Evidence for Dense Gas Heated by the Explosion in Orion KL

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Abstract

We mapped the kinetic temperature structure of Orion KL in a ~20′ (~8000 au) sized region with para-H2CS 707 – 606, 725 – 625, and 725 – 624, making use of Atacama Large Millimeter/submillimeter Array Band 6 Science Verification data. The kinetic temperatures obtained with a resolution of 1″65 × 1″14 (~550 au) are deduced by modeling the measured averaged velocity-integrated intensity ratios of para-H2CS 725 – 625/707 – 606 and 725 – 624/707 – 606 with a RADEX non-LTE model. The kinetic temperatures of the dense gas, derived from the para-H2CS line ratios at a spatial density of 107 cm−3, are high, ranging from 43 to >500 K with an unweighted average of ~170 K. There is no evidence for internal sources playing an important role in the heating of the various structures identified in previous work, namely the elongated ridge, the northwestern clump, and the eastern region of the compact ridge, while the high temperatures in the western region of the compact ridge may be dominated by internal massive star formation. Significant gradients of kinetic temperature along molecular filaments traced by H2CS indicate that the dense gas is heated by the shocks induced by the enigmatic explosive event which occurred several hundred years ago and greatly affected the energetics of the Orion KL region. Thus, with the notable exception of the western region of the compact ridge, the high temperatures of the dense gas in Orion KL are probably caused by shocks from the explosive event, leading to a dominant component of externally heated dense gas.

Unified Astronomy Thesaurus concepts: Interstellar medium (847); Interstellar clouds (834)

1. Introduction

1.1. The Energetics of the Orion KL Nebula

The Kleinmann–Low (KL) nebula (Kleinmann & Low 1967) is one of the richest known sources of molecular line emission at millimeter and submillimeter wavelengths (e.g., Blake et al. 1987). There are several reasons for this: first, at a distance of ∼400 pc (Menten et al. 2007; Kim et al. 2008; Kounkel et al. 2017) it is the nearest interstellar source containing a molecular spectrum that is characterized by a high temperature, which in some parts exceeds 150 K. Second, it is located in the most (submillimeter) luminous part of a 7 pc long high column density filament (Johnstone & Bally 1999) that is heated to this high temperature. This causes a plethora of molecules to evaporate off dust grain mantles, where they attained substantial abundances in ice form while the region was at a lower temperature. This caused the region to become the eponymous “hot core” (Ho et al. 1979), although in contrast to the many hot cores found in high-mass star-forming regions, it does not contain a central heating source (Zapata et al. 2011). The energetics of the hot and dense molecular gas on a scale of a few thousand astronomical units, the topic of this study, has been the subject of abundant previous work.

An obvious cause for the high temperatures is the energetic explosion that is thought to have occurred in the Orion KL nebula about 550 yr ago (Bally & Zinnecker 2005; Zapata et al. 2009; Bally et al. 2011, 2017). Spectacular evidence comes from near-infrared (NIR) emission from shock-excited molecular hydrogen, H2, first detected by Beckwith et al. (1978) and from NIR and optical lines from neutral atoms and ions (Allen & Burton 1993) that were found to form finger-like filaments (e.g., Kaifu et al. 2000). The finger-like filaments were also detected in millimeter-wavelength emission from CO (Zapata et al. 2009). Emission in the CO J = 2–1 line was recently imaged with the Atacama Large Millimeter/submillimeter Array (ALMA). It shows, at velocities outside of vLSR = 0 to 20 km s−1, a large number of radial streamers covering the entire range of position angles and occupying a region with radius 50′ (Bally et al. 2017). This differs from the NIR H2 emission, part of which is absorbed by massive dust emission associated with the KL nebula (Johnstone & Bally 1999). The CO filaments and H2 fingers can be traced back to a common origin (Zapata et al. 2009; Bally et al. 2011, 2015, 2017) that is consistent with the position to which the proper motions of various radio- and NIR-emitting young stellar projects can be traced back in space and time (Gómez et al. 2005, 2008; Rodríguez et al. 2005, 2017, 2020; Luhman et al. 2017; Bally et al. 2020). Based on their Very Large Array (VLA) proper motion determinations, Rodríguez et al. (2017) determine the year 1445 ± 6 as the time when the most prominent radio sources, Source I (Src I) and the Becklin–Neugebauer object (BN), were closest together.

