The warm-up phase in massive star-forming cores around RCW 120

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ABSTRACT
We study molecular emission in a massive condensation at the border of the H II region RCW 120, paying particular attention to the Core 1 and Core 2 objects, the most massive fragments of the condensation found previously by ALMA. The latter fragment was previously suggested to host a high-mass analogue of Class 0 young stellar object. We present spectra of molecular emission in the 1 mm range made with the APEX telescope. We detect CH$_3$OH and C$^{34}$S lines in Core 1 and Core 2. The CH$_3$CN series and the SO$_2$ lines are only found in Core 2. We estimate gas physical parameters using methanol lines and obtain gas temperature less than 100 K in both regions. Molecular hydrogen number density in Core 2 is in the range of $10^5$ – $10^7$ cm$^{-3}$ and is more uncertain in Core 1. However, the detection of the CH$_3$CN lines corresponding to highly excited transitions ($E_u > 400$ K) in Core 2 indicates that the region contains hot gas, while the abundances of CH$_3$OH, CS, SO$_2$ and CH$_3$CN are quite low for a hot core stage. We propose that Core 2 is in the warm-up phase prior to the establishing of the hot gas chemistry. We suggest that Core 2 is in the beginning of the hot core stage. There are no detected CH$_3$CN lines in Core 1, therefore, it might be on an even less evolved evolutionary stage.

Key words: stars: formation – ISM: clouds – ISM: HII regions – ISM: molecules

1 INTRODUCTION
The initial stage of high-mass star formation is a subject of debates. While starless dense clumps of molecular clouds, precursors of protostellar cores for low-mass stars, were observed by, for example, Tafalla et al. (1998), similar high-mass objects are rare and more difficult to find and confirm (see, e.g. modelling by Pavlyuchenkov et al. 2011). Several candidates were proposed by Sridharan et al. (2005); Olmi et al. (2010); Fontani et al. (2012); Svoboda et al. (2019); Zhang et al. (2020). One of the most massive and well-known dense gas condensations at the border of the H II region RCW 120 has been considered as a high-mass analogue of a Class 0 object for about ten years since the studies by Deharveng et al. (2009); Zavagno et al. (2010). In particular, Deharveng et al. (2009) found a compact 870 µm core of 250 M$_\odot$ adjacent to the ionization front of RCW 120, which is embedded into a 800-M$_\odot$ gas condensation at the south-western border of RCW 120 (Clump 1 hereafter). Zavagno et al. (2010), using Herschel infrared data, confirmed Class 0 properties of the object and found that the emission towards the dense core is dominated by its 10$^2$ M$_\odot$ envelope. The formation of the gas condensation with the massive dense core at the border of the H II region was proposed as an outcome of a triggering collect-and-collapse (C&C) process related to expansion of RCW 120 in the studies by Zavagno et al. (2007); Deharveng et al. (2009); Minier et al. (2013). Tremblin et al. (2013) suggested that compression by an ionization front played a major role, along with gravity, for the dense core formation in Clump 1. Recently, Figueira et al. (2020) re-examined the triggered star-formation model with new observations of CO lines made by the APEX telescope, and confirmed that it might be at work at the edges of RCW 120. Zavagno et al. (2020) found a filamentary structure of a photodissociation region around RCW 120 using ArTéMiS on APEX. They concluded that the compression of pre-existing molecular filaments in Clump 1 may influence star-forming regions there.

Figueira et al. (2017) re-examined the Herschel data and identified 35 compact young stellar objects (YSOs) with reliable SEDs associated with RCW 120. They found that four out of five massive YSOs near RCW 120 are located in Clump 1. Analysing the ALMA data, Figueira et al. (2018) found that the most massive YSO (Core 2 hereafter, an object with ID 2 in Table 5 in Figueira et al. 2017) probably associated with an ultra-compact H II region (uH II). They reported the detection of CH$_3$CN and SO$_2$ emission at 3 mm but did not analyse this emission in detail and did not determine the physical properties of the gas in the cores.

In this paper, we analyse data on molecular emission in Clump 1 at 1 mm in order to determine physical parameters of the gas in Core 2, and also in Core 1, which is the second most massive YSO after Core 2 in Clump 1. We focus mainly on methanol and CH$_3$CN emission, as these molecules are reliable tracers of physical conditions in molecular gas. Methanol is an abundant, well-known interstellar molecule, especially in regions of star formation (see, e.g. Kalenskii et al. 2002; Leurini et al. 2007). Being a slightly asymmetric rotor,
methanol has a complex spectrum, sensitive to the physical conditions in dense interstellar gas (Kalenskii & Sobolev 1994; Leurini et al. 2004; Salii 2006). The CH$_3$CN transitions are used to obtain independent measurements of gas kinetic temperature, as has been shown, for example by Kalenskii et al. (2000); Gratier et al. (2013); Beltrán et al. (2018). We describe our observations in Sec. 2; we present our results (physical properties of the gas and molecular abundances) and analysis in Sec. 3. Our theoretical modelling of the chemical evolution of Core 2 is presented in Sec. 4; those results are discussed in Sec. 5. The summary of our study is presented in Sec. 6.

