

The rich molecular environment of the luminous blue variable star AFGL 2298^{★,★★}

J. R. Rizzo^{1,2} , C. Bordiu³ , C. Buemi³ , P. Leto³ , A. Ingallinera³ , F. Bufano³, G. Umana³,
L. Cerrigone⁴, and C. Trigilio³ 

¹ ISDEFE, Beatriz de Bobadilla 3, 28040 Madrid, Spain

² Centro de Astrobiología (CSIC-INTA), Ctra. M-108, km. 4, 28850 Torrejón de Ardoz, Spain
e-mail: ricardo.rizzo@cab.inta-csic.es

³ INAF – Osservatorio Astrofisico di Catania, Via Santa Sofia 78, 95123 Catania, Italy

⁴ Joint ALMA Observatory, Alonso de Córdova 3107, Vitacura, 8320000 Santiago, Chile

Received 23 May 2023 / Accepted 17 July 2023

ABSTRACT

Context. Luminous blue variable (LBV) stars represent a short-lived stage in the late evolution of the most massive stars. Highly unstable, LBVs exhibit dense stellar winds and episodic eruptions that produce complex circumstellar nebulae, the study of which is crucial for properly constraining the impact of these sources at a Galactic scale from a structural, dynamical, and chemical perspective. **Aims.** We aim to investigate the molecular environment of AFGL 2298, an obscured Galactic LBV that hosts a highly structured circumstellar environment with hints of multiple mass-loss events in the last few 10^4 a.

Methods. We present spectral line observations of AFGL 2298 at 1 and 3 mm performed with the IRAM 30 m radio telescope.

Results. We report the detection of several carbon- and nitrogen-bearing species (CO , ^{13}CO , C^{18}O , C^{17}O , HCO^+ , HCN , HNC , H^{13}CO^+ , CN , N_2H^+ , and C_2H) in the surroundings of AFGL 2298. We identified three velocity components that clearly stand out from the Galactic background. The morphology, kinematics, masses, and isotopic ratios, together with a comparative study of the fractional abundances, lead us to suggest that two of these components (36 and 70 km s^{-1}) have a stellar origin. The other component (46 km s^{-1}) most likely traces swept-up interstellar material, and probably also harbours a photon-dominated region.

Conclusions. We provide the first inventory of the circumstellar molecular gas around AFGL 2298. Our results are compatible with the hypothesis of former mass-loss events produced before the one that created the infrared nebula. The chemistry of this LBV suggests the presence of ejected stellar material, and also swept up gas. These findings will help us to better understand the mass-loss history of this class of evolved massive stars, which is important given that they heavily influence the overall chemical evolution of the Galaxy.

Key words. circumstellar matter – stars: evolution – stars: individual: AFGL 2298 – stars: mass-loss – ISM: molecules

1. Introduction

The late evolutionary stages of massive stars play a key role in the structural, dynamical, and chemical evolution of the Galaxy, releasing vast amounts of matter and radiative and mechanical energy into their surroundings (Langer 2012). In this context, the luminous blue variable phase (hereafter LBV), a brief interlude of just a few 10^4 a, is of particular interest, as it is responsible for a substantial fraction of the total mass loss. LBV stars are intrinsically variable and highly unstable objects that expel several solar masses of CNO processed material through steady, dense winds (typically from several 10^{-6} to few $10^{-4} M_{\odot} \text{ a}^{-1}$) and episodic outbursts that rip off the outermost stellar layers on timescales as short as a few years (Humphreys & Davidson 1994). All these physical processes create large and heterogeneous circumstellar nebulae of dust and gas, which are usually N-rich and C- and O-deficient (Lamers et al. 2001). The study

of these nebulae is therefore a potentially useful tool for reconstructing the mass-loss history of the central star.

Since their identification as excellent laboratories in which to investigate the interplay between evolved massive stars and the interstellar medium (ISM), LBV nebulae have been the target of numerous observational campaigns at infrared and radio continuum wavelengths, tracing their dust and ionised gas content (Waters et al. 1999; Duncan & White 2002; Umana et al. 2005, 2009, 2010). These efforts have provided valuable insights into energetic budgets, mass-loss rates, nebular composition, and dynamics. However, many questions remain unanswered: the phenomenology that triggers the eruptions is not totally understood, and the mechanisms that shape the expelled material (e.g. interaction with a binary companion, nearly critical rotation, magnetic fields) are yet to be fully established. The scarce number of LBVs, with approximately 60 members identified in the Galaxy (of which only ~ 20 are genuine LBVs, i.e., sources for which S Dor variability has been confirmed; Richardson & Mehner 2018), further complicates any general conclusions.

Over the past two decades, molecular spectroscopy has provided new possibilities to learn about LBVs and their mass-loss processes. Despite the harsh conditions to which the outskirts of these stars are exposed (strong and variable far-UV radiation beyond the Lyman limit and high temperatures), substantial

* Data used for the article (reduced spectra, data cubes, and model results) are available at the CDS via anonymous ftp to cdsarc.cds.unistra.fr (130.79.128.5) or via <https://cdsarc.cds.unistra.fr/viz-bin/cat/J/A+A/678/A55>

** This work is based on observations carried out under project number 043-17 with the IRAM 30 m telescope. IRAM is supported by INSU/CNRS (France), MPG (Germany), and IGN (Spain).

amounts of molecular gas have been detected around a handful of LBVs (see e.g., Rizzo et al. 2008; Loinard et al. 2012; Gull et al. 2020). This molecular component is believed to be a tracer of eruptive events, either being ISM material compressed by the expanding shock, or molecular gas formed in situ from the CNO-processed ejecta. In both scenarios, the distribution, kinematics, and chemistry of the molecular gas shed light on key evolutionary aspects of the central star. For instance, slowly expanding, equatorial molecular rings of CO have been reported around [GKF2010] MN101 (Bordiu et al. 2019) and AG Car (Bordiu et al. 2021), displaying low $^{12}\text{CO}/^{13}\text{CO}$ isotopic ratios, a clear indicator of CNO processing. These equatorial structures trace strong deviations from spherical symmetry, either due to binary interactions, or nearly critical rotation of the central star, which is the case for several LBV stars (Groh et al. 2009, 2011). On the other hand, more symmetric arrangements are found in other LBV sources (e.g., G79.29+0.46, Rizzo et al. 2008; Agliozzo et al. 2014, and [GKF2010] MN48, Bordiu et al., in prep.) in the form of shells, which match the distribution of circumstellar dust; these structures are probably the result of the accumulation of ambient gas after an isotropic wind and/or mass eruption event.

However, the molecular inventory of LBV nebulae is incomplete, in most cases limited to CO and its main isotopologues, with the notable exceptions of G79.29+0.46, where NH_3 and C_3H_2 have also been detected (Rizzo et al. 2014; Palau et al. 2014); and η Car, which hosts a rich molecular chemistry, with confirmed detection of multiple C-, N-, and O-bearing species (Loinard et al. 2012; Bordiu & Rizzo 2019; Gull et al. 2020; Morris et al. 2020) and, more recently, of Si-bearing molecules (Bordiu et al. 2022).

AFGL 2298 (=IRAS 18576+0341) is a particularly good candidate to host important amounts of molecular gas. This blue supergiant was first proposed as a candidate member of the LBV class by Ueta et al. (2001), owing to the discovery of an extended dusty shell of ~ 7 arcsec through mid-IR observations, with morphological features compatible with an equatorially enhanced mass-loss episode. Its LBV status was further reinforced (Pasquali & Comerón 2002) and eventually confirmed (Clark et al. 2003) on the basis of multi-epoch spectroscopic and photometric observations, which revealed spectral features typical of LBV spectra and hints of S-Dor variability. Clark et al. (2003) determined T_{eff} variations between 12.5 and 15 kK in the period 2001–2002, with mass-loss rates ranging from 5×10^{-5} to $1.2 \times 10^{-4} M_{\odot} \text{ a}^{-1}$ at a roughly constant bolometric luminosity of $\log(L/L_{\odot}) = 6.2$. These values were in close agreement with independent estimates by Umana et al. (2005) from multi-band VLA observations. Later, Clark et al. (2009) combined archival observations with the results of a long-term monitoring campaign (2001–2008) and reported significant bolometric variability for the first time, which the authors interpreted as the result of an outburst instead of a typical S-Dor excursion. High-resolution VLA and VLT observations (Buemi et al. 2010) provided an unprecedented view of the nebula around AFGL 2298 and revealed a rather homogeneous dusty shell coexisting with a strongly asymmetric ionised envelope. In the same study, even more interesting is the discovery of polycyclic aromatic hydrocarbons (PAHs), also asymmetric but with a morphological distribution totally different from that in the ionised gas. Despite this finding regarding the PAHs, the molecular content of AFGL 2298 remains relatively unexplored.

In this paper, we present a comprehensive study of the molecular environment of AFGL 2298 at millimetric wavelengths. In Sect. 2, we describe the observations; the main results are

outlined in Sect. 3; in Sect. 4 we place our findings in the wider context of LBV circumstellar chemistry, and derive the physical parameters of the gas and the abundances of the observed species. Finally, in Sect. 5 we present the conclusions of this work and lay out some aims for follow-up studies.

2. Observations

AFGL 2298 was observed with the IRAM-30 m radio telescope of the Institut de RadioAstronomie Millimétrique in Granada (Spain) as part of project P043-17 (PI: C. Bordiu). Observations took place on the nights of 2017 July 23 and 25 under good summer conditions ($\tau_{225} \sim 0.2$). We used the EMIR multi-band receiver at its 3 and 1 mm bands (E090 and E230, respectively).

We selected the FTS backend, which provided an instantaneous bandwidth of 4 GHz per polarisation, with approximate channel widths of ~ 0.25 and $\sim 0.5 \text{ km s}^{-1}$ at 3 and 1 mm, respectively. The main goal was to simultaneously map the distribution of the $J = 1 \rightarrow 0$ and $J = 2 \rightarrow 1$ transitions of CO and its most abundant isotopologues. Additionally, we took advantage of the large bandwidth of the FTS backend in different spectral setups to cover all the rotational transitions indicated in Table 1.

