Probing the physical and chemical structure of the CS core in LDN 673: multitransitional and continuum observations

Oscar Morata,1* Josep Miquel Girart,2 Robert Estalella3 and Robin T. Garrod4

1Institute of Astronomy & Astrophysics, Academia Sinica, PO Box 23-141, Taipei 10617, Taiwan
2Institut de Ciencies de l’Espai (CSIC-IEEC), Campus UAB, Facultat de Ciències, C5 par 2a, E-08193 Bellaterra, Catalunya, Spain
3Departament d’Astronomia i Meteorologia (IEEC-UB), Institut de Ciències del Cosmos, Universitat de Barcelona, Marít i Franquès 1, E-08028 Barcelona, Catalunya, Spain
4Department of Astronomy, Cornell University, Ithaca, NY 14853, USA

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ABSTRACT

High angular resolution observations of dense molecular cores show that these cores can be clumpier at smaller scales and that some of these clumps can also be unbound or transient. The use of chemical models of the evolution of the molecular gas provides a way to probe the physical properties of the clouds. We study the properties of the clump and interclump medium in the starless CS core in LDN 673 by carrying out a molecular line survey with the IRAM 30-m telescope towards two clumps and two interclump positions. We also observed the 1.2-mm continuum with the MAMBO-II bolometer at IRAM. The dust continuum map shows four condensations, three of them centrally peaked, coinciding with previously identified submillimetre sources. We confirm that the denser clump of the region, \( n \sim 3.6 \times 10^5 \) cm\(^{-3}\), is also the more chemically evolved, and it could still undergo further fragmentation. The interclump medium positions are denser than previously expected, likely \( n \sim 1 \times 10^3 - 1 \times 10^4 \) cm\(^{-3}\) due to contamination, and are chemically young, similar to the gas in the lower density clump position. We argue that the density contrast between these positions and their general young chemical age would support the existence of transient clumps in the lower density material of the core. We were also able to find reasonable fits of the observationally derived chemical abundances to models of the chemistry of transient clumps.

Key words: stars: formation – ISM: abundances – ISM: clouds – ISM: individual objects: LDN 673 – ISM: molecules – radio lines: ISM.

1 INTRODUCTION

It has been long known that molecular clouds are highly structured (e.g. Blitz & Stark 1986) and their structure is greatly affected by the motions induced by supersonic turbulence (e.g. Scalo et al. 1998), self-gravity of the gas and magnetic fields inside the clouds (McKee & Ostriker 2007; Kainulainen et al. 2009). All these processes control the formation and evolution of the density enhancements, of different scale sizes and densities, such as the cores and clumps that will finally give birth to stars. However, there are still great uncertainties in identifying the connection between starless cores and protostars (Johnstone et al. 2000; Smith, Clark & Bonnell 2008). Starless cores are not all the same, despite their overall similarity in structure (Keto & Caselli 2008), and differences in total mass, density and temperature might account for the differences in dynamical properties, structure and future evolution of starless cores (Keto & Field 2005; Keto & Caselli 2008).

Higher angular resolution observations are also finding that dense cores in molecular clouds that appeared homogeneous in single-dish observations are clumpier at smaller scales (Peng et al. 1998; Morata, Girart & Estalella 2003), showing structures as small as 0.02 pc and masses as low as 0.01 M\(_\odot\). Many of these smaller clumps are unbound and/or showing evidence of being transient (Peng et al. 1998; Morata, Girart & Estalella 2005) and will never be able to form low-mass stars or even brown dwarfs. The mix of bound and unbound structures in dense cores is also found in several regions, such as the Pipe nebula, where recent molecular line and continuum observations (Lombardi, Alves & Lada 2006; Muench et al. 2007; Rathborne et al. 2008; Frau et al. 2010) found numerous cores, more than 100, most of which appear to be pressure confined and gravitationally unbound (Lada et al. 2008).

Observations of the emission of molecular lines at millimetre and submillimetre wavelengths in cloud cores combined with the modelling of the chemistry of the gas provide a way of obtaining information on the physical structure and the chemical and physical evolutionary stages of the cores. We proposed a time-dependent chemical model that also explored the consequences of the presence...
of unresolved and transient structures in the gas that would form and disperse in a timescale of \(~1–2\) Myr (Taylor, Morata & Williams 1996), in order to explain the systematic differences between CS and NH lines (Pastor et al. 1991; Morata et al. 1997). Simulations of the evolution of these cores (Garrod et al. 2005; Garrod, Williams & Rawlings 2006) find that clouds that are ensembles of such transients have a clearly different chemistry from a ‘traditional’ static cloud. The gas chemistry appears to be ‘young’ at all times, and the recycling of the material frozen out on to dust grains produces a general molecular enrichment of the clouds, even after re-expansion of the transient structures. The background gas in which these inhomogeneities are embedded would be fairly diffuse, but chemically enriched. These chemical enhancements might also account for the variety of chemistries observed in diffuse clouds.

We carried out interferometric high angular resolution observations of several molecules (CS, HCO\(^+\) and \(N_2H^+\)) (Morata et al. 2003, hereafter MGE03), which we later combined with single-dish intermediate angular resolution maps (Morata et al. 2005, hereafter MGE05) towards the starless CS core in LDN 673 (\(d = 300\) pc), in order to test the predictions of the chemical models. The combined single-dish and interferometer maps showed emission of both background and clumped gas, with a clear segregation of clump properties between the northern and southern halves of our observed region, and allowed us to identify 15 resolved clumps in our data cube. The derived clump masses are well below the virial mass, which would point to their being transient, except for the more massive one, which might have a mass, \(~1\) M\(_\odot\), closer to the virial mass. The starless core appears to be constituted by a heterogeneous medium of condensations, of various densities and at different stages of chemical evolution, in agreement with theoretical studies that postulate the existence of transient clumps or the transient nature of dense cores generated by dynamical flows within molecular clouds (see e.g. Falle & Hartquist 2002; Vázquez-Semadeni et al. 2005; Van Loon et al. 2008). Recently, Whyatt et al. (2010) also found evidence of a heterogeneous medium in scales of less than \(0.1\) pc near HH objects, as traced by strong HCO\(^+\) (3–2) emission. These clumps would have gas volume densities \(<10^{4} \text{cm}^{-3}\).

In order to study the properties of the clump and interclump gas in the starless CS core in LDN 673, we selected two positions associated with identified clumps (CL1 and CL6) and two positions where the interclump gas would be dominant (where we did not detect any clump). A multitransitional survey of several early- and late-type molecules in these positions allows us to sample the chemical composition of the gas and compare it to the predicted different chemistry of the pre-clump and post-clump gas in the models. We additionally observed the dust continuum emission in LDN 673. The structure of this paper is as follows. In Section 2, we describe the IRAM 30-m spectral line and continuum observations. In Section 3, we describe the characteristics of the detected spectra and the structure of the dust continuum emission. The analysis of the observational results and the determination of the physical parameters of the gas and dust are shown in Section 4. Finally, Section 5 contains the discussion of the results of our analysis and how they can be related to the previous observations, the chemistry of the clouds and the structure of the core.

