ALMA IMAGING OF MILLIMETER/SUBMILLIMETER CONTINUUM EMISSION IN ORION KL

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ABSTRACT

We have carried out high-resolution observations with the Atacama Large Millimeter/Submillimeter Array (ALMA) of continuum emission from the Orion Kleinmann–Low (KL) region. We identify 11 compact sources at ALMA band 6 (245 GHz) and band 7 (339 GHz), including the Hot Core, Compact Ridge, SMA1, IRc4, IRc7, and a radio source I (Source I). A spectral energy distribution (SED) of each source is determined by using previous 3 mm continuum emission data. Physical properties such as size, mass, hydrogen number density, and column density are discussed based on the dust graybody SED. Among 11 identified sources, Source I, a massive protostar candidate, is a dominant energy source in Orion KL. We extensively investigate its SED from centimeter to submillimeter wavelengths. The SED of Source I can be fitted with a single power-law index of 1.97, suggesting an optically thick emission. We employ the H$^+$ free–free emission as an opacity source of this optically thick emission. The temperature, density, and mass of the circumstellar disk associated with Source I are constrained by the SED of H$^+$ free–free emission. Still, the fitting result shows a significant deviation from the observed flux densities. Combined with the thermal dust graybody SED to explain excess emission at higher frequency, a smaller power-law index of 1.60 for the H$^+$ free–free emission is obtained in the SED fitting. The power-law index smaller than two would suggest a compact source size or a clumpy structure unresolved with the present study. Future higher resolution observations with ALMA are essential to reveal more detailed spatial structure and physical properties of Source I.

Key words: ISM: individual objects (Orion KL) – radio continuum: stars – stars: formation – stars: individual (Orion Source I)

1. INTRODUCTION

Located at a distance of 420 pc from the Sun (Hirota et al. 2007; Menten et al. 2007; Kim et al. 2008), the Orion Kleinmann–Low (KL; Kleinmann & Low 1967) region is known as the nearest site of active massive-star formation. It has been recognized as one of the best laboratories to study massive-star formation processes (Genzel & Stutzki 1989; Bally et al. 2008). Because of its extremely high opacity, observations have been made mainly in the centimeter, millimeter/submillimeter, and infrared wavelengths. In particular, radio interferometers have been powerful tools to study in detail the physical properties of young stellar objects (YSOs) in Orion KL (e.g., Beuther et al. 2004, 2005, 2006; Tang et al. 2010; Favre et al. 2011; Friedel & Weaver 2011; Zapata et al. 2011; Plambeck et al. 2013) at the highest spatial resolution. These observational studies have identified some of the remarkable sources, such as the Becklin–Neugebauer (BN; Becklin & Neugebauer 1967) object, Hot Core, Compact Ridge, a radio source labeled I (Source I), an infrared source labeled n (Source n), and a submillimeter source identified as Submillimeter Array (SMA), SMA1, although their properties are still a matter of debate.

Among these compact sources, the most prominent energy source in Orion KL is thought to be Source I (Menten & Reid 1995). It is a candidate of a massive protostar driving a so-called low-velocity bipolar outflow along the northeast–southwest direction with a scale of 1.000 AU traced by the thermal SiO lines and H$_2$O masers (Genzel & Stutzki 1989; Gaume et al. 1998; Hirota et al. 2007; Plambeck et al. 2009; Niederhofer et al. 2012; Zapata et al. 2012; Greenhill et al. 2013; Kim et al. 2015). At the center of this outflow, there is a cluster of vibrationally excited SiO masers tracing a disk wind emanating from the surface of the circumstellar disk with a diameter of ~100 AU (Kim et al. 2008; Matthews et al. 2010; Greenhill et al. 2013). A compact radio continuum source is associated at the center of the SiO masers that is interpreted as an edge-on circumstellar disk (Reid et al. 2007; Goddi et al. 2011; Plambeck et al. 2013). Such a disk–jet system was recently studied in the submillimeter H$_2$O lines by using the newly constructed Atacama Large Millimeter/Submillimeter Array (ALMA; Hirota et al. 2012, 2014a).

Nevertheless, the nature of Source I and the associated disk/outflow system are still far from a complete understanding. One of the long-standing issues is the origin of the radio continuum emission associated with Source I. A spectral energy distribution (SED) of Source I from centimeter to submillimeter wavelengths can be fitted to a power-law function, $F_{\nu} \propto \nu^{\alpha}$, indicative of optically thick emission up to submillimeter wavelengths (Plambeck et al. 2013, and references therein). Based on such an SED of Source I, it has been interpreted as either a combination of free–free emission and thermal dust emission (Beuther et al. 2004, 2006; Reid et al. 2007; Plambeck et al. 2013) or a H$^+$ free–free emission from a neutral atomic/molecular gas (Reid et al. 2007; Plambeck et al. 2013). Although the physical properties of Source I such as mass, temperature, and ionization degree are still under debate, more recent results support the latter scenario (e.g., Plambeck et al. 2013).
Table 1
Summary of Observations

| Band | Date (in 2012) | Center Frequencies (GHz) | Total Bandwidth (MHz) | Effective Bandwidth (MHz) | Number of Antennas | On-source Time (sec) | FWHM (" × ") | PA (degree) | rms (mJy beam⁻¹) |
|------|---------------|--------------------------|-----------------------|--------------------------|--------------------|---------------------|-----------------|-------------|-----------------|
| 6    | Jan 20        | 231                      | 1875                  | 167                      | 16                 | 1196.1              | 1.76 × 1.19     | −1          | 19              |
|      | Apr 08        | 250                      | 8000                  | 3547                     | 17                 | 30.3                | 0.68 × 0.50     | −75         | 5               |
|      | All uv        | 245                      | ...                   | ...                      | ...                | ...                 | 0.81 × 0.64     | 70          | 9               |
|      | uv > 100 kλ   | 245                      | ...                   | ...                      | ...                | ...                 | 0.63 × 0.47     | 72          | 5               |
| 7    | Oct 23        | 350                      | 8000                  | 3641                     | 23                 | 100.8               | 0.47 × 0.44     | 0           | 9               |
|      | Jul 16, Aug 25, Oct 21b | 329 | 1875 | 648 | 21,28,22 | 326.8 | 0.55 × 0.46 | 59 | 12 |
|      | All uv        | 339                      | ...                   | ...                      | ...                | ...                 | 0.49 × 0.45     | 59          | 9               |
|      | uv > 100 kλ   | 339                      | ...                   | ...                      | ...                | ...                 | 0.46 × 0.41     | 57          | 5               |

a Center frequencies for LSB (lower side band) and USB (upper side band). Only one spectral window in LSB is employed for band 6 data on 2012 January 20 (SV data).
b Combine three epochs for spectral line monitoring at band 7.

taken on 2012 January 20 in the compact configuration with 16 × 12 m antennas separated from 14 to 203 kλ (from 17 to 265 m). The tracking center position of Orion KL was set to be R. A. = 05h35m14.3 35 and decl. = −05°22'35''0 (J2000), which is 4° northeast of that of the cycle 0 data.

In this paper, we define the band 6 frequency to be 245 GHz because it is the central frequency of all of the combined data.

2.2. Band 7 Data

For band 7, observations in two different frequency settings were carried out: continuum mode and spectral line mode. The tracking center position was the same as band 6 cycle 0 data: R.A.(J2000) = 05°35'14.3 1250, decl.(J2000) = −05°22'36''486.

Observations in the continuum mode were done in the extended configuration on 2012 October 23 with 23 × 12 m antennas. The primary beam size of each 12 m antenna is 17''. The baseline lengths ranged from 19 to 425 kλ (from 17 to 372 m). The observed frequency ranges were 341.5 –345.4 GHz and 353.5–357.5 GHz consisting of four 2 GHz bandwidth spectral windows with dual polarization. The ALMA correlator was set for low-resolution wide-band continuum observations, and the spectral resolution was 15.625 MHz. The total on-source integration time was 100 s. The primary flux calibrator, bandpass calibrator, and secondary gain calibrator were Callisto, J0423-013, and J0607-085, respectively. The system noise temperatures ranged from 116 to 162 K depending on the spectral window.

