A multi-line study of the filamentary infrared dark cloud G351.78-0.54

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ABSTRACT
We present results of a multi-line study of the filamentary infrared dark cloud G351.78-0.54 in the 1.3 and 0.8 mm wavelength bands. The lines of the three isotopologues of carbon monoxide CO, N2H+, CH3CCH and HNCO were observed. The aim was to study the general structure of the filamentary cloud, its fragmentation and physical parameters with the emphasis on properties of dense clumps in this cloud. Several dense clumps are identified from the N2H+ (3–2) data, their masses and virial parameters are determined using the C18O (2–1) line. Temperatures of some clumps are estimated from the CH3CCH and HNCO data. Almost all clumps appear to be gravitationally unstable. The density estimates obtained from the C18O (3–2)/(2–1) and N2H+ (3–2)/(1–0) intensity ratios are in the range n ~ (0.3 – 3) x 10^5 cm^-3. The HNCO emission is detected exclusively toward the first clump which contains the luminous IR source IRAS 17233-3606, and indicates an even higher density. It is observed in the outflow, too. The velocity shift of the higher excitation HNCO lines may indicate a movement of the hot core relative to the first clump which contains the luminous IR source IRAS 17233-3606, and indicates an even higher density. It is observed in the outflow, too. The velocity shift of the higher excitation HNCO lines may indicate a movement of the hot core relative to the filamentary structure is clearly visible in emission at 500 μm, and as a dark lane in the 8 μm map. There is a network of fibers associated with the main structure (Leurini et al. 2019).

Key words: stars: formation — ISM: clouds — ISM: molecules — ISM: individual objects (G351.78-0.53)

1 INTRODUCTION
Filamentary structures in the interstellar medium are known for a long time already. They have been observed in the far infrared range surveys (e.g. Low et al. 1984), in the H I emission (e.g. McClure-Griffiths et al. 2006) and in molecular lines (e.g. Bally et al. 1987; Myers 2009). They attracted an enhanced attention since the Herschel Space Observatory (Pilbratt et al. 2010) demonstrated the ubiquitous presence of filaments in nearby clouds (André et al. 2010, 2014). Pre-stellar cores are observed predominantly along the filaments. As a result, a new paradigm of star formation was suggested, in which filaments play a leading role in this process (André et al. 2014).

While Herschel observations were focused on nearby clouds, extensive galactic-wide surveys of filamentary structures have been performed to date (e.g. Li et al. 2016; Schisano et al. 2020). Statistical distributions of basic physical parameters of interstellar filaments have been derived. Nevertheless, detailed studies of individual objects are required for better understanding their physical properties and processes of star formation. In this respect, infrared dark clouds (IRDC) attract special attention. At least some of them may represent birth places of massive stars (Rathborne et al. 2006; Kauffmann & Pillai 2010). The process of high mass star formation is still puzzling in many respects and is actively investigated (e.g. Tan et al. 2014; Motte et al. 2018). Many IRDCs are filamentary (Schisano et al. 2020).

Reliable estimates of the physical conditions in interstellar clouds require multi-transitional data. Here we present the results of such multi-transitional study of the filamentary infrared dark cloud G351.78-0.54. It is worth noting that several designations are used for this object in the literature: G351.77-0.54 (Beuther et al. 2017), G351.77-0.51 (Leurini et al. 2011b), G351.776-0.527 (Leurini et al. 2019). In the middle part of this cloud the luminous IR source IRAS 17233-3606 (α(J2000) = 17h26m42s8, δ(J2000) = −36°09'17") is located. This source was a target for many studies (Beuther et al. 2017, 2019; Antyufeyev et al. 2016; Klaassen et al. 2015; Leurini et al. 2008, 2011a, 2014). The distance to this object is estimated in the range of 0.7 – 1 kpc (Leurini et al. 2011b; Wienen et al. 2015). We adopt here the distance of 1 kpc. Investigations of the filament itself are more limited. The length of the filament is 4.6 parsecs, the width is 0.2 pc, the mass exceeds 1300 M☉ (Leurini et al. 2011b; Antyufeyev et al. 2016). In Leurini et al. (2011b) twelve clumps were identified and described with the help of the CLUMPFIND method on the basis the 870 μm continuum emission and lines of the CO isotopologues. The authors conclude that star formation is continuous at different stages of evolution. The broad profiles of molecular lines can be a consequence of shock compression due to the expanding H II regions. However, it was not possible to determine the driving source (Leurini et al. 2011b).

Fig. 1 shows this region in the infrared range at λ = 500 μm (Herschel) and 8 μm (Spitzer). The filamentary structure is clearly visible in emission at 500 μm, and as a dark lane in the 8 μm map. There is a network of fibers associated with the main structure (Leurini et al. 2019).

The aim of the current work is to investigate further the fragmentation and physical properties of this cloud with the emphasis on properties of dense clumps. For this purpose we observed this...
area in several molecular lines. Here, we present the observations and analysis of the data, including dense clump identification and determination of their properties.

2 OBSERVATIONS AND DATA ANALYSIS

The observations were carried out with the APEX radio telescope (Güsten et al. 2006) in 2010–2017 in the wavelength ranges of 1.3 mm and 0.8 mm (projects O-085.6–9323, O-086.5–9316, O-097.6–9303, O-098.5–9306) using SHExFI receivers (Vassilev et al. 2008; Belitsky et al. 2006). The beam width at the half power level (HPBW) ranged from 27″ to 17″. The data are converted to the main beam temperature scale using the main beam efficiencies ($\eta_{mb}$) presented on the APEX web site. We adopt $\eta_{mb} = 0.75$ at 1.3 mm and $\eta_{mb} = 0.7$ at 0.8 mm as derived from Jupiter observations since the size of the observed compact structures is comparable to Jupiter. At 0.8 mm there is a rather large scatter in the estimates of this parameter. The adopted value is in a reasonable agreement with the most of these estimates and with the Ruze formula.

The list of the observed lines, which are analyzed here, is presented in Table 1. It includes CO (2–1), $^{13}$CO (2–1), C$^{18}$O (2–1), $^{15}$CO (3–2), C$^{18}$O (3–2), N$_2$H$^+$ (3–2), CH$_3$CCH (13$\nu$ – 12$\nu$) and several HNCO transitions. The line parameters are taken mainly from the Cologne Database for Molecular Spectroscopy (CDMS) (Müller et al. 2001, 2005; Endres et al. 2016) and from the Jet Propulsion Laboratory (JPL) catalog1 (Pickett et al. 1998). The spectral resolution (channel width) was 244 kHz in the $^{13}$CO (2–1), C$^{18}$O (2–1), N$_2$H$^+$ (3–2) and HNCO observations. In the CO (2–1), $^{13}$CO (3–2), C$^{18}$O (3–2) and CH$_3$CCH observations it was 76 kHz. The corresponding resolution in velocity is 0.10 kms$^{-1}$ in CO (2–1) and CH$_3$CCH, 0.33 kms$^{-1}$ in $^{13}$CO (2–1), C$^{18}$O (2–1) and HNCO (10–9), 0.07 kms$^{-1}$ in $^{15}$CO (3–2), C$^{18}$O (3–2) and HNCO (15–14), 0.26 kms$^{-1}$ in N$_2$H$^+$ (3–2).

