**ABSTRACT**

We have identified 453 compact dense cores in 3 mm continuum emission maps in the ATOMS (ALMA Three-millimeter Observations of Massive Star-forming regions) survey, and compiled three catalogues of high-mass star forming cores. One catalogue, referred to as H/UC-H\(\text{\textsc{ii}}\) catalogue, includes 89 cores that enshroud hyper/ultra compact (H/UC) H\(\text{\textsc{ii}}\) regions as characterized by associated compact H\(40_\alpha\) emission. A second catalogue, referred to as pure s-cHMC, includes 32 candidate Hot Molecular Cores (HMCs) showing rich spectra (\(N \geq 20\) lines) of complex organic molecules (COMs) but not associated with H/UC-H\(\text{\textsc{ii}}\) regions. The third catalogue, referred to as pure w-cHMC, includes 58 candidate HMCs with relatively low levels of COM richness and not associated with H/UC-H\(\text{\textsc{ii}}\) regions. These three catalogues of dense cores provide an important foundation for future studies of the early stages of high-mass star formation across the Milky Way. We also find that nearly half of H/UC-H\(\text{\textsc{ii}}\) cores are candidate HMCs. From the number counts of COM-containing and H/UC-H\(\text{\textsc{ii}}\) cores, we suggest that the duration of high-mass protostellar cores showing chemically rich features is at least comparable to the lifetime of H/UC-H\(\text{\textsc{ii}}\) regions. For cores in the H/UC-H\(\text{\textsc{ii}}\) catalogue, the width of the H\(40_\alpha\) line increases as the core size decreases, suggesting that the non-thermal dynamical and/or pressure line-broadening mechanisms dominate on the smaller scales of the H/UC-H\(\text{\textsc{ii}}\) cores.

**Key words:** stars: formation - stars: kinematics and dynamics; ISM: H\(\text{\textsc{ii}}\) regions; ISM: clouds.

1 INTRODUCTION

High-mass stars (\(M_\star > 8 M_\odot\)) play a crucial role in many astrophysical processes, for example from the formation of solid material in the early Universe (Dunne et al. 2003) to the influence on the evolution of their host galaxies and future generations of star formation in their natal molecular clouds (e.g., Kennicutt 2005; Urquhart et al. 2014). Despite its importance on different (time and spatial) scales, high-mass star formation remains much less understood than low-mass star formation due to the observational challenges presented by increased distances, rarity, opaque surroundings, and short formation timescales (e.g., Zinnecker & Yorke 2007; Tan et al. 2014; Motte, Bontemps, & Louvet 2018). In addition, high-mass protostars are embedded in a rich cluster environment (e.g., de Wit et al. 2005), which makes it very difficult to disentangle the physical formation processes of high-mass stars and numerous low-mass cluster members.

Despite the observational difficulties mentioned above, it has been known for the past 15 years that high-mass stars spend a considerable fraction of their lifetime (> 10%) embedded in their natal molecular clouds (e.g., van der Tak 2004). From an observational perspective, this embedded phase can be generally subdivided into...
four different groups of objects that represent different evolutionary stages. 1) Massive dense cores (MDCs, M $\gtrsim 30 M_\odot$ within ~ 0.1 pc), they are generally the nurseries of high-mass star formation (e.g., Zhang et al. 2009; Wang et al. 2011; Zhang et al. 2015; Motte, Bontemps, & Louvet 2018; Sanhueza et al. 2019; Li et al. 2019; Svoboda et al. 2019), and perhaps analogous to the prestellar cores in low-mass star formation regions if they are completely starless. 2) High-mass protostellar objects (HMPOs). They are very luminous, with bolometric luminosities above $10^3 L_\odot$, and deeply embedded within massive envelopes having centrally-peaked temperature and density distributions. At this stage, a (pseudo) disk is formed to transfer onto the HMPOs the infalling material from the envelope (e.g., Beuther et al. 2002; McKee & Tan 2003; Cesaroni et al. 2007). 3) Hot molecular cores (HMCs). They correspond to the compact (< 0.1 pc), dense ($\gtrsim 10^5 - 10^6$ cm$^{-3}$), massive ($\sim 100 M_\odot$), and hot ($\gtrsim 100 K$) molecular material that is radiatively heated intensively (e.g., Kurtz et al. 2000; Rathborne et al. 2011; Hosokawa & Omukai 2009). Consequently, the intense radiative heating enriches the gas phase with many complex organic molecules (COMs) such as CH$_3$OCH$_3$ and CH$_3$OCHO. 4) Hyper/ultra compact (H/UC)-Hi regions. The UC-Hi regions refer to those with sizes $\lesssim 0.1$ pc, densities $> 10^6$ cm$^{-3}$, and emission measures $> 10^7$ pc cm$^{-6}$ (e.g., Wood & Churchwell 1989; Hoare et al. 2007). The HC-Hi regions, which are a newly identified class of compact Hi regions after the discovery of UC-Hi, correspond to those with sizes $< 0.05$ pc, densities $> 10^6$ cm$^{-3}$, and emission measures $> 10^6$ pc cm$^{-6}$ (Kurtz & Hofner 2005; Hoare et al. 2007; Yang et al. 2019, 2020).

During the past decades, studies of the embedded phase of high-mass star formation have made much progress. After a large number of IRDCs were revealed by Infrared Space Observatory (ISO, Perault et al. 1996), Midcourse Space Experiment (MSX, Egan et al. 1998), and Spitzer (Peretto & Fuller 2009), several surveys in (sub)millimeter continuum and spectral lines followed (e.g., Rathborne, Jackson, & Simon 2006; Ragan et al. 2006; Simon et al. 2006; Rathborne et al. 2010; Dirienzo et al. 2015; Sanhueza et al. 2019), and have established that massive IRDCs harbor the early, embedded stages of high-mass star and cluster formation. In particular, the recent ALMA 1 mm survey ASHES led by Sanhueza et al. (2019), which was designed to model 12 massive (> 500 M$_\odot$), cold ( $\lesssim 15$ K), 3.6-70 $\mu$m dark-cloud clump at the resolution ~ 4000 AU and mass sensitivity better than 0.2 M$_\odot$, revealed a large population of low-mass(< 1 M$_\odot$) cores but no high-mass (> 30 M$_\odot$) prestellar cores on the 0.01–0.1 pc scales. With detailed analysis, the authors also put several strong observational constraints on cloud fragmentation, the clustering mode of dense cores, and the dynamical collapse scenario at the early stages of high-mass star formation.

