A multi-wavelength study of filamentary cloud G341.244-00.265

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Abstract We present a multi-wavelength study toward the filamentary molecular cloud G341.244-00.265, to investigate the physical and chemical properties, and star formation activities taking place therein. Our radio continuum and molecular line data were obtained from the Sydney University Molonglo Sky Survey (SUMSS), The Atacama Pathfinder Experiment Telescope Large Area Survey of the Galaxy (ATLASGAL), Structure, excitation, and dynamics of the inner Galactic interstellar medium (SEDIGISM) and Millimeter Astronomy Legacy Team Survey at 90 GHz (MALT90). The infrared archival data come from Galactic Legacy Infrared Midplane Survey Extraordinaire (GLIMPSE), Wide-field Infrared Survey Explorer (WISE) and Herschel InfraRed Galactic Plane Survey (Hi-GAL). G341.244-00.265 displays an elongated filamentary structure both in far-infrared and molecular line emissions, with its “head” and “tail” associated with known infrared bubbles S21, S22 and S24. We made H2 column density and dust temperature maps of this region by the spectral energy distribution (SED) method. From the ATLASGAL catalog, we found eight dense massive clumps associated with this filamentary cloud. All of these clumps have sufficient mass to form massive stars (≥ 8 M⊙). We also searched the young stellar objects (YSOs) in G341.244-00.265. We found an age gradient of star formation in this filamentary cloud: most of the YSOs distributed in the center are Class I sources, while most Class II candidates locate in the “head” and “tail” of G341.244-00.265, indicating star formation at the two ends of this filament is prior to the center. The abundance ratio of N(N2H+) / N(C18O) is higher in the center than that in the two ends, also indicating the gas in the center is less evolved. The so-called “end-dominated collapse” mechanism might be responsible for star formations in G341.244-00.265.

Key words: ISM: individual object (G341.244-00.265) - ISM: molecules - ISM: abundances - stars: formation - stars: protostars

1 INTRODUCTION

Massive stars play an important role in the evolution of our universe. They release large amounts of energy into their surrounding interstellar medium (ISM) and have an immense impact on subsequent star formation therein. However, their formation is still poorly understood compared with their low-mass counterparts. One reason is that they are rare and evolve quickly. The other reason is that they used to form in dense clusters in giant molecular clouds (GMCs) at large distances, which makes it hard to study them individually. In the last few decades, a lot of research have been done to understand the formation of massive stars (e.g. Zinnecker & Yorke 2007; Deharveng et al. 2010, and references
therein). Based on far-infrared and/or millimetre sky surveys such as Herschel InfraRed Galactic Plane Survey (Hi-GAL) (Molinari et al. 2010) and the Atacama Pathfinder Experiment Telescope Large Area Survey of the Galaxy (ATLASGAL) (Schuller et al. 2009), it is demonstrated that filamentary structures are ubiquitous in the interstellar medium and play an important role in the processes of star formation. They could fragment into clumps due to gravitational instabilities (e.g. André et al. 2010; Ragan et al. 2014; Li et al. 2016; Dewangan et al. 2017, and references therein). However, the nature of filamentary structures is still unknown. The mechanisms leading to their formation and their link to star formation processes are also still not clear.

In order to study the properties of filamentary structures, Li et al. (2016) recently identified 517 filamentary structure candidates from the ATLASGAL survey. Their study reveals that massive star formation is ongoing within ~22% of these filaments. G341.244-00.265 is one of their candidates. According to the Brand & Blitz (1993) Galactic rotation model, Schuller et al. (2017) estimate the distance of this filament is about 3.6 kpc to the solar system. Figure 1 displays the Spitzer two-color image of G341.244-00.265. We divide this filamentary structure into three parts: “head”, “body” and “tail”. The “head” of this filamentary cloud involves three dense massive clumps (Contreras et al. 2017). The gas distribution here shows a shell-like structure around the infrared bubble S24. The interactions between the “head” and S24 were studied by Cappa et al. (2016). They found that even though star formations are active in this region, the bubble S24 seems too young for triggering to have begun. The “body” of G341.244-00.265 involves four dense clumps. Two of them (AGAL341.219-00.259 and AGAL341.230-00.271) are associated with “extended green objects” (EGO) by Cyganowski et al. (2008). Molecular line observations support that EGOs are good candidates of massive young stellar objects with ongoing outflow activities (e.g. Chen et al. 2010; Cyganowski et al. 2011). The “tail” of G341.244-00.265 is associated with S21 and S22. On the border of S22, the dense gas shows an arc-like morphology, indicating that it is also being compressed by the expanding HII region. On the south and southwest locate bubble S23 and MWP1G341176-003905 (Simpson et al. 2012). The bottom panel of Figure 1 displays the the radio continuum emission at 843 MHz from the Sydney University Molonglo Sky Survey (SUMSS) (Mauch et al. 2003). Radio emissions from infrared bubble S21, S22, S23, S24 and MWP1G341176-003905 can be seen. The morphology of radio emission is relatively consistent with that of Spitzer 24 µm infrared emissions, which trace warm gas. In order to investigate its physical and chemical properties, and star formation activities, here we present a multi-wavelength study toward this region. We introduce the data we use and analysis in Section 2, discussions are given in Section 3, and finally we summarize in Section 4.

