APEX-SEPIA660 Early Science:
Gas at densities above $10^7$ cm$^{-3}$ towards OMC-1 *

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ABSTRACT

Context. The star formation rates and stellar densities found in young massive clusters suggest that these stellar systems originate from gas at densities $n(H_2) > 10^6$ cm$^{-3}$. Until today, however, the physical characterization of this ultra high density material remains largely unconstrained in observations.

Aims. We investigated the density properties of the star-forming gas in the OMC-1 region located in the vicinity of the Orion Nebula Cluster (ONC).

Methods. We mapped the molecular emission at 652 GHz in OMC-1 as part of the APEX-SEPIA660 Early Science.

Results. We detect bright and extended N$_2$H$^+$ $(J=7$–$6)$ line emission along the entire OMC-1 region. Comparisons with previous ALMA data of the $(J=1$–$0)$ transition and radiative transfer models indicate that the line intensities observed in this N$_2$H$^+$ $(7$–$6)$ line are produced by large mass reservoirs of gas at densities $n(H_2) > 10^7$ cm$^{-3}$.

Conclusions. The first detection of this N$_2$H$^+$ $(7$–$6)$ line at parsec-scales demonstrates the extreme density conditions of the star-forming gas in young massive clusters such as the ONC. Our results highlight the unique combination of sensitivity and mapping capabilities of the new SEPIA660 receiver for the study of the ISM properties at high frequencies.

Key words. ISM: clouds – ISM: molecules – ISM: structure – Stars: formation – Submillimeter: ISM

1. Initial gas conditions in massive clusters

Investigating the origin of massive stellar clusters ($> 10^4$ M$_\odot$, Portegies Zwart et al.
2010) in the Milky Way is of paramount importance to understand the star-formation process across Cosmic Times (Krumholz et al.
2019). Massive clusters represent the most extreme examples of star-formation and the local analogues for the gas conditions at high redshifts (see Longmore et al.
2014). Usually located at kpc distances (e.g. towards the Galactic Centre), the characterization of these massive clusters is limited by sensitivity and resolution effects. Massive clusters form inside highly extincted gas clumps that can only be scrutinized using radio interferometric observations (e.g. Ginsburg et al.
2018). The molecular material in these massive clusters is also quickly disrupted by the strong stellar feedback generated by their active stellar populations. As result, the initial gas conditions inside massive clusters remain largely unconstrained in observations.

Stellar densities of $n(H_2) > 10^6$ cm$^{-3}$ (or $> 10^7$ M$_\odot$/pc$^3$) have been identified in massive clusters (Portegies Zwart et al.
2004), which suggests that these clusters originated from gas cloud at even higher densities. Different studies indicate that the molecular precursors of these massive clusters in the Milky Way may present average gas densities of $n(H_2) \sim 10^4$ cm$^{-3}$ (e.g. Kauffmann et al.
2017). Super star clusters, such as Arches, are expected to be originated from gas clumps at densities above $n(H_2) > 10^6$ cm$^{-3}$ (Walker et al.
2015). These gas densities largely exceed the mean values observed in nearby clouds predicting dramatically different free-full times ($\tau_{ff} \propto n(H_2)_{1/2}^2$) and star-formation rates (SFR $\propto n(H_2)^{1/2}$) between these regions (see Krumholz et al.
2012). However, and while extreme density values are reported for compact hot cores (< 0.1 pc) in massive environments (e.g. Genzel et al.
1982), the detection of gas at densities above $n(H_2) \gtrsim 10^7$ cm$^{-3}$ at parsec-scales remains elusive.

The increasing sensitivity of both single-dish and interferometers has popularized the use of N$_2$H$^+$ as density selective tracer in star formation studies (e.g. Caselli et al.
2002). A combination of excitation and chemical effects (critical density, abundance, and depletion) enhances the emission of this N-bearing...
Molecule in dense environments ($>10^4$ cm$^{-3}$) with respect to other standard cloud tracers (e.g. CO, HCN, or HCO$^+$) commonly biased towards lower density ($\sim10^3$ cm$^{-3}$) and/or warm material ($T_K>20$ K, e.g. Pety et al. 2017). The relatively higher abundances of N$_2$H$^+$ also make this molecule a favourable target for observations in comparison with other deuterated isotopologues (e.g. N$_2$D$^+$) and species (e.g. DCO$^+$). Most studies typically investigate low frequency transitions of this molecule, such as N$_2$H$^+$ (1–0) (93 GHz; e.g. Hacar et al. 2013) or N$_2$H$^+$ (3–2) (279 GHz; e.g. Teng & Hirano 2020). Limiting the dynamic range of these observations to densities of $n$(H$_2$)$\leq10^6$ cm$^{-3}$. However, the observation of high-J transitions ($J>4$–3) necessary to confirm the existence of gas at higher densities has been largely hampered by the more challenging access to frequencies above $>300$ GHz.