As for the HMPO and HMC stages, both have many observational similarities except for the abundance of COMs; for example, they both are accompanied by massive molecular outflows, infall and even rotation (e.g., Zhang et al. 2001, 2005; Beuther et al. 2002; van der Tak 2004; Liu et al. 2017). Some important physical processes including mass accretion and disk rotation related to the HMPOs can therefore be understood from the investigation into the HMCs since the latter is generally accompanied by rich molecular line emission that bears both physical and chemical imprints of high-mass star formation (e.g., Keto & Zhang 2010; Qiu et al. 2012). Focusing on the HMCs, we find that most of the efforts so far have been toward individual sources or small samples through single-dish and/or interferometric observations in the (sub)millimeter regime (e.g., van der Tak 2004; Beuther 2007; Qin et al. 2008; Purcell et al. 2009; Cesaroni et al. 2010; Furuya, Cesaroni, & Shimaga 2011; Rathborne et al. 2011; Xu & Wang 2013; Hernández-Hernández et al. 2014; Qin et al. 2015; Silva et al. 2017; Csengeri et al. 2019; Coletta et al. 2020; Belloche et al. 2020; Sato et al. 2020). Although these studies have demonstrated the HMC as an ideal laboratory in which to search for infall, outflow, and rotation motions related to high-mass star formation, these important physical processes are still far from being well understood mainly due to the lack of deep, interferometric (sub)millimetre observations toward a sufficiently large sample of HMCs. For the H/UC-Hii stage, the situation improves; there are several surveys that serve to characterize the H/UC-Hii regions, such as IRAS warm dust continuum at far-IR wavelengths (Wood & Churchwell 1989; Kurtz, Churchwell, & Wood 1994), CORNISH 5 GHz radio continuum (Hoare et al. 2012; Purcell et al. 2013), and ATLASGAL 870 $\mu$m cold dust continuum (Schuller et al. 2009; Urquhart et al. 2013) surveys. These surveys help define observationally the H/UC-Hii regions reasonably well in terms of their sizes, densities, and emission measures (see above).

In addition, some H/UC-Hii regions are likely still accreting mass, despite the high pressure of ionized gas (e.g., Sollins et al. 2005; Keto 2007; Keto, Zhang, & Kurtz 2008). However, the role that H/UC-Hii regions play in the early stages of high-mass star formation remains to be understood. Hopefully, the H/UC-Hii regions can light up their immediate surroundings and allow the investigation of the properties (e.g., density distribution, and velocity field) of the surrounding region in which high-mass stars are formed (e.g., Hoare et al. 2007). The immediate vicinities of H/UC-Hii regions have been the subject of (sub)millimeter observation studies, however, the lack of high-angular resolution observations has impeded anything like complete understanding of H/UC-Hii region physics.

In this paper, the third in a series from ATOMS (e.g., Liu et al. 2020a, Liu et al. 2020b), hereafter, Paper I and Paper II, respectively, we take advantage of deep, high-resolution ALMA 3 mm observations (see below) of the ATOMS survey. In Paper I, we introduced the main scientific goals of the survey through a case study for the G9.62+0.19 complex, including to systematically investigate the spatial distribution of various dense gas tracers in a large sample of Galactic massive star-forming clumps, to study the roles of stellar feedback in star formation, and to characterize filamentary structures inside massive clumps. In Paper II, we studied the star formation scaling relations inferred from different dense gas tracers, and suggested that both the main and isotopologue lines (i.e., HCO$^+$/$^{13}$CO, HCN/H$^{13}$CN) are good tracers of the total mass of dense gas in Galactic molecular clumps, and that the large optical depths of the main lines do not affect the interpretation of the slopes in star formation relations.

With the ATOMS survey data, in this paper we aim to establish catalogues of a large sample of both candidate HMCs and H/UC-Hii regions as a crucial foundation for future studies for the early stages of high-mass star formation. The ATOMS survey targeted a large sample of 146 IRAS clumps (Bronfman, Nyman, & May 1996; Liu et al. 2016), which have masses 5.6 to 2.5 × 10$^4$ M$_\odot$ with a median value of 1.4 × 10$^5$ M$_\odot$, radii 0.06 to 4.26 pc with a median value of 0.86 pc, and bolometric luminosities 16 to 8.1 × 10$^5$ L$_\odot$ with a median value of 5.7 × 10$^4$ L$_\odot$ (see Table A1 of Paper I). All the targets except I080763556 and I115906452 have bolometric luminosities of greater than 10$^3$ L$_\odot$, and actually more than 90% of them are high-mass star-forming regions (see Paper I, and Paper II). In addition, the ATOMS targets are located in the first and fourth Galactic

\footnote{ATOMS: ALMA Three-millimeter Observations of Massive Star-forming regions survey}
Quadrants of the inner Galactic plane (−80° < l < 40°, |b| < 2°) at distances 0.4 to 13.0 kpc (the corresponding Galactocentric distances 0.5 to 12.7 kpc, see Appendix A for the distance calculations). Twenty-seven distant (d ≥ 7 kpc) sources are either close to the Galactic Centre or mini-starbursts (like W49N/H19078+0901), representing extreme environments for star formation. Overall, the ATOMS survey contains a diversity of objects suitable for studying the early stages of high-mass star formation, especially HMC and H/UC-HII stages, with different physical conditions – including densities and luminosities – and in different environments, across a large range of Galactocentric distances.

This paper is organized as follows: Section 2 gives a brief description about the ALMA observations of the ATOMS survey, Section 3 presents the results of the extraction and search of the candidate HMC and H/UC-HII cores, Section 4 presents a discussion, and Section 5 includes the conclusions and a summary of our results.

2 ALMA OBSERVATIONS

We make use of the ATOMS survey data (Project ID: 2019.1.00685.S; PI: Tie Liu, see Paper I and Paper II). The observations were conducted towards the 146 IRAS clumps in the single-pointing mode with both the Atacama Compact 7-m Array (ACA; Morita Array) and the 12-m array (C43-2 or C43-3 configurations) in band 3. Eight spectral windows (SPWs) were tuned to cover 11 commonly-used lines including the dense gas tracers (e.g., HCO+, HCN, and their isotopes), HMC tracers (e.g., CH₃OH and HC₅N), shock tracers (e.g., SiO, and SO), and ionized gas tracers (Hα). The basic parameters (e.g., rest frequency, transition, critical density, and upper energy temperature) of these lines can be found in Table 2 of Paper I. The SPWs 1−6 for the lower side band, with spectral resolutions of ∼2 − 0.4 km s⁻¹ were chosen to resolve the line profiles in order to investigate the kinematics within high-mass star forming clumps, while the SPWs 7−8 at the upper side band, each with a broad bandwidth of 1875 MHz at a spectral resolution of ∼1.6 km s⁻¹, were chosen for continuum emission and line scan observations. Note that the original spectral resolution of the SPWs 7−8 is ∼1.6 km s⁻¹ instead of ∼3 km s⁻¹ as given in Paper I.

The ACA and 12 m-array data were calibrated and imaged separately with the CASA software package version 5.6 (McMullin et al. 2007), where the continuum image centred at ∼93.8 GHz was cleaned in an aggregated ∼4 GHz frequency bandwidth free of the line-emission. More details on the data reduction can be found in Paper I and Paper II. As we focus in this work on the very dense, compact HMCs and H/UC-HII regions, in what follows we will only consider the 12 m-array data and the analysis is focused on the primary-beam corrected data. The reduced 12m-array continuum image and line cubes for the 146 target clumps have angular resolutions of ∼1"5−2"0 (for reference, 2"0 corresponds to 0.1 pc at a distance of 10 kpc), and maximum recoverable angular scales ∼14"5−20"3. The sensitivity of the 12m-array data is better than 10 mJy beam⁻¹ per 0.122 MHz channel (see Table 1 of Paper I) for lines, and ∼0.4 mJy beam⁻¹ for continuum.