2 DATA AND ANALYSIS

In the followings we present our analysis of archival multi-wavelength data from Hi-GAL in Section 2.1, ATLASGAL in Section 2.2, Structure, excitation, and dynamics of the inner Galactic interstellar medium (SEDIGISM) in Section 2.3, and Millimeter Astronomy Legacy Team Survey at 90 GHz (MALT90) in Section 2.4.

2.1 Hi-GAL

The Hi-GAL data set is comprised of 5 continuum images of the Milky Way Galaxy using the PACS (70 and 160 µm) and SPIRE (250, 350 and 500 µm) instruments. It helps us to identify an unbiased catalogue of filament candidates throughout the Galaxy (e.g., Molinari et al. 2010; André et al. 2010; Wang et al. 2015). The angular resolutions range from 5.2″ to 35.2″ between 70 µm and 500 µm. The high-frequency components provide high angular resolution and are less affected by large-scale background and foreground emissions. We made H2 column density and dust temperature maps of this region by the spectral energy distribution (SED) method described by Wang et al. (2015). Given Hi-GAL is sensitive to low-density gas of about 1021 cm−2, background and/or foreground contaminations make a serious problem when analysing the Hi-GAL data. Following the steps described by Wang et al. (2015), we first remove the background and foreground emissions. After removing the background and
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Fig. 1 Two-color image of G341.244-00.265: 8 µm emission in green and 24 µm emission in red. The magenta pluses mark the eight dense clumps from Contreras et al. (2013). The ATLASGAL 870 µm emissions (in white) are superimposed with levels 0.2, 0.4, 0.8, 1.6 and 3.2 Jy/beam in the top panel. The 843 MHz SUMSS radio continuum emissions (in white) are superimposed with levels 0.02, 0.04, 0.08, 0.16 and 0.32 Jy/beam in the bottom panel.

foreground emissions, we convolve all images at a resolution of 35″, which is the beam size of Hi-GAL at 500 µm. For each pixel, we use equation

\[ I_\nu = B_\nu (1 - e^{-\tau_\nu}) \]  

(1)

to model intensities at various wavelengths. The optical depth \( \tau_\nu \) could be estimated through

\[ \tau_\nu = \mu_{HI} m_HI N_{HI}/R \]  

(2)
We adopt a mean molecular weight per H$_2$ molecule of $\mu_{H_2} = 2.8$ to include the contributions from Helium and other heavy elements. $m_H$ is the mass of a hydrogen atom. $N_{H_2}$ is the column density. $R$ is the gas-to-dust mass ratio which is set to be 100. According to Ossenkopf & Henning (1994), dust opacity per unit dust mass ($\kappa_\nu$) could be expressed as

$$\kappa_\nu = 5.0(\frac{V}{600\text{GHz}})^{\beta} \text{cm}^{-2}\text{g}^{-1}$$

where the value of the dust emissivity index $\beta$ is fixed to 1.75 in our fitting. The two free parameters ($N_{H_2}$ and $T_{dust}$) for each pixel could be fitted finally. Figure 2 displays the derived H$_2$ column density and dust temperature maps of G341.244-00.265. The morphology of column density is similar to the
Table 1  Physical parameters of the ATLASGAL clumps.

<table>
<thead>
<tr>
<th>Source Name</th>
<th>l (deg)</th>
<th>b (deg)</th>
<th>R_eff (pc)</th>
<th>M^a (M⊙)</th>
<th>Type^b</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGAL341.196-00.221</td>
<td>341.196</td>
<td>-0.221</td>
<td>0.42±0.05</td>
<td>837±180</td>
<td>Quiescent</td>
</tr>
<tr>
<td>AGAL341.217-00.212</td>
<td>341.217</td>
<td>-0.212</td>
<td>0.46±0.05</td>
<td>1070±230</td>
<td>Protostellar</td>
</tr>
<tr>
<td>AGAL341.216-00.236</td>
<td>341.216</td>
<td>-0.236</td>
<td>0.83±0.09</td>
<td>1930±290</td>
<td>Protostellar</td>
</tr>
<tr>
<td>AGAL341.219-00.259</td>
<td>341.219</td>
<td>-0.259</td>
<td>0.75±0.06</td>
<td>1910±110</td>
<td>Protostellar</td>
</tr>
<tr>
<td>AGAL341.236-00.271</td>
<td>341.236</td>
<td>-0.271</td>
<td>0.57±0.06</td>
<td>1290±290</td>
<td>Protostellar</td>
</tr>
<tr>
<td>AGAL341.266-00.302</td>
<td>341.266</td>
<td>-0.302</td>
<td>0.70±0.07</td>
<td>2290±500</td>
<td>HII region</td>
</tr>
<tr>
<td>AGAL341.281-00.297</td>
<td>341.281</td>
<td>-0.297</td>
<td>0.68±0.07</td>
<td>1320±260</td>
<td>PDR</td>
</tr>
<tr>
<td>AGAL341.267-00.287</td>
<td>341.267</td>
<td>-0.287</td>
<td>0.53±0.06</td>
<td>360±80</td>
<td>Uncertain</td>
</tr>
</tbody>
</table>

