THE DENSE FILAMENTARY GIANT MOLECULAR CLOUD G23.0–0.4: BIRTHPLACE OF ONGOING MASSIVE STAR FORMATION

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ABSTRACT

We present observations of 1.5 square degree maps of the 12CO, 13CO, and C18O (J = 1 − 0) emission toward the complex region of the supernova remnant (SNR) W41 and SNR G22.7−0.2. A massive (∼5 × 10^5 M_⊙), large (∼84 × 15 pc), and dense (∼10^4 cm^−3) giant molecular cloud (GMC), G23.0–0.4 with V_{SR} ∼ 77 km s^−1, is found to be adjacent to the two SNRs. The GMC displays a filamentary structure along the Galactic plane. The filamentary structure of the dense molecular gas, traced by C18O (J = 1 − 0) emission, is also coincident well with the distribution of the dust-continuum emission in the direction. Two dense massive MC clumps, two 6.7 GHz methanol masers, and one H ii/SNR complex, associated with the 77 km s^−1 GMC G23.0−0.4, are aligned along the filamentary structure, indicating the star-forming activity within the GMC. These sources have periodic projected spacing of 0′18−0′26 along the giant filament, which is consistent with the theoretical predictions of 0′′22. This indicates that the turbulence seems to dominate the fragmentation process of the dense gaseous filament on a large scale. The established 4.4 kpc distance of the GMC and the long dense filament traced by C18O emission, together with the rich massive star-formation groups in the nearby region, suggest that G23.0−0.4 is probably located at the near side of the Scutum–Centaurus arm in the first quadrant. Considering the large scale and the elongation structure along the Galactic plane, we speculate that the dense filamentary GMC is related to the spiral density wave of the Milky Way.

Key words: ISM: clouds – ISM: individual objects (GMC G23.0–0.4) – ISM: molecules – stars: formation

1. INTRODUCTION

The molecular gas is mostly within the Galactic plane and the giant molecular clouds (GMCs) are more concentrated toward the spiral arms of the Milky Way (Solomon et al. 1985; Stark & Lee 2006). The GMCs, as tracers of the large-scale structure in the Galaxy, are the birthplaces of most of massive stars in the Galactic plane. Although they are rare in the Galaxy, massive stars significantly affect their surroundings (e.g., Walch 2014). Determining the nature of massive star formation is difficult because of its complexities (e.g., the short lifetime, the obscuration by their parent dust clouds, and the many processes therein). Therefore, understanding the properties of the GMCs is a key step toward understanding massive star formation. Moreover, the dense GMCs are also helpful in constructing the large-scale Galactic structure because they are a good tracer of the spiral structure in the Milky Way (e.g., Goodman et al. 2014).

André et al. (2014) recently synthesized a comprehensive physical picture to describe star formation in the dense cores of filamentary networks of molecular clouds (MCs). Several cases were also studied in observations, such as the infrared dark cloud (IRDC) Nessie (Jackson et al. 2010), the Rosette GMC (Schneider et al. 2012), the IRDC G14.225−0.506 (Busquet et al. 2013), the Cygnus OB 7 GMC (Dobashi et al. 2014), and the IRDC G011.11−0.12 (Ragan et al. 2015). Takahashi et al. (2013) summarized the hierarchical fragmentation structure of the Orion Molecular Cloud (OMC) filaments from GMCs scale (∼35 pc) to the small-scale clumps scale (∼0.3 pc). Along the dense filament, massive stars probably form from these dense fragmentational regions (Jackson et al. 2010). However, the fragmentation structures of other long dense GMC filaments are less studied. This is partly due to the complicated morphology of MCs, the superposition of the emission of molecular gas along the line of sight (LOS), and the strong disruption of GMCs by the massive star’s feedback within it (Li et al. 2013; Ragan et al. 2014).

On the other hand, combining the dust emission and the molecular line data set is a powerful aid for investigating the nature of the filamentary structure. In the paper, the column density distributions of the densest structures can benefit from the ATLASGAL dust-continuum survey, while the kinematical information about the dense filament can be gotten from our CO and their isotopes survey (see Section 2).