The observing strategy involved on-the-fly (OTF) maps in position-switching mode, covering a square region of 1.5×1.5 arcmin around AFGL 2298. Mapping was done in a zigzag pattern along two orthogonal directions, with a speed of 3 arcsec per second, and using a Nyquist-compliant subscan spacing of 4.3 arcsec. The reference position was located ~ 20 arcmin away from AFGL 2298, to minimise contamination from background or foreground diffuse emission. The total scan time was ~ 2 h. In addition, two deep integrations of ~ 45 min were performed towards the star position and a random control position offset by (40, -30) arcsec from the star. At the time of observation, no small planet or strong quasar was observable close to the target, and so Saturn was used instead for initial pointing and focus. In any case, we used the quasar 1749+046 – the closest in projection to AFGL 2298 – for pointing in the vicinity of the source, reaching an accuracy of greater than 5 arcsec. G34.3+0.2 was used as a line calibrator. Pointing was regularly checked during the observations, and calibrations were done between consecutive OTF runs.

The resulting calibrated spectra were then processed using the GILDAS software package. Spectra were first deplatformed (when needed) and baseline subtracted, and then combined to generate position-position-velocity data cubes for each transition and species. In this work, we adopt the following conventions: (1) spectra are presented in T_{A}^* scale unless noted otherwise; (2) velocities refer to the local standard of rest (LSR) frame; and (3) positions are given as offsets from the J2000 coordinates of AFGL 2298, which are $(\alpha, \delta) = (19^{\text{h}}00^{\text{m}}10.9^{\text{s}}, +3^{\circ}45^{\text{m}}47.2^{\text{s}})$.

3. Results

3.1. Velocity ranges of interest

The $J = 1 \rightarrow 0$ and $2 \rightarrow 1$ lines of CO and its most abundant isotopologues (^{13}CO , C^{18}O , and C^{17}O) towards the star position are depicted in Fig. 1. Because of the location in the first quadrant of the Galactic plane, the CO emission is complex and spreads over a wide range of positive velocities. As the tangent point velocity is around 90 km s^{-1} (Brand & Blitz 1993; Reid et al. 2014), no forbidden velocities are found.

As expected, all the velocity components fade or disappear when going from high- to low-abundance isotopologues (from

Table 1. Rotational transitions of the molecules observed.

Molecule	Transition	Frequency (GHz)	E_{up} (K)	HPBW (arcsec)
CO and isotopologues				
CO	$J = 1 \rightarrow 0$	115.271202	5.5	21.3
	$J = 2 \rightarrow 1$	230.538000	16.6	10.7
^{13}CO	$J = 1 \rightarrow 0$	110.201354	5.3	22.3
	$J = 2 \rightarrow 1$	220.398684	15.9	11.2
C^{18}O	$J = 1 \rightarrow 0$	109.782173	5.3	22.4
	$J = 2 \rightarrow 1$	219.560354	15.8	11.2
C^{17}O	$J = 1 \rightarrow 0$	112.358982	5.4	21.9
	$J = 2 \rightarrow 1$	224.714187	16.2	10.9
Other molecules				
HCO^+	$J = 1 \rightarrow 0$	89.188525	4.3	27.6
HCN	$J = 1 \rightarrow 0$	88.631848	4.3	27.8
HNC	$J = 1 \rightarrow 0$	90.663568	4.4	27.1
H^{13}CO^+	$J = 1 \rightarrow 0$	86.754288	4.2	28.4
CN	$N = 1 \rightarrow 0$	113.191278	5.4	21.7
	$J = 1/2 \rightarrow 1/2$			
	$N = 1 \rightarrow 0$	113.490970	5.4	21.7
N_2H^+	$J = 1 \rightarrow 0$	93.173770	4.5	26.4
	$N = 1 \rightarrow 0$	87.316925	4.2	28.2
	$J = 3/2 \rightarrow 1/2$			
C_2H	$N = 1 \rightarrow 0$	87.402004	4.2	28.1
	$J = 1/2 \rightarrow 1/2$			
	$N = 1 \rightarrow 0$			

Notes. Angular resolutions (HPBW) computed as $2460/\text{frequency}$, according to the IRAM web pages (<https://publicwiki.iram.es/Iram30mEfficiencies>). As C^{17}O , HCN , CN , N_2H^+ and C_2H have hyperfine splitting, the quoted frequencies correspond to the most intense hyperfine component.

top to bottom in Fig. 1). The observed $J = 2 \rightarrow 1$ to $1 \rightarrow 0$ line ratios are mostly lower than 1, as usual in cold Galactic clouds.

The two most intense components at $32\text{--}38\text{ km s}^{-1}$ (hereafter component A) and at $44\text{--}50\text{ km s}^{-1}$ (hereafter component B) depart from this trend and display a $J = 2 \rightarrow 1$ intensity comparable to or higher than their corresponding $J = 1 \rightarrow 0$ one. These two components are also those that remain in the C^{18}O $J = 2 \rightarrow 1$ and C^{17}O lines. Component A is less intense and broader than component B, with some asymmetry and a ‘shoulder’ at the most positive velocities ($47\text{--}50\text{ km s}^{-1}$). Component B is nearly Gaussian and considerably narrow.

Figure 2 displays all the CO isotopologues towards AFGL 2298 and the control position. As a first approach, their mutual comparison would help us to disentangle the velocity components probably related to the target star. Component A is broadly present in the two positions. However, it systematically peaks at a lower velocity at the star position than at the control position. The difference, noted only in this component and across all the isotopologues, may be ascribed to the presence of an additional feature related only to the star. On the contrary, the much narrower component B is evident only in the pointing towards the star. A third component (approximately at 70 km s^{-1}) is solely detected at the star position, and is totally absent at the control position. We hereafter refer to this feature as component C.

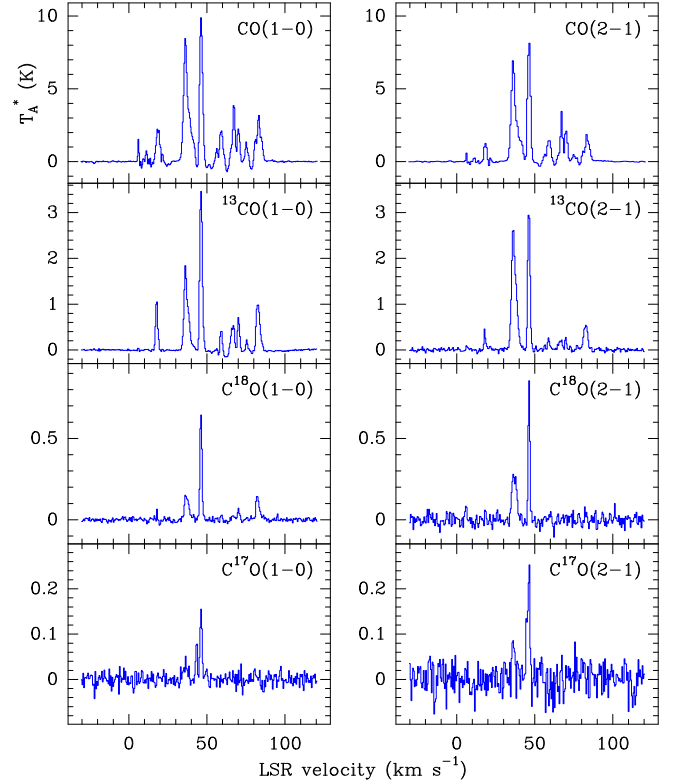


Fig. 1. CO and isotopologues in the direction of AFGL 2298. The species and their corresponding rotational lines are indicated in the upper-left corner of each spectrum. All spectra are displayed at the same velocity range. To ease a comparison, the $J = 1 \rightarrow 0$ (left column) and the $2 \rightarrow 1$ (right column) lines are plotted on the same intensity scale. The most intense components, roughly at 38 and 46 km s^{-1} (components A and B, see text) are the only ones present in all the lines. The C^{17}O lines have hyperfine structure, which is noted in the splitting at component B.

Components B and C are clearly different in the two positions, which points to a possible relationship with the star. Although component A is more ubiquitous, the $J = 2 \rightarrow 1$ to $1 \rightarrow 0$ line ratio is rather high and the line has some velocity structure; therefore, part of this extended component may also be affected by some interaction with the nebula and is not fully discarded. In the following sections, we concentrate our study on the three components identified.

3.2. Distribution of the CO gas

In order to obtain more precise insights into the spatial distribution of the three components, we integrated the lines over their velocity extension. The results for the four $J = 2 \rightarrow 1$ lines of the CO isotopologues are depicted in Fig. 3. The corresponding $J = 1 \rightarrow 0$ lines display similar characteristics, although with poorer angular resolution.

Component A is relatively extended over the entire region, with increasing intensity towards the northeast. Overall, it resembles a typical interstellar Galactic cloud, without any evident features associated with the target star. However, in more detailed channel maps, a relative maximum of emission – at $10\text{--}15$ arcsec from the centre – is detached from the general emission. This feature is consistent with the velocity difference noted already in the previous subsection.

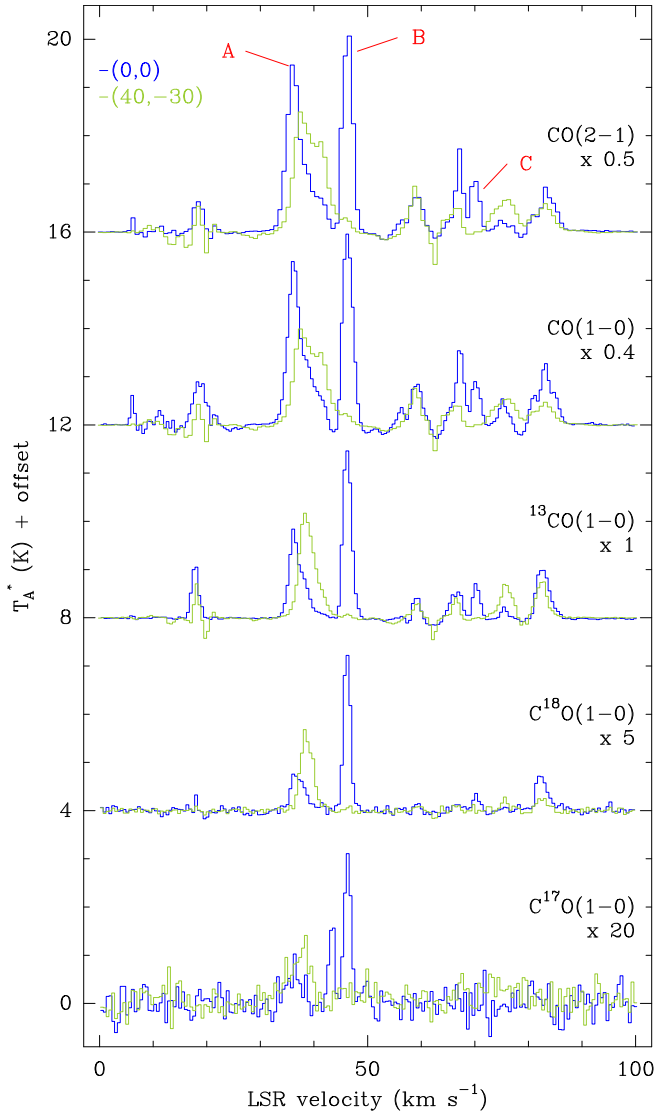


Fig. 2. Comparison of spectra observed at the star position and a control position outside the IR nebula. The star position is plotted in blue, while the control position is in green. Different velocity components considered in this article are marked in red. The most remarkable features are the difference in the peak velocities in component A, and the lack of emission at the control position from components B and C.

