Molecular Distributions of the Protostellar Envelope and the Outflow of IRAS 15398–3359: Principal Component Analysis

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Abstract

Using the Atacama Large Millimeter/submillimeter Array, we have imaged 15 molecular-line emissions and the dust continuum emission around the Class 0 protostellar source IRAS 15398–3359. The outflow structure is mainly traced by the H2CO (K_a = 0 and 1), CCH, and CS emissions. These lines also trace the disk/envelope structure around the protostar. The H2CO (K_a = 2 and 3), CH3OH, and SO emissions are concentrated toward the protostar, while the DCN emission is more extended around the protostar. We have performed principal component analysis (PCA) for these distributions on two different scales, the outflow and the disk/envelope structure. For the latter case, the molecular-line distributions are classified into two groups, according to the contribution of the second principal component, one having a compact distribution around the protostar and the other showing a rather extended distribution over the envelope. Moreover, the second principal component value tends to increase as an increasing quantum number of H2CO (K_a = 0, 1, 2, and 3), reflecting the excitation condition: the distribution is more compact for higher excitation lines. These results indicate that PCA is effective at extracting the characteristic features of the molecular-line distributions around the protostar in an unbiased way. In addition, we identify four blobs in the outflow structure in the H2CO lines, some of which can also be seen in the CH3OH, CS, CCH, and SO emissions. The gas temperature derived from the H2CO lines ranges from 43–63 K, which suggests shocks due to the local impact of the outflow on clumps of the ambient gas.

Unified Astronomy Thesaurus concepts: Young stellar objects (1834); Interstellar medium (847); Interstellar molecules (849); Protostars (1302); Star formation (1569)

1. Introduction

Observations of protostellar envelope/disk systems around very young protostars are of fundamental importance in elucidating the physical and chemical evolution of protostellar cores into planetary systems. Thanks to high-resolution and high-sensitivity molecular-line observations with the Atacama Large Millimeter/submillimeter Array (ALMA), a basic kinematic structure around a protostar, that is a rotationally supported disk surrounded by an infalling and rotating envelope, has been revealed for a number of low-mass protostellar sources (e.g., Codella et al. 2014; Ohashi et al. 2014; Oya et al. 2014, 2016, 2018; Sakai et al. 2014a, 2014b; Yen et al. 2015; Aso et al. 2017). Moreover, a complex chemical structure in a disk/envelope system has also been recognized: molecular distributions reflect the physical conditions, and hence they are different from molecule to molecule and even from transition to transition. (e.g., Sakai et al. 2014b; Oya et al. 2016, 2017, 2019; Lee et al. 2017; Jacobsen et al. 2019). It is thus suggested that the molecular distributions can be used as a useful tool to study the physical processes of disk formation in the envelope.

Recently, sensitive observations with a broad instantaneous bandwidth become popular in various radio telescopes including ALMA, so that many molecular lines can be observed in a single observation. This situation enables us to obtain rich information on chemical composition as well as physical structure. On the other hand, it takes a huge effort to characterize the distributions of all the observed lines in a one-by-one way (e.g., Imai et al. 2016; Jørgensen et al. 2016; Watanabe et al. 2017). For this reason, physical and chemical structures are often explored by using only a few selected lines, where interpretations could be biased by the selection. To make full use of the observed lines without any preconception, the introduction of a machine-learning process is essential.

Principal component analysis (PCA) is a powerful method to characterize these distributions comprehensively (Jolliffe 1986). This method has already been used for radio astronomical observations of molecular lines. It was conducted for large-scale observation data for external galaxies and galactic molecular clouds (e.g., Ungerechts et al. 1997; Meier & Turner 2005; Watanabe et al. 2016). Spezzano et al. (2017) used this method to investigate the chemical structure of the L1544 starless core and successfully highlighted four characteristic distributions. Thus, it is now important to apply this method to various sources including protostellar sources.

IRAS 15398–3359 is a low-mass Class 0 protostellar source (T_{bol} = 44 K; Jørgensen et al. 2013) in the Lupus 1 molecular cloud (d = 155 pc; Lombardi et al. 2008). Star formation activities of this source were studied by observing a molecular outflow in the CO lines with single-dish telescopes (Tachihara et al. 1996; van Kempen et al. 2009). On the other hand, chemical characteristics of this source were investigated by Sakai et al. (2009). Based on single-dish observations, they identified this source as a warm carbon-chain chemistry (WCCC) source, which is rich in various carbon-chain related molecules such as CCH, C_2H, and CH_3CCH on the scale of a few thousand astronomical units around the protostar. These molecules are produced through the gas-phase reactions triggered by the evaporation of CH_4 from the grain mantles in a lukewarm region (T ~ 30 K). IRAS 15398–3359 was actually the second WCCC source discovered after L1527 (Sakai et al. 2008; Sakai & Yamamoto 2013).
This source has been a good target for star formation studies in the ALMA era. Jørgensen et al. (2013) conducted subarcsecond-resolution observations toward IRAS 15398−3359. A ring structure of the H^{13}CO^+ (J = 4 − 3) emission was found at a 150 ∼ 200 au scale, which was proposed to be a sign of a recent accretion burst: H^{13}CO^+ seems to be destroyed through the gas-phase reaction with H_2O evaporated due to enhanced luminosity by the episodic accretion. The ALMA observations of the HDO (I_{0.1} = 0_{0.0}) emission revealed that it locally resides on the cavity wall near the protostar, which was also interpreted in terms of the recent accretion burst (Bjerkeli et al. 2016a).

Oya et al. (2014) characterized the bipolar outflow extending along the northeast–southwest axis on a 2000 au scale by observing the H_2CO (5_{1,5} − 4_{1,4}) line with ALMA at a resolution of 0.5" (∼80 au). By analyzing the kinematic structure of the outflow, they derived the inclination angle of the disk/envelope structure to be 70° (0° for a face-on configuration), meaning that the outflow is blowing almost parallel to the plane of the sky. This result is further confirmed by the CO observation with the Submillimeter Array (Bjerkeli et al. 2016b). The upper limit to the protostellar mass is derived to be 0.09 M_☉ from the velocity structure of the H_2CO (5_{1,5} − 4_{1,4}) emission (Oya et al. 2014), and 0.01 M_☉ from the analysis of the C^{18}O (J = 2 − 1) line (Yen et al. 2017) at a resolution of 0.5". In spite of such a low protostellar mass, Oya et al. (2014) reported a high-velocity component in the H_2CO emission toward the protostar position, which could possibly be ascribed to a disk structure. Indeed, Okada et al. (2018) found the Keplerian disk structure based on the observation of the SO line at a higher angular resolution (∼0.2") with ALMA and determined the protostellar mass to be 0.007^{+0.004}_{-0.003} M_☉. Since this source is deeply embedded in a parent dense gas (Kristensen et al. 2012; Jørgensen et al. 2013), the protostar is likely to be young. Hence, the result by Okada et al. (2018) indicates that the disk formation has already started around a newly born protostar in its very early evolutionary stage.

In this protostellar source, various molecular lines are detected on different scales with ALMA. In this paper, we apply the PCA to the molecular-line and continuum images observed toward this source to characterize their distributions.

### 2. Observation

The ALMA observations were carried out toward IRAS 15398−3359 in the Cycle 2 and Cycle 3 operations. Major points are summarized below.

The Cycle 2 observation was conducted on 2015 July 20. Spectral lines of CCH, SO, and CS listed in Table 1 were observed in the frequency range from 244–263 GHz with the Band 6 receiver. The original synthesized beam size is 0.21 × 0.15 (P.A. 58°) for the continuum image, while those of the line images are summarized in Table 1. The rms noise levels for the continuum, CCH, SO, and CS emissions are 0.12, 4, 4, and 4 mJy beam^{-1}, respectively, at a resolution of 61 kHz. Other details of the observations are described elsewhere (Okada et al. 2018).

The Cycle 3 observation was conducted on 2016 March 31. Spectral lines of H_2CO, c-C_3H_2, CCH, CH_3OH, and DCN listed in Table 1 were observed in the frequency range from 349–365 GHz with the Band 7 receiver. Forty-two antennas were used in the observations, where the baseline length ranged from 14.70–452.72 m. The field center was (α_2000, δ_2000) = (15:54:33.02, 42:34:09.06, 70°), which was the same as that of the Cycle 2 observation. The total on-source time was 19.30 minutes. The primary beam (half-power beam) width was 17°08. The backend correlator for
molecular-line observations except for the DCN observation was set to a resolution of 122 kHz and a bandwidth of 59 MHz, and that for the DCN observation was set to a resolution of 977 kHz and a bandwidth of 938 MHz. It should be noted that the velocity of all spectral windows is blueshifted by 2.5 km s\(^{-1}\) due to the fault in the observation setting. Hence, we do not discuss the velocity structures and only focus on the distribution of the molecules. The original synthesized beam size of the continuum image is 0\(')48 \times 0\(')45 (P.A. 83\(^{\circ}\)), while those of the lines are summarized in Table 1.

