MASSIVE QUIESCENT CORES IN ORION. V. THE INTERNAL STRUCTURES AND PHYSICAL AND CHEMICAL PROPERTIES OF TWO EXTREMELY DENSE CORES

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\textbf{ABSTRACT}

We present a high-resolution (~1\arcsec.5) observational study of two massive dust–gas cores, ORI8nw_2 and ORI2_6, in the Orion molecular cloud using the Combined Array for Research in Millimeter-wave Astronomy. In each region the 3.2 mm continuum emission exhibits a dense and compact dust core at the center with 1–3 solar masses. The cores have number densities exceeding $10^9$ cm\(^{-3}\), which are among the highest volume densities observed in star-forming cores. In both regions the N\(_2\)H\(^+\) shows clumpy structures that are spatially displaced from the densest gas. In ORI8nw_2 in particular, the N\(_2\)H\(^+\) shows a noticeable filament structure with a central cavity shell. The calculation for the dynamical state shows that this core can be potentially supported by the magnetic field against its gravitational instability, but the fragmentation might still occur and produce the observed N\(_2\)H\(^+\) clumps if the gas density exceeds $5 \times 10^5$ cm\(^{-3}\) and this value is available within the observed density range. Also, the extremely high density at the core center suggests super-Jeans condition and the possibility for further fragmentation. For the chemical properties, the N\(_2\)H\(^+\)-to-HCO\(^+\) abundance ratios are shown to be different than those observed in infrared dark clouds. A combined analysis with the other Orion cores and the chemical model suggests that the different abundance ratios can be explained by the low CO abundances in our cores. To further reveal the evolution of such dense cores, higher resolution and sensitivity are required.

\textbf{Key words:} ISM: abundances – ISM: clouds – ISM: individual objects (Orion) – ISM: kinematics and dynamics – ISM: molecules – stars: formation – stars: pre-main sequence

\textbf{Online-only material:} color figures

1. INTRODUCTION

The Orion A molecular cloud (Orion A hereafter) is the closest star-forming site that is in the vicinity of an OB cluster. It mainly consists of a dense central gas complex Orion KL, which contains plenty of young stellar objects (YSOs) surrounding the central OB stars, and two major giant filaments including the northern branch OMC-1,2,3 and southern branch OMC-4,5 to L1641 (Johnstone & Bally 1999; Shimajiri et al. 2001). This entire system stores ample resources for the star formation at different mass scales and evolutionary stages. Numerous observations have been performed to explore its physical properties, including the large-scale gas distribution, individual YSOs, and the stellar feedback from the OB clusters. The densest molecular gas in Orion A is mainly distributed along the giant filament that has a length of 4 deg (13 pc) from north to south (Bally et al. 1987; Johnstone & Bally 1999, etc.). These studies also show that the molecular gas and the star formation therein are severely influenced by the radiation from the central OB stars. In the vicinity of the central stars, the molecular gas is compressed by the radiation pressure and gas expansion from the H\(_\alpha\) region, thereby has a tendency to form high-mass cores (Ikeda et al. 2007). Further to the south of OMC-1, the gas temperature, the turbulence, and the molecular core masses all decrease (Bally et al. 1987; Tatematsu et al. 1993, 2008; Buckle et al. 2012), which might lead to an increased forming rate of low-mass stars (Buckle et al. 2012).

To investigate the environmental influence to the star formation, observations were performed toward individual young star forming sites such as L1641N (Fukui et al. 1986), Gålfalk & Olofsson (2008) systematically surveyed the YSOs in this region. Bright H\(_\alpha\) outflows were found emanating from a number of stellar objects (Reipurth et al. 1998; Gålfalk & Olofsson 2007, 2008). A closer inspection showed that the CO outflow actually has a more complex quadruple structure (Stanke & Williams 2007, SW07 hereafter). Nakamura et al. (2012) further showed that the stellar emissions might mainly trace the population at later stages (Classes I and II), while the less evolved YSOs may still be embedded in the dust envelope and thus remain undetected. These younger sources may be critical for revealing the initial conditions in the Orion star-forming regions and may help us to understand the difference in the forming conditions for the low- and high-mass stars.

In order to better characterize the initial conditions of the star formation in Orion and to evaluate the possibility of forming high-mass stars, surveys with dust and dense gas tracers were performed toward regions with potential dense and quiescent gas and faint infrared emissions (Li et al. 2003, 2007, 2013). Li et al. (2007, Paper II hereafter) identified 51 dust cores from seven fields in the Orion A region. There is a fraction of the sources shared in common with other two surveys of Orion YSOs. Manoj et al. (2013) observed 21 protostars in the far-infrared and measured their temperatures. The sample covered five sources in Paper II, including ORI1_8, ORI1_13, ORI2_6, ORI2_7, and ORI8nw_2. They were all measured to have $T_{bol} < 70$ K and thus are classified as Class 0 objects. Megaeath et al. (2012) carried out another extensive survey of Orion YSOs based on the Spitzer/IRAC emissions and covered 16 sources in Paper II.
For all the shared sources, the IR counterparts were identified as “(protostellar),” indicating evolutionary stages earlier than Class 1.

On the other hand, a large fraction of the sources in Paper II (20 objects) exceed the equivalent Bonnor–Elbert (B-E) mass limit, suggesting that the core mass can be barely supported by the thermal pressure alone. In this case, the cores may possibly undergo gravitational collapse or otherwise be stabilized by the turbulence and/or the magnetic pressure. These two possibilities would critically determine the subsequent star formation and thus require further examination. Moreover, the NH$_3$ observations on arcsecond scales revealed a possible temperature and turbulence decline toward the molecular core center (Li et al. 2003), suggesting that the cores have very weak internal heating and thus may approximate the prestellar stage. Further observations with higher resolution and appropriate molecular tracers are needed to better reveal the star-forming conditions of the cores.

In this work, we present the millimeter interferometry observations toward two cores, ORIGw_2 and ORI2_6, in the Paper II sample. These two cores have the highest mass ratio to the B-E limit. The 350 μm continuum emission in ORIGw_2 coincides with several YSOs in L1641N (Gälfalk & Olofsson 2008), while ORI2_6 only has one faint IR source (HOPS 11 in Manoj et al. 2013 and No. 1100 in Megeath et al. 2012). The two cores were observed in the 3.2 mm continuum and N$_2$H$^+$ and HCO$^+$ (1–0) lines. The N$_2$H$^+$ can trace the dense quiescent gas because of its relatively stable abundance in the cold prestellar environment where many other species are frozen onto the dust grains (depleted). The HCO$^+$ is one of the depleted molecules in the prestellar environment and would increase in the gas phase as a result of being heated by the protostars.

The molecular and dust continuum emissions can reveal three aspects of the stellar evolution: (1) the gas distribution near the YSOs previously unresolved by the single dish; (2) the dynamical properties of the cores, including the turbulence and the potential core collapse and fragmentation; and (3) the molecular abundances that can be further compared with the chemical models and other molecular surveys. We introduce the observations and data reduction in Section 2 and present the reduced data in Section 3. In Sections 4–6, we analyze the kinematical, dynamical, and chemical properties in the cores and discuss the influence from the outflow and star-forming activities. A summary is given in Section 7.

2. OBSERVATION AND DATA REDUCTION

We used the Combined Array for Research in Millimeter-wave Astronomy (CARMA) to observe the N$_2$H$^+$ and HCO$^+$ J = 1–0 lines in our two targets. These data were taken in 2007 and 2008. During the observations the CARMA array consisted of 15 antennae, including nine 6.1-m dishes and six 10.4-m dishes. We used two different array configurations: B array (baselines 100–1000 m) and C array (baselines 30–350 m). More details of the observations are shown in Table 1.