GMC G23.0–0.4, which is centered at (l, b, v) = (23°0′, −0°4′, 77 km s^−1) and roughly aligned with the Galactic Plane, has a coherent velocity structure over about 1′′1 × 0′′2 as traced by 13CO (J = 1–0) and C18O (J = 1–0) emissions (Figure 2, also see Su et al. 2014). Several H ii regions (see the H ii region catalogs in Lockman 1989; Lockman et al. 1996; Anderson et al. 2011, 2014), a group of early-type massive stars (Messineo et al. 2014), and two supernova remnants (SNRs) (Green 2014) are located in the field of view (FOV) of the GMC. The distances of most of the above objects are consistent with that of GMC G23.0–0.4 (Messineo et al. 2010, 2014; Su et al. 2014). G23.0–0.4, as a long dense GMC, is a good laboratory to investigate the properties of the filament. The locally massive stars’ feedback near/within the dense GMC also gives us a good opportunity to study the relationship between them.

In this paper we mainly focus on the nature of the filamentary GMC G23.0–0.4 in the complicated interstellar medium (ISM). We also discuss the relationship between the GMC and the ambient star-forming activity. We present the observations of 12CO (J = 1–0), 13CO (J = 1–0), and C18O
(J = 1−0), and the data reduction in the following section. Section 3 shows the properties of the GMC. In Section 4, we mainly discuss the fragmentation process along the dense filament. We summarize our conclusions in Section 5.

2. OBSERVATIONS AND DATA REDUCTION

Observations in the $^{12}$CO (J = 1−0), $^{13}$CO (J = 1−0), and C$^{18}$O (J = 1−0) were made simultaneously with the 13.7 m millimeter-wavelength telescope located at Delingha in China. The nine-beam Superconducting Spectroscopic Array Receiver (SSAR) was working as the front end in sideband separation mode (see the details in Shan et al. 2012).

The data were observed using the on-the-fly (OTF) mode, with the standard chopper wheel method for calibration. In the mode, the telescope beam is scanned along lines in the Galactic longitude and latitude directions on the sky at a constant rate of 0.3 km s$^{-1}$, and the receiver records spectra every 0.3 s. The data scanned in both longitude and latitude directions were combined to reduce the fluctuation of noise perpendicular to the scanning direction.

We adopted the main beam efficiency $\eta_{mb} = 0.44$ for $^{12}$CO (J = 1−0) and 0.48 for $^{13}$CO (J = 1−0) and C$^{18}$O (J = 1−0). The mean rms noise level of the calibrated brightness temperature ($T_{B}$) was $\sim 0.5$ K for $^{12}$CO (J = 1−0) at a resolution of 0.16 km s$^{-1}$ and $\sim 0.3$ K for $^{13}$CO (J = 1−0) and C$^{18}$O (J = 1−0) at 0.17 km s$^{-1}$. All CO data were reduced using the GILDAS/CLASS package.$^5$

The available CO High Resolution Survey (COHRS, Dempsey et al. 2013) data and the Galactic Ring Survey (GRS, Jackson et al. 2006) data were also used for comparison. The 1.4 GHz VLA Galactic Plane Survey (VGPS, Stil et al. 2006) data and the 870 $\mu$m ATLASGAL survey (Schuller et al. 2009) data were used to trace the thermal/non-thermal radio emission and the cold dust emission, respectively. We also use the H I data of VGPS to resolve the kinematic distance ambiguity of GMC G23.0−0.4 (see Section 4.1). We briefly summarized the information of the survey data in Table 1.

3. RESULTS

The molecular gas toward the observational region contains a number of velocity components, which indicates the overlapping MCs along the LOS in the complicated region. This is not surprising when we consider that a large amount of molecular gas is located in the inner Galaxy. In the direction of $l = 23^\circ$0, our LOS will cross several spiral arms (the local/Orion–Cygnus arm, the Carina–Sagittarius arm, the Scutum–Centaurus arm, and the Perseus arm) and the Galactic Bar (e.g., Hammersley et al. 2000; Benjamin et al. 2005).

Figure 1 shows the typical spectra that is extracted from a $30' \times 30'$ region centered at ($l = 23^\circ25$, $b = -0^\circ25$). We find that even for an optically thin C$^{18}$O (J = 1−0) line, the spectrum is crowded in the velocity interval of 50–110 km s$^{-1}$. Four distinct C$^{18}$O peaks can be discerned at 52.6, 63.6, 77.4, and 96.8 km s$^{-1}$, which probably indicates the different MC components along the LOS. In addition, several other MC components (e.g., 57.4, 81.6, and 101.2 km s$^{-1}$) can be seen near the above C$^{18}$O peaks.