Images were prepared by using the CLEAN algorithm, where the Briggs’ weighting with a robustness parameter of 0.5 was employed. The continuum image was obtained by averaging line-free channels, and the line images were obtained after subtracting the continuum component directly from the visibilities. Self-calibration was not applied in this study, because the continuum emission is not bright enough. Since these largest angular sizes are 2\(')5, for both of these observations, the intensities of the structures extended more than that size could be resolved out.

In order to compare the molecular distributions at the same spatial resolution, the beam size was set to be 0\(')5 \times 0\(')5 by using a Gaussian kernel with imsmooth, which is the task of the Common Astronomy Software Applications package (McMullin et al. 2007) to smooth a data cube across spatial dimensions. The pixel sizes were set to be (2048, 2048) for the whole observed area in the CLEAN procedure.

Now, we have 16 images including the continuum emission. It should be noted that there are a few pairs of lines unresolved in the observation. The velocity width of the line is typically 0.9–1.3 MHz and 1.2–1.8 MHz for the Band 6 and Band 7 observations, respectively. Hence, the hyperfine splitting of CCH \((F = 5 – 4 \text{ and } 4 – 3 \text{ of the } N = 4 – 3, J = 9/2 – 7/2 \text{ transition})\) and that of CCH \((F = 4 – 3 \text{ and } 3 – 2 \text{ of the } N = 4 – 3, J = 7/2 – 5/2 \text{ transition})\) are not resolved. Similarly, the \(9_1–8_{2,7}\) and \(9_{2,8}–8_{1,7}\) lines of \(c\text{-C}_3\text{H}_2\) are degenerated, and the \(10_{0,10} – 9_{1,0}\) and \(10_{1,10} – 9_{0,0}\) lines of that are, too. These unresolved pairs were treated as a single line. For the CCH \((N = 3 – 2)\) lines \((F = 4 – 3 \text{ and } 3 – 2)\), a single image was prepared in order to increase the signal-to-noise ratio.

3. Molecular Distributions

Figure 2 shows the continuum map and the moment 0 maps of the observed molecular lines, while Figure 3 depicts their enlargements around the protostar. Figures 2(a) and 3(a) show the 0.8 mm continuum distribution (Cycle 3), whose peak intensity is 23.95 \(\pm\) 0.48 mJy beam\(^{-1}\). The coordinates of the peak are derived from a 2D Gaussian fit to the image: \((\alpha_{2000} = \delta_{2000}) = (15^h 43^m 02^s 2359 \pm 0.0004, -34^\circ 09' 06'' 8348 \pm 0.0045)\), which are consistent with the previous reports (e.g., Oya et al. 2014; Okoda et al. 2018). The continuum emission has a single peak with a circular distribution.

As shown in Figure 2, the distribution is different from molecular line to molecular line. The outflow structure along the northeast–southwest axis reported previously (Oya et al. 2014; Bjerkeli et al. 2016b; Okoda et al. 2018) can be seen particularly in the CCH, CS, and \(H_2CO\) \((K_a = 0 \text{ and } 1)\) lines. The outflow seems to have the double-ring structures in the CS emission. This may be caused by the episodic accretion (Bjerkeli et al. 2016b).

The \(c\text{-C}_3\text{H}_2\) emission does not have a component clearly associated with the protostar. It traces a part of the outflow cavity wall of the southwestern side. DCN seems to be distributed in the outflow cavity wall to some extent and also has a compact distribution around the protostar. The SO, \(CH_3OH\), and \(H_2CO\) \((K_a = 2 \text{ and } 3)\) emissions reveal blobs in the outflow as well as the compact distribution around the protostar.

In the enlarged version of the moment 0 maps (Figure 3), the component associated with the protostar can be found in most of the observed lines except for the \(c\text{-C}_3\text{H}_2\) lines. The disk/
envelope structure perpendicular to the outflow direction is seen more clearly. The CCH emission traces the envelope extending from northwest to southeast (Okoda et al. 2018). Note that the distribution of the CCH \((N = 4 - 3, J = 7/2 - 5/2, F = 3 - 3)\) line looks slightly different from those of the other CCH lines. This is probably due to the low signal-to-noise ratio of the line. The CS emission seems to be distributed over the envelope around the protostar. However, the CS emission in the southeastern side of the envelope is brighter than that in the northwestern side, as shown in Figure 3(b). For the CS emission, there is asymmetry in the distribution around the protostar, which is also seen for the H$_2$CO \((K_a = 0)\) emission. As above, the distributions of the observed molecular emissions look different from one another. However, their classification by eye may suffer from our preconception, and hence, an objective way to characterize the distributions is needed.

4. Principal Component Analysis

We conduct a PCA (Jolliffe 1986) for the two scales shown in Figures 2 and 3 to explore similarities and differences of molecular-line distributions and the Cycle 3 continuum distribution in an unbiased way. We exclude the Cycle 2 continuum data from the analysis, because the signal-to-noise ratio is lower than that of the Cycle 3 continuum data. Thus, we use the 16 dimension data set which consists of 15 molecular-line data and the Cycle 3 continuum data for the whole.
structure. For the disk/envelope structure, we exclude c-C_3H_2 (9_{1.8}−8_{2.7} and 9_{2.8}−8_{1.7}) because there are not enough data above the threshold level defined below. We write the code for the PCA by using the python libraries *numpy*, *matplotlib*, *pandas*, and *astropy*.

We represent the observed distribution of the jth emission as the vector x_j. In PCA, we look for the functions z_i (i = 1–16 or 1–15) formed by a linear combination of data x_j (j = 1–16 or 1–15), where the ith function is uncorrelated with the others. The main features can be extracted from the multidimensional data set by picking up a few components of z_i, which have a large variance. Thus, this process means “reduction” of the dimension. In this paper, these functions are obtained by diagonalizing the correlation matrix, because the intensities are different from molecular line to molecular line. In the calculation of the correlation coefficients between two intensity distributions, the data above threshold levels for both distributions are used. Three times the rms noise level (Table 2) is employed as the threshold level. The correlation matrices for the 16 or 15 distributions (15 or 14 lines and one continuum) thus obtained for the whole structure and the disk/envelope structure are shown in Tables 2 and 3, respectively. The matrix is diagonalized to find the orthogonal linear functions called the principal components. Here, their eigenvalues are also derived at the same time. The ith principal component z_i is denoted as PC_i (i = 1–16 or 1–15), where the number i is assigned in a decreasing order of the eigenvalue (Tables 4 and 5 for the whole structure and the disk/envelope structure, respectively). As the correlation matrix is used to find a set of orthogonal linear functions, the principal components
are defined as:

\[ z = Ax^*, \]

and

\[ x^*_j = x_j / \sigma_{jj}^{1/2}, \]

where \( A \) is the transformation matrix for the diagonalization of the correlation matrix, \( x^* \) the normalized distribution, and \( \sigma_{jj} \) the variance of \( x_j \). Hence, \( PC_i \) is dimensionless. A contribution ratio of each principal component is calculated by dividing the eigenvalue by the dimension (16 or 15), as shown in Tables 4 and 5. It represents how much \( PC_i \) contributes to all the original sample distributions.

### 4.1. PCA of the Whole Structure

As mentioned above, we can almost reproduce the molecular-line and continuum distributions by using only a few principal components. According to Table 4, PC1 and PC2 have the two largest contribution ratios, 42.1% and 20.3%, respectively. The sum of the contribution ratios of the two components is 62.4%, which indicates that these two components can be regarded as the main components. The contribution ratios of PC3 and PC4 are 8.7% and 8.2%, respectively, which are significantly smaller than that of PC2. Hence, we discuss the first two components here. In this case, the observed images can approximately be reproduced by the linear combinations of the two component images, which means the reduction of the original dimension of the images (16) to 2. PC3 and PC4 are discussed in Appendix A for reference.

Figures 4(a) and (b) show the maps of PC1 and PC2, respectively. PC1 represents an overall shape of the outflow, two blobs in the outflow, and a component concentrated around the protostellar position. PC2 mainly represents the disk/envelope structure. The foot of the outflow can also be seen partly.

