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Star formation and chemical complexity in the Orion nebula: A new view with the IRAM and ALMA interferometers

Formation stellaire et complexité chimique dans la nébuleuse d'Orion : une image renouvelée par les interféromètres IRAM et ALMA

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ABSTRACT

The Orion nebula is one of the most observed celestial regions in the Milky Way. It is an active massive star-forming region, especially well studied in the millimeter and submillimeter domains that allow us to unveil the cool and obscured regions in which stars are being formed. After a brief introduction to the main properties of a radio telescope, we recall that the most sensitive radio interferometers, the IRAM mm array and, especially, the recently built ALMA millimeter/submillimeter array, offer an outstanding spatial resolution reaching the sub-arcsecond scale, or even about 10 milli-arcseconds for ALMA (about four times the Earth's orbit radius at the Orion distance). These interferometers can reveal the fine spatial details of the Orion clouds of gas and dust within which new stars and associated planetary systems are being formed. The high spectral resolution and sensitivity of both interferometers and the broad instantaneous bandwidth offered by ALMA allowed us to map the emission from a number of complex organic molecules, to estimate the molecular abundances, and to address some important aspects of the molecular complexity in Orion. Our observations do not lead to a unique molecular formation and excitation scheme, but the chemistry at work in the proto-stellar 'fragments' at the center of the Orion nebula can be compared with the chemistry prevailing in comets of the Solar system. We have underlined the possible links between the prebiotic molecules observed in space and the chemistry leading to the early terrestrial life.

RÉSUMÉ

La nébuleuse d'Orion est l'une des régions célestes les plus observées de la Voie lactée. Elle est le siège d'une intense formation stellaire particulièrement bien étudiée dans les domaines millimétriques et submillimétriques, qui révèlent l'intérieur des régions froides et sombres, inobservables en optique, où se forment les étoiles. Après une brève introduction aux propriétés principales d'un radiotélescope, nous rappelons que les interféromètres les plus sensibles, celui de l'Iram en onde millimétrique, et spécialement le tout nouveau réseau ALMA en onde millimétrique/submillimétrique, offrent une résolution

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spatiale exceptionnelle, pouvant atteindre la fraction seconde de degré, voire la dizaine de milliseconde de degré pour ALMA (soit environ quatre fois le rayon de l'orbite terrestre à la distance d'Orion). Ces interféromètres peuvent révéler les détails spatiaux fins des nuages de gaz et de poussière de la nébuleuse d'Orion où se forment de nouvelles étoiles et leurs systèmes planétaires associés. La haute résolution spectrale et sensibilité de ces deux interféromètres, ainsi que la grande bande instantanée offerte par ALMA nous ont permis de cartographier l'émission de plusieurs molécules complexes organiques, d'estimer les abondances moléculaires, et de nous confronter à quelques questions importantes en lien avec la complexité moléculaire dans Orion. Nos observations ne conduisent pas à un schéma unique de formation et d'excitation moléculaire, mais la chimie à l'œuvre dans les « fragments » proto-stellaires au centre de la nébuleuse d'Orion peut être comparée à la chimie qui domine dans les comètes du Système solaire. Nous avons souligné les liens possibles entre les molécules prébiotiques observées dans l'espace et la chimie qui a conduit à la vie primitive sur Terre.

1. Introduction

After a short description of the Orion nebula and associated star-forming clusters (Sect. 1.1), we briefly introduce the main properties of a radio telescope used either as a single dish or as a radio interferometer, and we highlight some of the characteristics of the sensitive IRAM and ALMA millimeter/submillimeter arrays (Sect. 1.2) that have been used to observe Orion. We recall, without being exhaustive, that millimeter single dishes and interferometers enabled one to discover and map the regions of stellar formation in Orion (Sects. 2.1 and 2.2). These regions, and especially the BN/KL region defined in Sect. 1.1, exhibit extreme molecular complexity, which we will discuss in the light of selected results gathered with the IRAM and ALMA arrays (Sects. 3.1 and 3.2). A brief comparison of the relative abundance of complex molecular species observed in both Orion and comets is presented in Sect. 3.3, and brief final remarks are made in Sect. 4.

Addressing the full question of the molecular complexity in the Orion environment is beyond the scope of this paper. However, a brief summary is useful since nearly all molecules that have been discovered in the interstellar medium are also present in the Orion BN/KL region which, together with the center of our Galaxy, is one of the two richest molecular 'factories' known in the Milky Way. Molecules detected in BN/KL include simple species such as CO, CS, SiO, HCN, HCO^+, etc., and complex O- and N-bearing species with 6 or more atoms such as methanol (CH_3OH), acetone $(CH_3)_2CO$ or ethanol (CH_3CH_2OH), and less known species such as methyl formate ($HCOOCH_3$), acetonitrile (CH_3CN), ethyl cyanide (C_2H_5CN), etc. (see Sects. 3.1 and 3.2). The observations strongly suggest that this complexity results from a variety of processes involving gas heating, the release of molecules from dust grain mantles and/or multiple shocks generated by the dynamical interaction between young objects (e.g., [1]). We show in Sect. 3 that many details of the chemical complexity in BN/KL are unraveled thanks to the high spatial and spectral resolution provided by interferometers. However, the molecular complexity observed in BN/KL was revealed primarily by spectral line surveys performed in various frequency ranges with different radio telescopes across large bandwidths (e.g., [2] or [3]). The IRAM 30-m millimeter telescope, for example, has been extensively used to identify around 50 different molecular species from more than 15,000 spectral lines (e.g., [2]), including the complex and long methyl acetate molecule CH_3OCOCH_3 [4]. It is worth mentioning that the identification in a 'forest' of thousands of astronomical lines is made possible with the help of published spectral line catalogs and thanks to an ongoing close collaboration with laboratory spectroscopists. A detailed introduction to the observation and chemistry of complex organic molecules probing the physical conditions of various interstellar regions in our Galaxy can be found in [5].