We carried out monitoring observations of the submillimeter H₂O lines at band 7 to study the H₂O maser burst event at 22 GHz in multifrequency (Hirota et al. 2014a). For this purpose, three sessions of spectral line observations were carried out on 2012 July 16, August 25, and October 21 during the cycle 0 period. The number of 12 m antennas was different from epoch to epoch: 21, 28, and 22 at the first, second, and third epochs, respectively. Array configurations were in the extended mode with the baseline lengths of 16–427 kλ (15–398 m), 22–416 kλ (21–388 m), and 18–389 kλ (17–363 m) at the first, second, and third epoch, respectively. Four spectral windows were set at the frequencies of 321.0–321.5 GHz, 322.1–322.6 GHz, 334.4–334.9 GHz, and 336.0–336.5 GHz with the bandwidth of 469 MHz for each. Spectral resolution was set to be 0.122 MHz. The on-source integration time of the target source was about 100 s for each

In order to reveal the physical properties of continuum sources in Orion KL, in particular Source I, we present an observational study of multiband continuum emission with subarcsecond resolution by using ALMA. The ALMA observations open new wavelength windows with the higher spatial resolution. Combined with previous high-resolution observations at lower frequency bands, we will discuss the basic physical properties of some of the key sources in Orion KL.

2. OBSERVATIONS AND DATA ANALYSIS

Observations of the millimeter and submillimeter continuum emission were carried out with ALMA in several sessions during the early science operation in the cycle 0 period at bands 6 and 7 (ADS/JAO.ALMA#2011.0.00199.S). We also employed the ALMA Science Verification (SV) data (ADS/JAO.ALMA#2011.0.00009.SV) at band 6. Details of each session are summarized in Table 1.

2.1. Band 6 Data

The observation in cycle 0 was done in the extended configuration on 2012 April 8 with 17 × 12 m antennas. The primary beam size of each 12 m antenna is 25''. The baseline lengths ranged from 17 to 310 kλ (from 21 to 385 m). The observed frequency ranges were 240–244 GHz and 256–260 GHz and consisted of four spectral windows with a bandwidth of 2 GHz for each. Dual polarization data were obtained simultaneously. The ALMA correlator was set for low-resolution, wide-band continuum observations, and the spectral resolution was 15.625 MHz. The target source was Orion KL, and the tracking center position was taken to be the bursting 22 GHz H₂O maser, R.A.(J2000) = 05h35m14.3 1250, decl.(J2000) = −05°22'36''486 (Hirota et al. 2011; Hirota et al. 2014b). The total on-source integration time was 30 s. The primary flux calibrator, bandpass calibrator, and secondary gain calibrator were Callisto, J053851-440507, and J0607-085, respectively. The system noise temperatures ranged from 102 to 122 K, depending on the spectral window.

To improve the image quality, we combined the ALMA SV data at band 6 with our cycle 0 data. The SV data were obtained in the 20 frequency settings to cover full spectral emissions from 214 to 247 GHz. We here only employed part of the frequency range from 230 to 232 GHz to achieve an image sensitivity comparable to the cycle 0 data. The SV data were

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The primary flux calibrator, bandpass calibrator, and secondary gain calibrator were Callisto, J053851-440507/ J0423-013, and J0607-085, respectively. The system noise temperature ranged from 125–341 K, in which the frequency around 322 GHz was significantly affected by the strong atmospheric absorption of the 325 GHz H2O line. Similar to the band 6 data, we define the band 7 frequency to be 339 GHz as the central frequency of all of the combined data.

2.3. Synthesis Imaging

The data were calibrated and imaged with the Common Astronomy Software Applications (CASA) package. For the band 6 data, we combined calibrated SV and cycle 0 data by using the task `concat` in CASA. Plots of uv coverages of the full array are shown in Figure 1. For band 7 data, we combined all of the calibrated data for both continuum and spectral line modes by using the CASA task `concat`. After combining the data, continuum images of Orion KL were made using the CASA task `clean`. The line emissions were excluded to make continuum images by integrating over the line-free channels. The resultant effective bandwidths were almost half of the observed frequency range, as listed in Table 1. Both phase and amplitude self-calibrations were done with the continuum images by the CASA task `gaincal`, and these results were applied to the visibility data by the CASA task `applycal`. The resultant image rms noise level of the continuum emission and the uniform-weighted synthesized beam size are summarized in Table 1.

3. RESULTS

Figures 2 and 3 show continuum images of Orion KL at bands 6 and 7, respectively, obtained with various uv coverages. To achieve higher image quality and sensitivity, we combined different data sets observed in different uv coverage, as explained in the previous section. The overall spatial structures of the band 6 and band 7 images with full uv coverage (Figures 2(a) and 3(a)) appear quite similar to each other. The main emission region shows an elongated ridge-like structure ("main dust ridge" in Tang et al. 2010) along the northeast–southwest direction consisting of Source I, Hot Core, and SMA1, as labeled in Figure 4. At the western side of this main dust ridge and south of the BN object, there are several diffuse emission components located along the north–south direction, which can be identified as the Northwest Clump and the Compact Ridge (Figure 4). Our ALMA images trace part of these extended emissions corresponding to the compact highest-density condensations.

In order to identify compact continuum sources, we made synthesized images by employing only baselines longer than 100 kλ, as shown in Figures 2(b) and 3(b). The extended emission components are resolved out in our ALMA images (Figures 2(b) and 3(b)) because of the lack of short baselines in the ALMA extended configuration. Although the high-resolution images (Figures 2(b) and 3(b)) show lower intensities than those of full uv coverage (Figures 2(a) and 3(a)), compact sources are clearly detected with sufficiently high signal-to-noise ratios greater than 5σ. Note that there are negative contour levels in these images due to insufficient uv coverage for shorter baselines. When we employ the visibility data with baselines longer than 200 kλ, only Source I remains unresolved, implying a compact structure (Beuther et al. 2004).

For band 6 data, we compare the cycle 0 data (Figure 2(c)) and SV data (Figure 2(d)) obtained in the extended and compact configurations, respectively. Only the higher resolution cycle 0 data resolve the compact cores, as can be seen in the main dust ridge (Figure 2(c)). In contrast, we cannot see an extended NW clump in the cycle 0 data that is evident in the SV data (Figure 2(d)). By combining both data (Figures 2(a)), we can significantly improve the source structure by recovering both extended and compact features.

Because we have carried out three epochs of monitoring observations at band 7 in the spectral line modes as well as a single-epoch continuum observation, we compared these four observational results. For the spectral line mode, we notice an apparent difference in the synthesized images from epoch to epoch. Because such a difference is not significant for the most compact condensation identified as Source I, we attribute it to the difference in the uv coverage. When comparing an image...
from the single-epoch continuum observation (Figure 3(c)) with that of the combined image of all three epochs observed in the spectral line mode (Figure 3(d)), both results are in good agreement with each other. Taking into account these effects, we estimate the accuracy of the flux measurement to be 20%.

We determine positions and intensities of the compact cores by fitting the two-dimensional Gaussian on the images made with uv coverages of >100 kλ (Figures 2(b) and 3(b)) by using the CASA task imfit. The flux densities are measured by employing the images after correction for primary beam attenuation. Because there could be false detection due to side lobes or noises, we conservatively regard the sources as real detections if their signal-to-noise ratio is greater than five for both bands 6 and 7. As a result, we identify a total of 11 sources, as listed in Tables 2 and 3. In this paper, we define the source name as HKKH (an acronym of the authors’ initials) followed by the ID number.

For the band 6 images, the missing flux in the highest resolution images with uv coverage of >100 kλ (Figure 2(b)) compared with the image with full-uv coverage (Figure 2(a)) are larger than 90% for sources HKKH1, HKKH6, and HKKH9. In contrast, more than 90% of flux densities at band 6 are recovered for sources HKKH2, HKKH4, and HKKH10, implying compact structures. For the band 7 images, a fraction of the missing flux in the highest resolution images with uv coverage of >100 kλ (Figure 3(b)) is less than 50% in comparison with those of full-uv coverage (Figure 3(a)). This difference in the degree of missing flux between bands 6 and 7 would be attributed to the different uv coverages and beam sizes.