We observed several different quasars for phase, bandpass, and flux calibration. For the two 2007 data sets, we used 0541-056 as the phase calibrator. The bandpass and flux calibrators were 3C273 (2007 February 10) and 0530+135 (2007 March 12). In all 2008 observations we used 0530+135 as the phase calibrator. We used 3C84 as both a flux and bandpass calibrator, except for 2008 November 29 data, where we used 0423-013 for bandpass and flux. On November 23, 2008, we used 0423-013 for the bandpass. The substitution became necessary when 3C84 was above an elevation of 80°. The quasars for the flux calibration are routinely observed. On the basis of the variation in those values, we estimate our overall flux accuracy to be ∼10%.

We set up our correlator so that each sideband had three windows all centered at the same frequency. In each sideband we had one wide-band window (approximately 500 MHz in 15 channels), one narrowband window (approximately 8 MHz in 63 channels), and one medium-band window (approximately 32 MHz in 63 channels). In 2007 we only observed N$_2$H$^+$, while in 2008 a slightly different correlator setup was used so that N$_2$H$^+$ and HCO$^+$ could be simultaneously observed in the two sidebands. The medium-band window was used to help identify emission in both molecules. This was especially useful for N$_2$H$^+$, which has seven hyperfine components (HFCs) spaced over a ~15 km s$^{-1}$ range (Caselli et al. 1995). The narrowband window covers the frequency range of all seven hyperfine components and with better spectral resolution (0.4 km s$^{-1}$). Therefore, we focused on the narrowband data to analyze the two molecular lines.

The data were calibrated using the MIRIAD software package. After visually inspecting the data and flagging intermittent electronic noise on certain baselines and antennas, we performed

Table 1

| Source | R.A. (J2000) | Decl. (J2000) | Date Observed (YYYY-MM-DD) | Array Config. | Time (hr) | Molecular Transition |
|--------|-------------|-------------|-----------------------------|---------------|-----------|---------------------|
| ORI2_6 | 05°35'13"13' | -05°57'58"5 | 2007 Feb 10 C | 4.9 | N$_2$H$^+$ |
| 2007 Mar 12 C | 1.7 | N$_2$H$^+$ |
| 2008 Nov 24 B | 3.0 | N$_2$H$^+$, HCO$^+$ |
| 2008 Nov 29 B | 3.8 | N$_2$H$^+$, HCO$^+$ |
| 2008 Dec 09 B | 2.6 | N$_2$H$^+$, HCO$^+$ |
| ORI8nw_2 | 05°36'18"6 | -06°22'10"4 | 2008 Nov 05 C | 3.4 | N$_2$H$^+$, HCO$^+$ |
| 2008 Nov 11 C | 2.3 | N$_2$H$^+$, HCO$^+$ |
| 2008 Nov 23 B | 5.4 | N$_2$H$^+$, HCO$^+$ |
| 2008 Dec 18 B | 4.0 | N$_2$H$^+$, HCO$^+$ |

Notes.

a Core names follow that in Li et al. (2007; Paper II).
b Positions are the phase tracking centers.
c The time indicates the on-source integration time.

5 http://carma.astro.umd.edu/miriad/
calibrations for the bandpass (frequency-dependent variation of the gains) and flux using the calibrators as shown above. After the calibrations, we excluded the channel containing N$_2$H$^+$ and HCO$^+$ emissions to obtain the 3.2 mm continuum data. Then the different observing tracks (obtained from B and C arrays, respectively) for each source are combined together and inverted from the (u,v) plane to the image plane using the robust parameter of 0.5. This value provides a compromise between the sensitivity of natural weighting and the lower side-lobes of uniform weighting. The combined data has the shortest baseline of 40 k$\lambda$, corresponding to an angular size of 50″. The spatial structures larger than this scale will not be recovered in our CARMA maps. The dirty map produced by inversion was deconvolved using the maximum entropy method (MEM). The final clean map was created by convolving the model image produced from MEM with a synthesized Gaussian clean beam (using the RESTORE command in MIRIAD). For ORI8nw_2, the clean beam is 1′′.67 × 1′′.48 with a position angle of −54° and for ORI2_6 it is 1′′.38 × 1′′.10 with an angle of 83.5°. The images were corrected for efficiency of the primary beam, which has an FWHM of 60″.

Figures 1 and 2 show the channel maps of HCO$^+$ and N$_2$H$^+$ $J = 1$–0 lines in the two regions. In ORI8nw_2, we displayed the velocity range that covers the $F_1 F = 01 \rightarrow 12$ component. The other two groups of HFCs, $F_1 = 2 \rightarrow 1$ and $1 \rightarrow 1$, have overall similar morphologies but blended components and are not shown here. The HCO$^+$ emission in ORI8nw_2 shows emission at the systemic velocity and, in addition, highly redshifted emission around $V_{lsr} = 11$ km s$^{-1}$. In ORI2_6 (Figure 2) the N$_2$H$^+$ is much weaker; thus, the strongest $F_1 = 2 \rightarrow 1$ transition is adopted for the display. The N$_2$H$^+$ is marginally detected at $V_{lsr} = 7.0$ to 7.5 km s$^{-1}$, while the HCO$^+$ emission is below the detection limit. The rms noise level $\sigma$ is measured from the emission-free areas in the channel.
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Figure 3. Velocity-integrated images of the N$_2$H$^+$ and HCO$^+$ emissions in ORI8nw_2. (a) The N$_2$H$^+$ (thin white contours) and 3.2 mm (thick yellow contours) emissions overlaid on the CSO 350 μm continuum (grayscale and dashed contours); (b) The HCO$^+$ (1–0) emission (contours) overlaid on the N$_2$H$^+$ (1–0) emission (gray). The dashed arrows indicate the direction of the collimated NE–SW CO outflow (Staniek & Williams 2007). The asterisks indicate the positions of the YSOs. (c) The N$_2$H$^+$ overlaid on the IRAC RGB image for ORI8nw_2. For the N$_2$H$^+$ and HCO$^+$ emissions, the contours are from 4σ in steps of 2σ (σ = 0.06 Jy beam$^{-1}$ km s$^{-1}$ for N$_2$H$^+$ and 0.04 Jy beam$^{-1}$ for HCO$^+$). For the 3.2 mm continuum, the contours are 10, 30, 50, 70, and 90 % of the maximum intensity (0.398 Jy beam$^{-1}$). The N$_2$H$^+$ emissions are integrated from the F$_l$ = 1–1 component (see Figure 6 for the spectra). The component is adopted to plot the N$_2$H$^+$ image. This component has a moderate optical depth and a high intensity at the same time and thus can exhibit the gas distribution better than the other two components.

(A color version of this figure is available in the online journal.)

Figure 4. Same as Figure 3, but for ORI2_6. The flux density of the 3.2 mm continuum peak is 0.114 Jy beam$^{-1}$.

(A color version of this figure is available in the online journal.)

images, which is σ = 0.02 Jy beam$^{-1}$. In ORI8nw_2, it is equal to $T_b = 1.1$ K for both lines; in ORI2_6, it corresponds to $T_b = 1.8$ K and 1.5 K for the N$_2$H$^+$ and HCO$^+$ lines, respectively.