2 OBSERVATIONS AND DATA ANALYSIS

In July 2009, using APEX$^1$, we observed several selected positions in Clump 1 around the maximum of 870 μm emission found by Deharveng et al. (2009): $\alpha_{2000} = 17^h^{12}08^m$ and $\delta_{2000} = -38^\circ30'45''$ (project number O-083-F-9311A-2009). Several selected positions and methanol spectra at 241791.431 MHz are shown in Fig. 1. Relative coordinates of the all observed positions are given in Table A1. The observations were carried out in service mode in good weather conditions, with a Precipitable Water Vapor (PWV) amount between 0.4 and 0.7 mm. Two spectral windows$^2$, at $\sim$ 220 and $\sim$ 241 GHz, were observed with the SHeFI receiver APEX-1 (Belitsky et al. 2006; Vassilev et al. 2008). The spectrometer consisted of two FFTS units configured to provide a spectral resolution of 122 kHz (0.17 km s$^{-1}$) and to cover frequency bands of 1400 MHz for the 220 GHz spectral window and 1200 MHz for the 241 GHz window (0.16 km s$^{-1}$). The main instrumental parameters are summarised in Table 1. The data reduction was performed using the GILDAS software$^3$. The identification of the detected lines was performed using the CDMS database (Endres et al. 2016).

The observed methanol line series allow us to estimate excitation conditions and line opacities. We used large velocity gradient (LVG) analysis to determine the physical parameters of gas where the methanol emission appears, namely: gas kinetic temperature ($T_{\text{gas}}$, K), hydrogen number density ($n_{\text{H}_2}$, cm$^{-3}$), methanol specific column density ($N_{\text{CH}_3\text{OH}}/\Delta V$, cm$^{-3}$ s) and methanol relative abundance ($N_{\text{CH}_3\text{OH}}/N_{\text{H}_2}$). Since the beam filling factor for the methanol emission ($f$) is not known, we include this additional parameter in the methanol line intensity analysis. The details of the LVG calculation and a database of population numbers for the methanol energy levels, calculated for several values of linewidth (1, 3 and 5 km s$^{-1}$) can be found in, for example, the work by Kirsanova et al. (2017); Salii et al. (2018). In the present calculations, we use a line width of 5 km s$^{-1}$ for the detected methanol lines since this is the closest value to the observed widths given in Table 2. Dust emission and absorption within the emission region are taken into account, as described by Sutton et al. (2004), where dust and gas temperatures were set to be the same. Using this approach, we can obtain a fit with the best coincidence between the modelled and observed line intensities (with $\chi^2$ minimum). The upper limits of the undetected methanol lines were included in the consideration: it was controlled that their model intensities not exceed the rms level from Table 1.

To extend the analysis of the methanol emission and estimate the parameters in the regions with the weaker lines, we applied a Bayesian analysis (e.g. Ward et al. 2003) to obtain the confidence intervals. We calculated methanol model intensities ($I_{\text{mod}}(p)$) for a regular network of parameters:

$$p = (T_{\text{gas}}, N_{\text{CH}_3\text{OH}}/\Delta V, n_{\text{H}_2}, N_{\text{CH}_3\text{OH}}/N_{\text{H}_2}, f)$$

using the database of the population numbers for methanol quantum energy levels.

The probability to observe $N$ methanol lines with intensities $T_{\text{obs}}$ and uncertainties $\sigma_{T_{\text{obs}}}$ using a set of parameters $p$ can be calculated as:

$$P(T_{\text{obs}}|p) = \prod_{i} \frac{1}{\sqrt{2\pi}\sigma_{T_{\text{obs}}}} e^{-\frac{1}{2}\left(\frac{T_{\text{obs}} - T_{\text{mod}}(p)}{\sigma_{T_{\text{obs}}}}\right)^2}.$$  (1)

Integrating over each parameter, we obtain the Bayesian probability function and estimate the parameters and confidence intervals.