For band 7, sources HKKH1, HKKH2, and HKKH3 are outside of the primary beam size of the ALMA 12 m antenna, but they are within the field of view of band 6. Although flux calibration is not reliable for these sources, we regard them as

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Figure 2. Continuum emission maps for band 6 data. Synthesized beam size is indicated at the bottom-left corner in each panel. The contours start at the −5σ level with an interval of 10σ (5, 15, 25, ...). The (0, 0) position is the tracking center position of the cycle 0 data. R.A.(J2000) = 05h35m14s.1250, decl.(J2000) = −05°22′36.486″. The HKKH source ID numbers are indicated in panels (a) and (b). (a) Combine both the SV and cycle 0 data. The noise level (1σ) is 9 mJy beam⁻¹; (b) Same as (a) but excluding those with uv length less than 100 kλ. The noise level (1σ) is 5 mJy beam⁻¹; (c) Cycle 0 data. The noise level (1σ) is 5 mJy beam⁻¹. A circle indicates a primary beam size of the 12 m antenna, 25″; (d) SV data. The noise level (1σ) is 19 mJy beam⁻¹. A circle indicates a primary beam size of the 12 m antenna, 25″. Note that the pointing center is 4″ northeast of that of the Cycle 0 data (see panel (c)).
detection in both bands 6 and 7. Similar to these sources, source HKKH5 is detected at the edge of the field of view of band 7 images. In addition, the BN object, a famous massive YSO in this region, is outside of the field of view of bands 6 and 7, as discussed later.

4. DISCUSSION

4.1. Comparison with Previous Observational Results

There have been a number of high-resolution observations of Orion KL with continuum emissions in a wide range of wavelengths. We compare some of the highest resolution data reported to date. Examples are shown in Figure 4. The positions of most of our detected sources are coincident with previous interferometric maps of the highest resolution millimeter continuum emission (Friedel & Weaver 2011), molecular lines of methyl formate, HCOOCH$_3$ (Favre et al. 2011), and radio continuum emission (Felli et al. 1993a, 1993b), as shown in Figure 4 and Table 4.

We compare the spatial structure of our millimeter/submillimeter maps with the midinfrared emission observed with the Subaru telescope (Okumura et al. 2011). As can be seen in Figure 4, the midinfrared emission shows an anticorrelation with those of millimeter/submillimeter emission. It is easily interpreted that the millimeter/submillimeter emissions are emitted predominantly from dust clouds with high opacity, even at the midinfrared bands.

We could not detect some of the possible counterparts of the millimeter/submillimeter continuum sources detected in other tracers (Figure 4). There are possible reasons for such differences. First, we employ a rather conservative detection criterion in which the continuum sources are regarded as detected if their peak intensities are greater than five times the noise level. This is because we eliminate contributions from

Figure 3. Continuum emission maps for band 7 data. Synthesized beam size is indicated at the bottom-left corner in each panel. The contours start at the -5σ level with an interval of 10σ (5, 15, 25, ...). The (0, 0) position is the tracking center position of the cycle 0 data, R.A. (J2000) = 05°35′14″1250, decl.(J2000) = -05°22′36.486. The HKKH source ID numbers are indicated in panels (a) and (b). (a) Combine all of the four epochs, including both spectral line mode and continuum mode. The noise level (1σ) is 9 mJy beam$^{-1}$. (b) Same as (a) but excluding those with uv length less than 100 kλ. The noise level (1σ) is 5 mJy beam$^{-1}$. (c) A single epoch of data observed in the continuum mode. The noise level (1σ) is 9 mJy beam$^{-1}$. A circle indicates a primary beam size of the 12 m antenna, 18′. (d) Combine three epochs of observations in spectral line mode. The noise level (1σ) is 12 mJy beam$^{-1}$. A circle indicates a primary beam size of the 12 m antenna, 18′.

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strong side lobes as much as possible. As a result, we might miss weak emissions in our map. Furthermore, we employ the uv lengths longer than 100 kλ to search for only compact sources. Thus, our continuum images significantly resolve out weak extended emission sources detected in the shorter baselines in previous interferometer observations.

4.2. Graybody Fitting of SED

As tabulated in Table 4, we identify 11 continuum sources detected in both band 6 and 7 images with the uv coverage of greater than 100 kλ. It is known that the SED of millimeter/submillimeter continuum emission associated with YSOs can be well fitted by the optically thin graybody function as a result of thermal dust emission. Thus we fit the observed flux densities at 245 and 339 GHz as listed in Table 4 to the graybody function:

\[ F_{\nu}^{\text{gb}} = \frac{M_{\text{tot}}}{D^2} \kappa_{\nu} B_{\nu}(T_{\text{dust}}) \]

\[ \kappa_{\nu} = \kappa_{\nu_0} \left( \frac{\nu}{\nu_0} \right)^{\beta} \]

where \( M_{\text{tot}} \) is the total mass, \( D \) the distance, \( \kappa_{\nu} \) the total mass opacity, and \( B_{\nu}(T_{\text{dust}}) \) the Planck function at the dust temperature of \( T_{\text{dust}} \). The total mass opacity \( \kappa \) is expressed as a power-law function of the frequency, and \( \kappa_{\nu_0} = 0.1 \text{ cm}^2 \text{ g}^{-1} \) at \( \nu_0 = 1.2 \text{ THz} \), or a wavelength of 250 μm, is adopted (Hildebrand 1983), assuming the gas-to-dust mass ratio of 100. If high-resolution millimeter continuum data at 90 GHz are available (Friedel & Weaver 2011), we also employ these results in the SED fitting.

The results of the graybody fitting are summarized in Table 5. The power-law index of the dust opacity, \( \beta \), is fitted by using two or three data points, as listed in Table 4. Because the dust temperatures cannot be determined from our continuum observations, we assume the temperature of 100 K as obtained from the molecular line observations (Favre et al. 2011) and a lower value of 20 K (Eisner et al. 2008) for comparison. The derived mass is anticorrelated with the temperature as a function of \( \exp(1/T_{\text{dust}}) \), and hence, the lower temperature values would yield an upper limit of the mass. The dust opacity index, \( \beta \), is close to one for most of the sources, except for Source I. The SED of Source I cannot be fitted by a simple optically thin thermal dust emission, as discussed later.

The origin of compact continuum sources is attributed to either star-forming or starless cores, although the detailed nature of each source is still unknown (see discussion about the individual sources). If the source is associated with an embedded YSO, the compact structure of 200–300 AU and high density of \( 10^8–10^9 \text{ cm}^{-3} \) are indicative of circumstellar disks as one of the possible origins of millimeter/submillimeter sources. The derived masses \((0.08–0.27 \text{ M}_\odot)\) for an assumed temperature of 20 K) correspond to the smaller end of the masses for disk candidates in another massive star forming region NGC 6334I(N) (Hunter et al. 2014). Due to the closer distance of Orion KL than that of NGC 6334I(N), 1.3 kpc, the derived source sizes are significantly smaller than those in NGC 6334I(N) (Hunter et al. 2014). On the other hand, the derived mass range is smaller than the typical circumstellar disk masses associated with massive YSOs (Cesaroni et al. 2007),

\[ \text{Figure 4. ALMA band 7 continuum maps (contour) superposed on the Subaru midinfrared image (Okumura et al. 2011). Positions of band 7 continuum sources (Table 3) are indicated by magenta smaller crosses with the HKKH ID numbers. Peaks of methyl formate (MF; Favre et al. 2011), 3 mm continuum emission (Friedel & Weaver 2011), and radio continuum emission (Felli et al. 1993a, 1993b) are indicated by green squares, blue crosses, and yellow triangles, respectively. The (0, 0) position is that of the 22 GHz H$_2$O maser burst in the Compact Ridge (Hirota et al. 2011; Hirota et al. 2014b).} \]
but it is larger than those of low-mass YSOs, including members of the Orion Nebula Cluster (Eisner et al. 2008). The smaller circumstellar mass compared with another massive YSO was also recognized for Source I in Orion KL by the previous SMA observation (Beuther et al. 2004). If our millimeter/submillimeter sources trace the circumstellar disk of massive YSOs, the lower-mass range could imply a relatively later evolutionary stage in massive disk formation, as proposed in Beuther et al. (2004). Nevertheless, we cannot rule out the possibilities of an envelope around YSO, shocked dense gas, or starless dense gas, which are significantly resolved with our high-resolution images, or a disk associated with low/intermediate-mass YSO. The key parameters to distinguish these possibilities are gas temperature and velocity structure traced by molecular lines in multiple transitions to investigate physical and dynamical properties of the continuum sources.

