Star formation timescale in the molecular filament WB 673

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ABSTRACT

We present observations of ammonia emission lines toward the interstellar filament WB 673 hosting the dense clumps WB 673, WB 668, S233-IR and G173.57+2.43. LTE analysis of the lines allows us to estimate gas kinetic temperature (∼ 30 K in all the clumps), number density (7 − 17 × 10^3 cm^3), and ammonia column density (∼ 1 − 1.5 × 10^15 cm^-2) in the dense clumps. We find signatures of collapse in WB 673 and presence of compact spatially unresolved dense clumps in S233-IR. We reconstruct 1D density and temperature distributions in the clumps and estimate their ages using astrochemical modelling. Considering CO, CS, NH_3 and N_2H^+ molecules (plus HCN and HNC for WB 673), we find a chemical age of t_chem = 1 − 3 × 10^5 yrs providing the best agreement between the simulated and observed column densities in all the clumps. Therefore, we consider t_chem as the chemical age of the entire filament. A long preceding low-density stage of gas accumulation in the astrochemical model would break the agreement between the simulated and observed column densities. We suggest that rapid star formation over a ∼ 10^5 yrs timescale take place in the filament.

Key words: stars: formation — ISM: clouds — ISM: molecules — ISM: individual objects (WB89 673, S233-IR)

1 INTRODUCTION

Interstellar molecular clouds appear as interconnected networks of elongated filaments (e. g. Myers 2009; André et al. 2014; Li et al. 2016, and many others). According to numerical simulations, multiple episodes of interstellar gas compression by supersonic waves or shells produce these filaments (see e. g. Inoue & Inutsuka 2009; Ntormousi et al. 2011; Inutsuka et al. 2015; Inoue et al. 2018), but other scenarios, such as the development of hydrodynamic instabilities (e. g. Padoan et al. 2001) or cloud-cloud collisions (Inoue & Fukui 2013; Kumar et al. 2020; Fukui et al. 2021) are also possible. Particularly, Ntormousi et al. (2011) show how the collision of two expanding gas shells, created by stellar winds or by supernova explosions, forming so-called bubbles, can lead to the creation of massive filamentary clouds (up to 10^4 M⊙) in the region where the two bubbles overlap. Dense molecular clumps, being potential star formation sites, are formed after fragmentation of the filaments (e. g. Fiege & Pudritz 2000). A high density of young stellar clusters and massive young stellar objects is observed in the clumps around infrared bubbles (Thompson et al. 2012; Chavarría et al. 2014; Saral et al. 2015; Kendall et al. 2016). Kendall et al. (2012) estimated that the formation of up to 20% of all massive stars in the Galaxy could be triggered by the expanding H II regions. Therefore, feedback from massive stars is an important ingredient that determines the star formation rate in molecular clouds. Grudić et al. (2018) concluded that star formation is feedback-moderated in simulated turbulent molecular clouds over spatial scales from several to hundreds of parsecs.

Over the last twenty years, the majority of studies provide evidence in favour of a ‘rapid’ star formation scenario with a typical timescale of ∼ 10^5 − 10^6 yrs. Namely, Lee & Myers (1999) estimate a typical lifetime of starless cores as 0.3 − 1.6 × 10^6 yrs using a sample of 406 dense cores. McKee & Tan (2003) simulate the formation of massive stars in dense clumps and suggest a shorter timescale for the formation of a massive star, namely ∼ 10^5 yrs. Vázquez-Semadeni et al. (2007) also advocate rapid star formation over ∼ 10^5 yrs in the clumps, albeit with a long (up to several Myrs) period of initial gas accumulation into the cores. Jessop & Ward-Thompson (2000) and Ward-Thompson et al. (2007) estimate a lifetime of ∼ 10^6 yrs for cold cores without active star formation. Gong et al. (2021) report a rapid formation of the Serpens filament during less than 2 × 10^5 yrs using a timescale for the CO freeze-out process. They showed that the chemical timescale agrees with the age of this filament, obtained with a time-dependent accretion model.

The aim of the present study is to estimate a chemical age of the molecular filament WB 673 using a set of molecular abundances including both ‘early’ (CO, CS) and ‘late’ (NH_3, N_2H^+) species, with NH_3 data presented in this paper and other abundances taken from Ryabukhina & Kirsanova (2020). We confirm the scenario of the ‘rapid’ formation for dense clumps in high-mass star-forming regions without a long initial stage of gas accumulation in the WB 673 filament, by showing that the chemical age of the filament is 1 − 3 × 10^5 yrs. We also show that ammonia is depleted in the dense clumps. In addition to CO and CS depletion, found by Ryabukhina & Kirsanova (2020), this indicates that internal heating sources, related to embedded high-mass young stellar objects, still do not impact much chemistry of the surrounding medium.

