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Research Article

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Molecular gas in high-mass filament WB 673

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Abstract: We studied the distribution of dense gas in a filamentary molecular cloud containing several dense clumps. The center of the filament is given by the dense clump WB 673. The clumps are high-mass and intermediate-mass star-forming regions. We observed CS (2–1), $^{13}$CO (1–0), C$^{18}$O (1–0), and methanol lines at 96 GHz toward WB 673 with the Onsala Space Observatory 20-m telescope. We found CS (2–1) emission in the inter-clump medium so the clumps are physically connected and the whole cloud is indeed a filament. Its total mass is $10^4 M_\odot$ and mass-to-length ratio is $360 M_\odot \text{pc}^{-1}$ from $^{13}$CO (1–0) data. Mass-to-length ratio for the dense gas is $3.4 - 34 M_\odot \text{pc}^{-1}$ from CS (2–1) data. The PV-diagram of the filament is V-shaped. We estimated physical conditions in the molecular gas using methanol lines. Location of the filament on the sky between extended shells suggests that it could be a good example to test theoretical models of formation of the filaments via multiple compression of interstellar gas by supersonic waves.

Keywords: star formation, massive stars, H II regions, bubbles

1 Introduction

Molecular clouds often appear as elongated filamentary structures. Observations with the Herschel Space Observatory provide evidence that filamentary structure is a ubiquitous property of molecular clouds, see Andre et al. [1]. Theoretical calculations, e.g. Inutsuka et al. [2], predict formation of filamentary molecular clouds after multiple compression of interstellar gas by supersonic waves. So the periphery of extended bubbles (H II regions or supernova remnants) could be reliable places for the formation of the molecular filaments. We have thus initiated a study of giant molecular clouds which contain multiple bubbles to study the properties of the filamentary structure in them.

Giant molecular cloud G174+2.5 is situated in the Perseus Spiral Arm. Massive stars formed in the cloud belong to the Auriga OB2 association. Results of $^{12}$CO and $^{13}$CO observations of the cloud by Heyer et al. [10] show complex kinematic structure of the gas. They find evidence for the compression of the molecular gas by H II regions and mention interconnected molecular filaments in the vicinity of optical H II regions. A list of the H II regions as well as their mutual location and location of young stellar clusters can be found in recent studies by Bieging et al. [3] and Ladeyschikov et al. [17]. Kirsanova et al. [13, 14] and Dewangan et al. [5] present evidence of triggered star formation process in the G174+2.5 cloud around the brightest H II region Sh2-235 (S235 below), Sharpless catalogue Sharpless [22]. Ladeyschikov et al. [16] also propose triggered star formation near H II region Sh2-233 (S233 below). Ladeyschikov et al. [17] find a large filamentary molecular structure with dense clumps and embedded young stellar clusters on the border of G174+2.5 to the west from the extended H II region Sh2-231 (S231 below): G173.57+2.43 associated with IRAS 05361+3539, S233 IR associated with IRAS 05358+3543, WB89-673 (WB 673 below) and WB89-668 (WB 668 below) associated with IRAS 05345+3556 and IRAS 05335+3609, respectively, see Wouterloot, Brand [27]. The center of the filamentary structure is given by WB 673. Analysis of $^{12}$CO and $^{13}$CO (1–0) emission shows that the clumps are gravitationally unstable, Ladeyschikov et al. [17]. Their masses range from about 1000 to 2000 $M_\odot$.

Inspection of infrared images by the Wide-field Infrared Survey Explorer (WISE) and Herschel reveals...
2 Observations

We mapped emission in the CS (2–1) and $^{13}$CO (1–0) transitions towards WB 673 with the Onsala Space Observatory 20-m telescope in December 2016 and February 2017. We used a 3 mm dual polarization sideband separating receiver by Belitsky et al. [2] with an FFTS in 2×2.5 GHz mode. The LSB was tuned to 97.2 GHz and USB to 109.2 GHz. The spectral resolution was 76 kHz. The observations were done in frequency-switch mode with the frequency offset 5 MHz. The main lines of our interest were $^{13}$CO (1–0) at 110.20 GHz in USB and CS (2–1) at 97.98 GHz in LSB. We also got C$^{18}$O (1–0) at 109.78 GHz, C$^{34}$S(2-1) at 96.41 GHz and methanol series at 96.7 GHz simultaneously with the main lines. Typical system temperature was from 80 to 250 K for LSB and from 160 to 340 K for USB. We excluded data with the system temperature higher than 500 K from the analysis. Typical RMS level for our data is 0.3 K in $T_{mb}$ scale for CS (2–1) and 1.1 K for $^{13}$CO (1–0). We made full sampling observations with 20″ step towards the dense clumps and the inner part of the filament. The outer parts were mapped with 40″ sampling. Data were reduced with the GILDAS software. Line profile fitting of CS (2–1), $^{13}$CO (1–0) and C$^{18}$O (1–0) was done by gauss function using curve_fit from python scipy.optimize. All analysis of the methanol lines was done with GILDAS.

