Digging into the Interior of Hot Cores with ALMA (DIHCA). I. Dissecting the High-mass Star-forming Core G335.579-0.292 MM1

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Abstract

We observed the high-mass star-forming region G335.579–0.292 with the Atacama Large Millimeter/submillimeter Array (ALMA) at 226 GHz with an angular resolution of 0.03 (∼1000 au resolution at the source distance). G335.579–0.292 hosts one of the most massive cores in the Galaxy (G335–MM1). The continuum emission shows that G335–MM1 fragments into at least five sources, while molecular line emission is detected in two of the continuum sources (ALMA1 and ALMA3). We found evidence of large- and small-scale infall in ALMA1 revealed by an inverse P-Cygni profile and the presence of a blueshifted spot at the center of the first moment map of the CH$_3$CN emission. In addition, hot gas expansion in the innermost region is revealed by a redshifted spot in the first moment map of HDCO and (CH$_3$)$_2$CO (both with $E_B > 1100$ K). Our modeling reveals that this expansion motion originates close to the central source, likely due to reversal of the accretion flow induced by the expansion of the H II region, while infall and rotation motions originate in the outer regions. ALMA3 shows clear signs of rotation, with a rotation axis inclination with respect to the line of sight close to 90°, and a system mass (disk + star) in the range of 10–30 $M_☉$.

Unified Astronomy Thesaurus concepts: Star formation (1569); Star forming regions (1565); Massive stars (732)

1. Introduction

High-mass stars form in dense “hot cores” (sizes of a few 1000 au), within massive molecular clumps that have been recently found to be preponderantly under global collapse (Jackson et al. 2019). Observational evidence shows that many “hot cores” are located in the intersection of large parsec-scale filaments, the so-called hubs, which are fed through filaments (e.g., Lu et al. 2014, 2018; Chen et al. 2019; Treviño-Morales et al. 2019). Similarly, at smaller scales (<0.1 pc), streams of gas feeding individual cores have been observed (e.g., Izquierdo et al. 2018; Schwörer et al. 2019). At even smaller scales, spiral arm-like structures have been identified in disks within cores (e.g., Johnston et al. 2020), which may play a role in the formation of multiple systems (e.g., Kratter et al. 2010; Ahmadi et al. 2019). Hence, a characterization of the kinematics of the gas at core and smaller scales is key to understanding how high-mass stars in single or multiple systems form, in addition to providing better constraints for numerical simulations. In particular, cores inside infrared dark clouds (IRDCs; Rathborne et al. 2006; Chambers et al. 2009; Sanhueza et al. 2012, 2019; Li et al. 2019, 2020) are more likely to be young enough that ionization plays a minor role, thus limiting the number of physical processes to account for in a detailed study.

The IRDC G335.579–0.292 is a massive cloud with a mass of 5.5 × 10$^4$ $M_☉$ at a distance of 3.25 kpc (Peretto et al. 2013), Peretto et al. (2013) identified two cores using 3 mm Atacama Large Millimeter/submillimeter Array (ALMA) observations, which are massive enough to form high-mass stars. The most massive core, G335–MM1, is one of the most massive cores in the Galaxy with a mass of 545 $M_☉$ (comparable to only few other cores; e.g., Stephens et al. 2015). G335–MM1 is being fed by large-scale infalling gas at a rate of $10^3$ $M_☉$ yr$^{-1}$ (Peretto et al. 2013). Avison et al. (2015) estimated a bolometric luminosity of (1.6–1.8) × 10$^7$ $L_☉$ for G335–MM1. Their radio centimeter wavelength observations revealed that G335–MM1 further fragments into at least two sources (MM1a and MM1b) with spectral indices consistent with hyper-compact (HC) H II regions, and with free–free emission equivalent to those of zero age main-sequence B-type stars (9–10 $M_☉$). Class II methanol masers, which are exclusively associated with high-mass star formation, and water masers have also been observed toward both regions within G335–MM1 (Breen et al. 2010; Caswell et al. 2011; Avison et al. 2015). Regardless of these efforts, there are no studies so far of the gas kinematics at the scale sizes directly related to the star formation process (∼1000 au).

In order to further characterize the formation of high-mass stars within this region, we have observed G335–MM1 with ALMA at 226 GHz to study the fragmentation process in this source and the kinematics of the gas at much smaller scales than previously reported. The observations of G335–MM1 are part of a larger survey called Digging into the Interior of Hot Cores with ALMA (DIHCA), in which we have observed 30 high-mass star-forming regions. Details on the whole sample of DIHCA will be presented in a forthcoming paper (K. Ishihara et al. 2021, in preparation).
Section 2 we present our ALMA observations of this source. The results are presented in Section 3. Finally, our discussion and conclusions are presented in Sections 4 and 5.