These findings constitute persuasive evidence that the explosion resulted from the merger of young stellar objects, at least one of them massive (Src I), a scenario first discussed by Bally & Zinnecker (2005) in which the 1048–1049 erg injected into the region represent binding energy released by
Velocities were integrated from $v_{LSR} = 3$ to $11$ km s$^{-1}$. The black contour levels start at 2.2 Jy beam$^{-1}$ km s$^{-1}$ ($-32\sigma$) and increase in intervals of 2.2 Jy beam$^{-1}$ km s$^{-1}$ for para-H$_2$CS $7_{07} - 6_{06}$ (left) and at 1.1 Jy beam$^{-1}$ km s$^{-1}$ ($-16\sigma$) with spacings of 1.1 Jy beam$^{-1}$ km s$^{-1}$ for para-H$_2$CS $7_{25} - 6_{24}$ (middle) and $7_{26} - 6_{25}$ (right), respectively. The green contours represent the 1.2 mm continuum emission with levels from 0.07 ($-7\sigma$) to 1.07 Jy beam$^{-1}$ and steps of 0.2 Jy beam$^{-1}$. The red star, red circle, red square, red diamond, and red points show the locations of the putative explosive center, Src I, SMA1, H$_2$O maser burst, and compact continuum sources (Hirot a et al. 2015), respectively. The beam size is shown in the lower left corner.

Figure 1. Gray maps and black contours show velocity-integrated intensity distributions of para-H$_2$CS $7_{07} - 6_{06}$ (left), $7_{25} - 6_{24}$ (middle), and $7_{26} - 6_{25}$ (right). The radio source Src I (Churchwell et al. 1987; Menten & Reid 1995), the primary remnant source of the erstwhile multiple stellar system, has been speculated to be a close binary itself that is surrounded by a Keplerian disk whose rotation curve indicates a mass of $15\ M_\odot$ (Ginsburg et al. 2018). To make an already complex situation even more complicated, Src I is driving a bipolar molecular outflow along a northeast-southwest axis that may also contribute to the KL region’s energetics (Plambeck et al. 2009).

Indeed, imaging of the high excitation NH$_3$ ($J, K$) = (6,6)–(12,12) inversion transitions suggests that substantial parts of the NH$_3$-bearing hot molecular gas in Orion KL may be heated by the outflow from Src I and also by ram pressure due to the source’s motion reaching NH$_3$ temperatures up to $\sim490$ K (Goddi et al. 2011). This picture is corroborated by observations of CH$_3$CN $J = 18$–17 reported by Wang et al. (2010). Within this context, Favre et al. (2011) and Wang et al. (2011) suggested that this outflowing gas may also heat a part of the compact ridge, which is located $\sim8''$ ($\sim3300$ au) to the southwest (see Figure 1).

In contrast (or complementarily), Zapata et al. (2011) and Orozco-Aguilera et al. (2017) proposed that the hot core in the elongated ridge is externally heated by the abovementioned explosion. Recent observations of H$_2$CO $J = 3$–2 also indicate that the dense gas may be influenced by this explosion (Tang et al. 2018a). While an impact from the violent explosion on the surrounding gas in the Orion KL region may be expected, it is not yet clear whether this can be considered as the dominant heating source in at least some parts of the Orion KL region.

1.2. H$_2$CS as a Temperature Probe

Thioformaldehyde (H$_2$CS), like H$_2$CO a slightly asymmetric rotor molecule, exhibits a large number of millimeter and submillimeter transitions (e.g., Wootten et al. 2009; Tercero et al. 2010; Widicus Weaver et al. 2017; Luo et al. 2019; Brinkmann et al. 2020; Hoff et al. 2020; Johnston et al. 2020). It is a sensitive tracer for probing the kinetic temperature, $T_{kin}$, of dense gas with line ratios involving different $K_a$ ladders because the relative populations of the $K_a$ ladders of H$_2$CS are governed by collisions (Mangum & Wootten 1993; Wootten et al. 2009; Oya et al. 2016; Hoff et al. 2020). Since the frequencies are close for the same J transitions belonging to different $K_a$ ladders (e.g., $J = 7$–6, 8–7, 10–9), these transitions can be easily covered within a single spectral band and be observed simultaneously. This minimizes observational uncertainties, such as differences in spatial resolution, uncertainties in absolute flux calibration, and deviating pointing errors. Previous observations indicate that H$_2$CS has a lower abundance than H$_2$CO in star formation regions (e.g., Tercero et al. 2010; Nagy et al. 2015). The transitions of H$_2$CS at millimeter or submillimeter wavelengths are only weakly affected by opacity effects (e.g., Nagy et al. 2015; Luo et al. 2019, and our Section 3.4). Therefore, H$_2$CS can trace physical conditions of denser gas than H$_2$CO (e.g., Mangum & Wootten 1993; Wootten et al. 2009; Tang et al. 2017a, 2017b, 2018a, 2018b; Hoff et al. 2020).