3 Spatial distribution of the molecular gas

The main result of the mapping is the detection of the CS (2–1) emission in the inter-clump medium. The dense clumps G173.57+2.43, S233 IR, WB 673 and WB 668 are not isolated from each other. They are connected into a large filament. Fig. 2 shows a CS (2–1) emission map. Only pixels with signal-to-noise ratio higher than 3 are shown in Fig. 2. We do not show a map of the $^{13}$CO (1–0) emission here because there are recent already published larger maps by Bieging et al. [3]. The emission in CS (2–1), $^{13}$CO (1–0) and C$^{18}$O (1–0) lines is detected from the south-east to the north-west of the filament. The emission peaks in $^{13}$CO (1–0) C$^{18}$O (1–0) and CS (2–1) lines are given by the WB 673 dense clump. Brightness of CS (2–1) in S233 IR is almost the same as in WB 673. Emission in C$^{34}$S(2-1) line is not detected with signal-to-noise ratio

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1 http://www.iram.fr/IRAMFR/GILDAS
higher than 3. We assume the distance to the filament to be \( d = 1.8 \text{ kpc} \) after Evans, Blair [8], and zero projection angle and determine that the length of the filament from WB 668 in the north-west to G173.57+2.43 in the south-east to be 24.9 pc. So the WB 673 filament is four and two times longer than the integral shaped filament in the Orion A, see Hacar et al. [9] and NGC 6334 filament, Zernickel et al. [28], respectively.

We calculate the column density of CS molecules \( N_{\text{CS}} \) in LTE using standard approach described by Mangum, Shirley [19], Eq.80. In the beginning \( N_{\text{CS}} \) is calculated under assumption that CS (2–1) line is optically thin but then optical depth correction factor, Goldsmith, Langer [8], is used to make the value of \( N_{\text{CS}} \) reliable. For diatomic linear molecules:

\[
N_{\text{thin}}^{\text{CS}} = \frac{3h}{8\pi^2\mu^2} \times \frac{Q_{\text{rot}}}{g_1 g_2 g_1} \times \exp \left( \frac{E_{\text{ex}}}{kT_{\text{ex}}} \right) \times \exp \left( \frac{h\nu}{kT_{\text{ex}}} \right) - 1 \\
\times \left( \frac{1}{J_{\nu}(T_{\text{ex}})} - \frac{1}{J_{\nu}(T_{\text{bg}})} \right) \int \frac{T_{\text{R}} \, dv}{f},
\]

where total molecular partition function \( Q_{\text{rot}} \approx \frac{h^3 \nu_c}{k^3 T_{\text{ex}}} + \frac{1}{\gamma}, g_2 = 2g_1 + 1, g_k = 1, g_1 = 1, S = \frac{P}{J_{\nu}(T_{\text{ex}}) + 1} \int J_{\nu}(T) = \frac{h \nu}{k T} \left( \exp \left( \frac{h \nu}{k T} \right) - 1 \right) \right. \). We assume filling factor \( f = 1, T_{\text{bg}} = 27 K \) and \( \int T_{\text{R}} \, dv \) defined as integrated intensity on \( T_{\text{mb}} \) scale. Other constants we use are given in Table 1.