The analysis of the CH$_3$CN line emission was done with the population diagram method (see, e.g. Goldsmith & Langer 1999; Kalenskii et al. 2000). The column densities of CS and SO$_2$ molecules were determined under LTE assumption using a standard approach described by Mangum & Shirley (2015) and using the gas kinetic temperature derived from the methanol emission analysis as the excitation temperature in the LTE approach. We recognise all the restrictions of the LTE approach and consider the LTE analysis only as a way to obtain estimates of molecular column densities since we have only one line for each molecule. To convert column density of C$_3$S to CS, we used an elemental abundance ratio $[S]/[^{13}S] = 22.5$ (Wilson 1999).

In order to calculate the molecular abundances relative to molecular hydrogen from their column densities, we use the column density of H$_2$ molecules $N_{\text{H}_2} = 3.254\times10^{23}$ cm$^{-2}$ obtained in the VlaLectra project (Marsh et al. 2015, 2017), which is also in agreement with the column density values obtained by Anderson et al. (2012); Tremblin et al. (2013) and Figueira et al. (2017).

3 RESULTS

The full list of the detected lines in Cores 1 and 2 and the parameters of Gaussian fits are shown in Table 2. The spectra of the methanol and CS line emission are shown in Fig. 1, 2 and 3, while the spectra of CH$_3$CN are shown in Fig. 5. We note that the lines with an upper level energy $E_u > 50$ K are detected only towards Core 2. Three lines with $T_{\text{mb}} \approx 0.5 \pm 1$ K around 220050, 241895 and 240903 MHz remain unidentified in Fig 2. The brightest among of them at 220050 MHz is detected in both Core 1 and 2 with $T_{\text{mb}} \approx 1$ K.

3.1 Methanol emission towards Cores 1 and 2

The methanol lines are bright both in Core 1 and in Core 2, but the brightest lines are detected in Core 2 (see Fig. 2). We note that only lines with $E_u < 70$ cm$^{-1}$ ($\approx 100$ K) were confidently (at level
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Figure 1. Herschel image of Clump 1 at 70 μm. White contours represent the 870 μm ATLASGAL contours for 1, 5 and 10 Jy beam⁻¹. Methanol spectra at 241791.431 MHz in the observed positions are shown by black lines. The spectra towards Core 1 (southern part of Clump 1) and Core 2 (northern part of Clump 1) are shown by red colour. The methanol line (red), overlaid upon the C^{14}S(5–4) line (yellow, multiplied by a factor of 20), towards Core 2 are also shown in the separate bottom frame. The overall brightness temperature and velocity scales are shown on this frame. The numbers above four methanol spectra represent $N_{\text{CS}}$ divided by $10^{13}$. The APEX beam of $26''$ at 241 GHz is shown by the black circle.

above 3σ) detected in the unsmoothed spectra. Only three lines with $E_u \leq 50$ K were detected at a level above 3σ in Core 1. All the detected methanol lines have single-peaked profiles.

The brightest methanol lines at 241700, 241767 and 241791 MHz in Core 2 have a Gaussian shape with red (about 4 km s⁻¹) and blue (about 2 km s⁻¹) wings at 15% level from the intensity maximum. The line wings in Core 2 are better seen in Fig. 3. The wings also can be fitted by Gaussian profiles with centres close to the main line centres, but with widths about 3–5 times larger than the main line. The methanol emission fades quickly to the north and west and stretches to the south and south-east following the distribution of $^{13}$CO emission presented by Kirsanova et al. (2019) and Figueira et al. (2020). There is a negative velocity gradient of the methanol lines from Core 2 to Core 1, similar to the $^{13}$CO and C$^{15}$O lines (Kirsanova et al. 2019; Figueira et al. 2020), and almost no velocity gradient perpendicular to the dense shell. The methanol spectra at Core 1 also have pronounced red and blue wings. The most prominent wings are found to the west of Core 1 (see Fig. 3), where the integrated intensity of the red wing is comparable with the intensity under the Gaussian profile centered at the peak intensity.

