The complexity of Orion: an ALMA view

III. The explosion impact

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ABSTRACT

The chemistry of complex organic molecules in interstellar dark clouds is still highly uncertain in part because of the lack of constraining observations. Orion is the closest massive star-forming region, and observations making use of ALMA allow us to separate the emission regions of various complex organic molecules (COMs) in both velocity and space. Orion also benefits from an exceptional situation, in that it is the site of a powerful explosive event that occurred ~550 years ago. We show that the closely surrounding Kleinmann-Low region has clearly been influenced by this explosion; some molecular species have been pushed away from the densest parts while others have remained in close proximity. This dynamical segregation reveals the time dependence of the chemistry and, therefore allows us to better constrain the formation sequence of COMs and other species, including deuterated molecules.

Key words. ISM: kinematics and dynamics – ISM: clouds – ISM: evolution – Astrochemistry – ISM: molecules – ISM: individual objects : Orion KL

1. Introduction

Though Orion is a well-studied region and has been explored with a wide variety of instruments, including the NOEMA (former Plateau de Bure) Interferometer, the Berkeley-Illinois-Millimeter-Array (BIMA), the Combined Array for Research in Millimeter-wave Astronomy (CARMA), and the Submillimeter Array (SMA), the arrival of the Atacama Large Millimeter Array (ALMA) holds the promise of new discoveries thanks to its higher angular resolution and sensitivity. The ALMA instrument provides high-velocity resolution while maintaining a high dynamic range that enables the detection of previously unseen structures, leading to a better understanding of the source evolution.

Based on the search for the lowest observable rotational transition of $^{16}$O$^{16}$O at 234 GHz, we performed deep observations of this source during Cycle 2 with 37–39 antennas, surveying 16 GHz in ALMA band 6, and improving the sensitivity by a factor ~5 compared to the Cycle 0 Science Verification (SV0) observations for the frequencies in common (Pagani et al. 2017 hereafter Paper I). Paper II presents a more detailed history of the recent work on Orion. In Paper I, we present the data and first results including the detection of several species not previously seen in Orion (n- and i- propyl cyanide, C$_3$H$_7$CN,...) as well as several vibrationally excited levels of cyanoacetylene (HC$_2$N) and of its $^{13}$C isotopologues. A companion paper (Favre et al. 2017) presents the first detection of gGg$^-$ ethylene glycol (gGg$^-$ (CH$_2$OH)$_2$) and of acetic acid (CH$_3$COOH$^-$) in Orion.

One remarkable feature present in the central region of Orion is an explosive event that occurred 550 ± 25 years ago (J.Bally, priv. communication) and was revealed by the three runaway stars BN, n, and I (Gómez et al. 2003, Rodríguez et al. 2005, 2017), and by the CO and H$_2$ fingers (e.g., Allen & Burton 1993, Zapata et al. 2009, Nissen et al. 2012, Youngblood et al. 2016, Bally et al. 2017). However, Luhman et al. (2017) showed that the object n is no longer a runaway member because its real proper motion is much lower than previously estimated; but conversely another object, named x, is moving away at high speed from the same explosion center. J. Bally (priv. comm.) confirms the fast proper motion of x and the absence of movement of n from ground-based H$_2$ images 14 years apart. X is further out having passed our 20 % beam coupling mark (see Fig. 1 of Paper I), and therefore does not appear in the figures presented in this Letter. Zapata et al. (2011) and Orozco-Aguilera et al. (2017) in their follow-up work with ALMA proposed that the hot core (HC) is externally heated despite its high temperature, and that the heating source could be the nearby explosion. Similarly, Blake et al. (1987), Wang et al. (2011), and Favre et al. (2011)
advocated that the Compact Ridge is also externally heated, although the heating source should not be the same since we presented evidence in Paper I that the Compact Ridge has not yet been affected by the impact of the explosion. A possibility could be the outflow from source I hitting the Compact Ridge (Liu et al. 2002). In Paper I we also presented evidence for an interaction between the explosive event and the main components of the Orion KL region including the HC, several infrared (IR) components (Kieke et al. 1973), and methyl formate (CH$_3$CHO; hereafter MF) peaks (Favre et al. 2011). We showed that the IRC6/MF5 and IRC20/MF4 sources, west of the explosion center, display emission lines of various species having only red wings, while sources on the east and south sides display emission lines having only blue wings. We also confirmed that excited emission lines are found preferentially surrounding the explosion center and that complex organic molecules (COMs) rich in oxygen (OCOMs) do not occupy the same volumes as CN rich COMs (CN-COMs). We identified the ethylene glycol peak (EGP) to be coincident with a hollow sphere of material, which we interpreted to have originated from the impact of a “bullet” launched from the explosion center (Favre et al. 2017; Wright & Plambeck 2017). We also proposed that the Compact Ridge (MF1) is sufficiently far away from the rest of the KL region to have not yet been perturbed by the explosion, the evidence being the absence of asymmetric emission line wings and the narrowness of the lines themselves (−1 km s$^{-1}$). In this Letter, we study further the interaction of the explosion blowout with the surrounding gas and dense sources.