Contrarily, although the peak is not coincident with the star, component B has a certain symmetry with respect to the star position. Overall, the component depicts an arc-like feature around the IR nebula, extending approximately from northeast to south.

Component C is round and compact, and it is clearly centred at ~ 15 arcsec to the southwest of the hot star. Despite its small angular scale, this component is not a point source, as can be seen from a comparison of the 50% contour and the half power beam width (hereafter HPBW).

Finally, it is worth noting that the intensity distribution is slightly different among the isotopologues, meaning that the kinematic components are stratified. This is particularly evident for component B, when comparing the positions of the relative maxima in Fig. 3: ^{13}CO , C^{18}O , and C^{17}O are located closer to the star within the inner rim of the arc-like feature defined by CO, and also extending over a more limited angle. In addition, the

relative maxima of C^{18}O and C^{17}O appear anti-correlated. Such a spatial distribution suggests chemical stratification towards the northwest, which turns out to be one of the ‘preferential’ directions of AFGL 2298 (see Sect. 4.2).

3.3. Other molecules detected

As mentioned in Sect. 2, the large bandwidth of EMIR allowed us to observe some of the most simple molecules in addition to the CO isotopologues (Table 1). We carried out deep integrations towards the star position, and also on-the-fly maps covering roughly 90 arcsec around AFGL 2298.

Figure 4 depicts the resulting spectra of these molecules towards the star position. For those molecules with hyperfine splitting, red lines indicate the positions and relative sizes of their components. The most intense lines are HCO^+ and HCN , two of the most abundant molecules in all environments besides H_2 and CO.

Both components A and B are present in all the spectra, except N_2H^+ , where component B is not detected. Component C, on the other hand, is not detected in any of the nine molecular lines, which is probably due to insufficient sensitivity. As in the case of the CO isotopologues, component A appears wider than component B. Notably, the relative intensities of these two components are different for each molecule: component A is more intense in HCO^+ , HCN , HNC , and N_2H^+ , and is similarly or even less intense in the others (see the case of CN in the central panel).

The maps are rather noisy and with poor angular resolution, but are sufficient to provide us with a rough idea of the distribution of the seven molecules, especially for component A. Detailed maps – integrated in the velocity ranges of the three components – are provided in the Appendix. Component A is well traced by several molecules, and depicts different distributions, preferentially to the north and the east of the mapped region. Component B is detected with high S/N only in HCO^+ , HCN , HNC , and the most intense CN and C_2H transitions ($N = 1 \rightarrow 0; J = 3/2 \rightarrow 3/2$ in both cases), with a morphology roughly similar to the CO isotopologues. The non-detection of H^{13}CO^+ and N_2H^+ is consistent with the results obtained in the deep on-source integrations described above. In any case, it should be stressed that the angular resolution and the noise level of the maps are not sufficient to firmly establish morphological differences among the observed molecules.

3.4. Kinematics

The kinematics of the velocity components may, in principle, be inferred from position–velocity (PV) plots. In this case, the most adequate molecule for studying the structure in velocity is ^{13}CO because it is less affected by Galactic contamination than CO and, at the same time, shows sufficient intensity to clearly distinguish the three components. Figure 5 displays two ^{13}CO $J = 2 \rightarrow 1$ PV plots in orthogonal directions: panel a from northeast to southwest includes both the peak of component A and the whole component C, and panel b, which crosses the component B.

In the first PV plot, component C again appears as a compact and weak feature located just outside the IR nebula (roughly traced by the vertical yellow lines). It is also notable that, as opposed to component C, the emission from 38 to 40 km s^{-1} in component A is concentrated at the northeast. In the second PV plot, it is possible to note that, as inferred also by the

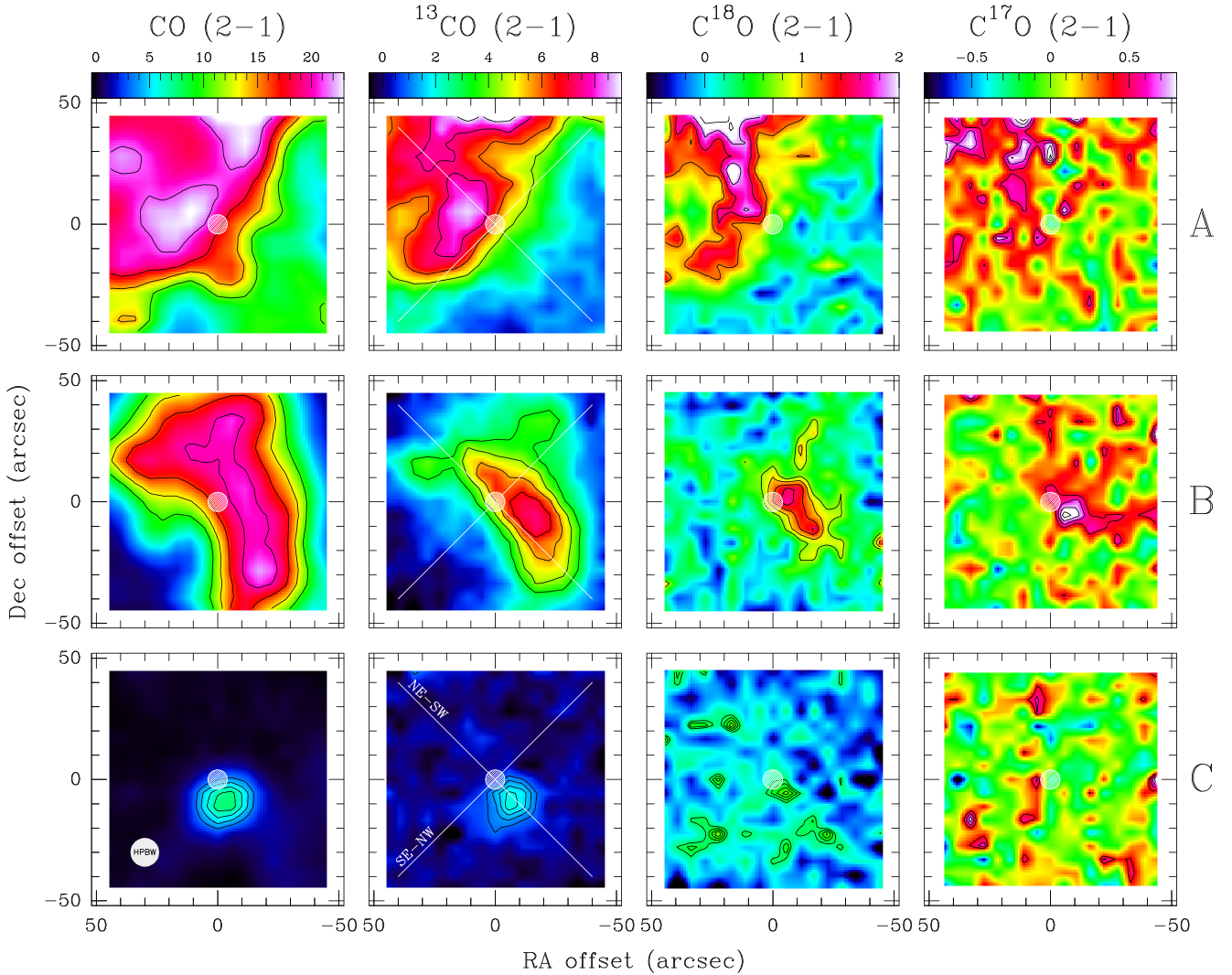


Fig. 3. Overview of the intensity distribution of the analysed components. Top, middle, and bottom rows correspond to components A, B, and C, respectively. Velocity ranges of integration are (35, 38), (45, 48), and (69, 72) km s⁻¹. Spectral lines are indicated above the top maps. Equatorial coordinates are relative to the star position. The colour scale is the same for all three components of a given molecule, and is indicated in the top panels in units of K km s⁻¹. Contours are 45%, 60%, 75%, and 90% of the peak values. The white circle sketches the position and size of the IR nebula. The HPBW is indicated in the bottom-left corner of the CO(2-1) map of component C. The white lines plotted onto the ¹³CO maps indicate the direction of the *PV* plots of Fig. 5.

previous figures, component B seems more concentrated towards the centre of the field.

Despite the interesting nature of these results, we are far from disentangling the dynamics of the molecular gas due to an evident lack of angular resolution. This source is indeed an excellent target to be observed by interferometry due to its richness in molecular species and also because it hosts several molecular lines with relatively high intensities.

4. Discussion

4.1. Distance to AFGL 2298

The first estimate of the distance to AFGL 2298, of namely 10 ± 3 kpc, was provided by Ueta et al. (2001). This ample range is the necessary to fit the observed IR features in the nebula, under the assumption of a LBV nature for the exciting star. Despite the large uncertainty, subsequent works continued assuming 10 kpc due to different observational constraints which

prevented further estimates (Clark et al. 2003, 2009; Buemi et al. 2010).

The stellar light is highly absorbed by interstellar extinction and also by extinction from the surrounding nebula. At visual wavelengths, we searched in the literature and the catalogues using VizieR¹, and only found firm measurements from Pan-STARRS (objID 112512850453746126; Chambers et al. 2016), and only in the *z* and *y* bands, with apparent magnitudes of 20.4 ± 0.1 and 17.5 ± 0.1 mag, respectively. AFGL 2298 is not included in any release of the *Gaia* mission (Gaia Collaboration 2016, 2018, 2023), and so it is not possible to obtain any distance estimate by direct measurement of its parallax.