3 ANALYSIS AND RESULTS

3.1 Core extraction

To extract compact cores from the 3 mm continuum maps, we make use of both the Dendrogram algorithm and CASA-imfit function. Dendrogram can be easily used to extract the dense leaf-like structures (hereafter referred to as cores), which are the smallest structures without substructures in the terminology of the algorithm, and thus customarily taken to be the candidates for cores. This technique does not always provide good measurements of the core parameters such as size and position angle, while CASA-imfit performs better in this regard through a two-dimensional Gaussian fit to the emission. A visual inspection of the continuum images of the 146 target sources, shows that their outer parts, i.e., the area beyond a radius of 0.01" from the image center, are much noisier than the inner parts, where the 0.01" radius corresponds to the pblimit = 0.4. Therefore, we masked out the outer part of the images before identifying the core structures. To identify cores we followed two steps. First, using Dendrogram we find cores and determine their parameters (i.e., centre position, peak flux density, minor and major-axis sizes, and position angle), toward each target clump. Then we made a more accurate measurement of the core parameters using the CASA task imfit adopting as initial guesses the parameters determined in the previous step. This approach has been employed in Li et al. (2020), and demonstrated to work very well.

In the first step, as inputs of the three key parameters to the Dendrogram algorithm we used: (i) min_value = 2σ₃mm, where σ₃mm is the noise level. In practice, we first run the Dendrogram algorithm to identify the compact cores in the 3 mm continuum image, then subtract them to obtain a nearly-flat residual 3 mm image, and finally estimate the rms level of the residual image as the noise (σ₃mm) of the original 3 mm continuum image as the starting level to construct the dendrogram. In addition, we used (ii) min_delta = σ₃mm, the default value in the algorithm to recognise an independent leaf (i.e., the core structure); and (iii) min_npix = N pixels, where N was chosen to be equivalent to the area of one beam (depending on the pixel and beam sizes of the image of each target clump). This was imposed to ensure a core to be resolvable. Given the above three parameters, the Dendrogram algorithm automatically locates the cores, and measures their parameters (see above). To avoid spurious cores, we performed a post-selection to require the selected cores must have peak flux greater than 5σ₃mm.

In the second step, we used the parameters of the post-selected cores determined in the first step as inputs to run the CASA-imfit task to accurately identify the cores, and measure their parameters, including peak position, major and minor sizes (FWHMmax, FWHMmin), position angle (PA), peak flux (Fₚ₃mm), and integrated flux (Fₚ₃mm). The measurement uncertainties on the flux are given by CASA-imfit. The uncertainties related to the missing flux effect are not taken into account in this work since it is found not significant for compact cores by comparing the 12M data with the combined 12M+7M data (Paper I). Through careful visual inspection of the 3 mm continuum map overlaid with the identified cores, we removed a few fake cores with poorly-fitted shapes. Such cores tend to have a large aspect ratio (>3) between the major and minor-axis sizes, appearing either as a filamentary structure or as a diffuse emission feature. As a result, we finally obtained 453 cores from the 146 ATOMS target clumps.

The entire extraction procedure is illustrated in Fig. 1, where we

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Footnotes:

1 The frequency ranges of the eight spectral windows (SPWs) are [86.311, 86.369] GHz for SPW 1, [86.725, 86.784] GHz for SPW 2, [86.818, 86.876] GHz for SPW 3, [87.288, 87.346] GHz for SPW 4, [88.603, 88.661] GHz for SPW 5, [89.159, 89.218] GHz for SPW 6, [97.530, 99.404] GHz for SPW 7, [99.468, 101.341] GHz for SPW 8.

2 https://dendrograms.readthedocs.io/en/stable/
take the target clump I18032-2032 as an example of identifying the cores that are contained. The procedure starts from the compact core extraction on the 3 mm continuum map with Dendrogram in the left panel, and then moves to the finer core fitting with CASA-imfit in the right panel. Due to the marginal angular resolution (∼ 2″) and small intensity contrast in the 3 mm continuum emission maps, some cores may be missed in the core extraction. For example, comparing with the higher intensity-contrast range HCN (11-10) emission map, one can see that one molecular core between G009.6197+00.1940 and G009.6207+00.1950 revealed by HCN (11-10) is missing in the core extraction procedure. This is because that core cannot be separated from its adjacent cores or background emission in the 3 mm continuum emission map but emerges in higher intensity-contrast HCN (11-10) emission map. This issue very rarely occurs in the full sample and predominantly affects low flux (so presumably low-mass) core (specifically, those in the “unknown core” category that contains the cores with unknown nature of star formation so far, see Sect. 3.3). Hence, the analysis in what follows is largely unaffected by this issue.

In addition, with both Dendrogram and CASA-imfit used in the core extraction, several major parameters measured from both methods can be compared. Actually, we find that the flux and position measurements are consistent in both methods. However, the size measured by CASA-imfit is larger than that in Dendrogram mainly for the low-flux cores (i.e., in the “unknown cores” category, see Sect. 3.3). The position angle measurement in CASA-imfit generally matches the 3 mm continuum dense structure orientation better than that in Dendrogram. These differences mainly come from the different methods of parameter determination used in Dendrogram and CASA-imfit. In the former the size and position angle parameters are derived from the intensity-weighted second moments along the two spatial dimensions (Rosolowsky et al. 2008) while in the latter the two parameters are directly derived from Gaussian fitting to the unweighted intensity spatial distribution. Therefore, to better reflect the core geometry as seen in 3 mm continuum, we prefer to use the core parameters measured by CASA-imfit.

3.2 Search for candidate HMCs and H/UC-H\(\text{II}\) cores

One important step towards understanding high-mass star formation is to search for the massive cores that harbor the early stages of high-mass star and cluster formation. Clues to high-mass star formation can be inferred from the properties of massive starless and/or prestellar cores (e.g., Yuan et al. 2017), the SED of high-mass protostellar objects (HMPOs, e.g., Rathborne et al. 2005), HMCs (e.g., Kurtz et al. 2000; Rathborne et al. 2011), H/UC-H\(\text{II}\) regions (e.g., Churchwell 2002; Hoare et al. 2007), and some masers (e.g., Class II CH\(\text{3}\)OH masers), which exclusively trace high-mass star formation (e.g., Wang et al. 2014). Here, we focus on the search of massive cores associated with HMCs and H/UC-H\(\text{II}\) regions. The advantage of the ATOMS survey strategy is that the two wide SPWs 7–8 cover many transitions of the COMs (i.e., HMC tracers; see Fig. 12 of Paper I) and the H\(\alpha\) transition (i.e., the ionized gas tracer). In what follows, we discuss the search for H/UC-H\(\text{II}\) cores in Sect. 3.2.1 and COM-containing cores in Sect. 3.2.2 that could correspond to candidate HMCs.

3.2.1 Search for H/UC-H\(\text{II}\) Cores

The entire procedure of the H/UC-H\(\text{II}\) core search is illustrated in Fig. 2, where the core G009.6190+00.1933 from the clump I18032-2032 is taken as an example. In Fig. 2a, the velocity-integrated intensity of H\(\alpha\) emission over a velocity range of 150 km s\(^{-1}\) centered...
at the systemic velocity of the core (in both the grayscale and red contours) is overlaid with the 3 mm continuum (cyan contours). The core in question is indicated by the white ellipse. Figure 2b presents the beam-averaged spectrum of H40α at the core center. If the H40α emission appears compact and is spatially associated with the compact continuum core, the core will be classified as an H/UC-H II core from H/UC-H II emission. Figure 2 presents an example of the H/UC-H II core search. (a): velocity-integrated intensity map of H40α in both grayscale and red contours over [-70, 80] km s⁻¹ for the core G009.6190+00.1933 (in white ellipse) in the target clump I18032-2032. The map is centered at the core peak with a size of 10'' (1.7 pc). For comparison, the 3 mm continuum is also superimposed in cyan contours. The synthesized beam and a scale bar of 0.04 pc are drawn at the bottom of the panel. (b): beam (2'')-averaged spectrum of H40α at the core centre. G009.6190+00.1933 is an H/UC-H II core as characterized by strong, and compact H40α emission.