2 OBSERVATIONS

The spectral line observations were carried out in 2005 August using the 30-m IRAM telescope in Granada (Spain). We used the capability of the ABCD multireceiver system to observe 10 different molecules (and a total of 23 transitions) with just six frequency setups in the 3-, 2- and 1-mm bands. Table 1 shows the transitions and frequencies observed. We used the VESPA autocorrelator as a spectral backend, which provided a total bandwidth of 80 MHz, and selected a 20-kHz channel spacing for the receiver at 100 GHz and a 40-kHz channel spacing for the other three receivers. The achieved velocity resolutions range from 0.4 to 0.07 km s\(^{-1}\). Table 2 gives the coordinates and names of the four observed positions. Table 1 shows the transitions and frequencies observed. We used the VESPA autocorrelator as a spectral backend, which provided a total bandwidth of 80 MHz, and selected a 20-kHz channel spacing for the receiver at 100 GHz and a 40-kHz channel spacing for the other three receivers. The achieved velocity resolutions range from 0.4 to 0.07 km s\(^{-1}\). Table 2 gives the coordinates and names of the four observed positions. Fig. 1 plots the location of the observed positions over the combined BIMA–FCRAO map of the CS (\(J = 2–1\)) emission of MGE05. The four positions were selected according to the following criteria: (1) two positions centred in two of the CS clumps are detected by MGE05 – CL1, the most massive and chemically evolved clump, and CL6, a chemically young clump found in the northern region of the BIMA map; (2) two interclump positions,

### Table 1. Lines observed with the 30-m IRAM telescope.

| Transition | Frequency (GHz) | HPBW (arcsec) | \(B_{\text{eff}}\) |
|------------|----------------|---------------|----------------|
| CCH 1–0 2 \(\frac{7}{2}\) \(-\frac{5}{2}\) \(F = 2–1\) | 87.316 925 | 28 | 0.78 |
| CCH 2–1 2 \(\frac{7}{2}\) \(-\frac{5}{2}\) \(F = 3–2\) | 174.663 222 | 14 | 0.64 |
| CCH 3–2 2 \(\frac{7}{2}\) \(-\frac{5}{2}\) \(F = 4–3\) | 262.004 260 | 9 | 0.46 |
| CN 1–0 2 \(\frac{3}{2}\) \(-\frac{1}{2}\) | 113.490 982 | 22 | 0.74 |
| CN 2–1 2 \(\frac{3}{2}\) \(-\frac{1}{2}\) | 226.874 764 | 11 | 0.54 |
| CS 5–4 | 244.935 606 | 10 | 0.50 |
| c-C3H2 2\(1,2\)–0\(|0,1|\) | 85.338 906 | 29 | 0.78 |
| c-C3H2 4\(1,4\)-3\(0,3\) | 150.851 899 | 16 | 0.68 |
| HCN 3–2 | 265.886 432 | 9 | 0.45 |
| H2CO 2\(1,2\)–1\(|1,1|\) | 140.839 515 | 18 | 0.70 |
| H2CO 3\(1,3\)–2\(|1,2|\) | 211.211 448 | 12 | 0.57 |
| H2CO 3\(1,2\)–2\(|1,1|\) | 225.697 773 | 11 | 0.54 |
| H\(^1\)CO\(^+\) 1–0 | 86.754 330 | 28 | 0.78 |
| H\(^1\)CO\(^+\) 2–1 | 173.506 782 | 14 | 0.64 |
| H\(^1\)CO\(^+\) 3–2 | 260.255 480 | 10 | 0.46 |
| NO \(\frac{3}{2}\) \(\frac{3}{2}\) \(-\frac{1}{2}\) \(\frac{1}{2}\) \(\Pi^+\) | 150.176 459 | 16 | 0.68 |
| NO \(\frac{5}{2}\) \(\frac{5}{2}\) \(-\frac{3}{2}\) \(\frac{3}{2}\) \(\Pi^+\) | 250.456 845 | 10 | 0.48 |
| SO 3\(3–2\) | 99.299 905 | 25 | 0.76 |
| SO 4\(5–3\) | 206.176 062 | 12 | 0.58 |
| SO 6\(5–4\) | 219.949 433 | 11 | 0.55 |
| SO 7\(6–5\) | 261.843 756 | 10 | 0.46 |
| SO2 3\(1,3\)–2\(|0,2|\) | 104.029 410 | 24 | 0.76 |
| SO2 7\(1,7\)–6\(|0,6|\) | 165.225 436 | 15 | 0.66 |

\(^1\) http://www.iram.fr/IRAMFR/GILDAS

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Table 2. Coordinates of the positions selected for the spectral line observation.

| Position | Counterpart  | RA (J2000) | Dec. (J2000) |
|----------|--------------|------------|--------------|
| CL1      | N$_2$H$^+$ peak | 19:20:51.747 | 11:13:49.50  |
| CL6      | CS peak       | 19:20:50.003 | 11:14:53.00  |
| ICLN     | Interclump N  | 19:20:51.701 | 11:15:30.00  |
| ICLS     | Interclump S  | 19:20:54.501 | 11:14:10.00  |

3 RESULTS

3.1 Spectral line observations

Figs 2 and 3 show the spectra obtained in the four selected positions for the detected molecules (19 of the 23 lines observed). Tables A1–A4 (online-only; see Supporting Information) show the line parameters obtained using a Gaussian fit for the transitions detected in the CL1, CL6, ICLN, and ICLS positions, respectively. Table A5 (online-only; see Supporting Information) shows the hyperfine structure fit parameters (obtained using the HFS method of the CLASS package) for the detected CN, CCH and NO transitions (Fig. 4 shows the full spectra of all the detected hyperfine structure lines). Finally, Table A6 (online-only; see Supporting Information) gives the upper limits for the line intensities of the transitions not detected at each position. The CCH (3–2), CS (5–4), SO (76–65) and SO$_2$ (71–60) lines were not detected at any position. The first three lie in the 1-mm band, which presents higher $T_{\text{sys}}$, and typically shows a higher rms than the 3- and 2-mm band values in our spectra.

All the 19 detected transitions are at the CL1 position, whereas the other three positions show detection in 10 (CL6 and ICLN) or 11 (ICLS) transitions. If we compare the intensity for the same line across the four positions, the emission is always more intense at the CL1 position. Lines at the CL6 position tend to be more intense than at ICLS, while lines at the ICLN position are typically the less intense ones.

There are no important differences in the line central velocities among the four positions. The four observed positions show $v_{\text{LSR}}$ velocity differences of 0.1–0.2 km s$^{-1}$ between them, and are in agreement with the velocity pattern found by MGE05. Linewidths towards CL1 tend to be the narrowest ($\sim$0.4–0.5 km s$^{-1}$, typically). This suggests that the turbulence is lower in CL1 than in the rest of the region.

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3.2 Dust continuum emission

Fig. 5 shows the 1.2-mm continuum map obtained with the MAMBO-II bolometer. We find four emission condensations with different degrees of extension and intensity. These four condensations were previously detected at 850 μm by Visser, Richer & Chandler (2002). Table 3 gives the emission parameters derived for these four condensations and the association with the sources of Visser et al. (2002). These four condensations were also recently identified by Tsitali et al. (2010) using the Spitzer Space Telescope, which they classify as starless cores.

The three southern condensations show an approximately rounded shape and with centrally peaked emission, whereas the northern condensation rather looks like an extended patch of weak emission. The most intense emission peak (the central clump in Fig. 5), SMM5, coincides with CL1 and with the NH emission of MGE03. Another, slightly smaller, bright condensation is SMM3, with a similar value of the emission peak and located about ≃50 arcsec west of SMM5. A third condensation, again slightly smaller, but with a similar emission peak to the previous two, is SMM8, located ∼2.5 arcmin south-east (SE) of SMM5, near the edge of the 1.2-mm observation field of view. This condensation was also detected in H13CO+(1–0) and C34S (2–1) in single-dish observations (MGE05). The fourth condensation, associated with SMM6, presents diffuse and extended dust emission in an approximately east–west (E–W) strip ∼2 arcmin north of SMM5 that coincides with a ridge of molecular emission found in an E–W direction in the maps obtained with the FCRAO telescope (MGE05).