Table 1. Constants for CS (2–1) and \(^{13}\text{CO} (1–0) \) column density calculations from NIST

|          | \( \mu \) (esu) | \( B_0 \) (MHz) | \( E_u \) (K) | \( J_u \) |
|----------|----------------|----------------|-------------|---------|
| CS (2–1) | 1.96 - \( 10^{-18} \) | 1.1 - \( 10^{-19} \) | 7.1 | 2 |
| \(^{13}\text{CO} (1–0) \) | | 24495.576 | 55101.014 | 1 |

Excitation temperature \( T_{\text{ex}} = 20 K \) for CS (2–1) in LTE is taken the same as for CO lines in the same region by Bieging et al. [3]. To calculate the optical depth correction factor \( \tau/(1 - \exp(-\tau)) \), we use the ratio of \(^{34}\text{S}(2–1) \) to CS (2–1) line intensities:

\[
\frac{T_{\text{mb}}(^{34}\text{S}(2–1))}{T_{\text{mb}}(\text{CS}(2–1))} = \frac{1 - \exp(-\tau_{\text{CS}(2–1)}/r)}{1 - \exp(-\tau_{\text{CS}(2–1)})},
\]

where \( r \) and \( \tau_{\text{CS}(2–1)} \) are adopted from Zinchenko et al. [29]. We use relative abundance ratio of CS to \(^{34}\text{S} \) of \( r = 22.5, \) Wilson [26]. This equation was solved using \( \text{fsolve} \) from \( \text{python} \) module \( \text{scipy.optimize}. \)

\( N_{\text{CS}} \) towards the emission peak in WB 673 is up to 8 \( \times 10^{14} \) cm\(^{-2} \). Mean value of \( \tau_{\text{CS}(2–1)} \) is 5.7. Adopting relative abundance of CS to H\(_2 \) molecules \( x_{\text{CS}} \) in the range \( 10^{-9} - 10^{-8} \), see e.g. van Dishoeck and Blake [24], we determine the total mass of the dense gas in the filament:

\[
M_{\text{dense}} = a_{\text{pix}} \times 2.8 m_H \times x_{\text{CS}}^{-1} \times \sum N_{\text{CS}, \text{pix}}
\]

where \( a_{\text{pix}} \) is the pixel area and 2.8 is the mean molecular weight. This calculation gives a range 80 < \( M_{\text{dense}} \) < 800 \( M_\odot \) and mass-to-length ratio 3.4 - 34 \( M_\odot \) pc\(^{-1} \) for the dense gas. We estimate the hydrogen mass surface density \( \Sigma_H \) of the dense gas as 700-27000 \( M_\odot \) pc\(^{-2} \) towards WB 673 and up to 2700-27000 \( M_\odot \) pc\(^{-2} \) towards S233 IR.

We do the same analysis in LTE for \(^{13}\text{CO} (1–0) \) and \(^{13}\text{C}\text{O} (1–0) \) lines to determine the CO column density \( N_{\text{CO}} \) and compare our results with Bieging et al. [3], who did it for \(^{12}\text{CO} \) and \(^{13}\text{CO} \). Isotopic ratio for our analysis is \( r = 8 \) for \(^{13}\text{CO} / {^{13}\text{C}\text{O}} \), e.g. Wilson [26], and \( r = 80 \) for \(^{12}\text{CO} / {^{13}\text{C}\text{O}} \), Bieging et al. [3]. We assume \( T_{\text{ex}} = 20 K \) again. Mean value of \( \tau_{\text{CO}(1–0)} \) is 5.0. \( N_{\text{CO}} \approx 10^{18} \) cm\(^{-2} \) towards the emission peak in WB 673. Using CO relative abundance \( x_{\text{CO}} = 10^{-4} \), e.g. van Dishoeck and Blake [24], we get peak \( \Sigma_H \) value of 17000 \( M_\odot \) pc\(^{-2} \) toward WB 673 and 12000 \( M_\odot \) pc\(^{-2} \) to Sh2-233 and S233IR. This result is in agreement with LTE analysis by Bieging et al. [3]. The total mass of the gas in WB 673 filament is \( 10^3 \) \( M_\odot \), mass-to-length ratio is 360 \( M_\odot \) pc\(^{-1} \). Mass, length and mass-to-length ratio for the filament are comparable with other filaments identified in the Northen sky by Wang et al. [25].
Table 2. Methanol lines quartet at 96.7 GHz has been detected in the clamps. Offset positions are given relative to \( \alpha(J2000.0) = 03^h 38^m 00^s \) and \( \delta(J2000.0) = +35^\circ 59^\prime 12^\prime\prime \).