2. Observations

We observed G335–MM1 in band 6 (226.2 GHz, 1.33 mm) with ALMA during 2016 November, cycle 4 (Project ID: 2016.1.01036.S; PI: Sanhueza). Observations were performed with the 12 m array using 41 antennas in a configuration similar to C40-5, with minimum and maximum baselines of 18.6 and 1100 m, respectively. With this configuration, the observations achieved a resolution of $\sim 0''.3$ ($\sim 1000$ au) and a maximum recoverable scale of $3''.2$ ($\sim 10,000$ au). The spectral setup was divided into four spectral windows with a spectral resolution of 976.6 kHz ($\sim 1.3$ km s$^{-1}$) and a bandwidth of 1.875 GHz. These windows covered the frequency ranges between 233.5–235.5 GHz, 231.0–233.0 GHz, 216.9–218.7 GHz, and 219.0–221.0 GHz.

The data were calibrated using the CASA 4.7 reduction pipeline (version r38377; McMullin et al. 2007). According to the ALMA Proposer’s User Guide, the estimated error in the absolute flux is 10%. The data were then self-calibrated, and a continuum map from line-free channels and continuum-subtracted data cubes were produced. The channel identification procedure is detailed in the Appendix. The script and continuum subtraction pipeline are available on GitHub9 under an MIT License. Version 2.0 of the script is archived in Zenodo (Olguin & Sanhueza 2020). We used the tclean task with Briggs weighting and a robust parameter of 0.5 to image the data, resulting in a continuum sensitivity of 0.4 mJy beam$^{-1}$ (versus expected thermal noise level of 0.15 mJy beam$^{-1}$). The cleaned continuum map is shown in Figure 1. The synthesized beam of the continuum map is $0''.36 \times 0''.30$ with position angle (P.A.) of $-58^\circ$.

We used the automatic masking procedure YCLEAN (Contreras et al. 2018; Contreras 2018) to CLEAN the data cubes for each spectral window. YCLEAN iterates between CLEANing steps with increasingly deeper thresholds, and mask generating steps. The emission that is added to the masks is subtracted data cubes were produced. The channel identification procedure is detailed in the Appendix. The script and continuum subtraction pipeline are available on GitHub9 under an MIT License. Version 2.0 of the script is archived in Zenodo (Olguin & Sanhueza 2020). We used the tclean task with Briggs weighting and a robust parameter of 0.5 to image the data, resulting in a continuum sensitivity of 0.4 mJy beam$^{-1}$ (versus expected thermal noise level of 0.15 mJy beam$^{-1}$). The cleaned continuum map is shown in Figure 1. The synthesized beam of the continuum map is $0''.36 \times 0''.30$ with position angle (P.A.) of $-58^\circ$.

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In this section, we describe the G335–MM1 high-mass star-forming region in 1.3 mm dust continuum emission and selected molecular lines. Those will be good tracers to investigate the morphology and kinematic structures of high-mass star-forming cores.

3. Results

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3.1. Morphology and Line Identification

The single G335–MM1 region identified at 3 mm observations ($\sim 5''$ resolution) by Peretto et al. (2013) fragments into at least five continuum sources (Figure 1). These sources were identified by visual inspection. The positions and 1.3 mm fluxes of these sources were derived from a 2D Gaussian fit to the continuum emission and are listed in Table 1. The fit indicates that the sources are elongated with ratios between their axes in the 1.2–2.0 range. The brightest of the five 1.3 mm sources identified by us (ALMA1) matches with the position of one of the two radio continuum sources identified by Avison et al. 2015, MM1a. The second radio source, MM1b, is located in between two of the 1.3 mm sources (ALMA3 and ALMA4).

We have identified two sources potentially associated with MM1b (ALMA3 and ALMA4). Avison et al. (2015) argue that the spectral indices from radio emission for MM1b are consistent with a collimated jet or a compact H II region. They suggested that this emission is not associated with MM1a, but rather with another source due to the presence of CH$_3$OH maser emission closer to MM1b. They discarded the jet hypothesis due to the misalignment of MM1b with the HNC emission tracing the molecular outflow associated with MM1a. Given the offset position of MM1b to the ALMA sources, we argue that the radio emission is possibly tracing the lobe of an ionized jet likely associated with the high-mass source ALMA3. However, higher-resolution observations at wavelengths $\lambda \geq 3$ mm are needed to resolve the radio emission and determine its orientation with respect to the ALMA sources.

