a certain radius. The best-fit result, shown in the solid line in Figure 4(b), demonstrates that the rotation profile within 100 AU could be explained by two power laws having a break at a radius of 53.7 ± 0.4 AU. The sum of the squared residuals is 1.3 \( \times 10^{-4} \), suggesting that the fitting with two power laws is somewhat better than that with the single power law, even when smaller degrees of freedom with two power laws are taken into account. The shallower rotation profile within ~54 AU has a power-law index of ~−0.41 ± 0.24, whereas the index outside ~54 AU is ~−1.16 ± 0.13. Although the power law within the break is ~−0.4, with a relatively larger error, this could suggest the existence of a Keplerian disk of ~50 AU in radius. If this is the case, the dynamical mass of the central protostar is estimated to be ~0.3 \( M_\odot \). We note that if the break due to formation of a Keplerian disk appears at a smaller radius than 50 AU on the dashed line in Figure 4(b), the resultant dynamical mass becomes larger than 0.3 \( M_\odot \). In this sense, ~0.3 \( M_\odot \) can be considered as a lower limit to the dynamical mass of the central protostar.

It is important to estimate the mass of the possible Keplerian disk. Although the size of the continuum emission, ~900 AU \( \times 50 \) AU (see Section 4.1) is slightly larger than the size of the disk, it would still be feasible to use the continuum emission to estimate the mass of the disk. On the assumption that the dust mass opacity is 0.1 cm\(^2\) g\(^{-1}\) at 220 GHz, which is extrapolated from 0.1 cm\(^2\) g\(^{-1}\) (Beckwith et al. 1990) at 1 THz with \( \beta = 0 \) (Tobin et al. 2013), and the dust temperature is ~50 K, which is estimated from the temperature profile (see Section 4.3), the mass of the disk is estimated to be ~2.8 \( \times 10^{-3} \) \( M_\odot \). When the mass opacity at 220 GHz is assumed to be 0.022 cm\(^2\) g\(^{-1}\), which is derived with \( \beta = 1 \), the mass is estimated to be ~1.3 \( \times 10^{-2} \) \( M_\odot \). Because the size of the dust emission is slightly larger than the size of the disk, these masses may give upper limits to the actual disk mass. Although the disk mass still strongly depends on the dust mass opacity, it seems to be at least one order of magnitude smaller than the mass of the central protostar, suggesting that the disk would be gravitationally stable.

### 4.2. Origin of the SO Emission: A Ring?

As shown in Section 3.3, the SO emission arising from the inside of the C\(^{18}\)O flattened envelope also shows rotation, although the nature of the rotation of the SO emission is quite different from that of the C\(^{18}\)O emission. How do these two emission lines show quite different kinematics, even though they arise from similar regions?

One possible and natural explanation is that only a part of the whole envelope is seen in SO. Suppose the SO emission arises from a rotating ring having an edge-on configuration to observers. Such a ring rotates at a constant angular velocity, whereas the observed velocity gradient due to the rotation becomes linear because of a projection effect.

The linear velocity gradient is seen between ~−1 km s\(^{-1}\) to ~1 km s\(^{-1}\) in the relative velocity, suggesting that the rotation velocity of the ring is ~1 km s\(^{-1}\). Because this ring is a part of the C\(^{18}\)O flattened envelope, the radius of the ring can be estimated to be ~120 AU according to the rotation profile of the C\(^{18}\)O emission. The radius of the ring is larger than that of the possible Keplerian disk discussed in the previous section, suggesting that the ring is located in the infalling envelope. On the other hand, the ring probably has some radial width because there is additional SO emission at higher velocities than ~1 km s\(^{-1}\) in the relative velocity, located closer to the central star.

How can only a part of the whole envelope be seen in SO as a ring? The most probable solution to make it possible is to locally enhance the fractional abundance of SO in the ring. SO molecules in envelopes are considered to be depleted on dust particles because of their low temperature (~10 K), whereas they can come back to gas phase when the temperature of dust particles becomes high enough; when the adsorption energy of SO is assumed to be 2600 K based on laboratory data (Garrod & Herbst 2006 and references therein), its sublimation temperature is estimated to be ~60 K, whereas it is estimated to be ~40 K when the adsorption energy is assumed to be 2000 K (Hasegawa & Herbst 1993). Although the sublimation temperature of SO has some uncertainty, this suggests that when the dust temperature becomes higher than ~40–60 K, the abundance of gaseous SO becomes larger.