2. Observations

The observations have been described in detail in Paper I and we give here only a short summary. Observations were carried out in December 2014, during the Cycle 2 period, with 37 antennas, and 39 antennas for the last run. Sixteen GHz of discontinuous bandwidth were covered in the frequency range 215 to 252 GHz. One band, centered on $^{16}$O$^{18}$O at 234 GHz, was observed all the time (2.5 hours), reaching a sensitivity of ∼2 mJy/beam while the other bands were observed only in one setup each (30 minutes duration), with 488 kHz channel spacing and reaching a typical noise of 5 mJy/beam (see Table 1 in Paper I). As in Paper I, the part of the data discussed in this work are centered on $\text{H}_2\text{CO}$ at 231 K to keep its spatial extent within the limits of efficient primary beam coupling; and $\text{H}_2\text{CO}$ and OCS, which are mildly distorted but still provide information on the small scale components in the KL region. At 2.5 km/s, the $\text{D}_2\text{CO}$ and NH$_3$D maps are missing owing to line blending. Depending on the species, the elongations are present or not and when absent, the peak emission is generally centered on the infrared peaks or at least on the continuum ridges. In a few cases, and mostly around the IRC7 peak, the local maximum emission is on the inner side of the infrared peak, i.e., displaced toward the explosion center while the extended emission on the other edge of the continuum peak is still present. This is the case for CH$_3$COCH$_3$, CH$_3$NCO, c-C$_2$H$_4$O, D$_2$CO, and without extension for NH$_3$D and $\text{H}_2\text{CNH}$, at 7.5 and ∼9 km s$^{-1}$ (Figs. B.2 & B.3).

4. Discussion

From Figs. [B.1] and [B.2][B.3] we see clear evidence for the effect of the explosion in many species. This was already mentioned in Paper I, in which we revealed the existence of blue

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wings for the sources east and south of the explosion center and of only red wings for the western sources (MF4 and MF5). We also showed that systemic velocities are below 7 km s\(^{-1}\) for the eastern sources and above 7 km s\(^{-1}\) for the western sources. We explained these features in terms of the sources expanding away from the explosion center. In this picture the eastern sources are in front of the center and the western sources are behind (Fig. 30 of Paper I). The asymmetrical wings were explained as gas being accelerated by the explosion blowout. Wright & Plambeck (2017) and ourselves (Favre et al. 2017) also presented evidence for a bullet having hit the dense ridge near MF6. This bullet was most probably launched by the explosion. That the HC has no internal source and is heated from outside, most probably by the explosion, has been advocated by Zapata et al. (2011) and Orozco-Aguilera et al. (2017). This is particularly obvious when 12 \(\mu\)m maps of the region are superimposed on our 1.2 mm continuum map (see Fig. A.1). The IRc2 spot marked by Greenhill et al. (2004) is halfway between the explosion center and the HC while the latter is isible at 12 \(\mu\)m.
With the channel maps, we see some direct evidence of the fast expansion as many species are being driven away from the explosion center at the same velocities: from -2 to 3 km s\(^{-1}\) eastward, through MF10; from 6 to 11 km s\(^{-1}\) southeastward through MF6; from 6 to 9 km s\(^{-1}\) northward through MF5; from 7 to 14 km s\(^{-1}\) in between MF4 and MF5 and then through MF4 (especially visible in H\(_2\)CO, D\(_2\)CO, and OCS, Fig. 3), and from 2 to 6 (or depending on the species) km s\(^{-1}\) southward through IRC7. These offsets are due to the winds from the explosion center that pass near the dense dust cores, collect the molecules recently released from the grains, and push these molecules away. The different velocities possibly reflect the direction of propagation if we suppose the winds to be spherically expanding. For example, the long southeast extension crossing MF6 probably passes behind the dust ridge since its velocity range (from 6 to 11 km s\(^{-1}\)) is globally higher than the HC-MF6 range (4 – 6 km s\(^{-1}\)).