Contributions of the first two principal components for each molecular-line distribution are represented on the PC1–PC2 plane, as shown in Figure 4(c). Correlations between \( PC_i \) (\( i = 1–4 \)) and the observed distributions are also presented in Appendix B. Gray dashed ellipses in Figure 4(c) represent the estimated errors due to noise, whose details are described in Section 4.3. The majority of the line emissions and the continuum emission show the positive values of PC1, as shown in Figure 4(c). For this case, the positive and negative values on the PC2 axis can classify the samples into two groups, one with a compact distribution around the protostar (Group 1) and the other showing rather extended structures (Group 2). The CCH and CS lines as well as the \( \text{H}_2\text{CO} \) \( (K_a = 0) \) line belong to Group 2, which trace the extended feature of the outflow well. Indeed, these lines are often employed as a tracer of the outflow cavity wall on a 1000 au scale (e.g., Codella et al. 2014; Oya et al. 2015, 2019; Zhang et al. 2018). On the other hand, \( c\text{-C}_3\text{H}_2 \) \( (10_{0,10} - 9_{1,9} \) and \( 10_{1,10} - 9_{0,9}) \), \( c\text{-C}_3\text{H}_2 \) \( (9_{1,8} - 8_{2,7} \) and \( 9_{2,8} - 8_{1,7}) \) and CCH \( (N = 4 - 3, J = 7/2 - 5/2, F = 3 - 3) \) have negative PC1 and positive PC2. This result represents that these molecular lines have a clumpy feature in the outflow.
The molecular emissions distributed in the blobs are represented by the positive PC1 and positive PC3 values (see Appendix A). These blobs are most likely a shocked region caused by a local impact of the outflow on an ambient gas, as described below. The molecular lines showing the positive PC1 and the positive PC3 ($\text{H}_2\text{CO}$, CS, CCH ($N = 3 - 2$), SO, and CH$_3$OH) trace both or one of the two blobs. We finally identify four blobs (A–D in Figure 5) in the outflow structure by using the $\text{H}_2\text{CO}$ ($K_a = 1$) line (Table 6). They are also seen in the other $\text{H}_2\text{CO}$ lines, although blobs B and C can hardly be seen in the highest excitation lines of $\text{H}_2\text{CO}$ ($K_a = 3$). Blob D is bright in the CS and SO emissions, although blob A is seen in

Figure 3. The enlargements of Figure 2 around the protostar. The outflow and envelope direction (P.A. 130°) are drawn with arrows and the dashed line, respectively, in (a). The blue cross marks in (f) represent the peak positions for the calculation of the column density ratios relative to $\text{H}_2\text{CO}$ in Section 5. The circle in the bottom shows the beam size. The black cross marks show the continuum peak position. Contour levels are the same as those of Figure 2.
the CS and CCH \( (N = 3 - 2) \) lines. The \( \text{CH}_3 \text{OH} \) emission has an extended distribution from the protostar to blob A.

The gas kinematic temperature for each blob is evaluated from the detected \( \text{H}_2 \text{CO} \) lines under the non-LTE (local thermodynamic equilibrium) method assuming the large velocity gradient approximation. The data used in the analysis are shown in Table 7. The derived gas kinematic temperature ranges from 43–63 K (Table 8). Such high temperatures as well as the absence of associated continuum emission indicate that the four blobs should be the shocked regions caused by the outflow impact. It seems that a local shock is occurring on the cavity wall by the interaction with an ambient gas. This
situation is also pointed out for blob A by Oya et al. (2014). Such a shocked region can be seen in L1157 B1, where strong emissions of various molecules including H₂CO, CS, SO, and CH₃OH are detected (e.g., Bachiller and Pérez Gutiérrez 1997; Benedettini et al. 2007; Codella et al. 2010). These molecules are thought to be liberated from dust grains and/or produced through the gas-phase shock chemistry. Detailed comparison with the L1157 B1 result for exploring shock chemistry would require observations of more molecular lines including SiO.

4.2. PCA of the Disk/Envelope Structure

The PCA for the observed distributions in the narrower range (Figure 3) is helpful for investigating the chemical structure around the protostar in more detail. We use 14 molecular-line data except for c-C₃H₂ (9₁,₈ − 8₂,₇ and 9₂,₈ − 8₁,₇) in addition to the Cycle 3 continuum data. Table 5 shows the eigenvalues and eigenvectors obtained by diagonalizing the correlation matrix. On the disk/envelope scale, PC1 and PC2 stand for 76.7% of the contribution ratio. The molecular distributions can mostly be reproduced by only the first two components, so that we discuss PC1 and PC2 here. The contribution ratio of PC3 is 8.5%, which is similar to that of PC4 (7.8%). PC3 and PC4 are discussed in Appendix A for reference. Correlation between PCI (i = 1–4) and the observed distributions are presented in Appendix B.

In Figure 6(a), PC1 shows the distribution centered near the protostellar position with extension along the northwest–southeast direction. This component apparently represents the disk/envelope structure. All the molecular lines except for CCH (N = 4 − 3, J = 7/2 − 5/2, F = 3 − 3) and c-C₃H₂ (10₀,₁₀ − 9₁,₉ and 10₁,₁₀ − 9₀,₀) have the positive PC1 component, as shown in Figures 6(c). Here, gray dashed ellipses represent the estimated errors (Section 4.3). The exception for CCH (N = 4 − 3, J = 7/2 − 5/2, F = 3 − 3) and c-C₃H₂ (10₀,₁₀ − 9₁,₉ and 10₁,₁₀ − 9₀,₀) means that they are not mainly distributed in the disk/envelope system, as noted in Sections 3 and 4.1. PC2 has negative values at almost all the positions with two large negative peaks at both sides of the protostellar position (Figure 6(b)). Its “red part” in the northeastern and southwestern extension is close to zero. SO shows a large positive value for the PC2 axis, as shown in Figure 6(c). This result means that its distribution is very compact toward the protostar: the southeastern and northwestern extension of PC1 is almost compensated by the positive PC2. It is consistent with our previous finding of the compact SO distribution (Okoda et al. 2018). Similarly, the
| Molecular Species | Transition | \( c\text{-}c\text{-}\text{H}_2 \) (10 - 9) | \( c\text{-}c\text{-}\text{H}_2 \) (9 - 8) | CCH (3 - 2) | CCH (4 - 3 a) | CCH (4 - 3 b) | CCH (4 - 3 c) | CH\(_3\)OH | CS | DCN | H\(_2\text{CO} \) | H\(_2\text{CO} \) \( K_u = 0 \) | H\(_2\text{CO} \) \( K_u = 1 \) | H\(_2\text{CO} \) \( K_u = 2 \) | H\(_2\text{CO} \) \( K_u = 3_a \) | H\(_2\text{CO} \) \( K_u = 3_b \) | SO | Continuum (Cycle 3) |
|------------------|------------|-----------------|-----------------|-------------|-------------|-------------|-------------|----------|-----|-----|-------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| \( c\text{-}c\text{-}\text{H}_2 \) (10 - 9) | 0.0701 | 0.0701 | 0.2025 | 0.1514 | 0.0125 | 0.0806 | -0.5217 | 0.0407 | -0.0718 | 0.0229 | -0.0012 | -0.1951 | -0.3934 | -0.5902 | -0.5435 | -0.1789 |
| \( c\text{-}c\text{-}\text{H}_2 \) (9 - 8) | 0.2025 | 0.3635 | 1 | -0.0859 | 0.6308 | 0.5969 | 0.3057 | 0.4118 | 0.5671 | 0.3846 | 0.4195 | 0.3982 | 0.2723 | 0.4117 | 0.479 |
| CCH (3 - 2) | 0.1514 | 0.4171 | -0.0859 | 1 | 0.3216 | 0.2884 | -0.2207 | 0.1013 | -0.1804 | 0.135 | -0.058 | 0.0228 | 0.0936 | -0.1387 | -0.2487 | -0.0685 |
| CCH (4 - 3 a) | 0.0125 | 0.3925 | 0.6308 | 0.3216 | 1 | 0.9726 | 0.1568 | 0.3827 | 0.548 | 0.6669 | 0.3183 | 0.335 | 0.5353 | 0.2789 | 0.0086 | 0.5312 |
| CCH (4 - 3 b) | 0.0806 | 0.3666 | 0.5969 | 0.2884 | 0.9726 | 1 | 0.0176 | 0.3561 | 0.5355 | 0.6511 | 0.3314 | 0.326 | 0.5103 | 0.2236 | -0.0362 | 0.5254 |
| CH\(_3\)OH | -0.5217 | -0.7422 | 0.3057 | -0.2207 | 0.1568 | 0.0176 | 1 | 0.3185 | 0.1145 | 0.3633 | 0.3024 | 0.2747 | 0.3566 | 0.2606 | 0.5191 | 0.6838 |
| CS | 0.0407 | 0.0419 | 0.5005 | 0.1013 | 0.3827 | 0.3561 | 0.3185 | 1 | 0.2621 | 0.5845 | 0.5144 | 0.4508 | 0.2112 | 0.1348 | 0.0559 | 0.3402 |
| DCN | -0.0718 | -0.5622 | 0.4118 | -0.1804 | 0.548 | 0.5355 | 0.1145 | 0.2621 | 1 | 0.5817 | 0.6523 | 0.4827 | 0.6319 | 0.2087 | 0.018 | 0.6525 |
| H\(_2\text{CO} \) | 0.0229 | 0.268 | 0.5671 | 0.135 | 0.6669 | 0.6511 | 0.3633 | 0.5845 | 0.5817 | 1 | 0.794 | 0.7737 | 0.6021 | 0.541 | 0.5379 | 0.6023 |
| \( K_u = 0 \) | -0.0012 | 0.1289 | 0.3846 | -0.058 | 0.3183 | 0.3314 | 0.3024 | 0.5144 | 0.6523 | 0.794 | 1 | 0.777 | 0.5855 | 0.6165 | 0.6532 | 0.4361 |
| \( K_u = 1 \) | -0.1951 | 0.0137 | 0.4195 | 0.0228 | 0.335 | 0.326 | 0.2747 | 0.4508 | 0.4827 | 0.7737 | 0.777 | 1 | 0.6729 | 0.6473 | 0.4643 | 0.843 |
| \( K_u = 2 \) | -0.3934 | -0.6535 | 0.3982 | 0.0936 | 0.5353 | 0.5103 | 0.3566 | 0.2112 | 0.6319 | 0.6021 | 0.5855 | 0.6729 | 1 | 0.6974 | 0.4244 | 0.8205 |
| \( K_u = 3_a \) | -0.5902 | -0.4883 | 0.2723 | -0.1387 | 0.2789 | 0.2236 | 0.2606 | 0.1348 | 0.2087 | 0.541 | 0.6165 | 0.6473 | 0.6974 | 1 | 0.355 | 0.6219 |
| \( K_u = 3_b \) | -0.5435 | -0.7263 | 0.4117 | -0.2487 | 0.0086 | -0.0362 | 0.5191 | 0.0559 | 0.018 | 0.5379 | 0.6532 | 0.4643 | 0.4244 | 0.355 | 1 | 0.3517 |
| SO | -0.1789 | -0.1822 | 0.479 | -0.0685 | 0.5312 | 0.5254 | 0.6838 | 0.3402 | 0.6525 | 0.6023 | 0.4361 | 0.843 | 0.8205 | 0.6219 | 0.3517 | 1 |