If the radius of the ring is ~120 AU, as was mentioned above, the dust temperature has to become locally higher than ~40–60 K at a radius of ~120 AU. Such a high dust temperature cannot happen at a radius of ~120 AU with the radiation from the central protostar; the radiative equilibrium temperature at a radius of 120 AU around L1527 is estimated to be ~33 K (see Section 3.3). When accreting material releases its kinetic energy as accretion shock, the dust temperature could become higher. Accreting material around L1527 has its accreting velocity, together with a H\(_2\) density of ~10\(^7\) cm\(^{-3}\) at a radius of ~1200 AU with a accreting velocity of ~2 km s\(^{-1}\) (see Section 4.3). With a H\(_2\) density of ~10\(^7\) cm\(^{-3}\), the dust temperature may become ~40 K (Neufeld & Hollenbach 1994; Aota & Aikawa 2014). We note that the radius of the hot ring where accretion shock may occur is larger than the radius of the possible Keplerian disk discussed in the previous section. Such a case
can be explained when we consider that the streamlines of the flow upstream of the shock are well approximated by ballistic trajectories (Cassen & Moosman 1981).

Although dust temperature is expected to become higher due to a shock, it is still not clear what the actual dust temperature is at a radius of 120 AU. Because it is not easy to estimate the dust temperature from the current observational data, we estimate the kinetic temperature of the SO gas instead of the dust temperature. In order to estimate the kinetic temperature of the SO gas, we perform statistical equilibrium calculations based on a large velocity gradient (LVG) model (Goldreich & Kwan 1974). Details of the calculations are described in the Appendix. According to the calculations, it is found that the kinetic temperature of the SO gas is most likely \( \sim 32 \) K, which is not as high as 40–60 K, but quite similar to the radiative equilibrium temperature at a radius of 120 AU around L1527 of 2.7 \( L_\odot \) in luminosity. Nevertheless, without a hot region, the abundance of the SO molecule cannot be locally enhanced at a radius of 120 AU. We therefore suggest that the SO ring is mostly \( \sim 32 \) K, but has a thin layer with a higher temperature at its outermost radius.

Such a ring with two zones of different temperatures is actually quite reasonable because the SO gas in the postshock region may cool down very quickly, and its temperature becomes the ambient temperature. According to theoretical calculations (Aota & Aikawa 2014), a high-temperature zone in a postshock region is spatially very thin. Because the LVG calculations assume a structure with one zone, it is impossible for us to obtain two temperatures. The reason why the temperature estimated from the LVG calculations is 32 K instead of a higher temperature is that most of the SO emission arises from the 32 K zone, which is optically thick, rather than the high-temperature zone, which is spatially and optically thin.

One may wonder how long SO molecules can stay in the gas phase after the temperature drops below the sublimation temperature. Its time scale is given by \( 10^7 \times (10^7 / n_{H_2} \text{ cm}^{-3}) \text{ yr} \). Because \( n_{H_2} \) at 120 AU is \( \sim 10^3 \text{ cm}^{-3} \) (see Section 4.3 and also Figure 6), the SO molecules can stay in the gas phase for \( \sim 500 \) yr. Because SO gas together with \( H_2 \) gas in the envelope accretes toward the central star at a speed of \( \sim 0.5 \text{ km s}^{-1} \) at 120 AU in radius (see Section 4.3), the SO ring can spread inward across a width of \( \sim 50 \) AU. In the next section, models of an infalling envelope, including a possible SO ring, will be used to reproduce the observations. Note that if a different infall velocity is assumed, the width of the SO ring also changes, although the width is fixed at 50 AU in our models (see Section 4.3).

Higher transition of SO was also detected in L1527 (Sakai et al. 2014), which also has suggested that the SO emission may be due to shock, although they estimated the SO gas temperature to be at least \( \sim 60 \) K. SO emission having a similar nature was also detected in L1489 IRS (Yen et al. 2014).