In this paper we report the first detection of extended N$_2$H$^+$ ($J=7$–6) emission at $\sim652$ GHz in the vicinity of the Orion Nebula Cluster (ONC) mapped with the new SEPIA660 heterodyne receiver (i.e. ALMA Band 9) recently installed at the APEX-12m radiotelescope (Sect.2). The widespread detection of bright N$_2$H$^+$ (7–6) emission at scales of $>0.5$ pc demonstrates the presence of gas at densities $n$(H$_2$)$>10^5$ cm$^{-3}$ (Sect.3 & 4).

Our new SEPIA660 observations provide us with the first direct evidence of the presence of large gas reservoirs at extremely high densities during the early evolution of young massive clusters (Sect.5).

2. New SEPIA660 observations

The ONC is the nearest high-mass star-forming region (D=414 pc, Menten et al. 2007) regularly used as local template for cluster studies. The ONC is partially embedded in the OMC-1 region, an active star-forming cloud including the Orion BN/KL region, widely investigated in the past at large-scales using both millimeter single-dish (e.g. Ungerechts et al. 1997) and interferometric observations (e.g. Wiseman & Ho 1998). Highlighting the filamentary nature of this OMC-1 cloud (Martin-Pintado et al. 1990), recent ALMA (Band 3) observations of N$_2$H$^+$ ($J=1$–0) revealed the intrinsic structure of the star-forming gas in this region forming a complex networks of narrow fibers (Hacar et al. 2018). Continuum (e.g. Teixeira et al. 2016) and line measurements (Hacar et al. 2018) in this massive cloud suggest that these fiber structures may present densities significantly larger than those found in low-mass environments (see Hacar et
We have mapped the central part of the OMC-1 region with the new Swedish-ESO PI instrument for APEX (SEPIA) (Belitsky et al. 2018) installed at the APEX-12m telescope in Chajnantor (Chile). Our observations used the new SEPIA660 detector, a dual polarization 2SB receiver operating between 578 and 738 GHz (similar to an ALMA Band 9 receiver) developed by the Netherlands Research School for Astronomy (NOVA) instrumentation group at the Kapteyn Astronomical Institute in Groningen (The Netherlands) (Baryshev et al. 2015). Our maps cover the entire OMC-1 region (see Fig. 1) from its northern OMC-1 Ridge to the Orion South proto-clusters, including the Orion BN/KL region (see labels in Fig. 1). We combine four on-the-fly (OTF) maps covering a total area of \( \sim 450 \times 200 \) arcsec\(^2\), or approximately \( \sim 0.9 \times 0.4 \) pc\(^2\) in size at the distance of Orion. Each OTF submap, with a typical area of \( 150 \times 150 \) arcsec\(^2\), was obtained in Position-Switching mode and was executed multiple times combining orthogonal coverages. Our observations were carried out in August 2019 under excellent weather conditions with a Precipitable Water Vapor (PWV) of PWV \( \leq 0.5 \) mm as part of the NOVA Guaranteed Time (ESO Proj. ID: E-0104.C-0578A-2019).\(^1\) Our study targets two specific lines, namely, \( \text{N}_2\text{H}^+ (J=7−6) (652095.865 \text{ MHz}) \) and \( \text{C}^{18}\text{O} (J=6−5) (658553.278 \text{ MHz}) \) (CDMS and VAMDC databases, Müller et al. 2005; Endres et al. 2016), observed simultaneously with a native spectral resolution of 240 kHz (or 0.11 km s\(^{-1}\)) thanks to the large instantaneous bandwidth (8 GHz) of the new SEPIA660 receiver connected to an XFFTS backend.\(^2\) Each molecular species was extracted, reduced, and combined independently using the software GILDAS/CLASS. We convolved our \( \text{N}_2\text{H}^+ (7−6) \) and \( \text{C}^{18}\text{O} \) 

\(^{1}\) This work is a continuation of the ORION-4D project (PI: A. Hacar). See more information in https://sites.google.com/site/orion4dproject.