Line emission is detected mainly toward ALMA1 and ALMA3. Multiple lines are detected toward ALMA1, which is characteristic of young high-mass sources, like hot cores and ultra-compact H II regions (e.g., Hatchell et al. 1998). A lower number of species is detected toward ALMA3. The lines detected in ALMA3 are weaker than those of ALMA1. We focus our analysis in a handful of lines to explore the kinematics of these two cores. These lines and their properties are summarized in Table 2. The molecular lines detected in other sources correspond to transitions tracing more extended material (e.g., $^{13}$CO, C$^{18}$O), and thus cannot be assigned to one source in particular. The lack of line emission toward the other
3.2. Physical Properties

From the 2D Gaussian fit to the dust continuum image, we estimate the size of the sources. The radius is defined as the geometric mean of the deconvolved semimajor and minor axes (see Table 1). The results are listed in Table 3. All sources are compact (~400–800 au) with radii typical of inner envelope/disk scales (<5000 au).

To estimate the dust temperature, we attempt to fit the CH$_3$CN $J = 12–11 K = 7–8$ transitions toward the continuum peak of the sources with a local thermal equilibrium (LTE) 1D model. However, the line emission toward ALMA1 becomes quickly saturated; hence, we only fit the temperature toward ALMA3. The fit was performed with the Markov Chain Monte Carlo method within XCLASS (Möller et al. 2017). We obtain a gas temperature at the continuum peak of ALMA3 of 290 K. For ALMA1, we estimate a dust mass using a temperature of 100 and 300 K. The former correspond to roughly the brightness temperature at which the lower-$K$ transition lines saturate. As the emission is becoming optically thick, the brightness temperature should converge to the kinetic temperature. However, the beam filling factor is likely less than 1 (e.g., Su et al. 2009); hence, this provides a temperature lower limit and in turn a dust mass upper limit. The latter temperature is based on the result for ALMA3.

Assuming that the dust and gas temperatures are in equilibrium, we estimate the gas mass as

$$M_d = \frac{F_c d^2 R_{gd}}{\kappa_d B_v(T_d)}$$

(1)

with $F_{1.3 \text{ mm}}$ the flux density from Table 1, $d = 3.25$ kpc the source distance, the gas-to-dust mass ratio $R_{gd} = 100$, the dust opacity $\kappa_{1.3 \text{ mm}} = 1 \text{ cm}^2 \text{ gr}^{-1}$ (Ossenkopf & Henning 1994), and $B_v$ the Planck blackbody function. The H$_2$ column density is estimated from the dust emission as

$$N_{\text{H}_2} = \frac{L_{1.3 \text{ mm}} R_{gd}}{B_v(T_d) \mu_{\text{H}_2} m_{\text{H}}}$$

(2)

with $L_{1.3 \text{ mm}}$ the peak intensity from Table 1, $\mu_{\text{H}_2} = 2.8$ the molecular weight per hydrogen molecule (e.g., Kauffmann et al. 2008), and $m_{\text{H}}$ the atomic hydrogen mass. The results are listed in Table 3. We estimate that the contribution from free–free emission to the 1.3 mm flux densities is less than 5 mJy for ALMA1 and less than 1 mJy for ALMA3 from the fit to the radio centimeter observations in Avison et al. (2015), and is thus negligible.

The 1.3 mm flux density of G335-MM1 is 1.4 Jy from aperture photometry and 0.9 Jy by summing the values in Table 1. The expected flux at 1.3 mm from the spectral energy distribution in Avison et al. (2015), obtained by interpolating the data points at 870 $\mu$m and 3.2 mm, is ~2.1 Jy. On the other hand, the sum of the masses is ~10% of the total mass estimated by Peretto et al. (2013) from 3.2 mm observations. The discrepancy in mass can be explained primarily by the temperature estimates, followed by extended emission not included in the 2D Gaussian fit measurements, and finally emission filtered out by the interferometer.
Corrected by the systemic velocity lines, marking the rest frequency of the dense region marked with a blue triangle in panel emission toward continuum peak, which is marked with a green cross in panel. Contour level corresponds to 20\(^{\text{cont}}\) in the ALMA1 continuum map. The light blue dashed line shows the arc-shaped structure.