4.3. Infalling Motions in the Flattened Envelope

As was shown above, the \(^{18}\text{O}\) line profile shows a negative absorption at the systemic velocity. This redshifted absorption is created against the continuum emission and should be due to infalling motions in the envelope. As was discussed in the previous subsection, the overall rotation profile of the \(^{18}\text{O}\) flattened envelope can be explained with a power law having an index of \( \sim -1 \), suggesting conservation of the specific angular momentum of the rotating material. Such a case is naturally expected when the rotating material is also infalling at the same time. In this subsection, nature of the infalling motions, as well as rotation in the flattened envelope, is discussed in more detail.

In order for us to investigate the nature of the motions in the envelope, we construct models to reproduce the \(^{18}\text{O}\) and SO line profiles and PV diagrams. As shown in Figure 5, our models are composed of three parts, i.e., an envelope, an SO ring, and a Keplerian disk. The model envelope is based on that discussed by Tobin et al. (2008), who modified the infalling envelope model of Terebey et al. (1984) to reproduce the NIR scattering light around L1527. Note that the structure of the model envelope is not flattened, even though the observed envelope has a flattened structure. It is, however, still reasonable to use such a model envelope because we basically discuss only the line profile at the center and the PV diagram cutting along the disk midplane. The model envelope rotates with a power-law index of \( -1 \) (\( j = 6.1 \times 10^{-4} \text{ km s}^{-1} \text{ pc} \)), whereas it has a temperature profile with a radial dependence of \( 360(r/1 \text{ AU})^{-0.5} \), which is the radiative equilibrium temperature in Kelvin with the total luminosity of L1527 (2.75 \( L_\odot \); Tobin et al. 2008) under the optically thin assumption. The model envelope has a SO ring region of 32 K in temperature with its outer and inner radii of 120 AU and 70 AU, respectively. Within the SO ring region, the fractional abundance of SO is \( 9 \times 10^{-7} \), which is 5000 times higher than that outside and inside of the hot ring. Within 54 AU in radius, a Keplerian disk orbiting a central star of 0.3 \( M_\odot \) is considered, based on the power-law disk model (e.g., Kitamura et al. 2002). Infall velocities in model envelopes are adjusted to reproduce the observations, as will be described below. Expected line emissions along lines of sight were calculated with radiative transfer equations, assuming the local thermal equilibrium and an edge-on configuration of the ring and the disk (their inclination angles are 90\(^\circ\)), and the CASA simulator was used to reproduce the observed line profiles and PV diagrams.

In the first model (Model 1), infall velocities are simply equal to the free-fall velocities yielded by the gravity of the central star, whereas there is no infall in the Keplerian disk, as shown in Figure 6(a). The \(^{18}\text{O}\) line profile produced with this model is shown in Figure 1(a) in the red line. The \(^{18}\text{O}\) profile of Model 1 shows a typical infall profile having a deep dip at a redshifted velocity and a stronger blueshifted peak, which is similar to the observed profile. However, the velocities of the two peaks in the model profile are not consistent with those in
the observations. This suggests that the infall velocity in the model is too large because two peaks in an infalling profile appear at the characteristic infall velocity.

The C^{18}O PV diagram of Model 1 is compared with the observation in Figure 3(c). Although the overall shapes of the PV diagram produced from the model are similar to the observations, the model cannot reproduce emissions at lower blueshifted and redshifted velocities ($\Delta V \lesssim 0.5\,\text{km\,s}^{-1}$) well. In addition, the blueshifted emission between $V_{\text{LSR}} = 4.5$ and $5.5\,\text{km\,s}^{-1}$ in the model PV diagram is more extended to the north compared with the observation. Similarly, the redshifted emission between $V_{\text{LSR}} = 7\,\text{km\,s}^{-1}$ and $7.5\,\text{km\,s}^{-1}$ in the model PV diagram extends more to the south compared with the observation. The discrepancies are also considered to be due to the larger infalling velocity, making two peaks at higher velocities in the model line profile shown in Figure 1(c).

The SO line profile produced by Model 1 presented in Figure 1(b) shows that the model profile has two strong peaks at $V_{\text{LSR}} \sim 4\,\text{km\,s}^{-1}$ and $\sim 8\,\text{km\,s}^{-1}$, which is very different from the observations having a single peak at the systemic velocity of $5.9\,\text{km\,s}^{-1}$. Because of the two strong peaks, the line profile is much wider than the observation as well. The SO PV diagram produced by Model 1 is also compared with the observation in Figure 3(d); the model PV diagram has two strong peaks at $V_{\text{LSR}} \sim 4\,\text{km\,s}^{-1}$ and $\sim 8\,\text{km\,s}^{-1}$, whereas the observed PV diagram has peaks close to the systemic velocity. In addition to the discrepancy in the peak velocities, the overall velocity gradient of the SO emission in the model PV diagram is larger than that in the observed PV diagram. These two strong peaks at higher velocities are due to the infall motions, suggesting that the infall velocity is too high to reproduce the observations.