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2 TARGET REGION

The giant molecular cloud G174+2.5 at a distance of 1.6 kpc (Burns et al. (2015); 40″ correspond to 0.3 pc) was extensively mapped in CO lines by Heyer et al. (1996) and Bieging et al. (2016). They found that the spatial distribution and kinematics of the molecular gas are affected by the extended and optically prominent H ii regions Sh2-231, Sh2-232, Sh2-235 (S231, S232 and S235 hereafter) around massive O-type stars. There are several B-type stars in G174+2.5, which are deeply embedded in parental molecular material. They are surrounded by the compact H ii regions S233, S235A and S235C. A significant fraction of the molecular gas in G174+2.5 is concentrated in a single filamentary cloud, WB 673, with a projected length of 25 pc (~50 arcmin), total mass of $10^4$ M⊙ and mass-to-length ratio of 3.4 – 34 M⊙ pc$^{-1}$ (Kirsanova et al. 2017). The filament is located between S231 and a large unnamed envelope, which can be a supernova remnant (Kang et al. 2012; Kirsanova et al. 2017). Therefore, WB 673 is a reliable candidate of a region exposed to multiple compression events from expanding shells.

Ladeyschikov et al. (2016) and Kirsanova et al. (2017) observed emission of various molecular lines at wavelengths λ ~ 3 and 1.3 mm in four dense clumps within the WB 673 filament. A mid-infrared image of the filament and a map of the $^{13}$CO (1–0) line emission are shown in Fig. 1, where the dense clumps are designated as WB 668, WB 673 (WB89 668 and WB89 673 in Wouterloot & Brand 1989), S233-IR and G173.57+2.43. Water masers at 22 GHz, Class II methanol masers and IRAS (InfraRed Astronomical Satellite) and MSX (Midcourse Space Experiment) sources were found in all the clumps, which is a sign of active star formation (see Ladeyschikov et al. 2016, for details). The infrared flux ratios in IRAS point sources 05345+3556 and 05358+3543 are consistent with H ii regions in WB 673 and S233-IR. The latter clump hosts a well-studied molecular outflow (e. g. Beuther et al. 2007; Leurini et al. 2007).

Ryabukhina & Kirsanova (2020) found that abundances of CS, CO, N$_2$H$^+$, HCN and HNC relative to H$_2$ decrease in the dense central parts of the clumps in comparison with their periphery. In other words, the clumps demonstrate typical cold chemistry in spite of signs of active high-mass star formation. In the following we investigate the filament where the star formation process is at its early stage.

3 OBSERVATIONS

We performed observations of the ammonia (1,1), (2,2) and (3,3) inversion transitions with the 100-m Effelsberg telescope (Germany) in 2–7 January 2019. The total ON+OFF observational time was 60 hours. The observations were carried out in continuous mapping mode (on-the-fly) using a 1.3 cm secondary focus receiver with a bandwidth of 300 MHz, providing a spectral resolution of 0.2 km s$^{-1}$. The ammonia emission data covered the entire area of the filament with a size 10′ × 50′ with respect to the minor and major axes. The obtained maps have an angular resolution of 40″. The observations were done in the position switching mode with the OFF-position at α(ICRS) = 05h37m30s, δ(ICRS) = +35°30′00″. The list of observed transitions is given in Table 1.

The calibration involved a correction for the atmospheric opacity, that is based on an atmospheric model and the water vapour radiometer at the Effelsberg telescope. The elevation dependent telescope gain was also implemented. The antenna efficiencies and sensitivities (i.e. Kelvin per Jansky coefficients) were derived from an analytical model and the full width at half maximum (FWHM) of the pointing measurements. The temperature of the noise diode, providing an initial intensity scale, was calibrated using radio continuum pointing scans toward the planetary nebula NGC 7027 (Ott et al. 1994). Pointing and focus were performed approximately every hour. $T_{sys}$ was mostly kept within the range of 100–120 K on a $T_A^*$ scale. However, it increased to 200 K in bad weather conditions. We excluded spectra with a noise level higher than $0.3$ K from our analysis. The median of the signal-to-noise ratio of the determined lines is three. In the densest regions at the centers of the WB 673 and S233-IR clumps it exceeds 10 and 5 for the (1,1) and (2,2) transitions, respectively.

The gridding of the data and the baseline correction were processed using the CLASS program from the GILDAS$^1$ package. Further analysis was done using MIRIAD (Sault et al. 1995), Astropy (Astropy Collaboration et al. 2018) and PySpecKit (Ginsburg & Mirocha 2011) packages.

| Molecule | Transition | Frequency (GHz) | $E_{ut}$ (K) |
|----------|------------|----------------|-------------|
| NH$_3$   | (1,1)      | 23.6945        | 23.4        |
|          | (2,2)      | 23.7226        | 64.9        |
|          | (3,3)      | 23.8701        | 124.5       |

Figure 1. Pseudo-colour image of the WB 673 filament composed of WISE IR data (Wright et al. 2010) at 22 µm (red), 12 µm (green), and 3.4 µm (blue). The integrated intensity of the $^{13}$CO (1–0) emission line is shown by white contours at levels of 14, 24, 35 K km s$^{-1}$ from Ryabukhina & Kirsanova (2020); beam size is 43″. An arch, related with S231, is seen to the east of the filament.