In summary, we see that some molecular species show emission elongated to significant distances all pointing away from the explosion center, while other species do not. A number of these species are predominantly formed on grain surfaces, and these channel maps may be understood as due to the evolution of these species after they are released from the dust grains and are driven outward by the explosion. Those molecules that do not show elongations, such as H\(_2\)CNH and NH\(_2\)D, are probably rapidly destroyed after their release in the gas phase. In the case of NH\(_3\)D, the tentative detection of NH\(_3\)D\(^+\) by [Cernicharo et al. (2013), later confirmed by laboratory measurements of Stoofels et al. (2016)], could suggest an explanation. NH\(_3\)D can react with H\(_2\) to form NH\(_2\)D\(^+\) in two-thirds of the cases, and NH\(_2\)+ + HD in one-third of the cases. Although the probability of dissociative recombination of NH\(_3\)D\(^+\) to form NH\(_3\) is statistically three times less probable than the formation of NH\(_3\)D, the rapid destruction of NH\(_3\)D is still expected since 50% of the reactions with H\(_2\)\(^+\) eventually lead to NH\(_3\) and in this warm environment (100 – 300 K), deuteration is not expected to occur in the gas phase to replenish NH\(_3\). Similarly, D\(_2\)CO extends away from the explosion center but less than H\(_2\)CO. D\(_2\)CO is converted back to HDCO and next to H\(_2\)CO by repeated reactions with H\(_2\)\(^+\), followed by dissociative recombinations. To test this idea, we ran our gas-phase chemical model including our deuteration network with the spin states of H\(_2\) and H\(_2\)\(^{15}\) isotopologues [Pagani et al. (2011)]. Starting from a gas rich in deuterated species (D\(_2\)CO/H\(_2\)CO ≈ 0.01 and NH\(_2\)D/NH\(_3\) ≈ 0.3) at a density of 1 x 10\(^3\) cm\(^{-3}\), a temperature of 150 K, low extinction to the ISRF and a harsh environment (approximated by a cosmic ionization rate ζ of 1 x 10\(^{-15}\) s\(^{-1}\)), we found that the D\(_2\)CO/H\(_2\)CO ratio drops by a factor of 3 to 40 in 500 to 1000 years, the abundance of D\(_2\)CO itself drops by a factor 3 to 100 in the same time, while the NH\(_2\)D/NH\(_3\) ratio drops by a factor 6 to 200 in 500 years, and the abundance of NH\(_3\)D itself decreases by a factor 20 to 5000 (Fig. 3). The decrease of NH\(_2\)D is much more rapid than the decrease of D\(_2\)CO, which is illustrated by the fact that NH\(_3\)D does not expand at all away from the icy dust evaporation sites, unlike D\(_2\)CO. It would be interesting to map H\(_2\)CO\(^+\) (2 and 3 mm transitions of this ion have been detected in a number of sources, including Orion KL; Ohishi et al. (1996)) and NH\(_2\)D\(^+\) in the source at a similar resolution and make quantitative statements about the abundance of each species in each velocity channel, but this is beyond the scope of this letter.

Species such as ethyl cyanide and vinyl cyanide are only slightly displaced outward. They probably survive longer than NH\(_2\)D or H\(_2\)CNH before being destroyed or converted to other species.

It seems therefore that the closeness of Orion, combined with the ongoing expansion and availability of high spatial resolution observations opens a new window on the time evolution of different species soon after their release in the gas phase in a way similar to a time-of-flight experiment. This will allow us to select the important chemical paths between species and possibly constrain the chemistry of COMs. Recently, Tercero et al. (2018) have suggested segregation of various O-bearing COMs based on spatial variation inside BN-KL. Including the channel information presented in this work, combined with quantitative estimates, which require the inclusion of zero-spacing data that is not yet available, will allow us to follow the abundance variations of each species along the expanding paths and better understand the chemistry in hot cores, both in the gas phase and on grain surfaces.
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Appendix A: Mid-infrared and millimeter continuum map comparison

Fig. A.1. 1.2 mm continuum emission (white contours) superimposed on the 12.5 μm map from Greenhill et al. (2004) shown in colors. The two runaway stars (BN and I) plus the quasi-static object n are indicated by five-pointed stars (yellow or red) while the 10 sources studied in Paper I are identified and denoted by crosses (white or red; see Paper I for more details). The presumed position of the origin of the explosion is denoted by a multi-pointed red and blue star.