3.2.2 Search for COM-containing cores

To quantitatively describe the chemical richness of a core, we use the number of lines (N_{line}) detected in the two line-scan windows SPWs 7–8. These spectral windows cover tens of transitions from COMs (e.g., CH₂CHO, CH₂CHO, CH₂OH, C₂H₂CN) that are usually detectable in a HMC, and only two or three transitions of non HMC-tracer molecules (i.e., CS (2–1), SO (3–2) or H₂CO, see Fig. 12 of Paper I). Counting the emission lines is therefore useful in a search for the COM-containing cores.

The number of emission lines was determined by searching for emission peaks above the 3 σ level across the entire spectrum of the two SPWs, which was also adopted in Sánchez-Monge et al. (2017). In practice, the 1 σ level was calculated individually for each source from the standard deviation of the amplitudes in the line-free emission channels usually located on either or both ends of the wide SPWs. This method works very well for the sources without a forest of detectable lines. However, it is generally conservative for the sources (e.g., the one in Fig. 3a) with a forest of detectable lines since it is difficult to find completely line-free channels, leading to an overestimate of the sigma level. To avoid counting spurious peaks, for example from the broad line wings of the spectrum of the outflow sources, the separation between the nearest neighbours was required to be at least five velocity channels (i.e., ~ 8 km s⁻¹). In addition, a valid peak detection was required to have at least three channels above the 3 σ level.

Figure 3 displays an example of the search for the emission lines from the beam-averaged spectrum of the two SPWs at the peak position of two cores, demonstrating that our method works well in counting emission lines. Note that the two sources given in the example were in different ALMA observing clusters with the center frequencies slightly different, so that the frequency ranges of the sources are different accordingly. The final COM-containing cores are defined by the following two criteria, N_{line} > 5 and a compact feature of HC₃N emission. The former ensures at least one transition of the COMs for each candidate (see above, and Fig. 3), while the latter requires each candidate to be a compact source in molecular line emission. Figure 4 presents an example of the compact COM-containing core in HC₃N emission. Figure 4a shows the velocity-integrated intensity of HC₃N (in both grayscale and red contours) over a velocity extent of 80 km s⁻¹ centered at the systemic velocity of the core (in white ellipse) and 3 mm continuum (in cyan contours), while Fig. 4b displays the beam-averaged spectrum of HC₃N at the core center.

Following the above two criteria, 138 COM-containing cores were selected. We find that 48 out of these 138 COM-containing cores are spatially associated with H/UC-HII cores (positions matching within a radius of 2'', comparable to the beam size), and thus are H/UC-HII-associated candidate HMCs (CHMCs, hereafter). Note that the HMC is a definition from the molecular chemistry study, and has been observationally found to overlap the H/UC-HII regions. Given their masses and densities (see Sect. 4.2) most of the...
Figure 3. Beam (2′′)-averaged spectrum of SPWs 7–8 at the emission peak of the two COM-containing cores (see definition in text) from two ATOMS clumps. The core and clump names are labelled on top of each panel. The red squares indicate the emission lines above 3 rms and their total number is given to the parameter $N_{\text{line}}$. The horizontal dashed line indicates the 3 rms noise level across the two spectral windows. For reference, the five lines of panel b in an order of decreasing intensity are CS (2-1), SO (3-2), HC$_3$N (11-10), CH$_3$OH and H$_2$CO, respectively.

Figure 4. (a): velocity-integrated intensity map of HC$_3$N over [-35, 45] km s$^{-1}$ (in both grayscale and red contours) for the G009.6197+00.1940 core (in white ellipse) and its surroundings. The map is centred at the core peak with a size of 10″. For comparison, the 3 mm continuum is superimposed in cyan contours. The synthesized beam and a scale bar of 0.04 pc are drawn at the bottom left of the panel. (b): beam (2′′)-averaged spectrum of HC$_3$N at the core centre (i.e., the white ellipse in panel a).
effective radius equal to measured core size while compiled into the two catalogues, one called pure s-cHMCs and the other one pure w-cHMCs. The threshold \(N_{\text{line}}\) is the difference between 75th and 25th percentiles, or between upper and lower quartiles. The median radius is

\[ R_{\text{med}} = 20 \]
58 pure w-cHMCs. These results suggest that most of the 90 COM-containing cores are indeed compact.

Note that contamination from free-free radiation to continuum may not be trivial for the cores associated with H/UC-HII. In practice, we calculated at a temperature of 100 K the masses for two types of cores, pure cHMCs and cHMCs associated with H/UC-HII sources (i.e., compact H40a emission). In comparison, we found that the mass of the latter cores ($\sim 10^4 M_\odot$) is on average about two magnitude higher than that of the former cores ($\sim 10^2 M_\odot$). This result suggests that contamination by free-free radiation is non-negligible in calculating the flux-related parameters. Since this contamination cannot be accurately determined, we do not give the estimate of the continuum flux-related parameters for the H/UC-HII cores such as the mass.

3.3 Compact dense core list not associated with either cHMC or H/UC-HII.

As described above, we extract 453 cores in 3 mm continuum. Of these, 89 are classified as H/UC-HII, 32 as s-cHMC, and 58 as w-cHMC. The remaining 274 cores lack observationally-quantifiable metrics for association into any of the three categories above. Hence we refer to these as "unknown cores" (see Table 4). These "unknown cores" could be simple continuum flux condensations in an earlier evolutionary stage. Indeed, chemically poor HMOs and candidate massive prestellar cores have been detected in some massive protoclusters (e.g., Liu et al. 2017). However, it is also possible that some (to date) unknown but potentially significant fraction of these "unknown cores" may actually be cHMC or H/UC-HII cores that fall below our sensitivity limit due to spatial resolution, distance, and/or flux limitations. These will be investigated in more detail in a forthcoming paper.

For reference, the mass, number density, and mass surface density of the "unknown" cores (see Table 4), were calculated (see Appendix B) assuming a dust temperature of 25 K. This temperature is comparable to the median value of the clumps that do not have cHMC or H/UC-HII signatures. As a result, these cores have a median radius of $2.4 \times 10^{-2}$ pc in an IQR of [1.3, 4.6]($\times 10^{-2}$ pc, a median mass of 19 $M_\odot$ in an IQR of [5, 99] $M_\odot$, a median number density of $0.6 \times 10^6$ cm$^{-3}$ in an IQR of [0.3, 1.3] $\times 10^6$ cm$^{-3}$, and a median mass surface density of $2.2$ g cm$^{-2}$ in an IQR of [1.1, 4.3] g cm$^{-2}$. The properties of the "unknown" cores will be more thoroughly investigated in a forthcoming paper.

4 DISCUSSION

4.1 Limitations in dense core extraction and classification

Our ATOMS survey consists of a uniform sensitivity and angular resolution survey toward regions located over a large range of distances. Consequently, the dense core extraction, as discussed above, is affected by variations of factors of order of $\sim$ 10 in distance across the sample. Here we focus on the most robust (brightest) portion of our sample (i.e. w-cHMC, s-cHMC and H/UC-HII cores, see Sect. 3.2).