Table 1. List of observed transitions

1 http://www.iram.fr/IRAMFR/GILDAS
4 DATA ANALYSIS

The lowest meta-stable energy states of ammonia are only excited by collisions. Therefore they are widely used for measuring the gas temperature in dense molecular gas. A review and a theory are presented in Ho & Townes (1983). Our LTE analysis of the ammonia lines follows this classical paper.

We used the CLASS routine 'nh3(1,1)' to estimate the optical depth of the (J, K) = (1, 1) line, connecting the two states of the (J, K) = (1, 1) inversion doublet, accounting for hyperfine components and excitation temperature \( T_{\text{ex}} \). This method assumes Gaussian line shapes in the optically thin case and equal excitation temperatures for all the hyperfine components. For the (1,1) transition, the optical depth of the main (the central one of five) group of hyperfine components \( \tau_{(1,1)m} \) is related to the total optical depth over the multiplet given by the \('nh3(1,1)'\) routine as \( \tau_{(1,1)m} = \tau_{(1,1)/2} \) (see Appendix in Mangum et al. (1992)). Moreover, we found the intensity of the main components \( T_{\text{MB}} \), LSR velocity \( V_{\text{LSR}} \) and line width \( \Delta V \) using PySpecKit for all three observed transitions. Their values for the peaks of the clumps are given in Table 2.

Using the (1,1) and (2,2) line intensities, we can find the rotational temperature, which is consistent with the relative populations of these two inversion doublets:

\[
T_{\text{rot}} = -41.5 \ln \left( \frac{-0.282}{\tau_{(1,1)m}} \ln \left( 1 - \frac{T_{\text{MB}}(2,2)}{T_{\text{MB}}(1,1)} \left( 1 - \exp(-\tau_{(1,1)m}) \right) \right) \right)^{-1} \text{(K)},
\]

where \( T_{\text{MB}}(1,1) \) and \( T_{\text{MB}}(2,2) \) are the main beam brightness temperatures of the main components of the (1,1) and (2,2) lines, respectively. The ammonia column density at the (1,1) level can be calculated following Mangum et al. (1992) with:

\[
N_{1,1} = 6.6 \times 10^{14} \frac{T_{\text{rot}}}{\nu_{(1,1)}} \tau_{(1,1)m} \Delta V_{(1,1)} \text{(cm}^{-2}),
\]

where \( \nu_{(1,1)} \) is the frequency of the NH\(_3\) (1,1) in GHz and \( \Delta V_{(1,1)} \) is the line width in kilometres per second. In those pixels, where the (2,2) peak intensity is at a \(<3\sigma\) level, we assumed \( T_{\text{rot}} = 10 \text{ K} \), to be consistent with Ryabukhina & Kirsanova (2020).

In those directions, where \( \tau_{(1,1)m} \ll 1 \) or the hyperfine components are not visible, the (1,1) line is considered as optically thin. In this case \( T_{\text{rot}} \) and \( N_{1,1} \) are determined in the low optical depth approximation:

\[
T_{\text{rot}} = -41.5\ln \left( 0.2 \frac{\int T_{\text{MB}}(2,2) dv}{\int T_{\text{MB}}(1,1) dv} \right) \text{(K)},
\]

where \( \int T_{\text{MB}}(2,2) dv \) and \( \int T_{\text{MB}}(1,1) dv \) are the integrated intensities of the (2,2) and (1,1) lines, respectively (see Appendix). The \( N_{1,1} \) value is determined as:

\[
N_{1,1} = 3.3 \times 10^{14} \frac{T_{\text{rot}}}{\nu_{(1,1)}} \frac{\int T_{\text{MB}}(1,1) dv}{\int T_{\text{rot}} dv} - J(T_{\text{bg}}) \text{(cm}^{-2}),
\]

where \( T_{\text{bg}} = 2.73 \text{ K} \) is the background temperature, and \( J(T) = \left( h\nu_{(1,1)}/k \right) \exp \left( \frac{h\nu_{(1,1)}}{kT} - 1 \right) \).

