ALMA Observations of the Archetypal “Hot Core” That Is Not: Orion-KL

M. T. Orozco-Aguilera1, Luis A. Zapata2, Tomoya Hirota3, Sheng-Li Qin4, and Josep M Masqué5

1 Instituto Nacional de Astrofísica, Óptica y Electrónica, Luis Enrique Erro 1, Tonantzintla, Puebla, México
2 Instituto de Radioastronomía y Astrofísica, UNAM, Apdo. Postal 3-72 (Xangari), 58089 Morelia, Michoacán, México; lzapata@crya.unam.mx
3 Mizusawa VLBI Observatory, National Astronomical Observatory of Japan, Osawa 2-21-1, Mitaka-shi, Tokyo 181-8588, Japan
4 Department of Astronomy, Yunnan University, and Key Laboratory of Astroparticle Physics of Yunnan Province, Kunming 650091, China
5 Departamento de Astronomía, Universidad de Guanajuato, Apdo. Postal 144, 36000 Guanajuato, México

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Abstract

We present sensitive high angular resolution (~0′′.1–0′′.3) continuum Atacama Large Millimeter/Submillimeter Array (ALMA) observations of the archetypal hot core located in the Orion Kleinmann-Low (KL) region. The observations were made in five different spectral bands (bands 3, 6, 7, 8, and 9) covering a very broad range of frequencies (149–658 GHz). Apart from the well-known millimeter emitting objects located in this region (Orion Source I and BN), we report the first submillimeter detection of three compact continuum sources (ALMA1–3) in the vicinities of the Orion-KL hot molecular core. These three continuum objects have spectral indices between 1.47 and 1.56, and brightness temperatures between 100 and 200 K at 658 GHz, suggesting that we are seeing moderate, optically thick dust emission with possible grain growth. However, as these objects are not associated with warm molecular gas, and some of them are farther out from the molecular core, we thus conclude that they cannot heat the molecular core. This result favors the hypothesis that the hot molecular core in Orion-KL is heated externally.

Key words: evolution – ISM: jets and outflows – ISM: molecules – stars: formation

1. Introduction

Hot molecular cores (HMCs) are dense (≥10⁶ cm⁻³), warm (≥100 K) and compact (≤10⁵ au) dusty regions within molecular clouds that are thought to harbor massive young stars (Kurtz et al. 2000). These regions are characterized by a strong line emission from a large amount of molecules, but in particular, from complex organic molecules (COMs), as CH₃CN, CH₃OH, HCOOH, HCOOCH₃, CH₃OCH₃, CH₃CH₂CN, and CH₃COCH₃. COMs are defined by molecules composed of more than six atoms containing C and H elements (Herbst & van Dishoeck 2009). One of the first identified HMCs was the one located in the Orion Kleinmann-Low (KL) region (Ho et al. 1979). Ho et al. (1979) identified it as a compact source of hot ammonia emission embedded in a more extended ridge of dense material. Later interferometric observations revealed the peculiar and cumbly “heart” or “U” morphology of the Orion-KL HMC (Genzel et al. 1982; Wilner et al. 1994; Wright et al. 1996; Favre et al. 2011b). Such morphology is not seen in the southern compact HMCs located in Orion South, even when observed at the same spatial scales (Zapata et al. 2007, 2010).

The nature of the Orion-KL HMC was first questioned by Blake et al. (1996) using continuum/line Owens Valley Radio Observatory (OVRO) observations, which found no evidence of a luminous internal heating source within the Orion-KL HMC. This result was more aggravated with Berkeley-Illinois-Maryland Association (BIMA) line observations of the formic acid (that also trace the HMC) and the position in the sky of water masers, which suggested that these molecules trace the interaction region between the outflow and the molecular gas at nearly systemic velocities (Liu et al. 2002). Moreover, using CO (carbon monoxide) BIMA observations, Chernin & Wright (1996) proposed that the biconical outflow in Orion-KL is partly truncated by the hot molecular core.

Recent studies have also confirmed that the HMC in Orion-KL is indeed externally heated, possibly by an explosive outflow that occurred some 500 years ago (Zapata et al. 2009, 2011; Bally et al. 2017), or maybe by the Orion Source I (Goddi et al. 2011; Wright & Plambeck 2017) or the expanding bubble-like outflow (Zapata et al. 2011). Some other works also confirming this externally heating hypothesis include: Favre et al. (2011a), Hirota et al. (2011), Peng et al. (2012, 2013, 2017), Bell et al. (2014), Gong et al. (2015), and Wright & Plambeck (2017). For example, Peng et al. (2017) found that the Orion-KL HMC emission peaks of vibrationally excited HC₃N lines move from south to northeast with increasing Eₜₚ, and that the HC₃N higher-energy lines have higher rotational temperatures and low column densities, which appear to support that the hot core is externally heated.