Among the four positions observed in spectral lines, only CL1 is associated with a dust peak matching very well with SMM5. CL6 and ICLN are associated with weak dust emission at 2σ, and ICLS is associated with even weaker emission.

4 ANALYSIS

4.1 Radiative transfer analysis

The detection of multiple transitions at the same position of some molecules allows us to constrain the physical properties of the emitting gas. We used the RADEX radiative transfer model code (Van der Tak et al. 2007), which treats optical depth effects with an escape probability method, to find the set of molecular column densities, N(X), volume densities, n(H2), and kinetical temperatures, T_K, that best reproduced the observed lines. Appendix B gives more details on how the calculations were done.

4.1.1 Results of the RADEX analysis: uncertainties

Table 4 shows the best-fitting results we obtained from our χ² analysis using RADEX on the set of lines from the H2CO, SO and H13CO+ molecules, for which at least three transitions have been detected at each position. Table 5 shows the best set of parameters that we found for c-C3H2, HCN and SO2, assuming the temperature, volume density and size derived from the previous best fit, plus the results from the hyperfine-line fitting for CCH, CN and NO.

We estimate that the volume density determination has an uncertainty of 50–70 per cent of the best-fitting value (shown in Table 4) at the 1σ level. The column densities, N(X), are less well constrained than the volume density. The derived column densities of all the
molecules have an uncertainty of \( \sim 65 \) per cent on average from the best-fitting value for the CL1 position. For the other positions, the column densities are only constrained within a factor of 2 of the best value.

We alternatively explored how well constrained were the results of our analysis by fixing the \( H_2CO \) column density and the filling factor for each position to the best-fitting values, and running a range of models with different kinetical temperatures and volume densities. Fig. 6 shows the goodness of fit over the parameter space spanned by \( n(H_2) \) and \( T_K \). Similarly to the results in Table 4, \( n(H_2) \) is relatively well constrained for all positions, but except for CL1, that is not the case for \( T_K \). Temperatures are rather badly determined for the two interclump positions, probably due to the lower volume density and the lower signal-to-noise ratio (S/N) of the 1-mm lines. The best-fitting values of \( T_K \) show clear differences between the CL1 and CL6 positions, \( T_K \simeq 10 \) K, and the interclump positions, \( T_K \simeq 23 \) K (see also Section 4.1.2). However, the uncertainties in the interclump positions are too large to be significant. We adopt a value of 20 K for the interclump gas, since their lower visual extinction may allow the interstellar ultraviolet radiation to heat the gas (see e.g. Nejad & Wagenblast 1999).

As shown in Fig. 1, the 2- and 3-mm beams of the telescope at both interclump positions could have contribution from higher density gas. This effect could be important for the ICLS position, which is the one we studied more carefully (the effect of the emission of CL6 on ICLN is probably very small because the emission in CL6 is much less intense). We used the 1.2-mm continuum map, with an angular resolution \( \sim 10.5 \) arcsec, to estimate the contribution to the intensity of the lines at the ICLS position coming from emission from the CL1 position. In order to have an upper limit estimate of the error beam of the telescope at 2 and 3 mm, we convolved the 1.2-mm continuum map with a Gaussian with the same HPBW as the main beam of the telescope at 2 and 3 mm obtained from Greve, Kramer & Wild (1998) and Bensch et al. (2001). Then, we compared the intensities at the clump and interclump positions for the original and the convolved maps. We calculated the contribution of the error beam at the CL1 position to the \( H_2CO \), \( SO \) and \( H^{13}CO^+ \) lines at the ICLS position as representatives of the different beams we used. We found that the error beam contribution to the molecular line emission in ICLS can be \( \lesssim 0.1 \)–0.5 K, or \( \lesssim 18–50 \) per cent range of the intensity of the detected lines. Thus, though not negligible, we expect a minor contribution of the higher density gas to the lines in the ICLS position. In order to check how much the results of the analysis for the ICLS position can be affected by this contribution, we remade the analysis after subtracting the estimated intensity coming from the CL1 position in the lines measured in ICLS. The resulting number density for ICLS becomes \( \sim 3 \) times smaller, \( \sim 6.6 \times 10^3 \) cm\(^{-3} \), while the column densities of \( H_2CO \) and \( SO \) are around \( \sim 2 \) times larger, and \( H^{13}CO^+ \) remains practically constant.

### 4.1.2 Results of the RADEX analysis: volume density, excitation temperature and line opacity

The line intensities and line ratios of our data are best reproduced if we use beam filling factor and kinetical temperature, \( \eta_{bf} \leq 1 \) and \( T_K \simeq 10 \) K, for CL1 and CL6, but \( \eta_{bf} \simeq 1 \) and \( T_K \simeq 20 \) K give better results for the two ‘interclump’ positions. We performed an additional test to check if the ‘best values’ of the filling factors are consistent with previous data. From the maps by MGE05, we calculated the main beam antenna temperatures at each of the four

![Figure 5. 1.2-mm dust continuum map obtained with the MAMBO-II bolometer after convolving with a 15-arcsec Gaussian beam. The rms noise of the map is 7 mJy beam\(^{-1}\). The minimum contour is 21 mJy beam\(^{-1}\) with increments of 7 mJy beam\(^{-1}\). The circles show the beam size of the 30-m telescope at 3 mm, ~25 arcsec, centred at each of the positions of the spectral line survey (solid squares). The solid triangles mark the positions of the SMM sources found by Visser et al. (2002).](https://academic.oup.com/mnras/article-abstract/425/3/1980/981640)
Table 4. Physical parameters derived from the best-fitting model defined by the minimum value of the $\chi^2$ function of a series of radex models compared to the lines of H$_2$CO, SO and H$^{13}$CO$^+$ observed in the four positions.

| Position | Species        | $\theta_i$ (arcsec) | $T_K$ (K) | n(H$_2$) ($\times 10^5$ cm$^{-3}$) | $N(X)^a$ (cm$^{-2}$) | Transition | $T_{ex}b$ (K) | $\tau^b$ |
|----------|----------------|---------------------|-----------|----------------------------------|----------------------|------------|--------------|---------|
| CL1      | H$_2$CO        | 50                  | 10        | 3.6                              | $\chi^2$             | 2$_{1,2}$--1$_{0,1}$ | 6.3        | 1.0     |
|          | SO             |                     |           | 8.4 $\times 10^{12}$             |                      | 3$_{2}$--1$_{1}$     | 8.2        | 2.0     |
|          | H$^{13}$CO$^+$ |                     |           | 4.8 $\times 10^{13}$             |                      | 1--0        | 9.5        | 0.4     |
| CL6      | H$_2$CO        | 50                  | 10        | 0.7                              | $\chi^2$             | 2$_{1,2}$--1$_{0,1}$ | 4.7        | 4.4     |
|          | SO             |                     |           | 2.8 $\times 10^{13}$             |                      | 3$_{2}$--1$_{1}$     | 6.7        | 7.2     |
|          | H$^{13}$CO$^+$ |                     |           | 1.3 $\times 10^{14}$             |                      | 1--0        | 5.0        | 0.4     |
| ICLN     | H$_2$CO        | 1000                | 20        | 0.2                              | $\chi^2$             | 2$_{1,2}$--1$_{0,1}$ | 3.9        | 3.6     |
|          | SO             |                     |           | 3.0 $\times 10^{13}$             |                      | 3$_{2}$--1$_{1}$     | 4.9        | 2.9     |
|          | H$^{13}$CO$^+$ |                     |           | 6.6 $\times 10^{13}$             |                      | 1--0        | 4.2        | 0.3     |
| ICLS     | H$_2$CO        | 1000                | 20        | 0.2                              | $\chi^2$             | 2$_{1,2}$--1$_{0,1}$ | 4.0        | 6.1     |
|          | SO             |                     |           | 2.5 $\times 10^{13}$             |                      | 3$_{2}$--1$_{1}$     | 5.0        | 4.9     |
|          | H$^{13}$CO$^+$ |                     |           | 7.6 $\times 10^{13}$             |                      | 1--0        | 3.8        | 0.5     |

$^a$Beam-averaged column densities.