\(^{2}\) For each 4 GHz subband, the XFFTS backend installed at APEX has a maximum resolution of 65536 channels (or 61 kHz per channel). In order to reduce the data rate in our high cadence OTF-maps, our observations reduced the effective spectral resolution down of this XFFTS backend to 16384 channels (or 240 kHz) per sideband and polarisation.
datasets into a uniform Nyquist sampled grid with a final resolution of 10 arcsec. After that, each individual spectrum was baseline subtracted and calibrated into main beam temperature units (T_{mb}) assuming a typical main-beam efficiency of η_{mb} = 0.4 measured in Uranus.

We display the total integrated intensity of our new SEPIA660 observations along the OMC-1 region in Figure 1. Remarkably, we clearly detect extended N2H+ (7–6) emission with a total integrated intensity W(N2H+) > 2.5 K km s^{-1} showing different cores and fibers along the whole extension of our maps (Fig. 1). Extremely bright emission peaks, exceeding values of W(N2H+) > 8 K km s^{-1}, are identified at the north of the Orion BN/KL region as well as the Orion South proto-cluster. Additional emission peaks in this N2H+ (7–6) transition, typically with W(N2H+) >5 K km s^{-1}, are found coincident with similar concentrations detected in N2H+ (1-0) by ALMA (white contours in Fig. 1 see also Fig. 3). Several of these peaks appear to be connected by a more diffuse N2H+ (7–6) emission extending North-South along the main spine of the OMC-1 region. Overall, the N2H+ (7–6) emission is restricted to regions containing high column density material traced in the continuum above N(H2) > 10^{23} cm^{-2} (e.g. Lombardi et al. 2014).

In contrast, our C18O (6–5) map shows a clear radial distribution in emission centred at the position of the Orion BN/KL region (Fig. 2). At its central peak, the C18O (6–5) emission reaches values of W(C18O)>100 K km s^{-1}, including prominent line wings associated to the Orion BN/KL outflow (Bally et al. 2011). Bright C18O (6–5) emission, with W(C18O)>50 K km s^{-1}, is also observed towards the southern end of the OMC-1 Ridge as well as the northern half of the OMC-1 South proto-cluster. More diffuse but still clearly detected, this emission continues at large scales below N(H2) ~ 10^{21} cm^{-2}, tracing the warm molecular material around the Orion Nebula in agreement with similar 12CO (J=4–3) (Ishii et al. 2016) and [CII] (Pabst et al. 2019) observations in this region. Moreover, the C18O (6–5) emission shows an arc-like structure tracing the edge of the HII region previously detected in H recombination lines (e.g. Harc et al. 2020). These properties denote the preference of this C18O (6–5) transition to trace low column density material directly illuminated by the Orion cluster.

3. Dense gas exposed to the ONC

The observed anticorrelation between N2H+ and C18O is generated as part of the chemical evaporation of the gas during the collapse and formation of stars in molecular clouds (see Bergin & Tafalla 2007 and reference therein). As part of Nitrogen chemistry, N2H+ is directly formed from N2 via:

\[ \text{H}^+_2 + \text{N}_2 \rightarrow \text{N}_2\text{H}^+ + \text{H}_2 \] (1)

in direct competition with CO:

\[ \text{H}^+_2 + \text{CO} \rightarrow \text{HCO}^+ + \text{H}_2. \] (2)

On the other hand, N2H+ is destroyed proton transfer with CO:

\[ \text{N}_2\text{H}^+ + \text{CO} \rightarrow \text{HCO}^+ + \text{N}_2 \] (3)

as well as via dissociative recombination:

\[ \text{N}_2\text{H}^+ + e^- \rightarrow \text{NH} + \text{H} \text{ or N}_2 + \text{H}. \] (4)

Critical densities calculated using the latest LAMDA collision coefficients for both para- and orto-H2 for C18O and total H2 in the case of N2H+.