Making use of the attractive properties of thioformaldehyde, we provide maps of the kinematic temperature structure of the Orion KL region based on the three transitions of para-H$_2$CS $J_{K_a,K_c} = 7_{07} - 6_{06}$, $7_{26} - 6_{25}$, and $7_{25} - 6_{24}$, and investigate the potential heating sources of the dense gas. In Sections 2 and 3, we introduce archival H$_2$CS data, describe the data reduction, and outline the main observational results. The obtained dense gas temperatures are then discussed in Section 4. Our main conclusions are summarized in Section 5.

2. Archival Data and Their Analysis

The data of the para-H$_2$CS triplet were taken as part of the ALMA Science Verification. The observations of Orion KL (Project: 2011.0.00099.SV) were carried out by ALMA in band 6 with the 12 m array including 16 antennas on 2012 January 20. The projected length of the baselines ranged from 17–265 m. Flux and bandpass fluctuations were calibrated by
observations of Callisto, while the phase fluctuations were calibrated using the quasar J0607-085. Twenty spectral windows of 1.875 GHz bandwidth and 3840 channels each were used during the observations resulting in a spectral resolution of 0.488 MHz (~0.61 km s\(^{-1}\) at 240 GHz). Here, only the spectral window “spw 12” (239.848–241.723 GHz) was selected, which includes all the para-H\(_2\)CS \(J = 7–6\) lines used in this work.

The data reduction was performed using CASA\(^5\) (McMullin et al. 2007). The calibrated data was imaged using the tclean algorithm with Briggs robust parameter 0.5, achieving a beam size of 1\(^\prime\)65 \(\times\) 1\(^\prime\)14 and setting a pixel size of 0\(^\prime\)2 \(\times\) 0\(^\prime\)2. The cleaned image was corrected for the primary beam response of the ALMA antenna. From the corrected image, a continuum image and a continuum-subtracted line cube were simultaneously produced using the python-based tool STATCONT\(^6\) (Sánchez-Monge et al. 2018). The line cubes of para-H\(_2\)CS \(J = 7_{07}–6_{06}\), \(7_{25}–6_{24}\), \(7_{25}–6_{25}\), \(7_{26}–6_{24}\), \(7_{26}–6_{25}\), \(240.382\) GHz; \(E_u/k = 98.8\) K, and \(7_{26}–6_{25}\) (240.382 GHz; \(E_u/k = 98.8\) K) were then extracted from the continuum-subtracted line cube. The typical rms for the lines is \(~30\) and \(~10\) mJy beam\(^{-1}\) for the continuum. Observed spectra toward three selected positions of Orion KL are shown in Figure 2.

3. Results

3.1. Continuum Emission

The \(~1.2\) mm (240 GHz) continuum emission distribution is presented in Figure 1. It is mainly associated with the elongated ridge seen on a large scale (Johnstone & Bally 1999) with the major axis along northeast–southwest direction, the compact ridge and the northwestern clump of the Orion KL region. This is consistent with previous observational results obtained with the Submillimeter Array (SMA; e.g., Tang et al. 2010; Feng et al. 2015), Plateau de Bure Interferometer (e.g., Favre et al. 2011), and ALMA (e.g., Hirota et al. 2015; Pagani et al. 2017). In the Orion KL region, 11 compact sources (see Figure 1) with convolved sizes \(<1\)\(^\prime\) (<450 au) and volume densities \(10^{8}–10^{9}\) cm\(^{-3}\), including well-known sources such as Src I and SMA1, have been identified using subarcsecond angular resolution and sensitive ALMA data at both bands 6 and 7 (Beuther et al. 2004; Hirota et al. 2015). One of the compact sources detected in the western region of the compact ridge is associated with the location of the strong, occasionally bursting, water masers (Hirota et al. 2011, 2014, 2015). No compact source is detected in the northwestern clump where the continuum emission detected in our data is completely resolved in higher angular resolution ALMA data (Hirota et al. 2015). In addition, three of the compact sources identified by Hirota et al. (2015) are not located in one of the main molecular components. Two of these compact objects are associated with infrared sources (IRc4 and IRc7) while the remaining one is not detected in our data due to limited sensitivity (Shuping et al. 2004; Hirota et al. 2015).