$^b$Calculated for the lower frequency transition (the best determined in the observations).

Table 5. Physical parameters for the rest of the molecules observed in the four positions of LDN 673 obtained from the best-fitting models after fixing $T_K$, n(H$_2$) and $\theta_i$ to the values reported in Table 4, or from the hyperfine structure fitting (see Section B2).

| Position | Species        | $N(X)^a$ (cm$^{-2}$) | Transition | $T_{ex}b$ (K) | $\tau^b$ |
|----------|----------------|----------------------|------------|--------------|---------|
| CL1      | c-C$_3$H$_2$   | $4.5 \times 10^{12}$ | 2$_{1,2}$--1$_{0,1}$ | 6.5        | 0.9     |
|          | HCN            | $1.5 \times 10^{13}$ | 3--2       | 4.9        | 6.9     |
|          | SO             | $3.7 \times 10^{12}$ | 3$_{1,3}$--2$_{0,2}$ | 4.5        | 0.2     |
| CL6      | c-C$_3$H$_2$   | $1.3 \times 10^{12}$ | 2$_{1,2}$--1$_{0,1}$ | 3.4        | 0.6     |
| ICLN     | c-C$_3$H$_2$   | $6.0 \times 10^{11}$ | 2$_{1,2}$--1$_{0,1}$ | 3.3        | 0.3     |
| ICLS     | c-C$_3$H$_2$   | $1.9 \times 10^{12}$ | 2$_{1,2}$--1$_{0,1}$ | 3.2        | 0.9     |
|          | SO             | $5.3 \times 10^{12}$ | 3$_{1,3}$--2$_{0,2}$ | 3.2        | 0.6     |

Hyperfine structure calculation

| Position | Species | $N(X)^a$ (cm$^{-2}$) | Transition | $T_{ex}b$ (K) | $\tau^b$ |
|----------|---------|----------------------|------------|--------------|---------|
| CL1      | CCH     | $1.7 \times 10^{13}$ | 1--0       | 5.7        | 0.3     |
|          | CN      | $3.4 \times 10^{13}$ | 1--0       | 4.3        | 5.9     |
|          | NO      | $5.3 \times 10^{14}$ |            | 5.4        | 0.4     |
| CL6      | CCH     | $4.7 \times 10^{12}$ | 1--0       | 4.5        | 0.1     |
|          | CN      | $9.1 \times 10^{12}$ | 1--0       | 3.3        | 1.4     |
|          | NO      | $2.2 \times 10^{14}$ |            | 7.1        | <0.1    |
| ICLN     | CCH     | $5.3 \times 10^{12}$ | 1--0       | 4.1        | 0.1     |
|          | CN      | $7.3 \times 10^{12}$ | 1--0       | 3.1        | 1.1     |
|          | NO      | $1.7 \times 10^{14}$ |            | 5.0        | 0.1$^c$ |
| ICLS     | CCH     | $7.0 \times 10^{12}$ | 1--0       | 3.9        | 0.2     |
|          | CN      | $1.1 \times 10^{13}$ | 1--0       | 3.0        | 2.2     |
|          | NO      | $2.5 \times 10^{14}$ |            | 5.2        | 0.1$^c$ |

$^a$Beam-averaged column densities.

$^b$Calculated for the lower frequency transition (the best determined in the observations).

$^c$Calculated after fitting the spectra assuming optically thin lines.

The volume densities yielded by the $\chi^2$ analysis show a clear distinction between the physical characteristics of the four positions traced by the molecular line emission. The volume density is highest in CL1, $\sim 3.6 \times 10^5$ cm$^{-3}$, $\sim 5$ times larger than the density derived for CL6, and more than one order of magnitude larger than for the interclump positions.

Table 4 also shows the values of excitation temperatures, $T_{ex}$, and line opacities, $\tau$, yielded by the ‘best-fitting’ models for each position and molecule: H$_2$CO (2$_{1,2}$--1$_{0,1}$), SO (3$_{2}$--1$_{1}$) and H$^{13}$CO$^+$ (1--0). We can see that the H$_2$CO and SO lines tend to be optically thick or very thick, especially for the CL6, ICLN and ICLS positions, which is also reflected in apparently larger values of the column density, compared to the ones found at CL1. This effect is possibly due to the lower volume density in CL6, ICLN and ICLS. The rotational levels involved in the H$_2$CO and SO lines are not of the fundamental rotational level, which makes them more

positions after convolving the maps with beams of full width at half maximum (FWHM) 14 and 28 arcsec and tried to estimate the size of the ‘apparent’ emitting region. The results for the ICLN and ICLS positions agree with $\theta_{ex} \approx 1$. For CL1 and CL6, the results agree with $\theta_i \sim 30$ and 45 arcsec, respectively, not far from the adopted value, $\theta_i \sim 50$ arcsec.

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4.1.3 Results of the RADEX analysis: column density

H$_2$CO and SO column densities are lowest at CL1, by factors of $\sim$3.0–3.6 and $\sim$1.4–2.8, respectively, compared to the other positions, while $\mathcal{N}$(H$^{13}$CO$^+$) is the largest at CL1 by a factor of $\sim$2. Both ICLN and ICLS show rather similar values for the column densities of the three molecules.

The column density variations for CCH, c-C$_2$H$_2$, CN and NO follow similar trends, with small differences. The CL1 position shows the largest column densities for all these molecules, while ICLS has the second largest column density. Column densities in CL6 tend to be slightly larger or similar to the ones in ICLN. The column density of SO$_2$, which was only detected in two positions, is also $\sim$50 per cent larger for ICLS than for CL1.

4.2 Dust continuum emission

We calculated the mass of the molecular gas traced by the dust from the continuum emission flux density (Frau et al. 2010). Table 3 gives the H$_2$ mass and H$_2$-averaged column and volume density contained inside the FWHM contour of each of the four condensations found in the 1.2-mm continuum map, assuming a dust temperature of 10 K.

The calculated masses of the four condensations range from 1.6 M$_{\odot}$ for the SE condensation, which is also the smallest one ($\sim$0.05 pc), to 5.1 M$_{\odot}$ for the CL1/SMM5 condensation. The H$_2$ volume densities for the three centrally peaked condensations are rather similar, $\sim$3 $\times$ 10$^4$ cm$^{-3}$, which is very close to the value derived for the CL1 position from the spectral line observations. The weaker and more diffuse emission of the SMM6 condensation is reflected in a volume density $\sim$4 times lower, 7 $\times$ 10$^4$ cm$^{-3}$, slightly larger than the value derived for the CL6 position. Interestingly, the condensations associated with CL1/SMM5 and SMM3 have similar extensions ($\sim$0.07 versus $\sim$0.06 pc), volume densities and, to a lesser extent, column densities.