Figure 6 shows how the radii (R) and masses (M) depend on distances (D) for the three groups (w-cHMC, s-cHMC and H/UC-HII) of dense cores. There are clear increasing trends in R vs. D and M vs. D relations, further suggesting that distant sources were not well resolved. With future higher resolution observations, we expect that these distant cores with sizes of $\sim$ 0.1 pc would break down to smaller sub-cores or condensations with sizes of $\sim$ 0.01 pc. Moreover, the masses of the w-cHMC and s-cHMC cores can be found in Figure 6b far above the detection limit, which is in agreement with the nature of bright emission in continuum for those two types of cores.

Moreover, beam dilution impairs detection of hot and H/UC-HII cores at large distances. Therefore, we assume a smaller detection rate of such cores at larger distances. We tested this assumption by re-examining the detectability of the COM and H40a lines after pushing the observations of the relatively nearby sources to a large distance. In practice, we smoothed the cubes of SPWs7–8 for 10 cHMCs and 5 H/UC-HII cores at distances $\lesssim$ 2 kpc to the larger beam size that was transferred from the ATOMS typical angular resolution ($\sim$ 1.6$''$) at a fixed far distance of 5 kpc. In consequence, only 30% of the selected cHMCs were re-identified using the same HMC identification method as in Sect. 3.2.2, while 80% of the selected H/UC-HII sources have been re-identified. This result suggests that beam dilution affects the detectability for cHMCs more than it does for H/UC-HII cores at the ATOMS sensitivity.

Furthermore, Fig. 7 shows the distance distributions of three groups of clumps, which contain w-cHMC, s-cHMC and H/UC-HII. For comparison, we also plot the distance distribution of the full sample. Indeed, we find that the candidate hot cores (w-cHMC and s-cHMC) tend to be located at nearer distances (Fig. 7b,c), with their cumulative distribution curves (in red and blue colors in Fig. 7a) above the curve (in gray color) for the full sample.

We test whether the distance distributions of clumps containing different kinds of dense cores follow the same distribution as the full sample with Kolmogorov-Smirnov test. The unknown hypothesis is that two distributions follow the same distribution. The tests are consistent with the unknown hypothesis for the w-cHMCs group (P-value$=0.37$) and H/UC-HII group (P-value$=0.67$) due to their P-values being greater than 0.05, suggesting that the detection rates of w-cHMCs and H/UC-HII are not greatly affected by the distance issue. In contrast, the P-value for s-cHMCs is 0.06, indicating that the detection of s-cHMCs is significantly limited by distances. It may imply that the detection rate of s-cHMCs is significantly underestimated for distant sources. This is in line with the cumulative distribution function of distances (Fig. 7a). In the figure, clumps with s-cHMC appear to show smaller distances ($\sim$ 2.6 kpc on average) than those ($\sim$ 3.2 kpc on average) with w-cHMC, indicating that the detection of hot cores at large distances is incomplete.
Figure 6. (a): Radius versus distance for w-cHMC, s-cHMC, and H/UC-HII cores. The p value of the KS test 0.03 suggests that the size distributions of w-cHMC and s-cHMC come from an identical distribution. (b): Mass versus distance for w-cHMC, and s-cHMC cores. H/UC-HII cores are not shown here since their masses cannot be estimated from 3 mm continuum due to free-free contamination (see text in Sect.3.2.2). The curve is the mass sensitivity distribution as a function of the distance.

Figure 7. Distance distribution of the four groups of clumps. (a): cumulative distribution function. (b–d): histograms of all clumps against w-cHMC group, s-cHMC group, and H/UC-HII group of clumps, respectively.
Table 4. Parameters of the “unknown” cores (i.e., no signature of H/UC-H\textsc{ii} nor c/H\textsc{mc})

| Clump | Core | $D$ | $FWHM$ | $FWHM_{\text{iso}}$ | PA | $FWHM_{\text{iso}}$ | $n_{\text{crit}}$ | $R_{\text{core}}$ | log($M_{\text{core}}$) | log($R_{\text{core}}$) | $\Sigma_{\text{core}}$ |
|-------|------|-----|---------|-------------------|---|-------------------|-----------------|-------------|------------------|-----------------|--------------|
| I08076-3556 | G253.2971-01.6156 | 1.0 | 5.1 | 1.3 | 86.4 | 4.9 | 1.3 | 0.9 | −0.1 | 5.9 | 7.2 |
| I08076-3556 | G253.2930-01.6113 | 1.0 | 2.2 | 1.6 | 96.3 | 1.6 | 1.1 | 0.9 | −0.1 | 5.9 | 7.2 |
| I08303-4303 | G261.6446-02.0899 | 2.4 | 9.9 | 2.5 | 6.9 | 4.7 | 2.0 | 1.8 | 1.1 | 6.0 | 3.4 |
| I08303-4303 | G261.6444-02.0876 | 2.4 | 4.0 | 3.8 | 40.0 | 3.8 | 3.5 | 1.8 | 1.2 | 5.7 | 3.0 |
| I08448-4334 | G263.7776-00.4332 | 1.4 | 5.2 | 3.0 | 116.0 | 5.0 | 2.8 | 8.8 | 1.7 | 5.6 | 2.8 |
| I08448-4334 | G263.7729-00.4364 | 1.4 | 2.5 | 1.8 | 72.0 | 2.1 | 1.1 | 2.1 | 0.8 | 6.0 | 3.4 |
| I08448-4334 | G263.7732-00.4350 | 1.4 | 4.4 | 2.2 | 80.6 | 3.6 | 1.8 | 7.3 | 0.0 | 6.0 | 3.4 |
| I08448-4334 | G263.7744-00.4328 | 1.4 | 2.5 | 2.2 | 18.0 | 2.1 | 1.6 | 11.5 | 0.9 | 6.0 | 3.4 |
| I08448-4334 | G263.7712-00.4363 | 1.4 | 3.2 | 1.8 | 157.0 | 2.9 | 1.1 | 2.4 | 0.9 | 6.0 | 3.4 |

Note: The parameters $FWHM$, $FWHM_{\text{iso}}$, and $R_{\text{core}}$ are derived in the same way as in Table 1. The errors on $R_{\text{core}}$, $M_{\text{core}}$, and $\Sigma_{\text{core}}$ mainly come from the distance uncertainties, those on the fluxes from the 2D Gaussian fitting in the core extraction. Only a small portion of the data is provided here, and the full table will be available as supplementary material.

4.2 Nature of the COM-containing and not H/UC-H\textsc{ii}-associated cores

Since emission in the COM transitions covered by the ATOMS observations can be detected towards several distinct objects, including low/high-mass prestellar cores, HMPO cores, HMCs, and even hot corinos associated with low-mass protostars (e.g., Vastel et al. 2014; Jiménez-Serra et al. 2016; Soma et al. 2018; Csengeri et al. 2019; Molet et al. 2019; Jørgensen, Belloche, & Garrod 2020; Hsu et al. 2020), it is necessary to constrain the nature of the 90 COM-containing cores that are not associated with H/UC-H\textsc{ii} (see Sect. 3.2.2). To this end, we investigate the distribution of both the mass ($M_{\text{core}}$) and the mass surface density ($\Sigma_{\text{core}}$) of the 90 COM-containing cores, as shown in Fig. 8. They have a median value of mass equal to $\sim 57 M_\odot$ in an IQR of 19–138 $M_\odot$, and surface densities with a median value of $\sim 6.5 g cm^{-2}$ in an IQR of 3.3 to 15.6 $g cm^{-2}$.

Theoretically, cores (on scale $<0.1 pc$) with $\Sigma_{\text{crit}} \geq 1 g cm^{-2}$ will most likely form high-mass stars (Krumholz & McKee 2008).