Notes: a: These values are from Contreras et al. (2017); b: Guzmán et al. (2015).

Fig. 3  Averaged spectra of $^{13}$CO (2-1), C$^{18}$O (2-1) and H$^{13}$CO$^{+}$ (1-0) over the filamentary molecular cloud of G341.244-00.265.

ATLASGAL 870 μm emissions. The mean H$_2$ column density is $1.9 \times 10^{22}$ cm$^{-2}$. The total mass of G341.244-00.265 is $\sim 18919 \pm 7080$ M$_\odot$, with a projected length of 11.1 pc. In the “head” and “tail”, the gas is much warmer than that in the “body” of G341.244-00.265. This is probably because the dust there is heated by S22 and S24.

2.2 ATLASGAL clumps

The ATLASGAL also helps us to identify an unbiased catalogue of filament candidates throughout the Galaxy in the emissions of 870 μm (Li et al. 2016). It is the first systematic survey of the inner Galactic plane in the submillimetre (Siringo et al. 2009; Contreras et al. 2013). It provides high angular resolution (~ 19.2 arcsec) of cold dust emissions in the Galaxy. For a dust temperature of 20 K, ATLASGAL is sensitive to gas with H$_2$ column densities exceeding $10^{22}$ cm$^{-2}$. We found eight dense ATLASGAL clumps from the catalog of Contreras et al. (2013) distributing along this filament, like beads on a string. From Table 1, we can see that most of these clumps have masses $> 10^3$ M$_\odot$. Given a typical star formation efficiency of 10%-30% (Lada et al. 2010) and a cluster having a Salpeter-type initial stellar mass function (IMF), we could expect a $10^3$ M$_\odot$ clump to form a star cluster with massive stars $> 20$ M$_\odot$. Therefore, this filamentary cloud is a candidate of massive star forming region.
Fig. 4  The $^{13}$CO (white) and C$^{18}$O (black) line emission contours superimposed on the images of Siptzer-IRAC 8.0 $\mu$m (top), H$_2$ column density (middle) and dust temperature (bottom). The emissions are integrated from -48 to -40 km s$^{-1}$. Contour levels are 40, 50, ..., 90% of each peak emission.
2.3 SEDIGISM

We analyzed $^{13}$CO (2-1) and C$^{18}$O (2-1) emissions in the region of G341.244-00.265 using the SEDIGISM (Schuller et al. 2017) data. The data has been collected with the 12m Atacama Pathfinder Experiment telescope (APEX), which is located on Llano de Chajnantor in Chile. The spacial and velocity resolution of this data is about 28$''$ and 0.1 km s$^{-1}$, respectively. According to the APEX telescope efficiencies Home Page$^1$, the beam efficiency of APEX is 0.75 at the frequency of 230 GHz. A more detail instruction of this survey can be found in Schuller et al. (2017). The $^{13}$CO (2-1) and C$^{18}$O (2-1) cubes are publicly available and can be downloaded from a dedicated server hosted by MPIfR$^2$. Using software packages of CLASS (Continuum and Line Analysis Single-Disk Software) and GREG (Grenoble Graphic), we conducted the data analysis. To compare with the reduced data of Hi-GAL introduced above and the following data of MAL T90, a Gaussian smoothing was applied to convolve the SEDIGISM data into a new resolution of 38$''$.