The complicated MC components in the velocity interval of 50–110 km s$^{-1}$ prevent us from discussing the relationship between the different MCs. Fortunately, in the velocity range of 70–80 km s$^{-1}$, the C$^{18}$O (J = 1−0) emission of GMC G23.0−0.4 that we are interested in suffer less from contamination from other MC components along the LOS. The filamentary structure of the GMC can be confirmed to be coherent in velocity space, especially from the C$^{18}$O emission (Section 3.1). Moreover, we have shown that the distance of the GMC with LSR velocity of 77 km s$^{-1}$ was determined (see Section 4.1). The established distance allows us to investigate more reliable physical properties of the GMC accordingly. In this section, we mainly study the properties of GMC G23.0−0.4 ($V_{LSR} \sim 70–84$ km s$^{-1}$; Section 3.1). We also investigate other interesting MCs adjacent to the filamentary GMC that have a similar LSR velocity of $\sim 77$ km s$^{-1}$ (Section 3.2).

3.1. Dense Filamentary GMC G23.0−0.4

3.1.1. Distribution of the CO Emission

We made the three-color intensity image in the velocity interval of $V_{LSR} = 74–79$ km s$^{-1}$, overlaid on the VGPS 1.4 GHz radio continuum contours (Figure 2). It is clear that the overall distribution of the molecular gas is quite complicated in the FOV (Figure 2). We also note that the characteristics of our $^{13}$CO (J = 1−0) emission are consistent with that of GRS data. Meanwhile, the C$^{18}$O (J = 1−0) emission in our observations can provide further insight into the nature of the dense molecular gas. Here we focus on the brightest filamentary structure: GMC G23.0−0.4.

In the three-color image, the $^{12}$CO (J = 1−0) emission in blue is more diffuse and extended than the $^{13}$CO (J = 1−0;
green) and C$^{18}$O ($J=1$−0; red) emission. By contrast, the C$^{18}$O ($J=1$−0) emission is only seen in the region of bright $^{13}$CO ($J=1$−0) emission. This is probably because the typical densities they trace are different—$\sim 10^2$ cm$^{-3}$ for optically thick $^{12}$CO ($J=1$−0), $\sim 10^3$ cm$^{-3}$ for median optical depth $^{13}$CO ($J=1$−0), and $\sim 10^4$ cm$^{-3}$ for optically thin C$^{18}$O ($J=1$−0) (e.g., Yonekura et al. 2005). We thus expect that the $^{12}$CO ($J=1$−0), $^{13}$CO ($J=1$−0), and C$^{18}$O ($J=1$−0) emission is from the enveloping layer of low density, the middle layer of intermediate density, and the inner core of high density of an MC, respectively. The C$^{18}$O ($J=1$−0) emission, which is a good tracer of the high-density molecular gas ($\sim 10^3$ cm$^{-3}$), can reveal the nature of the dense part of a GMC. The blue envelopes, green intermediate layers, and red dense cores of the MCs are distinguished in Figure 2. Therefore, combining the $^{12}$CO ($J=1$−0), $^{13}$CO ($J=1$−0), and C$^{18}$O ($J=1$−0) data set is useful for studying the properties of the GMC.

The brightest portion of GMC G23.0−0.4, which appears roughly parallel to the Galactic plane, generally displays a long filamentary structure. The dense gas of the GMC traced by C$^{18}$O ($J=1$−0) emission is actually inclined by 20° with respect to the Galactic plane. The dense filament of GMC G23.0−0.4 extends $\sim 1\arcmin$ in length and is distinguished by bright CO emissions. The mean width of the filamentary GMC traced by C$^{18}$O ($J=1$−0) emission is about 6′, whereas the width of the thin filament in the denser region is near 2′ or less. This indicates that there are some substructures (e.g., thin filaments, dense cores, and clumps) within the filamentary GMC G23.0−0.4 (Figure 2). Future observations at higher spatial resolution will be helpful in investigating these interesting characteristics of the GMC.

In general, the filamentary structure of GMC G23.0−0.4 is hierarchical. In our spatial resolution ($\sim 0.8\arcmin$), GMC G23.0−0.4 displays wave-like and branch structures along the trunk of the filament. Some thin filaments with $\sim 2′$ width and pc-scale dense clumps are distributed along the 77 km s$^{-1}$ giant filament (e.g., see Figures 2–4).