In order to reduce the discrepancies described above, another model (Model 2) is made with a different radial profile of the in fall velocity, as shown in Figure 6(b). The infalling velocity at radii $\gtrsim 250\,\text{AU}$ is half of the free-fall velocity yielded by the gravity of the central star. This makes the characteristic infall velocity of the C^{18}O envelope slower. In addition, the infall velocity between 120 AU and 54 AU in radius is slower than the free-fall velocity by one fifth. This makes the infall velocity in the SO ring significantly slower. The infalling velocity at radii between 54 AU and 250 AU, except for the hot ring region, remains the free-fall velocity, possibly because the infalling gas is decoupled from the magnetic field by ambipolar diffusion (Mellon & Li 2009).

The resultant C^{18}O profile calculated from Model 2 is shown in Figure 1(c) in the red line; it has two peaks at $5.4\,\text{km\,s}^{-1}$ and $6.5\,\text{km\,s}^{-1}$, which is consistent with the observation. The model profile also shows two additional peaks at higher blueshifted and redshifted velocities where the observed profile has shoulders. Although these additional peaks do not appear as shoulder-like observations, the overall shape of the observed C^{18}O line profile is mostly reproduced by that calculated from Model 2. Note that the reason why the two additional peaks appear in the model profile is that the infall velocity is the same as the free-fall velocities toward a $0.3\,\text{M}_\odot$ protostar at radii between 120 AU and 250 AU. The resultant C^{18}O PV diagram of Model 2 is compared with the observed PV diagram in Figure 3(e); Model 2 reproduces the overall characteristics of the observed PV diagram, including lower blueshifted and redshifted velocities that cannot be reproduced well by Model 1. The diagram made from Model 2, on the other hand, shows dips at $V_{\text{LSR}} \sim 5\,\text{km\,s}^{-1}$ and $\sim 7\,\text{km\,s}^{-1}$, which do not appear in the observed diagram.

The SO line profile and PV diagram of Model 2 are presented in Figure 1(d) and 3(f), respectively. Although the line profile made from Model 2 still does not have a single peak at the systemic velocity like the observations, its peaks appear close to the systemic velocity. The diagram made from Model 2 is quite similar to the observations, including the overall velocity gradient. On the other hand, the model diagram has two peaks at $\sim 5.2\,\text{km\,s}^{-1}$ and $\sim 6.7\,\text{km\,s}^{-1}$ in LSR velocity, whereas the two peaks in the observed diagram appear at slightly different LSR velocities ($\sim 5.9\,\text{km\,s}^{-1}$ and $\sim 6.5\,\text{km\,s}^{-1}$). These results suggest that Model 2 seems to reproduce the observations better than Model 1, overall.

The key feature to reproduce the observations is an infall velocity slower than the free-fall velocity yielded by the central star. In our calculation described above, the free-fall velocity was estimated from the dynamical mass of $0.3\,\text{M}_\odot$, whereas our conclusion is still valid even if we use the smaller mass of the central protostar, $0.2\,\text{M}_\odot$, estimated by Tobin et al. (2012) (see also Sakai et al. 2014). Although we also tried different values for other parameters, such as the density profile (absolute value of the density and the power-law index) of the model envelope, the power-law index of the temperature profile, and the specific angular momentum of the infalling gas, they were not essential to reproduce the observed characteristics. The deceleration of the infall velocity may be due to magnetic fields. For the region at radii $\gtrsim 250\,\text{AU}$, magnetic braking may be a possible mechanism for the deceleration of the infall velocity. In fact, in previous MHD simulations of star formation processes, it was demonstrated that the accretion flow perpendicular to the magnetic field lines is considerably slower than the free-fall velocity (e.g., Machida et al. 2011; Tomida et al. 2013). In contrast to the region at radii $\gtrsim 250\,\text{AU}$, it is not very clear how the infalling velocity in the hot ring region can be decelerated. One possible mechanism to decelerate the infall velocity is the
so-called magnetic wall (e.g., Li & McKee 1996; Tassis & Mouschovias 2005a, 2005b; Kunz & Mouschovias 2010), where magnetic fields are transported from the inner region by nonideal MHD effects. In this region, the enhanced magnetic pressure can decelerate the accretion flow and form a shock. Spiral arms, possibly formed around the Keplerian disk by transportation of angular momentum from the disk, are another possible mechanism to decelerate the infall velocity in the hot ring. Many hydrodynamic simulations show that spiral arms with large specific angular momentum spread into outer infall regions (e.g., Saigo et al. 2008; Tsukamoto et al. 2014). Such spiral arms cause shocks by interactions with supersonic infalling gas.