3.2. Spatial Distribution of H\(_2\)CS

In addition to the 1.2 mm continuum, Figure 1 also shows the integrated intensity maps of para-H\(_2\)CS \(J = 7_{07}–6_{06}\), \(7_{25}–6_{24}\), and \(7_{26}–6_{25}\) overlaid on the continuum emission. It shows that the morphology of the H\(_2\)CS triplet is consistent with the continuum emission, indicating that dense gas traced by para-H\(_2\)CS \(J = 7–6\) is closely associated with the dust traced at 1.2 mm in the Orion KL region. Few H\(_2\)CS emission peaks reveal minor offsets from the continuum emission peaks (see Figure 1). The largest offset is \(~18\)\(^{\prime}\) (\(~750\) au) between the peaks of continuum emission and H\(_2\)CS in the elongated ridge. The morphology of para-H\(_2\)CS \(7–6\) emission in the Orion KL region is similar to results previously obtained with other molecular tracers, e.g., NH\(_3\), H\(_2\)CO, CH\(_3\)OH, CH\(_3\)CN, HCOOCH\(_3\), HC\(_3\)N, and SO\(_2\) (e.g., Wilson et al. 2000; de Vicente et al. 2002; Wang et al. 2010; Favre et al. 2011;
Goddi et al. 2011; Gong et al. 2015; Peng et al. 2017; Luo et al. 2019; Pagani et al. 2019). However, the northern clump was not always detected. For example, it was seen in the metastable NH₃(J,K) = (6,6)-(9,9) transitions but not in transitions beyond J = K = 9 (Goddi et al. 2011). Furthermore, it was only detected in one transition of the CH₃CN J = 18–17 multiline study by Wang et al. (2010), in the K = 4 transition.

3.3. H₂CS Line Ratios

Since para-H₂CS 725 – 624 and 726 – 625 have similar upper-state energies above the ground state (see Section 2) and similar line profiles (for flux densities, line widths, and velocities of our data, see Figure 2), the averaged ratio para-H₂CS 0.5 × [(725 – 624 + 726 – 625)/707] between para-H₂CS 725 – 624/707/606 and 726 – 625/707/606 is used in this work. Velocity-integrated intensity ratio maps of para-H₂CS 0.5 × [(725 – 624 + 726 – 625)/707] detected above a signal-to-noise ratio of ~30 and derived from velocity-integrated intensities in the Orion KL region are shown in Figure 3. The para-H₂CS line ratios range from 0.30 to 1.42 with an average of 0.68 ± 0.16 (errors given here and elsewhere are standard deviations of the mean) for the colored regions in Figure 3. Ratios are found between 0.65 and 1.42 with an average of 0.87 ± 0.13 in the elongated ridge, between 0.38 and 0.99 with an average of 0.65 ± 0.12 in the compact ridge, and between 0.30 and 0.91 with an average of 0.58 ± 0.11 in the northwestern clump. Averages were calculated, taking each line ratio value with the same weight. Figure 3 shows immediately, even without a detailed analysis, that ratios are particularly high near Sgr I and the supposed location of the explosive event, becoming lower farther away from it. Locally, higher para-H₂CS line ratios are also associated with the western dense gas component of the compact ridge.

For the para-H₂CS triplet, compared to the single-dish APEX 12 m data (beam size ~26″, Brinkmann et al. 2020), the fluxes recovered by ALMA data are ~70%, ~90%, and ~90% for para-H₂CS 707 – 606, 725 – 624, and 726 – 625, respectively. Since the maximum recoverable scale is ~8″7, the missing flux may mostly be due to large-scale structure filtered out by the interferometer. And the larger amounts of the missing flux in the 707 – 606 transition may be caused by the fact that this transition requires less excitation to become detectable than the other two. Thus line ratios can be overestimated by not more than 22% if the missing flux densities are assumed to be ~30%, ~10%, and ~10% for para-H₂CS 707 – 606, 725 – 624, and 726 – 625, respectively. However, the more compact and dense the regions are, the smaller the proportion of the flux that will be missed. The para-H₂CS triplet traces compact emission regions, and exhibits nearly identical structures in Orion KL (see Figure 1), so the line ratios of para-H₂CS may only be weakly influenced by filtered out emission.