(see Aikawa et al. 2015 van ‘t Hoff et al. 2017, for a full discussion). At the standard low-densities (n(H2) > 10^{2} cm^{-3}) and cold temperatures (T_K ≈ 10 K) of the ISM the efficient formation of N2H+ (reaction 1) is inhibited by the presence of large amounts of CO in the gas phase (reactions 2 and 3). The abundance of N2H+ is rapidly enhanced during the gas collapse after the depletion of CO once this latter species is frozen onto the dust grains at densities above n(H2) > 10^{5} cm^{-3}. N2H+ is later destroyed once the CO is evaporated from the dust heated at temperatures above T_K = 20 K (reaction 5) or under the presence of free electrons (reaction 4) produced in HII regions such as the Orion Nebula. These selective properties make N2H+ an ideal tracer of the dense and cold material in molecular clouds (n(H2) > 10^{7} cm^{-3}, T_K ≲ 30 K). Interestingly, while the N2H+ formation rate is almost independent of temperature (reaction 1), the rate of dissociative recombinations (reaction 4) decreases at increasing temperatures (e.g. Vigren et al. 2012) reducing the destruction rate of this molecule at high temperatures.

The excitation conditions of the high-J N2H+ and C18O transitions obtained in our SEPIA660 observations enhance the chemical differences of these tracers. Due to its high dipole moment (μ ≈ 3.4 D), N2H+ (J=7–6) (E_u = 125 K) line can only be collisionally excited at densities comparable to its critical density n_{crit}(N2H+ (7–6) ~ 5 × 10^{4} cm^{-3}. In contrast, the lower dipole moment of C18O (μ = 0.11 D) reduces the critical density of similarly high-J transitions, such as the C18O (J=6–5) line, down to n_{crit}(C18O (6–5) ~ 5 × 10^{3} cm^{-3}. The reduction of the effective critical density at high column densities and temperatures (see Shirley 2015, for a full discussion), similar to those found in the OMC-1 region, make the C18O (J=6–5) transition (E_u = 110 K) sensitive to more diffuse (≤ 10^{4} cm^{-3}) and typically hotter material (T_K > 60 K). The different gas regimes traced by these two molecules can be seen in previous observations of lower-J transitions in Orion such as N2H+ (J=1–0) (e.g. Harc et al. 2018) and C18O (J=1–0) (e.g. Kong et al. 2018).

The different gas regimes traced by the N2H+ (7–6) and C18O (6–5) lines become apparent by the complementary distribution of their emission maps shown in Figure 2. Similar to the (1-0) transition (Fig. 2a), we find no significant N2H+ (7–6) emission at the position of the hot Orion BN/KL region (see also Schilke et al. 2001), coincident with emission peak of the C18O (6–5) line (Fig. 2b). We observe this same behaviour at the bright edge of the HII nebula devoid of N2H+ (7–6) emission but well delineated by brighter C18O (6–5) emission. On the other hand, most of the N2H+ (7–6) peaks, as well as of the (1-0) emission, are located in well shielded and typically colder regions with no significant C18O (6–5) detections (see OMC-1 Ridge region in Fig. 2a). The OMC-1 South protocluster appears as the only exception to this general behaviour. The extraordinary conditions of this cluster, engulfed by the Orion Nebula and seen face-on along the line-of-sight (O’Dell 2001), can explain the bright emission of both molecules in this region.

Although not coincident, many of the N2H+ (7–6) emission peaks are indeed located next to regions with enhanced C18O (6–5) emission (see different contours in Fig. 2b). This systematic shift is particularly visible along the OMC-1 Ridge, where multiple clumps detected in N2H+ seem to be illuminated in C18O in the direction of the ONC. These results suggest that the detected N2H+ (7–6) emission may be showing the densest molecular gas...
in the OMC-1 region in the close proximity to the edge of the Orion Nebula.