Our LVG analysis of methanol emission, described above, allows us to conclude that all the detected methanol lines have modest optical depth. In particular, the brightest methanol lines at 241700 and 241791 MHz have optical depths around 0.8. For Core 2, we obtain the best agreement between the model and observed line intensities for the parameters: $T_{\text{gas}} = 30^{40}_{20}$ K, $N_{\text{CH}_3OH}/\Delta V = 5.01^{3.9}_{1.0} \times 10^9$ cm⁻³ s, $n_H = 1.0^{3.1}_{0.6} \times 10^6$ cm⁻³ and a relative abundance of methanol $x_{\text{CH}_3OH} = 3.2^{3.16}_{1.7} \times 10^{-9}$ and $f = 50^{60}_{20}$%. A comparison between the observed and best-fit model line brightness temperatures is shown in Fig. 4. The number of the detected methanol lines towards Core 1 is insufficient to estimate the parameters using the $\chi^2$ fit with the LVG method. Therefore, we only estimated the Bayesian confidence intervals for the parameters. These intervals are $T_{\text{gas}} < 60$ K, $N_{\text{CH}_3OH}/\Delta V = (7.9 - 20) \times 10^9$ cm⁻³ s,
Table 2. Detected molecular lines towards Core 1 and Core 2 in RCW 120. We used single-peaked Gaussian profiles to fit the lines. *Velocities and widths of the $K \leq 3$ CH$_3$CN lines are assumed to be the same in the fitting. **Velocities and widths of the $K \geq 4$ CH$_3$CN lines are also assumed to be the same. The methanol lines at 241832.716 and 241833.104 MHz are not resolved in our spectrum, therefore, their parameters are set to be same in our analysis. The same is for the lines at 241842.324 and 241843.646 MHz. Spectroscopic entries are taken from the CDMS database: C$^{34}$S, ver. 2. Jan. 2004; SO$_2$, ver. 2. July 2005; CH$_3$OH, ver. 3. May 2016; CH$_3$CN, ver. 2. Nov. 2016.

| Sym | Transition | Frequency [MHz] | $E_u$ [K] | $\int T_{mb}dV$ [K km s$^{-1}$] | $V_{LSR}$ [km s$^{-1}$] | $\Delta V$ [km s$^{-1}$] | $T_{mb}$ [K] |
|-----|------------|----------------|----------|----------------|----------------|----------------|---------|
| Core 1 | CH$_3$OH | E $5_0 - 4_0$ | 241700.159 | 47.9 | 3.01 ± 0.20 | -6.66 ± 0.17 | 5.27 ± 0.44 | 0.54 ± 0.06 |
| | | E $5_{-1} - 4_{-1}$ | 241767.234 | 40.4 | 10.74 ± 0.23 | -2.73 ± 0.06 | 6.00 ± 0.17 | 1.68 ± 0.06 |
| | A* $5_0 - 4_0$ | 241791.352 | 34.8 | 12.70 ± 0.25 | -7.24 ± 0.06 | 6.36 ± 0.16 | 1.88 ± 0.06 |
| Core 2 | C$^{34}$S | E $3_0 - 2_7$ | 220078.561 | 96.6 | 3.14 ± 0.35 | -6.65 ± 0.33 | 5.11 ± 0.79 | 0.21 ± 0.04 |
| | | CH$_3$OH | E $5_0 - 4_0$ | 241700.159 | 47.9 | 6.98 ± 0.21 | -6.33 ± 0.06 | 3.90 ± 0.14 | 1.68 ± 0.08 |
| | | E $5_{-1} - 4_{-1}$ | 241767.234 | 40.4 | 14.85 ± 0.19 | -6.41 ± 0.03 | 4.38 ± 0.07 | 3.19 ± 0.07 |
| | A* $5_0 - 4_0$ | 241791.352 | 34.8 | 16.00 ± 0.19 | -6.25 ± 0.03 | 4.38 ± 0.06 | 3.43 ± 0.07 |
| | A* $5_1 - 4_3$ | 241832.718 | 84.6 | 0.31 ± 0.14 | -6.96 ± 0.57 | 2.21 ± 0.76 | 0.13 ± 0.09 |
| | A* $5_0 - 4_3$ | 241833.106 | 84.6 | -2.00 ± 0.07 | -6.74 ± 0.56 | 3.45 ± 0.92 | 0.15 ± 0.09 |
| | A* $5_1 - 4_2$ | 241842.284 | 72.5 | 0.56 ± 0.17 | -6.24 ± 0.14 | 2.87 ± 0.32 | 0.55 ± 0.09 |
| | A* $5_1 - 4_1$ | 241879.025 | 55.9 | 1.66 ± 0.17 | -6.29 ± 0.19 | 2.63 ± 0.22 | 0.10 ± 0.09 |
| | A* $5_2 - 4_2$ | 241887.674 | 72.5 | 2.33 ± 0.19 | -6.29 ± 0.19 | 2.63 ± 0.22 | 0.10 ± 0.09 |
| | CH$_3$CN | A $12_0 - 11_1$ | 220747.261 | 68.9 | 1.29 ± 0.11 | -6.60 ± 0.17 | 4.81 ± 0.22 | 0.25 ± 0.02 |
| | | E $12_0 - 11_1$ | 220743.011 | 76.0 | 1.28 ± 0.11 | -6.60 ± 0.17 | 4.81 ± 0.22 | 0.25 ± 0.02 |
| | | E $12_0 - 11_2$ | 220730.261 | 97.4 | 0.89 ± 0.12 | -6.60 ± 0.17 | 4.81 ± 0.22 | 0.18 ± 0.02 |
| | A $12_0 - 11_2$ | 220709.017 | 133.6 | 0.87 ± 0.11 | -6.60 ± 0.17 | 4.81 ± 0.22 | 0.17 ± 0.02 |
| | E $12_0 - 11_4$ | 220679.287 | 175.1 | 0.68 ± 0.14 | -5.22 ± 0.59 | 9.11 ± 0.84 | 0.07 ± 0.02 |
| | E $12_0 - 11_5$ | 220641.084 | 247.6 | 0.40 ± 0.14 | -5.22 ± 0.59 | 9.11 ± 0.84 | 0.04 ± 0.02 |
| | A $12_0 - 11_6$ | 220594.424 | 326.2 | 0.56 ± 0.15 | -5.22 ± 0.59 | 9.11 ± 0.84 | 0.06 ± 0.02 |
| | E $12_7 - 11_7$ | 220539.324 | 418.9 | 0.47 ± 0.17 | -5.22 ± 0.59 | 9.11 ± 0.84 | 0.05 ± 0.02 |
| | SO$_2$ | 5$2_4 - 4_1_{13}$ | 241615.797 | 23.6 | 0.57 ± 0.13 | -6.10 ± 0.50 | 4.27 ± 1.02 | 0.13 ± 0.03 |