We determined the total ammonia column density over the lowest metastable energy levels as:

\[
N_{\text{NH}_3} = N_{1,1} \left( \frac{\exp(21.3/T_{\text{rot}})}{3} + 1 + \frac{5 \exp(-41.2/T_{\text{rot}})}{3} + \frac{14 \exp(-99.4/T_{\text{rot}})}{3} \right) \text{(cm}^{-2}).
\]

Walmsley & Ungerechts (1983) and Tafalla et al. (2004) provide an equation for the gas kinetic temperature \( T_{\text{kin}} \):

\[
T_{\text{kin}} = \frac{T_{\text{rot}}}{1 - \frac{T_{\text{rot}}}{41.5} \ln(1 + 1.1 \exp \left( \frac{41.5}{T_{\text{rot}}} \right))} \text{(K)},
\]

where 41.5 K is the energy gap between the (1,1) and (2,2) levels. This equation is derived from fitting \( T_{\text{kin}} \) to the density distribution \( n(r) = n_0/(1 + (r/r_0)^2)^{3/2} \) to compare their observationally determined approximately constant rotational temperatures with modeled kinetic temperatures in dense quiescent molecular clouds (Tafalla et al. 2004; Tursun et al. 2022).

Using the obtained \( T_{\text{ex}} \) and \( T_{\text{kin}} \) values, Ho & Townes (1983) gave the following equation for the gas number density:

\[
n(H_2) = \frac{A}{C} \frac{J(T_{\text{ex}}) - J(T_{\text{bg}})}{J(T_{\text{kin}}) - J(T_{\text{ex}})} \left( 1 + \frac{J(T_{\text{kin}})}{h\nu/k} \right) \text{(cm}^{-3}),
\]

where \( A \) and \( C \) are the Einstein coefficient for spontaneous emission and the collision rate, respectively. According to Schöier et al. (2005), for typical \( T_{\text{kin}} = 25 \text{ K} \), the coefficients become \( A = 1.7 \times 10^{-7} \text{ s}^{-1} \) and \( C = 8.6 \times 10^{-11} \text{ cm}^{-3} \).

Under LTE conditions and without a line-of-sight velocity gradient, the two inner satellite lines and two outer satellite lines of the NH\(_3\) (1,1) transition have the same pairwise intensities. However, sometimes hyperfine intensity anomalies are observed in molecular clouds (see e.g. Stutzki & Winnewisser 1985; Park 2001; Zhou et al. 2020), in the sense that the intensities of red-shifted components are not equal to the intensities of their blue-shifted counterparts. We quantify these anomalies calculating the ratios of the satellite’s intensities after fitting them by independent Gaussian functions. We designate intensities of the red-shifted inner (I) and outer (O) satellites divided by intensities of the corresponding blue-shifted satellites as \( A_{IS} \) and \( A_{OS} \). The ratios \( A_{OS} = A_{IS} = 1 \) imply no anomaly. The case of \( A_{OS} > 1 \) and \( A_{IS} < 1 \) (brighter red-shifted outer component and fainter red-shifted inner component) can be explained by a model of unresolved small dense gas condensations embedded into a less dense medium (see Stutzki & Winnewisser 1985). Local velocity gradients can explain the case of \( A_{OS} > 1 \), \( A_{IS} > 1 \) (expansion) or \( A_{OS} < 1 \), \( A_{IS} < 1 \) (contraction) (see e.g. the radiative transfer calculations of Park 2001; Troitsky et al. 2004; Pavlyuchenkov et al. 2008).

5 RESULTS OF THE OBSERVATIONS

5.1 Ammonia emission in the dense clumps

Maps of the integrated intensities of the NH\(_3\) (1,1) and (2,2) lines in the dense clumps WB 668, WB 673, S233-IR and G173.57+2.43 are shown in Fig. 2. The critical density of the observed ammonia lines is quite high: \( n_{\text{crit}} = 1.8 \times 10^{3} \text{ cm}^{-3} \) for \( T_{\text{kin}} = 20 \text{ K} \) (Shirley 2015). Therefore, in the absence of depletion onto dust, the ammonia emission peaks mark the densest regions of the clumps. There is a coincidence between the ammonia emission peaks and IRAS sources in all the observed clumps except WB 673, where the sources are situated at the periphery of the clump with \( N_{\text{H}_2} < 2 \times 10^{22} \text{ cm}^{-2} \). However, all positions of the ammonia peaks correlate with the dust emission peaks of the 1.1 mm Bolocam data. While we do not have a convincing explanation for this discrepancy, in the following we will use the Bolocam data, because they were obtained at longer wavelengths, thus sampling the entire dust. To summarize, the dust emission peaks do not only indicate high column densities but are also characterised by particularly high volume densities. Contours
in Fig. 2 show the H$_2$ column densities ($N_{\text{H}_2}$), with the levels being $7 \cdot 10^{21}$, $2 \cdot 10^{22}$, and $7 \cdot 10^{22}$ cm$^{-2}$ (Ryabukhina & Kirsanova 2020). The NH$_3$ (1,1) integrated intensity increases with total hydrogen column density. The brightest lines appear in the WB 673 and S233-IR clumps, where the peak intensities reach 18 K km s$^{-1}$, and 5 K km s$^{-1}$ for the (1,1) and (2,2) lines, respectively. Weaker ammonia lines are found in the clumps WB 668 and G173.57+2.43, where the peak intensities reach 8 K km s$^{-1}$ for the (1,1) transition and 2.5 K km s$^{-1}$ for the (2,2) transition.