1.1. The Orion nebula and the BN/KL region

The Orion nebula (or Messier 42) is a small diffuse nebula, which is visible with the naked eye in the southern part of the large quadrilateral figure[1] formed by the brightest stars of the Orion constellation. It is embedded in a large complex of gas and dust, the 'Orion cloud', which covers most of the northern (Orion B) and southern (Orion A) parts of the quadrilateral constellation. The Orion nebula is brightened by young (a few 10^5 years) bright stars known as the Trapezium cluster, a compact region about 0.15 light-year in size[2] (Fig. 1). Exploration of the Orion stellar, gaseous and dusty components has been revolutionized in the years 1970s and beyond thanks to the rapid instrumental development made in the infrared and millimeter domains, which revealed new compact stellar objects or giant molecular clouds that are thought to lead to

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[1] The quadrilateral figure is formed by four bright stars, Betelgeuse and Bellatrix to the north, and Rigel and Saiph roughly 16 degrees to the south. In the middle of this figure three other bright stars are aligned along an inclined line. The Orion Nebula lies to the south of this inclined line, in-between two stars, and to a few degrees above Rigel and Saiph.

[2] Let us recall that the 'dwarf' planet Pluto of the Solar system is at a distance from the Sun of about 4 to 7 hours at the speed of light and that the typical distance between stars in the Solar neighborhood is 3–4 light-years.

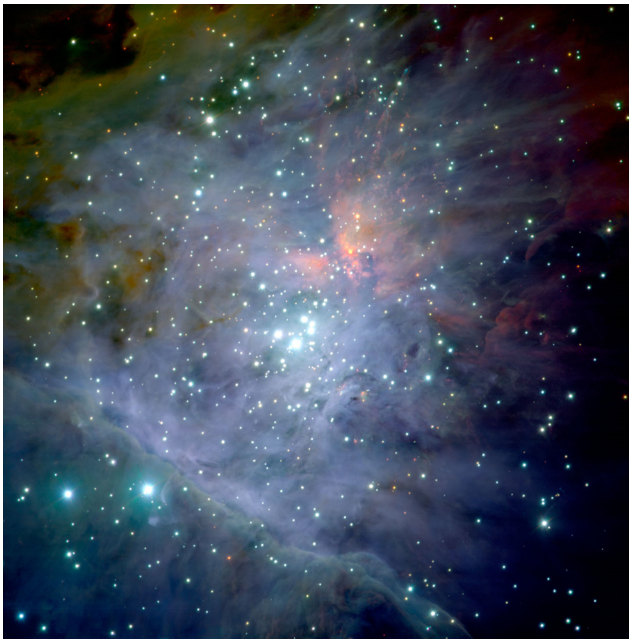

Fig. 1. The Orion Nebula, Trapezium cluster and BN/KL region. This image is a color composite mosaic image of the central part of the Orion Nebula, based on 81 images obtained with the infrared ISAAC instrument on the ESO Very Large Telescope. The main four stars of the Trapezium cluster (roughly 0.15 light-year in size) are visible in the center of the image. The reddish nebulosity immediately above the Trapezium corresponds to the BN/KL region. This image also shows about 1000 young stars of the Orion Nebula Cluster. Image credit: ESO/M. McCaughrean et al. (AIP).

newly formed stars. In this paper, we focus our attention on the Kleinmann and Low region (KL) where new stars are being formed. The KL region contains several bright infrared sources that are interpreted as dense gas cloud inhomogeneities and as deeply embedded young stars. Among the remarkable objects contained in this region, the Becklin–Neugebauer infrared source (BN), was detected in the immediate vicinity of the Trapezium (the BN to Trapezium projected separation on the sky is about 0.4 light-year); it is a luminous massive star embedded in the surrounding gas. More generally, the BN/KL region and the Trapezium system of stars (Fig. 1) are remarkable components of the vast Orion Nebula Cluster comprising thousands of young stars extending over more than 20 light-years. The distance to the Orion Nebula Cluster has recently been accurately determined from the radio interferometric measurements of the trigonometric parallax of a few stars in the Orion cluster [6]. The measured distance is small at the astronomical scale, 1350 light-years, and makes Orion an ideal target for detailed studies of stellar formation and chemical processes at work in a proto-stellar environment.