4. Gas at densities > $10^7$ cm$^{-3}$ in OMC-1

In addition to their bright emission, the observed N$_2$H$^+$ (7–6) lines in OMC-1 show unprecedentedly high main-beam peak temperatures ($T_{mb}$). As illustrated by several representative spectra shown in Fig.3, we observe N$_2$H$^+$ (7–6) lines clearly detected well above the noise level out our data with $<rms> \sim 0.65$ K. We fitted all our N$_2$H$^+$ (7–6) spectra using a single Gaussian velocity component. 384 independent beams in our maps show N$_2$H$^+$ (7–6) spectra with signal-to-noise (S/N) larger than 3. Among them, the detected N$_2$H$^+$ (7–6) emission presents mean values of $T_{mb}$(N$_2$H$^+$ (7–6)) $\sim$ 4 K and linewidths $\Delta V$(N$_2$H$^+$ (7–6)) $\sim$ 1.3 km s$^{-1}$ (Fig.3a & b). Extremely bright spectra, with $T_{mb}$(N$_2$H$^+$ (7–6)) $\sim$ 10 K, are observed in the OMC-1 South region (Fig.3c). In many of these positions we find that the peak temperature of the N$_2$H$^+$ (7–6) transition (red spectra) matches and sometimes exceed the corresponding peaks of their N$_2$H$^+$ (1–0) counterparts (blue spectra). At the OMC-1 ridge, comparisons between our SEPIA660 and ALMA data show values with $T_{mb}$(N$_2$H$^+$ (7–6)) $\sim$ 0.5 while in the OMC-1 South and the surroundings of Orion BN/KL reach values above $T_{mb}$(N$_2$H$^+$ (7–6)) $>10$ K (see representative spectra).

We used the radiative transfer calculations provided by RADEX (van der Tak et al.2007) to obtain the direct comparisons between the predicted N$_2$H$^+$ line intensities at different densities. Our calculations assume the latest collisional coefficients and energy levels provided by the Leiden Molecular Database (Schöier et al.2005) without hyperfine structure. We model the main properties of our lines adopting average line intensities and linewidth similar to those reported in our SEPIA660 observations (see above) for a characteristic column density of N(N$_2$H$^+$) $= 5 \times 10^{13}$ cm$^{-2}$ derived from detailed analysis of the hyperfine opacities obtained in our previous N$_2$H$^+$ (1–0) observations (see Appendix B in Hacar et al.2018 for a discussion). Our models include three representative gas kinetic temperatures, namely, $T_K$ = 15 K, 25 K, and 35 K, describing the typical gas temperatures for the dense gas in OMC-1 consistent with previous temperature estimates (see Fig.2b, Hacar et al.2020). Larger temperature values were not considered because the effective chemical destruction of N$_2$H$^+$ at $T_K$ $>35$ K (see Sect.3).

Some caveats should be considered when interpreting our model results and their comparison with our observations. Most of these uncertainties are typically associated to the poorly characterized N$_2$H$^+$ (J $\geq 7$–6) transitions in comparison with its better known properties of lower J lines (J $\leq 6$–5, e.g. Daniel et al.2005, Pagani et al.2009). First, the absence of accurate estimates for the collisional coefficients for the N$_2$H$^+$ (7–6) hyperfine transitions limits the depth of our analysis. Thus, our models deliberately calculate the excitation conditions of N$_2$H$^+$ assuming a single line transition. With this approach we effectively add the contribution of all hyperfine components into a single line increasing the predicted N$_2$H$^+$ (1–0) and (7–6) line opacities and intensities up to a factor of ~5–7 respect to their main hyperfine components. This choice is particularly justified in the case of our N$_2$H$^+$ (7–6) showing a compact hyperfine structure with almost all hyperfine components blended within $\Delta V \lesssim 1.5$ km s$^{-1}$ (see Fig.5). Second, Our RADEX models adopt the LAMDA collisional rate coefficients that are extrapolated from those of HCO$^+$ (see Flower1999). Recent collisional rate coefficients calculations include the hyperfine structure of N$_2$H$^+$-H$_2$ up to J=7–6 (Lique et al.2015). The difference between the two approximately introduces an uncertainty of a factor of 3-5 in our density estimates (Lique et al.2015). For consistency with our RADEX models, we fit our N$_2$H$^+$ spectra using a unique gaussian component. Comparisons with the raw line intensities predicted using the full hyperfine information (CDMS) indicate that our gaussian fits accurately reproduce the line peak temperatures of the observed N$_2$H$^+$ (1–0) and (7–6) spectra within $\pm 15\%$. Linewidths, on the other hand, are affected by the superposition of multiple hyperfine components in both N$_2$H$^+$ (1–0) (central group) and (7–6) (full hyperfine structure) lines. Our analysis focuses on a simplified description of the N$_2$H$^+$ (1–0) and (7–6) peak temperatures ($T_{mb}$) meant to obtain a first order approximation to the gas densities along the ONC region. A more precise determination of the local gas densities in different positions of this cloud would require a more detailed treatment of the hyperfine structure and collisional coefficients of N$_2$H$^+$ (e.g. see Keto & Rybicki 2010) as well as the simultaneous analysis of additional intermediate transitions such as (J=3–2) (Teng & Hirano 2020).