Searching from existing maser catalogue\textsuperscript{5} (Ladevèze, Bayadina, & Sobolev 2019), we find that $\sim 34\%$ of the 90 COM-containing cores are associated with Class II CH$_3$OH masers located within the core size (red dots in Fig. 8). Class II CH$_3$OH masers have been found to be exclusively associated with high mass star forming regions (e.g., Cyganowski et al. 2009). The spread of $\Sigma_{\text{core}}$ for the cores associated with the CH$_3$OH masers is consistent with the theoretical prediction (i.e., the red dots versus the vertical dashed line in the figure). Following the threshold $\Sigma_{\text{crit}} \geq 1 g cm^{-2}$, we find that $\sim 96\%$ of the 90 COM-containing cores above it will most likely form high-mass stars. We note that there are six COM-containing cores, three of which are associated with Class II masers, above the threshold but with $M_{\text{core}} < 10 M_\odot$. We suggest that these cores could have been in the process of forming high-mass stars for a significant fraction of their lifetime, so that a large fraction of their mass has been accreted onto the central HMPOs. We also note that if the actual temperature of the 90 COM-containing cores is lower than 100 K, the possibility that they form high-mass stars will be higher. For reference, if the temperature is assumed to be 50 K, the mass and surface density will be about two times higher.

Overall, the probability that the identified COM-containing cores are associated with low-mass star forming objects (i.e., low-mass prestellar cores, and hot corinos) is rather low. Given that emission in the COMs transitions available in the ATOMS data has been already observed towards other HMPO and HMC regions (Csengeri et al. 2019; Jørgensen, Belloche, & Garrod 2020), we conclude that most (if not all) of the 90 COM-containing cores should be either HMPO cores or HMCs. Note that HMPOs are simply assumed here to be younger than HMCs although this timescale relation has yet to be determined.

To distinguish definitely between the two types of high-mass star-forming cores requires knowledge of their temperatures. The temperature is usually computed from a rotational diagram analysis of multiple transitions of one or more COM species (e.g., CH$_3$OCHO, and CH$_2$OH). However, the range of upper level energy of the COM lines covered in the ATOMS survey is too narrow to permit a reliable temperature determination. This thus requires follow-up observations of higher frequency transitions that arise from higher energy levels.

\textsuperscript{5} http://maserdb.net/download.pl
in the very early stages of high-mass star formation. We include them in two separate catalogues: one including 32 s-cHMCs and the other including 58 w-cHMCs, with the former catalogue presumably containing more robust HMCs candidates than the latter. These catalogues constitute a unique database of objects for future follow-up higher-resolution observations to investigate the dynamical processes related to high-mass star formation, such as infall, outflow, and rotation.

### 4.3 Constraints on the Duration of the HMC Phase

Because heating by the forming star precedes ionization, the general picture is that HMCs precede H/UC-HII in the evolution of a core to a massive star (Garay & Lizano 1999; Kurtz et al. 2000; van der Tak 2004; Cesaroni 2005; Rathborne et al. 2011). Our large sample, unbiased towards either HMCs or H/UC-HII cores, enables further study. First, the two phenomena are not exclusive, as there is a substantial overlap between HMCs and H/UC-HII (Fig. 5). Nearly half (48/89) of H/UC-HII in the sample show COMs, indicating that hot cores may persist during nearly half of H/UC-HII lifetime even when the central high-mass protostars start to ionize the surroundings.

Second, with certain assumptions, we can use the numbers of candidate HMCs and cores with H/UC-HII to estimate the relative duration of the HMC phase. For a rigorous result, the survey must be complete, the evolution through the phases must be a continuous process proceeding at a steady rate for a period longer than the last phase considered, and other variables, such as the mass of the star, cannot be important. Further study of this sample is needed to check these assumptions, so we offer here only some preliminary considerations.

As discussed in Sect. 4.1, the ATOMS survey is more complete in the detection of H/UC-HII regions than HMCs, so we have a lower limit on the number counts of HMCs. The total number (138) of COM-containing dense cores (w-CMC and s-CMC) is already larger than the number (89) of H/UC-HII cores. The number of strong candidate HMCs (56) is smaller than the number (89) of H/UC-HII cores but may be greatly underestimated due to the distance effect. The most important unknown is the mass of the forming star because the number of ionizing photons is a very strong function of stellar mass. If all these cores will form stars capable of producing a H/UC-HII, the current lack of one is due to evolution. Further study of the luminosity of the individual cores with JWST observations could test this assumption.

With all these caveats, we suggest that the duration of candidate hot cores is at least comparable to the lifetime of H/UC-HII and is probably greater.

### 4.4 The origin of chemical differentiation among high-mass star forming cores

Some high-mass star forming cores are found to be chemically rich while others are not. Even cHMCs show differing richness in molecular lines especially in COMs. The median $N_{\text{line}}$ values are 8 within an IQR of [5, 16] for the 58 w-cHMCs, and 57 within an IQR of [28, 123] for the 32 s-cHMCs. Would this different chemical richness (i.e., $N_{\text{line}}$) be related to an evolutionary sequence from w-cHMCs → s-cHMCs?

The chemical differentiation among high-mass star forming cores could be partially attributed to an evolutionary effect. More evolved cores with higher luminosity can heat a larger volume of their surroundings, evaporating molecules from ices and thus increasing the gaseous molecular abundances.

The 146 analyzed ATOMS clumps can be classified into four main groups according to the types of cores they harbour: (i) the w-cHMC group with 28 clumps hosting w-cHMC cores, (ii) the s-cHMC group with 17 clumps hosting s-cHMC cores, (iii) the H/UC-HII group with 68 clumps containing H/UC-HII cores, and (iv) the “unknown” group with 28 clumps without cHMC or H/UC-HII cores.

There are five clumps with both w-cHMC and s-cHMC cores. Note that if a clump hosts both H/UC-HII core and cHMC, it will be placed into the H/UC-HII group. In addition, the w-cHMC group could contain s-cHMC cores that are not detectable yet or appear as w-cHMC cores due to the limited angular resolution and sensitivity. That is, there could be an underlying overlap between w-cHMC and s-cHMC groups of clumps, so the following analysis should be treated with caution. To explore the evolutionary stage of the clumps in the different groups we resort to two parameters available for the ATOMS clumps (see Paper I): the bolometric luminosity to mass ratio $L_{\text{bol}}/M_{\text{clump}}$ and the dust temperature $T_d$. These parameters, which cannot be directly determined for the cores with the ATOMS data alone, are distance independent and have been proposed as indicator of the evolutionary stage of clumps (e.g., Guzmán et al. 2015).

Figure 9 plots the distribution of the two parameters for the four groups of clumps. The “unknown”, w-cHMC, s-cHMC, and H/UC-HII groups have respective median $L/M$ values 28.1, 26.9, 29.7, 32.7 $L_\odot/M_\odot$. These values fall into the range of $2 \lesssim L/M \lesssim 40 L_\odot/M_\odot$ observationally defined for the high-mass star-forming objects (Giannetti et al. 2017; Elia et al. 2017). This result suggests that the four groups of clumps harbour embedded phases of high-mass star formation. As such, many of the clumps in the “unknown” group could not be really devoid of high-mass star-forming cores, and instead harbour HMPO objects or even more evolved HMC that could not be detected with the sensitivity of the ATOMS data. If we only consider the w-cHMC, s-cHMC, and H/UC-HII groups, there is a weak increasing trend in the median values of the $L_{\text{bol}}/M_{\text{clump}}$ ratio. A similar, but stronger, trend also appears in the temperature distribution among these three groups of clumps.