Figure 2. G335 ALMA1 continuum map and CH\(_3\)CN \(J = 12–11\) \(K = 0\) to 8 line emission examples. (a) Locations of the example spectra marked over the continuum map. The light blue dashed line shows the arc-shaped structure. Contour level corresponds to 20 \(\times \sigma_{\text{cont}}\) with \(\sigma_{\text{cont}} = 0.4\) mJy beam\(^{-1}\). (b) Line emission toward continuum peak, which is marked with a green cross in panel (a). (c) Line emission toward the southwest of the dust peak position, in a less-dense region marked with a blue triangle in panel (a). The dashed gray vertical lines mark the rest frequency of the \(K\) transitions (0–8 from left to right) corrected by the systemic velocity (\(v_{\text{LSR}} = -46.9\) km s\(^{-1}\)).

The mass of the gas reservoir of ALMA3 is 1 \(M_\odot\) (Table 3). However, this value is likely a lower limit, because cooler regions of the envelope also contribute to the dust emission. Emission from the region may have also been filtered out by the interferometer.

### 3.3. Kinematics

Line emission from CH\(_3\)CN transitions, a commonly used tracer of gas rotation, is detected only toward two sources (ALMA1 and ALMA3). In ALMA1, transitions \(K = 0\) to 5 are saturated and blended with other molecular lines (e.g., Figure 2). We therefore calculated the moments 0, 1, and 2 for transition \(K = 7\), which are presented in Figure 3 (line width is displayed instead of velocity dispersion). For ALMA3, the transition \(K = 4\) is used in the moments shown in Figure 4 as there is less contamination from other molecular lines. The first and second moments were calculated only with data over 5\(\sigma_{\text{rms}}\) with \(\sigma_{\text{rms}} = 5\) mJy beam\(^{-1}\). Line emission from CH\(_3\)CN is only detected in ALMA1 and ALMA3 as shown by the contours in Figures 3(a) and 4(a). The deconvolved size of the emission in the contours of Figure 3(a) is 0.76 (\(\sim 2000\) au); thus, it is likely tracing the inner region of the circumstellar envelope and/or disk.

Outflow emission is detected in the \(^{13}\text{CO}\) \(J = 2–1\) and SiO \(J = 4–3\) transition lines. We separated the red- and blueshifted line components to study the directions of the flows (Figure 5). The blue and red windows are separated ±3.25 km s\(^{-1}\) from the \(v_{\text{LSR}}\) and have widths of \(\sim 22.75\) and 13 km s\(^{-1}\) for \(^{13}\text{CO}\) and SiO, respectively. A clear molecular flow is detected toward ALMA1 in the NE–SW direction, consistent with outflow A of Avison et al. (2021). From the blueshifted emission, we estimate a P.A. \(\sim 210^\circ\). Additionally, the arc-shaped structure observed in the dust emission toward the west of ALMA1 (Figure 2(a)) is likely associated with emission from the base of the outflow cavity as seen in \(^{13}\text{CO}\). This may be the result of a wide angle wind interacting with the envelope (e.g., Kuiper et al. 2015), as observed in the diffuse dust emission and outflow emission of G16.64+0.16 (Maud et al. 2018). Toward ALMA3, \(^{13}\text{CO}\) seems to be tracing the envelope of the source with the blue- and redshifted orientation consistent with the rotation pattern observed in CH\(_3\)CN. The redshifted SiO emission toward the NW shows structures that may be associated with ALMA3 (SE–NW direction, P.A. \(\sim -45^\circ\)) and ALMA4 (SW–NE direction, P.A. \(\sim 45^\circ\)). Avison et al. (2021) detected CO outflow emission likely associated with the radio source MM1b roughly in the EW direction. However, the CO outflow lobe is blueshifted rather than redshifted as seen in the SE–NW SiO emission, and the origin of the SiO emission does not coincide with ALMA3. Hence, we cannot rule out that the SiO emission is related to an unresolved source.

We have identified two lines with upper energy levels higher than 1000 K: HDCO (285.23 – 293.26) with \(E_{\text{up}}\) equal to 1460 K and (CH\(_3\))\(_2\)CO (547.28 – 547.29) AE with \(E_{\text{up}}\) equal to 1140 K. Their moment maps are displayed in Figure 6. The emission of

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Table 3

| ALMA Source | \(R\) (au) | \(T\) (K) | \(M_J\) (\(M_\odot\)) | \(N_{\text{H}_2}\) (10\(^{24}\) cm\(^{-2}\)) | \(N_{\text{CH}_3\text{CN}}\) (cm\(^{-2}\)) |
|-------------|----------|--------|-----------------|-----------------|-----------------|
| \(^{1}\)    | 710      | 100    | 19              | 10.4            | —               |
| \(^{2}\)    | 570      | 300    | 6.2             | 3.3             | —               |
| \(^{3}\)    | 730      | 290    | 1.0             | 0.6             | 10\(^{13}\)     |
| \(^{4}\)    | 470      | > 20   | > 10            | 8.7             | —               |
| \(^{5}\)    | 960      | > 20   | > 10            | 3.9             | —               |

Notes. The radius, \(R\), corresponds to half of the geometric mean of the deconvolved sizes (FWHM) from Table 1.