The median value of the RMS noise at this resolution at the $T_{mb}$ scale is 0.13 K in the CO (2–1) spectra, ~ 0.1 K in the $^{13}$CO (2–1) and C$^{18}$O (2–1) spectra, ~ 0.6 K in the $^{13}$CO (3–2) and C$^{18}$O (3–2) spectra, ~ 0.1 K in the N$_2$H$^+$ (3–2) spectra, 0.02–0.11 K in the CH$_3$CCH spectra, ~ 0.07 K in the HNCO (10–9) spectra and ~ 0.09 K in the HNCO (15–14) spectra.

The observations were performed in the position-switching mode. The reference positions were different for different observations. In some cases a significant emission was apparently present at the reference position resulting in negative features in the measured spectra. In particular this is a case for the $^{13}$CO (2–1) and C$^{18}$O (2–1) observations. At least a part of these data contains a narrow such feature at ~ 3.6 kms$^{-1}$. Its width is ~ 0.6 kms$^{-1}$ in C$^{18}$O (2–1) and ~ 1 kms$^{-1}$ in $^{13}$CO (2–1). The integrated intensity of this feature in the average spectra is ~ 0.3 K kms$^{-1}$ in C$^{18}$O (2–1) and ~ 2 K kms$^{-1}$ in $^{13}$CO (2–1). For C$^{18}$O (2–1) it constitutes about 4% of the integrated intensity of the average spectrum and therefore has a negligible effect on the estimates of the C$^{18}$O column density. However this feature should be taken into account when analyzing the line profiles. In the CO (2–1) spectra there is a negative feature at about ~ 7 kms$^{-1}$ with the amplitude of about 2.5 K and also several features around ~ 20 kms$^{-1}$. All these features are far from the systemic velocity of the investigated object.

The line data were processed using the CLASS program from the GILDAS2 (Maret et al. 2011) package, and for further analysis of the obtained images, the MIRIAD (Sault et al. 1995) and Astropy (Astropy Collaboration et al. 2018) packages were used. Starlink software package (Currie et al. 2014) was used to identify molecular clumps. Estimates of the rotational temperature for the CH$_3$CCH transitions were obtained with the CASSIS software3. The package PySpecKit (Ginsburg & Mirocha 2011) was used to simulate the hyperfine structure of the N$_2$H$^+$ (3–2) line. For the excitation analysis of $^{15}$CO, C$^{18}$O and N$_2$H$^+$, the Radex program was used (Van der Tak et al. 2007).

3 RESULTS

3.1 Gas distribution and kinematics

In Fig. 2 we present maps of the integrated intensity (0th moment, $M_0$) in the lines $^{13}$CO(2–1), $^{13}$CO(3–2), C$^{18}$O(2–1), C$^{18}$O(3–2) and N$_2$H$^+$(3–2). The filamentary structure is visible in all maps.

Fig. 3 shows the map of the integrated intensity ratio C$^{18}$O(3–2)/C$^{18}$O(2–1). To construct this map the C$^{18}$O(3–2) map was smoothed to the same angular resolution as the C$^{18}$O(2–1) map. This ratio may serve as an indicator of the physical conditions in the emission regions. The ellipses show clumps detected by GaussClump using a dense gas tracer N$_2$H$^+$ (Sect. 3.3).

| Molecule | Transition | Frequency (GHz) | $E_J$ (K) |
|----------|------------|----------------|----------|
| CO       | 2–1        | 230.538        | 5.53     |
| $^{13}$CO | 2–1        | 220.399        | 5.29     |
| C$^{18}$O | 3–2        | 330.588        | 15.87    |
| N$_2$H$^+$ | 3–2        | 219.560        | 5.27     |
| CH$_3$CCH | 130–120   | 222.166        | 63.98    |
| HNCO     | 10$_{1,0}$–9$_{0,9}$ | 219.798 | 47.47 |
|          | 10$_{1,1}$–9$_{1,0}$ | 218.981 | 90.57 |
|          | 10$_{1,2}$–9$_{1,1}$ | 220.585 | 90.92 |
|          | 10$_{1,3}$–9$_{1,2}$ | 219.734 | 217.74 |
|          | 10$_{1,4}$–9$_{1,3}$ | 219.737 | 217.74 |
|          | 10$_{1,5}$–9$_{1,4}$ | 219.657 | 422.42 |
|          | 10$_{1,6}$–9$_{1,5}$ | 219.657 | 422.42 |
|          | 15$_{0,1}$–14$_{0,14}$ | 329.664 | 110.76 |
|          | 15$_{1,2}$–14$_{1,1}$ | 329.573 | 281.01 |
|          | 15$_{1,3}$–14$_{2,1}$ | 329.585 | 281.01 |
|          | 15$_{1,4}$–14$_{3,1}$ | 329.460 | 485.67 |
|          | 15$_{1,5}$–14$_{4,1}$ | 329.460 | 485.67 |
|          | 15$_{1,6}$–14$_{5,1}$ | 329.295 | 761.39 |
|          | 15$_{2,1}$–14$_{6,10}$ | 329.295 | 761.39 |

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1 https://spec.jpl.nasa.gov
2 http://www.iram.fr/IRAMFR/GILDAS
3 http://cassis.irap.omp.eu
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3.2 Column density

In order to characterize the general distribution of the CO and N$_2$H$^+$ molecules we constructed maps of their column densities. The column densities of the C$^{18}$O and N$_2$H$^+$ molecules were calculated using the method presented in Mangum & Shirley (2015) on the basis of the C$^{18}$O(2–1) and N$_2$H$^+$(3–2) data. The first line is a tracer of the total molecular gas column density, while the second one is known to depict denser molecular gas compared to the C$^{18}$O data. We assume a low optical depth in the lines and the local thermodynamic equilibrium (LTE) conditions:

$$N = \frac{3h}{8\pi^3\mu^2} \frac{Q_{\text{rot}}}{g_J g_K g_I} \exp\left(\frac{E_u}{kT_{\text{ex}}}\right) \left[ \int T_R dv \right],$$