3.4. Kinetic Temperatures from H₂CS Line Ratios

Using the non-local thermodynamic equilibrium (non-LTE) radiation transfer code RADEX7 (van der Tak et al. 2007) coupled with collision rates from the Leiden Atomic and Molecular Database8 derived by Wiesenfeld & Faure (2013), a set of simulations has been carried out in order to explore the relationship between the gas kinetic temperature and the integrated intensity ratios of para-H₂CS 725 – 624/707/606 and 726 – 625/707/606 (see Figure 4). In the Orion KL region, previous measurements indicate that gas volume densities of H₂ are quite high, around 10⁹ cm⁻³, and even higher in compact regions (e.g., Gong et al. 2015; Pagani et al. 2017). Additionally, the column densities of H₂ measured from H₂CO are ≥10²⁴ cm⁻² (Mangum & Wootten 1993). Figure 4 shows that the gas kinetic temperatures estimated from the para-H₂CS 7–6 line ratios are nearly independent of the H₂ volume density (n_H₂) and para-H₂CS column density (N_p-H₂CS) at n_H₂ ≥ 10⁷ cm⁻³ and N_p-H₂CS ≤ 6 × 10¹⁵ cm⁻² per km s⁻¹. Therefore, the gas kinetic temperatures can be directly estimated from the integrated intensity ratios of para-H₂CS.

Observations of H₂CS and its isotopologues suggest that para-H₂CS(7–6) lines are optically thin in the Orion KL region (Tercero et al. 2010; Luo et al. 2019). The total velocity-integrated beam-averaged (~10⁹) column density of para-H₂CS is ~5 × 10³⁴ cm⁻², obtained from IRAM 30 m observations (Tercero et al. 2010). Under the assumption of optically thin conditions for the para-H₂CS(7–6) triplet, n_H₂ = 10¹⁰ cm⁻³, and N_p-H₂CS = 5 × 10¹⁴ cm⁻² and an adopted line width Δν = 5 km s⁻¹ from our data and a 2.73 K background temperature, the gas kinetic temperature is estimated from the line ratios of para-H₂CS 0.5 × [(725 – 624 + 726 – 625)/707] (see the right panel of Figure 4).

As mentioned in Section 2, para-H₂CS 725 – 624 and 726 – 625 have almost identical upper-state energies above the ground state (E_u/k = 98.8 K) and, according to Section 3.3, similar observed line profiles. The resulting gas kinetic temperatures derived from para-H₂CS 725 – 624/707/606 and 726 – 625/707/606 are similar at n_H₂ = 10⁷ cm⁻³ and N_p-H₂CS = 5 × 10¹⁴ cm⁻² (see Figure 4), so we use the averaged integrated ratio of para-H₂CS 0.5 × [(725 – 624 + 726 – 625)/707] already introduced in Section 3.3, as a measure of excitation to determine the gas temperature in this work. The simulated results indicate that the optical depth for para-H₂CS 7–6 decreases as the gas temperature increases. The optical depths for N_p-H₂CS = 5 × 10¹⁴ cm⁻² are less than 0.3 for para-H₂CS 707 – 606 and less than 0.09 for para-H₂CS 725 – 624 and 726 – 625 when the gas temperature is greater than 43 K. The optical depth for para-H₂CS 707 – 606 decreases rapidly to 0.09 when the gas temperature increases to 100 K.

Uncertainties of the gas temperature can be estimated from formula (dR/dT_k) = R × (S/N) × √(0.5 + R²), where the dR/dT_k represents the first derivative of T_k as a function of the R, which can be calculated numerically. R represents the velocity-integrated ratio of para-H₂CS 0.5 × [(725 – 624 + 726 – 625)/707] and S/N represents the signal-to-noise ratio of the para-H₂CS 707 – 606 line. For our data, the uncertainties are <15%, <20%, and >25% for gas temperatures ≤200, ≤400, and >500 K, respectively. The uncertainties estimated here are exclusively based on the errors of the integrated line intensity fits, because the relative calibration errors for the three lines should be very small in view of the simultaneous measurements and virtually identical atmospheric conditions.

Generally, higher para-H₂CS line ratios indicate higher kinetic temperatures (see Figure 4, right panel), so the line ratio map of para-H₂CS (Figure 3) can be used as a proxy for kinetic...
temperatures. The kinetic temperatures of dense gas derived from the para-H$_2$CS 7–6 line ratios in the Orion KL region are high and cover a wide range, from 43 to $>500$ K with an average of $\sim$170 K at density $n_{\text{H}_2} = 10^7$ cm$^{-3}$. Gas kinetic temperatures from 148 to $>500$ K with an average of $>500$ K are found in the elongated ridge, from 56 to $>500$ K with an average of $\sim$150 K in the compact ridge, and from 43 to $>500$ K with an average of $\sim$110 K in the northwestern clump. The average values of gas kinetic temperatures are directly derived from the averaged values of the para-H$_2$CS(7–6) line ratios (taking each line ratio value with the same weight) presented in Section 3.3, making use of the monotonic rise of $T_{\text{kin}}$ with increasing integrated line intensity ratio.