3.1.2. Physical Parameters of the GMC

Physical parameters of the GMC can be derived from the following description (e.g., see the appendix in Bourke et al. 1997). First, the excitation temperature of the CO gas $T_{ex}$ can be derived using the equation:

$$T_{mb} = f \left[ J(T_{ex}) - J(T_{bg}) \right] \left[ 1 - \exp(-\tau) \right],$$

where $\tau$ is the optical depth; $T_{ex}$ and $T_{bg}$ are the excitation temperature and the background temperature, respectively; and

$$J(T) = \frac{h
u}{k} \exp\left(\frac{1}{T} - 1\right) .$$

Assuming that the $^{12}$CO ($J=1$−0) emission is optically thick ($\tau_{12} \gg 1$) and its beam filling factor $f$ is equal to 1, we can get the excitation temperature from the peak temperature of $^{12}$CO ($J=1$−0) emission. The distribution of the excitation temperature is shown in Figure 3. The self-absorption from the cold foreground gas along the LOS is ignored and the derived excitation temperature as a result should be regarded as lower limit.

The optical depth of $^{13}$CO ($J=1$−0) and C$^{18}$O ($J=1$−0) of GMC G23.0−0.4 can be estimated by assuming that the excitation temperature of these molecular lines have the same
value as that of $^{12}$CO pixel by pixel (see Figure 3). Thus, in the local thermodynamic equilibrium (LTE) assumption, the optical depths of $\tau_{13}$ and $\tau_{18}$, the column densities of $^{13}$CO and $^{18}$O can be derived using the following equations (e.g., see the appendix in Bourke et al. 1997):

$$\tau_{13}(V) = -\ln \left[ 1 - \frac{T_{MB13}(V)}{5.29(J_{13}(T_{ex}) - 0.164)} \right],$$

$$\tau_{18}(V) = -\ln \left[ 1 - \frac{T_{MB18}(V)}{5.27(J_{18}(T_{ex}) - 0.167)} \right],$$

$$N(^{13}\text{CO}) = 2.42 \times 10^{14} \sum V \frac{0.2(\text{km s}^{-1})\tau_{13}(V)T_{ex}}{1 - \exp[-5.29/T_{ex}]} \text{ cm}^{-2},$$

and

$$N(^{18}\text{O}) = 2.42 \times 10^{14} \sum V \frac{0.2(\text{km s}^{-1})\tau_{18}(V)T_{ex}}{1 - \exp[-5.27/T_{ex}]} \text{ cm}^{-2},$$

where $T_{ex}$ is the excitation temperature of these molecules in K, and $J_{13}(T_{ex}) = 1/[\exp(5.29/T_{ex}) - 1]$ for $^{13}$CO ($J = 1 - 0$), and $J_{18}(T_{ex}) = 1/[\exp(5.27/T_{ex}) - 1]$ for $^{18}$O ($J = 1 - 0$). In the calculation, we divide each spectrum into 0.2 km s$^{-1}$ bins to estimate the optical depth in each bin. Accordingly, we can calculate the $^{13}$CO and $^{18}$O column density within the LSR velocity range from 72 to 81 km s$^{-1}$.

The $^{12}$CO column density of the GMC can be estimated from the optically thick $^{13}$CO ($J = 1 - 0$) and $^{18}$O ($J = 1 - 0$) emission. In the above calculation, the $^{13}$CO abundance of $N(\text{H}_2)/N(^{13}\text{CO}) \approx 7 \times 10^5$ (Ferking et al. 1982) and the $^{18}$O abundance of $N(\text{H}_2)/N(^{18}\text{O}) \approx 7 \times 10^6$ (Castets et al. 1982) are adopted. On the other hand, using the optically thick $^{12}$CO ($J = 1 - 0$) emission as the tracer of molecular gas, the H$_2$ column density of the GMC can be estimated directly by adopting the mean CO-to-H$_2$ mass conversion factor 1.8 $\times$ 10$^{20}$ cm$^{-2}$ K$^{-1}$ km s$^{-1}$s (Dame et al. 2001). In the estimation of the mass of the GMC, we adopt a mean molecular weight per H$_2$ molecule of 2.76. The distance of the GMCs was adopted as 4.4 kpc (see Section 4.1). The parameters of the filamentary GMC G23.0–0.4 are listed in Table 2.