where $h$ is the Planck constant, $S = J_u/(2J_u + 1)$ is the line strength, $\mu$ is the dipole moment, $Q_{\text{rot}}$ is the partition function, $g_J = 2J + 1$ is the rotational degeneracy, $g_K$ is $K$-degeneracy, $g_I$ is the degeneracy of the nuclear spin, $J_u(T)$ is the equivalent Rayleigh-Jeans temperature, $T_{\text{ex}}$ is the excitation temperature, $T_{\text{bg}}$ is the background temperature and the term $\int T_R dv$ is the integrated intensity of the line. For C$^{18}$O and N$_2$H$^+$ molecules, $g_K = g_I = 1$ and $Q_{\text{rot}} \approx kT/hB + 1/3$, where $B$ is the rotational constant. We assume that the molecules are thermalized with the excitation temperature being equal to the gas kinetic temperature, i.e., $T_{\text{ex}} = T_{\text{kin}}$, and that this equals the dust temperature, $T_{\text{dust}}$. We estimate the dust temperature from the Herschel Hi-GAL data at 160–500 $\mu$m using the approach described in Mallick et al. (2015). It is based on fitting the data with a modified black body spectrum. $T_{\text{dust}}$ and $N$(H$_2$) are free parameters. As a result, maps of the distribution of these parameters were obtained. The temperature lies in the range of 12 – 23 K, and rises towards the IRAS 17233–3606 source. However, in the direction of the IRAS source itself, it was not possible to inscribe such a model, and a temperature of 25 K was adopted there, as in Leurini et al. (2019). In general, the temperature values are very close to the map presented in (Leurini et al., 2019), so we do not show them here. Based on the 20% calibration uncertainty assigned to the Hi-GAL fluxes, a median temperature uncertainty is 13% – 18% (Battersby et al. 2011).

Assumption of $T_{\text{kin}} = T_{\text{dust}}$ is only accurate in dense regions ($n \geq 10^5$ cm$^{-3}$) shielded from the UV emission, however, the gas temperature may exceed the dust temperature near infrared sources (Koumpia et al. 2015). The C$^{18}$O column density is related to the hydrogen column density via a constant relative abundance C$^{18}$O/H$_2$ = 2.0 $\times$ 10$^{-7}$ (Liu et al. 2013) at the galactocentric distance of 7.4 kpc. The map of the hydrogen column density was obtained from the map of $N$(C$^{18}$O) using this relation. Although the hydrogen column density was estimated also from the Hi-GAL data, we use this map.
for consistency with the other works (e.g. Leurini et al. 2019). Next, pixel-by-pixel division of the column density maps of N$_2$H$^+$ to H$_2$ was performed. The obtained maps of the distribution of the C$^{18}$O, N$_2$H$^+$ column density and N$_2$H$^+$ relative abundance are shown in Fig. 4). On the map of the N$_2$H$^+$ column density dense clumps are marked by white ellipses (see Sect. 3.3). It can be seen that in the direction of the luminous IR source IRAS 17233–3606, the abundance of N$_2$H$^+$ decreases. Taking into account the uncertainties in the dust temperature and integrated intensity of the C$^{18}$O and N$_2$H$^+$ lines, we find that the N(C$^{18}$O) uncertainty does not exceed 5% and in the direction of dense clumps with a high signal-to-noise ratio it decreases to 3%. Taking into account the negative feature in the C$^{18}$O (2–1) observations caused by the emission at the reference position (Sect. 2), the column density is underestimated. Since the integrated intensity of this feature is $\sim 0.3$ K km s$^{-1}$, the corresponding column density is $1.5 \cdot 10^{14}$ cm$^{-2}$, while the median N(C$^{18}$O) is $6.7 \cdot 10^{15}$ cm$^{-2}$. Hence, the average underestimation does not exceed 2%. The uncertainty in N(N$_2$H$^+$) does not exceed 20% in the direction of dense clumps, in other directions it reaches 50%.

By integrating the column density map of hydrogen we obtain the total mass of the filament as $1800 \pm 50$ M$_\odot$. The integration area is limited by the integrated intensity of the C$^{18}$O (2–1) line of 5 K km s$^{-1}$ (Fig. 1). It roughly corresponds to the signal to noise ratio of about 5 for the most noisy C$^{18}$O (2–1) spectra.

The part of the filament we are studying has a length of 3.4 pc, and the mass to length ratio $M_{\text{line}} = 529$ M$_\odot$/pc. According to Dewangan et al. (2019), the virial (or critical) line mass for a filament with non-thermal gas motions is calculated as

$$M_{\text{line, vir}} = 1 + \left( \frac{\sigma_{NT}}{c_s} \right)^2 \times 16M_\odot \text{pc}^{-1} \times \left( \frac{T}{10K} \right),$$

where $c_s$ is the sound speed, $T$ is kinetic temperature and $\sigma_{NT}$ is the non-thermal velocity dispersion, which is defined by:

$$\sigma_{NT} = \sqrt{\frac{\Delta V^2}{8 \ln 2} - \frac{kT}{30m_H}},$$

where $\Delta V$ is the C$^{18}$O line width, $k$ is the Boltzmann constant, $m_H$ is the mass of a hydrogen atom. The averaged over the entire filament C$^{18}$O (2–1) line width is 2.5 km s$^{-1}$, the average temperature is 18 K. For our filament the critical line mass is $M_{\text{line, vir}} = 512$ M$_\odot$/pc. Taking into account the uncertainties, the mass to length ratio $M_{\text{line}}$ is practically equal to the critical value. However, under the conditions of a possible falling motion inside the filament the velocity dispersion shows larger values than under virial equilibrium, therefore the $M_{\text{line, vir}}$ artificially increases (Ballesteros-Paredes et al. 2011). Hence, the presented estimate is the upper limit of the linear critical mass. On the other hand, the derived mass to length ratio is also an upper limit since it does not take into account a possible inclination of the filament. In any case the observations show that the process of fragmentation is going on.
temperature according to Herschel data, \(M\) is the clump mass, \(M_{\text{vir}}\) is the virial mass, \(\sigma_{\text{vir}}\) is the virial parameter.

According to Kauffmann et al. (2013), clumps are unstable and star formation processes can start when \(\sigma_{\text{vir}} \leq \sigma_{\text{crit}} \approx 2\). According to the values we obtained, this criterion is met by all clumps except the sixth one.

Spectra averaged over clumps are shown in Fig. 5. The blue dashed lines indicate the systemic velocity of each clump as \(V_{\text{LSR}}\) of the \(^{18}\)CO (3–2) line. The velocity values are given in Table 2. The green solid lines indicate the velocity of the emission at the reference position in the \(^{13}\)CO and \(^{18}\)CO (2–1) lines. Optically thick CO (2–1) line shows a complex wide spectrum with dips. The maximum width (up to 10 km/s) is observed in the direction of the first clump, and such a width may indicate outflow in this direction. The spectra of \(^{13}\)CO \(J = 2–1\), 3–2 are narrower. The blue asymmetry of the \(^{13}\)CO (3–2) line seen in all clumps is indicative of infall (e.g. Snell & Loren 1977). The profiles of the \(^{13}\)CO (2–1) line can be influenced by the emission at the reference position. Nevertheless, they also show real self-absorption dips at least in the first and second clumps (at about −2 km s\(^{-1}\)). The optically thin \(^{18}\)CO line has an even smaller width and smaller dips, and in \(N_2H^+\) (3–2) toward the first clump there is no dip at all.