5. INDIVIDUAL SOURCES

5.1. Source I (HKKH4)

Source I is thought to be a dominant energy source in Orion KL (Menten & Reid 1995). A number of observational studies have been done for Source I to reveal its nature, whereas it can be detected only at longer wavelengths than the submillimeter band due to an extremely high opacity (Greenhill et al. 2004; Okumura et al. 2011; Sitarski et al. 2013). It can be identified as a color temperature peak derived from midinfrared images (Okumura et al. 2011). The position of Source I corresponds to the 3 mm continuum source C20 (Friedel &
Figure 5. Spectral energy distribution (SED) of Source I. A solid blue line indicates the best-fit single power-law model, \( F_\nu = \nu^p \) with the index of \( q = 1.97 \pm 0.10 \). A solid red line indicates the combination of power-law and graybody SEDs. The power-law and graybody terms are shown by the red dotted and dashed lines, respectively. Open squares represent all of the data including the present ALMA results (Plambeck et al. 2013, and references therein). Filled circles represent the data employed in the fitting, as indicated by Y in Table 6.

Weaver 2011). There is a nearby molecular peak MF10 at the western side of the submillimeter emission peak (Favre et al. 2011). Because the position offset between MF10 and Source I is significant and, in addition, there is no emission from organic molecules at Source I (Beuther et al. 2005), they are unlikely to be physically associated.

By using previous observational results of interferometric continuum observations at centimeter, millimeter, and submillimeter wavelengths, we plot an SED of Source I as shown in Figures 5 and Table 6 (see Plambeck et al. 2013, and references therein). At several frequencies, there are more than two observational results showing different flux densities. For example, the flux density of our band 6 data, 284 mJy, is consistent with that of CARMA, 310 mJy (Plambeck et al. 2013), within an error of \( \sim 10\% \). On the other hand, our band 7 data is intermediate between those of Beuther et al. (2004) and Tang et al. (2010) observed with SMA. The reason for such discrepancies could be that insufficient uv coverage affects the flux density measurements due to strong negative side lobes from the bright extended emission in the complex structure of the Orion KL region, as suggested in Plambeck et al. (2013). Another possibility could be a different degree of missing fluxes due to the different uv coverages. To avoid such an artifact, we employ the flux density observed with the highest resolution observations at each frequency. The data employed in the following discussion are indicated by Y in Table 6.

5.1.1. \( H^+ \) Free–free Emission

As shown in Figure 5 and Table 7, the SED of Source I can be fitted by a single power-law function

\[
\log F_\nu^p = p + q \log \nu
\]

with the power-law index \( q \) of \( 1.97 \pm 0.10 \) for the frequency range between 8.4 and 690 GHz. The power-law index is consistent with that expected for the blackbody radiation, \( q = 2.0 \), suggesting that the emission could be optically thick even at the submillimeter wavelengths. As proposed for typical massive YSOs, the emission mechanism of the centimeter to submillimeter continuum emission from Source I is a combination of graybody radiation from dust and free–free radiation from fully ionized gas (Beuther et al. 2004, 2006). However, the free–free emission from such a compact \( H^+ \) region is ruled out as a main opacity source of continuum emissions based on the observed source size and brightness temperature of \( \sim 1,500 \) K at 43 GHz (Reid et al. 2007; Plambeck et al. 2013). The observed SED could be reconciled by the free–free emission only if the beam filling factor (source size or clumpiness) were much smaller than 1 or the gas temperature was much lower than that expected for the fully ionized gas of \( \sim 8,000 \) K. Alternatively, it has been suggested that \( H^+ \) free–free radiation emitted from neutral gas could explain the single power-law SED (Reid et al. 2007; Plambeck et al. 2013).
Table 6
Flux Densities of Source I

| Frequency (GHz) | Flux (mJy) | HPBW (mas) | Array | Epoch | SED | Reference |
|----------------|-----------|-----------|-------|-------|-----|-----------|
| 8.4            | 1.1 ± 0.2 | 220       | VLA   | 1994.3| Y   | Menten & Reid (1995) |
| 8.4            | 1.2 ± 0.1 | 262 × 217 | VLA   | 2006.4| ... | Gómez et al. (2008) |
| 15             | 1.54 ± 0.18 | 140 × 130 | VLA   | 1986.3| Y   | Felli et al. (1993a) |
| 15             | 1.6 ± 0.4  | 150       | VLA   | 1990  | ... | Felli et al. (1993b) |
| 22             | 5.7 ± 0.9  | 109 × 97  | VLA   | 1991.5| Y   | Forbrich et al. (2008) |
| 23             | 13 ± 2     | 250       | VLA   | 1994.3| ... | Menten & Reid (1995) |
| 43             | 10.8 ± 0.6 | 1960 × 1410 | VLA | 1994.9| ... | Chandler & Wood (1997) |
| 43             | 13         | 41 × 28   | VLA   | 2000.9| Y   | Reid et al. (2007) |
| 43             | 14.5 ± 0.7 | 170 × 150 | VLA   | 2007.9| ... | Rodríguez et al. (2009) |
| 43             | 11 ± 2     | 58 × 39   | VLA   | 2009.0| ... | Goddi et al. (2011) |
| 86             | 34 ± 5     | 1000 × 380 | BIMA  | 1995.0| ... | Plambeck et al. (1995) |
| 90             | 50 ± 5     | 400 × 350 | CARMA | 2009.0| Y   | Friedel & Weaver (2011) |
| 229            | 310 ± 45   | 150 × 130 | CARMA | 2009.1| Y   | Plambeck et al. (2013) |
| 245            | 272 ± 13   | 630 × 470 | ALMA  | 2012  |     | Present study |
| 339            | 849 ± 29   | 460 × 410 | ALMA  | 2012  | Y   | Present study |
| 341            | 1400 ± 100 | 800 × 700 | SMA   | 2009.1| ... | Tang et al. (2010) |
| 348            | 320 ± 48   | 780 × 650 | SMA   | 2004.1| ... | Beuther et al. (2004) |
| 690            | 6700 ± 3200 | 1400 × 900 | SMA | 2005.1| Y   | Beuther et al. (2006) |

Note. See Plambeck et al. (2013).

* Y indicates the data employed in the SED fitting.

Table 7
SED of Source I

| Model                     | p     | q     | M(100 K) (M☉) | β     |
|--------------------------|-------|-------|---------------|-------|
| Single power law         | −1.99(19) | 1.97(10) | ... | ... |
| power law+graybody       | −1.51(30) | 1.60(24) | 0.082(49) | 1.34(83) |

Note. Dust temperature of 100 K is assumed.

Numbers in parentheses represent fitting errors (1σ) in units of the last significant digit.

In order to explain the observed SED of Source I from centimeter to submillimeter wavelengths, we first evaluate the physical properties of Source I in the case of the H free–free radiation. Detailed derivation of the H free–free radiation is summarized in the appendix following the discussion by Reid & Menten (1997). Hereafter we assume that Source I is an edge-on disk with uniform density and temperature for simplicity. The apparent size of Source I of 0′′20 × 0′′03 is employed (Plambeck et al. 2013), corresponding to the disk diameter and thickness of 84 and 12.6 AU, respectively. With these parameters, a total hydrogen density of 10²⁰ cm⁻³ corresponds to a column density of 1.26 × 10²⁷ cm⁻² (with a diameter of 84 AU) and a total mass of 0.20 M☉. As suggested from Figure 5, Source I seems to be optically thick at 245–339 GHz or even at 690 GHz. Thus, the turnover frequency at which the optical depth of the H free–free radiation becomes unity is as high as >300–600 GHz (see appendix). Using the relationship between the total hydrogen density (a sum of molecular and atomic hydrogen) and temperature to explain the turnover frequency (Figure A3 and Table A2 in the Appendix), we can constrain the ranges of gas density and temperature.