We also obtained images at other wavebands, including (1) the C$^{18}$O(2–1) lines from a molecular line survey toward the Orion cores using the Caltech Submillimeter Observatory (CSO; Z. Ren et al., in preparation); (2) the mid-infrared images at four Spitzer/IRAC bands (3.6, 4.5, 5.8, and 8 μm) and far-infrared images at Spitzer/MIPS 24 and 70 μm bands; and (3) the JCMT/SCUBA 850 μm continuum images. The JCMT and MIPS images are only used to measure the emission intensities and are not presented in the paper. The Spitzer images were retrieved from the Spitzer Heritage Archive. The JCMT data were downloaded from the JCMT science archive.

http://sha.ipac.caltech.edu/applications/Spitzer/SHA/

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3. REDUCED DATA

3.1. Dust Continuum Emission

In Figures 3 and 4, we show the 3.2 mm dust continuum emissions in ORI8nw_2 and ORI2_6, with the CSO/SHARC-II 350 μm continuum emission (grayscale) and the three-band IRAC image (blue = 3.6 μm, green = 4.5 μm, and red = 8 μm) overlaid. The molecular emissions are also shown on the figures and are described in Section 3.2. In ORI8nw_2, the 3.2 mm continuum emission exhibits a single compact core located within the 350 μm emission region (Figure 3(a)). In ORI2_6, the 3.2 mm continuum peak coincides with the 350 μm emission within the pointing accuracy of the CSO. We manually adjusted the coordinates of the 350 μm emission by 4.5" to the east so that its emission peak overlaps with the peak of the 3.2 mm continuum.

At the IRAC bands (Figure 3(c)), ORI8nw_2 contains five bright IR sources that are located within or near the 350 μm emission region. We encircled them with dashed lines and labeled them following the previous denominations.
with the 350 μm distribution (SED). We measured the flux densities of the cores and estimated the dust temperature by fitting the spectral energy distribution (SED). In ORI2_6 (Figure 4(c)), there is only one single isolated IR source associated with the 3.2 mm continuum core. In comparison, the other stellar objects (123, 124, etc.) can be clearly seen at the IRAC bands. Among them No. 116 is the closest to the 3.2 mm peak (zero offset in Figure 3(c)). In ORI2_6 (Figure 4(c)), there is only one single isolated IR source associated with the 3.2 mm continuum core.

The temperature, core mass, and other physical parameters of the dust cores can be estimated from the dust continuum emissions. The results are summarized in Table 2. We first estimated the dust temperature by fitting the spectral energy distribution (SED). We measured the flux densities of the cores at the IRAC 24 μm and MIPS 70 μm bands. At those bands, both ORI8nw_2 and ORI2_6 exhibit a compact core coincident with the 350 μm emission. The 850 μm flux densities are taken from Johnstone & Bally (2006). In addition, for ORI8nw_2 we also took the continuum flux density at 1.3 mm (3.1 Jy) from SW07 and at 2.0 mm (0.272 Jy) from Chen et al. (1996). We adopt a graybody emission model to fit the SED (Hildebrand 1983),

\[ F_ν = \frac{M_{\text{core}} \kappa_ν B_ν(T_d)}{g D^2}, \]

where \( F_ν \) is the flux density at frequency \( ν \), \( M_{\text{core}} \) is the total gas–dust mass of the core, \( g = 100 \) is commonly adopted gas-to-dust mass ratio, \( B_ν(T_d) \) is the Planck function at \( T_d \), the dust temperature, \( D = 415 \) pc is the source distance (Menten et al. 2007; Sandstrom et al. 2007), and \( \kappa_ν \) is the dust opacity and is assumed to have a power law shape, i.e., \( \kappa_ν = κ_{230\text{GHz}}(ν/230\text{GHz})^{β} \), with the reference value of \( κ_{230\text{GHz}} = 0.9 \text{ cm}^2 \text{ g}^{-1} \) (Ossenkopf & Henning 1994). The best-fit SED curves are shown in Figure 6. In ORI8nw_2, we found that the emission from 70 μm to 1.3 mm can be fitted with \( T_d = 24 \pm 3 \text{ K} \) and \( β = 1.6 \).

At shorter wavelengths (IRAC and MIPS 24 μm bands), the flux densities have excess above the SED curve, which should arise from the hot gas component at vicinity of the stars. The hot component is less accurately constrained by the available data points, but on the basis of its local maximum intensity at around 24 μm, we can roughly estimate \( T = 120 \text{ K} \) from Wien’s displacement law. The 2.0 mm and 3.2 mm continuum emissions are both below the SED curve because of the extended emission being filtered by the interferometers. In ORI2_6, the temperature (cold component) is only constrained by 75 μm (MIPS), 350 μm (CSO), and 850 μm (SCUBA) data. In order to reduce the parameters, we fit the SED assuming the same \( β \) as...
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Table 2

| Parameters                          | ORI8nw_2 | ORI2_6 | Unit |
|-------------------------------------|----------|--------|------|
| Peak Position                       |          |        |      |
| T_dust                              | 05°36′18″| 05°35′13″| K    |
| T_source(N_2H^+)                    | 23 ± 3   | 19 ± 4 | K    |
| L_3_2                                 | 90       | 20     | L_⊙  |
| L_3_2 (H_2)                          | 1.17     | 0.13   |      |
| M_3_2 (H_2)                          | 46       | 12     | M_⊙  |
| M_3_2 (H_2)                          | 2.8      | 1.6    |      |
| R_3_2                                 | 15″(6460 AU) | 11″(4600 AU) |      |
| R_3_2 (H_2)                          | ≤1″3 (520 AU) | ≤1″2 (490 AU) |      |
| M_3_2 (H_2)                          | 8.43     | 2.87   | M_⊙  |
| M_3_2 (H_2)                          | 0.627    | 0.307  | M_⊙  |
| M_3_2 (N_2H^+)                       | 1.6 × 10^{23} | 0.6 × 10^{23} | cm^{-2} |
| M_3_2 (H_2)                          | 2.0 × 10^{25} | 0.9 × 10^{25} | cm^{-2} |
| M_3_2 (H_2)                          | 2.1 × 10^{16} | 1.0 × 10^{16} | cm^{-3} |
| M_3_2 (H_2)                          | 1.6 × 10^{19} | 1.2 × 10^{19} | cm^{-3} |
| ΔV(N_2H^+)                          | 1.25 ± 0.03 | 0.94 ± 0.08 | km s^{-1} |
| ΔV(HCO^+)                           | 1.17 ± 0.02 | 1.80 ± 0.10 | km s^{-1} |
| ΔV(C^18O)                           | 2.61 ± 0.14 | 1.4 ± 0.2 | km s^{-1} |

Notes.

a For ORI8nw_2, L_3_2 is a summation of YSOs within the 350 μm emission region. The luminosities of the YSOs (123, 116, and so on) were integrated from their emissions between 3.6 and 8.0 μm as interpolated from the emissions at four IRAC bands (Gállfalk & Olofsson 2008, Table 11 therein). The luminosities of 117 and 120 are directly taken from their Table 6.

b From Paper II.

c In each case, the first and second values are calculated from the line widths of N_2H^+ and C^{18}O, respectively.

d The values at the core center (0′′, 0′′). Since the emission region is not fully resolved with the CARMA beam size, the derived N(H_2) and n(H_2) may represent lower limits.