Figure 3 displays the averaged spectra of $^{13}$CO (2-1) and C$^{18}$O (2-1) over the filamentary molecular cloud of G341.244-00.265. It can be seen that two components at velocity intervals -48 $\sim$ -40 km s$^{-1}$ and -40 $\sim$ -36 km s$^{-1}$ are detected by the two CO isotopologues. The former component is consistent with the ranges measured by Schuller et al. (2017). On the other hand, the -40 $\sim$ -36 km s$^{-1}$ component is undetected by H$^{13}$CO$^+$ (1-0) in the MAL T90 data. Thus it is likely to be foreground or background emissions unrelated with G341.244-00.265. We made the integrated intensity maps of $^{13}$CO (2-1) and C$^{18}$O (2-1) using the velocity range of -48 to -40 km s$^{-1}$. The emission contours overlaid on the Spitzer-IRAC 8.0 µm, H$_2$ column density and dust temperature maps derived in section 2.1 are shown in Figure 4. The regions traced by $^{13}$CO (2-1) show an elongated filamentary structure extending from north-west to south-east. On the borders of S22 and S24, a good morphological match can be seen between PDRs and CO emissions, indicating the gas is being compressed by the two infrared bubbles. C$^{18}$O (2-1) shows more compact gas than $^{13}$CO (2-1) due to its lower abundance. Most of the C$^{18}$O emissions come from the “head” and “tail” of G341.244-00.265, where the dust temperature is relatively high. In the “body”, where the dust temperature is around 20 K, the C$^{18}$O emission is relatively weak. Chemical models indicate that when $T_d$ is below 20 K, carbon species like CO and CS can be depleted in the cold gas (e.g. Lee et al. 2003; Bergin & Tafalla 2007). This may be the reason that the C$^{18}$O emission is relatively weak in the “body” of G341.244-00.265.

The C$^{18}$O line is very useful to quantify the column density, as its emissions are optically thin in most cases. We use the C$^{18}$O (2-1) to derive the column density by assuming the local thermodynamic equilibrium (LTE) conditions. The optical depth of C$^{18}$O (2-1) can be estimated by comparing with its isotopologue line $^{13}$CO (2-1). We assume that the $^{13}$CO and C$^{18}$O emissions arise from the same gas and share a common excitation temperature. The optical depth of the C$^{18}$O line could be derived through

$$
\frac{T_{mb}(^{13}CO)}{T_{mb}(C^{18}O)} = \frac{1 - e^{-A\tau_{ex}}}{1 - e^{-\tau_{ex}}}
$$

(4)

where $A$ is their isotope abundance ratio. In this paper, we adopt the isotopic ratio from Wilson & Rood (1994), which depends on the Galactocentric radius of the region:

$$
A \equiv \frac{[^{13}CO]}{[C^{18}O]} \approx \frac{[^{13}C][^{16}O]}{[^{13}C][^{18}O]} = \frac{58.8 \times R_{GC}[kpc] + 37.1}{7.5 \times R_{GC}[kpc] + 7.6}
$$

(5)

where $R_{GC}$ is the distance of the molecular cloud to the Galactic center. By solving Equation (4) in every map pixel, we got the map of $\tau_{ex}$, which is shown in the top panel of Figure 5. The derived $\tau_{ex}$ is in the range of 0.2 and 0.5, indicating the C$^{18}$O emission is indeed optically thin in this filamentary cloud.

Assuming a filled telescope beam and the excitation temperature is the same for the two isotopic species, we calculate the excitation temperature of C$^{18}$O using

$$
T_{ex} = \frac{h\nu_0}{k} \left[ \ln(1 + \frac{h\nu_0/k}{T_{mbl}/(1 - e^{-\tau}) + J_\nu(T_{ex})}) \right]^{-1}
$$

(6)

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2 http://sedigism.mpifr-bonn.mpg.de
Fig. 5 Maps of the optical depth (top), column density (middle) and abundance (bottom) of C^{18}O. The pluses mark the dense clumps from Contreras et al. (2013).
where ν₀ is the rest frequency of the transition, Tbg is the temperature of the background radiation (2.73 K) and

\[ J_ν(T) = \frac{hν₀}{k} \frac{1}{e^{hν₀/kT} - 1} \]  

(7)

Once τ₁₈ and Tₑ are obtained, the column density of C¹⁸O can be calculated through equation

\[ N(C¹⁸O) = \frac{8πν₀^3}{c^3(2J + 1)A} \sqrt{1 + \left( \frac{2JTₑ}{T₀} \right)^2 e^{(J+1)Tₑ/T₀} - 1} \int τ₁₈dν \]  

(8)

where A is the Einstein coefficient for spontaneous transition, T₀ ≡ hν₀/k = 10.55 K for C¹⁸O (2-1). On the other hand, given C¹⁸O (2-1) is optically thin, we use the approximation:

\[ \int τ₁₈dν = \frac{1}{J(Tₑ) - J(TBG)} \int T_{mb}dν \]  

(9)

For our column density estimate, errors mainly come optical depth. As we have calculated above, the derived τ₁₈ is in the range of 0.2 and 0.5. The errors caused by optical depth should be less than 30%. The abundance of C¹⁸O in each pixel can finally be calculated through \( χ(C¹⁸O) = \frac{N(C¹⁸O)}{N(H²)} \). The column density and abundance maps of C¹⁸O are also shown in Figure 5. The obtained C¹⁸O abundance is \((1.9 - 29.9) × 10^{-7}\), with a mean value of \(8.9 × 10^{-7}\). It can be noted that the C¹⁸O column density is relatively high on the PDRs around S22 and S24, where the gas is relatively warm. The \( T_d - χ(C¹⁸O) \) relation map in Figure 6 suggests a positive correlation. This is consistent with chemical models that as gas gets warmer, more CO species are evaporated from dust grains.