4. Discussion

4.1. Gas Temperatures

The gas kinetic temperatures obtained from para-H$_2$CS line ratios indicate a highly nonuniform temperature distribution in Orion KL, which reveals that highest temperatures
Figure 4. Gas kinetic temperature modeled with RADEX, with the $T_{\text{kin}}$ scale on the left representing the ordinate for all three panels. The gas kinetic temperature as a function of $n_{\text{H}_2}$ ($N_{-}\text{-HCS} = 5 \times 10^{14} \text{ cm}^{-2}$ and $\Delta v = 5 \text{ km s}^{-1}$) and para-HCS column density ($n_{\text{H}_2} = 10^2 \text{ cm}^{-3}$ and $\Delta v = 5 \text{ km s}^{-1}$) are shown in the left and central panel, respectively. Kinetic temperatures as a function of para-HCS line intensity ratios (the black line stands for the abovementioned $N_{-}\text{-HCS} = 5 \times 10^{14} \text{ cm}^{-2}$, $n_{\text{H}_2} = 10^2 \text{ cm}^{-3}$ and $\Delta v = 5 \text{ km s}^{-1}$) are shown in the right panel, which demonstrates that line ratios are insensitive to any relevant parameter except kinetic temperature as long as the lines are optically thin. Green circles provide para-H2CS $^{725}(N_{-}\text{-HCS} = 5 \times 10^{14} \text{ cm}^{-2}$, $n_{\text{H}_2} = 10^2 \text{ cm}^{-3}$ and $\Delta v = 5 \text{ km s}^{-1}$) are shown in the right panel, which demonstrates that line ratios are insensitive to any relevant parameter except kinetic temperature as long as the lines are optically thin. Green circles provide para-H2CS $^{725}$ line ratios for $n_{\text{H}_2} = 10^2 \text{ cm}^{-3}$, $N_{-}\text{-HCS} = 5 \times 10^{14} \text{ cm}^{-2}$, and $\Delta v = 5 \text{ km s}^{-1}$, and black plus symbols denote the corresponding values for the $725-6_{25}$ and $725-6_{26}$ line ratios. For para-H-CS column densities of $10^{13}$ and $10^{14} \text{ cm}^{-2}$ and the abovementioned density and line width, para-H2CS $0.5 \times (725-6_{24} + 725-6_{23} + 725-6_{26})$ line ratios are plotted by red and blue solid lines, respectively. Note that red, blue, and black lines become indistinguishable at high kinetic temperatures, even after magnification, on the scale of this plot.

$T_{\text{kin}} > 500 \text{ K}$ are not rotation but kinetic temperatures, making use of the suitable properties of the $N_{-}\text{-HCS}$ molecule. Furthermore, this molecule provides an insight into the densest parts of Orion KL, revealing an unprecedented and particularly detailed view of the kinetic temperature and its gradients across the source. Our resulting $T_{\text{kin}}$ values reach a maxima near the supposed location of the explosive event and become lower farther away from it (see Figure 3). This has not been seen in such clarity before, e.g., in the rotation temperature maps derived from NH3 and SO2 (Wilson et al. 2000; Goddi et al. 2011; Luo et al. 2019). While NH3 is thought to be an excellent and commonly used gas kinetic temperature tracer of star-forming regions (Ho & Townes 1983; Li et al. 2013; Lu et al. 2014; Friesen et al. 2017; Wu et al. 2018; Zhou et al. 2020), it is a lower density gas tracer and is not exclusively probing the very dense gas with $\sim 10^3 \text{ cm}^{-3}$ and even higher values in the Orion KL region. For example, the critical density of NH$_3$(6,6) is around $(1.7-2.5) \times 10^3 \text{ cm}^{-3}$, while the corresponding value for our para-H2-CS 7–6 lines is $\sim 2 \times 10^3 \text{ cm}^{-3}$ at kinetic temperatures 10–300 K. Besides, NH3(6,6), where the hyperfine satellite lines were not covered, is probably affected by line saturation. For example, we made an estimation of $N_{\text{H}_2}(6,6)$ opacity $\tau(N_{\text{H}_2}(6,6)) > 1$ by running RADEX under assumptions of $T_{\text{kin}} = 300 \text{ K}$, $n_{\text{H}_2} = 10^6 \text{ cm}^{-3}$, $N_{\text{ortho}}-N_{\text{para}} = 1.5 \times 10^{17} \text{ cm}^{-2}$, and $\Delta v = 10 \text{ km s}^{-1}$ following the results obtained from Goddi et al. (2011). It needs to be confirmed through further hyperfine structure observations (from a 40$''$ beam size single-dish measurement Hermens et al. (1988)