According to the SMA continuum observations (Tang et al. 2010), the mass of the main dust ridge including Source I is estimated to be 2–12 M☉. Favre et al. (2011) also derive a consistent value of 5.8 M☉ for their continuum source Ca, in which Source I is located at the western edge of the core. The total mass of Source I itself is estimated from the velocity structure of the rotating disk traced by the SiO masers and submillimeter H₂O lines (Kim et al. 2008; Matthews et al. 2010; Hirota et al. 2014a), >7 M☉, infrared spectroscopy (Testi et al. 2010), 10 M☉, or a momentum conservation law suggested by proper motion measurement (Goddi et al. 2011; Bally et al. 2011), 20 M☉. Thus, the circumstellar disk mass of Source I would be much lower than that of the central protostar and its host core, < 10 M☉. With this constraint, the total hydrogen density is lower than 5 × 10³³ cm⁻³, as indicated in Figure A3 in the Appendix. In this case, the gas temperature would be larger than 1,200 K for the turnover frequency of >300 GHz (Figure A3 and Table A2 in the Appendix). If the gas temperature is about 3,000 K or higher, the lower gas density of ∼10¹¹ cm⁻³ is allowed to explain the turnover frequency of >300 GHz.

Using the calculated optical depth, τH₂ and τH, for the above temperature (1,200–3,000 K) and density (10¹¹–
ranges, we calculate the flux density $F$ at each frequency for the source size of $\Omega$:

$$F = \int \frac{2\nu^2 k T_B}{c^2} d\Omega$$

$$T_B = (1 - e^{-\tau_{\text{tot}}})T$$

$$\tau_{\text{tot}} = \tau_{\text{H}_2} + \tau_{\text{H}_2}$$

The results are shown in Figure 6. Higher temperature or higher density results can explain the single power-law SED even for the SMA result at 690 GHz. In the case of total hydrogen densities of $10^{11}$ and $10^{12} \text{ cm}^{-3}$ corresponding to the mass of $\sim 0.02 - 0.2 \, M_\odot$ (Figures 6(a) and (b)), gas temperatures higher than 2,700 and 1,800 K, respectively, can explain the SED of Source I with a single power-law index of 2.0 up to the 339 GHz band. For larger densities on the order of $10^{13} \text{ cm}^{-3}$ or the mass of a few $M_\odot$ (Figure 6(c)), the lower temperature of 1,500 K can also match the slope of the SED of Source I up to 339 GHz. On the other hand, the higher temperature results tend to overestimate the flux densities by a factor of about two. When the emission is optically thick, the flux density is proportional to the apparent source size and gas temperature. To account for the observed flux density of Source I, the lower gas temperature of $\sim 1,500$ K would be more plausible if the source is resolved with the beam size of ALMA. Alternatively, the angular size of Source I, $\Omega$, would have to be smaller by a factor of two or the source structure would be clumpy with the beam filling factor of 50%. Higher resolution observations to resolve the source structure with accurate flux calibration will be able to solve this degeneracy of source size and temperature.

Hirota et al. (2014a) reported that the vibrationally excited H$_2$O line at 336 GHz is emitted from a circumstellar disk. The 336 GHz H$_2$O line is thought to be excited thermally with an excitation temperature of $>3,000$ K, probably heated via an accretion shock. This excitation temperature is slightly higher than that estimated from the present continuum data. According to the velocity structure, the 336 GHz H$_2$O line map is interpreted as a ring-like structure with a diameter of 0"2 (84 AU), although the spatial resolution is still insufficient to resolve the structure. It is proposed that the ring-like structure...
would reflect the distribution of the hot molecular (H$_2$O) gas probably heated via accretion (Hirota et al. 2014a). Alternatively, it is also likely that the 336 GHz H$_2$O line could trace only the edge of the disk due to the high continuum opacity even at 336 GHz, as suggested by the SED (Figure 5). If the optically thick H$^+$ free–free radiation is the main source of opacity at 336 GHz, the latter scenario would be more plausible.

5.1.2. H$^+$ Free–free Emission + Thermal Dust Emission

In Figure 5, our ALMA band 7 data still suggest a marginal excess flux compared with the single power-law fitting result. The flux density at 690 GHz also shows a significant excess probably originating from thermal dust emission, as suggested by Beuther et al. (2006) and Plambeck et al. (2013). There seems to be a systematic deviation between the best-fit model and observed results from 43 and 229 GHz, suggesting a change in the emission mechanism at the middle of the centimeter to millimeter wavelengths. Thus, we next consider the contribution from thermal graybody emission from dust. The H$^+$ free–free emission and dust graybody emission contribute to the flux densities at lower and higher frequency regions, respectively. In this case, the flux density $F_\nu$ at each frequency $\nu$ is fitted to the sum of the power-law function due to the H$^+$ free–free radiation and the graybody radiation from the thermal dust emission:

$$F_\nu = F_\nu^{pl} + F_\nu^{gb}.$$ (7)

The combined fitting result gives a lower power-law index of 1.60 ± 0.24 than that of the single power-law fitting, 1.97 (Table 7). The significant amount of the observed flux densities at higher frequency (>200 GHz) can be explained by the graybody radiation rather than the H$^+$ free–free radiation. In such a case, the turnover frequency could be as low as 200 GHz. The required density or temperature under this condition is reduced by a factor of about $(2/3)^2$ when we change the turnover frequency from 300 to 200 GHz (see Equation (A.19)).

Because of the lack of far-infrared wavelength data corresponding to the flux maximum of the graybody function, we cannot constrain the dust temperature of the emitting region. It is possible that the dust graybody emission arises from the different volume of gas mainly in a cooler outer layer of Source I or the same volume of gas as the H$^+$ free–free emission at a temperature higher than ~1,000 K. In the former case, the total dust+gas mass contributed by the graybody SED is estimated to be 0.082 $M_\odot$, assuming the dust-to-gas mass ratio of 100 and the dust temperature of 100 K (Table 7). This value is smaller than that obtained from the SMA observations, 0.2 $M_\odot$ (Beuther et al. 2004). In the latter case, the dust temperature would be higher than 1,000 K, as estimated from the continuum emission (Reid et al. 2007; Plambeck et al. 2013) and vibrationally excited H$_2$O lines (Hirota et al. 2014a). The resultant circumstellar dust+gas mass would be reduced by a factor of 10, ~0.008 $M_\odot$, compared with that of 100 K. Thus, the dust mass would be smaller by a factor of 100 (i.e., assumed dust-to-gas mass ratio), $8 \times 10^{-7} M_\odot$. This value is much smaller than the gas mass estimated from the H$^+$ opacity at this temperature, as discussed above (see Figure A3). In either case, our result may suggest that the dust-to-gas mass ratio is unusually low in the close vicinity of Source I within ~100 AU in diameter because of the dust sublimation under the temperature of >1000 K (e.g., Reid et al. 2007).

A power-law index smaller than 2.0 would reflect a density structure of the emitting region (e.g., discussion in Beuther et al. 2004; Plambeck et al. 2013). In the present analysis, we do not make any correction for the above flux densities such as the different source or beam sizes, which could more or less induce uncertainties in the derived parameters. To better constrain the emission mechanism, higher resolution observations with accurate flux calibration are required to resolve the size of Source I.

5.2. Hot Core (HKKH5)

The Hot Core in Orion KL has been recognized as a prototypical dense and hot molecular gas clump as is often found in massive star forming regions. The Hot Core is known to show a wealth of molecular line emissions in the millimeter and submillimeter wavelengths (e.g., Beuther et al. 2005). A submillimeter continuum source SMM3 detected with SMA (Zapata et al. 2011) corresponds to this compact millimeter/ submillimeter source. This source corresponds to the 3 mm continuum emission C18 (Friedel & Weaver 2011), but it cannot be seen in the molecular line map of methyl formate (Favre et al. 2011). It is most likely that methyl formate is deficient in the Hot Core where nitrogen-bearing organic molecules are dominant. According to the recent molecular line observations, the Orion Hot Core is most likely heated externally by the explosive outflow rather than by an embedded self-luminous source (Zapata et al. 2011). The mass derived from our ALMA data is 0.159 $M_\odot$ at the largest estimate, assuming the temperature of 20 K. The dust opacity index derived from the graybody SED model is consistent with 1.0. As discussed for Source I, the mass of the main dust ridge including Source I and Hot Core is estimated to be 2–12 $M_\odot$ (Tang et al. 2010) and 5.8 $M_\odot$ (Favre et al. 2011). Although the above estimated mass could not resolve more compact structures such as Source I and SMA1, our result only recovers a part of the total mass of the dense gas.