The H_2 column density N(H_2) and number density n(H_2) are also estimated from the continuum emissions. The N(H_2) is calculated from the intensity at the continuum peak, which represents an average within one beam area. To estimate n(H_2), we assumed the core to have a spherical shape so that the dust column length is equal to the mean diameter (measured from the 4σ contour size deconvolved with beam size as shown in Table 2). The derived column and number densities are also presented in Table 2. For both sources, the 3.2 mm core is comparable to the beam size, suggesting that the cores are marginally resolved. In this case, the derived N(H_2) and n(H_2) would represent a lower limit. Both ORI8nw_2 and ORI2_6 exhibit remarkably high N(H_2) and n(H_2) for the 3.2 mm continuum core. Such high densities are only observed in a few sources, including the Orion KL cores (Beuther et al. 2004) and some protostellar disk candidates (Fernández-López et al. 2011). In comparison, the 350 μm continuum cores have much lower column densities, suggesting that the gas distribution is very concentrated at the core center so that the extended envelope only has a minor contribution to N(H_2) in spite of its large mass. In the opposite case, i.e., if the density profile were relatively flat, a larger fraction of the column density would be resolved out by the interferometers so that the N(H_2) and n(H_2) values would be significantly lower than those for the 350 μm continuum core.

To better reveal the dust–gas distributions, we reconstructed the N(H_2) maps from the 3.2 mm and 350 μm continuum emissions, as shown in Figure 7. In the calculation, we first convolve the 3.2 mm emission with the CSO beam, as to mimic observing the central dense core with the CSO beam size at 350 μm. Then the N(H_2) map was estimated from the convolved 3.2 mm and 350 μm continuum images, respectively. As a result, the 3.2 mm emission exhibits a peak N(H_2) only slightly lower than that for the 350 μm emission. This is consistent with the speculation that the N(H_2) at the center is mainly contributed by the central dense core, while the extended envelope only has a minor contribution.

The morphology of the envelope can be better revealed by subtracting the dense gas component (calculated from the 3.2 mm emission) from the overall N(H_2) distribution (from the 350 μm emission). The residual N(H_2) distributions in ORI8nw_2 and ORI2_6 are shown in Figures 7(b) and (d), respectively. After subtraction, the residual N(H_2) map exhibits a quite flat profile within a spatial range of 1 arcmin, with a median value of 0.3 × 10^{23} cm^{-2}. The residual N(H_2) slightly increases toward the northeast and southwest of the center because of the slight elongation of the 350 μm core in this direction. In ORI2_6, after subtracting the 3.2 mm continuum core, N(H_2) also shows a roughly uniform distribution that has a slight decrease at the center and is elongated from NW to SE.

By averaging N(H_2) at each radius, we calculated the one-dimensional N(H_2) profile for the 350 μm core, the 3.2 mm core, and the envelope (residual). The three components are presented in Figures 7(e) and (f). From the center to outside, the residual N(H_2) (envelope component) shows a small variation scale of 0.1 to 0.2 × 10^{23} cm^{-2}. The figure also shows that in ORI2_6 the 3.2 mm continuum core takes up a lower fraction of N(H_2) than in ORI8nw_2. Considering the fact that ORI8nw_2 contains several more evolved YSOs, this may reflect the trend that molecular cores are becoming more centrally concentrated during the core evolution (Butler & Tan 2012). This trend is to be further examined from the density profiles in more prestellar and protostellar cores in the Orion molecular cloud.

3.2 Molecular Lines

The velocity-integrated N_2H^+ and HCO^+ emissions in both cores are presented in Figures 3 and 4. In ORI8nw_2, the N_2H^+ emission exhibits a filament with a spatial scale of ~60″ (0.13 pc) from northeast to southwest, and the filament is resolved into six major gas clumps, which are labeled as C1 to C6 in Figure 3(a). Besides the major filament, the N_2H^+ image also shows other two clumps to the north and south of the center cavity shell (labeled as C7 and C8, respectively) and, in
addition, some weak, dispersed gas fragments in the northwest. The HCO\(^+\) (1–0) emission (Figure 3(b)) has a smaller extent than the N\(_2\)H\(^+\). It has three major emission peaks, including one at the continuum peak and the other two in the southwest. The HCO\(^+\) (1–0) clumps are aligned roughly parallel to the N\(_2\)H\(^+\) filament but have an overall ∼5′′ shift to the north.

There are two HCO\(^+\) clumps coincident with the IR sources No. 123 and 116, while the N\(_2\)H\(^+\) apparently decreases toward these two sources. In ORI2_6, the N\(_2\)H\(^+\) emission mainly shows a weak and irregularly shaped gas clump located on the southwest side of the 3.2 mm continuum core, while the HCO\(^+\) (1–0) does not show an emission feature above the noise level (0.04 Jy beam\(^{-1}\) km s\(^{-1}\), as measured from the channel images). At the IRAC bands, ORI2_6 has only one faint point source associated with the 3.2 mm continuum and the HCO\(^+\) emission (Figure 4(c)). The less active star formation in ORI2_6 than in ORI8nw_2 is somewhat unexpected as seen from their larger-scale environments. Over several-arcmin scales, the ORI2 region exhibits multiple dust clumps aligned in filamentary structures, while ORI8nw_2 is almost isolated at the same scale and more distant from the OMC center (Paper II, Figures 3 and 5 therein). A possible explanation is that star formation in ORI8nw_2 is largely triggered by the cloud–cloud collision (Nakamura et al. 2012; see also Figure 5(b)). While in ORI2, although there are multiple cores in a small region, they may currently maintain a stable structure and have little interactions with each other.

In ORI8nw_2, both the N\(_2\)H\(^+\) and HCO\(^+\) emission exhibit multiple clumps at different velocities as shown in Figures 1 and 3. To more clearly elucidate the gas morphology and compare with the previous results, we show the velocity-integrated N\(_2\)H\(^+\) emissions and labeled the major gas structures...
in Figure 5. In general, the N$_2$H$^+$ emission shows a filamentary structure from northeast to southwest that is intercepted by a central cavity–shell structure. The 3.2 mm core is located at the northern edge of the cavity wall, and the quadruple outflow system (SW07, with the directions shown by arrows) is closely correlated with the N$_2$H$^+$ emission region. One can see that the collimated northeast–southwest outflow is nearly parallel to the N$_2$H$^+$ filament, while the more diffused north–south outflow is propagating through the filament and further to the south. Figure 5(b) shows the picture of the cloud–cloud collision on a larger spatial scale (Nakamura et al. 2012). The collisional interface is from northeast to southwest, thus roughly parallel to the N$_2$H$^+$ filament and the NE–SW outflow. The molecular gas may therefore be shaped by a net effect from the outflow and the cloud–cloud collision. The kinematical properties are discussed in more detail in Section 4.1.