\(^{1}\) CH\(_3\)CN emission is not detected toward these sources; hence, the temperature is a lower limit, and the gas masses and column densities are upper limits.

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these two lines is compact, but resolved toward ALMA1. Both lines are likely tracing the innermost regions of the hot core given the high temperatures required to be excited. The first moment maps of these lines show a consistent velocity gradient with that of CH$_3$CN, but remarkably, the lines are redshifted rather than blueshifted toward the center of the source.

4. Discussion

Here, we discuss the results focused primarily on the kinematics of ALMA1 and ALMA3.

4.1. ALMA1

4.1.1. Large-scale Infall

The velocity field in ALMA1 presents an overall gradient from east to west (Figure 3(a)). However, this gradient is likely masked as a result of a combination of gas motions. Possible reasons that make velocity gradients difficult to identify are (e.g., Silva et al. 2017): (i) CH$_3$CN is possibly tracing outflowing motions, for instance, from gas removed from a disk surface by stellar winds, together with rotation and infall (e.g., Beuther et al. 2017) making the interpretation of the velocity gradients less straightforward; (ii) the observed velocity field is potentially produced by the combination of gas motions due to the presence of unresolved sources; (iii) the orientation of the protostellar disk is close to face-on; and/or (iv) infall or expansion motions.

The first moment map of the $K = 7$ transition presented in Figure 3(a) shows a spot of velocities close to zero at the center of the core enclosed mainly by the $80 \times \sigma_{\text{rms}}$ level of the zeroth moment contour. These velocities are bluer than expected for a smooth transition of velocity from east to west, assuming CH$_3$CN is tracing the rotation of the core envelope/disk. Henceforth we refer to this region as the blueshifted spot. As shown in Figure 2, the CH$_3$CN lines up to $K = 4$ show an absorption feature at the center of the line, resembling the blue-asymmetry characteristic of infall motions (e.g., Zhang et al. 1998) and resulting in the blueshifted spot (e.g., Estalella et al. 2019). This blue-asymmetric
of $-46.9 \, \text{km s}^{-1}$ by $1.7 \, \text{km s}^{-1}$. On the other hand, the $\text{H}_2\text{CO}$ line in Figure 7(b) shows a dip consistent with the source $v_{\text{LSR}}$. In order to be excited, $^{13}\text{CO}$ requires lower densities and temperatures than $\text{H}_2\text{CO}$. We therefore suggest that the absorption against the continuum that is redshifted with respect to the $v_{\text{LSR}}$ in the $^{13}\text{CO}$ line is tracing a large-scale infall, consistent with the findings at the much lower resolution of 5$''$ ($\sim15000 \, \text{au}$) by Peretto et al. (2013). This is also supported by the position–velocity (pv) map of $^{13}\text{CO}$ in Figure 8, where the morphology of the emission resembles the “C” shape characteristic of infall motions (Zhang & Ho 1997). $\text{H}_2\text{CO}$ emission may be produced closer to the core center (or in the outflows) making harder the detection of infall signs (although the absorption dip is slightly redshifted with respect to the $v_{\text{LSR}}$).