2.4 MALT90

The N₂H⁺ molecular line data is from MALT90. It is one of the most frequently detected molecules in this survey (e.g. Rathborne 2016). MALT90 is an international project aimed at characterizing the sites within our Galaxy where massive star formation will take place (e.g., Foster et al. 2011; Jackson et al. 2013). This project was carried out with the Mopra 22-m telescope. The angular resolution of Mopra is 38′′, with a beam efficiency between 0.49 at 86 GHz and 0.42 at 115 GHz (Ladd et al. 2005). The velocity resolution is about 0.11 km s⁻¹. The target of this survey are selected from the ATLASGAL clumps found by Contreras et al. (2013). The size of the data cube is 4.6′ × 4.6′, with a pixel size of 9″. The data files are publicly available and can be downloaded from the MALT90 Home Page³. We

³ http://atoa.atnf.csiro.au/MALT90
searched the region of G341.244-00.265, and found 7 dust clumps from Contreras et al. (2013) have been observed by MALT90. The 7 regions observed by MALT90 are shown in Figure 2. We combined the 7 data into a new data cube by CLASS, remaining the same beamsize and spacing between adjacent rows. The new combined image of N$_2$H$^+$ is displayed in Figure 7.

N$_2$H$^+$ is a good tracer of dense gas in the early stages of star formation as it is more resistant to freeze-out on grains than the carbon-bearing species (Bergin et al. 2001). The emission maps of N$_2$H$^+$ overlaid on the Spitzer-IRAC 8 µm, H$_2$ column density and dust temperature are shown in Figure 8. We can see that the morphology of N$_2$H$^+$ integrated intensity is quite similar to that of the H$_2$ column density. N$_2$H$^+$ (1-0) has 7 hyperfine transitions (e.g., Pagani et al. 2009; Keto & Rybicki 2010). As shown in Figure 7, in our filament G341.244-00.265, the 7 hyperfine structures of N$_2$H$^+$ (1-0) are blended into 3 groups because of turbulent line widths. Following the method described by Purcell et al. (2009), we estimate the optical depth of N$_2$H$^+$ (1-0). Assuming that the line widths of the individual hyperfine components are all equal, the integrated intensities of group 1/group 2 (defined by Purcell et al. 2009) should be in the ratio of 1:5. The optical depth of N$_2$H$^+$ ($\tau_{N_2H^+}$) can then be derived using the following
Fig. 8 The $\text{N}_2\text{H}^+$ emission contours superimposed on the images of Siptzer-IRAC 8.0 $\mu$m (top), $\text{H}_2$ column density (middle) and dust temperature (bottom). Contour levels are from 2.5 to 8.5 in step of 1.0 K km s$^{-1}$.
Fig. 9 Maps of the optical depth (top), column density (middle) and abundance (bottom) of N$_2$H$^+$ (1-0). The pluses mark the dense clumps from Contreras et al. (2013).
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Fig. 10 The N(N$_2$H$^+$) / N(C$^{18}$O) relative abundance ratio map of G341.244-00.265. The pluses mark the dense clumps from Contreras et al. (2013).

equation:

\[
\frac{\int T_{MB,1}dv}{\int T_{MB,2}dv} = \frac{1 - \exp(-0.2\tau_{2})}{1 - \exp(-\tau_{2})}
\]  

(10)

By solving Equation (11) in every map pixel, we got the map of $\tau_{N_2H^+}$, which is shown in the top panel of Figure 9. We found that in most part of this molecular cloud, the N$_2$H$^+$ (1-0) has an intermediate optical depth, ranging from 0.2 to 0.8. Then, we use the following formula from Chen et al. (2013) to calculate the excitation temperature ($T_{ex}$) of N$_2$H$^+$:

\[
T_{ex} = \frac{4.47(K)}{\ln(1 + \frac{T_{mb}(K)}{4.47(K)(1 - \exp(-\tau_{2})) + 0.236} - 1)}K
\]  

(11)

Assuming LTE conditions and a beam filling factor of 1, the column density of N$_2$H$^+$ in every pixel can thus be calculated through:

\[
N(N_2H^+) = \frac{8\pi v^{3} Q_{rot}}{c^{3}R g_{u}A_{ul}} \frac{\exp(E_{u}/kT_{ex})}{1 - \exp(-\hbar\nu/kT_{ex})} \int \tau dv
\]  