5. CONCLUSIONS
L1527 IRS, a solar-type protostar surrounded by an infalling and rotating envelope, has been observed with ALMA in the C$^{18}$O 2–1, SO 6$_e$–5$_a$, and 1.3 mm dust continuum. Our conclusions are summarized as follows.

1. As previously shown, a flattened envelope was detected in C$^{18}$O around L1527 IRS. The emission shows strong redshifted absorption against the bright continuum emission associated with the protostar, strongly suggesting infall motions in the C$^{18}$O envelope. The C$^{18}$O envelope also shows differential rotation. The rotation velocity is mostly proportional to 1/r, where r is the radius, whereas the rotation profile at the innermost radius (∼54 AU) may be shallower than 1/r, suggestive of formation of a Keplerian disk around the central protostar of ∼0.3 M$_\odot$ in dynamical mass.

2. Compact SO emission arising from the inner part of the C$^{18}$O envelope was detected. The emission shows rotation in the same direction as the C$^{18}$O envelope. The rotation is, however, rigid-body-like, which is very different from the differential rotation shown by C$^{18}$O. The rigid-body-like rotation can be naturally explained when the SO emission has a ring-like structure, where the SO fractional abundance is locally enhanced due to higher dust temperature associated with a shock. The outer radius of the ring is estimated to be ∼120 AU, where SO molecules are locally enhanced due to a shock, whereas its inner radius is estimated to be ∼70 AU, where SO molecules would be depleted to dust grains again.

3. In order to explain the line profiles and the position–velocity (PV) diagrams of the C$^{18}$O and SO observed, simple models composed of an infalling envelope surrounding a Keplerian disk of 54 AU in radius orbiting a star of 0.3 M$_\odot$ are examined. Models also include an SO ring region in the envelope, within which SO emission is detectable due to its fractional abundance enhancement, to reproduce the rigid-like velocity gradient of the SO emission. It is found that when the infall velocity in the model is the same as the free-fall velocity yielded by a star of 0.3 M$_\odot$, characteristic features of the observed line profiles and PV diagrams are not reproduced well. In order to reproduce them, infall velocities have to be reduced by one half at radii more than 250 AU and by one fifth within 120 AU except for the Keplerian disk, where there is no infall.

Although the mass of the protostar is one of the most crucial physical parameters to understand the formation and evolution of the protostar, it has been previously estimated from infall velocities or accretion luminosities with various assumptions. Detection of Kepler motions around protostars allows us to derive the dynamical masses of the protostars, which would be the only mean to directly estimate masses of protostars without any assumptions. The dynamical mass can be directly compared with various physical parameters, including the infall velocity or the accretion luminosity, and such a comparison may shed a new light on the study of star formation.

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Facility: ALMA

APPENDIX

STATISTICAL EQUILIBRIUM CALCULATIONS FOR SO EMISSION

In order to investigate the physical condition in the SO emission region, we performed statistical equilibrium calculations of the three SO lines, which were observed in L1527 with ALMA (see Table 2), based on the large velocity gradient (LVG) model (Goldreich & Kwan 1974). For the calculations, all three SO lines were resampled with the same velocity resolution (0.28 km s$^{-1}$) and also convolved with the same beam size (0′.96 × 0′.73). The brightness temperature of each SO line was measured at the systemic velocity within the measurement area of 0′.75 × 0′.75 centered at the protostellar position. Rotational energy levels, statistical weights, Einstein A-coefficients, and line frequencies of SO are taken from the LAMDA database (Schöier et al. 2005). Collisional transition rates of SO below 50 K are taken from Lique et al. (2007), and those above 60 K are taken from Lique et al. (2006). The escape probability β in the case of a static, spherically symmetric, and homogeneous medium (Osterbrock & Ferland 2006) is adopted. The rotational energy levels included in the calculations are up to the 91st rotational energy level ($E_u$ = 972 K) in the case above 60 K and the 31st energy level ($E_u$ = 127 K) in the case below 50 K. These energy levels are high enough to discuss the physical conditions.