5.3. SMA1 (HKKH7)

The submillimeter continuum source SMA1 is first identified by Beuther et al. (2004) in the SMA observations at 348 GHz. This source is identified to be the 3 mm continuum source C21 (Friedel & Weaver 2011) and the methyl formate peak MF6 (Favre et al. 2011). SMA1 is proposed to be a powering source of the explosive outflow (Beuther & Nissen 2008), although the origin of this explosive outflow is still under debate (e.g., Zapata et al. 2009; Bally et al. 2011; Goddi et al. 2011). The flux density and peak intensity of our ALMA band 7 data are 534 mJy and 237 mJy beam$^{-1}$, respectively. On the other hand, SMA1 was not resolved with the previous SMA observations with the flux density and peak intensity of 360 mJy and 360 mJy beam$^{-1}$, respectively (Beuther et al. 2004). The difference between SMA and ALMA observations could be attributed to the different uv coverage. The dust opacity index, $\beta$, is consistent with 1.0. The derived circumstellar mass of SMA1 is only ~0.18 $M_\odot$, assuming the dust temperature of 20 K. It is much smaller than the total mass of the main dust ridge of this region, as discussed above.
5.4. **Irc7 (HKKH6) and Irc4 (HKKH10)**

We clearly see an anticorrelation between the millimeter/submillimeter emission and the midinfrared emission (Figure 4). However, we detect compact continuum emission sources associated with infrared sources Irc4 and Irc7. The nature of these sources, whether they are heated internally or externally, is still unclear. The infrared spectrum of Irc4 observed with the Subaru telescope can be fitted to the Planck function with a single temperature of 140 K (Okumura et al. 2011), and it is thought to be heated by an external energy source (Okumura et al. 2011). On the other hand, a color temperature map obtained from longer wavelength observations with SOFIA suggests that Irc4 is a self-luminous source (de Buizer et al. 2012). For Irc7, it is proposed that an outflow or radiation from Source n would form a fan-like structure in the infrared emission (Greenhill et al. 2004). According to near-infrared polarization observations with Hubble Space Telescope, Irc4 is thought to be a reflection nebula illuminated by a nearby source, and Irc7 is most likely heated by an embedded YSO (Simpson et al. 2006). In the 3 mm continuum map, Irc7 is identified as a compact source C23, but Irc4 is only found as a diffuse emission (Friedel & Weaver 2011). We detect compact high-density cores with the sizes and H2 densities of ~200–300 AU and >10^6 cm^-3 at the positions of Irc4 and Irc7. Circumstellar masses are estimated to be larger than 0.145 and 0.086 M_☉ for Irc4 and Irc7, respectively.

Except for Irc4, Irc7, and BN as discussed below, we cannot detect millimeter/submillimeter counterparts at the position of other Irc sources.

5.5. **Compact Ridge (HKKH11)**

We identify a compact millimeter/submillimeter emission corresponding to a submillimeter source SMM1 (Zapata et al. 2011), 3mm continuum source C32 (Friedel & Weaver 2011), and methyl formate peak MF1 (Favre et al. 2011) in the Compact Ridge. The mass of the continuum source at the Compact Ridge is estimated to be 4 M_☉ (Tang et al. 2010). Eisner et al. (2008) identified a compact 1.3 mm continuum source named HC 438 in the Compact Ridge by using CARMA at the highest resolution of 0.5″ compared with other previous results. They detected the 1.3 mm continuum emission with a flux density of 67.8 ± 14.2 mJy. This is consistent with our ALMA band 6 data at a similar spatial resolution. The circumstellar mass of HC 438 is derived to be 0.085 M_☉ with the assumed dust temperature of 20 K (Eisner et al. 2008). Our result, 0.105 M_☉, agrees well with that of Eisner et al. (2008). If the higher temperature of 100 K derived from the methyl formate data (Favre et al. 2011) is employed, the smaller mass of 0.010 M_☉ is obtained.

As discussed by Favre et al. (2011), there are possible counterparts physically associated with the millimeter/submillimeter continuum source: a radio continuum source labeled R (Felli et al. 1993a), a molecular peak traced by methyl formate lines, MF1 (Favre et al. 2011), and optical source Parenago 1822. In addition, an extremely bright 22 GHz H2O maser source appears in the Compact Ridge at the systemic velocity of ~6.9 and 7.5 km s^-1. It is sometimes called a supermaser (Hirota et al. 2011; Hirota et al. 2014b, and references therein). The supermaser is located within the millimeter/submillimeter continuum source detected with ALMA.

Favre et al. (2011) suggest that the supermaser would be related to the shocked molecular gas of the Compact Ridge (Liu et al. 2002). It is also suggested that the maser burst could occur as a result of an interaction with outflows and a preexisting YSO in the Compact Ridge (Garay et al. 1989). Hirota et al. (2014b) speculate that the compact continuum source would play an important role to amplify the supermaser, which can supply plenty of ambient molecular gas. Near the supermaser, a cluster of other 22 GHz H2O maser features detected with VLA (Gaume et al. 1998) are distributed around the continuum source. It may imply an embedded YSO as a powering source of the H2O maser cluster (Hirota et al. 2014b).

We note that an infrared source Irc5 is located at 1″ east of the ALMA continuum peak position and corresponds to another 3 mm continuum peak, C29 (Friedel & Weaver 2011). The infrared spectrum of Irc5 can be fitted with the Planck function at the temperature of 120 K (Okumura et al. 2011). Similar to Irc4, Irc5 is thought to be a shocked molecular gas heated externally (Okumura et al. 2011). Thus, Irc5 is not physically associated with the millimeter/submillimeter compact source detected with ALMA.

5.6. **BN**

The Orion BN object is another interesting source regarding the energy source of this region (Galván-Madrid et al. 2012; Plambeck et al. 2013) and a possible counterpart of the close encounter with Source I (Gómez et al. 2008; Bally et al. 2011; Goddi et al. 2011) or θC (Chatterjee & Tan 2012). It is a massive YSO associated with a hypercompact Hn region ionized by a zero-age, main-sequence B star (Plambeck et al. 2013). According to the ALMA SV data (Galván-Madrid et al. 2012) with a spatial resolution of 152 × 032, a compact continuum emission at 230 GHz is detected with a flux density of 126 mJy by using the baselines longer than 100 kλ to filter out extended emission. On the other hand, the higher resolution CARMA observation detects the 229 GHz continuum emission of 240 mJy with the resolution of 014 (Plambeck et al. 2013). A continuum emission source associated with the BN object is marginally seen in our ALMA bands 6 and 7 images outside the primary beam size of the ALMA antenna (Figures 2 and 3). Flux densities at bands 6 and 7 are derived to be 55 ± 4 mJy and 33 ± 6 mJy, respectively. When we correct for an effect of the primary beam attenuation by a factor of two, the calibrated peak intensities are 110 and 66 mJy, respectively. The marginal detection in our ALMA image at band 6 does not contradict the results of Galván-Madrid et al. (2012), although our ALMA results are quite uncertain. Thus, we do not consider the BN object as an identified source in the present paper.

5.7. **Source n**

Source n is also detected in the SMA observation at 348 GHz (Beuther et al. 2004). It is proposed to be a YSO associated with a bipolar radio jet (Menten & Reid 1995) and a circumstellar disk traced by a midinfrared emission (Greenhill et al. 2004). Our ALMA images at bands 6 and 7 show no compact emission at the position of Source n. The upper limit (5σ) of their peak intensities is 25 mJy beam^-1 for both bands 6 and 7. The peak intensity derived from the SMA observation, 300 mJy beam^-1, is much larger than our ALMA result. The nondetection of Source n in our ALMA images is possibly due to our lower sensitivities for extended emission components.
6. SUMMARY

We have carried out millimeter/submillimeter continuum imaging of the Orion KL region by using the newly constructed ALMA at a resolution of 0\,5, corresponding to a linear scale of 200 AU. Compact continuum emission sources are detected, and 11 sources are identified at both band 6 (245 GHz) and band 7 (339 GHz). They include some of the remarkable sources in Orion KL, such as Source I, Hot Core, SMA1, IRC4, IRC7, and Compact Ridge. Their physical properties such as size, mass, H2 number density, and column densities are discussed by employing published 3 mm continuum data (Friedel & Weaver 2011) to construct an SED of dust graybody emission.