Examples of the NH$_3$ (1,1), (2,2) and (3,3) lines at the ammonia emission peaks are shown in Fig. 3. From the initial spectral resolution of 0.2 km s$^{-1}$, the spectra of the (3,3) transitions are smoothed to 0.4 km s$^{-1}$. The five groups of hyperfine components are detected in the (1,1) line towards dense clumps. Regions between these clumps are often devoid of detected emission. Parameters of the Gaussian fits are given in Table 2, where $\tau_{(1,1)}$ is the total optical depth over the (1,1) multiplet, $T_{\text{MB}}$ and $\Delta V$ are the main beam brightness temperature and the width of the (1,1), (2,2) and (3,3) lines. In all the observed positions the line widths contain a thermal and a non-thermal contribution. The thermal line width is 0.22 km s$^{-1}$ for a gas temperature $T = 20$ K (see below), while the observed line widths are $\approx 1.1$ km s$^{-1}$ in G173.57+2.43 and $\approx 2.0$ km s$^{-1}$ in the other clumps.

We find a moderate peak optical depth of the ammonia emission $\tau_{(1,1)} < 2$ in all observed clumps, where $\tau_{(1,1)} \approx 0.8$ in the two inner clumps (WB 673 and S233-IR) and reaching 1.8 in the two outer clumps (WB 668 and G173.57+2.43).

### 5.2 Physical conditions in the dense clumps

Maps of the ammonia column density ($N_{\text{NH}_3}$), gas kinetic temperature ($T_{\text{kin}}$) and the relative ammonia abundance ($X_{\text{NH}_3}$) in the dense clumps are presented in Fig. 4. The highest $N_{\text{NH}_3}$ values coincide with the dust emission peaks at 1.1 mm as we expected from the integrated intensity maps. Peak values are $N_{\text{NH}_3} = 1 - 2 \cdot 10^{15}$ cm$^{-2}$ in WB 668, WB 673 and S233-IR, but the value is lower by a factor of two in G173.57+2.43.

The gas kinetic temperature is confined to the range of 18–30 K. The highest $T_{\text{kin}} \approx 30$ K values are found in the central part of S233-IR. Values of $T_{\text{kin}} \approx 18 - 22$ K are observed throughout the whole area of WB 668 and WB 673. In G173.57+2.43, the inner part with $T_{\text{kin}} \approx 18$ K is surrounded by a warmer envelope with $T_{\text{kin}} \approx 26$ K. Therefore, these four observed clumps represent several distinct environments, namely a warm core with a cold envelope (S233-IR), a cold core with a warm envelope (G173.57+2.43) and quite uniform temperature distributions in WB 668 and WB 673. Median relative temperature errors are 12% for the WB 668 clump, 6% for WB 673, 10% for S233-IR and 16% for G173.57+2.43.

The relative ammonia abundance $X_{\text{NH}_3}$ decreases by up to an order of magnitude in the central and densest parts of WB 673 and S233-IR relative to their outskirts. The maximum $X_{\text{NH}_3} = 2 \cdot 10^{-7}$ is observed in the northern part of WB 673, but decreases to $2 \times 10^{-8}$ at the dust emission peak. The minimum abundance $\approx 1 - 2 \times 10^{-8}$ is found in the centre of S233-IR, and the abundance reaches $8 \times 10^{-8}$ at the periphery of the clump. There are north-south and west-east abundance gradients from about 0.2 to 1 $\times 10^{-7}$ in the WB 668 and G173.57+2.43 clumps, respectively, but no central depletion of ammonia abundance is discernible in the cores of these clumps. We note that the lowest value of $X_{\text{NH}_3}$ is observed in the warmest clump S233-IR. There are no other trends between such parameters as $N_{\text{NH}_3}$, $T_{\text{kin}}$ and $X_{\text{NH}_3}$ in the observed clumps, probably due to their complex structure unresolved in our data. Physical parameter values for the dust emission peaks at 1.1 mm with their respective errors are given in Table 4.

The gas number density reaches $2 \times 10^4$ cm$^{-3}$ in the two inner clumps (WB 673 and S233-IR), while it is $1.5 - 2$ times less in the outer clumps. The density peak in WB 673 coincides with the maximum of the dust continuum emission, while it is shifted to the south by $-36^\circ$ relative to the dust peak in S233-IR. The gas density peaks coincide with the dust emission peaks and locations of the infrared sources in the two peripheral clumps.