The differences in $L_{\text{bol}}/M_{\text{clump}}$ and $T_d$ of the natal clumps are not very significant. If the evolution from HMCs to H/UC-HII is correct for individual cores, the explanation for the poor correlation with clump-scale properties may be that the evolution of individual cores to stars within a clump differs, and the clump-scale evolution of $L_{\text{bol}}$ is driven by the most massive/evolved core. To study evolution at the core level, higher angular resolution and sensitivity in the mid-infrared to far-infrared is needed to pinpoint the embedded protostars, which cannot be well resolved at the current resolution of the infrared data, through the spectral energy distribution over a large dynamical frequency range.

In addition, recent studies of low-mass cores indicate that chemical richness of star forming cores may not be related to evolutionary sequence. Belloche et al. (2020) suggested a luminosity threshold of $4 L_\odot$, above which low-mass cores should exhibit spectral features from at least one COM and may contain hot corinos. However, in a recent study of a large sample of 49 low-mass star forming cores located in the Orion complex by Hsu et al. (2020), many protostellar objects with luminosities much greater than $4 L_\odot$ do not show any clear sign of COMs or hot corinos. This indicates that the chemical differentiation among star forming cores depends on their chemical history, as well as their luminosity.

An alternative scenario could be that some star forming cores in their “cold” core phase form abundant molecules such as COMs on ice mantles through grain-surface chemistry while other cores do not. These different behaviours are probably related to varying physical and chemical properties as well as initial conditions of dif-
ferent sources. When molecules evaporate from ice in the “hot” core phase, their gaseous molecular abundances should also vary greatly. This scenario could be tested by detailed chemical studies toward a sample of “cold clumps” like in infrared dark clouds that lack active star formation and may represent the very initial conditions of high-mass star formation. Detailed chemical investigations are beyond the scope of this work. More detailed chemical studies of molecular abundances of dense cores will be presented in forthcoming papers.

4.5 Size versus H\textsubscript{40}\_α linewidth relationship for H/UC-H\textsubscript{II} cores

The 89 H/UC-H\textsubscript{II} cores could be associated with either HC-H\textsubscript{II} or UC-H\textsubscript{II} regions, and we attempt to distinguish them by their observable properties (see Sect. 1). To this end, we focus on the size and line width of the radio recombination line ($\Delta V\text{H}_{40}\_\alpha$) of the H/UC-H\textsubscript{II} cores, as shown in Fig. 10. These cores have two types of sizes, one measured from 3 mm continuum and the other one from H\textsubscript{40}\_α emission. As shown in Fig. 10a, the two types of sizes match each other well until the size is greater than 0.1 pc. This result suggests that H\textsubscript{40}\_α emission mainly contributes to 3 mm continuum when the H/UC-H\textsubscript{II} core size is less than 0.1 pc. From distance information of the cores as indicated in the colorscale in Fig. 10a, it can be seen that the deviation of the two types of core sizes does not depend on the distance. We suspect that when the H/UC-H\textsubscript{II} core size is greater than 0.1 pc, more cold dust emission could be included within it, leading to an overestimation of the size of the real ionized gas region. In view of this, the size measured from H\textsubscript{40}\_α emission for the 89 H/UC-H\textsubscript{II} cores will be discussed in the following. These cores have sizes from $\sim 5.3 \times 10^{-3}$ to $3.7 \times 10^{-1}$ pc with a median value of $5.7 \times 10^{-2}$ pc.

The $\Delta V\text{H}_{40}\_\alpha$ of the 89 H/UC-H\textsubscript{II} cores range from $\sim 15$ to $55$ km s\textsuperscript{-1} with a median value of $28$ km s\textsuperscript{-1}. The measurement of $\Delta V\text{H}_{40}\_\alpha$ is not found to be distance-dependent, as shown in Fig. 10b. Actually, the $\Delta V\text{H}_{40}\_\alpha$ values are typical of both UC-H\textsubscript{II} and HC-H\textsubscript{II} regions, namely in a range of $\sim 10$ to $40$ km s\textsuperscript{-1} for the former and $40$ to $60$ km s\textsuperscript{-1} or even higher for the latter (e.g., Hoare et al. 2007; Rivera-Soto et al. 2020). Following the typical size and line width of radio recombination lines of H/UC-H\textsubscript{II} regions (see above), the 89 H/UC-H\textsubscript{II} cores can be divided into 79 UC-H\textsubscript{II} and 10 HC-H\textsubscript{II} cores (see Fig. 10c). That is, most ($\sim 90\%$) of the compact-H\textsubscript{II} cores are UC-H\textsubscript{II} cores while only a small fraction ($\sim 10\%$) of them are HC-H\textsubscript{II} cores. Therefore, if the lifetime of UC-H\textsubscript{II} is of the order of $10\textsuperscript{5}$ yr, the lifetime of HC-H\textsubscript{II} will be $\sim 10\textsuperscript{4}$ yr (e.g., Wood & Churchwell 1989; Davies et al. 2011).

In general, the widths of radio recombination lines are due to
a combination of thermal, dynamical, and/or pressure broadening mechanisms (e.g., Keto, Zhang, & Kurtz 2008; Nguyen-Luong et al. 2017; Rivera-Soto et al. 2020). The thermal broadening, $\Delta V_{th}$, is given by $\Delta V_{th} = (8 ln 2 k_B T_e / m_H)^{1/2}$ where $k_B$ is the Boltzmann constant and $m_H$ is the mass of the atom hydrogen. For electron temperatures of $T_e = 6,000$ K, 8,000 K, and 10,000 K, the respective thermal widths are 16.6 km s$^{-1}$, 19.1 km s$^{-1}$, 21.4 km s$^{-1}$, (see the three vertical color-gradient lines in Fig. 10c). Most (≈ 96%) of the H/UC-H$_2$ cores are found to have $\Delta V_{H40_{\alpha}}$, widths larger than $\sim$ 19 km s$^{-1}$, which corresponds to the thermal broadening for an electron temperature of 8,000K typical of an ionized plasma (e.g., Osterbrock & Ferland 2006). This result indicates that in addition to the thermal broadening, non-thermal (e.g., dynamical and/or pressure) broadening mechanisms are responsible for the observed large $\Delta V_{H40_{\alpha}}$ in most of the 89 H/UC-H$_2$ cores.

Moreover, we find that the H$_40_{\alpha}$ line width decreases as the size of the core increases. To investigate if the trend is distance-dependent or not, we present the distance information of each H/UC-H$_2$ core in colorscale in Fig. 10e. The figure shows that the decreasing trend persists rather than breaks at different distances, and thus it is physically meaningful. It indicates that non-thermal (e.g., dynamical and/or pressure) mechanisms dominate the broadening on smaller scales of the H/UC-H$_2$ cores (Garay & Lizano 1999).