Note. \( c\text{-}c\text{-}\text{H}_2 \) (10 - 9), (9 - 8), CCH (3 - 2), (4 - 3 a), (4 - 3 b), (4 - 3 c), H\(_2\text{CO} \) \( K_u = 0 \), \( K_u = 1 \), \( K_u = 2 \), \( K_u = 3_a \), and \( K_u = 3_b \) denote \( c\text{-}c\text{-}\text{H}_2 \) (10\( _{0,10} \) - 9\( _{1,9} \) and 10\( _{1,10} \) - 9\( _{0,9} \)), \( c\text{-}c\text{-}\text{H}_2 \) (9\( _{1,9} \) - 8\( _{1,8} \)), CCH \( (N = 3 \) - 2, \( J = 7/2 \) - 5/2, \( F = 4 \) - 3 and \( 3 \) - 2), (\( N = 4 \) - 3, \( J = 7/2 \) - 5/2, \( F = 3 \) - 3, (\( N = 4 \) - 3, \( J = 7/2 \) - 5/2, \( F = 4 \) - 3 and \( 3 \) - 2), (\( N = 4 \) - 3, \( J = 9/2 \) - 7/2, \( F = 5 \) - 4 and \( 4 \) - 3), H\(_2\text{CO} \) \( (5_0,3 \) - 4\( _{0,4} \), \( 5_1,5 \) - 4\( _{1,4} \), \( 5_2,4 \) - 4\( _{2,3} \), \( 5_3,2 \) - 4\( _{3,1} \), and \( 5_3,3 \) - 4\( _{3,2} \), respectively. The units of rms are \( \text{mJy beam}^{-1} \text{km s}^{-1} \) and \( \text{mJy beam}^{-1} \) for the molecular lines and the continuum data, respectively.
Table 3
Correlation Matrix for the Disk/Envelope

| Molecular Species | c-C$_3$H$_2$ (10 − 9) | CCH (3 − 2) | CCH (4 − 3 a) | CCH (4 − 3 b) | CCH (4 − 3 c) | CH$_3$OH | CS | DCN | H$_2$CO $K_a = 0$ | H$_2$CO $K_a = 1$ | H$_2$CO $K_a = 2$ | H$_2$CO $K_a = 3$ | H$_2$CO $K_a = 3$ | SO | Continuum (Cycle 3) |
|-------------------|------------------------|-------------|--------------|--------------|--------------|---------|----|-----|-----------------|-----------------|-----------------|-----------------|-----------------|----|-----------------|
| c-C$_3$H$_2$ (10 − 9) | 1 | 0.0113 | 0.1657 | 0.5656 | 0.5949 | −0.429 | 0.4517 | −0.1288 | 0.2988 | 0.1921 | −0.3543 | −0.6046 | −0.5911 | −0.6924 | −0.198 |
| CCH (3 − 2) | 0.0113 | 1 | −0.2787 | 0.6607 | 0.7061 | 0.2147 | 0.5318 | 0.4118 | 0.6789 | 0.6262 | 0.4443 | 0.3952 | 0.3602 | 0.1209 | 0.4145 |
| CCH (4 − 3 a) | 0.1657 | −0.2787 | 1 | 0.1107 | 0.0151 | −0.2921 | −0.1203 | −0.1804 | −0.2132 | −0.2431 | −0.063 | 0.0539 | −0.2268 | −0.2487 | −0.2696 |
| CCH (4 − 3 b) | 0.5656 | 0.6607 | 0.1107 | 1 | 0.9888 | 0.3357 | 0.8041 | 0.3622 | 0.9099 | 0.6555 | 0.4827 | 0.5609 | 0.5075 | 0.0518 | 0.4411 |
| CCH (4 − 3 c) | 0.5949 | 0.7061 | 0.0151 | 0.9888 | 1 | 0.1952 | 0.8226 | 0.4028 | 0.9089 | 0.6669 | 0.466 | 0.4068 | 0.427 | −0.0568 | 0.4256 |
| CH$_3$OH | −0.429 | 0.2147 | −0.2921 | 0.3357 | 0.1952 | 1 | 0.0393 | 0.1145 | 0.6638 | 0.7567 | 0.7953 | 0.4929 | 0.7601 | 0.8797 | 0.7287 |
| CS | 0.4517 | 0.5318 | −0.1203 | 0.8041 | 0.8226 | 0.0393 | 1 | 0.0297 | 0.7369 | 0.6131 | 0.2341 | 0.174 | 0.2541 | −0.0589 | 0.1175 |
| DCN | −0.1288 | 0.4118 | −0.1804 | 0.3622 | 0.4028 | 0.1145 | 0.0297 | 1 | 0.472 | 0.5036 | 0.3842 | 0.6319 | 0.2087 | 0.018 | 0.5621 |
| H$_2$CO ($K_a = 0$) | 0.2988 | 0.6789 | −0.2132 | 0.9099 | 0.9889 | 0.6638 | 0.7369 | 0.472 | 1 | 0.8341 | 0.7556 | 0.7234 | 0.6727 | 0.5264 | 0.7105 |
| H$_2$CO ($K_a = 1$) | 0.1921 | 0.6262 | −0.2431 | 0.6555 | 0.6669 | 0.7567 | 0.6131 | 0.5036 | 0.8341 | 1 | 0.8873 | 0.7993 | 0.7796 | 0.6823 | 0.8143 |
| H$_2$CO ($K_a = 2$) | −0.3543 | 0.4443 | −0.063 | 0.4827 | 0.466 | 0.7953 | 0.2341 | 0.3842 | 0.7556 | 0.8873 | 1 | 0.7817 | 0.8834 | 0.8691 | 0.9289 |
| H$_2$CO ($K_a = 3$) | −0.6046 | 0.3952 | 0.0539 | 0.5609 | 0.4068 | 0.4929 | 0.174 | 0.6319 | 0.7234 | 0.7993 | 0.7817 | 1 | 0.7436 | 0.5551 | 0.8988 |
| H$_2$CO ($K_a = 3$) | −0.5911 | 0.3602 | −0.2268 | 0.5075 | 0.427 | 0.7601 | 0.2541 | 0.2087 | 0.6727 | 0.7796 | 0.8834 | 0.7436 | 1 | 0.8139 | 0.8934 |
| SO | −0.6924 | 0.1209 | −0.2487 | 0.0518 | −0.0568 | 0.8797 | −0.0589 | 0.018 | 0.5264 | 0.6823 | 0.8691 | 0.5551 | 0.8139 | 1 | 0.8104 |
| Continuum | −0.198 | 0.4145 | −0.2696 | 0.4411 | 0.4256 | 0.7287 | 0.1175 | 0.5621 | 0.7105 | 0.8143 | 0.9289 | 0.8988 | 0.8934 | 0.8104 | 1 |