\footnote{The critical density (assuming optically thin emission) is estimated from $n_{\text{crit}} = A_{\text{sp}}/C_{\text{e}}$, $A_{\text{sp}}$ and $C_{\text{e}}$ represent the Einstein coefficient for spontaneous emission and the collision rate, respectively. The values are obtained from the Leiden Atomic and Molecular Database via \url{https://home.strw.leidenuniv.nl/~moldat/d/}.}
derive an overall opacity of 14 (their Table 4) for the (6,6) line in the hot core).

SO$_2$ is generally not thought to be a gas kinetic temperature tracer and the rotation temperatures derived may differ from the gas kinetic temperatures. In the cases of CH$_3$CN, HC$_3$N, and HCOOCH$_3$, there are no rotation temperature maps available for the Orion KL region. Based on present calculated results on several positions, low transitions of CH$_3$CN(18$K$–17$K$; $K = 0$–4) are optically thick in Orion KL (Wang et al. 2010). Furthermore, HCOOCH$_3$ is likely to trace lower temperatures of gas compared to other molecular tracers (Favre et al. 2011). As mentioned in Section 1, para-H$_2$CO($J = 3$–2 and 4–3) is a good dense gas kinetic temperature tracer. However, line ratios of para-H$_2$CO $J = 3$–2 and 4–3 are insensitive to the detection of temperatures in excess of 150 K (Mangum & Wootten 1993; Immer et al. 2016; Tang et al. 2018b).

To summarize, for the specific case of the very dense and hot Orion KL region the molecular species mentioned above appear not to be suitable for tracing the kinetic temperature of the dense gas as well as H$_2$CS. Various limitations, e.g., opacity, sensitivity, and poorly constrained correlations between excitation and kinetic temperatures will affect the results. So, para-H$_2$CS appears to be quite a suitable tracer to measure high temperatures of dense gas in Orion KL region.

4.2. Impact of the Explosive Outflow

High temperatures are associated with the northern and southwestern edges of the elongated ridge region (see Figure 3). These two regions appear to be associated with the outflow traced by SiO emission along a northeast–southwest axis emanating from Src I (see Figure 1 in Plambeck et al. 2009). However, this outflow is quite slow ($<20$ km s$^{-1}$), suggesting that the outflow may not play a significant role in heating the dense gas in the northern edge and southwestern corner of the elongated ridge region. Instead, the maximum velocity of the CO $J = 2$–1 bullets produced from the explosion can reach up to $\sim 160$ km s$^{-1}$ within a radius of $\sim 50^\prime$ ($\sim 0.1$ pc) centered on the location of the explosive event revealed by recent ALMA observations with a beam size of $\sim 1^\prime$ (Bally et al. 2017). This indicates that it is the explosion that strongly impacts on the dense gas in the $\sim 20^\prime$ sized region of Orion KL. High-velocity ($>100$ km s$^{-1}$) CO $J = 2$–1 and 3–2 bullets ejected from the explosion and detected by the SMA appear to be blocked and absorbed in the elongated ridge (Zapata et al. 2009, 2011). Further observations show that the dense regions including the compact ridge and the northern clump also lack the CO bullets, while strong class I CH$_3$OH maser emission in the $J_2 – J_1$ $E$ transitions near 25 GHz $J = 4$, 5, ... is found in this general area (Johnston et al. 1992). Class I CH$_3$OH masers are excited by shocks (Leurini et al. 2016). However, no direct spatial correspondence appears to exist between these masers and other energetic phenomena, a fact that remains to be investigated.