We calculated the N$_2$H$^+$ column density on the basis of the optical depth derived from fitting the HFCs. We assume that for each HFC, the optical depth as a function of the radial velocity is

$$\tau_i(V) = \tau_0 \exp \left( - \frac{(V - V_{\text{sys}})^2}{2\sigma^2} \right), \quad (2)$$

and the total optical depth is

$$\tau(V) = \sum \tau_i(V).$$

The brightness temperature of the line emission would be

$$T_b(V) = f [J(T_{\text{ex}}) - J(T_{\text{bg}})] (1 - e^{-\tau(V)}),$$

where $f$ is the filling factor (assumed to be 1.0), $\tau_0$ is the optical depth of the line, $T_{\text{bg}} = 2.73$ K is the cosmic microwave background temperature, and $J(T)$ is the Planck-corrected brightness temperature:

$$J(T) = \frac{h \nu}{k} \frac{1}{e^{h \nu/kT} - 1}, \quad (4)$$

where $k$ is the Boltzmann constant. The hyperfine fitting to the observed spectra was performed using the CLASS program in the GILDAS software package. The best-fit spectra are shown in Figure 8. For each core, the observed spectra can be reasonably fitted by adjusting the input parameters $\tau$, $\sigma$, and $T_{\text{ex}}$. In ORI8nw_2, we obtained $\tau(F_1F = 23–12) = 0.5$ and $T_{\text{ex}} = 15$ K. In ORI2_6 we have $\tau(F_1F = 23–12) \sim 0.2$ and $T_{\text{ex}} = 16$ K. The excitation temperatures are close to the dust temperatures from the SED fitting. The column density is calculated from $\tau_0$, using

$$N_\text{tot} = \frac{8\pi v_0^3}{c^3} \frac{Q}{A_{\text{d}g_{\text{u}}} \exp(h v_0/kT_{\text{ex}})} \int \tau dV, \quad (5)$$

where $Q$ is the partition function at the temperature $T_{\text{ex}}, A_{\text{d}}$ is the Einstein coefficient, and $g_{\text{u}}$ is the degeneracy of the upper level. For both molecules, we calculate the column density at two cases: (1) the maximum column density at their emission peak and (2) the average column density within one CSO beam size ($9\arcsec$) at the continuum peak. In the calculation, two temperature limits are considered, including the values from the SED fitting in this paper (Figure 6) and the bolometric temperatures from Manoj et al. (2013). With two different values in beam sizes and temperatures, we altogether have four column density estimates for each species in each source, which are all presented in
Table 3. Chemical Properties of the N$_2$H$^+$, HCO$^+$, and CO

| Species | Peak | Average$^b$ |
|---------|------|-------------|
|         | ($N$($N_2$H$^+$)) |              |
|         | (1.3−14.0) × 10$^{14}$ | (1.6−16) × 10$^{13}$ |
|         | ($N$(HCO$^+$)) |              |
|         | (3.0−7.3) × 10$^{13}$ | (0.4−1.3) × 10$^{13}$ |
| $N$(CO)$^a$ | ... | (1.0−2.2) × 10$^{8}$ |
| $[C\text{O}]$ | ... | (0.6−1.3) × 10$^{-5}$ |
| $[N_2$H$^+]/[\text{HCO}^+]$ | ... | 4−12 |

| (ORI8nw, 2) | $N$(N$_2$H$^+$) | (0.68−7.1) × 10$^{14}$ | (0.8−6.8) × 10$^{13}$ |
|            | $N$(HCO$^+$) $^b$ | (3.1−6.1) × 10$^{12}$ | (0.7−1.7) × 10$^{12}$ |
|            | $N$(CO)$^a$ | ... | (2.2−4.5) × 10$^{7}$ |
|            | $[\text{CO}]$ | ... | (1.6−5.0) × 10$^{-6}$ |
|            | $[N_2$H$^+]/[\text{HCO}^+]$ $^b$ | ... | 11−40 |

Notes. For each quantity, the variation range is calculated at two temperature limits, including the currently fitted dust temperature and the bolometric temperatures provided by Manoj et al. (2013). The temperature limits are 23−63 K for ORI8nw, 2 and 19−59 K for ORI2, 6.

$^a$ For each core, it is calculated from the CSO C$^{18}$O(2−1) line at the 350 µm core center at the two temperature limits, with the assumption that $[^{12}\text{CO}] /[^{13}\text{CO}] = 375$.

$^b$ For N$_2$H$^+$ and HCO$^+$, the value represents an average over an area equal to the CSO beam at 350 µm (9$''$).

$^c$ The HCO$^+$ is only marginally detected in ORI2, 6. Therefore, its $N$(HCO$^+$) may represent an upper limit and $[N_2$H$^+]/[\text{HCO}^+]$ a lower limit.

The fraction of the HCO$^+$ covered by the outflow also shows moderate redshift features at several positions overlapped in the south. However, the cavity wall only shows redshifted CO outflow lobe. The outflow extends to the cavity wall and propagates further to the south, as indicated by the arrow in Figure 9(a). The red lobe has a small fraction on its southern edge overlapped with the N$_2$H$^+$, while the blue lobe propagates throughout the central cavity wall to the northeast and has cleared out almost all the N$_2$H$^+$ along its pathway.

The different outflow components seem to have different chemical consequences. The more extended southern red lobe is sweeping the gas onto the cavity wall, while the collimated NE−SW flow is likely causing more disruption of N$_2$H$^+$. As shown in SW07 (and also seen in Figure 1), the collimated NE−SW flow has a velocity distribution from $V_{lsr} = 10$ to 20 km s$^{-1}$, while the southern branch of the red lobe becomes weak at $V_{lsr} > 12$ km s$^{-1}$. Although the actual outflow velocities are uncertain because of the inclination angle, the NE−SW flow is likely to have higher velocities because of the compact and collimated shape. This suggests that the outflow velocity should be a key factor to determine the chemical effect.

Since the N$_2$H$^+$ and HCO$^+$ both appear to be affected by the outflow, their kinematic properties should be further examined. We plotted the intensity-weighted radial velocity field (first moment map) and the velocity dispersion (second moment map) of the N$_2$H$^+$ in Figures 9(b) and (c), respectively. The two maps are calculated from the single-peaked $F_r/F = 01$−12 component ($f = 93.17613$ GHz). As shown in Figure 9(b), the velocity field of N$_2$H$^+$ shows no significant deviation from the systemic $V_{lsr}$ nor any velocity gradient over the emission region. It only shows moderate redshift features at several positions overlapped with the outflow, including the southern edge of the cavity wall and the northwestern edge of the filament where the red lobe (dashed contours) goes over.

Nakamura et al. (2012) identified three concentrically expanding shells on larger scales, which are also plotted in Figure 5(b). A question is whether the cavity wall in the N$_2$H$^+$ emission represents another recently formed shell in a similar physical process. To our expectation, an expanding shell would exhibit both blueshift and redshift features as well as an increased velocity dispersion since it is moving toward all directions. However, the cavity wall only shows redshifted emission (Figure 9(b)) and a slightly higher velocity dispersion (up to 1 km s$^{-1}$; Figure 9(c)). Inside the cavity wall, the N$_2$H$^+$ is not detected above the uncertainty level of 0.06 Jy beam$^{-1}$ km s$^{-1}$, which limits the column density to be $N$(N$_2$H$^+$) < 4.5 × 10$^{12}$ cm$^{-2}$. This upper limit is almost two orders of magnitudes smaller than $N$(N$_2$H$^+$) at the cavity wall, suggesting that the cavity wall is more likely a two-dimensional ringlike structure rather than a spherical shell.

The HCO$^+$ is closely associated with the outflow for its velocity distribution. Its spatial correlation with the outflow, radial velocity, and velocity dispersion map are shown in Figures 9(d)−(f). Figure 9(d) shows that the three major HCO$^+$ gas clumps reasonably coincide with the local emission peaks in the red lobe. Figure 9(e) shows that the redshift pattern in HCO$^+$ well coincides with the spatial extent of the CO outflow. The fraction of the HCO$^+$ covered by the outflow also shows increased velocity dispersion (increasing from the average value of $\sigma = 2$ km s$^{-1}$ to $\sigma = 3$ km s$^{-1}$; Figure 9(f)). From Figure 1 we see that a bulk of the redshifted HCO$^+$ emission appears at $V_{lsr} = 10$ to 12 km s$^{-1}$ and becomes weaker at lower velocities together with the N$_2$H$^+$ and HCO$^+$ emissions (grayscale). For the N$_2$H$^+$, the major filament structure is nearly parallel to the outflow axis but with an overall offset to the south. The central cavity of the N$_2$H$^+$ is filled by the southern branch of the redshifted CO outflow lobe. The outflow extends to the cavity wall and propagates further to the south, as indicated by the arrow in Figure 9(a). The red lobe has a small fraction on its southern edge overlapped with the N$_2$H$^+$, while the blue lobe propagates throughout the central cavity wall to the northeast and has cleared out almost all the N$_2$H$^+$ along its pathway.