The observed variations on the N$_2$H$^+$ line intensities can be understood from our RADEX models. In Fig.4 we present the individual line peak temperatures $T_{mb}$ (upper panel) and densities $\tau$ (lower panel) for all J-transitions (J=10–9) considered in our RADEX models. For simplicity, we display only two characteristic density values, namely, n(H$_2$) = $5 \times 10^3$ cm$^{-3}$ and n(H$_2$) = $5 \times 10^5$ cm$^{-3}$, representing both low- and high-density regimes in our data, respectively. Overall, higher temperatures and densities typically increase the excitation and emission of higher J-transitions. However, each of these variations show different behaviours along the N$_2$H$^+$ J-ladder. As seen in Fig.4 (upper panel), while temperature variations can potentially increase the peak temperatures in all J-transitions, only density is able to effectively excite high-J levels above J $\geq 6$–5. On the other hand, the opacity changes observed in Fig.4 (lower panel) demonstrated how the combination of high temperatures and densities increases the population of high-J levels at expenses of those in lower J. In high density and warm environments, the effective excitation of high-J levels J $\geq 6$–5 is accompanied by a rapid reduction of the line opacities in all N$_2$H$^+$ transitions J $\leq 4$–3. While only calculated for a single-component in our RADEX models, a similar variations of both line intensities and opacities with increasing densities are observed in radiative transfer calculations for the N$_2$H$^+$ (1–0) line including its entire hyperfine structure (see Figure 8.4 in Hacar et al.2018).

Our previous plots demonstrate how the large energy difference between the N$_2$H$^+$ (1–0) ($E_u = 4.7$ K) and (7–6) ($E_u = 125$ K) lines provides crucial information about the densities of the star-forming gas in OMC-1. In more detail, Fig.5 illustrates the line peak temperature $T_{mb}$(N$_2$H$^+$ (7–6)) (top panel) and line ratios $T_{mb}$(N$_2$H$^+$ (7–6))/ $T_{mb}$(N$_2$H$^+$ (1–0)) (bottom panel) for densities between $10^2$ and $10^3$ cm$^{-3}$ predicted by our RADEX models. For all temperatures our radiative transfer calculations show higher $T_{mb}$(N$_2$H$^+$ (7–6)) values and $T_{mb}$(N$_2$H$^+$ (7–6))/ $T_{mb}$(N$_2$H$^+$ (1–0)) ratios with increasing densities. The variations in both line peaks and ratios are primarily driven by the combination of both high densities and lukewarm temperatures required to effectively excite the N$_2$H$^+$ (7–6) transition (see Fig.3). Even at relatively high temperatures, the detection of spectra showing $T_{mb}$(N$_2$H$^+$ (7–6)) $>3$ K guarantees the detection of gas at densities n(H$_2$) $>10^6$ cm$^{-3}$. For the same detection threshold our models predict larger densities for decreasing temperatures (see coloured lines in the plots) or column densities (not shown).
The use of RADEX radiative transfer models allows us to constrain the gas densities traced by our new SEPIA660 observations. The $T_{\text{mb}}(\text{N}_2\text{H}^+\ (7-6))$ and $T_{\text{mb}}(\text{N}_2\text{H}^+\ (7-6))/T_{\text{mb}}(\text{N}_2\text{H}^+\ (1-0))$ values detected along the OMC-1 region (see also horizontal lines in Fig. 5) rule out densities below $n(\text{H}_2) < 10^6$ cm$^{-3}$ and temperatures $T_K < 20$ K. Instead, the observed high values for both peak temperatures and line ratios detected can only be reproduced if the gas detected in $\text{N}_2\text{H}^+\ (7-6)$ is at densities $n(\text{H}_2) > 5 \times 10^7$ cm$^{-3}$. Even higher densities, with $n(\text{H}_2) > 10^8$ cm$^{-3}$, would be also consistent with the detected line ratios in the OMC-1 South proto-cluster. Secondary differences between these two regions can be attributed to the slightly warmer conditions found towards OMC-1 South ($T_K \sim 35$ K) compared to the OMC-1 Ridge ($T_K \sim 25$ K) (Hacar et al. 2020).