One of the indirect methods to assign a distance is by establishing a membership to a stellar cluster or association with known distance. By combining high-resolution IR spectroscopy and high-sensitivity photometry from 2MASS and UKIDSS, Ramírez Alegría et al. (2018) reported the existence of a stellar

¹ <https://doi.org/10.26093/cds/vizier>

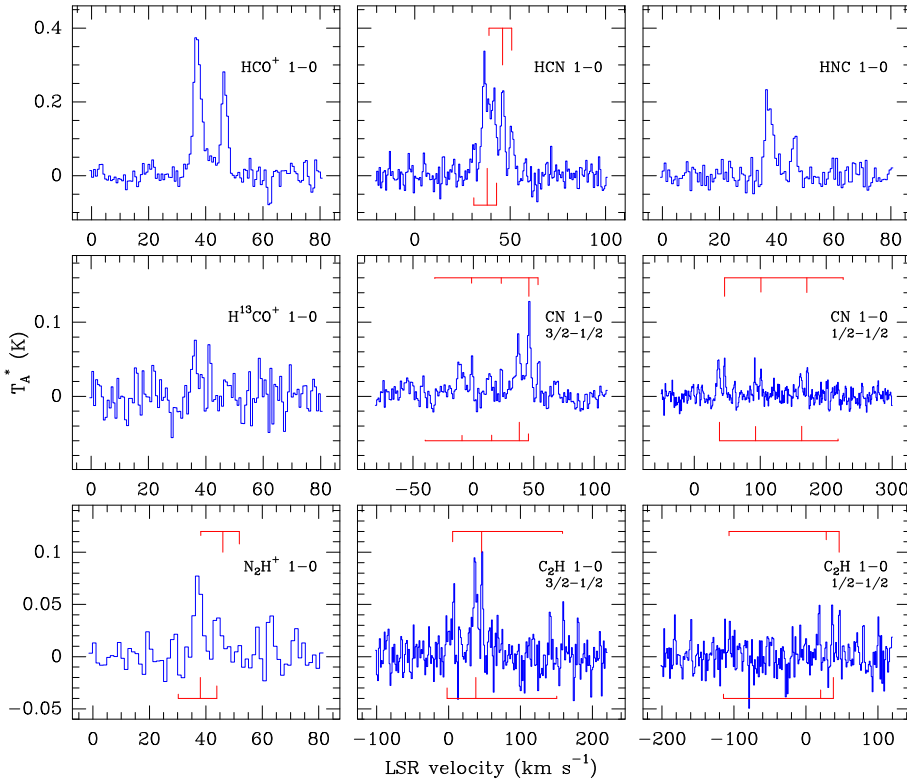


Fig. 4. Other molecules detected in the direction of AFGL 2298. Molecules and transitions are indicated inside each spectrum. We note that different velocity ranges are depicted, and that the temperature scale is kept the same for each row. In the case of molecules with hyperfine splitting, the positions and relative intensities are indicated by the red lines below (above) the spectrum, for velocities of 36 (46) km s^{-1} .

population – Masgomas-6b – at a distance of 9.6 ± 0.4 kpc, which includes AFGL 2298 as a member.

Interestingly, [Ramírez Alegría et al. \(2018\)](#) also report 65 km s^{-1} as the mean velocity of Masgomas-6b, although AFGL 2298 does not contribute to this value. The velocity of Masgomas-6b is also consistent with its quoted distance: according to the Galactic rotation model of [Reid et al. \(2014\)](#), the LSR velocity of Masgomas-6b corresponds to a far distance of $9.3^{+1.2}_{-1.9}$ kpc.

Another key result to better constrain the distance is the detection of radio recombination lines (RRLs) reported by [Anderson et al. \(2015\)](#) in their survey of WISE sources with IR features consistent with HII regions². We searched the catalogue using Vizier (catalogue J/ApJS/221/26/table4) and identified the source G037.277-00.226 as the ionised counterpart of AFGL 2298, with two LSR velocities reported: 41.8 ± 0.2 and $77.7 \pm 0.9 \text{ km s}^{-1}$. The first velocity lies in the middle of those corresponding to components A and B, while the second one is shifted by $\sim 8 \text{ km s}^{-1}$ from that corresponding to component C. In the same archive, the quoted kinematic distances correspond to 41.8 km s^{-1} , with near and far distances of 2.8 and 10.7 kpc, respectively. The distance ambiguity is solved in favour of the far distance in order to maintain consistency with the electron temperature derived from their own continuum observations.

The kinematic distances associated with components A and B, in very good agreement with all the results previously discussed, reinforce the link between these components and our target star. The velocity range from 37.3 to 47.9 km s^{-1} translates to a distance range of 10.3 to 10.9 kpc using the model of [Reid et al. \(2014\)](#) as before. Taken altogether, our CO data are therefore consistent with a kinematic distance of 10.6 ± 0.4 kpc.

In summary, Table 2 shows all the individual distance estimates, together with their uncertainties. The photometric distance from [Ramírez Alegría et al. \(2018\)](#) allows us to definitely adopt the far kinematical distance, which is reliably established as 10.1 ± 0.6 kpc, as indicated in the last row of the table.

4.2. Molecular gas related to the star

As explained in the above sections, the three components display a morphology with a peculiar location with respect to the star and the IR nebula: components A and C are compact and close to the star, while component B is arc-like, with the hot star approximately at its centre. In addition, two of these components (A and B) have velocities compatible with the inferred distance to AFGL 2298, and are the only ones that have emission in other molecules.

There are two preferential directions, which are the ones chosen for the PV plot displayed in Fig. 5. The first direction, approximately from northeast to southwest, includes the peak of components A and C, which are symmetrically located with respect to the star and the nebula. The second direction, roughly perpendicular to the first, is relatively well aligned with the symmetry axis of component B. Interestingly, [Buemi et al. \(2010\)](#), who observed radio continuum at 6 and 20 cm with VLA, and five IR bands from 11.26 to $17.65 \mu\text{m}$ with VLT/VISIR, already identified this lack of symmetry. In the Fig. 6, we compare the relative position of the circular nebula as seen by the band 3 of *Spitzer*/IRAC, our data, and the [Buemi et al. \(2010\)](#) continuum VLA and VLT observations.

Figure 6a shows the $^{13}\text{CO } J = 2 \rightarrow 1$ line as blue and red contours for components A and C, and also the most intense part of the continuum emission at 6 cm. As expected, the [NeII] emission is well correlated with the radio continuum, and it is not shown here for clarity. The three features (radio continuum, and components A and C) are very well aligned in

² The catalogue presents a stack of RRLs from H87 α to H93 α .

Table 2. Distances.

Data source	Method	d (kpc)	Error (kpc)	comment
Ueta et al. (2001)	Model	10.0	3	Distance range necessary to fit IR data.
Ramírez Alegría et al. (2018)	Spectro-photometry	9.6	0.4	Based on a stellar group at similar distances.
Ramírez Alegría et al. (2018)	Galactic rotation model	9.3	1.9	(1)
Anderson et al. (2015)	Galactic rotation model	10.7	0.9	(2)
This work	Galactic rotation model	10.6	0.4	Including full range of components A and B.
Adopted value	Weighted average	10.1	0.6	

Notes. (1) The distance uncertainty quotes results after considering a velocity uncertainty of 21 km s^{-1} , which is the standard deviation of the radial velocities of the members of Masgomas-6b. (2) Uncertainty after assuming 15 km s^{-1} of line velocity uncertainty, which is half of the HPBW of the radio recombination lines.

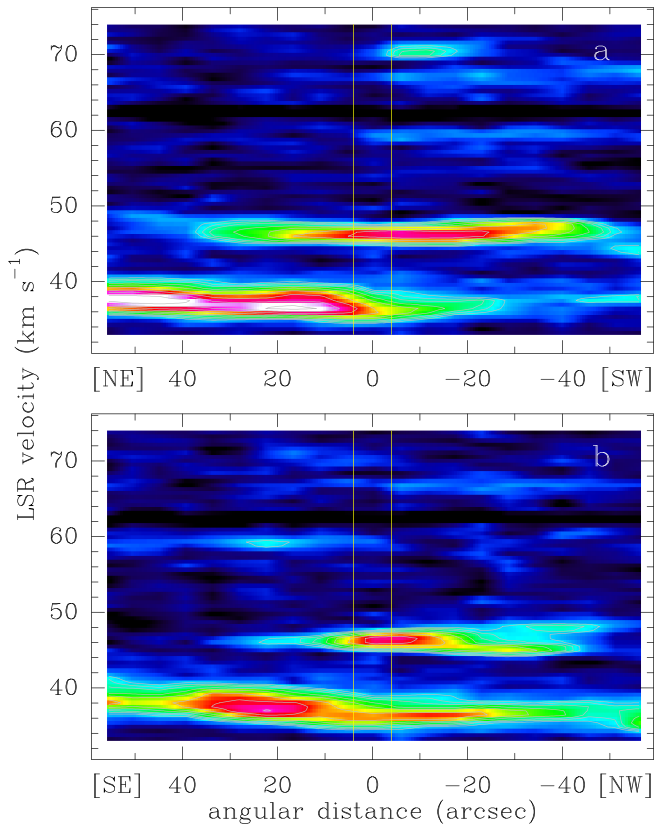


Fig. 5. Position–velocity plots of the $^{13}\text{CO } J = 2 \rightarrow 1$ line. Slices are traced (a) from northeast ($+40'', +40''$) to southwest ($-40'', -40''$); and (b) from southeast ($+40'', -40''$) to northwest ($-40'', +40''$). Contour levels are 0.6, 0.75, 0.9, 1.2, 1.5, 2.0, 2.5, 3.0, and 3.5 K km s^{-1} . Vertical yellow lines mark the approximate extension of the IR dust nebula. In plot a the three components are clearly noted, with component C and part of the component A positioned just outside the nebula. In plot b, component C is not present and component B is concentrated on the nebula.

the northeast–southwest direction. Interestingly, the alignment may support the shock-ionisation scenario proposed by Buemi et al. (2010) as an explanation for the asymmetric 6 cm emission, indicating the presence of denser material in the NE-SW direction.

Figure 6b shows green contours representing the CO $J = 2 \rightarrow 1$ line emission representative of the component B (a single spectral channel at 48.4 km s^{-1}), and the PAH emission at $11.26 \mu\text{m}$ as yellow contours. As shown in the inset, the

most intense emission from PAH arises in the innermost region and is directed towards the northwest, which is in excellent agreement with the CO. PAH emission is also correlated with the dust emission at $17.65 \mu\text{m}$. As discussed by Buemi et al. (2010), the observed asymmetry could be tracing significant anisotropies in the mass-loss event that produced the dusty nebula, which in principle is different from the event that triggered the shock-ionisation towards the northeast.