$n_{H_2} = 3.2 \times 10^3 - 6.3 \times 10^6$ cm$^{-3}$, $N_{CH_3OH}/N_{H_2} > 10^{-8}$, $f > 10\%$ for a 1σ significance level.

### 3.2 CH$_3$CN emission towards Core 2

We find eight 12$K - 11K$ CH$_3$CN lines towards Core 2. Four lines with excitation energies below 140 K, corresponding to $K = 0, 1, 2, 3$, are visible with the original spectral resolution (Fig. 5, upper panel). In comparison, four lines with excitation energies above 140 K ($K = 4, 5, 6, 7$) are clearly seen only on the spectrum, where the resolution is reduced to 1.3 km s$^{-1}$ by double Hanning smoothing (Fig. 5, middle panel). As the widths of the low-excitation and high-excitation lines are different, we fitted them separately. First, the low-excitation lines were fitted, setting their velocities and widths to be the same, and then the same procedure was applied to the high-excitation lines. For the low-excitation lines, we obtained $V_{LSR} = -6.6$ km s$^{-1}$ and $\Delta V = 4.8$ km s$^{-1}$, which is close to the same parameters of the methanol lines. The high-excitation lines are broader, $\Delta V = 9.1$ km s$^{-1}$, and the central line velocity is slightly different, $V_{LSR} = -5.2$ km s$^{-1}$.

The four detected low-excitation lines allow us to estimate the CH$_3$CN excitation temperature using the rotational diagram method. The points corresponding to their upper-level populations lie on a straight line (Fig. 5, lower panel). We find $T_{ex} = 61$ K and column density $N_{CH_3CN} = 8.1 \times 10^{12}$ cm$^{-2}$ applying an optically thin analysis. We consider these lines as optically thin, because their intensity becomes lower for higher $E_u$, values. This is in contrast, for example, with excitation of the lower K transitions in a recent study by Liu et al. (2020). Since the LSR velocities and widths of low-excitation CH$_3$CN lines coincide well with those of the CH$_3$OH lines, most likely both of them arise in the same region. Using $N_{H_2} = 3.2 \times 10^{23}$ cm$^{-2}$, as above, we obtain an abundance of CH$_3$CN $x_{CH_3CN} = 2.5 \times 10^{-11}$ in the low-excitation molecular gas towards the centre of Core 2. This value is typical for dense cores in massive star-forming regions (Kalenskii et al. 2000). The relative abundance is $[CH_3CN/CH_3OH] = N_{CH_3CN}/N_{CH_3OH} \approx 10^{-2}$.