It is worth mentioning the apparent velocity shift between \(N_2H^+\) (3–2) and CO isotopologues in some clumps. We discuss this later.

According to Fig. 3, the ratio of the integrated intensities \(^{18}\)CO(3–2)/CO(2–1) reaches a value ~ 1.5 toward the first clump, however, in Fig. 5 the intensities are approximately equal. The reason is that in Fig. 5 spectra averaged over clumps are presented; therefore, the high ratio, which appears in some pixels, is smoothed out.

We modelled the \(^{18}\)CO (3–2)/(2–1) ratio with the Radex package (Fig. 6) assuming the \(^{18}\)CO column density sufficiently low to ensure a low optical depth in the lines. By comparison with the observations this model places some constraints on the density and/or temperature of the clumps. For the first clump the observed ratio reaches a value ~ 1.5. This is inconsistent with the temperature of 25 K from the Herschel data (Table 2). However for the average spectra the ratio is ~ 1, which implies density ~ \(4 \times 10^4\) cm\(^{-3}\) at \(T_K = 25\) K. For the second clump the average ratio is also ~ 1. At the temperature of 18 K from Herschel this implies a very high density \(\gtrsim 10^6\) cm\(^{-3}\). However, our \(CH_3CCH\) data indicate a somewhat higher temperature (see below) which is consistent with the density similar to that in the first clump. For the other clumps the \(^{18}\)CO (3–2)/(2–1) ratio varies from ~ 0.5 to ~ 0.75 and their temperature according to Herschel is ~ 15 K. This implies densities ~ \(3 \times 10^4\) cm\(^{-3}\).

In order to better characterize kinematics of the clumps we present in Fig. 7 maps of the first moment (which correspond to the velocity) and the line width (obtained from fitting by a single Gaussian) in the \(N_2H^+(3–2)\) line toward all six clumps. In most clumps there are apparent velocity gradients. The line width peaks in the center of the clumps. We discuss these maps in Sect. 4.

Fig. 8 shows the map of the region G351.78–0.54 in the mid-infrared range at \(\lambda = 24\) \(\mu\)m (Spitzer) with clumps, obtained in this work. There is a chain of mid-IR sources along the filament, but in clumps 1–3 and 5 they are the most luminous.

3.4 Kinetic temperature from \(CH_3CCH\)

The kinetic temperature of the gas was estimated from observations of the \(CH_3CCH\) (13–12) line using the “rotation diagram” or “population diagram” method (Goldsmith & Langer 1999). The methylacetylene molecule is a type of symmetric top and is a reliable indicator of kinetic temperature even at rather low densities (Bergin...
These calculations were performed using the Cassis program. For several lines of the same rotational transition with different values of the $K$ projection for a molecule of the symmetric top type, under the LTE conditions the following relation holds:

$$\ln \frac{N_u}{g_u} = \ln \frac{N_{\text{tot}}}{Q(T_{\text{rot}})} = \frac{E_U}{kT_{\text{rot}}}$$

where $N_u$ is the population of each level, $g_u$ is statistical weight, $N_{\text{tot}}$ is total column density. Up to 7 lines of the CH$_3$CCH (13–12) transition are detected (see Table 1), for which we build the dependence of $\ln \frac{N_u}{g_u}$ on $\frac{E_U}{kT_{\text{rot}}}$. The kinetic temperature $T$ is found as the reciprocal of the slope of a straight line approximated by this dependence. A total of six positions were observed along the filament, however, a sufficiently strong emission is detected only toward the
Table 2. Clumps parameters

| Clump | \(\alpha_{2000}\) | \(\delta_{2000}\) | D, pc | FWHM C\(^{18}\)O (2–1), km s\(^{-1}\) | \(V_{LSR}\) C\(^{18}\)O (3–2), km s\(^{-1}\) | T, K | M, M\(^\odot\) | M\(_{\text{vir}}\), M\(^\odot\) | \(\alpha_{\text{vir}}\) |
|-------|-----------------|-----------------|---------|---------------------|---------------------|---------|----------|----------------|--------------|
| 1     | 17 26 43        | −36 09 18       | 0.30 × 0.26 | 5.46 ± 0.04        | −3.15 ± 0.01        | 25      | 635 ± 25 | 889           | 1.4          |
| 2     | 17 26 39        | −36 08 09       | 0.17 × 0.22 | 3.39 ± 0.03        | −2.39 ± 0.02        | 18      | 173 ± 13 | 235           | 1.35         |
| 3     | 17 26 25        | −36 04 58       | 0.19 × 0.14 | 2.73 ± 0.05        | −2.76 ± 0.04        | 15      | 84 ± 9  | 130           | 1.55         |
| 4     | 17 26 21        | −36 04 36       | 0.20 × 0.15 | 2.32 ± 0.06        | −2.65 ± 0.06        | 14      | 57 ± 8  | 100           | 1.75         |
| 5     | 17 26 46        | −36 12 17       | 0.20 × 0.29 | 2.17 ± 0.04        | −3.15 ± 0.02        | 17      | 160 ± 13| 121           | 0.76         |
| 6     | 17 26 33        | −36 06 28       | 0.25 × 0.15 | 2.85 ± 0.07        | −3.46 ± 0.04        | 14      | 77 ± 9  | 166           | 2.15         |

Figure 6. Model dependence of the intensity ratio of C\(^{18}\)O (3–2)/C\(^{18}\)O (2–1) on the gas temperature and density. White contours correspond to ratios 0.5, 0.75, 1.0, 1.25, 1.5.

first and second clumps. An example of the \(\ln \frac{N_c}{N_\infty}\) dependence for the first spectrum in the IRAS 17233–3606 direction is shown in the Fig. 9. In this direction, 7 CH\(_2\)CCH (13–12) lines are detected (Fig. 10), however, the first two lines \(J = 13_0 - 12_0\) and \(13_1 - 12_1\) are blended and it is impossible to reliably determine the integrated intensities for them. The temperature derived from the higher excitation lines from \(13_3 - 12_3\) to \(13_5 - 12_5\) is 119.7 ± 2.1 K. In the direction of the second clump, lines from \(13_0 - 12_0\) to \(13_2 - 13_2\) are observed, and the temperature according to the rotation diagram is 26 ± 4.5 K.