It is worth noting that the catalogue of Anderson et al. (2015) reports the existence of extended radio emission at the position of AFGL 2298, with an angular size of 97 arcsec. After deconvolving this size by the beam of the GBT telescope at 9 GHz (87 arcsec), we obtain an angular diameter of 42 arcsec. This feature, sketched by a dashed red circle in Fig. 6b, clearly traces the inner part of the component B.

If all these components are connected, the CO is tracing older mass-loss events and the emission associated with the IR nebula is clearly younger. By assuming a characteristic velocity of 15 km s^{-1} (approximately the geometric mean of the differences between the A–B and B–C components), and a size of 0.6 pc (corresponding to 12 arcsec at 10 kpc), we obtain a characteristic dynamic time of $3.8 \times 10^4 \text{ a}$, which is compatible with the LBV phase. A crude estimate of the age of the nebula may be deduced from the width of the Br γ line (Clark et al. 2009), which is 70 km s^{-1} , and a radius of 0.2 pc, corresponding to 4 arcsec at 10 kpc. The resulting dynamical time for the nebula is of about 2700 a. Therefore, the molecular gas reported here appears to be the relic of older mass-loss events produced in the same direction as the newer ones, traced by the ionised gas inside the nebula.

Speculating further, component B may constitute the remnants of an equatorially enhanced mass-loss event (a ring), while components A and C may represent polar mass ejections. The lack of symmetry in velocity (component B is not halfway between components A and C) may be explained by non-homogeneous expansion; the receding part of the jet may have encountered less resistance to expansion because it may have reached the border of the natal molecular cloud, where the approaching part is still embedded. This picture is also consistent with the lack of space symmetry depicted by radio continuum and recombination lines (Umana et al. 2005; Buemi et al. 2010; Clark et al. 2009).

4.3. Radiative transfer modelling

4.3.1. CO, ^{13}CO , and C^{18}O

In principle, the molecular gas studied here is not seriously affected by radiative excitation from AFGL 2298 or any other nearby exciting sources. Therefore, the gas should be primarily

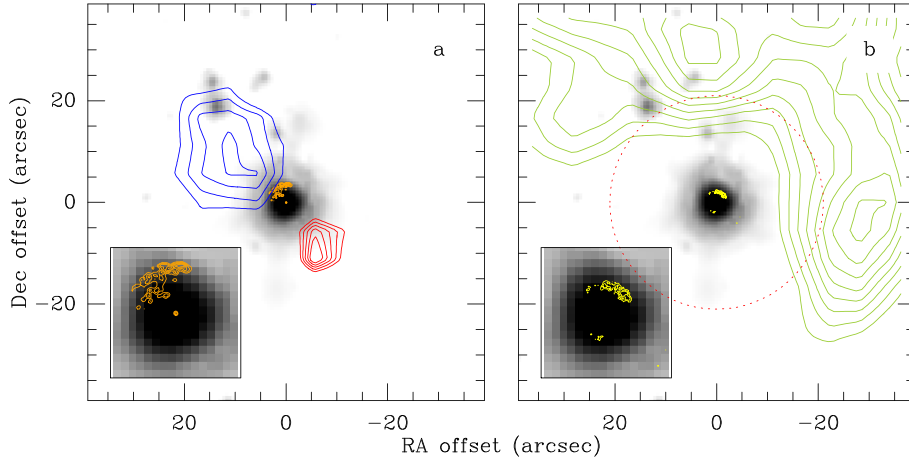


Fig. 6. Relationship of the kinematic molecular components with the warm dust and the ionised gas. Greyscale corresponds to the *Spitzer*/IRAC band 3 (5.7 μm) and clearly indicates the extension of the IR nebula. (a) Blue and red contours correspond to components A and C in the ^{13}CO $J = 2 \rightarrow 1$ line. Levels are from 70% to 95% of the peak value (5.68 and 1.76 K km s^{-1} , respectively), in steps of 5%. Orange contours correspond to 6 cm continuum emission (Buemi et al. 2010) from 0.6 to 1 mJy in steps of 0.1 mJy. (b) Green contours depict component B in the CO $J = 2 \rightarrow 1$ line from 2 to 9 K km s^{-1} in steps of 0.5 K km s^{-1} . Yellow contours correspond to the continuum-subtracted PAH emission at 11.26 μm (Buemi et al. 2010) from 0.7 to 1.3 mJy in steps of 0.2 mJy. The red circle indicates the deconvolved size of the radio recombination line emission reported by Anderson et al. (2015). The insets in both panels contain the same greyscale and contours, but zoomed to the central 10 arcsec to ease the visualisation.

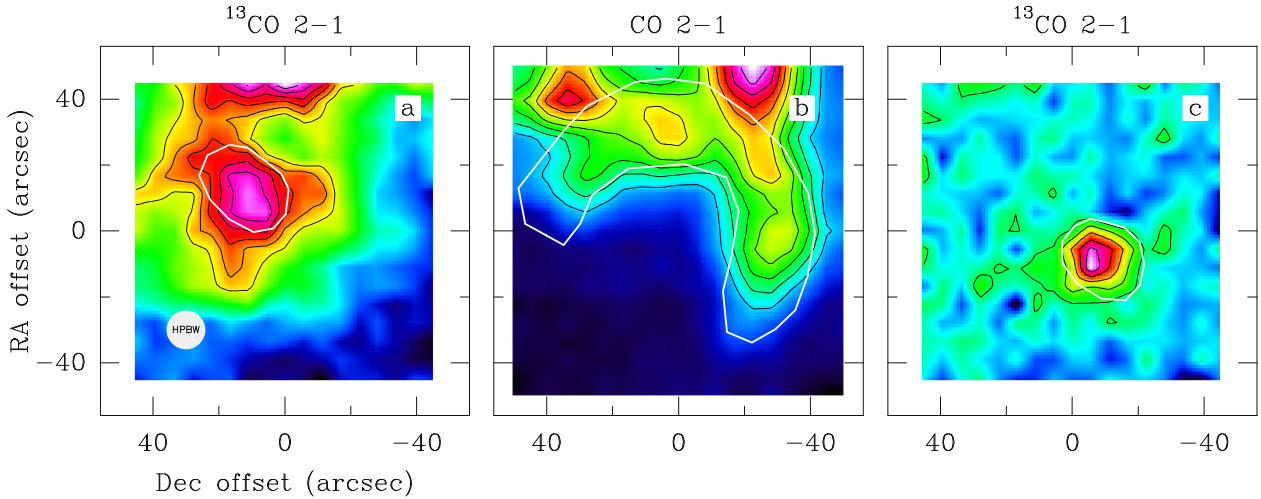


Fig. 7. Regions defined for the column density estimates of the three velocity components sketched as polygons in white. Lines, velocity intervals of integration, first contours, and spacing are: (a) ^{13}CO $J = 2 \rightarrow 1$, 35.4 to 37.0 km s^{-1} , 3 K km s^{-1} , and 0.4 K km s^{-1} ; (b) CO $J = 2 \rightarrow 1$, 47.6 to 49.1 km s^{-1} , 1.4 K km s^{-1} , and 0.7 K km s^{-1} ; (c) ^{13}CO $J = 2 \rightarrow 1$, 69.6–70.7 km s^{-1} , 0.3 K km s^{-1} , and 0.3 K km s^{-1} . The HPBW is shown near the bottom-left corner of panel a.

excited by collisions and close to local thermodynamic equilibrium (LTE). However, the time necessary to reach LTE in this environment is not well determined. Our data allow us not only to estimate the global physical conditions of the gas, but also to explore whether or not the LTE assumption may be applicable to it.

To determine the physical parameters of the gas in the three velocity components, we employed the *ndradex* package³, a Python wrapper of the state-of-the-art radiative transfer code RADEX (van der Tak et al. 2007). Instead of assuming LTE, RADEX applies the escape probability formulation (Sobolev 1960) to solve the radiative transfer equation under non-LTE conditions, thus predicting molecular line intensities and level populations for a given set of physical conditions. *ndradex* allows us to

explore large grids of models in a space parameter defined by the column density of the molecule(s) under analysis $N(X)$, the H_2 volume density $n(\text{H}_2)$, and the kinetic temperature of the gas T_k .

To compute the global physical parameters $n(\text{H}_2)$ and T_k , we relied on ^{12}CO , ^{13}CO , and C^{18}O . We took advantage of the availability of measurements of both the $J = 1 \rightarrow 0$ and $J = 2 \rightarrow 1$ transitions for the three species, which allow us to simultaneously fit six lines, minimising the degeneracy between T_k and $n(\text{H}_2)$. Using the velocity ranges where the three components are seen more clearly, we defined a characteristic region for each component in its corresponding integrated intensity map (see Fig. 7). We then averaged the spectra of each molecule in each region, significantly improving the S/N. The resulting spectra were finally used for comparison with the synthetic spectra produced by *ndradex*. To find the best-fitting model, that is, the

³ <https://github.com/astropenguin/ndradex>

set of physical parameters that best reproduces the observed line intensities for all the six lines observed, we applied a reduced χ^2 minimisation, defined as

$$\chi^2 = \sum_{i=1}^3 \sum_{J=1}^2 \left(\frac{I_{iJ}^{\text{obs}} - I_{iJ}^{\text{mod}}}{\Delta I_{iJ}} \right)^2, \quad (1)$$

where i stands for the different isotopologues; J represents the transition $J \rightarrow J-1$; I_{iJ}^{obs} and I_{iJ}^{mod} are the line intensities in main beam temperature scale⁴ ($\int T_{\text{MB}} dv$) observed and predicted by RADEX, respectively; and ΔI_{iJ} is the uncertainty in I_{iJ}^{obs} .

As the spectra are averaged over regions that are substantially larger than the IRAM-30 m beam, it was not necessary to convolve the data to a common angular resolution, nor to apply a correction by beam filling factor. Because we are providing mean values over each region, it is implicitly assumed that the emission from all the lines is co-spatial and shares the same kinematics. We therefore adopted a common line width for all the species in each region, computed as the weighted average of the individual line widths, and defining the weights as the inverse square of the individual uncertainties.

We employed a two-step approach for the fitting. First, we built a coarse grid of about 17 000 models for each component, with T_k in the range 10–100 K, $N(\text{CO})$, $N(^{13}\text{CO})$, and $N(\text{C}^{18}\text{O})$ in the range 10^{13} – 10^{19} cm^{-2} , and $n(\text{H}_2)$ in the range 10^1 – 10^5 cm^{-3} . Within this coarse grid, we found several solutions (i.e. relative minima of χ^2) for all three velocity components. In some of the solutions, we found that the excitation temperature (T_{ex}) reaches values without physical meaning, that is, negative or excessively high. Taking into account that there is no significant source of radiative excitation (the gas is located far away from the star), the modelled molecular gas is primarily excited by collisions and T_{ex} should not be too different from the T_k used as input. In consequence, we adopt the criterion to exclude those solutions with $T_{\text{ex}} > 1.5T_k$.