The points corresponding to the spectral lines with $K \geq 4$ do not lie on the straight line approximating the low-excitation level populations. The fact that the points are located above the approximating line demonstrates excess emission in the high-excitation lines, which, in turn, implies the presence of hot gas in Core 2. These points do not
lie on any straight line, which can be naturally explained, assuming that the high-excitation lines are not optically thin. Note that the point corresponding to the doubly degenerate \( K = 6 \) line jumps down with respect to its neighbors, and such behavior of the degenerate lines is an indicator of high optical depth (Kalenskii et al. 2000; Remijan et al. 2004; Beltrán et al. 2018). The observed high-excitation lines are very weak, and if they are optically thick, the hot region must be very compact. We estimated \( T_{\text{ex}} \) assuming an optically thin approximation for the lines with \( K \geq 4 \) in order to consider all possible scenarios, but did not obtain a statistically significant result for the \( T_{\text{ex}} \) value, due to the weakness of the lines. Therefore, additional observations are needed in order to confidently determine the gas temperature in Core 2. We should nevertheless point out that the high-excitation \( CH_3CN \) lines in star-forming regions trace hot cores (Olmi et al. 1996; Kalenskii et al. 2000; Remijan et al. 2004; Beltrán et al. 2018), therefore we suggest that Core 2 is at the very beginning of the hot core stage. 

Neither low-excitation nor high-excitation \( CH_3CN \) lines are detected in Core 1.

### 3.3 Emission of \( C^{34}S \) and \( SO_2 \) molecules in Core 2

The spectrum of the \( C^{34}S(5–4) \) line towards Core 2 is shown in Fig. 1. The line profile is similar to that of the methanol line at 241791.431 MHz (we multiply the \( C^{34}S(5–4) \) profile by a factor of 20 to show this in Fig. 1). Therefore, the methanol and \( C^{34}S(5–4) \) emission mainly originates in the same region. We found \( C^{34}S(5–4) \) lines not only directly towards Core 2, but also in the surrounding area with a radius \( \approx 15 – 30'' \) (0.1–0.2 pc at a distance of 1.34 kpc Russell (2003)). Assuming LTE conditions and using \( T_{\text{ex}} = 30 \) K, \( T_{\text{bg}} = 2.7 \) K, \( \mu = 1.96 \times 10^{-18} \) esu, \( B_0 = 24495.576 \) MHz, \( E_u = 27.8 \) K, \( J_u = 5 \) and filling factor \( f = 0.4 \) (from the methanol emission analysis), we calculate the column density of CS (\( N_{\text{CS}} \)).

The parameters of the \( C^{34}S(5–4) \) lines are shown in Table 2. The values of \( N_{\text{CS}} \), obtained as \( N_{\text{CS}} = 22.5N_{\text{CS}} \), in Core 2 and around are shown in Fig. 1. The relative abundance of CS, \( x_{\text{CS}} \), towards Core 2 is \( 4.5 \times 10^{-10} \). The value of \( N_{\text{CS}} \) is about 2 times lower at an offset of 15'' offset in the direction perpendicular to the ionization front (14 vs \( 8 \times 10^{13} \) cm\(^{-2} \)) and 4.5 times lower in two 15'' offsets along the front of the photodissociation region, visible as a bright bar in Fig. 1. Bearing in mind the high critical density of the \( C^{34}S(5–4) \) transition, which is higher than \( 10^6 \) cm\(^{-3} \) for gas temperatures from 10 to 100 K, we conclude that the dense gas distribution in Core 2 is asymmetric and elongated in the south-west direction from the centre of Core 2.

Our frequency setup covers the \( SO_2(5_{2,3} – 4_{1,3}) \) line at 241615.779 MHz, and we find this line in the spectrum towards Core 2 after smoothing by factor of 4. The parameters of the detected \( SO_2(5_{2,4} – 4_{1,3}) \) line towards Core 2 are shown in Table 2. Assuming LTE conditions with \( T_{\text{ex}} = 30 \) K, as we used for the analysis of \( C^{34}S \) emission, \( T_{\text{bg}} = 2.7 \) K, \( \mu = 1.63 \times 10^{-18} \) esu, rotational constants \( A_0 = 60788.550 \) MHz, \( B_0 = 10318.074 \) MHz, \( C_0 = 8799.703 \) MHz, \( E_u = 23.6 \) K, filling factor \( f = 0.4 \) (from the methanol emission analysis) and using Eq. 57 from Mangum & Shirley (2015) for the asymmetric molecule partition function, we obtain \( SO_2 \) column density \( N_{\text{SO}_2} = 2.32 \times 10^{12} \) cm\(^{-2} \) and relative abundance \( x_{\text{SO}_2} \) in Core 2 of \( 6.6 \times 10^{-12} \).

### 4 ASTROCHEMICAL MODELLING

In order to check whether our abundance estimates are viable for any particular stage of the star-formation process, we performed a simple astrochemical analysis relying upon the physical parameters found above for Core 2. The astrochemical model PRESTA (Kochina et al. 2013) is used for that purpose. This model solves the chemical
kinetic equations accounting for both gas-phase and solid-phase processes, which are taken from the ALCHEMIC database (Semenov & Wiebe 2011) with additions described by Wiebe et al. (2019). Abundances and physical constraints are summarised in Table 3. We note that chemical modelling procedure normally uses number density of hydrogen atoms $n_H = 2n_{H_2}$.