3.5 HNCO toward IRAS 17233–3606

HNCO is a valuable probe of high mass star-forming regions (Zinchenko et al. 2000). Our data set includes several HNCO lines, which belong to the \(J = 10 - 9\) and \(J = 15 - 14\) transitions with the excitation energies up to ~ 800 K above the ground level (Table 1). The HNCO emission is detected exclusively toward the IR source IRAS 17233–3606. Examples of the detected lines are given in Fig. 11. The size of the emission region in the \(J_{K-1} = 10_0 - 9_0\) line is comparable to the beam size. A 2D Gaussian fit gives the size \(\approx 41'' \times 34''\). Leurini et al. (2011a) measured with the Submillimeter Array (SMA) the deconvolved size in this line 2''5 × 2''1. The emission in the \(J_{K-1} = 10_3 - 9_3\) was point-like with their beam (5''4 × 1''9). A comparison of our HNCO line intensities with those measured by Leurini et al. (2011a) shows a significant flux loss (by a factor of 3) in the \(J_{K-1} = 10_0 - 9_0\) line observations with the SMA. At the same time there is no flux loss for the \(J_{K-1} = 10_3 - 9_3\) line. It shows that the emission in the latter line is really point-like while the \(J_{K-1} = 10_0 - 9_0\) emission contains an extended component resolved out with the SMA.

The \(J_{K-1} = 10_0 - 9_0\) and \(J_{K-1} = 15_0 - 14_0\) emission spectra show broad wings, which most probably arise in the outflow. It is known that HNCO is an outflow tracer (Zinchenko et al. 2000). The orientation of the HNCO outflow is in a good agreement with the observations of the outflowing gas in the lines of other molecules (Leurini et al. 2008; Klaassen et al. 2015).

The rotation diagram for the HNCO lines detected toward IRAS 17233–3606 is presented in Fig. 12. The \(J = 15 - 14\) transitions are well fitted by a single component with the rotational temperature of \(T_{rot} = 297 ± 8\) K. The excitation energy of the upper levels of these transitions exceeds 100 K. The \(J = 10 - 9\) transitions with lower excitation temperatures clearly indicate a lower rotational temperature. However its a more or less reliable estimate from these data looks difficult. A rough value is between 50 and 100 K. The point corresponding to the \(J_{K-1} = 10_3 - 9_3\) transitions with the excitation energy of the upper level about 430 K lies somewhat lower than the fit to the \(J = 15 - 14\) data. This can be explained by the source compactness since no correction for the beam size was applied. Taking into account the difference in the beam sizes for the \(J = 10 - 9\) and \(J = 15 - 14\) transitions, this point is in a good agreement with the least squares fit mentioned above.

An interesting feature in the HNCO data is the apparent dependence of the central velocity (as derived from Gaussian fitting) on the excitation energy of the transition (Fig. 13). This shift greatly exceeds the measurement uncertainties and cannot be explained by instrumental effects since some of the high-excitation HNCO lines are close in frequency to other strong lines in this source, in particular C\(^{18}\)O, which are observed at a "normal" velocity. We also cannot explain this picture by a possible misidentification of the high-excitation HNCO lines. No other reasonable identification of these lines could be found. Therefore, this dependence reflects apparently the internal kinematics of the source. It is worth noting that Leurini et al. (2011a) also measured a significant difference in the velocities of the \(J_{K-1} = 10_3 - 9_3\) and \(10_0 - 9_0\) transitions in the same sense as in our data. This dependence makes the rotational diagram analysis questionable, since the emission in different transitions comes apparently from different regions. At the same time the widths of the higher excitation HNCO lines \((E_u \gtrsim 200\) K) do not show any dependence on the excitation energy, while the lower excitation lines are somewhat broader (Fig. 14). These broader line widths include apparently the contribution from the line wings arising in the outflow.

4 DISCUSSION

In Leurini et al. (2011b), a search for clumps by the ClumpFind method was also performed in the maps of the 870 \(\mu\)m continuum and their parameters were found. The position of our first clump
corresponds to the first clump from Leurini et al. (2011b), the second

corresponds to the second, third, to fifth, fourth to sixth, fifth to

to third, sixth to seventh. The numbering of our clumps is based on

the intensity of the emission peak, which decreases with increasing

the number. The clumps we found are relatively large (for example, 43° × 38° in Leurini et al. (2011b) and 64° × 54° for our first clump).

The intensities and profiles of the $^{13}$CO (2–1) and $^{18}$O (2–1) lines

presented here and in Leurini et al. (2011b) are similar in general.

Some differences can be related to the fact that we present spectra

averaged over the clumps, while in Leurini et al. (2011b) spectra at

single positions are given. In addition, the spectra, especially $^{13}$CO

(2–1) can be influenced by the emission at the reference position

(Sect. 2).

The filament contains sources at different stages of evolution. The central source IRAS 17233–3606 is considered the most evolved and probably a region of massive star formation (Yu et al. 2018). Three protostellar objects (AGAL351.774-00.537, 351.784-00.514, 351.804-00.449) are distributed along the filament. AGAL351.774-00.537 corresponds to the first clump. AGAL351.784-00.514 corresponds to the second clump, AGAL351.804-00.449 corresponds to the third clump. In the southern part of the filament there is a region of ionized hydrogen AGAL351.744-00.577, which is associated with our fifth clump (Contreras et al. 2013). It is worth noting that all our clumps are associated with the mid-IR sources (Fig. 8), which confirms their protostellar nature.

In our analysis the main filamentary body has a mass of ~ 1800 M$_\odot$. This value is somewhat higher than obtained by Leurini et al. (2019) using dust temperature from Herschel and $^{18}$O (2–1) molecular data (~ 1200 M$_\odot$). However, the estimate of the filament mass from the dust emission using the Hi-GAL column density map is ~ 1870 M$_\odot$, disregarding the region near the first clump, which is ~ 190 M$_\odot$ (Leurini et al. 2019). Our filament mass is closer to the latter value. As shown in Sect. 3.2 the mass to length ratio $M_{\text{line}}$

is practically equal to the critical value, although both values represent upper limits. Nevertheless, the presence of several dense clumps along the filament shows that the process of fragmentation is going on.

The average clump densities estimated from the $J = 2 - 1$ and $J = 3 - 2$ $^{18}$O line intensity ratio are ~ $(3 - 4) \times 10^4$ cm$^{-3}$ (Sect. 3.3). Another estimate can be obtained from comparison of our $^{12}$H$^+(3–2)$ data with the $^{12}$H$^+$ (1–0) observations in Leurini et al. (2011b).