| Frequency (GHz) | SO 6$_e$–5$_a$ | SO 7$_e$–6$_s$ | SO 7$_e$–6$_t$ |
|----------------|---------------|---------------|---------------|
| $E_u$ (K)      | 34.98         | 47.55         | 81.24         |
| Observed brightness temperature (K) | 6.16 ± 0.30 | 6.00 ± 0.15 | 5.64 ± 0.11 |
| Reference      | 1             | 2             | 2             |

Notes.
A For the lines observed by Sakai et al. (2014), the calibrated data were downloaded from the ALMA archive, and clean maps were made by us.

References. (1) This work; (2) Sakai et al. (2014).
of molecular gas in low-mass protostellar envelopes. We confirmed that our calculations provide the same results as those from the RADEX code (van der Tak et al. 2007).

There are three free parameters for the LVG calculations, i.e., the kinetic temperature, the number density of H$_2$, and X/dV/dr, where X is the fractional abundance of the SO molecule and dV/dr is the velocity gradient. Brightness temperatures of each SO line are calculated with various sets of the three parameters and are compared with the observed brightness temperatures with a $\chi^2$ test to find the best solution explaining the observations. When the calculated brightness temperatures are compared with the observed values, it is important to consider the filling factor that is the fraction of the emission size to the measurement area. In order to estimate the filling factor, we consider which part of the edge-on ring can be observed at the systemic velocity within the measurement area of 0$''$.75 $\times$ 0$''$.75 (105 AU $\times$ 105 AU) centered at the protostellar position. The edge-on ring is observed within the measurement area as a rectangle, and the filling factor is given as $S_V \times S_H / (105 \text{ AU})^2$, where $S_V$ and $S_H$ are the size of the rectangle along the vertical and horizontal directions, respectively. $S_V$ and $S_H$ are estimated as follows.

1. It is considered that $S_V$ is determined by the scale height of the ring $h(T)$, which is expressed as

$$h(T) = 0.05 \times \left( \frac{T}{300 \text{ K}} \right)^{0.5} \left( \frac{R}{1 \text{ AU}} \right)^{1.5} \left( \frac{M}{M_\odot} \right)^{-0.5} \text{ AU}$$  

(A1)

where $T$ is the temperature, $R$ is the distance from the central star, and $M$ is the mass of the central star. When $R = 120$ AU and $M = 0.3 M_\odot$,

$$S_V = 2h(T) = 240 \left( \frac{T}{300 \text{ K}} \right)^{0.5} \text{ AU}. \quad \text{(A2)}$$

2. $S_H$ is estimated by considering the part of the edge-on ring with its line-of-sight velocity less than 0.14 km s$^{-1}$ with respect to the systemic velocity because emission within ±0.14 km s$^{-1}$ with respect to the systemic velocity is detected at the central channel with a velocity resolution of 0.28 km s$^{-1}$. Because the ring is considered to rotate at 1 km s$^{-1}$ speed at the radius of 120 AU, $S_H$ is estimated to be $\sim 34$ AU.

Figure 7 summarizes the results of the $\chi^2$ test. Each panel shows a result with a different value of X/dV/dr. We consider that parameter sets with $\chi^2 < 10$ can reproduce the observations very well. The area with $\chi^2 < 10$ appears at a temperature of $\sim 32$ K at each panel, whereas it spreads over a wide range of the H$_2$ density. This indicates that the temperature can be determined well with the current LVG analysis, whereas it is difficult to constrain the H$_2$ density and X/dV/dr. This is quite reasonable when the optical depth of the SO line is examined; the part where $\tau = 1$ shown in each panel indicates that the best solutions with $\chi^2 < 10$ appear when SO is optically thick. Because SO is optically thick, it is impossible for us to estimate the H$_2$ density and the abundance of SO. With this LVG analysis,
we consider that the kinetic temperature of the SO gas within the ring is \(\sim 32\) K.

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