Table 3. Parameters of the astrochemical model for Core 2.

| parameter | value               |
|-----------|---------------------|
| $n_H$     | $10^4 - 10^6$ cm$^{-3}$ |
| $x_{CS}$  | $4.5 \times 10^{-10}$ |
| $x_{SO_2}$| $6.6 \times 10^{-12}$ |
| $x_{CH_3OH}$| $3.2 \times 10^{-9}$ |
| $x_{CH_3CN}$| $2.5 \times 10^{-11}$ |
First, we run a small set of models for number densities $n_H$ from $10^4$ cm$^{-3}$ to $10^6$ cm$^{-3}$ and for temperatures from 10 K to 30 K (gas and dust temperatures are assumed to be equal), neglecting any UV irradiation, except for cosmic-ray-induced photons. The results, shown in Fig. 6, indicate that the observed methanol abundance can only be reproduced in models with $T = 20$ K, $n_H = 10^4 - 10^5$ cm$^{-3}$, and a chemical age of about 1 Myr or greater. This age should be treated with caution, as its zero moment probably predates the formation of RCW 120. The abundances of CH$_3$CN and CS give more weight to formation of RCW 120. The abundances of CH$_3$OH are not straightforward signposts of a hot core stage. The warm-up phase in cores around RCW 120 detected six methanol maser spots at 36 GHz and seven spots at 44 GHz towards Clump 1. Four of these are observed in the same directions (their source G348.18+0.48). These Class I methanol masers arise via collision pumping by molecular hydrogen (e.g. Cragg et al. 1992; Leurini et al. 2016) and are often considered as tracers of interface regions of outflows (see, e.g., Voronkov et al. 2012). Indeed, the maser spectra in the spots observed by Voronkov et al. (2014) have profiles with significant wings, indicating complex kinematics and probably outflows in Clump 1. The wings of the thermal methanol lines reported by us suggest that both types of the methanol emission (maser and partly thermal) arise in the outflows. Water vapour masers were detected here by Braz & Scalcione (1982), which are also associated with collision pumping and molecular outflows (e.g. Genzel et al. 1981; Gwinn et al. 1992; Reid et al. 1995), but sometimes also with uCH$_3$N regions (Hunter et al. 1994). However, no methanol maser at 6.7 GHz was found here during the Methanol Multibeam Survey (Caswell et al. 2010), while the 6.7 GHz masers are considered as excellent signposts of the location of massive YSOs (e.g., Breen et al. 2013) and often observed near uCH$_3$N regions (e.g., van der Walt et al. 2003).

We show that warming-up gas-phase chemistry, related with the appearance of a heating source, is observed in Core 2. The methanol abundance in Core 2 found here is higher than observed in massive and low-mass dark clouds (e.g. Friberg et al. 1988; Kalenskii & Sobolev 1994; Dickens et al. 2000; Sanhueza et al. 2013; Vasyunina et al. 2014; Punanova et al. 2018). It is possible to obtain both high density and high gas-phase methanol abundance by adding a warm-up phase. We treat this in a simple manner, by considering a second stage with the same density of $10^5$ cm$^{-3}$, but with elevated temperatures. To reproduce the observed abundance, a growth of the gas/dust temperature up to ~90 K or higher is needed to evaporate a sufficient amount of methanol from icy mantles for the adopted desorption energy of 4235 K (Cuppen et al. 2017). It should be kept in mind that even in this case, the gas-phase methanol abundance rapidly drops due to enhanced ion-neutral chemistry. Also, after the temperature increase, the abundances of other species grow well above the observed values. This again hints that the emission regions for the various molecules are not spatially coincident. For example, there is a possibility that the methanol emission is associated with outflows (see Sec. 5), and we find line wings on the observed spectra of methanol in contrast with the CS spectra. Note that the abundances of CH$_3$CN, CS and SO$_2$ can be underestimated because of the unknown beam filling factor for these molecules.

In summary, we conclude that our estimates for the abundances of CH$_3$OH, CH$_3$CN (low-excitation value), CS and SO$_2$ are reasonable. The specific values of the abundances hint at the warm-up phase in Core 2. The detection of the high-excitation CH$_3$CN lines suggest that the central source, responsible for the warm up, might develop a compact hot core, but does not provide enough warming to enhance the abundances up to values typical for hot gas. Therefore, we may be observing the beginning of hot-core chemistry in Core 2. To extract more clues from the molecular composition of the cores, more thorough modelling is needed to take into account the physical and evolutionary complexity of the region.