1.2. Millimeter-wave radio telescopes and the IRAM and ALMA interferometers

Just like an optical telescope, a radio telescope (also called radio dish or antenna) captures the electromagnetic emission emitted by the celestial bodies. The time-variable electrical field generated by an observed source is focused to a feed and the signal is later processed by a number of electrical components (mixer, amplifier, filter) until final detection. The source signal mixing stage uses a ‘local’ oscillator signal to convert the incoming high-frequency signal into a lower frequency for easier amplification and detection (this process is called heterodyne detection). In a modern radio telescope, the signal voltage is being digitized early in the processing chain and the final detection stage is accomplished with a digital auto- or cross-correlator engine, depending on whether a single-dish or a radio interferometer is used for the observations.[3] When signal detection is made over a relatively large frequency band (typically 8–10% or less of the central high-frequency signal captured by the antenna), one says that the observations are made in the ‘continuum mode’. Another observing mode called ‘spectral mode’ consists in detecting the emission in several narrow bands across a broader bandwidth in order to characterize the emission radiated by celestial molecular line sources. Since around 1970, mm-wave radio astronomy made tremendous advances mainly because of (i) major technological progress in different domains (cryogeny, mixer junctions, antenna panels etc.), (ii) the development of new data reduction tools adapted to the mm domain, and (iii) the continuous progress made in fundamental molecular spectroscopy, enabling accurate analysis of the astronomical line data. These advances have led the astronomers to discover from their continuum and spectral mode observations the extreme complexity (both spatially and chemically) of the interstellar medium and to conclude that cold and dark regions

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[3] Fundamental elements of radio astronomy are given for instance in Kraus, J.D., *Radio Astronomy*, 2nd edition (Cygnus-Quasar, Powell, Ohio), or in Rohlfs, K., Wilson, T.L. and Huttemeister, S., *Tools of Radio Astronomy*, 5th edition (Springer-Verlag, Berlin Heidelberg).

are forming new generations of stars. The infrared radiation, like the mm-wave domain, probes these obscured regions, but it is more absorbed by the interstellar medium than the radio waves. In addition, the radio astronomers have worked with the physical-chemistry community to successfully search for always more complex molecules in a variety of astrophysical environments such as the rarefied and cold interstellar medium, the expanding or infalling circumstellar medium around evolved or newly formed stars, or the extra-galactic medium. The chemical complexity of the Universe is bewildering (see, e.g., [5]), the Orion nebula being one of the richest molecular factories and active star-forming region ever observed (see introduction and Sect. 3).

There are two categories of radio instruments, the single-dish radio telescope and the radio interferometer array which combines the signals from two or more dishes to enhance sensitivity and angular resolution. In the first case, the signal is captured within the far-field beam pattern, or radio lobe, whose main response is the equivalent of the diffraction pattern of an optical aperture; the response is nearly Gaussian with half-power width close to $1.2\lambda/D$, where λ is the wavelength and D the dish size. In the second case, the signals are combined together to form fringe patterns characterized by their amplitude and phase. The fringe amplitude (or visibility) is large for objects angularly small compared to the interferometer angular resolution given by $\lambda/D_{\max}$, where $\mathrm{D}_{\max}$ is the maximum separation between the antennas of the array. The sensitivity of large arrays with respect to the single-dish telescope increases roughly as the number of antennas when this number is large.

The most sensitive mm and submm arrays are those of the IRAM institute ('Institut de radioastronomie millimétrique'), which gathers 7 and soon 12 antennas (Northern Extended Millimeter Array or NOEMA project) on the Plateau de Bure at an elevation of 2550 m in the French Alps,[4] and the large mm/submm ALMA array (Atacama Large mm/submm Array), with 66 antennas deployed on a 5050-m-high plateau in northern Chile's Atacama desert.[5] The NOEMA antennas are 15 m in size, while the ALMA array includes 50–12-m dishes and, for synthesis imaging optimization, a 'compact' array formed of 12–7-m and 4–12-m dishes. These arrays achieve angular resolutions better than one arcsecond ($4.85 \cdot 10^{-6}$ radian), while ALMA may reach resolutions around tens of milliarcseconds for its largest antenna configuration (16 km spacing). The sensitivity defined in terms of the minimum detectable flux density (source brightness at a given frequency multiplied by its angular size) depends on the receiver band used, the integration time and various instrumental parameters. The conventional unit for flux density in radio astronomy is measured in jansky (Jy), where $1\ \mathrm{Jy} = 10^{-26}\ \mathrm{W} \cdot \mathrm{m}^{-2} \cdot \mathrm{Hz}^{-1}$. The minimum flux density that ALMA can detect for an integration time of 60 s is around ten or a few tens of milli-jansky (mJy) in the spectral mode where the bandwidth is typically 10^{-6} times he antenna receiver center frequency, whereas in the continuum mode, the achieved sensitivity is better than one milli-jansky and can reach tens of micro-jansky. ALMA is a powerful spectral imager that can restore the source brightness distribution on the sky with high fidelity; this is achieved thanks to the simultaneous cross-correlation of many different antenna pairs which sample different spatial frequencies. IRAM and ALMA use different receivers installed at the antenna focus to observe over a large frequency range. IRAM provides several frequency bands up to about 300 GHz owing to its rather low elevation site compared to ALMA. Ten receiver bands matching good atmospheric transparency 'windows' are provided at the ALMA site to cover frequencies from around 35 GHz up to nearly 1 THz (300 micrometers).