Once we had identified the regions of the parameter space that produce physically plausible models, we recomputed the grids around those regions using smaller sampling steps ($\Delta T_k = 5 \text{ K}$, $\Delta n(\text{H}_2) = 500 \text{ cm}^{-3}$, ~ 2500 models per component). In all these models, we observe that T_{ex} of the $J = 1 \rightarrow 0$ transition is always moderately higher than that of the $J = 2 \rightarrow 1$ lines. This difference may indicate some small departure from LTE conditions.

For each component, we adopted the average and standard deviation of T_k , $n(\text{H}_2)$, and $N(X)$ of the best models (i.e. around the absolute χ^2 minimum) as the final values and their associated uncertainties.

As we note in Sect. 3, the detached emission feature that defines component A (i.e. the region A of Fig. 7) is embedded in an extended emission plateau that is probably unrelated to the star. This plateau may bias the column densities towards higher values. To deal with this bias, we subtracted the contribution of the plateau by making a crude estimate of its intensity over several regions right outside region A. Table 3a shows the values adopted as the best-fitting cases with physical meaning.

The densities of the three components are moderately high (of the order of 10^3 – 10^4 cm^{-3}), are not typical of interstellar clouds, and therefore reinforce a possible link to the circumstellar environment of the hot star. Kinetic temperatures are around

20 K, which is consistent with the distance to the star and slightly above typical values of the diffuse Galactic ISM.

The total molecular masses quoted in Table 3a were computed after the integration of $N(\text{CO})$ over the solid angles of the three regions, assuming a distance of 10.1 kpc. We also considered a factor of 1.36 to account for the helium contribution to the molecular mass. The components A and C have masses of the order of one solar mass, which is also compatible with a stellar origin. On the contrary, component B has $78 M_{\odot}$, which is almost impossible to obtain by mass ejection alone. The mass derived for component B reinforces the origin suggested in Sect. 4.2.

The very low $[\text{CO}/^{13}\text{CO}]$ ratio is noteworthy; in the range ≈ 2 to 10, it is far from the solar vicinity value of 89 (Clayton & Nittler 2004, and references therein). It is well known that intermediate-mass stars, such as asymptotic giant branch (AGB) stars, reach values for this latter ratio in the range of 20–30 (Abia et al. 2017), which is probably due to extra-mixing processes of CNO by-products added to the first dredge-up (Wiescher et al. 2010). However, the ratio measured in AFGL 2298 is only comparable to those found in evolved massive stars, such as the red supergiant α Ori (Lambert et al. 1984), the yellow hypergiant IRC+10420 (Quintana-Lacaci et al. 2016), or the LBVs MN101 (Bordiu et al. 2019) and η Car (Loinard et al. 2012; Gull et al. 2020). The reaction rates of the different CNO processes increase exponentially with the temperature, and therefore it is unlikely that the same mixing mechanisms operate in these very hot stars (Przybilla et al. 2010). Therefore, the dramatic changes in the survival times of isotopes and the dominant mixing mechanisms would explain the very different observationally measured ratios. Therefore, it is possible that the unusually low $[\text{CO}/^{13}\text{CO}]$ is the consequence of an overproduction of ^{13}C during the CNO cycle, and/or a dominant destruction of ^{12}C to form ^{14}N (Wiescher et al. 2010).

4.3.2. Other molecules

For the remaining molecules, most of which were only observed at 3 mm, we followed a different approach. As they are likely less abundant and optically thin, we estimated their respective column densities under LTE conditions using the software package MADCUBA. In particular, we used the task SLIM-AUTOFIT (Martín et al. 2019), which performs a non-linear least-squares fit to one or more observed spectra of a given species. MADCUBA is also able to deal with molecules with hyperfine splitting, such as C^{17}O , CN, HCN, N_2H^+ , and C_2H . Using initial guesses from Gaussian fittings to the lines, convergence was reached in all cases, with the only assumption being an excitation temperature of 20 K.

The column densities obtained by this method are shown in Table 3b. After C^{17}O , the largest values are found in C_2H and CN, with column densities of the order of 10^{13} cm^{-2} . On the contrary, the lowest values are from N_2H^+ , which exhibits a column density of only $9 \times 10^{11} \text{ cm}^{-2}$ in component A. We did not detect any of these molecules in component C, not even in the stacked spectra.

4.4. Abundances

To broadly compare AFGL 2298 with other astrophysical environments, and also to investigate possible chemical differences between components, we translated the column densities in Table 3 into fractional abundances relative to H_2 . As we lack direct measurements of $N(\text{H}_2)$ towards AFGL 2298, we assumed a CO/H_2 abundance of 8×10^{-5} (Dickman 1975). The results are

⁴ Computed as $T_{\text{MB}} = T_{\text{A}}^*/\eta_{\text{eff}}$, where η_{eff} is the main beam efficiency obtained from <https://publicwiki.iram.es/Iram30mEfficiencies>

Table 3. Modelling and parameters.

(a) RADEX/ndradex results								
Comp.	Vel. range (km s ⁻¹)	$n(\text{H}_2)$ (10 ⁴ cm ⁻³)	T_k (K)	mass ($M_\odot$)	$N(\text{CO})$ (10 ¹⁶ cm ⁻²)	$N(^{13}\text{CO})$ (10 ¹⁵ cm ⁻²)	$N(\text{C}^{18}\text{O})$ (10 ¹⁴ cm ⁻²)	$\text{CO}/^{13}\text{CO}$
A	(35.4, 37.0)	0.5 ± 0.1	24 ± 4	1.0 ± 0.2	0.30 ± 0.06	1.39 ± 0.06	5.6 ± 0.2	2.2
B	(47.6, 49.1)	0.6 ± 0.2	19 ± 5	78 ± 22	4.7 ± 1.3	4.9 ± 0.5	3.9 ± 0.3	9.6
C	(69.4, 71.0)	2.1 ± 0.9	18 ± 5	1.4 ± 0.2	0.47 ± 0.05	1.09 ± 0.07	1.20 ± 0.02	4.3

(b) MADCUBA results								
Comp.	$N(\text{C}^{17}\text{O})$ (10 ¹⁴ cm ⁻²)	$N(\text{HCO}^+)$ (10 ¹² cm ⁻²)	$N(\text{HCN})$ (10 ¹² cm ⁻²)	$N(\text{HNC})$ (10 ¹² cm ⁻²)	$N(\text{H}^{13}\text{CO}^+)$ (10 ¹¹ cm ⁻²)	$N(\text{CN})$ (10 ¹³ cm ⁻²)	$N(\text{N}_2\text{H}^+)$ (10 ¹¹ cm ⁻²)	$N(\text{C}_2\text{H})$ (10 ¹³ cm ⁻²)
A	1.9 ± 0.5	2.7 ± 0.3	8.2 ± 0.7	2.2 ± 0.2	< 1.6	1.2 ± 0.3	9 ± 1	4.0 ± 0.8
B	0.9 ± 0.3	0.9 ± 0.2	1.74 ± 0.07	0.94 ± 0.1	< 0.76	0.5 ± 0.1	< 1.2	1.1 ± 0.3
C	< 0.42	< 0.12	< 0.39	< 0.16	< 1.4	< 0.15	< 2.1	< 0.80

Table 4. Average fractional abundances with respect to H₂.

Species	A	B	C
¹³ CO	3.5×10^{-5}	8.3×10^{-6}	1.9×10^{-5}
C ¹⁸ O	1.5×10^{-5}	6.6×10^{-7}	2.1×10^{-6}
C ¹⁷ O	5.1×10^{-6}	1.5×10^{-7}	$< 7.3 \times 10^{-7}$
HCO ⁺	7.2×10^{-8}	1.5×10^{-9}	$< 2.1 \times 10^{-9}$
HCN	2.2×10^{-7}	3.0×10^{-9}	$< 6.8 \times 10^{-9}$
HNC	5.8×10^{-8}	1.6×10^{-9}	$< 2.8 \times 10^{-9}$
H ¹³ CO ⁺	$< 4.3 \times 10^{-9}$	$< 1.3 \times 10^{-10}$	$< 2.4 \times 10^{-9}$
CN	3.2×10^{-7}	8.5×10^{-9}	$< 2.6 \times 10^{-8}$
N ₂ H ⁺	2.4×10^{-8}	$< 2.0 \times 10^{-10}$	$< 3.7 \times 10^{-9}$
C ₂ H	1.1×10^{-6}	1.7×10^{-8}	$< 1.4 \times 10^{-7}$

Notes. Assumed a [CO/H₂] ratio of 8×10^{-5} .

listed in Table 4. However, we note that the method described in the previous section only provides mean values of the column densities and assumes that all the molecular emission arises in the same volume and from comparable depths. This is not necessarily expected to be the case, because the less abundant molecules usually show higher critical densities and emit mostly from deeper regions than CO. Therefore, the abundances of the detected molecules should be regarded as averages over the whole regions, and eventually considered as lower limits of the real abundances in the volumes in which they emit.

Components A and B appear chemically different, with fractional abundances in component B being systematically lower than those in component A by one or even two orders of magnitude. The abundances of some of the molecules in component B are not far from those measured in cold clouds (see, e.g. Hirota et al. 1998; Jin et al. 2015).

Figure 8 compares the fractional abundances of the two components with those measured in other well-studied evolved stars: the LBV η Car (Loinard et al. 2012), the yellow hypergiant IRC+10420 (Quintana-Lacaci et al. 2016), and the oxygen-rich giant IK Tau (Velilla Prieto et al. 2017). While component B has abundances systematically below the values found in all the stars sampled here (except the upper limit of C₂H in IK Tau), the abundances of component A are comparable to those found in the three other stars.