In order to estimate the abundances of the observed molecular species (see Section 4.3), we also calculated the H$_2$ column density traced by the dust continuum emission at the four spectral positions using three different angular resolutions: 27, 22 and 17 arcsec, corresponding to the angular resolution of the spectral line observations at 3.4, 2.7 and 2.1 mm, respectively (Table 6). We adopted a dust temperature value of 10 K for the four positions, given that because of the lack of any internal heating source and because the densities of the gas seem to be $\gtrsim$10$^4$ cm$^{-3}$, we do not expect higher dust temperatures (Goldsmith 2010). The column densities at the CL1 position are significantly larger than at the other three positions, by factors of $\sim$3–4 with respect to CL6 and ICLN, and of $\sim$5–10 with respect to ICLS.

Figure 7. Grey-scale of the CS (2–1) integrated emission (from MGE05) overlapped with the contour map of the 1.2-mm dust emission. The angular resolution of both images is $\approx$15 arcsec. The contours of the dust continuum map start at 14 mJy beam$^{-1}$, with increments of 7 mJy beam$^{-1}$; the contours of the CS (2–1) map begin at 0.496 K, with increments of 0.248 K. The two maps were convolved with the primary beam response of the BIMA two-point mosaic observations presented by MGE05. The inner and outer dashed lines show the 0.5 and 0.25 levels of the BIMA primary beam response. The thick crosses show the four positions observed with the IRAM 30-m telescope.

4.2.1 Comparison of dust and CS emission

We convolved the dust map with the two-point mosaic response of the BIMA telescope in order to properly compare the CS (2–1) and 1.2-mm dust maps. Fig. 7 shows the overlap of the CS (2–1) integrated emission from MGE05 with the convolved dust continuum emission at the same angular resolution, 15 arcsec. In general, the CS and 1.2-mm emissions are not correlated. For the CL1/SMM5 condensation, the CS emission peak is slightly displaced with respect to the dust emission peak, by $\approx$2 arcsec. The western condensation, SMM3, lies just at the limit of the BIMA primary beam, but it seems to be associated with CS clump 12 (following MGE05).

Table 6. H$_2$ average column density traced by the dust continuum emission on the positions of the spectral line observations for three different beam sizes.

| Position | $T_{\text{dust}}$ (K) | 27 arcsec | 22 arcsec | 17 arcsec |
|----------|----------------------|-----------|-----------|-----------|
| CL1      | 10                   | 31.1      | 34.8      | 40.1      |
| CL6      | 10                   | 10.8      | 10.9      | 10.2      |
| ICLN     | 10                   | 9.0       | 9.5       | 11.2      |
| ICLS     | 10                   | 6.0       | 5.5       | 4.3       |

*aUsing the parameters given in footnote $d$ of Table 3.
The structure of the CS core in LDN 673

4.3 Molecular abundances

For each position, we calculated the molecular abundances of our molecules (Table 7) from the ratio of the beam-averaged molecular column density to the beam-averaged H2 column density from Table 6. Taking into account the uncertainties in the calculation of both sets of column densities, we estimate that the uncertainties in the determination of the molecular abundances should be between factors of 2 and 2.5. For easier comparison, we plotted in Fig. 9 the upper and lower limits that we estimated for the abundances of each molecular species in CL6, ICLN and ICLS relative to the abundance in CL1. The abundances of CCH, CN and H2CO at CL1 are similar to the abundances at CL6 and ICLS, but for the rest of the molecules (Table 7) from the ratio of the beam-averaged molecular column density to the beam-averaged H2 column density derived from the dust continuum emission.

Table 7. Molecular abundances calculated from the ratio of the beam-averaged molecular column density to the beam-averaged H2 column density derived from the dust continuum emission.

| Species     | Position | Beam size \(\text{arcsec}\) | \([X]/[H_2]\) |
|-------------|----------|-----------------------------|----------------|
| CCH         | CL1      | 27                          | \(5.4 \times 10^{-10}\) |
|             | CL6      | 4.3                         | \(3 \times 10^{-10}\) |
|             | ICLN     | 5.8                         | \(10^{-10}\) |
|             | ICLS     | 1.2                         | \(10^{-9}\) |
| CN          | CL1      | 22                          | \(9.9 \times 10^{-10}\) |
|             | CL6      | 8.3                         | \(10^{-10}\) |
|             | ICLN     | 7.6                         | \(10^{-10}\) |
|             | ICLS     | 2.0                         | \(10^{-9}\) |
| c-C3H2      | CL1      | 27                          | \(1.4 \times 10^{-10}\) |
|             | CL6      | 1.2                         | \(10^{-10}\) |
|             | ICLN     | 6.7                         | \(10^{-11}\) |
|             | ICLS     | 3.2                         | \(10^{-10}\) |
| HCN         | CL1      | 12                          | \(3.0 \times 10^{-10}\) |
| H2CO        | CL1      | 17                          | \(2.1 \times 10^{-10}\) |
|             | CL6      | 2.7                         | \(10^{-9}\) |
|             | ICLN     | 2.7                         | \(10^{-9}\) |
|             | ICLS     | 5.8                         | \(10^{-9}\) |
| H13CO+      | CL1      | 27                          | \(2.7 \times 10^{-11}\) |
|             | CL6      | 4.2                         | \(10^{-11}\) |
|             | ICLN     | 4.4                         | \(10^{-11}\) |
|             | ICLS     | 6.6                         | \(10^{-11}\) |
| NO          | CL1      | 17                          | \(1.3 \times 10^{-8}\) |
|             | CL6      | 2.2                         | \(10^{-8}\) |
|             | ICLN     | 1.5                         | \(10^{-8}\) |
|             | ICLS     | 5.7                         | \(10^{-8}\) |
| SO          | CL1      | 22                          | \(1.4 \times 10^{-9}\) |
|             | CL6      | 1.2                         | \(10^{-8}\) |
|             | ICLN     | 6.9                         | \(10^{-9}\) |
|             | ICLS     | 1.4                         | \(10^{-8}\) |
| SO2         | CL1      | 22                          | \(1.1 \times 10^{-10}\) |
|             | ICLS     | 9.6                         | \(10^{-10}\) |

\(a\)Beam size over which the molecular and H2 column densities were averaged.

The other CS clumps found through the CLUMPFIND analysis done by MGE05 do not show any clear dust emission peaks. Some of these clumps in the northern part of the map could be associated with the diffuse dust emission arising from SMM6. More interesting is the existence of CS emission in the central parts of the map with very weak or no dust emission.

To estimate the CS molecular abundance in the observed BIMA field (see Fig. 7), we first convolved the CS and dust continuum maps with a beam size of 25 arcsec, in order to measure the dust emission with a higher S/N in the regions where it is diffuse and weak. We then calculated the CS column density assuming local thermodynamic equilibrium conditions, an excitation temperature of \(T_{ex} = 5\) K and a CS \((2-1)\) optical depth line of 3, values derived by MGE05 from multitransitional analysis of the CS and C34S molecules. The H2 column densities were derived from the dust map adopting a temperature of \(T_{dust} = 10\) K and dust absorption coefficient of 0.5 cm2 g\(^{-1}\). Fig. 8 shows the resulting CS abundance overlapped with the dust emission at the same 25-arcsec angular resolution. The CS abundance changes about one order of magnitude, from \(X(\text{CS}) \sim 10^{-9}\) around the CL1/SMM5 clump to \(X(\text{CS}) \sim 10^{-8}\) about 1 arcmin north of CL1/SMM5, closer to the position of the CL6 CS clump. CS abundances tend to be lower at the positions of the detected dust condensations.