2. Stellar formation in the Orion nebula and in the BN/KL region

2.1. Single-dish molecular line and continuum observations

Following the discovery around 1970 of the centimetric emission from interstellar molecules such as H_2O, NH_3 or H_2CO, it was realized that the mm waves would bring a large number of new discoveries. Subsequently, several observations have shown that the 115-GHz emission from the $J = 0$ to 1 rotational line transition of CO is widespread in the interstellar space. This molecule is excited by collisions with the dominant hydrogen molecule H_2, which has no permanent dipole moment and is not easily observable. The CO 115 GHz transition was thus widely used to survey the molecular gas content between stars and, especially, the gas lying in the direction of the Orion nebula (e.g., Maddalena et al. [7] who used a compact 1.2-m single dish). The latter survey has revealed an extended system of clouds centered on Orion (more than 15 degrees north–south or 30 times the Moon's angular size). The total mass was estimated to be around $2 \cdot 10^5$ solar masses and these clouds are seen as a huge reservoir of the material required to build new generations of stars. Better spatial resolution was achieved at a later stage with larger dishes and in ^{13}CO, which is less optically thick than the main isotopic species. ^{13}CO emission reveals new spatial details and is a better probe than CO of the molecular 'column density' along the line of sight, then leading to a better estimate of the gas cloud total mass provided that the $^{13}CO/H_2$ ratio is known. Using the Bell Labs. 7-m telescope in ^{13}CO, Bally et al. [8] have revealed the filamentary structure of the Orion molecular clouds. They suggested that the observed morphology supports both massive and low mass star formation resulting from the compression of the interstellar medium by shocks; these shocks are driven by recently formed Orion bright O and B stars according to [8].

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[4] The IRAM interferometer is currently doubling its collecting area (NOEMA project with a total of 12 antennas); details can be found at http://www.iram-institute.org/medias/uploads/NoemaBrochureFreFinal.pdf.

[5] ALMA, an international astronomy facility, is a partnership among Europe, East Asia and North America in cooperation with the Republic of Chile. General information can be found at http://www.almaobservatory.org/.

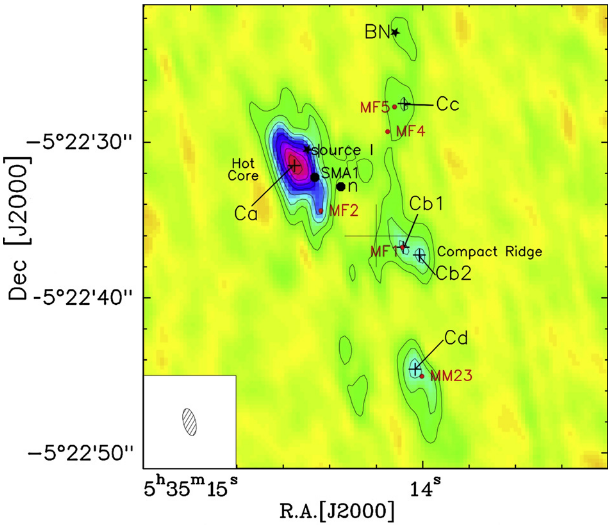

Fig. 2. Continuum emission map acquired with the IRAM interferometer at 1.3 mm toward the BN region. The synthesized beam size, 1.8″ × 0.8″, is shown in the lower left corner and the continuum contour lines are in steps of 60 mJy per beam. The Ca, b, c and d labels mark the continuum peak maxima associated with the dust emission, while the MF red dots mark the most prominent methyl formate emission peaks identified in [1]. Two to three arcseconds on the map, roughly the size of one continuum 'clump', represent 0.16 to 0.23 light-month (or about 800 to 1200 times the Earth–Sun distance) at the distance of the Orion nebula (1350 light-years). Each 'clump' has a mass of one to a few solar masses.

More recently, Ishii et al. [9] have combined their large scale CO ($J = 4$–3) observations around 461 GHz with the lower frequency CO ($J = 1$–0) and ^{13}CO ($J = 1$–0) observations of Wilson et al. [10] and Bally et al. [8] to estimate the gas density across the giant molecular cloud Orion A (H_2 density around 10^4 cm^{-3}) and show that the highest kinetic gas temperature is reached toward BN/KL (80–100 K).

Another way to identify the molecular 'fragments' or cloud 'cores' where the stars are being formed is to map the mm or submm wavelength continuum emission from the dust particles that are intimately mixed with the interstellar gas component. The dust completely absorbs or diffracts the stellar light, and it reddens the light emitted by stars. The dust composition is still uncertain, although its properties are explained by a mixture of carbonated and/or silicated grains whose dimensions are not uniform, but are typically around 0.1 micrometer. The dust grains may develop an icy 'mantle' together with simple molecules such as CO or CO_2, and one believes that the grain plays the role of a host particle catalyzing the formation of complex molecules before they are released to the general interstellar medium. (This formation process competes with molecular gas phase reactions both processes being active in the Orion nebula.) The dust grains exhibit low brightness continuum emission in the mm/submm. However, their emission is detectable with broad frequency band heterodyne receivers or with bolometers. The radio flux density is directly proportional to the dust opacity and hence to the total mass of gas if one supposes that the dust-to-gas mass ratio is constant (typically one takes 1/100). An array of bolometers installed at the focus of a large dish was used by Johnstone et al. [11] to map with 7 to 14 arcsecond spatial resolution more than half a degree of the BN/KL region. The bolometric data reveal a chain of compact sources embedded in a faint filamentary structure extended north–south. Recently, a catalog of dense cores has been established from 1.3 mm continuum observations made in the direction of BN/KL with various single dish antennas (see Shimajiri et al. [12]). The most massive cores are found to lie along, and not outside, the north–south filaments observed over nearly two degrees in the direction of Orion BN/KL.