4.1.2. Small-scale Expansion

The spot at the core center in the first moment map (Figure 6) of the hot lines HDCO and (CH$_2$)$_2$CO is redshifted with respect to the $v_{\text{LSR}}$ (and not blueshifted as in CH$_3$CN). Moment maps have so far been made by using windows of $\pm5.2$ and $\pm6.5 \, \text{km s}^{-1}$ symmetric from the $v_{\text{LSR}}$. The HDCO line profile toward the continuum source position presented in Figure 9 is single peaked with a red wing at higher velocities (shadowed region). In order to discard the red wing as the cause of the redshifted spot, we have derived the velocity structure in ALMA1 by first finding the peak at each pixel (defining a “local” pixel $v_{\text{LSR}}$) and then assuming different windows to make the first moment. The velocity maps are shown in Figure 10. This approach would be more robust to strong velocity gradients, and we have no need to adopt large windows for making moment maps that can introduce noise or contamination from neighboring spectral lines. Figure 10 shows that HDCO is redshifted toward the center of the continuum source and is increasingly blueshifted farther out, while toward the arc-shaped structure, the emission is blueshifted as observed in CH$_3$CN. The area of the redshifted region increases when more channels are included and shifts toward the south (see Figures 10(c) and (d)), indicating that the lines to the south are skewed toward the red due to high-velocity line wings. Overall, the velocity gradient is consistent with what is seen in CH$_3$CN, and as the window for making the moment map increases, the redshifted spot becomes more evident. Applying a similar reasoning to the origin of the blue-asymmetric/skewed lines (e.g., Zhou et al. 1993, see also the expansion line profiles in Keto et al. 2006), this pattern likely indicates gas expansion at the core center. Anglada et al. (1987) noted that an inverted profile to that of blue-asymmetric profiles is expected for expansion motions if the temperature increases toward the central region and the velocities decrease outwards. The first condition is likely satisfied since a high-mass young stellar object may have already been formed and started to ionize the circumstellar gas. They also assumed in their analysis that the Sobolev approximation is valid, but the expansion velocity of HDCO (see Section 4.3) is comparable to the line width. Hence the second condition may not necessarily be satisfied.

Using centimeter observations, Avison et al. (2015) determined that an HC H II region, unresolved at their 1$''$5 resolution observations, is located a the position of ALMA1. The HC H II region is an important evolutionary stage in the life of high-mass stars. HC H II regions tend to be smaller than...
0.03 pc (600 au), and the likely culprit of the ionized flow is the photoevaporation of an accretion disk surface (Kurtz 2005). While in this stage, it has been suggested that the star can continue growing into earlier types by nonspherical accretion flows (Keto 2007). Eventually it is believed that HC H II regions will expand into ultra-compact (UC) H II regions and then into classical H II regions. We suggest that in ALMA1, we are witnessing the early expansion of the ionized gas that is pushing outward the hot molecular gas. The effect of the expansion is more clear in the transitions tracing the hot, inner molecular core (e.g., HDCO).

Figure 11. The spatial distribution of the emission from the hot transition lines (Figure 6(a)) is closer to perpendicular to the outflow (P.A. = 210°), with P.A.s between 125° and 130° as measured from a 2D Gaussian fitted to the zeroth-order moments. Hence, it is likely coming from molecular gas in a putative disk surface.

4.2. ALMA3

The $K = 4$ transition first moment map in Figure 4(a) shows clear signs of rotation toward source ALMA3. We estimate an average P.A. of the rotation axis from the velocity gradient within a region of radius 0°16 (i.e., one beam) centered on the source of $P. A. _{\text{rot}} = 292° \pm 8°$ from the first moment map of the $K = 4$ transition. A similar value is obtained from the $K = 7$ transition but with a slightly higher error due to its smaller angular extent ($P. A. _{\text{rot}} = 290° \pm 9°$). We estimate the kinetic mass of source ALMA3 from the velocity extremes from the rotation axis. Assuming that the source is edge-on, the source mass is in the 10–30 $M_\odot$ range (hereafter kinetic mass). Lower inclination angles, i.e., toward a face-on configuration, would imply an even larger mass. This is one order of magnitude larger than the 1 $M_\odot$ derived from the dust emission (Table 3). Note that the kinetic mass includes the contribution of the central (proto)star, which may not contribute to the dust emission, and the circumstellar gas. On the other hand, the dust temperature estimation assumes an isothermal column of gas in LTE with the dust passing through the central (hotter) region. Given that the temperature can have a decreasing temperature profile with radius, the contribution of colder dust in the outer layers may be underestimated by these assumptions. The temperature can reach values of roughly 30 K at clump scales (>0.1 pc; e.g., Faúndez et al. 2004); hence, a lower average temperature than our estimation could explain discrepancies of less than one order of magnitude (assuming dust emission in the Rayleigh–Jeans regime: $M_d \propto T_d^{−1}$). Different dust opacity laws would explain discrepancies of a factor $\sim 2$. The lower number of lines detected and lack of radio emission suggest that this source is younger than ALMA1 and still deeply embedded.