Note. c-C$_3$H$_2$ (10 − 9), CCH (3 − 2), (4 − 3 a), (4 − 3 b), (4 − 3 c), H$_2$CO ($K_a = 0$), ($K_a = 1$), ($K_a = 2$), and ($K_a = 3$) denote c-C$_3$H$_2$ (10$_{10,10}$ − 9$_{10,9}$ and 10$_{10,10}$ − 9$_{0,9}$), CCH (3 − 2, J = 7/2 − 5/2, F = 4 − 3 and 3 − 2), (N = 4 − 3, J = 7/2 − 5/2, F = 3 − 3), (N = 4 − 3, J = 7/2 − 5/2, F = 4 − 3 and 3 − 2), (N = 4 − 3, J = 9/2 − 7/2, F = 5 − 4 and 4 − 3), H$_2$CO (5$_{0,5}$ − 4$_{0,4}$), (5$_{1,5}$ − 4$_{1,4}$), (5$_{2,4}$ − 4$_{2,3}$), (5$_{3,2}$ − 4$_{3,1}$), and (5$_{3,3}$ − 4$_{3,2}$), respectively. The units of rms are mJy beam$^{-1}$ km s$^{-1}$ and mJy beam$^{-1}$ for the molecular lines and the continuum data, respectively.
| Principal Component | PC1   | PC2   | PC3   | PC4   | PC5   | PC6   | PC7   | PC8   | PC9   | PC10  | PC11  | PC12  | PC13  | PC14  | PC15  | PC16  |
|---------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| c-C_{3}H_{5} (10−9) | −0.098| 0.298 | −0.131| −0.559| 0.215 | 0.234 | 0.188 | 0.46  | −0.165| 0.31  | −0.025| 0.077 | 0.018 | 0.102 | 0.018 | 0.288 |
| c-C_{3}H_{2} (9−8)  | −0.077| 0.514 | 0.385 | 0.213 | −0.014| −0.269| −0.188| 0.024 | 0.234  | −0.043| 0.125 | 0.062 | 0.178 | −0.093| −0.111| 0.546 |
| CCH (3 − 2)         | 0.249 | 0.203 | 0.136 | −0.267| −0.316| 0.178 | 0.263 | −0.296| −0.404 | 0.363 | −0.188| −0.041| 0.161 | 0.099 | −0.224|
| CCH (4−3 a)         | −0.006| 0.288 | −0.02  | 0.436 | 0.001 | 0.666 | 0.293 | 0.074 | 0.038  | −0.154| 0.287 | −0.138| −0.242| −0.069| −0.04  |
| CCH (4−3 b)         | 0.257 | 0.328 | −0.221| 0.15  | −0.242| −0.128| 0.121 | −0.145| −0.024 | 0.177 | 0.012 | −0.052| 0.141 | 0.762 | −0.021| −0.089|
| CCH (4−3 c)         | 0.244 | 0.345 | −0.249| 0.112 | −0.151| −0.155| 0.139 | −0.122| −0.034 | 0.16  | −0.345| 0.433 | −0.367| 0.376 | 0.236 | −0.024|
| CH_{3}OH             | 0.201 | −0.299| 0.033 | −0.086| −0.58 | 0.227 | −0.127| 0.047 | 0.228  | 0.337 | 0.302 | 0.044 | 0.057 | −0.073| 0.345 | 0.264 |
| CS                  | 0.203 | 0.147 | 0.224 | −0.277| −0.192| 0.423 | −0.405| −0.362| −0.385 | −0.217| −0.235| 0.073 | −0.02 | 0.05  | −0.178| 0.093 |
| DCN                 | 0.268 | 0.013 | −0.461| −0.279| 0.253 | −0.076| −0.054| −0.359| 0.286  | −0.206| 0.22  | −0.311| −0.232| −0.054| −0.033| 0.331 |
| H_{2}CO (K_{a} = 0) | 0.339 | 0.155 | 0.224 | −0.041| 0.078 | 0.063 | 0.122 | −0.079| 0.138  | 0.391 | −0.28 | −0.568| 0.262 | −0.302| −0.051| −0.208|
| H_{2}CO (K_{a} = 1) | 0.304 | 0.014 | 0.318 | −0.155| 0.386 | 0.041 | 0.091 | −0.244| 0.117  | 0.178 | 0.455 | 0.476 | 0.053 | 0.026 | −0.048| −0.279|
| H_{2}CO (K_{a} = 2) | 0.32  | −0.007| 0.216 | 0.061 | 0.297 | 0.079 | −0.252| 0.328 | 0.217  | 0.27  | −0.248| −0.036| −0.141| 0.264 | 0.556 | −0.029|
| H_{2}CO (K_{a} = 3_{a}) | 0.328 | −0.124| −0.3  | 0.191 | 0.123 | 0.103 | 0.154 | 0.077 | −0.182 | −0.261| −0.051| 0.208 | 0.689 | −0.168| 0.05  | 0.206 |
| H_{2}CO (K_{a} = 3_{b}) | 0.264 | −0.196| 0.047 | 0.336 | 0.237 | −0.162| −0.167| 0.096 | −0.591 | 0.331 | 0.182 | −0.158| −0.268| 0.005 | −0.04 | 0.258 |
| SO                  | 0.211 | −0.325| 0.348 | −0.053| −0.096| −0.049| 0.601 | −0.017| 0.09   | −0.141| −0.268| 0.061 | −0.214| 0.159 | −0.246| 0.344 |
| Continuum           | 0.334 | −0.046| −0.172| 0.042 | 0.108 | 0.015 | −0.309| 0.476 | 0.274  | 0.003 | 0.035 | 0.136 | −0.011| −0.04 | −0.625| −0.149|

**Table 4**

Eigenvectors of the Principal Components and Their Eigenvalues in the Analysis of the Whole Structure

| Eigenvalues | 6.731 | 3.243 | 1.397 | 1.310 | 1.108 | 8.830 | 7.450 | 5.940 | 4.710 | 2.960 | 1.660 | 8.100 | 1.300 | 4.000 | −8.900 | −9.540 |
| Contribution ratio (%) | 42.1 | 20.3 | 8.7 | 8.2 | 6.9 | 5.5 | 4.7 | 3.7 | 2.9 | 1.9 | 1.0 | 0.5 | 0.1 | 0.0 | −0.6 | −6.0 |

**Note.** c-C_{3}H_{5} (10−9), (9−8), CCH (3 − 2), (4−3 a), (4−3 b), (4−3 c), H_{2}CO (K_{a} = 0), (K_{a} = 1), (K_{a} = 2), (K_{a} = 3_{a}), and (K_{a} = 3_{b}) denote c-C_{3}H_{5} (10_{0,10} − 9_{1,9} and 10_{1,10} − 9_{0,9}), c-C_{3}H_{5} (9_{1,8} − 8_{2,7} and 9_{2,8} − 8_{1,7}), CCH (N = 3 − 2, J = 7/2 − 5/2, F = 4 − 3 and 3 − 2), (N = 4 − 3, J = 7/2 − 5/2, F = 3 − 3), (N = 4 − 3, J = 7/2 − 5/2, F = 4 − 3 and 3 − 2), (N = 4 − 3, J = 9/2 − 7/2, F = 5 − 4 and 4 − 3), H_{2}CO (5_{0,5} − 4_{0,4}, 5_{1,5} − 4_{1,4}, 5_{2,4} − 4_{2,3}, 5_{3,2} − 4_{3,1}), and (5_{3,3} − 4_{3,2}), respectively.
Table 5
Eigenvectors of the Principal Components and Their Eigenvalues in the Analysis of the Disk/Envelope

| Principal Component | PC1     | PC2     | PC3     | PC4     | PC5     | PC6     | PC7     | PC8     | PC9     | PC10    | PC11    | PC12    | PC13    | PC14    | PC15    |
|---------------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| c-C₃H₂ (10 – 9)     | −0.045  | −0.496  | −0.18   | 0.067   | 0.548   | −0.084  | −0.077  | 0.186   | 0.083   | −0.133  | 0.058   | 0.012   | −0.101  | 0.144   | −0.555  |
| CCH (3 – 2)         | 0.227   | −0.189  | 0.101   | −0.331  | −0.459  | −0.693  | −0.088  | 0.092   | 0.101   | −0.166  | 0.078   | −0.043  | 0.083   | 0.1     | −0.153  |
| CCH (4 – 3 a)       | −0.078  | −0.084  | 0.264   | 0.832   | −0.079  | −0.26   | −0.128  | −0.079  | −0.061  | 0.048   | 0.148   | −0.201  | 0.219   | 0.109   | 0.029   |
| CCH (4 – 3 b)       | 0.263   | −0.341  | 0.013   | 0.182   | −0.057  | 0.037   | 0.38    | −0.071  | 0.014   | −0.252  | 0.398   | 0.484   | −0.17   | −0.3     | 0.23    |
| CCH (4 – 3 c)       | 0.248   | −0.379  | 0.024   | 0.049   | −0.036  | −0.016  | 0.229   | 0.192   | −0.158  | 0.273   | −0.438  | −0.415  | −0.058  | −0.481  | 0.059   |
| CH₂OH               | 0.263   | 0.231   | −0.313  | 0.04    | 0.207   | −0.231  | 0.338   | −0.52   | −0.269  | −0.163  | −0.196  | 0.007   | 0.351   | −0.009  | −0.191  |
| CS                  | 0.177   | −0.366  | −0.259  | −0.027  | −0.35   | 0.431   | −0.377  | −0.182  | −0.044  | 0.163   | 0.072   | 0.113   | 0.463   | −0.006   | −0.147 |
| DCN                 | 0.178   | −0.036  | 0.664   | −0.3    | 0.283   | 0.063   | −0.01   | −0.234  | −0.259  | 0.295   | 0.331   | −0.054  | 0.1     | −0.031   | −0.143 |
| H₂CO (Kₐ = 0)       | 0.335   | −0.174  | −0.09   | −0.004  | 0.083   | 0.039   | 0.189   | −0.276  | 0.481   | 0.292   | 0.005   | −0.213  | −0.156  | 0.517   | 0.275   |
| H₂CO (Kₐ = 1)       | 0.341   | −0.048  | −0.085  | −0.025  | 0.213   | −0.014  | −0.551  | −0.083  | −0.34   | −0.384  | −0.005  | −0.196  | −0.248  | 0.04     | 0.392   |
| H₂CO (Kₐ = 2)       | 0.325   | 0.152   | −0.019  | 0.165   | 0.059   | −0.205  | 0.214   | 0.171   | −0.15   | 0.478   | 0.274   | 0.593   | 0.176   | 0.107    | −0.053  |
| H₂CO (Kₐ = 3ₐ)     | 0.297   | 0.131   | 0.408   | 0.152   | −0.163  | 0.291   | −0.068  | −0.155  | 0.311   | −0.381  | −0.374  | 0.04    | −0.193  | −0.041   | −0.378  |
| H₂CO (Kₐ = 3ₜ)     | 0.308   | 0.191   | −0.112  | 0.091   | −0.244  | 0.25    | 0.288   | 0.398   | −0.397  | 0.269   | −0.219  | −0.136  | 0.358   | 0.242    |
| SO                  | 0.241   | 0.36    | −0.273  | 0.082   | 0.047   | −0.085  | −0.211  | −0.039  | 0.331   | 0.204   | 0.42    | −0.222  | −0.156  | −0.474   | −0.222  |
| Continuum           | 0.32    | 0.153   | 0.109   | −0.016  | 0.299   | 0.049   | 0.018   | 0.504   | 0.282   | −0.162  | −0.012  | 0.04    | 0.598   | −0.018   | 0.222   |