2.2. *Interferometric observations in the continuum mode*

The high spatial resolution achieved by the mm interferometers is required to separate the compact sources found in the BN/KL region. We have used the IRAM interferometer with a spatial resolution as good as 0.8 to 2 arcseconds to map at 1.3 mm the dust emission from the KL region (Favre et al. [1]). The results are shown in Fig. 2 where we also place some of the major compact infrared sources of the BN/KL region, BN itself as well as 'source I' and 'source *n*', which are considered as young stellar objects. Our map reveals continuum emission peaks labeled Ca, Cb, and Cc (Fig. 2), whose total mass can be estimated from the source spatial extent, assuming that the dust temperature is close to the gas temperature observed in the same direction (see [1]). Further assuming that the dust-to-gas ratio is close to 1/100 in mass, we obtain masses in the range from 1 to 6 solar masses for the individual continuum components, and conclude that this mass reservoir will be used for future star-formation activity. The main dust condensations are observed in two sub-regions called the 'Hot Core' (where sources I and n are found) and the 'Compact Ridge' (Fig. 2). The continuum emission peaks (black crosses) do not exactly coincide with the molecular emission peaks shown in Fig. 2 as red dots. One exception is the brightest methyl formate emission peak MF1, which coincides with Cb1. We have discussed in [1] the possible physical association of MF1/Cb1 with

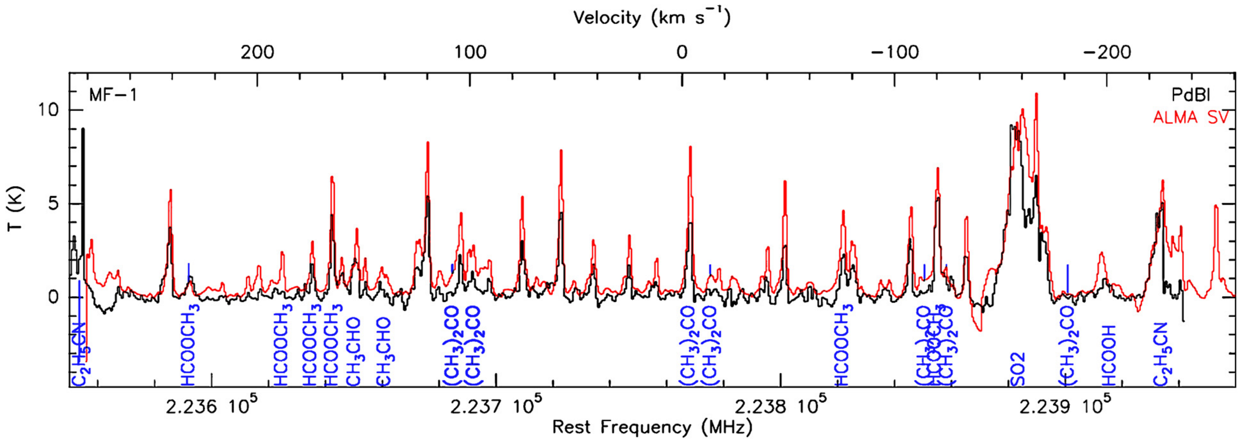

Fig. 3. Line spectra obtained from 223.55 to 223.96 GHz toward the Orion 'Compact Ridge' with the IRAM array (black line) and a subset of the ALMA antennas during the Science Verification campaign (red line). Several molecules are identified, among them the acetone $(CH_3)_2CO$ and the methyl formate $HCOOCH_3$. Small differences observed in the two spectra are attributed to different interferometric spatial filtering.

a young star and a powerful maser-like emission of water at 22 GHz. Continuum observations recently performed at 339 and 245 GHz with ALMA by Hirota et al. [13] show that the 'Hot Core' component Ca in our Fig. 2 is formed of fragments smaller than one arcsecond (i.e. smaller than about 400 times the Earth's orbit radius at the Orion nebula distance). In [1], we have derived a total mass of several solar masses for the 'Hot Core' Ca source and the 'Compact Ridge'. The Cc and Cd components north and south of the Ridge have masses of the order of one solar mass.

3. High-spectral-resolution observations of complex molecules

After general remarks on molecular complexity are made in Sect. 3.1 we discuss in Sect. 3.2 some examples taken from our high-angular-resolution observations made with the IRAM and ALMA arrays. In Sect. 3.3, we show that comparing the chemical content in BN/KL with molecules detected in comets may give interesting clues to the origin of complex molecules also present in the proto-Solar nebula.