4.3. Simple Modeling

In this section, we provide additional support for the interpretation of the moment maps by comparing qualitatively the data with simple LTE radiative transfer models. In these models, the molecular line emission arises from a spherically symmetric core with a radius of $a = 2000$ au, comparable to the extent of source ALMA1 shown in Figures 3, 6, and 10. We assume that this core is characterized by a density $\rho(r) \propto r^{−3/2}$, and a thermal gradient with temperature $T(r) \propto r^{−0.5}$, characteristic of radiative equilibrium under optically thin dust
We calculated models with solid body rotation at each radius combined with infall or expansion motions. The azimuthal velocity field of the core varies as $V_f \propto r^{-1/2}$. The radial velocities are proportional to $\pm r^{-1/2}$, with positive velocities for expansion motions and vice versa. This model is a simplified version of a pressure-less free-falling core solution dominated by the gravity of a central object (Ulrich 1976; Mendoza et al. 2004, 2009). Note that the models do not combine infall and expansion motions; thus, they can only explain the features of one line at a time. To fit the observations, we optimize numerically the central LSR and the line width. The remaining parameters are fine-tuned by visual inspection. The blue asymmetry, characteristic of infalling motions, requires a combination of partially optically thick emission and internal heating.

Figure 12(a) and (b) shows the first moment map of the CH$_3$CN $J = 12-11 K = 7$ line toward ALMA1 and the one derived from the model, respectively. We assume that the rotation axis of the core is inclined with respect to the line of sight by $i = 45^\circ$, and it forms a P.A. of $5^\circ$, as indicated by the approximate direction of the velocity gradient. Note that the angular velocity of the core and the inclination angle are degenerate parameters. We are able to reproduce the main features observed in ALMA1 with an infall velocity at the external radius $a$ of $V_{\text{in}}(a) = -1.15 \text{ km s}^{-1}$, an angular velocity $\Omega(a) \sin(i) = 3.34 \times 10^{-11} \text{ s}^{-1}$, a temperature $T(a) = 33 \text{ K}$, and a line absorption coefficient given by $\kappa_v(a) = 3.21 \times 10^{-17} \phi_v \text{ cm}^{-1}$. The line profile $\phi_v$ is assumed to be Gaussian with an FWHM of $\Delta v = 2 \text{ km s}^{-1}$. We note that, in agreement with infall, the rotation of the core is not enough to maintain the core in equilibrium at the assumed inclination. The gas mass within a radius $R$ from the model is given by

$$M(<R) = \frac{8\pi}{3} \rho(a)(Ra)^{3/2}. \quad (3)$$

From the line absorption coefficient and assuming a CH$_3$CN abundance of $10^{-8}$ (e.g., Hernández-Hernández et al. 2014), we obtain $\rho(a) = 2.9 \times 10^{-16} \text{ g cm}^{-3}$. The gas mass of the model at $R = 710 \text{ au}$ (same size derived from the dust continuum, see Table 3) is $M(<710 \text{ au}) = 6.8 \ M_\odot$. We note
However, the abundance of CH$_3$CN is very uncertain and can vary by one order of magnitude (Hernández-Hernández et al. 2014), precluding a direct comparison with the mass derived from dust continuum emission.

However, the abundance of CH$_3$CN is very uncertain and can vary by one order of magnitude (Hernández-Hernández et al. 2014), precluding a direct comparison with the mass derived from dust continuum emission.

Figures 12(c) and (d) show the maps of the HDCO velocity at peak line intensity obtained from the observations and a rotating and expanding core model. The expansion velocity is $V_{\text{exp}}(a) = +0.5$ km s$^{-1}$. Two features describe the shape of the HDCO line profile: (1) a relatively slow expansion that redshifts the line peak in $\lesssim 1$ km s$^{-1}$ in the directions of highest opacity, that is, toward the center of the core (see Figure 10(a)); (2) a distinct redshifted wing, typical of outflows (see Figure 9). A combination of these two effects produce the redshifted velocities shown in the first moment map (Figure 10(d)). We find that a model with an absorption coefficient four times less than that of CH$_3$CN and a line width $\Delta v = 2.5$ km s$^{-1}$ is able to reproduce fairly well these features of the HDCO line, particularly the redshifting of the peak toward the center of the core. This rotation-expansion model also has a different P.A. = 20° compared to the CH$_3$CN model, which is suggested by the velocity gradient shown in Figure 10. Models with the same P.A. produce fits that are not significantly worse.