According to Figure 3, we find that the excitation temperature in the region of the dense filamentary GMC G23.0–0.4 is higher compared with that of the other molecular gas in the FOV. The mean excitation temperature of the filamentary structure is about 20 K and the excitation temperatures in some interface regions between SNR W41 and SNR G22.7–0.2 are higher than 26 K. The value of the excitation temperature of GMC G23.0–0.4 is comparable to those of other GMCs, such as, 10–70 K for the Orion-A GMC (Nagahama et al. 1998) and 7–56 K for the W51 GMC (Parsons et al. 2012). We also note that the excitation temperature of GMC G23.0–0.4 is very close to that in the high-density layer of the W3 GMC (15–30 K, Polychroni et al. 2012).

The structures of GMC G23.0–0.4 can be readily distinguished in the maps of the optical depth of the $^{18}$O ($J = 1 - 0$) emission (the right panel in Figure 4). We find that the distribution of $\tau_{18}$ is more diffuse and extended than that of $\tau_{13}$. In the dense part of GMC G23.0–0.4, $\tau_{13}$ is larger than 0.5, which indicates that the optical depth of $^{13}$CO ($J = 1 - 0$) is not optically thin. On the other hand, $\tau_{18}$ is mostly less than 0.15 in the region of the filamentary GMC G23.0–0.4. The highest $\tau_{18}$ are 0.21–0.23 in the high $\tau_{13}$ region, which show the densest parts in the GMC. The distribution of the $^{18}$O gas is more compact than those of the $^{13}$CO and $^{18}$O gas, which indicates that the $^{18}$O emission can clearly reveal dense structures of GMC G23.0–0.4.

The column density, the mass, and the density of the main body of GMC G23.0–0.4 is ($1.7$–$2.9$) $\times$ 10$^{22}$ cm$^{-2}$, ($3.2$–$5.2$) $\times$ 10$^{5}$ M$_\odot$, and 730–1200 cm$^{-3}$, respectively. Note that the column density only represents the mean value for the filamentary GMC in the rectangle region. The column density is higher than $5 \times 10^{22}$ cm$^{-2}$ in some dense regions, which indicates that the volume density of these regions is higher than $6 \times 10^{3}$ cm$^{-3}$ (assuming a depth of 2 arcmin, the mean width of slim filaments, for the dense region). Therefore, the strong $^{18}$O ($J = 1 - 0$) emission, which represents the distribution of the high-density molecular gas in the GMC G23.0–0.4, is very likely tracing the potential star-formation regions (see Section 4.3.1).

The mass of the GMC listed in Table 2 is probably the lower limit because some diffuse molecular gas outside the rectangle region is not accounted for. Based on the optically thick $^{13}$CO ($J = 1 - 0$) emission, we estimate that the total mass of GMC G23.0–0.4 is $\sim 1.2 \times 10^6 M_\odot$ due to a large amount of low-density molecular gas in the enveloping layer of the GMC, which is outside the rectangle region. In the above calculation, all pixels above 40 K km s$^{-1}$ (about the half of the $^{12}$CO mean intensity of the GMC) are accounted for and the total mass of the GMC is derived from a $\sim 2200$ arcmin$^2$ region, in which region the velocity interval is 68–82 km s$^{-1}$ and the mean density is 87 K km s$^{-1}$, respectively. On the contrary, the dense gas (e.g., $>10^3$–$10^4$ cm$^{-3}$), which only represents a fraction of the GMC’s total mass, is mainly located in the trunk of the filamentary GMC G23.0–0.4 (388 arcmin$^2$ in Table 2, also see the right panel of Figure 4).

The filamentary GMC G23.0–0.4 is different from the giant molecular filaments studied by Ragan et al. (2014), in which samples these giant filaments have low dense gas mass fractions (2%–12%). In the analysis of Ragan et al. (2014), the authors selected the $^{13}$CO ($J = 1 - 0$) emission ($<10^3$ cm$^{-3}$) as the total mass tracer and the ATLASGAL 870 /m dust