Among these identified sources, the SED of Source I, which is a dominant energy source in Orion KL, is extensively studied by using previous observational results from centimeter to submillimeter wavelengths (see references in Plambeck et al. 2013). The SED model with H+ free–free emission is presented following the discussion by Reid & Menten (1997) to explain the power-law index of the SED, 1.97, consistent with an optically thick emission. We introduce a turnover frequency of the H+ free–free emission to constrain the gas temperature and total hydrogen density of the circumstellar disk of Source I. As a result, a total hydrogen density of 10\,11–10\,14 cm\(^{-3}\) is required to account for the single power-law index of 2.0 for the temperature of 1,200–3,000 K in the case of a turnover frequency of ~300 GHz. When we employ the combination of dust graybody emission and power-law SED, the turnover frequency would be as low as 200 GHz, which reduces the estimated temperature or density by a factor of (2/3)\(^2\). The fitting result yields a smaller power-law index of 1.60, suggesting a compact size or clumpy structure of the emission region unresolved with the present study (Beuther et al. 2004; Plambeck et al. 2013). The estimated temperature, density, and source size are strongly coupled with each other, and hence future higher resolution observations with ALMA will be key issues to solve these degeneracies in physical properties.

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Facilities: ALMA.

APPENDIX A

H+ FREE–FREE RADIATION

The free–free transition of electrons interacting with neutral hydrogen atoms and molecules is called H+ free–free emission. The formulas for the absorption coefficients of H+ free–free emission were first developed by Dalgarno & Lane (1966), Then, Reid & Menten (1997) applied the H+ free–free emission mechanism to explain radio photospheres of Mira-type variables by simplifying the formula of H+ free–free absorption coefficients. Taking into account a similarity in observed properties between Mira-type variables and Source I, the H+ free–free emission can be applied to Source I (Beuther et al. 2004; Reid et al. 2007; Plambeck et al. 2013). Here we follow the discussion by Reid & Menten (1997) to construct an SED of Source I, assuming the source diameter (path length) of 84 AU, corresponding to the major axis of Source I of 0\,2.

The H+ free–free absorption coefficients at 10 GHz for unit electron pressure per hydrogen atom, \(\kappa_{10\,\text{GHz},H^+}\), and molecule, \(\kappa_{10\,\text{GHz},H_2}\), at the temperature \(T\) are approximately expressed as

\[
\kappa_{10\,\text{GHz},H^+} = a_{0,H^+} + a_{1,H^+}T + a_{2,H^+}T^2 + a_{3,H^+}T^3, \quad (A.1)
\]

\[
a_{0,H^+} = +3.376 \times 10^{-17}, \quad (A.2)
\]

\[
a_{1,H^+} = -2.149 \times 10^{-20}, \quad (A.3)
\]

\[
a_{2,H^+} = +6.646 \times 10^{-24}, \quad (A.4)
\]

\[
a_{3,H^+} = -7.853 \times 10^{-28}, \quad (A.5)
\]

and

\[
\kappa_{10\,\text{GHz},H_2} = a_{0,H_2} + a_{1,H_2}T + a_{2,H_2}T^2 + a_{3,H_2}T^3, \quad (A.6)
\]

\[
a_{0,H_2} = +8.939 \times 10^{-18}, \quad (A.7)
\]

\[
a_{1,H_2} = -3.555 \times 10^{-21}, \quad (A.8)
\]

\[
a_{2,H_2} = +1.100 \times 10^{-24}, \quad (A.9)
\]

\[
a_{3,H_2} = -1.319 \times 10^{-28}, \quad (A.10)
\]

respectively, in units of cm\(^4\) dyn\(^{-1}\) (Reid & Menten 1997). The above equations are valid at low temperatures (<3,000 K) and in long wavelengths (>3 \(\mu\)m), as discussed in Reid & Menten (1997). Because the absorption coefficient is proportional to the inverse square of the frequency, \(\nu\), then the absorption coefficients can be written as

\[
\alpha_{\nu,H^+} = \alpha_{10\,\text{GHz},H^+} \left(\frac{10\,\text{GHz}}{\nu\,\text{GHz}}\right)^2
\]

\[
= \kappa_{10\,\text{GHz},H^+} n_e n_H k T \left(\frac{10\,\text{GHz}}{\nu\,\text{GHz}}\right)^2 \quad (A.11)
\]

\[
\alpha_{\nu,H_2} = \alpha_{10\,\text{GHz},H_2} \left(\frac{10\,\text{GHz}}{\nu\,\text{GHz}}\right)^2
\]

\[
= \kappa_{10\,\text{GHz},H_2} n_e n_{H_2} k T \left(\frac{10\,\text{GHz}}{\nu\,\text{GHz}}\right)^2 \quad (A.12)
\]

where \(k\) is the Boltzmann constant and \(n_e, n_H,\) and \(n_{H_2}\) are the number densities of electrons, hydrogen atoms, and hydrogen molecules, respectively. The optical depths for H+ free–free emission for hydrogen atoms and molecules are

\[
\tau_{\nu,H^+} = \tau_{\nu,H_2} = \tau_{\nu,H} = \alpha_{\nu,H} L = \kappa_{10\,\text{GHz},H^+} n_e n_H k T \left(\frac{10\,\text{GHz}}{\nu\,\text{GHz}}\right)^2 \quad (A.13)
\]
Table A1

Fractional Abundances of Atomic Hydrogen, Molecular Hydrogen, and Electrons

| T(K) | H  | H₂ | e  | H  | H₂ | e  | H  | H₂ | e  |
|------|----|----|----|----|----|----|----|----|----|
| 1000 | 1.0(-05) | 5.0(-01) | 2.6(-10) | 3.2(-06) | 5.0(-01) | 5.2(-11) | 1.0(-06) | 5.0(-01) | 1.3(-11) |
| 1100 | 1.1(-04) | 5.0(-01) | 1.4(-09) | 3.4(-05) | 5.0(-01) | 4.2(-10) | 1.1(-05) | 5.0(-01) | 1.3(-10) |
| 1200 | 8.0(-04) | 5.0(-01) | 8.9(-09) | 2.5(-04) | 5.0(-01) | 2.9(-09) | 8.0(-05) | 5.0(-01) | 9.5(-10) |
| 1300 | 4.3(-03) | 5.0(-01) | 4.0(-08) | 1.4(-03) | 5.0(-01) | 1.4(-08) | 4.3(-04) | 5.0(-01) | 4.9(-09) |
| 1400 | 1.8(-02) | 4.9(-01) | 1.1(-07) | 5.8(-03) | 5.0(-01) | 5.1(-08) | 1.8(-03) | 5.0(-01) | 1.9(-08) |
| 1500 | 6.2(-02) | 4.7(-01) | 2.0(-07) | 2.0(-02) | 4.9(-01) | 1.1(-07) | 6.4(-03) | 5.0(-01) | 5.5(-08) |
| 1600 | 1.7(-01) | 4.1(-01) | 4.9(-07) | 5.9(-02) | 4.7(-01) | 2.2(-07) | 1.9(-02) | 4.9(-01) | 1.2(-07) |
| 1700 | 3.9(-01) | 3.0(-01) | 1.1(-06) | 1.5(-01) | 4.3(-01) | 4.9(-07) | 5.0(-02) | 4.8(-01) | 2.2(-07) |
| 1800 | 6.8(-01) | 1.6(-01) | 1.9(-06) | 3.1(-01) | 3.4(-01) | 1.0(-06) | 1.1(-01) | 4.4(-01) | 4.4(-07) |
| 1900 | 8.8(-01) | 5.8(-02) | 2.6(-06) | 5.5(-01) | 2.2(-01) | 1.8(-06) | 2.3(-01) | 3.9(-01) | 8.8(-07) |
| 2000 | 9.7(-01) | 1.7(-02) | 3.7(-06) | 7.8(-01) | 1.1(-01) | 2.4(-06) | 4.0(-01) | 3.0(-01) | 1.5(-06) |
| 2100 | 9.9(-01) | 5.1(-03) | 5.3(-06) | 9.1(-01) | 4.3(-02) | 3.3(-06) | 6.1(-01) | 1.9(-01) | 2.2(-06) |
| 2200 | 1.0(-00) | 1.6(-03) | 6.7(-06) | 9.7(-01) | 1.5(-02) | 4.6(-06) | 7.9(-01) | 1.0(-01) | 2.9(-06) |
| 2300 | 1.0(-00) | 5.7(-04) | 8.0(-06) | 9.9(-01) | 5.6(-03) | 6.0(-06) | 9.1(-01) | 4.7(-02) | 3.9(-06) |
| 2400 | 1.0(-00) | 2.2(-04) | 1.1(-05) | 1.0(-00) | 2.2(-03) | 7.3(-06) | 9.6(-01) | 2.0(-02) | 5.1(-06) |
| 2500 | 1.0(-00) | 9.0(-05) | 1.6(-05) | 1.0(-00) | 9.0(-04) | 9.0(-06) | 9.8(-01) | 8.7(-03) | 6.3(-06) |
| 2600 | 1.0(-00) | 4.0(-05) | 2.4(-05) | 1.0(-00) | 4.0(-04) | 1.2(-05) | 9.9(-01) | 3.9(-03) | 7.7(-06) |
| 2700 | 1.0(-00) | 1.9(-05) | 3.4(-05) | 1.0(-00) | 1.9(-04) | 1.8(-05) | 1.0(-00) | 1.9(-03) | 9.7(-06) |
| 2800 | 1.0(-00) | 9.2(-06) | 4.3(-05) | 1.0(-00) | 9.2(-05) | 2.6(-05) | 1.0(-00) | 9.2(-04) | 1.3(-05) |
| 2900 | 1.0(-00) | 4.8(-06) | 5.2(-05) | 1.0(-00) | 4.8(-05) | 3.4(-05) | 1.0(-00) | 4.8(-04) | 1.8(-05) |
| 3000 | 1.0(-00) | 2.6(-06) | 6.3(-05) | 1.0(-00) | 2.6(-05) | 4.3(-05) | 1.0(-00) | 2.6(-04) | 2.5(-05) |