As discussed in Section 4.1, the expansion of the gas is likely caused by the expansion of the HC HII (see Figure 11). This may have already grown beyond the gravitational radius of the young star (Sartorio et al. 2019), which is 54 au for a 10$M_\odot$ HMYSO, in the innermost regions of the hot core. Note that the lower opacity associated with the HDCO model implies that the lines of sight associated with $\tau = 1$ cross the core much
closer to its center compared to those of CH$_3$CN. Indeed, while for CH$_3$CN, the lines of sight with impact parameter of 130 au are optically thick, for HDCO, optically thick lines of sight are those that pass within 30 au of the center. This difference in opacities explains why we are not able to see the expansion signature in the CH$_3$CN profiles and why we cannot discern the infall signature in the HDCO line. In the former case, the expansion is hidden within a very small radius associated with a large opacity. On the other hand, HDCO emission from gas in expansion is associated with optically thin emission, and therefore the blue asymmetry does not arise.

5. Conclusions

We observed the high-mass star-forming region G335.579–0.292, in particular the core G335–MM1, at 0″3 resolution with ALMA and resolved five sources within this region. Of these sources, ALMA1 is associated with radio continuum emission previously observed at $\sim$1″–2″ resolution, while the other radio continuum source toward this region possibly arises from a jet associated with ALMA3. From the study of the kinematics in these two sources, we conclude that they are likely to form or have already formed at least one high-mass star. Line emission was not detected in the remaining three continuum sources, and were thus not studied in detail.

ALMA1 has a complex kinematic structure. We observe large-scale infalling motions from $^{13}$CO inverse P-Cygni profiles, while CH$_3$CN blue-asymmetric profiles indicate infall motions at smaller scales. The overall CH$_3$CN velocity gradient may be indicative of rotation of the circumstellar material. This velocity gradient is roughly perpendicular to the outflow direction observed from $^{13}$CO and SiO emission. Finally, lines tracing hot molecular gas, HDCO and (CH$_3$)$_2$CO, show an expansion velocity pattern in their moment 1 map, which may
be the result of photoevaporation of the surface of a molecular disk due to the ionizing radiation of the HC H II region. To support these hypotheses, we model the rotating infall and expansion motions with a spherically symmetric envelope. We conclude that the expansion motion observed in hot lines is indicative of the reversing of the accretion flow in a region smaller than the one traced by the rotating infall seen in CH3CN. Higher angular resolution observations will reveal the scales at which expansion dominates and whether or not the complex kinematics toward this source can also be the result of unresolved sources.

In ALMA3, CH3CN line emission shows clear evidence of rotation, which implies a total mass for the source of 10–30M☉ assuming Keplerian rotation.

The nature of the remaining sources (ALMA2, ALMA3, and ALMA5) remains unclear due to their lack of line emission. They likely are prestellar cores that may or may not form high-mass stars.

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Facility: ALMA.

Software: astropy (Astropy Collaboration et al. 2013; Price-Whelan et al. 2018), CASA (McMullin et al. 2007), GoContinuum (Olguín & Sanhueza 2020), matplotlib (Hunter 2007), numpy (Harris et al. 2020), scipy (Virtanen et al. 2020), YCLEAN (Contreras et al. 2018; Contreras 2018).

Appendix

Continuum Subtraction

To obtain the line-free channels, we:

1. Compute a dirty data cube for each spectral window in the observations.
2. Compute a map with the maximum value along the spectral axis (hereafter maximum map) for each spectral window.
3. Obtain the peak position of the maximum map for each spectral window.
4. Average the values of the peak positions. We rejected the position that is farther from the centroid to avoid outliers.
5. Obtain the spectrum at the averaged peak position from each spectral window data cube.
6. Use asymmetric sigma clipping to obtain channels free of line contamination.
7. Recover bands of channels rejected by the asymmetric sigma clipping that span less than two channels (one spectral resolution).

In addition, 10 channels at each end of the spectral windows were not used for continuum calculations, as those channels tend to be noisier.

A corrected symmetric sigma clipping has been implemented by Sánchez-Monge et al. (2018) to subtract the continuum from data cubes. Their correction of the symmetric sigma clipping is based on the image noise, which cannot be calculated without having to CLEAN the data cube first. Based on their approach, we found that an asymmetric sigma clipping can obtain similar results without applying their correction to the symmetric one. Considering that our spectra are dominated by line emission, we found that an acceptance range of −3.0 to 1.3σ i with σ i the standard deviation at iteration i of the clipping algorithm, is enough to obtain similar results to those in Sánchez-Monge et al. (2018); their default range is ±1.8σ i. What our method provides at the end is the list of channels, in CASA format, to be used for making both the continuum-subtracted line cubes and the continuum image free of line contamination.

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