| Molecular Tracer | Area (arcmin$^2$) | $N(\text{H}_2)$ (10$^{22}$ cm$^{-2}$) | $M(\text{H}_2)$ (10$^5$ M$_\odot$) | $n(\text{H}_2)$ (cm$^{-3}$) |
|------------------|-----------------|----------------------------------|-------------------------------|-----------------|
| $^{12}$CO ($J = 1 - 0$) | 877 | 2.1 | 5.2d$^4_{12}$ | 890d$^4_{12}$ |
| $^{13}$CO ($J = 1 - 0$) | 863 | 1.7 | 4.2d$^3_{12}$ | 730d$^3_{12}$ |
| C$^{18}$O ($J = 1 - 0$) | 388 | 2.9 | 3.2d$^4_{12}$ | 1200d$^4_{12}$ |
emission as the dense gas mass tracer (>10^{22} \text{cm}^{-2}). In our study, we use ^{12}\text{CO} (J = 1–0) emission (≈10^2 \text{cm}^{-3}) and C^{18}\text{O} (J = 1–0) emission (>10^{22} \text{cm}^{-2}) to calculate the total mass and the dense gas mass of the GMC, respectively. The total mass of the GMC in our study is obviously larger than that from the \(^{12}\text{CO} (J = 1–0)\) emission, whereas the mass of the dense gas from the \(^{18}\text{CO} (J = 1–0)\) emission is roughly similar to that from the ATLASGAL 870 µm dust emission (see the discussion of FP1 in Section 4.3.1). Therefore, GMC G23.0–0.4 seems to be denser than the GMC samples studied by Ragan et al. (2014).

3.1.3. Velocity Structures of the Dense Molecular Gas

We made the channel maps of the C^{18}\text{O} (J = 1–0) emission in the interval of 69–85 km s\(^{-1}\) by a step of 2 km s\(^{-1}\) to investigate the spatial distribution of the dense molecular gas (Figure 5). The main body of filamentary GMC G23.0–0.4 is in the velocity interval of 75–79 km s\(^{-1}\). The molecular gas in 71–75 km s\(^{-1}\) is assembled in the interface between SNR W41 and SNR G22.7–0.2. On the other hand, the molecular gas in 79–85 km s\(^{-1}\) is roughly in the center of SNR W41.

In the position–velocity (PV) diagrams along the long filamentary GMC G23.0–0.4 (Figure 6), we can discern that the GMC is in the velocity interval of 70–84 km s\(^{-1}\). The interaction between SNR G22.7–0.2 and the GMC can be discerned from the \(^{12}\text{CO} (J = 1–0)\) PV diagram (see detail in Su et al. 2014). The \(V_{\text{LSR}} \sim 100 \text{km s}^{-1}\) MC component is from the molecular gas near the tangent point (MC G23.4, Ohishi et al. 2012), which is irrelevant to GMC G23.0–0.4. We also made the PV diagram of the \(^{18}\text{CO} (J = 1–0)\) emission along the interface between SNR W41 and SNR G22.7–0.2 (Figure 7). The PV diagram delineates some diffuse emission extended to 70 km s\(^{-1}\) besides the dense 74 and 78 km s\(^{-1}\) MCs. The feature probably relates to the star-forming activity near the region. Based on the spatial distribution of the molecular gas, it seems reasonable to assume that the emission within the velocity of 70–84 km s\(^{-1}\) comes from GMC G23.0–0.4, which is associated with the ambient SNRs (Su et al. 2014). The distance estimation of the MCs suggests that the GMC complex is probably in the near side of the Scutum-Centaurus arm (see Section 4.1).

3.2. Other Interesting MCs

In addition to the GMCs G23.0–0.4 (this paper) and G22.6–0.2 (Su et al. 2014), there are some interesting MCs with similar LSR velocity in the FOV. A partial shell structure \((l = 23^\circ4, b = -0^\circ6)\) is ambient to the southern edge of SNR W41, and a series of pillar-like protrusions are along a bright-rim structure near \(l = 23^\circ25, b = 0^\circ08\) (Figure 2).

The low-density (≈10^2–10^3 \text{cm}^{-3}) molecular gas of the partial shell structure is in the southern boundary of SNR W41, in which place the remnant shows very faint radio emission (see the left panel in Figure 4). An early-type massive star would create a wind bubble of radius 5600 \text{pc} (McKee et al. 1984). The radius of such a bubble would be about 23 pc, assuming the mean density of the region is 20 \text{cm}^{-3}. This value is less than that of the partial shell structure (radius of ≈28' or 36 pc at a distance of 4.4 kpc). Therefore, the partial shell structure, with a total mass of \(\sim 2 \times 10^5 \text{M}_\odot\), is likely the result of a series of massive stellar winds. On the other hand, supernova explosions may also be responsible for the formation of this structure.