Eigenvectors

| Contribution ratio (%) | 7.918 | 3.581 | 1.281 | 1.166 | 0.708 | 0.376 | 0.289 | 0.247 | 0.121 | 0.109 | −0.023 | −0.033 | −0.062 | −0.13 | −0.548 |

Note. c-C₃H₂ (10 – 9), CCH (3 – 2), (4 – 3 a), (4 – 3 b), (4 – 3 c), H₂CO (Kₐ = 0), (Kₐ = 1), (Kₐ = 2), (Kₐ = 3ₐ), and (Kₐ = 3ₜ) denote c-C₃H₂ (100₁₀ – 9₁₀,₉ and 10₁₀,₁₀ – 9₁₀), CCH (N = 3 – 2, J = 7/2 – 5/2, F = 4 – 3 and 3 – 2), (N = 4 – 3, J = 7/2 – 5/2, F = 3 – 3), (N = 4 – 3, J = 7/2 – 5/2, F = 4 – 3 and 3 – 2), (N = 4 – 3, J = 9/2 – 7/2, F = 5 – 4 and 4 – 3), H₂CO (5₁₅ – 4₁₅,ₙ₅), (5₁₅ – 4₁₅,ₙ₅), (5₃₃ – 4₃₃), and (5₃₃ – 4₃₃), respectively.
distribution around the protostar. Lines showing positive PC1 and positive PC2 have a compact distribution around the protostellar envelope, as revealed in the other sources (Sakai et al. 2016; Oya et al. 2017). The gas is significantly heated near the protostar. c-C3H2 (10–9), (9–8), CCH (N = 3–2), (N = 4–3 a), (N = 4–3 b), (N = 4–3 c), H2CO (K_a = 0), (K_a = 1), (K_a = 2), (K_a = 3) denote c-C3H2 (10_{0,10} – 9_{1,9} and 10_{1,10} – 9_{0,9}), c-C2H (9_{1,8} – 8_{2,7} and 9_{2,8} – 8_{1,7}), CCH (N = 3–2, J = 7/2 – 5/2, F = 4–3 and 3–2), (N = 4–3, J = 7/2 – 5/2, F = 3–3), (N = 4–3, J = 7/2 – 5/2, F = 3–3 and 3–2), (N = 4–3, J = 7/2 – 5/2, F = 5–4 and 4–3). H2CO (5_{0,5} – 4_{0,4}), (5_{1,5} – 4_{1,4}), (5_{2,4} – 4_{2,3}), (5_{3,3} – 4_{3,2}), and (5_{4,3} – 4_{4,2}), respectively.

Lines showing positive PC1 and positive PC2 have a compact distribution around the protostar (Group A). On the other hand, the lines showing positive PC1 and negative PC2 have a rather extended distribution (Group B). Thus, PC2 can be an indicator of how much the distribution is concentrated.

For the two large negative peaks of PC2, the southeastern side of the protostar has a stronger peak than the northwestern side (Figure 6(b)). This feature contributes to an asymmetric distribution in the disk/envelope system. The CS and H2CO (K_a = 0) distributions are clearly brighter in the southeastern side, and hence the PC2 values take a negative value. The chemical composition seems azimuthally nonuniform even in the protostellar envelope, as revealed in the other sources (Sakai et al. 2016; Oya et al. 2017).

Moreover, we focus on the behavior of the H2CO lines with different upper-state energies along the PC2 axis in Figure 6(c). For para H2CO, the K_a = 2 line shows the positive contribution of PC2, while the K_a = 0 line shows the negative contribution. Likewise, ortho H2CO reveals a similar trend: the K_a = 3 lines take the larger positive value of PC2, while the K_a = 1 line takes the negative PC2. This trend shows that the emissions of the higher excitation lines (i.e., higher K_a lines) tend to be more concentrated around the protostar. This is reasonable because the gas temperature and the gas density are expected to be higher when approaching the protostar. The gas kinematic temperature is calculated to be 54 K (Table 8) by using the non-LTE calculation applied to the analysis of the blobs. The gas is significantly heated near the protostar.

### 4.3. Effect of Noise

In order to evaluate the uncertainties for the PCA (Gratier et al. 2017; Spezzano et al. 2017), we derive the standard deviations for the principal component values of each molecular line in the following way. We generate Gaussian random noise for each pixel of the image field of each molecular or continuum distribution, and the noise distribution is convolved by the beam size of the observation (0.′′5 × 0.′′5). The standard deviation of the convolved noise image is adjusted to be one standard deviation of the observed noise. The artificial noise thus prepared for each molecular or continuum distribution is added to the observed distribution, and the PCA is then conducted. This procedure is repeated 1000 times, and the standard deviations of the PCA components are finally calculated.

In Figures 4(c), 6(c), 7(c) and (d), and 8(c) and (d), the gray dashed ellipses represent the uncertainties, whose major and minor axes are the standard deviation for each axis. On the whole-structure scale, all the standard deviation for PC1 is lower than 0.1. c-C3H2 (10_{0,10} – 9_{1,9} and 10_{1,10} – 9_{0,9}) shows the largest standard deviation for PC2 (0.17). The standard deviation for most molecular lines is less than 0.1 for PC2. Since the signal-to-noise ratio is high for the H2CO (K_a = 0) line, the standard deviation is smaller than 0.06 for PC1 and PC2. For PC3 and PC4, the standard deviation is from 0.06 to 0.2, which is slightly larger than those for PC1 and PC2 (Appendix A).
Figure 5. Blobs in the outflow indicated on the moment 0 map of H$_2$CO ($K_a = 1$). The positions of the blobs are listed in Table 6. The red circle shows the beam size of 0$''$.5 × 0$''$.5.

| Position | R.A. (J2000) | Decl. (J2000) |
|----------|--------------|---------------|
| A        | 15$^{h}$ 43$^{m}$ 02$^{s}$ 47 | −34$^\circ$ 09$'$ 04$''$ 94 |
| B        | 15$^{h}$ 43$^{m}$ 02$^{s}$ 25 | −34$^\circ$ 09$'$ 05$''$ 55 |
| C        | 15$^{h}$ 43$^{m}$ 02$^{s}$ 07 | −34$^\circ$ 09$'$ 09$''$ 23 |
| D        | 15$^{h}$ 43$^{m}$ 02$^{s}$ 08 | −34$^\circ$ 09$'$ 10$''$ 63 |
| Center   | 15$^{h}$ 43$^{m}$ 02$^{s}$ 24 | −34$^\circ$ 09$'$ 06$''$ 83 |

The standard deviation of the PCA components for the disk/envelope scale is comparable to that for the whole-structure scale. Even the molecular lines having a rather poor signal-to-noise ratio, such as c-C$_3$H$_2$ (10$_{0,10} - 9_{1,9}$ and 10$_{1,10} - 9_{0,9}$), CCH ($N = 4 - 3$, $J = 7/2 - 5/2$, $F = 3 - 3$), CH$_3$OH, and DCN, show a standard deviation smaller than 0.1 for PC1. c-C$_3$H$_2$ (10$_{0,10} - 9_{1,9}$ and 10$_{1,10} - 9_{0,9}$), CCH ($N = 4 - 3$, $J = 7/2 - 5/2$, $F = 3 - 3$), and DCN have a standard deviation smaller than 0.15 for PC2. While most lines have a standard deviation of 0.1–0.2 for PC3 and PC4, CCH ($N = 4 - 3$, $J = 9/2 - 7/2$, $F = 4 - 3$), ($N = 4 - 3$, $J = 7/2 - 5/2$, $F = 4 - 4$ and $F = 4 - 3$), H$_2$CO ($K_a = 0$, 1, and 2), and the dust continuum show a value smaller than 0.1. As a result, we find that our results of the PCA and the related discussions described above are not essentially changed by the effect of noise.