In Leurini et al. (2011b) spectra of the $^{12}$H$^+$ (1–0) are presented in the direction of the first, second and fifth clumps (which correspond to our first, second and third one). In the first clump, the spectrum has the antenna temperature ~ 2 K, and very broad lines: 7 hyperfine components merge into 2, and in the direction of the second and fifth clumps, the temperature is 1.4 and 1.2 K, respectively, and the lines merge into three. According to the MALT90 survey Rathborne et al. (2016), the $^{12}$H$^+$ (1–0) antenna temperature of the first clump is 2.2 ± 0.04 K, the line width is 5.03 ± 0.08 km/s. This width was obtained by approximating the line with three Gaussian functions. The $^{12}$H$^+$ (3–2) line splits into 38 hyperfine components closely spaced in frequency (Pagani et al. 2009). Due to turbulent line broadening, the components merge into one. We fit the observed profiles by a set of these components assuming a low optical depth in the line and equal excitation temperatures for all of them. For example, for the first clump, the line can be approximated by a single Gaussian function with an amplitude of 2.23 ± 0.01 K and a line width of 6.5
observational data achieve the best agreement at $N = 24$, the dense gas tracer $N$ column density is the maximum intensity for the $F_1 F = 4, 5 - 3, 4$ transition at $v = 279511.8577$ MHz. This estimate takes into account the convolution of the map with the same beam width as in Leurini et al. (2011b) ($35''$). For the $N_2H^+$ (1–0) line, the overlap is not so high, only three central components overlap. Modeling shows that for the first clump, the overlap of three components with a line width of 4.55 km/s (Leurini et al. 2011b) and a maximum intensity of the central component ($F_1 F = 2, 3 - 1, 2$) of 1.1 K gives an observed intensity of 2.2 K. For the second clump with a line width is 3.06 km/s a maximum intensity of the most intense component is 0.7 K, for the third clump it is 0.6 K. This analysis shows that the linewidth of $N_2H^+$ $J = 3 - 2$ line is higher than $J = 1 - 0$. It is likely that in the $J = 3 - 2$ line we see a denser gas with a higher turbulence.

Leurini et al. (2011b) determined the $N_2H^+$ column density for the first clump $5.5 - 10.3 \times 10^{13}$ cm$^{-2}$, for the second clump $2.5 \times 10^{13}$ cm$^{-2}$ and for the fifth clump $1.8 \times 10^{13}$ cm$^{-2}$, in our analysis under the LTE assumption the column density of the first clump is $1.7 \times 10^{13}$ cm$^{-2}$, for the second clump it is $1.4 \times 10^{13}$ cm$^{-2}$, and for the third clump it is $1.1 \times 10^{13}$ cm$^{-2}$. A non-LTE analysis using the RADEX software of the $N_2H^+$ $J = 1 - 0$ and $J = 3 - 2$ data shows that for the first clump the hydrogen density $n(H_2) \sim 3 \times 10^5$ cm$^{-3}$ at the gas kinetic temperature $T_{\rm kin} \sim 30 - 100$ K with the column density $N(N_2H^+) \approx 2.2 \times 10^{13}$ cm$^{-2}$, the model and observational data achieve the best agreement at $T_{\rm kin} \sim 40 - 50$ K and $N(N_2H^+) \approx 2.5 \times 10^{13}$ cm$^{-2}$. For the second and the third clumps $n(H_2) \sim 5 \times 10^5$ cm$^{-3}$ at $T_{\rm kin} \sim 15 - 30$ K with the averaged value of the column density of $N(N_2H^+) \approx 2 \times 10^{13}$ cm$^{-2}$ for the second clump and $N(N_2H^+) \approx 10^{13}$ cm$^{-2}$ for the third clump.

The HNCO data imply even higher densities in the first clump. As shown in Zinchenko et al. (2000) the $K_{-1} = 0$ transitions can be excited by collisions at densities $n \geq 10^6$ cm$^{-3}$. A collisional excitation of the $K_{-1} > 0$ transitions requires very high densities. Most probably they are excited by Far-IR radiation, but densities in the emission regions should still be quite high. The emission in these transitions should arise in the close vicinity of the luminous IR source IRAS 17233–3606, which is consistent with the observed compactness of this emission. This clump was a target for many studies as mentioned above. We see there a range of temperatures from $\sim 25$ K derived from the Herschel data to $\sim 300$ K from our HNCO data. Apparently, this reflects the fact that it contains a hot core surrounded by a much colder extended envelope. The shift of the high-excitation HNCO lines in velocity relative to the...
Figure 11. Examples of the HNCO $J = 15 - 14$ spectra measured toward IRAS 17233–3606. No baseline correction was applied. The spectra are shifted along the ordinate axis for clarity.

Figure 12. The rotation diagram for the HNCO transitions detected toward IRAS 17233–3606. The open symbols correspond to the $J = 10 - 9$ transitions and the filled symbols correspond to the $J = 15 - 14$ transitions. The solid line represents a least squares fit to the $J = 15 - 14$ data. Its slope corresponds to the rotational temperature of $T_{\text{rot}} \approx 300$ K.

Table 3. Derived parameters of the hyperfine structure of the N$_2$H$^+$ (3–2) line for the different clumps

| Clump | $T(F_1 F = 4, 5 – 3, 4)$ (K) | $\Delta V$ (km s$^{-1}$) |
|-------|-----------------------------|--------------------------|
| 1     | $0.401 \pm 0.001$          | $6.33 \pm 0.02$          |
| 2     | $0.361 \pm 0.002$          | $5.65 \pm 0.03$          |
| 3     | $0.219 \pm 0.002$          | $5.16 \pm 0.06$          |
| 4     | $0.196 \pm 0.003$          | $4.12 \pm 0.07$          |
| 5     | $0.149 \pm 0.001$          | $4.92 \pm 0.05$          |
| 6     | $0.117 \pm 0.002$          | $3.47 \pm 0.05$          |

Figure 13. The LSR velocities measured in the HNCO lines detected toward IRAS 17233–3606 in dependence on the excitation energy of the upper level. The symbols are the same as in Fig. 12.

Figure 14. Widths the HNCO lines detected toward IRAS 17233–3606 in dependence on the excitation energy of the upper level. The symbols are the same as in Fig. 12.

lower excitation lines cannot be explained in a spherically-symmetric or cylindrically-symmetric optically thin case. One possibility is to abandon the assumption of a low optical depth in the high-excitation HNCO lines. In this case we can try to attribute the velocity shift to a self-absorption in infalling outer layers of the hot core. However, the spectra presented in Fig. 11 do not show signs of self-absorption and a high optical depth in so highly excited lines seems unrealistic and has never been observed in similar objects (Zinchenko et al. 2000). Another possibility is to assume an asymmetric distribution of the high-excitation HNCO molecules. In this case the shift can be attributed to orbital or radial motions. It is worth noting that Beuther et al. (2017) observed the blue-shifted absorption in the CH$_3$CN high-excitation transitions at about the same velocities as the high-excitation HNCO lines in our data. They attribute this shift to a contribution from the outflow. In this picture we have to assume that the high-excitation HNCO emission arises exclusively in the blue-shifted outflow lobe and is absent at the systemic velocity. Such assumption is rather strange and unusual. A more natural explanation
is a movement of the hot dense core relative the surrounding medium at a velocity of a few km s\(^{-1}\) along the line of sight. Such supersonic movements of young massive stars are frequently suggested to explain the morphology of UC H\(\text{ii}\) regions (e.g. Wood & Churchwell 1989). Relative movements of a dense and more diffuse molecular gas have been reported, too, although at lower velocities (e.g. Kirsanova et al. 2008; Henshaw et al. 2013). In principle such a movement hints at the scenario of a triggered star formation under the influence of an external factor, such as an expanding shell or cloud collision.