The strong bursting observed in the water masers located in the direction of the HMC in Orion-KL could be caused by the interaction between the explosive outflow and the ambient quiescent gas (Hirota et al. 2011, 2014).

In this study, using the tremendous sensitivities, a better uv-plane coverage, and a very broad covering of frequency range at (sub)millimeter wavelengths offered by the recent operational Atacama Large Millimeter/Submillimeter Array observatory (ALMA), we carried out a search for compact and faint continuum sources (in five different continuum bands of ALMA) that are probably associated with (proto)stellar objects and hot molecular gas within the HMC in Orion-KL. We report, in addition to Orion Source I and Orion BN, the detection at submillimeter wavelengths of three new compact continuum sources (ALMA1–3) that are located in the vicinities of the HMC, but not with associated hot molecular gas. Additionally, one of these compact sources seem to be associated with high-mass stars, but it does not account for the internal heating of the HMC. We thus conclude that the hot molecular core in Orion-KL is indeed heated externally, as suggested by many observational works.
2. Observations

The observations were carried out with ALMA between 2014 and 2015 as part of the ALMA programs: 2013.1.01034.S (Band 4), 2012.1.00146.S (Band 6), 2013.1.00048.S (Band 8), and 2012.1.00123.S (Bands 7 and 9). The total bandwidth used to estimate the continuum emission in the ALMA observations was more than 2 GHz (see Table 1). However, as there are many lines detected in the spectral windows, and there is probably some contamination from very faint lines. In order to search for compact millimeter sources within the hot molecular core in Orion-KL, we constrain the uv-range of the observations (see Table 1 and Figures 1–3). We chose the uv-range based on a trade-off between removing as much extended emission as possible and keeping enough visibilities to obtain a good map. The resulting synthesized beams are presented in Table 1. The number of antennas used during the observations varied between 31 and 40 (see Table 1). Weather conditions were very good and stable, with an average precipitable water vapor of 6 mm (Band 3), 1 mm (Band 6), 0.3–0.7 mm (Band 7), 0.3 mm (Band 8), and 0.15 mm (Band 9).

The ALMA calibration includes simultaneous observations of the 183 GHz water line with water vapor radiometers that measure the water column in the antenna beam, which is used to reduce the atmospheric phase noise. Quasars J0529−0519, J0423−013, J0607−0834, and J0532−0307 were used to calibrate the bandpass, the amplitude, and the gain fluctuations.

The data were calibrated, imaged, and analyzed using the Common Astronomy Software Applications (ALMA; McMullin et al. 2007). The data presented in this paper were also analyzed using the karma software (Gooch 1996). We used ROBUST parameter of CLEAN equal to zero in the continuum maps presented in this study. This was made in order to obtain an optimal compromise between sensitivity and angular resolution. The resulting rms-noises for the continuum images and their respective angular resolutions are presented in Table 1. All of the resulting ALMA images are corrected by the primary beam attenuation. We self-calibrate all images in phase. On average, we give about one to two rounds in phase for every observation. This helped to decrease the rms-noises (on a few mJy) and thus increase the signal-to-noise ratio (S/N) on the final images. We also tried to perform a self-calibration in amplitude and phase, but we did not obtain substantial improvements on the images.

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**Table 1. Summary of the Observations**

| ALMA Band | Date       | Center Frequency (GHz) | Total Bandwidth (MHz) | uv Range (kλ) | Number of Antennas | On-source Time (Minutes) | Synthesized Beam (arcsec) | PA (degree) | rms (mJy beam⁻¹) |
|-----------|------------|------------------------|-----------------------|---------------|-------------------|--------------------------|--------------------------|-------------|-----------------|
| Band 4    | 2015 Sep 04| 149.5                  | 4000                  | 7–815         | 33                | ~8                      | 0.36 × 0.34              | −46         | 2.5             |
| Band 6    | 2015 Aug 28| 232.6                  | 2342                  | 200–1480      | 40                | ~46                     | 0.21 × 0.17              | 77          | 4.5             |
| Band 8    | 2014 Jun 26| 348.4                  | 7500                  | 39–870        | 31                | ~25                     | 0.29 × 0.26              | −89         | 6.1             |
| Band 7    | 2015 Sep 22| 433.7                  | 5624                  | 200–3100      | 35                | ~25                     | 0.10 × 0.08              | 70          | 5.0             |
| Band 9    | 2014 Aug 05| 658.5                  | 7500                  | 300–1400      | 35                | ~5                      | 0.17 × 0.14              | −42         | 34.0            |