5. Comparison with the Other Protostellar Sources

As mentioned in Introduction, IRAS 15398–3359 is regarded as a WCCC source which is rich in carbon-chain molecules on the scale of a few thousand astronomical units. Molecular distributions observed in the disk/envelope region (~100 au scale) of this source are therefore compared with those of the other WCCC

| Position | Transition | $T_{peak}$ (K) | $V_{LSR}$ (km s$^{-1}$) | FWHM (km s$^{-1}$) |
|----------|------------|----------------|-------------------------|-------------------|
| A        | $K_a = 0$  | 6.5 (0.15)     | 7.1 (0.01)              | 0.9 (0.04)        |
|          | $K_a = 1$  | 10 (0.22)      | 7.1 (0.02)              | 1.1 (0.06)        |
|          | $K_a = 2$  | 2.0 (0.08)     | 7.1 (0.03)              | 0.9 (0.04)        |
|          | $K_a = 3_0$ | 1.3 (0.09)     | 7.1 (0.05)              | 0.9 (0.07)        |
|          | $K_a = 3_1$ | 1.5 (0.07)     | 7.0 (0.03)              | 0.9 (0.04)        |
| B        | $K_a = 0$  | 3.4 (0.21)     | 5.7 (0.08)              | 1.4 (0.06)        |
|          | $K_a = 1$  | 5.6 (0.44)     | 6.0 (0.30)              | 1.5 (0.06)        |
|          | $K_a = 2$  | 0.6 (0.08)     | 5.7 (0.21)              | 1.5 (0.14)        |
|          | $K_a = 3_0$ | 0.6 (0.08)     | 5.3 (0.07)              | 1.1 (0.14)        |
|          | $K_a = 3_1$ | 0.3 (0.05)     | 5.9 (0.13)              | 1.1 (0.22)        |
| C        | $K_a = 0$  | 1.7 (0.15)     | 3.5 (0.24)              | 1.9 (0.14)        |
|          | $K_a = 1$  | 4.5 (0.33)     | 3.5 (0.24)              | 2.1 (0.11)        |
|          | $K_a = 2$  | 0.6 (0.04)     | 3.2 (0.16)              | 1.6 (0.14)        |
|          | $K_a = 3_0$ | 0.3 (0.09)     | 3.1 (0.11)              | 0.9 (0.31)        |
|          | $K_a = 3_1$ | 0.4 (0.05)     | 3.4 (0.12)              | 1.4 (0.20)        |
| D        | $K_a = 0$  | 4.5 (0.22)     | 4.6 (0.04)              | 1.1 (0.04)        |
|          | $K_a = 1$  | 7.6 (0.39)     | 4.5 (0.04)              | 1.2 (0.05)        |
|          | $K_a = 2$  | 1.1 (0.05)     | 4.6 (0.04)              | 1.0 (0.05)        |
|          | $K_a = 3_0$ | 0.5 (0.05)     | 4.5 (0.10)              | 1.3 (0.16)        |
|          | $K_a = 3_1$ | 0.6 (0.06)     | 4.6 (0.06)              | 0.9 (0.10)        |
| Center   | $K_a = 0$  | 6.0 (0.13)     | 5.5 (0.01)              | 0.9 (0.02)        |
|          | $K_a = 1$  | 8.0 (0.46)     | 5.6 (0.04)              | 1.1 (0.07)        |
|          | $K_a = 2$  | 1.9 (0.08)     | 5.5 (0.03)              | 0.9 (0.04)        |
|          | $K_a = 3_0$ | 0.8 (0.06)     | 5.2 (0.09)              | 1.6 (0.16)        |
|          | $K_a = 3_1$ | 0.7 (0.06)     | 5.5 (0.08)              | 1.4 (0.14)        |

Note. Measured for a circular area in Figure 6 with a diameter of 155 au. “Center” denotes the protostar position. The line parameters are obtained by using Gaussian fitting. The numbers in parentheses represent the Gaussian-fitting errors. $K_a = 0$, $K_a = 1$, $K_a = 2$, $K_a = 3_0$, and $K_a = 3_1$ denote H$_2$CO ($S_{0,5} - 4_{0,4}$), ($S_{1,5} - 4_{1,4}$), ($S_{2,4} - 4_{2,3}$), ($S_{3,2} - 4_{3,1}$), and ($S_{3,3} - 4_{3,2}$), respectively. For $V_{LSR}$, the 2.5 km s$^{-1}$ difference is corrected (see Section 2).
and 4 (distribution levels, respectively. The contour level interval is 1.0 starting from 0.0. The red dashed circles show the groups of the compact distribution the PC1 barrier and partly inward of it. H₂CO resides over the disk protostar with ALMA. According to their result, CCH, CS, and (sources. In the prototypical WCCC source L1527, Sakai et al. (2014a, 2014b) reported the chemical structure around the protostar with ALMA. According to their result, CCH, CS, and c-C₃H₂ mainly trace the infalling rotating envelope gas outward of its centrifugal barrier, while SO mainly exists near the centrifugal barrier and partly inward of it. H₂CO resides over the disk/envelope region, and CH₃OH seems to exist around the centrifugal barrier and in the disk region. For TMC-1A, which is the WCCC source in the Class I stage, the distributions of CS, SO, and SO₂ were observed with ALMA by Sakai et al. (2016). In this source, CS also traces the infalling rotating envelope gas, while SO seems to trace the centrifugal barrier.

These characteristic features are indeed found in IRAS 15398–3359. In the PCA for the disk/envelope structure, PC2 shows that CCH and CS can be classified to one group (Group B in Figure 6) showing the existence in the infalling rotating envelope, while SO and CH₃OH can be classified to another group (Group A in Figure 6) revealing more compact distributions. On the other hand, the H₂CO lines take different PC2 component values depending on their upper-state energy. This feature of H₂CO is consistent with that found in L1527, where H₂CO resides over the disk/envelope region.

An exception is c-C₃H₂. While this species clearly traces the infalling rotating envelope in L1527, it shows a rather different distribution in IRAS 15398–3359. In order to compare the c-C₃H₂ abundances between L1527 and IRAS 15398–3359, we derive the column density ratios of c-C₃H₂ relative to H₂CO at the intensity-peak positions of the c-C₃H₂ (10₁₀–0₁₀ and 10₁₁₀–0₁₀) line (Figure 3(f)) by using the RADEX code (van der Tak et al. 2007). Here, the northwestern and southeastern peak positions are (15°43′02″20, −34°09′06″80) and (15°43′02″28,

Figure 6. (a), (b) The principal components PC1 and PC2 for the disk/envelope structure (Figure 3). (c) The plot of the principal components for each distribution on the PC1–PC2 plane. The cross marks show the continuum peak position. The contours are drawn with the solid and dotted lines, which mean the positive and negative levels, respectively. The contour level interval is 1.0 starting from 0.0. The red dashed circles show the groups of the compact distribution (Group A) and the extended distribution (Group B). The gray dashed ellipses represent the uncertainties (see Section 4.3). c-C₃H₂ (10 − 9), CCH (N = 3 − 2), (N = 4 − 3 a, (N = 4 − 3 b, (N = 4 − 3 c), H₂CO (Kₐ = 0, (Kₐ = 1, (Kₐ = 2, (Kₐ = 3), and (Kₐ = 3) denote c-C₃H₂ (100,10 − 91,9 and 101,10 − 90,9), CCH (N = 3 − 2, J = 7/2 − 5/2, F = 4 − 3 and 5 − 2), (N = 4 − 3, J = 7/2 − 5/2, F = 3 − 3), (N = 4 − 3, J = 7/2 − 5/2, F = 5 − 4 and 4 − 3), H₂CO (Sₕ, Sₗ − 4n, a), (Sₕ, Sₗ − 4n, a), (Sₕ, Sₗ − 4n, a), (Sₕ, Sₗ − 4n, a), and (Sₕ, Sₗ − 4n, a), respectively.