As noticed in Sect. 3.3 there is a velocity shift between N\(2\)H\(^{+}\) (3–2) and CO isotopologues in some clumps. It is especially prominent in the third and forth clumps but is also noticeable in the sixth clump. Fig. 15 shows this shift in the third clump very clearly. The difference in the velocities is \(\sim 1\) km s\(^{-1}\). A very similar picture is observed in the forth clump. This shift is consistent with such scenario, too. Leurini et al. (2011b) suggested that an external agent might be the cause of the line broadening along the filament. The velocity shifts observed in our data support this suggestion.

Widths of all observed lines are highly supersonic. The N\(2\)H\(^{+}\) (3–2) line width is 1.2–2.1 times higher than the CH\(3\)CCH (3–2) line width in all clumps and than the N\(2\)H\(^{+}\) (1–0) line width in the clumps where it was observed. This hardly can be explained by the optical depth broadening (e.g. Phillips et al. 1979) since the brightness of the N\(2\)H\(^{+}\) (3–2) line and our modeling do not support an assumption of a high optical depth. Taking into account the fact that the critical density of the N\(2\)H\(^{+}\) (3–2) transition is much higher than critical density of the other transitions considered here, we can conclude that the velocity dispersion increases in the central denser regions of the clumps. This increase hardly can be attributed to turbulence since most clumps lack powerful sources in their interiors. Most probably the line widths increase due to Keplerian-like rotation and/or infall motions in the clumps. As mentioned above the clumps are associated with mid-IR sources, which indicates their protostellar nature. The maps of the first moment in the N\(2\)H\(^{+}\) (3–2) line (Fig. 7) show velocity gradients in the clumps which can indicate a rotation. In the first clump the gradient is similar to that observed at small scales (Klaassen et al. 2015), which was interpreted as an evidence for rotation. The sharp increase of the line width in the center of the clumps is consistent with Keplerian-like rotation, too. However, a rotation may not be a unique interpretation of the velocity gradients in some cases.

In the northern part where we see a significant difference between the velocities of N\(2\)H\(^{+}\) (3–2) and CO isotopologues, the observed gradient can probably arise under the influence of an external factor. High resolution observations are needed to clarify kinematics of this area.

The N\(2\)H\(^{+}\) abundance is close to the typical values (e.g. Pirogov et al. 2003). Fig. 4 shows N\(2\)H\(^{+}\) depletion in the direction of the first clump, which contains the luminous IR source. Such behavior is rather typical for massive cores and can be probably explained by the dissociative recombination of N\(2\)H\(^{+}\) (Pirogov et al. 2007; Zinchenko et al. 2009).

5 CONCLUSIONS

We performed a multi-line study of the filamentary infrared dark cloud G351.78–0.54 with the APEX radio telescope. The observed lines include CO (2–1), CH\(3\)CCH (3–2), CH\(3\)CCH (3–2), N\(2\)H\(^{+}\) (3–2), and several HNCO transitions. The main results are the following:

1. The main filamentary body was mapped in the CO (2–1), CH\(3\)CCH (3–2), CH\(3\)CCH (3–2), CH\(3\)CCH (3–2), and N\(2\)H\(^{+}\) (3–2) lines. Maps of the CH\(3\)CCH and N\(2\)H\(^{+}\) (3–2) line profiles are consistent with the LTE approximation. The total mass of the filament is estimated at \(\sim 1800\) M\(\odot\). The mass per unit length (\(M_{\text{line}} = 529\) M\(\odot\)/pc) is close to the critical value. However, both values represent upper limits. The presence of several dense clumps along the filament shows that the process of fragmentation is going on.

2. Six dense clumps are identified in the N\(2\)H\(^{+}\) (3–2) map. Their masses and virial parameters have been derived from the CH\(3\)CCH (2–1) data assuming gas temperature equal dust temperature obtained from the Herschel data. All clumps except one appear gravitationally unstable. For two clumps we obtained temperature estimates from the CH\(3\)CCH rotation diagrams. These temperatures are somewhat higher than the dust temperatures. In the first clump which contains the luminous IR source IRAS 17233-3606, the CH\(3\)CCH rotation temperature is about 120 K. We use the CH\(3\)CCH (3–2)/(2–1) intensity ratio for estimation of the clump density on the basis of non-LTE modeling. The densities obtained in this way are \(n \sim 3 \times 10^5\) cm\(^{-3}\).

For the three clumps with the available N\(2\)H\(^{+}\) (1–0) data (Leurini et al. 2011b) we estimate the density from the N\(2\)H\(^{+}\) (3–2)/(1–0) intensity ratio (taking into account the hyperfine splitting of these lines). These density estimates are about an order of magnitude higher, \(n \sim 3 \times 10^6\) cm\(^{-3}\), which is consistent with the fact that N\(2\)H\(^{+}\) traces denser regions than CH\(3\)CCH. The width of the N\(2\)H\(^{+}\) (3–2) lines is larger than the width of the N\(2\)H\(^{+}\) (1–0) and CH\(3\)CCH lines, which indicates a higher velocity dispersion in the denser parts of the clumps, which is most probably related to a Keplerian-like rotation or infall motions.

3. Exclusively toward the first clump we detected several HNCO lines with the excitation energy of the upper level up to \(\sim 800\) K. The emission in the K\(_{-1}\) = 0 transitions is rather extended and the spectra show broad wings indicative of the outflow. The orientation of the outflow lobes is in a good agreement with the observations of the outflowing gas in the lines of other molecules. The HNCO data imply even higher density in this clump, \(n \sim 10^6\) cm\(^{-3}\). The rotational temperature derived from the higher excitation transitions is \(\sim 300\) K. There is a clear velocity difference between the higher and lower excitation transitions, which most likely hints at a movement of the hot dense core relative the surrounding medium at a velocity of a few km s\(^{-1}\) along the line of sight.

4. In some clumps there is a velocity shift \(\sim 1\) km s\(^{-1}\) between N\(2\)H\(^{+}\) (3–2) and CO isotopologues. It indicates a relative movement of the...
dense and more diffuse gas and can be caused by an external agent as suggested earlier for explanation of the general line broadening in the filament (Leurini et al. 2011b).

5. The \( \text{N}_2\text{H}^+ \) abundance is close to the typical values in general but drops toward the luminous IR source IRAS 17233–3606 in the first clump. This behavior is consistent with other similar objects.

6 DATA AVAILABILITY

Data directly related to this publication are available by request from the corresponding author.