We superimposed our 1.2 mm ALMA continuum map on the Greenhill et al. (2004) 12.5 μm map. The hot sources at 12.5 μm do not coincide with our 1.2 mm strongest peaks. Alternately, the emission peaks coincide toward both BN and IRc4. The HC itself is particularly weak at 12.5 μm, while there is a strong mid-infrared zone between the explosion center and HC (known as IRc2) and a weaker mid-infrared zone on the other side of the HC ridge. This confirms the claim of Zapata et al. (2011) of the absence of an internal heating source for the HC but of external heating possibly due to the explosion. From the Feng et al. (2015) data, we find that the HC does not seem to be gravitationally bound. The effect of the explosion on the overall stability of the HC is yet to be determined.

Appendix B: Multi-species comparisons at three remarkable velocities
Fig. B.1. Selection of species at 3 different velocities (here $\sim 2.5$ km s$^{-1}$). There are no data for $\text{D}_2\text{CO}$ and $\text{NH}_2\text{D}$ due to line blending and for $\text{C}_2\text{H}_5\text{OH}$ and $c\text{-C}_2\text{H}_4\text{O}$ owing to lack of emission, i.e., maximum signal less than 10% of the peak emission. NO is partly masked, due to line blending. The top left corner indicates the channel velocity, the species, and its upper energy level. The white contours are 10 to 90% of the peak emission of the strongest channel for that species. The yellow arrows starting from the explosion center (red eight-pointed star) suggest possible displacement of gas linked to the explosive event, which occurred $\sim 550$ years ago. The species shown in the top three rows show such extensions, while the two bottom rows do not. The molecular species transitions are listed in Table B.1. All are channel maps of 488 kHz width (0.59 to 0.69 km s$^{-1}$).
Fig. B.2. Selection of species at 3 different velocities (here \( \sim 7.5 \text{ km s}^{-1} \)). The three top rows present species with extensions, the two bottom rows, without. NO is partly masked (where the emission is blended).
Fig. B.3. Selection of species at 3 different velocities (here ~9 km s\(^{-1}\)). The three top rows present species with expansions, the two bottom rows, without (except possibly c-C\(_2\)H\(_4\)). NO is partly masked (where the emission is blended).
| Name     | Transition   | $E_{up,k}$ (K) | Frequency (MHz) | $A_{ul}$ (s$^{-1}$) | Database |
|----------|--------------|---------------|-----------------|---------------------|----------|
| C$_2$H$_3$CN | $234.19$–$234.18$ | 160.4 | 218615.092 | 8.40(-4) | cdms |
| C$_2$H$_3$CN | $263.23$–$253.22$ | 162.2 | 237170.450 | 1.11(-3) | cdms |
| c-C$_2$H$_5$O | $80.8$–$71.7$ | 52.4 | 235105.022 | 2.33(-4) | cdms |
|            | $81.8$–$70.7$ | 52.4 | 235105.055 | 2.33(-4) | cdms |
| C$_2$H$_5$OH |             | 130.6 | 216415.624 | 9.07(-5) | jpl |
| CH$_3$CN | $124.1$–$111.1$ | 183.1 | 220679.287 | 8.21(-4) | cdms |
| CH$_3$COCH$_3$ | $220.22$–$219.21$ | 123.9 | 220361.881 | 3.95(-4) | jpl |
|            | $222.22$–$211.21$ | 123.9 | 220361.881 | 1.61(-4) | jpl |
|            | $222.22$–$212.21$ | 123.9 | 220361.881 | 1.61(-4) | jpl |
| CH$_3$NCO | $243.07$–$233.05$, $v_b=0$ | 191.0 | 217701.086 | 4.40(-4) | cdms |
| CH$_3$OCH$_3$ | $224.19.3$–$213.20.3$ | 254.4 | 217189.668 | 5.43(-5) | cdms |