(12)

where $c$ is the velocity of light in the vacuum, $\nu$ is the frequency of the transition, $g_{u}$ is the statistical weight of the upper level, $A_{ul}$ is the Einstein coefficient, $E_{u}$ is the energy of the lower level, $Q_{rot}$ is the partition function. We use approximation

\[
\int \tau dv = \frac{\tau}{1 - \exp(-\tau)}\frac{\int T_{mb}dv}{J(T_{ex}) - J(T_{bg})}
\]  

(13)

to take $\tau_{N_2H^+}$ into account. For the uncertainties of column density, if we only consider the errors from optical depth and integrated intensities, the uncertainty is no more than 30%. The abundance of N$_2$H$^+$ in each pixel can be calculated through $\chi$ (N$_2$H$^+$) = N(N$_2$H$^+$)/N(H$_2$). The column density and abundance maps of N$_2$H$^+$ is also shown in Figure 9. In G341.244-00.265, the column density of N$_2$H$^+$ ranges from 2.1 $\times$ 10$^{12}$ cm$^{-2}$ to 1.8 $\times$ 10$^{13}$ cm$^{-2}$, with a mean value of 0.9 $\times$ 10$^{13}$ cm$^{-2}$. In the dense part of this molecular cloud, the morphology of N$_2$H$^+$ column density is quite similar to that of $N_{H_2}$, suggesting N$_2$H$^+$ is really a good tracer for dense gas.
Chemical models indicate that in the early stages of star formation, as the cloud collapses and the density increases, C-species including CO are easy to be absorbed onto the dust surface, while N-bearing species such as NH$_3$ and N$_2$H$^+$ are hardly to be depleted. As the central star evolves, the molecular cloud gets warm and CO is evaporated from the dust grains when the dust temperature exceeds $\sim 20$ K (Tobin et al. 2013). N$_2$H$^+$ could be destroyed by CO through N$_2$H$^+$ + CO $\rightarrow$ HCO$^+$ + N$_2$ (e.g. Bergin & Langer 1997; Lee et al. 2004; Yu & Xu 2016). When HII regions have formed, N$_2$H$^+$ could also be destroyed by the electron recombination: N$_2$H$^+$ + e$^-$ $\rightarrow$ N$_2$ + H or NH + N (e.g. Dislaire et al. 2012; Vigren et al. 2012; Yu & Xu 2016). Thus, the N(N$_2$H$^+$) / N(C$^{18}$O) ratio could be used as a chemical clock for cloud evolution in star-forming regions. We would expect to find that this ratio decreases as the molecular cloud evolves. Figure 10 shows the map of N(N$_2$H$^+$) / N(C$^{18}$O) relative abundance ratio. We can see that in the center of G341.244-00.265, the ratio is relatively high compared to the other parts of this filament. We regard the gas in the center of G341.244-00.265 as less evolved.

Fig. 11 Top: GLIMPSE [5.8]-[8.0] versus [3.6]-[4.5] diagram for selected sources in the region of G345.244-00.265. Class I and Class II regions are indicated according to the criteria given by Allen et al. (2004). Bottom: YSO candidates from the WISE database.
2.5 Ionizing luminosity and ages of S22 and S24

We use the SUMSS 834 MHz radio continuum data to estimate the Lyman continuum fluxes and dynamical ages of S22 and S24. Assuming an electron temperature of $T_e = 10^4$ K, the number of UV ionizing photons needed to keep an HII region ionized could be given as (Chaisson 1976; Guzmán et al. 2012)

$$N_L = 7.6 \times 10^{46} \left(\frac{S_\nu}{Jy}\right) \left(\frac{D}{kpc}\right)^7 \left(\frac{\nu}{GHz}\right)^{0.1} \left(\frac{T_e}{10^4 K}\right)^{-0.45} \text{s}^{-1}$$

(14)

where $\nu$ is the frequency and $S_\nu$ is the integrated flux density, $D$ is the kinematic distance (3.6 kpc) to the HII region. We derived $N_L \sim 9.3 \times 10^{47}$ ph s$^{-1}$ and $9.0 \times 10^{47}$ ph s$^{-1}$ for S22 and S24, respectively. Based on the ionizing fluxes for massive stars given by Martins et al. (2005), we estimate the spectral types of the ionizing stars of S22 and S24 to be O9.5V.

Assuming the two HII regions expand in a homogeneous medium, their dynamical ages could be estimated through (Dyson & Williams 1980):

$$t_{dyn} = \frac{4R_s}{7c_s} \left[\left(\frac{R_{HII}}{R_s}\right)^{7/4} - 1\right]$$

(15)

where $c_s$ is the sound speed in the ionized gas, assumed to be 10 km s$^{-1}$, $R_{HII}$ is the radius of the HII region, $R_s$ is the original Strömgren radius given by $R_s = (3N_L/4\pi n_i^2 \alpha_B)^{1/3}$, where $N_L$ is the ionizing luminosity calculated above, $n_i$ is the initial H number density of the gas, $\alpha_B = 2.6 \times 10^{-13}$ cm$^3$ s$^{-1}$ is the hydrogen recombination coefficient. We found the dynamical ages are about $2.1 \times 10^5$ yr and $2.2 \times 10^5$ yr for S22 and S24, respectively.