*Note.*

*Center frequency after averaging the four spectral windows.*

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**Figure 1.** ALMA continuum band 4 (3.0 mm) contour and color-scale images of the HMC located in Orion-KL. Upper panel: continuum image using the full uv-range from the ALMA observations. The contours start at 15% and go up to 90% in steps of 5% of the intensity peak. The intensity peak is 0.130 Jy Beam⁻¹. The half-power contour of the synthesized beam of the image is shown in the bottom-left corner. Lower panel: continuum image using only part of the uv-range (>150 kλ) from the continuum observations. The contours start at 15% and go up to 90% in steps of 5% of the intensity peak. The intensity peak is 0.130 Jy Beam⁻¹. The synthesized beam size is shown in the bottom-left corner. The position of the source SMA1 is indicated with a cross, see Beuther et al. (2005). Both images are corrected by the primary beam attenuation. The spatial scale bar is presented in bottom-right corner.
3. Results

The main results of this study are presented in Table 2, and Figures 1–3.

In Figure 1, we present the results of the ALMA observations in band 4 (149.5 GHz). In this Figure, we include the observations of the HMC in Orion-KL using the full uv-range (7.5–800 kλ) and one map only using baselines that are sensitive to compact emission (>150 kλ) or structures with angular sizes of less than 1′′3. In the image using the full uv-range (upper panel), the HMC in Orion-KL is well detected together with the two strong compact objects (Orion Source I and BN) at these millimeter wavelengths. The ALMA band 4 observations revealed the “heart” or “U” shape of the HMC as already traced by many authors, see for example Goddi et al. (2011), where it is mapped by the NH₃ line emission. This “heart” structure, with its peculiar clumpy structure, is very well resolved. On the other hand, the map with the restricted uv-range revealed six compact sources above the 5-σ (7.5 mJy Beam⁻¹) noise level; see the lower panel of Figure 1. However, as some of these compact sources are not detected in other ALMA bands, we only count five real detections (Orion Source I, BN, ALMA1, ALMA2, and ALMA3). We give the physical parameters of these new sources in Table 2. We note that the submillimeter source SMA1 found using Submillimeter Array (SMA) observations and reported by Beuther et al. (2005) does not have any counterpart; perhaps it is resolved out by the present ALMA observations.

In Figure 2, we present the results of the ALMA observations in band 7 (348.4 GHz). In this Figure, we include the observations of the HMC using the full uv-range (38–951 kλ) and one map only using baselines that are sensitive to compact emission (>150 kλ) or structures with angular sizes of less than 1′′3. In the image using the full uv-range (upper panel), only the most compact structures of the HMC are detected. These compact and clumpy structures are located close to Orion Source I and form an arc-like structure. On the other hand, the map with the restricted uv-range revealed four compact sources above the 5-σ (23 mJy Beam⁻¹) noise level (see the lower panel of Figure 2). ALMA1 is present in the map, even though its emission is very faint. Despite starting the contours at 10-σ, we consider all of the sources below this level to be spurious because they do not show well-defined counterparts in all of the other ALMA bands, contrary to the observations in band 4.

Table 2

| Name   | α₂₀₀₀  | δ₂₀₀₀  | Flux Density | Spectral Index |
|--------|--------|--------|--------------|----------------|
| ALMA1  | 05 35 14.225 | −05 22 28.02 | 18 ± 2 | 1.47 ± 0.15 |
| ALMA2  | 05 35 14.428 | −05 22 33.56 | 41 ± 5 | 1.48 ± 0.18 |
| ALMA3  | 05 35 14.802 | −05 22 30.69 | 31 ± 3 | 1.56 ± 0.13 |

Notes.

a These parameters were obtained from a Gaussian fit using the viewer in CASA.

b Positional errors are ~0″05 for R.A. and decl.

Figure 2. ALMA continuum band 7 (0.8 mm) contour and color-scale images from the HMC located in Orion-KL. Upper panel: continuum image using the full uv-range from the ALMA observations. The contours start at 30% and go up to 90% in steps of 5% of the intensity peak. The intensity peak is 0.561 Jy Beam⁻¹. The half-power contour of the synthesized beam of the image is shown in the bottom-left corner. Lower panel: continuum image using only part of the uv-range (>150 kλ) from the continuum observations. The contours start at 10% and go up to 90% in steps of 5% of the intensity peak. The intensity peak is 0.453 Jy Beam⁻¹. The synthesized beam size is shown in the bottom-left corner. The position of the source SMA1 is indicated with a cross, see Beuther et al. (2005). Both images are corrected by the primary beam attenuation. The spatial scale bar is presented in bottom-right corner.
In these maps, the Orion BN object is marked with a red asterisk. The spatial scale bar is presented in bottom-right corner. The intensity peak of the source SMA1 is indicated with a cross. The half-power contour of the synthesized beam of the image is shown in the bottom-left corner. The position of the peak of the hot molecular gas as traced by the NH$_3$ is 0.461 Jy Beam$^{-1}$. The half-power contour of the synthesized beam of the image is shown in the bottom-left corner. The position of the peaks of the hot molecular gas as traced by the CH$_3$CN contours start at 55% and go up to 90% in steps of 5% of the intensity peak. The intensity peak of the source SMA1 is indicated with a cross, see Beuther et al. (2005). Both images are corrected by the primary beam attenuation. The blue asterisks mark the position of the peak of the hot molecular gas as traced by the CH$_3$CN(12$_{20}$, 11$_{11}$) with an upper level energy over the ground of 646 K, see Zapata et al. (2011). The red asterisk marks the position of the peak of the hot molecular gas as traced by the CH$_3$CN(12$_{20}$, 11$_{11}$) with an upper level energy over the ground of 1456 K, see Goddi et al. (2011). None of these positions coincide with the submillimeter compact sources reported in this paper. ALMA1 is not detected in the band 9 observations, possibly because the observations are too noisy and, in addition, this source is close to the edge of the primary beam.