Table 8

| Blob | Column Density (10¹⁴ cm⁻²) | ₉_gas (K) | Ortho/Para |
|------|---------------------------|-----------|------------|
| Center | 0.87 ± 0.06 | 54 ± 2 | 1.7 ± 0.13 |
| A     | 0.83 ± 0.03 | 63 ± 2 | 2.0 ± 0.09 |
| B     | 0.67 ± 0.07 | 43 ± 3 | 2.3 ± 0.26 |
| C     | 0.48 ± 0.05 | 54 ± 4 | 3.3 ± 0.39 |
| D     | 0.78 ± 0.06 | 45 ± 2 | 2.3 ± 0.2 |

Note. The H₂ density is assumed to be 10⁶ cm⁻³. The derived values are not much different even if the H₂ density is 10⁵ cm⁻³ or 10⁷ cm⁻³. The errors are derived from the least-squares analysis on the intensities of five H₂CO lines. “Center” denotes the protostar position.
J (the PC1 densities of ortho C\textsubscript{3}H\textsubscript{2} and ortho H\textsubscript{2}CO for the northwestern sources, L\textsubscript{483} and B\textsubscript{335}, where the envelope and its innermost column density range is due to the assumed temperature range. The Astrophysical Journal, L\textsubscript{1527} temperature dependence is mitigated. The ratios for the north–south and the southeastern side are 0.14, respectively. Those for the southeastern side are (0.12–0.75) × 10\textsuperscript{14} cm\textsuperscript{-2} and (0.92–3.5) × 10\textsuperscript{14} cm\textsuperscript{-2}, respectively. A large column density range is due to the assumed temperature range. The c\textsubscript{3}H\textsubscript{2}/H\textsubscript{2}CO ratio is calculated from the column densities and the dust continuum emission and have conducted PCA for characterization of their distributions. The PCA has been performed on two different scales. The assumptions are as follows: the ortho–para ratio of H\textsubscript{2}CO is 3 (statistical value), the H\textsubscript{2} density 10\textsuperscript{6} cm\textsuperscript{-3}, and the gas kine matic temperature from 20–40 K. We employ only the H\textsubscript{2}CO (K\textsubscript{u} = 0) line to estimate the column density of H\textsubscript{2}CO, because the other lines (K\textsubscript{u} = 1, 2, and 3) are weak at the intensity peaks of the c\textsubscript{3}H\textsubscript{2}(10\textsubscript{0,10} – 9\textsubscript{1,9} and 10\textsubscript{1,10} – 9\textsubscript{0,9}) line. On the above assumptions, the column densities of ortho c\textsubscript{3}H\textsubscript{2} and ortho H\textsubscript{2}CO for the northwestern side are (0.14–0.85) × 10\textsuperscript{14} cm\textsuperscript{-2} and (0.72–2.5) × 10\textsuperscript{14} cm\textsuperscript{-2}, respectively. Those for the southeastern side are (0.12–0.75) × 10\textsuperscript{14} cm\textsuperscript{-2} and (0.92–3.5) × 10\textsuperscript{14} cm\textsuperscript{-2}, respectively. A large column density range is due to the assumed temperature range. The c\textsubscript{3}H\textsubscript{2}/H\textsubscript{2}CO ratio is calculated from the column densities derived at the same assumed temperature. In this case, the temperature dependence is mitigated. The ratios for the northwestern and southeastern sides are from 0.2–0.3 and 0.1–0.2, respectively. These values are comparable to that found toward L\textsubscript{1527} (0.17–0.36; Sakai et al. 2014a). Hence, the abundance of c\textsubscript{3}H\textsubscript{2} is not very different between this source and L\textsubscript{1527}. The peculiar distribution of c\textsubscript{3}H\textsubscript{2} might be due to the overwhelming contribution of the outflow in this source, which is not significant in L\textsubscript{1527}.

It is interesting to note that the above characteristic distributions of molecules can also be seen in the hybrid sources, L483 and B335, where the envelope and its innermost part show WCCC and hot corino chemistry, respectively (Imai et al. 2016; Oya et al. 2017). Hot corino chemistry is characterized by the rich existence of saturated complex organic molecules such as HCOOCH\textsubscript{3} and (CH\textsubscript{3})\textsubscript{2}O (Bottinelli et al. 2004; Sakai & Yamamoto 2013). In these sources, the CCH distribution is extended over the envelope with deficiency toward the protostar. CS traces the infalling rotating envelope and the inward component, while SO mainly traces the region within the centrifugal barrier. Although the central concentration of CS looks different from the case of the WCCC sources including IRAS 15398–3359, the overall feature is similar. At present, the origin of the different feature of CS between the WCCC sources and the hybrid sources is puzzling. This may originate from an insufficient resolution. In addition, the chemical behavior of sulfur-bearing species in the protostellar core has not yet been investigated well by the chemical model (e.g., Aikawa et al. 2008, 2012). This will be an important target for future astrochemical studies.

6. Summary

We have imaged IRAS 15398–3359 in 15 molecular lines and the dust continuum emission and have conducted PCA for characterization of their distributions. The PCA has been performed on two different scales.
On the whole structure scale, we apply the PCA to 16 data sets consisting of 15 molecular-line data and the Cycle 3 continuum data. PC2 can classify the samples having the characteristic molecular distributions revealed by the PCA to various sources are awaited.

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**Appendix A**

The Third and Fourth Principal Components

In the PCA, the first two principal components (PC1 and PC2) can almost reproduce the molecular distributions on both scales.
PC3 and PC4 have similar contribution ratios, which are significantly smaller than PC2. Nevertheless, PC3 and PC4 show some trends in the distributions. Here, we briefly discuss their features.

On the whole structure scale, PC3 and PC4 indicate the characteristic features for a few molecular lines. Figures 7(a) and (b) show the maps of PC3 and PC4, respectively. PC3 represents two blobs in the outflow as PC1, where the southwestern one is brighter than the northeastern one in PC3 in contrast to PC1. Hence, the SO line showing a southwestern blob takes the large positive contribution of c-C3H2 and the large negative contribution of DCN near the protostar position, which is shown in the PC1 plane (Figure 7(a)). PC3 also has a negative component near the protostar position, which results in the large positive contribution of c-C3H2 (91,8 – 81,7 and 92,8 – 81,7) and the negative contribution of DCN (Figure 7(c)).

The meaning of PC4 is not as clear as PC3. According to the correlations between PC4 and the molecular distributions (Figure A1), PC4 mainly contributes to representing the peculiar distributions traced by some molecular lines, as described in Appendix A. On the whole structure scale, PC4 is well correlated with most of the distributions, indicating that it represents the overall disk/envelope structure. PC2 has a negative correlation with the molecules having a distribution mainly in the envelope around the protostar. The positive correlation coefficient between PC2 and SO means a compact distribution. PC3 shows the large correlation with DCN and H2CO (K = 3, J = 3). PC4 is well correlated with CCH (N = 4 – 3, J = 7/2 – 5/2, F = 3 – 3, K<sub>2</sub> = 3). These values are defined as (Jolliffe 1986):

\[
\text{Cor}(x^*, y_i) = \sqrt{\lambda_i} z_{ji},
\]

where \(\lambda_i\) is the eigenvalue for the \(i\)th eigenvector \(z_i, y_i\) the distribution for the \(i\)th principal component, and \(z_{ji}\) the eigenvector component for the \(j\)th emission. On the whole-structure scale, the correlation coefficients of PC1 to most of the molecular distributions are higher than 0.5, which means that PC1 represents the overall structure. PC2 is positively correlated with the molecular distributions mainly showing the clumpy structures in the outflow as discussed in Section 4.1. PC3 and PC4 are correlated with the peculiar distributions traced by some molecular lines, as described in Appendix A. On the disk/envelope scale, PC1 is well correlated with most of the distributions, indicating that it represents the overall disk/envelope structure.

Appendix B
Correlation Coefficients of the Principal Components to the Molecular Distributions

We calculate the correlation coefficients between the principal components and the molecular distributions on the whole-structure and disk/envelope scales, as shown in Figures A1(a) and (b), respectively. These results help us to understand which molecular-line distributions the principal component contributes to. These values are defined as (Jolliffe 1986):

\[
\text{Cor}(x^*, y_i) = \sqrt{\lambda_i} z_{ji},
\]

where \(\lambda_i\) is the eigenvalue for the \(i\)th eigenvector \(z_i, y_i\) the distribution for the \(i\)th principal component, and \(z_{ji}\) the eigenvector component for the \(j\)th emission. On the whole-structure scale, the correlation coefficients of PC1 to most of the molecular distributions are higher than 0.5, which means that PC1 represents the overall structure. PC2 is positively correlated with the molecular distributions mainly showing the clumpy structures in the outflow as discussed in Section 4.1. PC3 and PC4 are correlated with the peculiar distributions traced by some molecular lines, as described in Appendix A. On the disk/envelope scale, PC1 is well correlated with most of the distributions, indicating that it represents the overall disk/envelope structure. PC2 has a negative correlation with the molecules having a distribution mainly in the envelope around the protostar. The positive correlation coefficient between PC2 and SO means a compact distribution. PC3 shows the large correlation with DCN and H2CO (K = 3, J = 3). PC4 is well correlated with CCH (N = 4 – 3, J = 7/2 – 5/2, F = 3 – 3), whose correlation coefficient is almost 1. This indicates that PC4 represents the peculiar distribution of this line.

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