4. INFLUENCE OF THE STAR FORMATION AND DYNAMICAL ACTIVITIES ON THE MOLECULAR GAS

In ORI8nw, 2, the spatial morphology and velocity distribution of the molecular gas results from a net effect of the star-forming activities and dynamic processes, in particular the impact from the outflow. The significance of these factors is discussed as follows.

4.1. The Impact from the Outflow

To better reveal the potential influence from the outflow, in Figure 9 we plot the two outflow lobes in contours (SW07)
(8.5 to 9.5 km s\(^{-1}\)). This suggests that the HCO\(^+\) might be largely produced in the (redshifted) outflow rather than merely entrained from the ambient gas.

4.2. The Emission from the Stellar Objects

Both ORI8nw\(_2\) and ORI2\(_6\) have considerable total masses for their CSO 350 \(\mu\)m continuum cores (Table 2). However, the \(N_2H^+\) emissions reveal low-mass gas clumps at smaller scales, and the 3.2 mm continuum core also has gas masses of only \(\sim 1\) \(M_\odot\), suggesting that the two cores are currently only forming low-mass stars. Although the CARMA observations may have largely missed extended structures, their low bolometric luminosities (Table 2) also suggest the absence of high-mass stars.

The IR sources in ORI8nw\(_2\) are found to have a total luminosity even lower than the dust core luminosity. There are mainly six IR point sources observed at the IRAC bands labeled as No. 115, 116, 117, 120, 123, and 124 (Gál Falk & Olofsson 2008; also see Figure 3(c)). We can get their SEDs by interpolating the measured flux at four IRAC bands (Gál Falk & Olofsson 2008, Table 11 therein) and then derive the integrated luminosities. As a result, the IR sources all have luminosities at \(10^{-1}\) \(L_\odot\) scale. Among the IR sources, No. 117 and 120 are very faint at IRAC bands but are detected in the \(I, J,\) and \(K_s\) bands and estimated to have 0.15 and 0.02 \(L_\odot\) (Table 6 therein). For ORI2\(_6\), the central IRAC source is measured to have 0.12 \(L_\odot\), thus also much fainter than the entire dust core (20\(L_\odot\)). On the other hand, on the basis of the stellar reddening measured by Gál Falk & Olofsson (2008), we obtained a moderate extinction of \(A_{[4.5\mu m]} = 1.1\) for ORI8 region. This suggests that the stellar objects with high luminosities are not likely to be largely obscured at the IRAC bands. Considering the faintness of the IR sources, the bolometric luminosities of the dust cores should be mainly contributed by the external heating.

4.3. The Cloud–Cloud Collision

Another potential influence on the molecular distribution comes from the cloud–cloud interaction (Nakamura et al. 2012), which might have compressed the \(N_2H^+\) gas, causing it to be extended nearly in the same orientation with the collisional interface (Figure 7(b)). The interaction might also aid the mass accumulation, causing ORI8nw\(_2\) to become the most massive core over a one square degree region. But the interaction did not lead to high-mass star formation in this region.

5. DYNAMICAL CONDITIONS

Paper II investigated the gravitational instabilities of ORI8nw\(_2\) and ORI2\(_6\) on the basis of the assumption that the molecular cores are gravitationally bound. Using the currently observed molecular lines, we can better estimate the dynamical state in two major aspects: (1) whether the cores are gravitationally bound (the state of virial equilibrium) and (2) the possibility for gravitational collapse and fragmentation. The virial mass can be estimated from

\[
M_{\text{vir}} = \frac{5}{\alpha \beta} \frac{\sigma^2 r}{G},
\]

where \(r\) is the average radius, \(\sigma\) is the velocity dispersion, \(\beta = \arcsin e/e\) is the geometry factor determined by eccentricity \(e, \alpha = (1 - k_p/3)/(1 - 2k_p/5)\) for a power law density profile \(\rho \propto r^{-k_p}\) (Bertoldi & McKee 1992; McKee & Zweibel 1992), and \(G\) is the constant of gravity. We adopt \(k_p = 2\), which
characterizes a static singular isothermal sphere (Shu 1977), and $e = 0$ since both the 350 $\mu$m and the 3.2 mm cores are roughly spherical. Also, we considered the velocity dispersion from both the N$_2$H$^+$ and C$^{18}$O lines for the calculation, which would reflect the turbulence in the quiescent dense gas and the more extended gas components, respectively. The estimated virial masses are shown in Table 2.

In ORI8nw-2, from the velocity dispersion measured from the N$_2$H$^+$ line we can get $M_{\text{vir}} = 8 M_\odot$ for the 350 $\mu$m core, which is significantly smaller than the LTE gas mass. Using the C$^{18}$O line width instead, the derived $M_{\text{vir}}(20 M_\odot)$ is still lower than $M_{\text{core}}$, suggesting that the core should be gravitationally bound. One uncertainty is that the calculation of $M_{\text{core}}$ depends on the adopted temperature. For example, using $T_{\text{dust}} = 63$ K (Manoj et al. 2013), the core mass would decrease to $3 M_\odot$, which is significantly smaller than $M_{\text{vir}}$. For ORI2-6, using $T_d = 59$ K (Manoj et al. 2013) would provide $M_{\text{core},350\mu m} = 1.0 M_\odot$, which is also smaller than $M_{\text{vir}}$.

The dense prestellar and protostellar cores should be close to virial equilibrium. For example, Ikeda et al. (2007) studied a large sample of HCO$^+$ cores over the entire Orion A filament and found them to be mostly virialized. The HCO$^+$ cores on their observational scales are measured to have densities of only $10^3$ to $10^4$ cm$^{-3}$. In comparison, the compact massive dense cores on smaller scales should be more gravitationally bound. The suggestion is that the majority of the 350 $\mu$m continuum core should have moderately low temperatures, likely in a range of 20–30 K, so that the derived core masses can exceed the virial masses. In particular, assuming an ideal virial equilibrium, i.e., $M_{\text{core},350\mu m} = M_{\text{vir}}$, we can obtain $T_d \sim 25$ K from Equation (1). Miettinen et al. (2012) also used a two-temperature model to fit the SED of several Class 0 Orion cores and obtained $T \sim 10$ K for the cold components, which is consistent with the temperature estimate from the molecular lines. The high temperature values for our two cores should still be valid, but they mainly reflect the hot gas components surrounding the stars and can be distinguished from the cold gas in the SED fitting (Figure 5).