In Figure 3, we present the results of the ALMA observations in bands 6 and 9 with a temperature in the upper level of 1456 K, see Goddi et al. (2011). The positions of the peak of the hot molecular gas as traced by the CH$_3$CN(12$_{20}$, 11$_{11}$), with a temperature in the upper level of 646 K, is also included in Figure 3, see Zapata et al. (2011). None of these positions coincide with the submillimeter compact sources reported in this paper. ALMA1 is not detected in the band 9 observations, possibly because the observations are too noisy and, in addition, this source is close to the edge of the primary beam.

In Figure 4, we present the spectral energy distributions (SEDs) of the detected compact sources from the millimeter to submillimeter wavelengths.
so steep compared with those reported to be associated with optically thick thermal dust emission (about 2–3), but this is probably due to possible grain growth that flattens the spectral indices (Draine 2006). We thus conclude that we are possibly detecting moderate, optically thick thermal dust emission. Taking the values of their flux densities at 658 GHz, we estimate brightness temperatures of about 100 to 200 K. This again suggests that we are seeing dust emission. An estimation of the mass from the dust emission for these submillimeter objects seems unreliable, as the emission is moderate optically thick. Finally, we also construct the spectral index for Source I and compare the resulting value (see Table 2) with those reported in the literature, see Hirota et al. (2015, 2016), Plambeck & Wright (2016). The value of 1.8 for the spectral index for Source I reported in Hirota et al. (2015) is the closest to that found in this study, which confirm that the derived spectral indices of the ALMA1-3 continuum sources in this work are reliable. We also have compared the flux densities of the ALMA compact sources reported here with the full and restricted uv-ranges, and find that these are very similar. Moreover, we restrict the images to similar uv-ranges for band 6 and 9 observations, and find similar values for the flux densities presented in Table 2.

We found that ALMA1 is well coincident (within a 0′′8 error) with the millimeter source found in CARMA observations, FW2011-C14 (Friedel & Widicus Weaver 2011), and the mid-infrared extended object called [RLK73] IRc6E (Shuping et al. 2004). However, as the mid-infrared is very extended it is difficult to know if they are really connected. For ALMA2 and ALMA3, we also find that, within the position errors, these submillimeter objects are coincident with the CARMA millimeter objects FW2011-C14 and FW2011-C22 (Friedel & Widicus Weaver 2011), respectively. Additionally, we found that ALMA3 is associated with the compact mid-infrared object [RLK73] IRc12 (Shuping et al. 2004). Robberto et al. (2005) reported that [RLK73] IRc12 is a very luminous object with a bolometric luminosity of 4 × 10^5 L_☉, between 7.7 and 12.4 μm. This luminosity corresponds to a high-mass star.

As mentioned before in Figure 3, we have included the positions of the peaks of the hot molecular gas as traced by the NH3(12,12) and CH3CN(12a,11b), and found that these positions do not coincide with any of the submillimeter objects reported in this study. Even the infrared object [RLK73] IRc12, which is associated with ALMA3 and may be a high-mass (proto)star, is too far away from the hot molecular gas. Additionally, the other IR sources and massive stars are also not associated with hot molecular gas. We thus conclude that the hot molecular gas in the Orion-KL core is probably heated externally.

If the HMC is heated internally, we expect young massive stars in the middle of the hot molecular gas, but if the heating is external then the core should be illuminated from the edges; this physical effect has been already traced by radio observations made by Zapata et al. (2011) and Goddi et al. (2011). According to the results reported in the present paper, and those from Zapata et al. (2011) and Goddi et al. (2011), an externally heated model seems to fit much better with the HMC in Orion-KL. We thus favor the hypothesis that the hot molecular core in Orion-KL core is heated externally.

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ORCID iDs
Luis A. Zapata https://orcid.org/0000-0003-2343-7937
Tomoya Hirota https://orcid.org/0000-0001-1659-095X

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