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Figure 8. Colour image of the map of the CS abundance, overlapped with the contour map of the 1.2-mm continuum emission. The angular resolution of both images is 25 arcsec. The two maps were convolved with the primary beam response of the BIMA two-point mosaic observations presented by MGE05. The inner and outer dashed lines show the 0.5 and 0.25 levels of the BIMA primary beam response. The contours are 10, 15, 25, 35, 55, 75 and 95 per cent of the 1.2-mm continuum peak emission (66.2 mJy beam\(^{-1}\)). The grey crosses show the four positions observed with the IRAM 30-m telescope.

Table 7. Molecular abundances calculated from the ratio of the beam-averaged molecular column density to the beam-averaged H2 column density derived from the dust continuum emission.

| Species     | Position | Beam size \(\text{arcsec}\) | \([X]/[H_2]\) |
|-------------|----------|-----------------------------|----------------|
| CCH         | CL1      | 27                          | \(5.4 \times 10^{-10}\) |
|             | CL6      | 4.3                         | \(3 \times 10^{-10}\) |
|             | ICLN     | 5.8                         | \(10^{-10}\) |
|             | ICLS     | 1.2                         | \(10^{-9}\) |
| CN          | CL1      | 22                          | \(9.9 \times 10^{-10}\) |
|             | CL6      | 8.3                         | \(10^{-10}\) |
|             | ICLN     | 7.6                         | \(10^{-10}\) |
|             | ICLS     | 2.0                         | \(10^{-9}\) |
| c-C3H2      | CL1      | 27                          | \(1.4 \times 10^{-10}\) |
|             | CL6      | 1.2                         | \(10^{-10}\) |
|             | ICLN     | 6.7                         | \(10^{-11}\) |
|             | ICLS     | 3.2                         | \(10^{-10}\) |
| HCN         | CL1      | 12                          | \(3.0 \times 10^{-10}\) |
| H2CO        | CL1      | 17                          | \(2.1 \times 10^{-10}\) |
|             | CL6      | 2.7                         | \(10^{-9}\) |
|             | ICLN     | 2.7                         | \(10^{-9}\) |
|             | ICLS     | 5.8                         | \(10^{-9}\) |
| H13CO+      | CL1      | 27                          | \(2.7 \times 10^{-11}\) |
|             | CL6      | 4.2                         | \(10^{-11}\) |
|             | ICLN     | 4.4                         | \(10^{-11}\) |
|             | ICLS     | 6.6                         | \(10^{-11}\) |
| NO          | CL1      | 17                          | \(1.3 \times 10^{-8}\) |
|             | CL6      | 2.2                         | \(10^{-8}\) |
|             | ICLN     | 1.5                         | \(10^{-8}\) |
|             | ICLS     | 5.7                         | \(10^{-8}\) |
| SO          | CL1      | 22                          | \(1.4 \times 10^{-9}\) |
|             | CL6      | 1.2                         | \(10^{-8}\) |
|             | ICLN     | 6.9                         | \(10^{-9}\) |
|             | ICLS     | 1.4                         | \(10^{-8}\) |
| SO2         | CL1      | 22                          | \(1.1 \times 10^{-10}\) |
|             | ICLS     | 9.6                         | \(10^{-10}\) |
with $a$ the sound speed, $G$ the gravitational constant and $\rho$ the density. The separation between the condensations is $\sim 50$ arcsec, which at the distance of LDN 673 corresponds to $\sim 0.073$ pc ($\sim 15,000$ au). We used the average of the densities estimated for both condensations from the continuum observations, $\sim 3.3 \times 10^4$ cm$^{-3}$, as the volume density, $n_{H_2}$, and assumed $T = 10$ K. We obtained a Jeans length value of $\sim 0.033$ pc, about two times smaller than the measured separation on the sky, and similar to the values found by Tsitali et al. (2010) for some other condensations in the region. This value of the Jeans length is also smaller than the sizes of both condensations, which is an indication that they may still be subject to more thermal fragmentation. Indeed, there is evidence of fragmentation in the CL1/SMM5 condensation, since this clump is associated with two $N_2H^+$ condensations separated by $\sim 30$ arcsec (MGE05), which corresponds to $\sim 0.044$ pc ($\sim 9000$ au), very close to the Jeans length previously estimated. On the other hand, most of the CS clumps detected by MGE05 and not traced by the 1.2-mm dust map have typical sizes of $0.04$ pc and densities of a few $\times 10^4$ cm$^{-3}$. For a density of $\times 10^4$ cm$^{-3}$ (the CL6 density), the Jeans length is $0.07$ pc. Thus, these clumps are unlikely to have been formed as a result of thermal fragmentation, and we would need to invoke non-thermal processes (turbulence, magnetohydrodynamic waves, etc.) to explain their existence (Falle & Hartquist 2002; Klessen et al. 2005; Vázquez-Semadeni et al. 2005; Van Loo et al. 2008). This would agree with the transient nature of these clumps postulated by MGE05.

### 5 DISCUSSION

#### 5.1 Fragmentation in the core

The most intense emission in the central region of the 1.2-mm dust continuum map is contained inside the HPBW of the low angular resolution NH$_3$ map of Sepúlveda et al. (2011). The BIMA observations of MGE03 also only detected $N_2H^+$ emission in a region almost coinciding with CL1/SMM5 (the other dust continuum sources lie outside the BIMA primary beam). The dust and $N_2H^+$ emissions in CL1/SMM5 are similarly elongated in an approximately north–south direction with a close proximity between both emission peaks. A second clump, located just north of CL1/SMM5 could also be present in the dust emission, but it is not so clearly seen as in the $N_2H^+$ map. The sizes of the CL1/SMM5 condensation in the continuum and molecular (CS and $N_2H^+$) maps are very similar, $\sim 0.07-0.09$ pc, but the gas mass traced by the dust is $\sim 4$ times larger than the masses estimated, assuming standard abundances, from the CS and $N_2H^+$ maps by MGE05.

We showed in Section 4.2.1 that the CS and dust emissions do not seem to be particularly correlated (see Figs 7 and 8): the most intense CS emission around CL1/SMM5 follows the edges of the most intense dust emission, and many of the clumps detected in the combined FCRAO and BIMA maps are located in regions with no or very weak dust emission. These results suggest that there is some low-density/small-size structure which is revealed by the CS lines, but it is not detected at 1.2 mm, probably because the sensitivity of our observations is not high enough or due to the spatial filtering of the chopping bolometer observations.

The SMM8 dust condensation is also coincident with relatively weaker $H^3CO^+$ and CS emission detected with the FCRAO telescope by MGE05 at the tip of a very weak NW–SE filamentary structure or thin ridge found in the molecular line maps. This filamentary structure is undetected in the dust continuum map.

In order to study the fragmentation in the core, we calculated the Jeans length corresponding to the densities of the two main dust condensations, CL1/SMM5 and SMM3, following Hartmann (1998):

$$\lambda_J = \left( \frac{\pi a^2}{G\rho} \right)^{1/2} = 0.19 \text{ pc} \left( \frac{T}{10 \text{ K}} \right)^{1/2} \left( \frac{n_{H_2}}{10^4 \text{ cm}^{-3}} \right)^{-1/2},$$  \hspace{1cm} (1)

### 5.2 The nature of the clumps and the interclump medium

The interpretation of single-point observations of molecular lines as the ones presented here has to be taken with caution, because they will never provide the same level of detail of the chemistry as a full map would. However, our choice of positions with presumed different physical conditions, coupled with the dust continuum map, provides us with a sample of molecular abundances that can show some of the properties of our core.