3.1. Chemical complexity, interferometric observations and molecular line modeling

The detection of new molecules in the general interstellar medium continues to ramp up with an average rate of a few new species discovered each year. Nearly all of them are found in the Galactic center and/or the Orion nebula. As mentioned in the introduction, the BN/KL region exhibits a very rich molecular spectrum from which many lines have been assigned to about 50 different molecular species and, for a given species, to various isotopologues or different vibrational states (see for instance Tercero et al. [2]). In some spectral regions, the density of lines per frequency interval can be very high (tens to one hundred lines per GHz) and line blending problems may prevent any clean identification of the line carrier. Fig. 3 extracted from our IRAM and ALMA observations (see Peng et al. [14]) illustrates what we mean by line crowding, although even more severe cases are possible in other frequency ranges and may lead to complete line confusion. However, the most powerful interferometers offer sensitive imaging capability which, together with high spectral resolution and broad instantaneous bandwidths, allows us to accurately identify complex molecules; this is the case, for instance, when different transitions from a same molecule exhibit the same spatial distribution (see Fig. 5).

The formation of complex molecules such as methyl formate and ethylene glycol discussed in the following section is very difficult to explain because the densities and temperatures involved in space are very low compared to those prevailing in the laboratory. (Only exceptional vacuum chambers may reach densities of about 10^{2-4} particles per cm^{-3} in the laboratory, while this is the typical H_2 density in the interstellar medium.) However, the time scales involved in space are so large and the astrophysical conditions are so diverse that complex organic molecules can be formed in the Orion star-forming regions. Gas phase chemical codes have been developed to successfully explain the formation and abundance of simple molecules in the interstellar medium. More sophisticated codes involving both gas phase and solid grain-surface chemistry are now proposed to explain the formation of complex molecular species (see, e.g., Herbst and van Dishoeck [5]). However, there is no yet reliable chemical pathway leading to the formation of the most complex organic molecules with more than six atoms. Modeling the observed line intensities for complex species is another difficult task essentially because the collision rates are not accurately known or may even be totally unknown. Nevertheless, assuming Local Thermodynamic Equilibrium conditions in dense regions such as Orion BN/KL may be appropriate and often help to explain the observed line intensities. Clearly, the radio astronomy observations stimulate new molecular calculations of interest to the astronomy and spectroscopy communities.

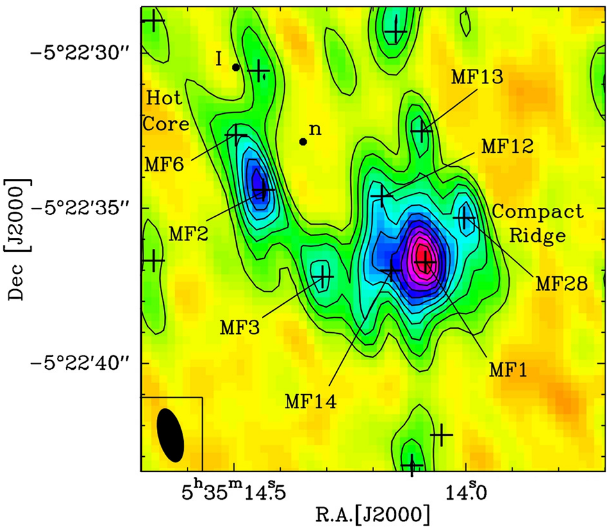

Fig. 4. IRAM interferometer map obtained from the sum of three different methyl formate lines around 223.5 GHz (see [1]) in the 5 to 12 km/s velocity range. The synthesized beam (lower left corner) is close to one arcsecond and allows us to reveal the complex cloud spatial structure in the 'Hot Core' and 'Compact Ridge' regions. MF1, MF2, etc. correspond to local molecular emission peaks, the maximum molecular emission (in red) being observed in the 'Compact Ridge'. The compact continuum radio source I and the IR source *n* are shown on the map. (The first black contour and contour step correspond to 3.2 $\mathrm{K \cdot km \cdot s^{-1}}$; the flux density conversion factor is 1 Jy per beam = 17.3 K.) Two arcseconds on the map represent 0.16 light-month at the distance of the Orion nebula (1350 light-years).

3.2. Interferometric observations of complex molecules

We briefly review below the results that we have recently obtained with the IRAM and ALMA arrays and concentrate our discussion on two molecules, the methyl formate and ethylene glycol, observed with both arrays. The ALMA data were taken from the public data acquired during the Science Verification campaign, where only a small subset of all ALMA antennas had been used while the array was still in construction.