Fig. 5 allows us to analyse the hyperfine intensity anomalies using $A_{IS}$ and $A_{OS}$ values. The dotted lines divide the plot into separate quadrants, where the values pertaining to the various situations mentioned above (see end of Sect. 4) reside. Most $A_{IS} + A_{OS}$ pairs in the WB 673 clump match the local velocity gradient model corresponding to an infall motion. In the S233-IR clump, most pairs fall into the upper left quadrant with $A_{IS} < 1$ and $A_{OS} > 1$, which corresponds to the model of small unresolved clumps. There are also several pairs in the upper right quadrant weakly hinting at an expanding motion. No significant hyperfine anomalies are seen in WB668 and G183.57+2.43.

### 6 ASTROCHEMICAL MODELLING

In order to estimate the chemical ages of the observed clumps, we performed astrochemical modelling relying upon the physical parameters found in the present study. For that purpose, we used the Presta astrochemical model (see description of the model in Kochina et al. 2013), which includes both gas-phase and solid-phase processes taken from the ALCHEMIC database (Semenov & Wiebe 2011) with additions described by Wiebe et al. (2019). The initial gas chemical composition was taken from Lee et al. (1996) and is presented in Table 3. We start with purely atomic initial abundances and follow the chemical evolution for $10^8$ years.

The Presta model simulates an evolution of a 1D object. In this study, we set up clump physical parameters assuming spherical symmetry. This is justified as all the considered cores appear as isolated dense objects surrounded by less dense envelopes in our observations. They probably contain more complex inner structure, but this is not resolved in our observations. We made radial cuts through the number density maps (Fig. 4, bottom row) and averaged the cuts over the position angle. After that, we fitted the averaged density profiles using a quasi-universal Plummer-like function,

$$n(r) = \frac{n_0}{(1 + (r/r_0)^2)^{p/2}},$$

(8)

which is believed to be appropriate for the clumps belonging to the filamentary structure (André et al. 2014). Here $n_0$ is the density at the centre of the clump, $r_0$ is the radius of the flat inner region, $p$ is the power-law exponent at $r > r_0$. Flat inner region means that at a radius less than $r_0$, the density is approximately $n_0$. Derived profile parameters are given in Table 4. The density profile for clump WB 673 is shown in Figs. 6. Since the temperature range in the clumps is narrow, a constant temperature $T$ is adopted in all the models. Gas and dust temperatures are assumed to be equal. Figs. 6 also shows radial profiles of the column densities of ammonia (this study) and other molecules (N$_2$H$^+$, CS, CO, HCN, HNC, taken from Ryabukhina & Kirsanova 2020) averaged over the azimuthal angle. Error bars over the radial profiles show the scatter of original values.

The Presta model produces radial abundance profiles for various molecules at different moments of the cloud evolution. These relative
Figure 2. Integrated intensities of NH$_3$ (1,1) (top) and NH$_3$ (2,2) (bottom) lines from WB 668, WB 673, S233-IR and G173.57+2.43. The colour bar shows the intensities in K km s$^{-1}$. Maps are cut at levels of 3$\sigma$, which are 0.35 and 0.33 K km s$^{-1}$ for the (1,1) and (2,2) lines, respectively. Compact red ellipses show IRAS sources (the size of the ellipse corresponds to the position uncertainties), compact blue circles show MSX sources. White contours provide H$_2$ column density, where the contours correspond to $7 \cdot 10^{21}$, $2 \cdot 10^{22}$ and $7 \cdot 10^{22}$ cm$^{-2}$ (Ryabukhina & Kirsanova 2020).

Figure 3. The observed ammonia lines at the emission peaks. Red lines show Gaussian fits obtained with the CLASS Gildas package.
7 MODELLING RESULTS

We used a chemical model with $T = 20\,\text{K}$ and zero intensity of the radiation field ($G_0 = 0$) as a reference model in our study. The adopted cosmic ray ionisation rate was $\zeta = 3 \times 10^{-17}\,\text{s}^{-1}$ for each clump. The simulations were performed for a broad range of input parameters, varied relative to the reference model. Namely, we tried lower and higher temperatures (up to $\pm 10\,\text{K}$), hydrogen volume density $n_0$ (up to $\pm$ one order of magnitude), cosmic ray ionisation rate (up to one order of magnitude). Also various non-zero interstellar radiation fields with depth-dependent $A_V$ were tested. In addition, we considered a model with a long ($5 \times 10^5\,\text{yrs}$) preceding stage of gas accumulation at $T = 10\,\text{K}$, the characteristic temperature for dark clouds (e.g. Myers & Benson (1983)). We found the best agreement between the simulated and observed molecular column densities in the reference model, described above.