MGE05 already showed that CS was probably depleted in CL1, while $N_2H^+$ was clearly centrally condensed. The estimation of the CS abundance in Fig. 8 confirms this result for the SMM5, SMM3 and SMM6 dust condensations. Additionally, Table 7 shows that H$_2$CO, SO, SO$_2$ and, to a lesser extent, H$_3$CO$^+$ are also depleted for CL1 with respect to the abundances at the other positions. On the other hand, the abundances of CCH, c-C$_3$H$_2$ and CN in CL1 do not seem to differ much from the values in CL6 and ICLN. Finally, the NO abundance at CL1 is also $\sim 40$ per cent lower than the one at CL6, and similarly to what Akyilmaz et al. (2007) found in L1544, the NO molecule could be partially depleted in CL1, while $N_2H^+$ is not.

The original models of Taylor et al. (1996), Taylor, Morata & Williams (1998) and Garrod et al. (2005, 2006) required the action of depletion to obtain the distribution of molecular abundances that would explain the results of MGE03 and MGE05. As has been extensively found in different starless cores, ‘early-time’, carbon-bearing molecules would be depleted in the more central regions of evolved starless cores, wherein ‘late-time’, nitrogen-bearing molecules would still be present in the gas (see e.g. Caselli et al. 1999; Tafalla et al. 2006; Hily-Blant et al. 2010). Thus, the results for CS, $N_2H^+$, H$_2$CO, SO and H$_3$CO$^+$ are approximately as expected, given the density of the CL1/SMM5 condensation. However, the low or no depletion of CCH, c-C$_3$H$_2$ and CN is much more unexpected. Frau, Girart & Beltrán (2012) also found a similar
result in several cores of the Pipe nebula, where SO shows depletion, but c-C\textsubscript{3}H\textsubscript{2} and CCH are more intense in the cores with higher $A_{V}$.

CL6 and the interclump positions show a poorer variety of molecules compared to that of CL1. Additionally, there is little evidence of depletion of the detected molecules – the abundances of early-time molecules are usually the largest in the interclump positions – with no detection of N\textsubscript{2}H\textsuperscript{+}. All this seems to indicate that the gas in CL6, ICLN and ICLS is chemically young. The gas density in CL6 is more similar to the densities found in the interclump medium (see Section 4.1.2) than to the density in CL1. However, the number density derived for CL6 is still a factor of $\sim$3.5 larger with respect to the two interclump positions, which indicates that the physical conditions are probably different. This factor is significant and probably a lower limit to the true density contrast, because the probable contribution to the emission from nearby clumps will have the effect of measuring a density higher than the true interclump density in ICLN and ICLS (see Section 4.1.1). In any case, it seems clear that the interclump positions are denser than initially expected, probably from a few $\times 10^{3}$ to $\times 10^{4} \text{ cm}^{-3}$.

5.2.1 Comparison with models of transient clumps

In order to have a more quantitative comparison, we compared the results of our observations to the ‘standard’ model of Garrod et al. (2005, 2006). We found that this model is able to explain reasonably the chemistry of the CL6 and ICLN positions. However, we used a ‘high-density’ model that reached a higher peak density, $\sim$5.5 $\times 10^{5} \text{ cm}^{-3}$, in 10$^{4}$ yr (Garrod 2005) to match better the chemistry in CL1. We did not compare the models to ICLS due to the contamination issues discussed in Section 4.1.1. We consider that the real evolutionary properties of the gas we observed are probably between these two models and some scaling of abundances would be needed to really fit our results, which is outside the purpose of this discussion. Given the traditional difficulty of matching the values of chemical models to observations, we looked for the time ranges in which the abundances of most of the molecules in the models ($>$70 per cent) were within a factor of 3 from the observed values, in order to account for the multiple sources of uncertainties in both observations and models.

The molecular abundances in CL1 are compatible with a clump in the ‘high-density’ model in a time range of 3–7 $\times 10^{4}$ yr. HCO$^{+}$ is the main outlier, depending on the $^{12}$C/$^{13}$C abundance ratio used, and ‘late-time’ molecules, NO and SO, tend to push the time range to later times. The abundances in CL6 are better reproduced with a clump following the standard model at times either 5–9 $\times 10^{4}$ or 1.4–1.6 $\times 10^{5}$ yr. Therefore, the clump in CL6 could be very close to the peak density maximum or just past it in the dissipation phase. We also found that the results for ICLN could be compatible with a clump of 0.9–1.6 $\times 10^{5}$ yr for the standard model. This could explain the relatively low contrast in density between CL6 and ICLN, if we think that the gas in ICLN could be the remains of a clump that has almost dispersed and what we found was lower density gas enriched by the molecular abundances of previous stages. This would reinforce one of the predictions of the Garrod et al. (2006) models: the formation and dispersion of transient clumps would result in a chemistry of the gas that is generally ‘young’, except in the denser and more evolved clumps, and a gas chemical composition that would show signs of ‘enrichment’ of abundances of some molecular species in the lower density material.

Garrod et al. (2006) also showed that a distribution of transient clumps at different stages of evolution (different points in time) could qualitatively reproduce the medium and high angular resolution maps of MGE03 and MGE05. Our results here suggest that those clumps could not only be in different stages of evolution, but also reach different peak densities, i.e. follow different evolutionary patterns. The mix of clumps with different evolutionary properties can shed a different light on the discussion about the molecular depletion between different clumps. We found that, for the times best fitted by the models, the differences in the abundances of CCH, c-C\textsubscript{3}H\textsubscript{2} and CN between the ‘high-density’ and ‘standard’ models are considerably smaller than for later time molecules, such as NO. This would simply explain the apparent low or no depletion of the former molecules compared to the latter.

6 CONCLUSIONS

We studied the properties of the clump and interclump gas in the CS starless core of LDN 673 using the 30-m IRAM telescope through the emission of several spectral lines in the 3-, 2- and 1-mm bands, in four positions associated with already detected, but physically and chemically different, clump gas (positions CL1 and CL6), or with interclump gas (positions ICLN and ICLS). We detected 19 spectral transitions of 10 molecular species at least in one of the four positions. We complemented the spectral observations with the mapping of the 1.2-mm dust continuum emission in LDN 673, which allowed us to obtain a more reliable estimate of the volume density of the gas and of the abundances of the detected molecules. The main results of our study are the following.

(i) The dust continuum observations revealed four emission condensations in the region, roughly coinciding with submillimetre sources found by Visser et al. (2002), three of them with a round shape and centrally peaked emission: CL1/SMM5 is the most intense and coincides with the N\textsubscript{2}H\textsuperscript{+} clump found by MGE03; SMM3, located $\sim$50 arcsec to the west, was not previously found in the molecular observations; and SMM8, located $\sim$2.5 arcmin SE of the centre of the map, and coinciding with an emission enhancement in the C\textsubscript{3}H\textsubscript{2} and H\textsuperscript{13}CO$^{+}$ maps of MGE05. Finally, there is a more diffuse emission strip extended E–W $\sim$2 arcmin north of CL1/SMM5. The masses of these condensations range from 1.6 to 5.1 M\textsubscript{O} and sizes from 0.05 to 0.07 pc. The northern condensation is sensibly more diffuse.