Methyl formate (*$HCOOCH_3$*). A few tens of lines of the methyl formate molecule (MF) have been identified by Favre et al. [1] with the IRAM array. Fig. 4 shows an example of the spatial distribution for three of these lines around the 'Hot Core' and 'Compact Ridge'. Several molecular 'cores', labeled MF1, 2, etc., are identified and nearly coincide or lie in the vicinity of the dust emission peaks seen in the continuum map (Fig. 2). We have observed a good spatial correlation of the MF emission peaks with the vibrationally excited 2.12 micrometer H_2 emission that traces the propagation of shocks across BN/KL. This correlation suggests that the methyl formate molecule could have been formed on the dust grains and ejected from the 'mantle' of these grains under the action of shocks. Recent observations from Brouillet et al. [15] show that the spatial distribution of the dimethyl ether CH_3OCH_3 mimics that of the methyl formate, suggesting that both molecules have a common chemical precursor. We have proposed that if both molecules are produced on the surface of grains, the common precursor could be the CH_3O radical; in a scheme, for example, where ultra-violet irradiates solid ices, this radical would be produced from the photodissociation of methanol CH_3OH. On the other hand, if the gas phase reaction scheme were dominant, the protonated methanol ion CH_3OHH^+ could be the precursor of both methyl formate and dimethyl ether. We further note that the methanol molecule is particularly abundant in Orion and has been extensively mapped in the millimeter domain from the ground and in the submillimeter from space (Herschel-HIFI instrument). We have also mapped the emission from another O-rich molecule, acetone $(CH_3)_2CO$, and compared its emission with the MF emission (Peng et al. [14]). Acetone shows a distinct spatial distribution, close to that observed for N-bearing molecules (see the end of this section). Clearly, the above results and the observed chemical 'differentiation' indicate that a single chemical formation scenario cannot explain all observations.

Ethylene glycol (*$HOCH_2$–CH_2OH*). Ethylene glycol (EG), a di-alcohol chemically related to ethanol, is difficult to identify in the interstellar medium because of its weak emission and complex spectrum. The identification of the EG conformer spectroscopically noted aGg' was made possible in Orion thanks to the sensitivity and broad bandwidth of the ALMA array (Brouillet et al. [16]). Twenty slightly overlapping spectral windows, each 1.9 GHz wide, were used and allowed us to identify tens of different lines of which only a few showed little or no spectral contamination due to line emission crowding. The spatial distribution of EG is strikingly different from that of other complex molecules in Orion BN/KL. It is compact for all detected transitions and does not coincide with the MF emission peaks (see Fig. 5). Moreover, no EG emission is observed in the 'Compact Ridge', while the MF emission peak is observed in the ridge. This suggests quite different chemical formation paths for the EG and MF molecules.

It is interesting to note that in Orion the ethanol abundance is larger than that of the di-alcohol EG, a fact that is commented in Sect. 3.3. We further note that the second main conformer of ethylene glycol, noted gGg', could not be firmly

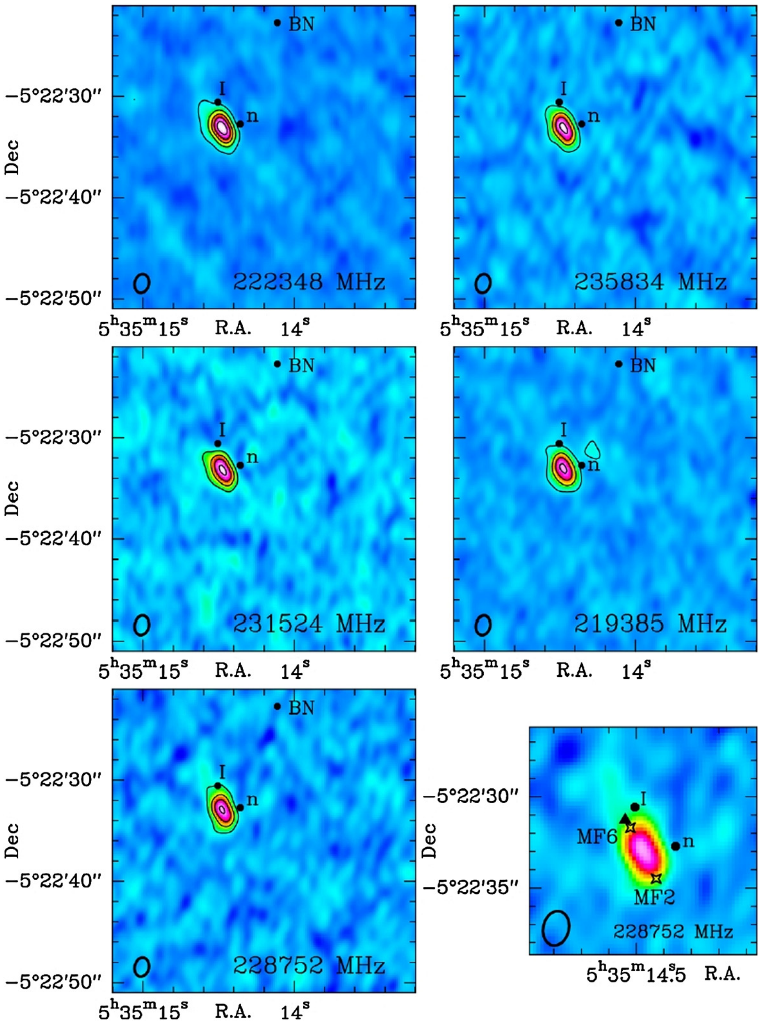

Fig. 5. Integrated intensity maps obtained with the ALMA array in Science Verification mode (subset of all antennas) for five different non-blended (or weakly blended) transitions of ethylene glycol (see [16]). The array synthesized beam, 1.9″ × 1.39″, is shown as a black contour in the lower left corner of each panel. These maps show good spatial similarity of the emission from different transitions as expected for the identification of a single molecular species without any (or little) contamination from another molecule. The bottom right panel shows a blow-up of the 228,752 MHz emission in the vicinity of the compact I and *n* objects (also shown in Figs. 2 and 4) and of the methyl formate peaks MF2 and MF6. (The contour level step and first contour are 4.4 and 2.9 K · km · s^{-1} at 228.752 GHz.) Two arcseconds on the map represent 0.16 light-month at the distance of the Orion nebula (1350 light-years).