The obtained $\Sigma$ values (see the end of Sect. 6) from our comparison between the model and the observations are shown for each clump in Fig. 6. There are several repeating patterns in the results of the simulations for all clumps in the filament. First, the computed column densities of CO and CS are lower than the observed ones over almost the entire modelled time interval. The differences exceed an order of magnitude for clump ages exceeding several Myr for both molecules. This seemingly excludes a large chemical age for the filament. Second, simulated CS column densities agree with the observed ones to within an order of magnitude for a model time $t \leq 10^5\,\text{yrs}$. Finally, simulated column densities of the N-bearing molecules NH$_3$ and N$_2$H$^+$ approach the observed values at $t \approx 2 \times 10^5\,\text{yrs}$ and at $t > 10^5\,\text{yrs}$. Simulated column densities of HCN and HNC molecules exceed the observed ones by 1 to 2.5 orders of magnitude throughout the entire model time for WB 673. Unfortunately, the lack of data on these molecules in the other clumps prevents us from analysing them.

The correspondence criteria $\Sigma$ for each clump are shown in Fig. 7. The Y-axis shows the sum of the $\Sigma$ values for all the considered molecules in the clump. $\Sigma = 1$ means an agreement for just one molecule at a specific model time, $\Sigma = 4$ means a full agreement for WB 668 and G173.57+2.43, but only agreement in two out of three cases for WB 673, where we have data from more molecular species. While the periods of the best agreement and the highest $\Sigma$ are not exactly the same for the clumps, they all show the best agreement at $t = 1 \sim 3 \times 10^5\,\text{yrs}$. Therefore, considering the clumps as parts of one single filament which was formed at some particular moment of time, we may assume this value as its chemical age. To summarise, the filament was formed rather quickly without a long previous stage of initial gas accumulation.

8 DISCUSSION

Two-phase (gas and dust) astrochemical models of molecular clouds show two regimes during the evolution of an interstellar molecular cloud, which are characterised by typical abundant species: ‘early’ and ‘late’ (e.g. Bergin & Langer 1997; Aikawa et al. 2001; Shevchutovich et al. 2003). The models show how molecules such as CO and CS are formed rapidly in the gas phase and they become tracers of ‘early’ chemistry. ‘Late’ N$_2$H$^+$ and NH$_3$ molecules are formed after accretion of CO on cold dust grains. Therefore, the stage of decreasing ‘early’ and increasing ‘late’ molecules, which takes place in our models at the time $t = 1 \sim 3 \times 10^5\,\text{yrs}$, represents the transition between the two chemical regimes, see Fig. 6.

Looking at the maps of $X_{\text{NH}_3}$ in Fig. 4, we note higher ammonia abundances at the edges of the clumps rather than in their centres. The same is true for CS, CO, and other molecules, observed in these clumps by Ryabukhina & Kirsanova (2020). Depleted molecular abundances at the centre of the clumps can be attributed to their freeze-out on the surfaces of dust grains and are commonly observed in dark starless clouds (e.g. Tafalla et al. 2002; Jiménez-Serra et al. 2016; Pineda et al. 2022, and many others). However, the dense clumps in this study demonstrate signs of high-mass star formation according to Ladevyschikov et al. (2016): water masers at 22 GHz, molecular outflows, IRAS and MSX sources with colors...
corresponding to embedded H II regions in WB 673 and S233-IR and young stellar clusters at least in S233-IR (see also Porras et al. 2000). Ladeyschikov et al. (2016) also found proofs of gravitational instability in the clumps as virial parameters ($\alpha = M_{\text{vir}}/M$) do not exceed the critical value $\alpha_{\text{crit}} = 2$ (Kauffmann et al. 2013).

The discrepancy between the existence of signs of star formation and cold chemistry in the clumps can be explained by the high density of the molecular gas surrounding the young stellar objects. Therefore, the rise of temperature, related to star formation activity is not sufficient to overwhelm the cold chemistry in the clumps. We mentioned above that the clumps are in an early stage of the star formation process. Another possible reason can be related to a deficit
Table 4. Parameters of the density distribution and derived physical parameters at clump centres

| Clump         | Plummer-like density distribution | Derived physical parameters |
|---------------|-----------------------------------|----------------------------|
|               | \( n_0 \)  \( r_0 \)  \( p \) | \( T_{\text{kin}} \)  \( N(\text{NH}_3) \)  \( x(\text{NH}_3) \) |
| WB 668        | 7.4  0.126  0.20               | 22 \( \pm \) 2  12 \( \pm \) 4  9 \( \pm \) 3 |
| WB 673        | 13.3  0.219  0.40             | 19 \( \pm \) 1  9 \( \pm \) 3  5 \( \pm \) 1 |
| S233-IR       | 16.9  0.014  0.11             | 29 \( \pm \) 2  12 \( \pm \) 3  3 \( \pm \) 1 |
| G173.57+2.43  | 12.8  0.040  0.35             | 20 \( \pm \) 2  7 \( \pm \) 3  5 \( \pm \) 2 |