| Notation | \( J_{1-0} \), \( dV \) | \( \Delta V \) | \( T_{mm} \) |
|----------|-----------------|-------------|-------------|
| WB 668 (-620”,-680”) | \( V_{LSR} = -17.60 \pm 0.05 \) km/s | 2.3 \pm 0.2 | 2.1 \pm 0.2 | 1.0 \pm 0.2 |
| 2\,-, 1\,-, v_t = 0 \( E \) | 3.6 \pm 0.2 | 2.7 \pm 0.1 | 2.2 \pm 0.2 |
| WB 673 (0”,-20”) | \( V_{LSR} = -19.31 \pm 0.03 \) km/s | 3.6 \pm 0.2 | 2.7 \pm 0.1 | 2.2 \pm 0.2 |
| 2\,-, 1\,-, v_t = 0 \( E \) | 1.3 \pm 0.1 | 1.2 \pm 0.1 | 1.0 \pm 0.2 |
| Sh2-233 (460”,-360”) | \( V_{LSR} = -19.00 \pm 0.03 \) km/s | 1.3 \pm 0.1 | 1.2 \pm 0.1 | 1.0 \pm 0.2 |
| S233 IR (860”,-800”) | \( V_{LSR} = -16.27 \pm 0.03 \) km/s | 7.3 \pm 0.2 | 3.6 \pm 0.1 | 1.9 \pm 0.1 |
| G173.57-z.43 (1060”,-1160”) | \( V_{LSR} = -16.27 \pm 0.03 \) km/s | 1.0 \pm 0.1 | 1.5 \pm 0.2 | 0.7 \pm 0.2 |

4 Physical conditions in the dense clumps

Methanol emission is a diagnostic tool to estimate physical parameters of molecular clouds, e.g. Leurini et al. \[18\], Salii \[20\], Salii, Sobolev \[21\], Zinchenko et al. \[30\]. All five clumps in the WB 673 filament are detected using a quartet of quasi-thermal (i.e., not maser) methanol lines. Fig. \[3\] shows the methanol lines in the clumps. The brightest methanol lines 2\,-, 1\,-, vit = 0 \( E \) and 2\,-, 1\,-, vit = 0 \( A^{++} \) (96.739 \& 96.741 GHz) are confidently detected (above 5 \( \sigma \)) in all clumps, 2\,-, 1\,-, vit = 0 \( E \) lines at 96.744 GHz are detected in 3 clumps with level about or above 3 \( \sigma \), and 2\,-, 1\,-, vit = 0 \( E \) emission at 96.755 GHz is detected only in one with level about 2 \( \sigma \) (Table 2).

Shift of radial velocities of the methanol lines is observed between the clumps, see Fig. \[3\] and Table 2. The velocity changes from \(-19.3 \) km s\(^{-1}\) in the central position of WB 673 clump, to \(-17.6 \) km s\(^{-1}\) in the north-west towards WB 668, and up to \(-16.3 \) km s\(^{-1}\) in the south-east towards G173.57+2.43. A similar velocity shift is observed in \(^{13}\)CO (1–0) and CS (2–1) lines, see Sect. 5.

To estimate the physical conditions in the regions emitting methanol lines, we use a simple radiative transfer model, which uses the LVG approximation. Our model has four parameters: gas kinetic temperature \( (T_g) \), hydrogen number density \( (n_H) \), methanol specific column density \( (N_{CH_3OH}/AV) \), and methanol relative abundance \( (x_{CH_3OH} = N_{CH_3OH}/N_{H_2}) \). Dust emission and absorption within the emission region is taken into account in the way described in Sutton et al. \[23\]. Since it is not known exactly if the cloud fill the beam totally or not, a filling factor, \( f = 0.95 \), is included to the line intensity calculation. The scheme of energy levels in this model includes rotational levels with quantum numbers J up to 22 and \( |K| \) up to 9; the levels include the rotational levels of the ground, first and second torsionally excited states. In total, 861
levels of A-methanol and 852 levels of E-methanol were considered according to Cragg et al. [4].

In order to estimate the physical parameters, we look for a set of parameters that exhibits the best agreement between the values of the calculated brightness temperatures \( T_{i}^{\text{mod}} \) and the measured brightness temperatures \( T_{i}^{\text{obs}} \). This corresponds to finding the minimum of

\[
\chi^2 = \frac{1}{N} \sum_{i} \left( \frac{T_{i}^{\text{obs}} - T_{i}^{\text{mod}}}{\sigma_i} \right)^2 ,
\]

where \( \sigma_i \) is the observational uncertainty for a particular line and \( N \) is the total number of explored lines.