Previous observations of several molecular species, e.g., SiO, H$_2$CO, and CH$_3$OH, show the filamentary structure of the Orion KL region (Plambeck et al. 2009; Gong et al. 2015; Pagani et al. 2019), which may be shaped by the explosion. To define the exact directions of the strong interaction between explosive outflow and dense gas, high sensitivity ALMA observations of several molecular species have been carried out (Pagani et al. 2019). Elongated molecular tail structures along arrows 1–8 in Figure 3 are clearly detected in H$_2$CO(9$_{15}$–9$_{19}$), which are interpreted in terms of a strong interaction of the dense gas with the high-velocity ejecta from the explosion (Pagani et al. 2019). Several of these molecular tail structures are also identified by our para-H$_2$CS ($\tau_{\text{line}} - \tau_{\text{line}}^0$) data (see arrows 4–8 in Figure 3), but they are not as long as those seen in H$_2$CO (Pagani et al. 2019), which can be used to trace less dense gas.

Following the directions of the molecular tails shown in Figure 3, we investigate the para-H$_2$CS line ratios and gas kinetic temperatures along these molecular tails. The farther from the location of the explosive event a molecular tail is starting, the higher the ratios and the gas kinetic temperature at the closest approach is (see Figures 3 and 5). This might be a consequence of our viewing angle toward the source, providing projected but not real distances. The temperature gradients along the molecular tails 2, 4, 5, 6, 7, and 8 identified with para-H$_2$CS (see Figures 3 and 5) indicate that the dense gas is heated by shocks initiated by the explosion, which occurred around 550 yr ago. This was not revealed by previous gas temperature measurements with NH$_3$ (4,4) and(10,9), and (6,6)–(12,12) (Wilson et al. 2000; Goddi et al. 2011) or SO$_2$ (Luo et al. 2019) and provides direct evidence for most parts of the Orion KL region being heated by an external source. This agrees with previous suggestions (e.g., Wilson et al. 2000; Wang et al. 2010, 2011; Favre et al. 2011; Goddi et al. 2011; Zapata et al. 2011; Orozco-Aguilera et al. 2017; Peng et al. 2017).

Very high temperatures are not associated with the dense gas in the northern clump (see Figure 3). However, this clump also shows a distinct temperature gradient (see the molecular tail 7 in Figures 3 and 5). This suggests that the dense gas in the northern clump is also most likely heated by shocks from the explosive outflow. The generally lower $T_{\text{kin}}$ values may be due to a location either a little in front or behind the elongated ridge. Additionally, the motions of the CO high-velocity ejecta toward the northwest might follow the plane of the sky (Bally et al. 2017), so that only a small percentage of the ejecta have...
interacted with the northwestern clump, leading to lower temperatures than in the other regions.

High temperatures are found in a tiny region near the southeastern edge of the northwestern clump. This region is associated with continuum source IRc7 (see Figure 3), suggesting that the continuum source IRc7 has some impact on its immediate neighborhood. However, because of its spatially limited impact, we still find that the dense gas in the northwestern clump is predominantly heated by the shocks produced from the explosion.

In the compact ridge, which is in projection farther away from the site of the explosion, internal heating plays a more important role. Intense 22 GHz H$_2$O maser emission (Hirota et al. 2011, 2014) is associated with the western half of the compact ridge (see Figure 3). This indicates that here the high temperature of the dense gas may be dominated by local massive star formation activity.

5. Conclusions

We have mapped the kinetic temperature structure of Orion KL in a ~20″ (~8000 au) sized region making use of the para-H$_2$CS $7_{07} - 6_{06}$, $7_{25} - 6_{24}$, and $7_{26} - 6_{25}$ lines in the ALMA Band 6 at frequencies near 240 GHz. The main results are summarized as follows.

1. The kinetic temperatures are derived from the measured averaged velocity-integrated intensity ratios of para-H$_2$CS $7_{25} - 6_{24}/7_{07} - 6_{06}$ and $7_{25} - 6_{24}/7_{26} - 6_{25}$ with RADE non-LTE modeling, which provides a monotonic increase in line ratios with rising kinetic temperatures. Kinetic temperatures range from 43 to ~500 K with an unweighted average of ~170 K at a spatial density of 10$^7$ cm$^{-3}$.

2. Our measurements of dense gas temperatures from para-H$_2$CS J = 7–6 line ratios reveal a temperature gradient from the explosive center to the outer regions of Orion KL. Significant gradients of kinetic temperature along molecular filaments traced by H$_2$CS indicate that the dense gas is heated by the shocks induced by the enigmatic event that occurred 550 yr ago. Internal sources do not play a dominant role in heating the elongated ridge, the northwestern clump, and the eastern region of the compact ridge, while the higher temperatures in the western compact ridge are likely caused by internal massive star formation activity. Furthermore, the kinetic temperature may also be enhanced by IRc4 and IRc7, but only in tiny, spatially highly-confined regions.

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