|            | $224.19.5$–$213.20.5$ | 253.4 | 217189.669 | 5.43(-5) | cdms |
|            | $224.19.1$–$213.20.1$ | 253.4 | 217191.400 | 5.43(-5) | cdms |
|            | $224.19.0$–$213.20.0$ | 253.4 | 217193.132 | 5.43(-5) | cdms |
| CH$_3$OCHO | $173.14.0$–$161.13.0$, $v_b=0$ | 99.7 | 218297.890 | 1.51(-4) | jpl |
| CH$_3$OH | $123.9$–$122.10$, $v_b=0$ | 230.8 | 250635.207 | 8.29(-5) | cdms |
| D$_2$CO | $40.4$–$30.3$ | 27.9 | 231401.234 | 3.47(-4) | cdms |
| DCN | $31$–$21$ | 20.9 | 217236.999 | 5.08(-5) | cdms |
|            | $32$–$21$ | 20.9 | 217238.300 | 3.84(-4) | cdms |
|            | $33$–$21$ | 20.9 | 217238.555 | 4.07(-4) | cdms |
|            | $33$–$22$ | 20.9 | 217238.612 | 4.57(-4) | cdms |
|            | $32$–$23$ | 20.9 | 217239.079 | 2.03(-6) | cdms |
|            | $32$–$22$ | 20.9 | 217240.622 | 7.12(-5) | cdms |
| H$_2$CNH | $71.6.6$–$70.7.6$, $v_7=0$ | 97.2 | 250161.110 | 1.47(-4) | cdms |
|            | $71.6.7$–$70.7.8$ | 97.2 | 250161.137 | 1.48(-4) | cdms |
|            | $71.6.7$–$70.7.6$ | 97.2 | 250161.945 | 2.65(-6) | cdms |
|            | $71.6.7$–$70.7.7$ | 97.2 | 250161.972 | 3.06(-6) | cdms |
|            | $71.6.7$–$70.7.8$ | 97.2 | 250161.990 | 2.66(-6) | cdms |
|            | $71.6.8$–$70.7.7$ | 97.2 | 250162.190 | 2.34(-6) | cdms |
|            | $71.6.7$–$70.7.7$ | 97.2 | 250162.807 | 1.45(-4) | cdms |
| H$_2$CO | $99.8$–$99.9$ | 174.0 | 216568.651 | 7.22(-6) | cdms |
| H$_2$N | $241.23$, $v_7=1$ | 452.3 | 219173.757 | 8.30(-4) | cdms |
| HNCO | $100.109$–$99.10$ | 101.1 | 218980.248 | 1.63(-6) | jpl |
|            | $100.109$–$99.9.10$ | 101.1 | 218981.031 | 4.10(-9) | jpl |
|            | $100.109$–$99.9.8$ | 101.1 | 218981.170 | 1.46(-4) | jpl |
|            | $100.109$–$99.9.9$ | 101.1 | 218981.170 | 1.46(-4) | jpl |
|            | $101.109$–$99.9.10$ | 101.1 | 218981.170 | 1.48(-4) | jpl |
|            | $100.109$–$99.9.10$ | 101.1 | 218981.900 | 1.48(-6) | jpl |
| NH$_2$CHO | $113.9$–$103.8$ | 94.1 | 233897.318 | 8.62(-4) | jpl |
| NH$_2$D | $32.2.0$–$31.2.1.2$ | 119.6 | 216562.487 | 5.44(-5) | jpl |
|            | $32.2.0$–$31.2.1.2$ | 119.6 | 216562.489 | 4.86(-6) | jpl |
|            | $32.2.0$–$31.2.1.4$ | 119.6 | 216562.621 | 5.74(-5) | jpl |
|            | $32.2.0$–$31.2.1.4$ | 119.6 | 216562.622 | 4.92(-6) | jpl |
|            | $32.2.0$–$31.2.1.3$ | 119.6 | 216563.000 | 6.80(-6) | jpl |
|            | $32.2.0$–$31.2.1.3$ | 119.6 | 216563.001 | 3.83(-6) | jpl |
|            | $32.2.0$–$31.2.1.3$ | 119.6 | 216563.002 | 5.15(-5) | jpl |
| NO$^c$ | $31.3.1.3$–$21.2.3$ | 19.3 | 250796.436 | 1.85(-6) | jpl |
|            | $31.3.1.3$–$21.2.2$ | 19.3 | 250815.594 | 1.55(-6) | jpl |
|            | $31.3.1.3$–$21.2.1$ | 19.3 | 250816.954 | 1.39(-6) | jpl |
| OCS | $18$–$17$, $v=0$ | 99.8 | 218903.356 | 3.04(-5) | cdms |

**Notes.**

(a) Energy expressed in Kelvins ($k = $ Boltzmann’s constant)

(b) Einstein spontaneous emission coefficient. $a(b) = a(x)10^{b}$

(c) To avoid contamination by strong nearby lines, NO maps are a combination of the 250.796 GHz transition for velocities from 6 to 19 km s$^{-1}$, and of the 250.81 lines for velocities from -3 to 11 km s$^{-1}$; the overlapping velocities are a sanity check.

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