identified in our study because of line blending problems, despite several emission lines have been observed at the expected frequencies in various spectral ranges.

N-bearing molecules. The N- or CN-bearing molecules such as CH_3CN, the complex vinyl cyanide molecule CH_2CN identified by Lopez et al. [17] or C_2H_5CN (Peng et al. [14]) show a spatial distribution different from that of O-bearing molecules. Their emission peaks are essentially found in the 'Hot Core' region and an associated northern region. Several authors think that this 'differentiated' chemistry is dominated by a recent dynamical event involving the BN, I and *n* young objects (shown in Figs. 2, 4 and 5) that occurred less than about 1000 years ago in the Orion nebula. This 'explosive' event, reconstructed from the motions of the BN, I and *n* objects, suggests that external heating of the gas might be responsible for the excitation of many different spectral lines (e.g., Zapata et al. [18]), and could have played an important role in the observed chemical differentiation. The dynamical evolution of the multi-star 'cluster' could also be at the origin of the different low- or high-velocity flows (characterized by different mean velocities and line widths) that are observed in the Orion molecular spectra. However, more observations and modeling are still needed to confirm the importance of the external heating scenario in the Orion chemistry.

3.3. Comparison of complex molecules with cometary abundances

Ethylene glycol, $(CH_2OH)_2$, is observed in comets of the Solar System. Its abundance relative to water is about 0.1 to 0.3% (whereas the methanol abundance relative to water may reach 2 to 3%). To compare the $(CH_2OH)_2$ abundance in Orion

BN/KL with that observed in three comets, Brouillet et al. [16] referred the abundance of this molecule to methanol, which is well detected in both the interstellar medium and comets. The $[(CH_2OH)_2]/[CH_3OH]$ relative abundance is close to 1/1000 in Orion, while it is around 1/10 in comets. On the other hand, ethanol, which shows a relative abundance of $6 \cdot 10^{-3}$ in Orion (6 times higher than the relative abundance of ethylene glycol) has not been identified in the three comets (Hale-Bopp, Lemmon and Lovejoy) used for comparison reasons in [16] (the upper limit is $4–7 \cdot 10^{-2}$). However, Biver et al. [19] have recently identified ethanol in another comet, C/2014 Q2 (Lovejoy), with an abundance ratio of $5 \cdot 10^{-2}$ relative to methanol. Glycoaldehyde (CH_2OHCHO) was also weakly detected in this comet; its relative abundance is around $7 \cdot 10^{-3}$, while it is not detected in BN/KL, with an upper limit of $8 \cdot 10^{-5}$ relative to methanol. These results show that complex molecular species are formed and excited in the BN/KL region as well as in the primitive cometary material of the Solar system. However, despite several uncertainties (in particular different spatial resolutions have been used for different molecules), these observations suggest that there might be a quantitative or qualitative difference between the chemistry prevailing in a proto-stellar environment and the chemistry of the proto-solar nebula. This idea will be investigated in future works, as it contrasts with the apparent similar abundances observed for the most abundant chemical species in the cometary and interstellar media (see Bockelée-Morvan et al. [20]).

4. Concluding remarks

We have shown that the most sensitive mm/submm-wave telescopes, especially the IRAM and ALMA interferometers, have led to the identification of many star-forming regions embedded in the Orion nebula, and we have addressed the question of the molecular complexity observed in the BN/KL region. A large number of complex molecules (with more than six atoms) have been identified, mapped and analyzed in BN/KL and, for some of them, the relative molecular abundances have been compared with three comets to show similarities and differences. Many details leading to the formation of complex organic molecules in the obscured regions of the Orion nebula still remain to be investigated. However, the relative abundances of several chemical species are now well estimated and the comparison with the cometary molecular abundances raise new questions in relation with molecular complexity and star formation. We anticipate that the availability of the full ALMA array (66 antennas soon offered to the community) and the new NOEMA interferometer, combined with the sustained development of spectroscopy works in the laboratory, will bring significant advances to our understanding of the chemistry in space and its relation to prebiotic molecules and molecules linked to the early terrestrial life. We believe, for example, that the search for the various amino acids that are detected in meteorites (including the simplest amino acid, NH_2CH_2COOH or glycine, which has also been identified in a sample returned from comet 81P/Wild2) will be actively pursued in the general interstellar medium and Orion. Especially as the amino acetonitrile NH_2CH_2CN, a plausible glycine precursor, was detected by Belloche et al. [21] in the Galactic center toward Sgr B2, another chemically-rich massive star-forming region.

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