Our result supports the idea by Inutsuka et al. (2015) about formation of molecular filaments after multiple compression by supernova remnants or expanding wind-blown bubbles or H \( \alpha \) regions. Kang et al. (2012) found young supernova remnants whose age is \( \approx 3.3 \times 10^5 \) yrs in the direction of G174+2.5. Kirsanova et al. (2017) report that the filament is situated on the border of a large and faint infrared envelope whose origin is still unknown. Therefore, we can not exclude external influence on the formation of the filament because its chemical age is similar to the age of the remnant Kang et al. (2012). The H \( \alpha \) region S231 is situated on the eastern side of the filament, see Fig. 1. We note a tighter location of star-forming regions in those parts of the filament which border the H \( \alpha \) region. This fact indirectly supports the influence of S231 on star formation in the filament.

9 CONCLUSIONS

We observe and analyse ammonia emission lines toward the interstellar filament WB 673 and perform astrochemical modelling using results of the analysis in the present study. While we map the whole filament, we detect emission in the (1,1), (2,2) and (3,3) ammonia lines only in four dense clumps: WB 668, WB 673, S233-IR and G173.57+2.43. Peaks of the emission are found in the direction of the dust emission peaks at 1.1 mm in the clumps. The ammonia lines are moderately optically thick with 0.8 \( \leq \tau_{(1,1)} \leq 1.8 \) at the emission peaks.

Using an LTE approach, we determine gas kinetic temperature, number density and ammonia column density in the dense clumps. The temperature reaches up to 30 K in the clumps. Therefore they are still cold in spite of embedded high-mass star-forming regions. The peaks of the ammonia column density in the densest parts of the clumps are almost the same, \( \approx 1 - 2 \times 10^{15} \) cm\(^{-2}\), based on an angular resolution of 40" and a corresponding linear resolution of 0.3 pc.

Considering anomalies of the ammonia hyperfine lines, we find signatures of a collapse in WB 673. Anomalies in S233-IR correspond to a model of a medium consisting of unresolved dense clumps. We also found signatures of expansion (outflow) in S233-IR.

We reconstructed 1D density and temperature distributions in the clumps and performed their astrochemical modelling to find a chemical age of the filament. Considering four molecules: CO, CS, NH\(_3\), N\(_2\)H\(^+\) (+ HCN and HNC for WB 673), we find that the best agreement between the simulated and observed column densities reaches at \( t_{\text{chem}} = 1 - 3 \times 10^5 \) yrs simultaneously for all the clumps. Playing with initial conditions of the chemical model, we conclude that the \( t_{\text{chem}} \) value represents the chemical age of the filament itself because for every clump the agreement is the best at this moment. Long preceding low-density stage of gas accumulation in the astrochemical model, breaks the agreement between the simulated and observed
column densities. Therefore, our results agree with a scenario of rapid star formation over a timescale of $\sim 10^5$ yrs.

Internal heating sources, related to embedded high-mass young stellar objects, do not impact much on the chemistry of the dense clumps, presumably due to a high density of the surrounding material.

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**DATA AVAILABILITY**

The data underlying this article are available in Zenodo at https://doi.org/10.5281/zenodo.7142880.

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In the following we discuss the methods used for calculating rotational temperature in an optically thin case.

From the Boltzmann equation, we can obtain the relation between the temperature and the populations in the levels (J, K) and (J', K') (Mangum et al. 1992):

\[
\frac{n(J', K')}{n(J, K)} = \frac{g(J', K')}{g(J, K)} \exp\left(-\frac{\Delta E(J', K'; J, K)}{T_{\text{rot}}}ight),
\]

(9)

where \( g(J, K) = 2J + 1 \). In the case of a homogeneous molecular cloud, the level populations are related as the column density of these levels:

\[
\frac{n(J', K')}{n(J, K)} = \frac{N(J', K')}{N(J, K)}.
\]

(10)

For ammonia, the column density in an optically thin case is:

\[
N(J, K) = \frac{3hJ(J+1)}{8\pi^2\mu^2k^2} \left(1 + \exp\left(-\frac{h\nu}{kT_{\text{ex}}}\right)\right) \int T_{\text{MB}}dV
\]

(11)

Combining equations 10, 11 for case (J, K) = (1, 1); (J', K') = (2, 2), assuming LTE \( T_{\text{ex}} \) is equal:

\[
\frac{n(2, 2)}{n(1, 1)} = \frac{3 \int T_{\text{MB}(2, 2)}dV}{\int T_{\text{MB}(1, 1)}dV}
\]

(12)

From equation 9, the rotational temperature in the optically thin case is defined as:

\[
T_{\text{rot}} = -\frac{41.5}{\ln\left(0.2 \frac{\int T_{\text{MB}(2, 2)}dV}{\int T_{\text{MB}(1, 1)}dV} \right)}(K)
\]

(13)