2.6 Distributions of YSOs

We used the highly reliable Galactic Legacy Infrared Midplane Survey Extraordinaire (GLIMPSE) I catalogue (Werner et al. 2004) to search YSOs in this filamentary cloud. The regions in the top panel of Figure 1.

**Fig. 12** Spacial distributions of YSOs on the three colour image created using the Spitzer 3.6 (blue), 4.5 (green) and 8.0 ($\mu$m) IRAC band filters. Class I candidates are shown by green circles, while Class II candidates are shown by yellow crosses. The white contours are the same as shown in the top panel of Figure 1.
Figure 11 indicate stellar evolutionary stages based on the criteria described by Allen et al. (2004): Class II sources are disk-dominated objects. They lie in the region $0<[3.6]-[4.5]<0.8$ and $0.4<[5.8]-[8.0]<1.1$, and their IR excess is caused by accretion disks around the YSOs. Class I sources are protostars with interstellar envelopes. Their locations in the color-color $[3.6]-[4.5]$ vs. $[5.8]-[8.0]$ diagram are delineated by the green lines in Figure 11. We also used photometric data from the Wide-field Infrared Survey Explorer (WISE) to identify YSO candidates in this region. According to the criteria of Koenig et al. (2012), Class I candidates are selected if their colors match $[3.4]-[4.6]>1.0$ and $[4.6]-[12.0]>2.0$, while Class II candidates are selected with colors $[3.4]-[4.6]>0.25 + \sigma ([3.4]-[4.6])$ and $[4.6]-[12.0]>1.0 + \sigma ([4.6]-[12.0])$, where $\sigma (...)$ indicates a combined error, added in quadrature. The locations of Class I and Class II candidates in CCD diagrams are shown in Figure 11. The spatial distributions of the selected YSOs are shown in Figure 12. We note that most of the YSOs distributed in the center of this filament are Class I sources, while most Class II candidates locate in the “head” and “tail” of G341.244-00.265, indicating star formation activities began on the two ends of this filament first.

3 DISCUSSIONS

3.1 Fragmentation

The gravitational stability of a filament can be estimated by comparing its linear mass density $(M/l)$ with the virial linear mass density $(M/l)_\text{vir}$, with $\sigma_r^2$ is the 1-dimensional total (thermal plus non-thermal) velocity dispersion of the average molecular gas. Here we derived the velocity dispersion from the average FWHM of $^{13}$CO (2-1) line. The linear mass per unit length $(M/l)$ of G341.244-00.265 is about 1654 $M_\odot$ pc$^{-1}$, while the virial linear mass density is only about 627 $M_\odot$ pc$^{-1}$, indicating turbulence inside is unable to prevent the cloud from gravitational collapse. We should mention here that the linear mass per unit length estimated here is projected to the plane of the sky, therefore is likely an upper limit. If this filament has a large inclination angle, its linear mass per unit length may be much smaller than this value. From the ATLASGAL catalog of Contreras et al. (2013), we found 8 dense clumps involved in this region. Half of them (AGAL341.236-00.271, AGAL341.266-00.302) show infall motions (He et al. 2015), indicating star formation activities are ongoing actively in this filamentary cloud. We consider the mass-size relationship of these clumps to find out whether they have sufficient mass to form massive stars. The effective radius can be determined by $r = \sqrt{L_{\text{maj}}L_{\text{min}}}$. Here, $L_{\text{maj}}$ and $L_{\text{min}}$ are the de-convolved major and minor axes of each clump. According to Kauffmann & Pillai (2010), the threshold for massive star formation is $M(r) \geq 870 M_\odot (r/pc)^{3.3}$. Figure 13 presents the mass versus radius plot of the eight clumps embedded in G341.244-00.265. We found all these dense clumps lie above the threshold, indicating they are candidates of massive star formation regions.