5 SUMMARY AND CONCLUSION

Using the 3 mm ATOMS survey data, we searched for the presence of compact cores towards 146 IRAS clumps located within the inner galactic disk in the range $-80^\circ < l < 40^\circ$ and $|b| < 2^\circ$. The compact cores were extracted from 3 mm continuum emission maps through a combination of the Dendrogram algorithm and CASA-imfit task. The main results of this work are summarized as follows:

- We compiled three catalogues of compact cores with different characteristics. One catalogue, referred to as the H/UC-H$_2$ catalogue, includes 89 cores that enshroud H/UC-H$_2$ regions as indicated by the presence of compact H$_40_{\alpha}$ emission; a second catalogue, referred to as the pure s-chMC catalogue, includes 32 s-chMHCs associated with a rich spectrum ($N \geq 20$ lines) of complex organic molecules (COMs); the third catalogue, referred to as the pure w-chMC catalogue includes 58 w-chMHCs with relatively low levels of COM richness (i.e., $5 \leq N_{\text{line}} < 20$). These three catalogues of compact cores provide a crucial foundation for future studies of the early stages of high mass star formation across the Milky Way. We find that nearly half of H/UC-H$_2$ cores are candidate hot molecular cores.

- For completeness, another catalogue that includes the remaining 274 cores without the signature of either chMC or H/UC-H$_2$, referred to as the “unknown” catalogue, is also provided. These cores deserve future detailed investigation, since some of them could be in the early stages of high-mass star formation prior to formation of a HMC, and they could be good targets for studying initial conditions of high-mass star formation.

- The detection rate of candidate distant hot cores is greatly underestimated due to relatively poorer linear resolution and line sensitivity than for nearer sources. However, the total number (138) of the detected COM-containing dense cores is still larger than the number (89) of H/UC-H$_2$ cores, indicating that the duration of high-mass protostellar cores (or cores) showing line-rich features could be at least comparable to the lifetime of H/UC-H$_2$ phase.

- We find weak increasing trends in $L/M$ ratio and dust temperature ($T_{d}$) for the natal clumps that contain different kinds of dense cores (w-chMC→s-chMC→H/UC-H$_2$). However, the chemical classes indicating core evolution are not well traced by the $L_{bol}/M_{clump}$, suggesting that the evolution of individual cores is not captured by that evolutionary indicator used for clumps.

- Based on the relationship between size and H$_40_{\alpha}$ line width, we conclude that of the 89 H/UC-H$_2$ cores, 79 are associated with UC-H$_2$ and 10 with HC-H$_2$ regions. We also find that the width of the H$_40_{\alpha}$ line increases as the core size decreases, suggesting that non-thermal (e.g., dynamical and/or pressure) line-broadening mechanisms are dominant on the smaller scales of the H/UC-H$_2$ cores.

The 3 mm interferometric catalogues of high-mass star-forming cores provided here can be used to study the kinematics and dynamics of molecular gas in the vicinity of newly-formed (proto)OB stars and somewhat-evolved H/UC-H$_2$ regions. Such studies will definitely advance our understanding of the dynamical processes in the early stages of high-mass star formation, such as infall, outflow, and rotational motions, and our knowledge of the roles of feedback (e.g., outflows, stellar winds, and H/UC-H$_2$ regions) in the process of high-mass star-formation.

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Data availability

The data underlying this article are available in the article and in its online supplementary material.
Due to the lack of distance uncertainty information from the literature (Faúndez et al. 2004; Urquhart et al. 2018) for the 146 target clumps, their kinematic distances were recalculated using the Monte Carlo kinematic tool developed by Wenger et al. (2018). With the Galactic coordinates and radial velocity parameters of a source inputted, the tool can return the distances and the uncertainties for the source leveraging the rotation curve of Reid et al. (2014) with the updated solar motion parameters (Reid et al. 2019) and the Monte Carlo technique with 10,000 samplings. The radial velocity measurements by Liu et al. (2016) rather than by Bronfman, Nyman, & May (1996) were adopted in this work since the velocity resolution (0.42 km s\(^{-1}\)) in Liu et al. (2016) at which the measurements were made better than that (0.76 km s\(^{-1}\)) in Bronfman, Nyman, & May (1996).

Apart from the two sources located near the Galactic center, kinematic distance solutions have been calculated for 144 ATOMS clumps. The distance ambiguities (if any) have been resolved following Faúndez et al. (2004); Urquhart et al. (2018). Moreover, the kinematic distance solutions have been improved for the three sources using maser parallax distances available in the literature (Reid et al. 2014; Urquhart et al. 2018). Overall, the typical relative distance uncertainty for the 144 ATOMS clumps is \(\sim 7\%\). For the remaining two sources located near the Galactic center, their kinematic distances could not be calculated from the rotation curve and thus the values from the literature along with a typical relative distance uncertainty of \(\sim 7\%\) have been adopted. The recalculated distances are listed in Table A.

Comparing the recalculated distances with those from Faúndez et al. (2004); Urquhart et al. (2018), we find a good agreement (Pearson correlation coefficient \(\rho = 0.97\)) as shown in Fig. A1. In addition, the relative distance uncertainties are found to have an IQR of \(\sim [5\%, \ 12\%]\) with a median value of \(\sim 7\%\).
To understand the nature of the 90 COM-containing cores not associated with the H/UC-HII signature (see Sect. 3.2.2) and 274 “unknown” cores, we calculated their mass $M_{\text{core}}$ in the following form:

$$M_{\text{core}} = \frac{F_{\nu}^{\text{int}} R_{\text{gd}} D^2}{B_0 (U_{\text{dust}})^{3/2}} n_\nu,$$

where $F_{\nu}^{\text{int}}$ is the measured integrated 3 mm flux over the core size, $R_{\text{gd}}$ is the gas-to-dust mass ratio (assumed to be 100), $D$ is the
distance to the core, $B_v$ is the Planck function for a dust temperature $T_{dust}$, and $\kappa_v$ is the opacity assumed to be $0.18 \text{ cm}^2 \text{ g}^{-1}$ of dust at $\nu \sim 94 \text{ GHz}$, taken directly from the “OHS” dust model, a combination of dust from Ossenkopf & Henning (1994) and Pollack et al. (1994) and extended to longer wavelengths by Young & Evans (2005). Moreover, the mass surface density $\Sigma_{core}$ was derived from $\Sigma_{core} = M_{core}/(\pi R_{core}^2)$, where $R_{core}$ is the core radius equal to the geometric mean of the $FWHM_{maj}^2$, $FWHM_{min}^2$ at the respective core distance. Given the median radius of the 90 COM-containing cores $\sim 0.02 \text{ pc}$, the $T_{dust} \sim 100 \text{ K}$ was assumed for a first-order approximation in the calculation, which is typical of HMCs at a radius of $\sim 0.01 \text{ pc}$ (Osorio, Lizano, & D’Alessio 1999). For the 274 “unknown” cores, the temperature $25 \text{ K}$ is assumed, which is comparable to the mean value of the clumps that do not have cHMC or H/UC-HII signatures.

The peak column densities are estimated from the peak flux density of the cores using the following equation:

$$N_{H_2} = \frac{F_p}{B_0(T_{dust}) \Omega \kappa_v \mu m_{H_2}},$$  

(B2)

where $\Omega$ is the beam solid angle, $\mu$ is the mean molecular weight of the gas, assumed to be 2.8, $m_{H_2}$ is the mass of the hydrogen atom. In turn, the number densities can be estimated via $n_{H_2} = N_{H_2}/2R$, assuming a spherical geometry for cores.

The three derived parameters $M_{core}$, $n_{H_2}$, and $\Sigma_{core}$ are arranged in last three columns of Tables 2 for the 32 s-cHMCs, and of Table 3 for 58 w-cHMCs.

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NOTE: I17441-2822 and 17455-2800 are close to the Galactic centre, whose distance values are adopted from Fainéndez et al. (2004); I18469-0132, I18507+0110, and I19097+0847 have the maser parallax distance measurements (Reid et al. 2014).