We also examined the virial state of the central 3.2 mm continuum cores. For ORI8nw-2, since the HCO$^+$ emission is closely associated with the 3.2 mm continuum cores, we adopt its line width and the upper limit of $r = 1''3$ and then estimated $M_{\text{vir}} \leq 0.6 M_\odot$, which is even smaller than $M_{\text{core},3.2\text{ mm}}$ estimated at $T = 63$ K. Thus, the 3.2 mm continuum core may also be gravitationally bound unless its temperature is even higher so that the gas mass is overestimated. In ORI2-6, the velocity dispersion for the 3.2 mm continuum core is less well determined because of the absence of molecular lines at the core center. Using the N$_2$H$^+$ line detected near the 3.2 mm continuum core, we can get $M_{\text{vir}} = 0.4 M_\odot$. In comparison, it has a total gas mass of 0.3–0.8 $M_\odot$ and thus should be close to the virial equilibrium.

The second aspect of the dynamical state is the stability against collapse and fragmentation. The critical mass $M_\chi$ to be sustained by the internal force is $M_\chi = M_f + M_\phi$, where $M_f$ and $M_\phi$ represent the mass to be supported by the random gas motion (thermal motion and turbulence) and magnetic pressure, respectively. The two components can be estimated using the same procedures in Li et al. (2013) and the references therein. The Jeans mass for a nonmagnetic isothermal cloud (Bonnor 1956; McKee & Zweibel 1992) is

$$M_f = 1.182 \frac{\sigma^4}{G^{3/2} P_{\text{ic}}}$$

where $P_{\text{ic}}$ is the external pressure and can be estimated as

$$P_{\text{ic}} = n_{\text{ic}} \mu m_{\text{H}} \sigma_{\text{ic}}^2,$$

where $m_{\text{H}}$ is the atomic hydrogen mass and $\mu = 2.33$ is the average molecular weight (Myers 1983). In our calculation we adopt an environmental velocity dispersion of $\sigma_{\text{ic}} = 1$ km s$^{-1}$, and density of $n_{\text{ic}} = 0.8 \times 10^4$ cm$^{-3}$ as measured from the extended H$^13$CO$^+(1–0)$ emission (Ikeda et al. 2007). The external pressure is calculated to be $P_{\text{ic}} = 2.3 \times 10^7$ K cm$^{-3}$.

Assuming that the observed N$_2$H$^+$ line width represents the total random gas motion (thermal motion and turbulence), we can get $\sigma_{\text{tot}} = 0.53$ km s$^{-1}$ and $M_{\text{tot}} \sim 4 M_\odot$. The total Jeans mass is much lower than the LTE gas mass, suggesting that the random gas motion (thermal motion and turbulence) can hardly support the core against collapse.

The maximum mass to be stabilized by the $B$ field is

$$M_\phi = c_\odot \pi B r^2 / G^{1/2},$$

where $c_\odot \sim 0.12$ (Tomisaka et al. 1988), Crutcher et al. (1999) measured $B = 0.36$ mG in the OMC-1 region where the gas density is $10^{10}$ cm$^{-3}$, and later derived a power law of $B \propto n^{0.65}$ from a number of Orion cores (Crutcher et al. 2010). Using this result, we can estimate $B = 0.66$ mG for gas density in ORI8nw-2 (2.1 $\times 10^6$ cm$^{-3}$). Norris (1984) observed OH masers in Orion-KL and derived $B \sim 3$ mG. Tang et al. (2010) observed the polarized dust continuum emission also in Orion-KL and suggested a field intensity of $B \gtrsim 3$ mG. For ORI8nw-2, we can then derive $M_\phi = 4.4$ to $20 M_\odot$ as the field varies from 0.66 to 3 mG. This suggests that the $B$ field is possible to provide a considerable support to the core if the field strength is at the milli-Gauss level.

If the collapse is ongoing, the typical fragmentation scale, namely the Jeans length can be estimated and compared with the N$_2$H$^+$ clumps to see whether they are close to each other. The Jeans length is calculated using $\lambda_J = \sqrt{\pi \sigma^2 / G \rho}$ (Jeans 1902), where $\rho = \mu m_{\text{H}} n_{\text{H}_2}$ is the gas density. Using the gas density of the 350 $\mu$m core and $\sigma$ from the N$_2$H$^+$ line width, the Jeans length is estimated to be $\sim 10$ arcsec. For the magnetic pressure, assuming a velocity dispersion comparable to the Alfvén velocity $v_A = B / \sqrt{\mu \rho}$, we can get its equivalent Jeans length of $\lambda_{J,B} = 15''$ to $100''$ as $B$ field varies from 0.66 to 3 mG. We see that as $B$ field increasing ($> 1$ mG), the total Jeans length would be dominated by the magnetic component and largely exceeds the N$_2$H$^+$ clamp scales ($5''$ to $10''$), thereby stabilize the core against fragmentation. Yet the fragmentation may still occur on the basis of the evidence from three aspects.

First, the Jeans length would become lower as the gas density increases toward the core center, while the $B$ field only moderately increases with the density if it follows the power law in Crutcher et al. (2010). Using the gas density in the central dense core (10$^5$ cm$^{-3}$), we can get $\lambda_{J,B} \sim 1''0$. To reach a fragmentation scale rightly at the N$_2$H$^+$ clamp scale ($\sim 5''$), a density of $\sim 5 \times 10^7$ cm$^{-3}$ is required, which can be satisfied by the overall density range.

Second, the magnetic turbulence can in the meantime cause density fluctuation and thus motivate the fragmentation (Hanawa et al. 1993; Takahashi et al. 2013, etc.). Using the method in Takahashi et al. (2013, Equations (5)–(7) therein), we can obtain a fragmentation length of $\lambda_{\text{frag}} = 40''$ to $1''0$ as the gas density varying from $10^4$ to $10^5$ cm$^{-3}$. This spatial range is compatible with the N$_2$H$^+$-clump scales. In fact, multiple clumps with sizes
around \( r \sim 5' \) have already been observed in Orion KL (Tang et al. 2010), and the clumps further exhibit substructures at even smaller scales. The condensations are apparently smaller than \( \lambda_{J,B} \) derived from the \( B \) field strength therein, suggesting that the \( B \) field might not effectively halt the fragmentation or might even provide an enhancement.

Third, if there is currently no fragmentation in ORI8nw_2, the observed \( N_2H^+ \) clumps may have to be solely shaped by the outflow or/and by the cloud–cloud interaction. This case is not fully consistent with the fact that the \( N_2H^+ \) clumps have a small velocity gradient and dispersion and in the meantime are spatially displaced from the observed outflow (Figure 9(a)).

The possibility of the fragmentation can be further examined by looking at internal structures in other similar Orion cores with sensitive dense gas tracers and by more accurately measuring the \( B \)-field strength and its spatial correlation with the gas structures.

### 6. THE CHEMICAL EVOLUTION

**WITH N\(_2\)H\(^+\) AND HCO\(^+\)**

In this section we discuss the chemical properties related to \( N_2H^+ \) and HCO\(^+\). In most cases, the \( N_2H^+ \) would closely trace the dense quiescent gas (e.g., Pirogov et al. 2003; Sanhueza et al. 2012). But the outflow and stellar heating may cause a deviation from the general trend, as observed in our two cores. As shown in Figure 3, in ORI8nw_2 the \( N_2H^+ \) is spatially displaced from the 3.2 mm continuum and the HCO\(^+\) emissions. In ORI2_6, the weakly detected \( N_2H^+ \) emission is also offset from the 3.2 mm continuum core (Figure 4).