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REFERENCES

André P., et al., 2010, A&A, 518, L102
André P., Di Francesco J., Ward-Thompson D., Inutsuka S.-I., Puget R. E., Pineda J. E., 2014, Protostars and Planets VI, pp 27–51
Antyufeyev O. V., Shulga V. M., Zinchenko I. I., 2016, Kinematics and Physics of Celestial Bodies, 32, 276
Astropy Collaboration et al., 2018, AJ, 156, 123
Ballesteros-Paredes J., Hartmann L. W., Vázquez-Semadeni E., Heitsch F., Zamora-Avilés M. A., 2011, MNRAS, 411, 65
Bally J., Langer W. D., Stark A. A., Wilson R. W., 1987, ApJ, 312, L45
Battersby C., et al., 2011, A&A, 535, A128
Belitsky V., et al., 2006, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series. p. 62750G, doi:10.1117/12.671383
Berger E. A., Goldsmith P. F., Snell R. L., Ungerechts H., 1994, ApJ, 431, 674
Beuther H., Walsh A. J., Johnston K. G., Henning T., Kuiper R., Longmore S. N., Walmsley C. M., 2017, A&A, 603, A10
Beuther H., et al., 2019, A&A, 621, A122
Contreras Y., et al., 2013, A&A, 549, A45
Currie M. J., Berry D. S., Jenness T., Gibb A. G., Bell G. S., Draper P. W., 2014, in Mansion N., Forsysh P., eds, Astronomical Society of the Pacific Conference Series Vol. 485, Astronomical Data Analysis Software and Systems XXII. p. 391
Dewangan L. K., Pirogov L. E., Ryabukhina O. L., Ojha D. K., Zinchenko I., 2019, ApJ, 877, 1
Endres C. P., Schlemmer S., Schilke P., Stutzki J., Müller H. S. P., 2016, Journal of Molecular Spectroscopy, 327, 95
Ginsburg A., Mirocha J., 2011, PySpecKit: Python Spectroscopic Toolkit (ascl:1109.001)
Goldsmith P. F., Langer W. D., 1999, ApJ, 517, 209
Güsten R., Nyman L. Å., Schilke P., Menten K., Cesarsky C., Booth R., 2006, A&A, 454, L13
Henshaw J. D., Caselli P., Fontani F., Jiménez-Serra I., Tan J. C., Hernandez A. K., 2013, MNRAS, 428, 3425
Kauffmann J., Pillai T., 2010, ApJ, 723, L7
Kauffmann J., Pillai T., Goldsmith P. F., 2013, ApJ, 779, 185
Kirsanova M. S., Sobolev A. M., Thomasson M., Wiebe D. S., Johansson L. E. B., Selezniev A. F., 2008, MNRAS, 388, 729
Klaassen P. D., Johnston K. G., Leurini S., Zapata L. A., 2015, A&A, 575, A54
Koumpia E., Harvey P. M., Ossenkopf V., van der Tak F. S. J., Mookerjea B., Fuente A., Kramer C., 2015, A&A, 580, A68
Leurini S., Hieriet C., Thorwirth S., Wyrowski F., Schilke P., Menten K. M., Güsten R., Zapata L., 2008, A&A, 485, 167
Leurini S., Codello C., Zapata L., Beltrán M. T., Schilke P., Cesaroni R., 2011a, A&A, 530, A12
Leurini S., Pillai T., Stanke T., Wyrowski F., Testi L., Schuller F., Menten K. M., Thorwirth S., 2011b, A&A, 533, A85
Leurini S., et al., 2014, A&A, 564, L11
Leurini S., et al., 2019, A&A, 621, A130
Li G.-X., Urquhart J. S., Leurini S., Csengeri T., Wyrowski F., Menten K. M., Schuller F., 2016, A&A, 591, A5
Liu T., Wu Y., Zhang H., 2013, ApJ, 775, L2
Low F. J., et al., 1984, ApJ, 278, L19
Mallick K. K., Ojha D. K., Tamura M., Linz H., Samal M. R., Ghosh S. K., 2015, MNRAS, 447, 2307
Mangum J. G., Shirley Y. L., 2015, PASP, 127, 266
Maret S., Hily-Blant P., Pety J., Bardeau S., Reynier E., 2011, A&A, 526, A47
McClure-Griffiths N. M., Dickey J. M., Gaenssler B. M., Green A. J., Havercorn M., 2006, ApJ, 652, 1339
Motte F., Bontemps S., Louvet F., 2018, ARA&A, 56, 41
Müller H. S. P., Thorwirth S., Roth D. A., Winnewisser G., 2001, A&A, 370, L49
Müller H. S. P., Schröder F., Sutizki J., Winnewisser G., 2005, Journal of Molecular Structure, 742, 215
Myers P. C., 2009, ApJ, 700, 1609
Pagani L., Daniel F., Dubernet M. L., 2009, A&A, 494, 719
Phillips T. G., Huggins P. J., Wannier P. G., Scoville N. Z., 1979, ApJ, 231, 720
Pickett H. M., Poynter R. L., Cohen E. A., Delitsky M. L., Pearson J. C., Müller H. S. P., 1998, J. Quant. Spectrosc. Radiative Transfer, 60, 883
Pilbratt G. L., et al., 2010, A&A, 518, L1
Pirogov L., Zinchenko I., Caselli P., Johansson L. E. B., Myers P. C., 2003, A&A, 405, 639
Pirogov L., Zinchenko I., Caselli P., Johansson L. E. B., 2007, A&A, 461, 523
Rathborne J. M., Jackson J. M., Simon R., 2006, ApJ, 641, 389
Rathborne J. M., et al., 2016, Publ. Astron. Soc. Australia, 33, e030
Ryabukhina O. L., Zinchenko I. I., Samal M. R., Zemlyanukha P. M., Ladecysnhkov D. A., Sobolev A. M., Henkel C., Ojha D. K., 2018, Re- search in Astronomy and Astrophysics, 18, 095
Sault R. J., Teuben P. J., Wright M. C. H., 1995, in Shaw R. A., Payne H. E., Hayes J. E., eds, Astronomical Society of the Pacific Conference Series Vol. 77, Astronomical Data Analysis Software and Systems IV. p. 433 (arXiv:astro-ph/9612759)
Schisano E., et al., 2020, MNRAS, 492, 5420
Snell R. L., Loren R. B., 1977, ApJ, 211, 122
Stutzki J., Guesten R., 1990, ApJ, 356, 513
Tan J. C., Beltrán M. T., Caselli P., Fontani F., Aumen A. M., Krumholz M. R., McKee C. F., Stolte A., 2014, Protostars and Planets VI, pp 149–172
Van der Tak F. S. J., Black J. H., Schöier V. L., Jansen D. J., van Dishoeck E. F., 2007, A&A, 468, 627
Vassilev V., et al., 2008, A&A, 490, 1157
Wienen M., et al., 2015, A&A, 579, A91
Wood D. O. S., Churchwell E., 1989, ApJS, 69, 831
Yu N.-F., Xu J.-L., Wang J.-L., Liu X.-L., 2018, ApJ, 865, 135
Zinchenko I., Henkel C., Mao R. Q., 2000, A&A, 361, 1079
Zinchenko I., Caselli P., Pirogov L., 2009, MNRAS, 395, 2234

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