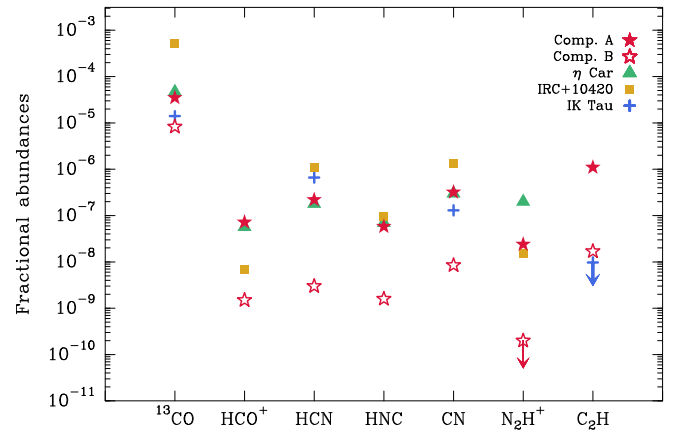


Fig. 8. Fractional abundances of ¹³CO, HCO⁺, HCN, HNC, CN, N₂H⁺, and C₂H in AFGL 2298 compared to other evolved stars. Abundances are taken from Loinard et al. (2012) for η Car, Quintana-Lacaci et al. (2016) for IRC+10420, and Velilla Prieto et al. (2017) for IK Tau.

In particular, the abundances of ¹³CO, CN, HCO⁺, HCN, and HNC in component A are strikingly similar to those reported in η Car (see Table 2 in Loinard et al. 2012), reaching an agreement of better than $\sim 30\%$ in most cases. The molecular gas in η Car is made of ejecta expelled in the Great Eruption of the 19th century, and so such chemical resemblance suggests that component A may be composed of stellar material as well.

A notable exception is the molecular ion N₂H⁺, which is under-abundant in component A with respect to the Homunculus by roughly an order of magnitude, and is not detected in component B with an upper limit at least three orders of magnitude below the measured abundance in η Car. The under-abundance in AFGL 2298 with respect to η Car may be explained by two destruction processes. For $T_k < 20$ K, provided that abundant gas-phase CO is available, N₂H⁺ is destroyed, producing HCO⁺ by the reaction $\text{N}_2\text{H}^+ + \text{CO} \rightarrow \text{HCO}^+ + \text{N}_2$ (Jørgensen et al. 2004). The abundance of HCO⁺ in component A, which is comparable to that of the Homunculus, might indicate that this destruction path dominates this component. In component B, dissociative recombination with free electrons may drive the destruction of N₂H⁺ through the reaction $\text{N}_2\text{H}^+ + e^- \rightarrow \text{N}_2 + \text{H}$, which is more efficient at higher

temperatures (Vigren et al. 2012). Component B lies in the preferential SE-NW direction, where PAHs are detected (see Fig. 6b) and where the suggestion of some stratification of the CO isotopologues is found (Fig. 3, middle row).

This arrangement of molecules and PAHs bears a resemblance to the well-studied photodissociation regions (PDRs), such as the Orion Bar (Cuadrado et al. 2015) and the Horsehead nebula (Pety et al. 2005), which both show a fractional abundance of C_2H around 10^{-8} . The overabundant C_2H , a prime tracer of PDRs (Rizzo et al. 2005), might be located in an intermediate region between the PAHs and the bulk of component B. Nevertheless, this (admittedly speculative) scenario cannot be investigated in this work. The angular resolution of our maps makes it difficult to establish firm conclusions about the chemical stratification and the existence of a PDR.

Taken together, these chemical footprints support the hypothesis that component A is the consequence of a relatively recent mass-loss event. Conversely, abundances of component B are compatible with interstellar material accumulated by the winds of the central hot star: the HCN and HCO^+ abundances, of 3×10^{-9} and 1.5×10^{-9} , respectively, are close to the typical values of the ISM and molecular clouds (see, e.g., Gerin et al. 2019; Fuente et al. 2019). This swept-up material would explain the rather large mass of $78 M_\odot$ derived in Sect. 4.3.1.

Finally, components A and C may be part of a single mass-loss event, considering the bipolar symmetry displayed (see Fig. 6a). This event would have been in any case a highly non-isotropic mass ejection, in line with the findings of Umana et al. (2005) and Buemi et al. (2010).

5. Conclusions

We present the first in-depth study of the molecular environment of the Galactic LBV AFGL 2298 based on observations carried out with the IRAM-30m telescope. Our main findings are summarised below:

- We detected emission from CO and its main isotopologues arising from multiple kinematic components in the observed field. While most of this emission is due to background or foreground molecular clouds unrelated to the source, we identified three velocities of interest where the emission exhibits morpho-kinematic features suggesting a connection with the star, namely at ~ 36 (component A), ~ 46 (B) and $\sim 70 \text{ km s}^{-1}$ (C);
- A further seven carbon- and nitrogen-bearing molecular species were detected in the field, all of them restricted to the specific velocity ranges of components A and B: HCO^+ , $H^{13}CO^+$, HCN, HNC, CN, N_2H^+ , and C_2H . All the lines are present in components A and B, except for N_2H^+ , which is not detected in component B;
- The most intense emission of components A and C appears to be aligned NE-SW, a preferential direction in which the radio continuum is strongly asymmetric, possibly explained in terms of a shock-ionisation scenario. Likewise, component B, which surrounds the dusty nebula from N to SE, seems chemically stratified in the SE-NW direction, where PAH emission appears in the IR spectrum;
- Components A and C depict a bipolar symmetry and could be part of a post-main sequence collimated mass-loss event. The morphology and abundances of component B suggest that this component is mainly made of swept-up material from the surrounding cloud;

- Following a detailed radiative transfer modelling, we determined the average physical conditions of the gas in the three components, along with the column densities of the detected molecules. The gas is moderately dense and close to LTE, with $n(H_2)$ of 10^3 – 10^4 cm^{-3} and kinetic temperatures of $\sim 20 \text{ K}$, slightly above the typical values for interstellar clouds. In addition, the $[^{12}CO/^{13}CO]$ ratio in components A and C is significantly lower than in B, which is compatible with heavily processed material. These components could be mostly composed of stellar ejecta, a hypothesis that is also reinforced by their masses (around $1 M_\odot$);
- The fractional abundances of most of the species match very well with those determined in η Car and the Homunculus nebula from single-dish observations, and are compatible with the nitrogen-rich nature of LBV ejecta, in further support of the possible stellar origin of some of the gas.

These detections are a first step towards a proper characterisation of the molecular environment of AFGL 2298, which is now the LBV with the second-largest molecular inventory after η Car. Unfortunately, the limited angular resolution of our data and the non-negligible contamination from extended emission limit the extent of our analysis. Follow-up interferometric observations will help us to further characterise the relative distribution, kinematics, and chemistry of the circumstellar molecular gas, which will help us to disclose its true nature and its relationship to the IR and radio continuum features.

Acknowledgements. J.R.R. acknowledges support from grant PID2019-105552RB-C41 funded by MCIN/AEI/10.13039/501100011033. This research has made use of the VizieR catalogue access tool (DOI: [10.26093/cds/vizier](https://doi.org/10.26093/cds/vizier)). We are grateful of the kind and professional support provided by the IRAM 30m staff during the observations. We also thank the anonymous referee for the comments and suggestions which improved this paper.

References

- Abia, C., Hedrosa, R. P., Domínguez, I., & Straniero, O. 2017, *A&A*, **599**, A39
- Agliozzo, C., Noriega-Crespo, A., Umana, G., et al. 2014, *MNRAS*, **440**, 1391
- Anderson, L. D., Armentrout, W. P., Johnstone, B. M., et al. 2015, *ApJS*, **221**, 26
- Bordiu, C., & Rizzo, J. R. 2019, *MNRAS*, **490**, 1570
- Bordiu, C., Rizzo, J. R., & Ritacco, A. 2019, *MNRAS*, **482**, 1651
- Bordiu, C., Bufano, F., Cerrigone, L., et al. 2021, *MNRAS*, **500**, 5500
- Bordiu, C., Rizzo, J. R., Bufano, F., et al. 2022, *ApJ*, **939**, L30
- Brand, J., & Blitz, L. 1993, *A&A*, **275**, 67
- Buemi, C. S., Umana, G., Trigilio, C., Leto, P., & Hora, J. L. 2010, *ApJ*, **721**, 1404
- Chambers, K. C., Magnier, E. A., Metcalfe, N., et al. 2016, *ArXiv e-prints* [arXiv:1612.05560]
- Clark, J. S., Larionov, V. M., Crowther, P. A., Egan, M. P., & Arkharov, A. 2003, *A&A*, **403**, 653
- Clark, J. S., Crowther, P. A., Larionov, V. M., et al. 2009, *A&A*, **507**, 1555
- Clayton, D. D., & Nittler, L. R. 2004, *ARA&A*, **42**, 39
- Cuadrado, S., Goicoechea, J. R., Pilleri, P., et al. 2015, *A&A*, **575**, A82
- Dickman, R. L. 1975, *ApJ*, **202**, 50
- Duncan, R. A., & White, S. M. 2002, *MNRAS*, **330**, 63
- Fuente, A., Navarro, D. G., Caselli, P., et al. 2019, *A&A*, **624**, A105
- Gaia Collaboration (Brown, A. G. A., et al.) 2016, *A&A*, **595**, A2
- Gaia Collaboration (Brown, A. G. A., et al.) 2018, *A&A*, **616**, A1
- Gaia Collaboration (Vallenari, A., et al.) 2023, *A&A*, **674**, A1
- Gerin, M., Liszt, H., Neufeld, D., et al. 2019, *A&A*, **622**, A26
- Groh, J. H., Damineli, A., Hillier, D. J., et al. 2009, *ApJ*, **705**, L25
- Groh, J. H., Hillier, D. J., & Damineli, A. 2011, *ApJ*, **736**, 46
- Gull, T. R., Morris, P. W., Black, J. H., et al. 2020, *MNRAS*, **499**, 5269
- Hirota, T., Yamamoto, S., Mikami, H., & Ohishi, M. 1998, *ApJ*, **503**, 717
- Humphreys, R. M., & Davidson, K. 1994, *PASP*, **106**, 1025
- Jin, M., Lee, J.-E., & Kim, K.-T. 2015, *ApJS*, **219**, 2
- Jørgensen, J. K., Schöier, F. L., & van Dishoeck, E. F. 2004, *A&A*, **416**, 603
- Lambert, D. L., Brown, J. A., Hinkle, K. H., & Johnson, H. R. 1984, *ApJ*, **284**, 223