We explore the parameter space to find the approximate location of the \( \chi^2 \) minimum. For this purpose, we use the database of population numbers for the quantum energy levels of methanol by Salii [20]. The \( T_k \) in the database ranges from 10 to 220 K, the \( n_{\text{H}_2} \) — from \( 10^3 \) to \( 10^6 \) cm\(^{-3}\), the \( N_{\text{CH}_3\text{OH}}/\Delta V \) — from \( 10^6 \) to \( 10^{13} \) cm\(^{-3}\)s, the relative abundance of methanol molecules relative to molecular hydrogen — from \( 10^{-9} \) to \( 10^{-6} \), Sutton et al. [23], van Dishoeck and Blake [24], Zinchenko et al. [30]. The lower values of these parameters correspond to the physical conditions of dark molecular clouds, while the higher values of both parameters can occur in shocked molecular material. Thus we can use this base to investigate molecular clouds at their different stages.

The set of the methanol lines is not very sensitive to variations of the \( x_{\text{CH}_3\text{OH}} \) for the dense clumps under consideration. Taking into account hydrogen column density estimations by \( ^{13}\text{CO} (1–0) \) and \( \text{CS} (2–1) \) lines in Sect. we find a reliable value of the \( x_{\text{CH}_3\text{OH}} = 10^{-8} – 10^{-7} \). With such limitat we estimate \( T_k = 15 – 35 \) K, \( N_{\text{CH}_3\text{OH}}/\Delta V = 1.8 \times 10^9 \) and \( 10^8 \) cm\(^{-3}\)s for WB 673 and S233IR, respectively, and \( n_{\text{H}_2} = 10^4 \) cm\(^{-3}\) for both sources. The \( T_k \) values are in good agreement with the results of Bieging et al. [3].

Since there are few detected methanol lines at the other sources we use \( T_k \) from Bieging et al. [3] and again \( n_{\text{H}_2} = 10^4 \) cm\(^{-3}\) for all of them. In this way, \( N_{\text{CH}_3\text{OH}}/\Delta V \), are estimated as \( 5 \times 10^8 \) and \( 3 \times 10^8 \) cm\(^{-3}\)s for Sh2-233 and G173.57+2.43 respectively. Assuming \( T_k = 20 \) K for WB 668, we get \( N_{\text{CH}_3\text{OH}}/\Delta V = 5 \times 10^8 \) cm\(^{-3}\)s too. We note that methanol abundance \( x_{\text{CH}_3\text{OH}} = 10^{-8} – 10^{-7} \) is greater than it is in dark clouds, so it can be explained by some star formation processes or by shock wave propagation.

5 Velocity field

Position-velocity (PV) diagrams for the emission in \( ^{13}\text{CO} (1–0) \), \( ^{13}\text{C}^{18}\text{O} (1–0) \) (middle) and CS (2–1) lines (bottom). Intensity in images increases linearly, with a maximum of 10 K in \( ^{13}\text{CO} (1–0) \), 1.5 K in \( ^{13}\text{C}^{18}\text{O} (1–0) \) and 3.3 K in CS (2–1).

Fig. 4 shows the velocity distribution of CS (2–1) line in the center of the filament – WB 673 dense clump. The area with the most negative velocities coincides with the peak of CS (2–1) and methanol emission. Velocities at the periphery of the clump are more positive. The velocity
The high-mass filament WB 673 in G174+2.5 giant molecular cloud could be a good example of a filament whose formation was influenced by expanding shells: H II regions S231 and S232 from one side and from the other side the unidentified shell-like nebula visible on infrared images by WISE and Herschel.

We find dense gas in WB 673 filament not only toward clumps with embedded stellar clusters but also in the inter-clump medium. So the filament is a large connected structure with the total mass $10^4 M_\odot$ and mass-to-length ratio $360 M_\odot pc^{-1}$. Mass-to-length ratio for the dense gas is $3.4 - 34 M_\odot pc^{-1}$ from CS (2–1) data. These parameters of the filament are comparable with other filaments identified in the Northern sky by Wang et al. [25]. V-shaped PV-diagram of the filament has red-shifted ends relative to the center. This shape could be a signature of gravitational contraction of the filament. Our analysis of the methanol emission in the dense clumps gives temperatures and densities in agreement with the results from $^{12}$CO and $^{13}$CO analysis by Bieging et al. [3]. The abundance of methanol is higher than in cold dark clumps. It can be explained by some star formation processes or by shock wave propagation from the embedded stellar clusters.

We conclude that the WB 673 filament is a promising region to study feedback from ‘older’ generation of stars to forming ‘younger’ generation.

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