In ORI8nw_2, the HCO\(^+\) mainly traces the outflow and lies in the close proximity of the \( N_2H^+ \). Toward the stellar objects No. 123 and 116 (Figure 3(b)), the HCO\(^+\) exhibits a local emission peak, while the \( N_2H^+ \) obviously declines. Therefore, the \( N_2H^+ \) is likely being directly converted to HCO\(^+\) via the reaction

\[
N_2H^+ + CO \rightarrow HCO^+ + N_2(a).
\]

The reaction is endothermic; thus, when the temperature is low, the energy source like outflow would sensitively reduce the \( N_2H^+ \) and increase the HCO\(^+\), causing the observed features. Besides reaction (a), the HCO\(^+\) can also be produced from

\[
CO + H_2 \rightarrow HCO^+ + H_2(b).
\]

Reactions (a) and (b) are both taking place in the infrared dark clouds (IRDCs; Vasyunina et al. 2012). However, (b) might be less important in producing the HCO\(^+\) in our dense cores since the HCO\(^+\) shows a close dependence on the \( N_2H^+ \) distribution. In a less dense and more extended gas component, reaction (b) would be more significant as the CO becomes depleted and \( H_2 \) also becomes more abundant because of the photodissociation. This speculation is consistent with the single-dish observation (Ikeda et al. 2007), which shows broad H\(^13\)CO\(^+\) emission over the ORI8 region (L1641N) with a spatial extent of 5 arcmin. The gas density at this scale was measured to be only \( 10^3 \) to \( 10^4 \) cm\(^{-3}\), which is largely different from the gas component in the compact dense cores.

The abundance ratio between \( N_2H^+ \) and HCO\(^+\) \([(N_2H^+)/[HCO^+])\] can reflect the chemical evolution in the molecular gas. Sanhueza et al. (2012) measured \([N_2H^+]/[HCO^+]\) in 37 IRDCs and obtained a distribution from 0.07 to 0.12. The \([N_2H^+]/[HCO^+]\) in the IRDCs exhibit a plausible variation among the different stages, but the entire variation range is lower than \([N_2H^+]/[HCO^+]\) in our two cores. In order to explain this difference, we referred to the chemical model presented by Jørgensen et al. (2004). The model estimated the evolution of \([N_2H^+]\) and \([HCO^+]\) as a function of the CO abundance (Figure 16 therein) in a physical condition of \( n(H_2) = 10^5 \) cm\(^{-3}\) and \( T = 20 \) K, which is comparable to the conditions in our cores. The major qualitative prediction of the model is that an increased \([CO]\) would continuously decrease \([N_2H^+]\) but increase \([HCO^+]\). This trend can be compared with the observed abundances.

In Figure 10, we plot \([N_2H^+]/[HCO^+]\) as a function of \([CO]\) derived from the model, and we overlaid the observed values in our two cores. The arrow on the ORI2_6 data represents the lower limit of \([N_2H^+]/[HCO^+]\) due to the barely detected HCO\(^+\) emission. In the figure, the abundances calculated at high temperatures (Manoj et al. 2013) are also presented in open squares. At both temperature limits, the observed data are consistent with general trend that \([N_2H^+]/[HCO^+]\) declines with \([CO]\). This proves that the CO should be a major controller for the HCO\(^+\) production. At low temperatures, the derived abundance ratios are close to the modeled curve, while at high temperatures, \([N_2H^+]/[HCO^+]\) become much higher. This is within expectation since the model parameters are also originated from the observed values at low temperatures. There are three IRDCs in Sanhueza et al. (2012) also with available \([CO]\) measurements (Vasyunina et al. 2011). Their \([N_2H^+]/[HCO^+]\) and \([CO]\) are presented together in Figure 10. The IRDCs have \([CO] \gtrsim 10^{-4}\) and \([N_2H^+]/[HCO^+] \gtrsim 0.1\) and thus are close to the modeled curve. This suggests that the different \([N_2H^+]/[HCO^+]\) ratios between our cores and the IRDCs can be explained by their different CO abundances.

In addition, we also searched for other Orion cores with available data. As a result, two cores in the BN-KL region (Ungerechts et al. 1997) and another one in Orion B (Miettinen et al. 2012) were found. The three additional Orion cores also show relatively high \([CO]\) and small \([N_2H^+]/[HCO^+]\) compared with ORI8nw_2 and ORI2_6. However, the Orion cores together show a more rapid decline trend than the model prediction, i.e., at \([CO] = 10^{-4}\), the modeled \([N_2H^+]/[HCO^+]\) approaches 0.1, while the three additional Orion cores have reached \([N_2H^+]/[HCO^+] \sim 10^{-2}\). From examining the two species individually, we see that the difference is mainly due
to [HCO$^+$], which largely exceeds the model prediction, as well as the IRDC values. The HCO$^+$ enhancement in these Orion cores can be tentatively attributed to the heating from outflow/shock and UV radiation, which all broadly exist in Orion. It still calls for more molecular lines and data from more Orion cores to examine the related chemistry, in particular whether $[\text{N}_2\text{H}^+]/[\text{HCO}^+]$ is also affected by other factors besides the CO abundance.

7. SUMMARY AND CONCLUSIONS

Using the CARMA, we studied the two Orion molecular cores ORI8nw_2 and OR12_6, the masses of which exceed the thermally stable B-E limit. We observed them in N$_2$H$^+$(1–0) and HCO$^+$(1–0) and examined their molecular distribution, chemistry, and gas kinematics. Our main findings are as follows.

1. As shown in the 3.2 mm continuum emission, for each core the central region is extremely dense, with $n(\text{H}_2) > 10^7 \text{cm}^{-3}$, and has a compact size of several 10$^2$ AU. The central dense core is surrounded by a flat envelope that extends to 4000–7000 AU and has a relatively lower density ($\sim 10^5 \text{cm}^{-3}$).

2. In both regions, the N$_2$H$^+$ is spatially displaced from the dense 3.2 mm continuum core. This should be mainly due to the disruption of N$_2$H$^+$ during the chemical evolution. In ORI8nw in particular, the strong outflow has cleared most of the N$_2$H$^+$ along its pathway and in the meantime generated a large amount of HCO$^+$.

3. The N$_2$H$^+$(1–0) emission in ORI8nw_2 is resolved into multiple clumps that are aligned in a 50 arcsec filamentary structure with a central cavity. The outflow, cloud–cloud collision, and fragmentation could all be involved in forming these gas clumps. Since the outflow impact or the cloud–cloud collision is not evidently shown in the velocity field of the N$_2$H$^+$(1–0), the fragmentation might be more important for producing the clumps. The analysis for the Jeans instability shows that the magnetic pressure can considerably stabilize the core, but the fragmentation is still possible if the gas density is sufficiently high ($n(\text{H}_2) \sim 5 \times 10^7 \text{cm}^{-3}$). ORI8nw_2 presents an example that a high-mass core is only forming low-mass stars possibly because of the fragmentation.

4. The molecular abundances in the Orion cores are roughly consistent with the modeled trend that the $[\text{N}_2\text{H}^+]/[\text{HCO}^+]$ ratio declines with [CO]. But together with other Orion core data, the decline of $[\text{N}_2\text{H}^+]/[\text{HCO}^+]$ shows a more significant decline than that of the modeled trend in quiescent gas. This may be due to the stellar emission and the outflow in the OMC, which increase the production of HCO$^+$.

The high resolution allows us to reveal the structures and chemical evolutions of two massive Orion cores. The effects of cloud evolution and protostellar feedback are revealed in detail. There are still some key properties to be investigated, in particular, whether the central dense core would undergo fragmentation or otherwise, monolithic core collapse, and further supported by core rotation and outflow. Considering their ample star-forming activities and nearby distance, these Orion cores will be ideal targets for future ALMA observations.

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