The unique detection of $\text{N}_2\text{H}^+\ (7-6)$ transition unambiguously demonstrates the presence of gas at ultra-high densities in OMC-1. Previous calculations based on the $\text{N}_2\text{H}^+\ (1-0)$ line opacities (Hacar et al. 2018) and the $\text{N}_2\text{H}^+\ (3-2)$ intensities (Teng & Hirano 2020) described density values between $n(\text{H}_2) = 10^8 - 10^9$ cm$^{-3}$. The inclusion of this new $\text{N}_2\text{H}^+\ (7-6)$ transition potentially increases the density estimates by at least a factor of 5 in regions such as the OMC-1 South. On the other hand, our new SEPIA observations demonstrate that part of the dense material traced in $\text{N}_2\text{H}^+$ is effectively heated by the ONC Nebula at temperatures above $T_K \geq 30$ K. Previous estimates derived temperatures for the dense gas traced in $\text{N}_2\text{H}^+$ at $T_K = 20$ K (see Teng & Hirano 2020). Our radiative transfer calculations indicate that significant fractions of this dense material are consistent with temperatures of $T_K \geq 30$ K.

The presence of large amounts of $\text{N}_2\text{H}^+$ at high temperatures appears to be counter-intuitive. CO is expected to be evaporated from the dust grains at $T_{\text{dust}} > 15$ K (Bergin & Tafalla 2007). Previous observations report dust effective temperatures ($T_{\text{dust}}$) similar to the gas kinetic temperatures along OMC-1 showing differences of $|T_{\text{dust}} - T_K| \leq 5$ K (see Hacar et al. 2020). At $T_{\text{dust}} \sim T_K = 20-30$ K observed along the ONC region (see Fig. 2), CO is then expected to quickly destroy $\text{N}_2\text{H}^+$ via reaction (1), once CO is back into the gas phase. This evaporation process could be counterbalanced by the short freeze-out timescales of this molecule ($\sim 100$ yr) expected at the ultra high gas densities detected in this region ($\tau_{f-o} \sim 5 \times 10^7/n(\text{H}_2)$ yr, see Bergin & Tafalla 2007) continuing operating at high temperatures (see Appendix B in Harsono et al. 2015). If mixed with other ices, CO could also desorb at higher temperatures delaying its evaporation from the dust grains (Viti et al. 2004). Moreover, the presence of $\text{N}_2\text{H}^+$ could be enhanced by the reduction of the dissociative recombination rate of reaction (4) at high temperatures (Vigren et al. 2012). The combination of these effects appear to favour the survival of $\text{N}_2\text{H}^+$ at lukewarm temperatures $20$ K $\leq T_K \leq 35$ K in extremely dense environments such as the surroundings of the ONC.

Based on our ALMA measurements, we estimate a minimum of $30$ $M_\odot$ at densities $n(\text{H}_2) > 10^7$ cm$^{-3}$ within our maps. Our calculations include those positions with significant emission in $\text{N}_2\text{H}^+\ (7-6)$ at $S/N \geq 3$. Due to the excitation conditions of this line, our selection criteria restrict these mass estimates to dense gas pockets at temperatures above $T_K > 25$ K (see Fig. 3). According to our (1–0) detections, larger mass reservoirs are likely present at lower temperatures towards the north and west of the OMC-1 region (e.g. see $\text{N}_2\text{H}^+\ (1-0)$ maps in Fig. 1). This conclusion is reinforced by the bright and extended $\text{N}_2\text{H}^+\ (3-2)$ emission detected towards the entire OMC-1 region (Teng & Hirano 2020). Our mass estimates should therefore be considered as lower limits of total amount of gas at ultra-high densities in this region.

5 The effective dust temperature ($T_{\text{dust}}$) is usually obtained from a single-component black-body fit of the observed FIR luminosities (e.g. Lombardi et al. 2014). This effective temperature describes the average dust grain temperature ($T_{\text{grain}}$) weighted along the line-of-sight. Biased towards warmer temperatures producing a bright FIR emission, the effective dust temperature typically overestimates the local dust grain temperatures in cold and dense (aka well-shielded) regions showing fainter FIR emission, that is, $T_{\text{dust}} \geq T_{\text{grain}}$.