Note. Abundances are calculated by $n(X)/n(\text{H})+2n(\text{H}_2))$. Values indicated by $a(b)$ mean a $\times10^a$. The abundance of hydrogen ions is negligible under the condition of low temperature ($<4000$ K).
The optical depths, $\tau_{\text{H}_2}$, and $\tau_{\text{H}^+} = \alpha_{\text{H}^+ L} n_{\text{H}^+} n_{\text{H}_2} L k T \left( \frac{10 \text{ GHz}}{\nu} \right)^2$, are obtained by solving the thermal equilibrium of hydrogen molecules, atoms, and ions at the fixed temperature (Cox 2000):

$$n_{\text{H}_2}^2 = \left( \frac{2m_{\text{H}_2} k T}{\hbar^2} \right)^2 \exp \left( - \frac{D}{k T} \right) \frac{U_{\text{H}_2}(T)}{U_{\text{H}_2}(T)}.$$

$$\frac{n_{\text{H}^+}}{n_{\text{H}}} = \left( \frac{2m_e k T}{\hbar^2} \right)^2 \exp \left( - \frac{I}{k T} \right) \frac{2U_{\text{H}^+}(T)}{U_{\text{H}^+}(T)}.$$ (A.17)

Here, $m_e$ and $m_{\text{H}_2}$ are the masses of electrons and hydrogen atoms, respectively, and $m_{\text{H}^+}$ is a reduced mass of the hydrogen molecule, 0.504 atomic mass unit (Cox 2000). The variables $D$ and $I$ are the dissociation energy of a hydrogen molecule, 4.478 eV, and the ionization energy of a hydrogen atom, 13.598 eV, respectively (Cox 2000). The partition functions of the hydrogen ion and atom are denoted as $U_{\text{H}^+}(T) = 1$ and $U_{\text{H}^+}(T) = 2$, respectively. The partition function of the hydrogen molecule is calculated as $kT/\hbar^2$ if $kT/\hbar^2$ is much larger than $D$. 

Figure A1. (a) Calculated number density of hydrogen atoms, hydrogen molecules, and electrons with the assumed total hydrogen density of $n(\text{H})+2n(\text{H}_2) = 10^{12} \text{ cm}^{-3}$. Electron density is calculated from the Saha equations of Na, Mg, Al, Si, K, Ca, Fe, and H (see text). (b) Calculated optical depth of H$^+$ free-free emission at 300 GHz. Contributions from H atoms and H$_2$ molecules are plotted separately. The total hydrogen density of $n(\text{H})+2n(\text{H}_2) = 10^{12} \text{ cm}^{-3}$ and path length of 84 AU are assumed.

Figure A2. (a) Turnover frequency as a function of temperature for the fixed total hydrogen density from $10^{11}$ to $10^{15} \text{ cm}^{-3}$. (b) Turnover frequency as a function of total hydrogen density for a fixed temperature from 1,200 K to 3,000 K with a step of 300 K. Filled and open symbols represent the calculated values. Solid lines represent the best-fit power-law function as summarized in Table A2. The path length is fixed to be 84 AU for both panels.
one, with the rotational constant $B$ in units of cm$^{-1}$. For the hydrogen molecule, $B$ is 60.85 cm$^{-1}$ (Cox 2000), so this approximation is valid at the temperature of $\gtrsim 88$ K.

As discussed in Reid & Menten (1997), the main sources of electrons at temperatures lower than $\sim 4,000$ K are abundant metals such as Na, Mg, Al, Si, K, Ca, and Fe, and the hydrogen ion is a dominant source of electrons at temperatures higher than $\sim 4,000$ K. We evaluate the ionization degree of Na, Mg, Al, Si, K, Ca, and Fe, along with H, by solving their Saha equations:

$$n_i/n_e = \left( \frac{2\pi m_e k T}{\hbar^2} \right)^{3/2} \exp \left( -\frac{I}{k T} \right) \frac{2U_i(T)}{U_0(T)}, \quad \text{(A.18)}$$

assuming solar system chemical abundances (Cox 2000). The ionization energy and partition function for each species are taken from Cox (2000) and Gray (2005), respectively. First, the Saha equation of each species is solved individually to estimate an ionization degree of each species and a total electron density. Then using these initial values, we solve the Saha equations of all species iteratively until all of the solutions are converged. In Table A1, we tabulate the calculated ionization degree for the temperature range from 1,000 K to 3,000 K, in which the approximation of the H$^-$ free–free absorption coefficients (Equations A.1 and A.6) are valid, with a step of 100 K. The results are also shown in Figure A1(a).

Molecular hydrogen is converted to atomic hydrogen at temperatures higher than $\sim 2,000$ K. On the other hand, the thermal ionization of hydrogen is not significant until the temperature exceeds $\sim 8,000$ K.

Using the number densities of electrons and atomic and molecular hydrogen, we calculate the optical depths of the H$^-$ free–free radiation. Figure A1(b) shows the optical depths of the H$^-$ free–free radiation as a function of temperature. The dominant opacity source of H$^-$ free–free emission is molecular hydrogen under temperatures of 1,700 K, and the optical depth due to molecular hydrogen shows a maximum at a temperature of 1,900 K. At the higher temperature range, atomic hydrogen becomes the dominant source of opacity of H$^-$ free–free emission.

The optical depth is proportional to the inverse square of frequency (Reid & Menten 1997). Even if the H$^-$ free–free radiation is optically thick at lower temperatures, the emission becomes optically thin at the higher frequency band. Thus, we can define the transition frequency from the optically thick to thin regime as a turnover frequency, $\nu_{\text{to}}$, as employed in the proton–electron free–free radiation. At the turnover frequency, the optical depth becomes unity. From Equations (A.13), (A.14), and (A.15), the turnover frequency can be expressed as

$$\nu_{\text{to}} = 10 \times \sqrt{\frac{\kappa T}{\kappa_1 \text{GHz,H} n_e n_\text{H} + \kappa_2 \text{GHz,H} n_e n_\text{H}}} \text{GHz}, \quad \text{(A.19)}$$

Figures A2(a) and (b) show the turnover frequency as functions of temperature and total hydrogen density, respectively. Although the turnover frequency cannot be expressed by a simple formula as a function of temperature, it can be estimated as a simple power-law function of the total hydrogen density at a given temperature:

$$\log \nu_{\text{to}} = A + B \log [n(\text{H}) + 2n(\text{H}_2)], \quad \text{(A.20)}$$

The fitting results are summarized in Figure A2(b) and Table A2. Using these results, we constrain the gas temperature and the total hydrogen density at the fixed turnover frequencies of 200, 300, and 600 GHz, as shown in Figure A3 and Table A2.

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