- Lamers, H. J. G. L. M., Nota, A., Panagia, N., Smith, L. J., & Langer, N. 2001, [ApJ](#), **551**, 764
- Langer, N. 2012, [ARA&A](#), **50**, 107
- Loinard, L., Menten, K. M., Güsten, R., Zapata, L. A., & Rodríguez, L. F. 2012, [ApJ](#), **749**, L4
- Martín, S., Martín-Pintado, J., Blanco-Sánchez, C., et al. 2019, [A&A](#), **631**, A159
- Morris, P. W., Charnley, S. B., Corcoran, M., et al. 2020, [ApJ](#), **892**, L23
- Palau, A., Rizzo, J. R., Girart, J. M., & Henkel, C. 2014, [ApJ](#), **784**, L21
- Pasquali, A., & Comerón, F. 2002, [A&A](#), **382**, 1005
- Pety, J., Teyssier, D., Fossé, D., et al. 2005, [A&A](#), **435**, 885
- Przybilla, N., Firnstein, M., Nieva, M. F., Meynet, G., & Maeder, A. 2010, [A&A](#), **517**, A38
- Quintana-Lacaci, G., Agúndez, M., Cernicharo, J., et al. 2016, [A&A](#), **592**, A51
- Ramírez Alegría, S., Herrero, A., Rübke, K., et al. 2018, [A&A](#), **614**, A116
- Reid, M. J., Menten, K. M., Brunthaler, A., et al. 2014, [ApJ](#), **783**, 130
- Richardson, N. D., & Mehner, A. 2018, [RNAAS](#), **2**, 121
- Rizzo, J. R., Fuente, A., & García-Burillo, S. 2005, [ApJ](#), **634**, 1133
- Rizzo, J. R., Jiménez-Esteban, F. M., & Ortiz, E. 2008, [ApJ](#), **681**, 355
- Rizzo, J. R., Palau, A., Jiménez-Esteban, F., & Henkel, C. 2014, [A&A](#), **564**, A21
- Sobolev, V. V. 1960, [Moving Envelopes of Stars](#) (Cambridge: Harvard University Press)
- Ueta, T., Meixner, M., Dayal, A., et al. 2001, [ApJ](#), **548**, 1020
- Umana, G., Buemi, C. S., Trigilio, C., & Leto, P. 2005, [A&A](#), **437**, L1
- Umana, G., Buemi, C. S., Trigilio, C., et al. 2009, [ApJ](#), **694**, 697
- Umana, G., Buemi, C. S., Trigilio, C., Leto, P., & Hora, J. L. 2010, [ApJ](#), **718**, 1036
- van der Tak, F. F. S., Black, J. H., Schöier, F. L., Jansen, D. J., & van Dishoeck, E. F. 2007, [A&A](#), **468**, 627
- Velilla Prieto, L., Sánchez Contreras, C., Cernicharo, J., et al. 2017, [A&A](#), **597**, A25
- Vigren, E., Zhaunerchyk, V., Hamberg, M., et al. 2012, [ApJ](#), **757**, 34
- Waters, L. B. F. M., Voors, R. H. M., Morris, P. W., et al. 1999, in [IAU Colloq. 169: Variable and Non-spherical Stellar Winds in Luminous Hot Stars](#), eds. B. Wolf, O. Stahl, & A. W. Fullerton, (Springer-Verlag Berlin Heidelberg New York), 523, 381
- Wiescher, M., Görres, J., Überseder, E., Imbriani, G., & Pignatari, M. 2010, [Annu. Rev. Nucl.](#), **60**, 381

Appendix A: Integrated maps of the other molecules

In this Appendix, we present the maps of the other molecules integrated in the velocity ranges of the three components.

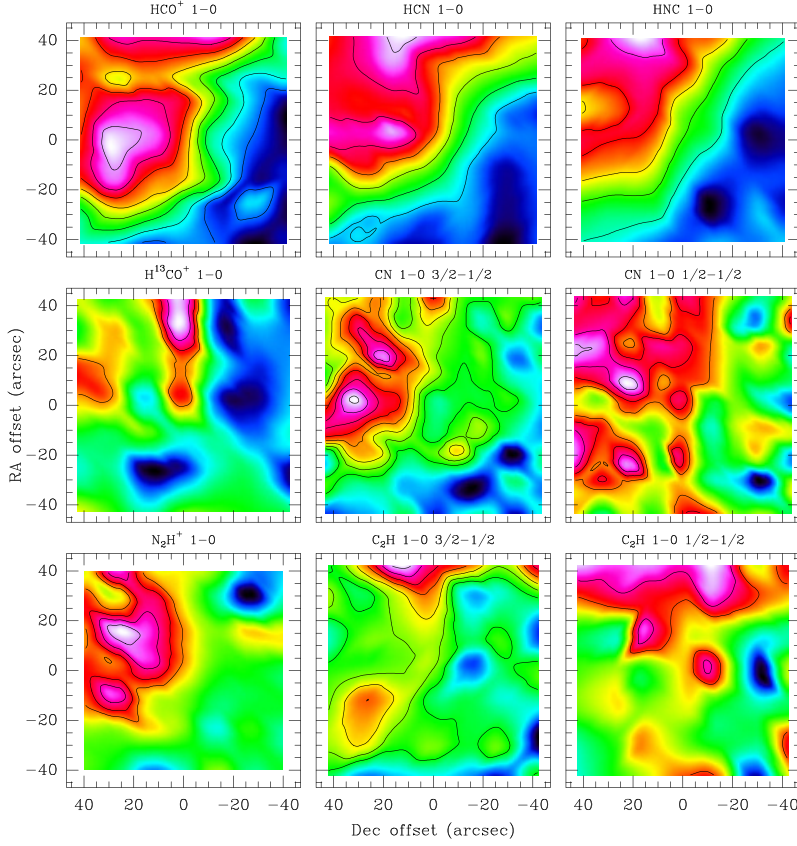


Fig. A.1. Emission of the other molecular lines integrated in the velocity range of the component A from 35 to 38 km s⁻¹. Molecule and transition are indicated at the top of each map. The first contour and spacing are 0.15 and 0.05 K km s⁻¹ in all cases except the top row, where they are 0.3 and 0.15 K km s⁻¹, respectively.

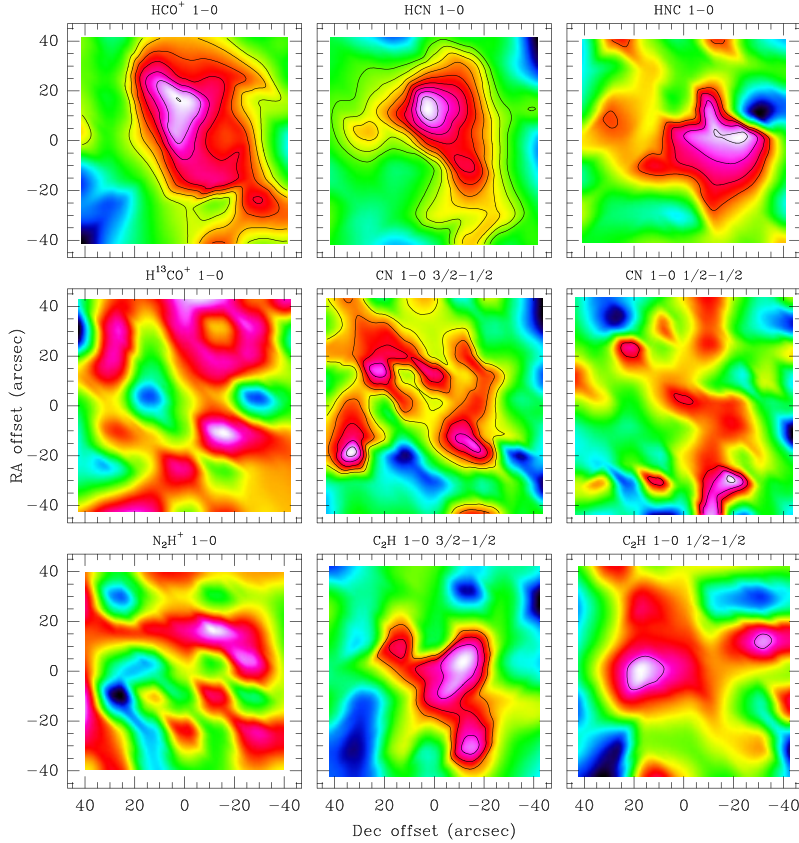


Fig. A.2. Emission of the other molecular lines integrated in the velocity range of the component B from 45 to 48 km s⁻¹. Molecules and transitions are indicated at the top of each map. The first contour and spacing are 0.2 and 0.05 K km s⁻¹ in all cases except HCO⁺, where they are 0.3 and 0.07 K km s⁻¹, respectively.

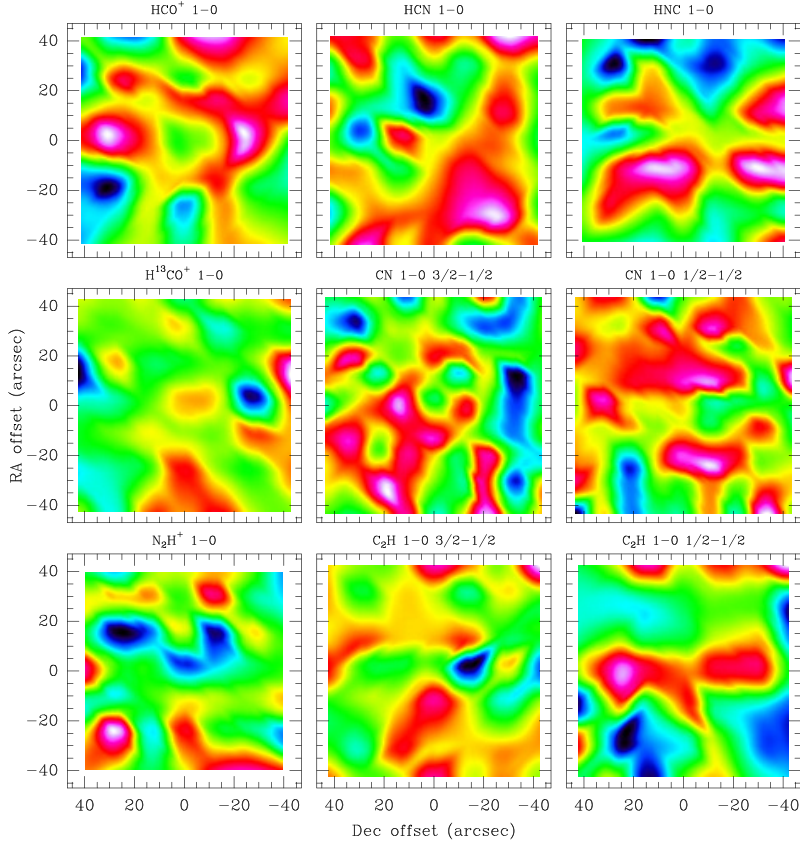


Fig. A.3. Emission of the other molecular lines integrated in the velocity range of the component C from 69 to 72km s⁻¹. Due to a lack of significant signal, contour levels are not included.