5. Star-formation at extremely high densities

The widespread detection of $\text{N}_2\text{H}^+\ (7-6)$ emission shown in our observations (Sect. 2) illustrates the extreme physical conditions of the gas in young massive clusters such as the ONC. Our Early Science SEPIA660 observations demonstrate the existence large volumes of gas at densities $n(\text{H}_2) > 10^7$ cm$^{-3}$ in close proximity to the ONC (Sect. 3). These densities are at least two orders of magnitude higher than the protostellar region, and this gas is likely traced by sulfur-bearing molecules such as $\text{S}_2\text{S}^+$.
magnitude larger than those gas densities found in the densest cores in low-mass star-forming regions, typically with n(H$_2$) $\approx$ 10$^5$ cm$^{-3}$ (e.g. Caselli et al. 2002 (Sect. 4)). Previously suggested to be restricted to the Orion BN/KL hot core (Goddi et al. 2011), our new observations extend the presence of lukewarm gas at densities above n(H$_2$) $> 10^7$ cm$^{-3}$ at scales of approximately 1 pc.

These results explain the extraordinary star-formation properties found along the OMC-1 Ridge and the OMC-1 South proto-cluster. Recent millimeter continuum and X-ray surveys found a typical separation between young embedded sources of 2000 AU (OMC-1 Ridge, Teixeira et al. 2016) and 600 AU (OMC-1 South, Rivilla et al. 2013). These values are in excellent agreement with the corresponding Jeans fragmentation lengths ($\lambda_J = \frac{\sqrt{\pi}}{\sqrt{\pi}}$) for a gas at temperatures of $T_K = 30$ K (i.e. $c_s = 0.35$ km s$^{-1}$) at densities between n(H$_2$) = 10$^7$ cm$^{-3}$ ($\lambda_J \sim 1450$ AU) and n(H$_2$) = 10$^8$ cm$^{-3}$ ($\lambda_J \sim 450$ AU). With expected free-fall times of $\tau_{ff} \leq 10^5$ yrs, these densities are also consistent with the young ages and high SFRs found in the embedded populations in regions such as OMC-1 South (see Rivilla et al. 2013). Moreover, our SEPIA660 results also confirm the density values predicted for the star-forming fibers found in the OMC-1 region by Hacar et al. (2018). Compared to those low-mass Herschel filaments showing widths of $\sim 0.1$ pc (Arzoumanian et al. 2011), the reported densities of n(H$_2$) $> 10^7$ cm$^{-3}$ explain the much narrower fibers widths of $< 0.03$ pc found in this massive OMC region (see Hacar et al. 2018 for a discussion).

The unusually large volume densities of the gas found in OMC-1 illustrate the extraordinary properties of this cloud. The high densities detected in fibers and cores (traced in N$_2$H$^+$) allow these structures to survive the strong radiative and mechanical feedback produced by the O-type stars in the Trapezium shielded behind large column densities of warm molecular material (observed in C$^{18}$O). Still, two competing mechanism operate in this cloud. First, the reported $T_K \geq 20$ K values in the surroundings of the OMC indicate that some of these structures could be photoevaporated by the HII nebula in relative short timescales $\tau_{photo}$. On the other hand, this destruction process is counteracted by the rapid $\tau_{ff}$ collapse of the ultra dense star-forming gas revealed by our N$_2$H$^+$ (7–6) observations (see above). The detection of large number of young embedded sources in regions like OMC-1 South (e.g. Rivilla et al. 2013) indicates that $\tau_{photo} \gg \tau_{ff}$ even under these extreme gas conditions. In agreement to recent simu-
lations [Dale et al. 2014], our observations suggest that feedback may have little effect on the evolution of the gas at extremely high densities found in this massive cluster.

The unique combination of sensitivity and mapping capabilities of the new APEX-SEPIA660 receiver opens a new window for ISM studies at high frequencies. These ultra high gas densities reported in OMC-1 mimic the physical conditions of more distant and massive environments such as the Central Molecular Zone or Starburst Galaxies. Our new SEPIA660 observations reveal this OMC-1 cloud as unique laboratory to investigate the fragmentation, collapse, and chemical evolution of the gas at extreme density conditions with unprecedented detail. Moreover, the confirmed detection of bright and extended emission of N$_2$H$^+$ (7–6) (652 GHz) offers the possibility of observing these regions at ultra high resolutions with ALMA (Band 9).

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