5 DISCUSSION

Core 1 and Core 2 consist of two and five fragments, respectively, on a 0.01 pc scale, according to the ALMA 3-mm continuum observations made by Figueira et al. (2018). The most massive fragment is found in Core 2, with an estimated mass of 27 M$_\odot$ with a factor of 2 for the absolute mass uncertainty. Figueira et al. (2018) detected CH$_3$CN and SO$_2$ lines there and proposed the existence of an uCH$_3$N region on the basis of the detection of both of these lines. However, no radio continuum emission point sources was found toward Clump 1 in the NVSS image (Kirsanova et al. 2019).
Figure 6. Results of astrochemical modelling for Core 2. Colours are used to indicate gas/dust temperature, with blue denoting 10 K, green denoting 20 K, and red denoting 30 K. Line styles correspond to different density values, dotted being $10^4$ cm$^{-3}$, dashed being $10^5$ cm$^{-3}$, and solid being $10^6$ cm$^{-3}$. The thick black lines indicate the abundances for each species, obtained from the observations.
detection of lines of such molecules as CS and SO\textsubscript{2} suggests that the cold phase of protostellar evolution has completed. During the warm-up phase, H\textsubscript{2}S molecules evaporate from grain mantles and give rise to gas-phase sulfur chemistry, producing SO, SO\textsubscript{2}, CS, etc. (see, e.g. chemical modelling by Charnley 1997). However, the abundance of SO\textsubscript{2} found in this work is up to several orders lower than the typical value found at the hot core stage as shown in the review of several hot cores by Schöier et al. (2002) and Wakelam et al. (2004). The value of $x_{\text{CS}} \approx 10^{-10}$ – $10^{-9}$ obtained in this study is typical for the stage of freeze-out of molecules onto dust grains (e.g. Schöier et al. 2002). Beuther et al. (2002) studied several dozen high-mass protostellar candidates and found an average abundance of $x_{\text{CS}} \approx 8 \times 10^{-9}$, which is about an order of magnitude higher than our value in Core 2. More-evolved stages of ucH\textsc{ii} regions show similar abundances (Zinchenko et al. 2009, e.g.). Therefore, the cold stage seems to have finished quite recently, and the abundances are still quite low. We note again that our CS and SO\textsubscript{2} abundances are obtained using the same filling factor as we found from the analysis of the methanol emission. If the emission of SO\textsubscript{2} and CS arise in less extended regions as compared to methanol, the SO\textsubscript{2} and CS filling factors should be smaller; therefore, the abundances will be higher.

Bearing in mind the studies mentioned above, and our own results, we state that the Core 2 cannot be considered as an example of a high-mass analogue of a pre-stellar Class 0 object. We find warm-up chemistry and signatures of the beginning of the hot core stage there.

6 CONCLUSIONS

We report the detection of methanol lines towards massive Core 1 and Core 2, belonging to the neutral envelope of the H\textsc{ii} region RCW 120, and also the detection of CH\textsubscript{3}CN, CS and SO\textsubscript{2} lines towards Core 2. We estimate the gas physical parameters using the methanol lines and obtain gas temperature less than 100 K in both regions. The value of $n(H\textsubscript{2})$ is in the range of $10^5$ – $10^7$ cm\textsuperscript{-3} in Core 2, and has a higher uncertainty in Core 1. However, the detection of high-excitation CH\textsubscript{3}CN lines in Core 2 indicates that the region might contain hot gas. The relative abundances of CH\textsubscript{3}OH, CS, SO\textsubscript{2} and CH\textsubscript{3}CN found in the present study are quite low for a hot-core stage, but agree with a model of warm chemistry in dense gas. We suggest that Core 2 is in the beginning of the hot core stage.

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\textsuperscript{4} http://www.astropy.org

DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.

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| Offset | Position 1 | Position 2 | Position 3 |
|--------|------------|------------|------------|
| 30",0" | 15",15"    | 0",30"     | -30",60"   |
| 30",0" | 15",-15"   | -15",15"   | -30",30"   |
| 30",-30"| 15",-45"   | 0",-30"    | -30",0"    |
| 30",-60"| 15",-90"   | 0",-60"    | -30",-60"  |
| 30",-90"| 15",-90"   | 0",-90"    | -30",-60"  |

Table A1. Offsets of positions where the methanol lines were observed. Reference position is $\alpha_{2000} = 17^h12^m08^s$ and $\delta_{2000} = -38^\circ30'45"$. 