3.2 Dynamic structure of the filament

The dynamic structure can be a useful tool to study the formation and evolution of a filament. Velocity gradients perpendicular to the major axis have been explained as mass inflowing toward the cloud cores (e.g. Kirk et al. 2013; Dhabal Testi 2002) and/or convergent flows (Schneider et al. 2010). On the other hand, velocity gradients along the axes of each clump. According to Kauffmann & Pillai (2010), the threshold for massive star formation is $M(r) \geq 870 M_\odot (r/pc)^{3.3}$. Figure 13 presents the mass versus radius plot of the eight clumps embedded in G341.244-00.265. We found all these dense clumps lie above the threshold, indicating they are candidates of massive star formation regions.
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The mass versus radius plot of the eight clumps embedded in G341.244-00.265. The grey region represents the parameter space to be devoid of massive star formation, where $M(r) < 870 M_\odot(r/pc)^{1.33}$ (Kauffmann & Pillai, 2010).

$$E_t = \frac{4}{3} \pi n_i \left( \frac{7}{4} R_i^5 + R_i^3 \right)^{6/7} k_B T_4$$

(17)

where $\chi_0$ is the ionization potential (13.6 eV) of hydrogen in the ground state. We found the ionization energy and thermal energy of S22 is about $5.1 \times 10^{47}$ erg and $0.3 \times 10^{47}$ erg, respectively. The ionization energy of S22 is 4 times larger than its surrounding PDR turbulent energy. Thus we regard S22 is the likely driving source of velocity gradient 1. The direction of velocity gradient 2 is from southwest to northeast, with a value of 0.62 km/s pc$^{-1}$. In figure 1, we can see that there seems to be an ionized shock in the southwest of G341.244-00.265. Bubble MWP1G341176-003905 may be the driving source for velocity gradient 2. However, the SUMSS radio emission of MWP1G341176-003905 is quite irregular. We could not estimate its ionization energy and thermal energy. If S22 and MWP1G341176-003905 are indeed the driving sources of the two velocity gradients, our study indicates at least part of the large-scale dynamics in G341.244-00.265 originate from turbulence injections. The velocity gradients in the “head” are quite complex. They can not be explained by rotation of the filament and/or shocks from bubble S24.

3.3 Star formation scenario

The distributions of YSOs suggest there is an age gradient of star formation in this filamentary cloud: most of the YSOs distribute in the center of this filament are Class I sources, while most Class II candidates locate in the “head” and “tail” of G341.244-00.265, indicating star formation activities began on the two ends of this filament first. The abundance ratio of N(N$_2$H$^+$) / N(C$^{18}$O) is relatively higher in the center than that in the two ends of G341.244-00.265, also indicating the gas in the center is less evolved. Both observations and theories indicate expanding HII regions may trigger the next generation of star formation (e.g. Cichowolski et al. 2009; Miao et al. 2009; Panwar et al. 2014). Triggered star formation scenario indicates there should be an age gradient: the ages of stars decrease from center to the outside of an expanding HII region. According to André & Montmerle (1994), the age of Class I YSOs is $\sim 10^5$ yr, while Class II YSOs have a timescale of $\sim 10^6$ yr. However, the dynamical age of S22 and S24 is only about $2.2 \times 10^5$ yr. They are too young to trigger the star formation of the surrounding Class II YSOs. The study of Cappa et al. (2016) also indicate bubble S24 is too young for triggering to have begun. Thus the age gradient could not be explained by the triggered star formation scenario. Numerical studies show that in a long but finite-sized filament, collapse may act a factor of two to three...
times faster at the ends of the filament than at its center (e.g. Pon et al. 2011, 2012), suggesting star formation at the ends of the filament prior to its center. Recently, Kainulainen et al. (2016) found the fragmentation strongly at the ends of the Musca cloud. Dewangan et al. (2017) found massive clumps and YSO clusters prefer to locate at the both ends of the filamentary molecular cloud S242. Like the star formation in the Musca cloud and S242, we also suggest the so-called “end-dominated collapse” may be responsible in G341.244-00.265. More observations and dynamical models are required to check our speculations.

4 SUMMARY

We made a multi-wavelength study toward molecular cloud G341.244-00.265 to investigate the physical and chemical properties, and star formation activities taking place therein. The cloud shows an elongated filamentary structure both in far-infrared and molecular line emissions, with its “head” and “tail” associated with infrared bubbles S21, S22 and S24. G341.244-00.265 has a linear mass density of about 1654 $M_\odot$ pc$^{-1}$, with a projected length of 11.1 pc. The cloud is likely collapsing based on the virial analysis. From the ATLASGAL catalog, we found eight dense massive clumps associated with this filamentary cloud. All of these clumps have sufficient mass to form massive stars. At least two velocity gradients have been found. S22 and MWP1G341176-003905 may be the driving source of the two velocity gradients. Using data from the GLIMPSE and WISE survey, we search YSO candidates in this region. We found an age gradient of star formation in this filamentary cloud: most of the YSOs distributed in the center is Class I sources, while most Class II candidates locate on the two ends of G341.244-00.265, indicating star formation at the two ends of this filament is prior to the center. The abundance ratio of $\text{N(N}_2\text{H}^+)/\text{N(C}^{18}\text{O))}$ is higher in the center than that in the two ends, also indicating the gas in the center is less evolved. The so-called “end-dominated collapse” mechanism might be responsible for star formations in G341.244-00.265.

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