(ii) We made a radiative transfer analysis using the RADEX code to determine the molecular column densities, volume density and kinetrical temperature at each position. The best fits to our observations found $T_{k} \simeq 10$ K for the CL1 and CL6 positions and $T_{k} \simeq 20$ K for the ICLN and ICLS positions, and volume densities ranging from $\sim$3.6 $\times 10^{5} \text{ cm}^{-3}$ at CL1 to $\sim$1.7 $\times 10^{5} \text{ cm}^{-3}$ at ICLS.

(iii) CL1 presents the largest column densities for most of the molecules (H\textsuperscript{13}CO$^{+}$, c-C\textsubscript{3}H\textsubscript{2}, CCH, CN and NO), but the smaller column densities for H\textsubscript{2}CO and SO. The estimated molecular abundances of most of the molecules are smallest at CL1, while the abundances at CL6 and ICLN tend to be very similar.

(iv) The comparison of the dust continuum emission to previous interferometer and single-dish observations shows very little or no correlation between the CS (2--1) and the 1.2-mm emissions, with most of the clumps found in the CS emission not detected in the continuum observations. On the other hand, the dust continuum and N\textsubscript{2}H\textsuperscript{+} emissions are much more similar.

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The chemistry of CL1 appears to be much more evolved than for the other positions, with signs of not only depletion of several molecular species (CS, H$_2$CO, SO, H$_{13}$CO$^+$ and partially NO), but also relatively unexpected high abundances of CCH, c-C$_3$H$_2$ and CN. The density contrast between CL6 and the two interclump positions, which are denser that initially expected, is relatively low. The gas at the CL6 and interclump positions seems to be generally chemically ‘young’.

In summary, the central condensation, CL1/SMM5, is probably approaching the ‘peak-time’ state of the models of Garrod et al. (2005, 2006), and it is also the place with a larger probability of future undergoing of star formation (see MGE05). The SMM3 condensation is probably in a very similar state, from its shape and gas density, but we cannot firmly determine it until further observations provide us with more information about its chemistry. The low density contrast between CL6 and the interclump positions and their similar young chemical age seem to support the idea of the presence of lower density transient clumps in the core as proposed by Garrod et al. (2006).

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APPENDIX A: LINE PARAMETERS OF THE OBSERVED LINES

Tables A1–A4 (online-only; see Supporting Information) show the line parameters obtained using a Gaussian fit for the transitions detected in the CL1, CL6, ICLN and ICLS positions, respectively. Each table lists the molecular species and transition and the four parameters resulting from the Gaussian fit: line intensity (in main-beam units), central velocity of the line, linewidth and intensity integrated under the Gaussian.

Table A5 (online-only; see Supporting Information) shows the hyperfine structure fit parameters, obtained using the HFS method of the CLASS package, for the CN, CCH and NO transitions detected at 3 mm. The table lists position, molecular species and transition, $\Delta v$, central velocity of the hyperfine line of reference and optical depth of this line.
Finally, Table A6 (online-only; see Supporting Information) gives the $3\sigma$ upper limits for the line intensities of the transitions not detected at each position.

**APPENDIX B: DETERMINATION OF THE BEST-FITTING SOLUTIONS USING THE RADEX MODELLING**

**B1 Method for multiple-line-detected molecules**

We used for our calculations the line intensities, $T_{mb}^{i}$, of H$_2$CO, H$^{13}$CO$^+$ and SO, which have at least three observed transitions at each of the four positions. We ran a grid of RADEX models using the following ranges in temperature, volume density and molecular column density: $T_k = 10$–30 K; $n$(H$_2$) = $10^3$–$10^5$ cm$^{-2}$; and $N$(X) = $10^{11}$–$10^{15}$ cm$^{-2}$. For each set of temperature, volume density and column density values, RADEX provides the line intensity for each $i$ transition, $T_{rx}^i$. The expected, or calculated, mean beam temperature is given by

$$T_{cal}^i = T_{rx}^i \eta_{ibl},$$

where $\eta_{ibl}$ is the beam filling factor of the $i$-transition. Assuming a 2D Gaussian distribution for the source emission profile, the filling factor can be expressed as

$$\eta_{ibl} = \frac{\theta_s^2}{\theta_s^2 + \theta_{mb}^2},$$

where $\theta_{mb}$ is the FWHM of the antenna main beam at the frequency of the $i$-transition and $\theta_s$ is the FWHM source size.

We obtained the ‘best-fitting model’ after searching for the minimum of the reduced $\chi^2$ function (Nummelin et al. 2000), $\chi^2_n$, resulting from comparing the measured and calculated line intensities and line intensity ratios for the three aforementioned molecules:

$$\chi^2_n = \frac{1}{n-p} \sum_{k=1}^3 \left[ \left( \frac{R_{obs}^{12k} - R_{calc}^{12k}}{\sigma_{12k obs}} \right)^2 + \left( \frac{R_{obs}^{13k} - R_{calc}^{13k}}{\sigma_{13k obs}} \right)^2 \right]$$

where $R_{calc}^{12k}$ is the observed line intensity of the lowest frequency transition (which is usually the best determined) of the $k$ molecule, $R_{obs}^{ij/k}$ is the observed line intensity ratio between the $i$ and $j$ transitions of the $k$ molecule, $\sigma_{12k obs}$ is the $1\sigma$ uncertainty associated with the observed line intensity of the lowest frequency of the $k$ molecule, $\sigma_{13k obs}$ is the uncertainty associated with $R_{obs}^{ij/k}$, $n$ is the number of data points and $p$ is the number of free parameters. The calc subindices indicate the equivalent values for the line intensities derived with RADEX. For the undetected transitions, we only included in our calculations the intensities from RADEX that were larger than or equal to, within errors, the observed ones.

Since the real size of the emitting area at each position was unknown, we used two sets of values of filling factors in our analysis: $\eta_{ibl} \approx 1$, obtained by choosing $\theta_s = 1000$ arcsec, and $\eta_{ibl} < 1$. For the second case, we tested values between 30 arcsec, similar to the beam size at 3 mm, and 50 arcsec, the deconvolved size of the CL1/SMM5 dust condensation as well as the size of the CL6 clump derived by MGE05.

**B2 Method for the rest of molecules**

Following a method similar to the one described in Section B1, but fixing the values of $n$(H$_2$), $T_k$ and $\theta_s$ to the best-fitting values determined for each position, we looked for the best set of values of column density, $N$, excitation temperature, $T_{ex}$, and line opacity, $\tau$, for the rest of molecules.

We did not follow this method for the CCH lines, because the collisional rates for this molecule are still unknown (see e.g. Padovani et al. 2009), nor for the CN and NO transitions, because the RADEX code does not take into account the hyperfine line structure, which in this case ends up underestimating the opacity of the lines. Instead, we calculated $T_{ex}$ and $\tau$ of the lines from the simultaneous fitting of the hyperfine components. In this last case, we assumed a beam filling factor, $\eta = 1$.

**SUPPORTING INFORMATION**

Additional Supporting Information may be found in the online version of this article:

- **Table A1.** Line parameters for the transitions detected in clump 1 (CL1).
- **Table A2.** Line parameters for the transitions detected in clump 6 (CL6).
- **Table A3.** Line parameters for the transitions detected in interclump north (ICLN).
- **Table A4.** Line parameters for the transitions detected in interclump south (ICLS).
- **Table A5.** Line parameters for the transitions with hyperfine structure.
- **Table A6.** Line intensity $3\sigma$ upper limits for the transitions not detected.

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