In the northern region of the FOV, some small, pillar-like protrusions seem to be located along a partial shell near \(l = 23^\circ25, b = 0^\circ08\). These small, pillar-like protrusions have bright \(^{12}\text{CO} (J = 1–0)\) and \(^{18}\text{CO} (J = 1–0)\) emission (see Figure 4), which can be distinguished from the diffuse \(^{12}\text{CO} (J = 1–0)\) surroundings (Figure 2). At the apexes of the pillar-like molecular clouds, bright 870 µm dust emission (5.94 Jy for G23.1989 + 0.0009 and 4.85 Jy for G23.2646 + 0.0774) is coincident with the peak emission of \(^{18}\text{CO} (J = 1–0)\). The interesting structures are probably related to the energetic radiation of the nearby early-type stars. Such bright-rim clouds are often associated with the photoevaporation from the nearby massive star (e.g., Taylor et al. 1999; Bally et al. 2010). A diffuse H\alpha region G23.162 + 0.023 (Lockman et al. 1996), which is indeed located to the west of these pillar-like MCs, is probably responsible for these bright-rim clouds.

Both of the interesting MCs adjacent to GMC G23.0–0.4 are very likely associated with stellar feedback from massive stars. It shows that GMC 23.0–0.4 is located near the region of massive stars in the view of the adjacent interesting MCs, which is consistent with Section 4.2.
Figure 5. Velocity channel maps of the C$^{18}$O ($J = 1\rightarrow 0$) emission line in units of K km s$^{-1}$, overlaid with the VGPS 1.4 GHz radio continuum emission contours. The velocity range used for the integration is indicated in the top-right corner of each panel. Note that the intensity scales are different from each other.
4. DISCUSSION

4.1. Distance of GMC G23.0–0.4

We use two methods to determine the distance of the dense filamentary GMC G23.0–0.4. In the first method, the distance of the GMC can be derived from the trigonometric parallax assuming the association between the GMC and the 6.7 GHz methanol maser G23.01–0.41. The distance of it is 4.59±0.33 kpc (Brunthaler et al. 2009). This appears reasonable because the 6.7 GHz methanol maser G23.01–0.41, which is located in the center of the GMC, has a similar LSR velocity \( V_{\text{LSR}} \sim 81 \) \( \text{km s}^{-1} \), see Table 2 in Brunthaler et al. 2009) to GMC G23.0–0.4.

In the second method, the distance of the GMC can be estimated from its LSR velocity \( (\sim 77 \text{ km s}^{-1}) \). Using the Galactic rotation curve of Reid et al. (2014), we thus place the GMC G23.0–0.4 at a near kinematic distance of 4.4 ± 0.4 kpc. The kinematic distance ambiguity can be resolved from the H\(_2\) self-absorption method (HISA, see Figures 1 and 2 in Roman-Duval et al. 2009). Based on the HISA method, a molecular cloud located at the near kinematic distance will exhibit the 21 cm absorption feature that is coincident with the \(^{13}\text{CO}\) peak from the cloud (Roman-Duval et al. 2009). These authors suggested that the \( \sim 70-82 \text{ km s}^{-1} \) MCs (see Table 1 in their paper), which is mostly associated with GMC G23.0–0.4 in the FOV, is located at the near kinematic distance. We also checked the method for other small regions in GMC G23.0–0.4 using VGPS H\(_2\) data and our CO data, and find that the GMC is indeed in the near side. Accordingly, we exclude the far kinematic distance of the GMC, which is consistent with that of Ellsworth-Bowers et al. (2013). In their work, the \( \sim 77 \text{ km s}^{-1} \) GMC is also in the near side (see Table 3 in Ellsworth-Bowers et al. 2013).

We note that the near kinematic distance of the GMC is in agreement with the trigonometric distance and that of other works (Leahy & Tian 2008; Messineo et al. 2010, 2014). We suggest that the dense filamentary GMC G23.0–0.4, together with the rich massive star-formation groups ambient to the giant filament (Section 4.2), is probably located at the near side of the Scutum-Centaurus arm in the first quadrant (e.g., see the spiral arm models of the Milky Way, Taylor & Cordes 1993; Reid et al. 2014). For simplicity, we adopt the value of 4.4 kpc as the distance of the GMC throughout the paper.

4.2. Environment of GMC G23.0–0.4

We have shown that SNRs G22.7–0.2 and W41 are both interacting with the \( V_{\text{LSR}} \sim 77 \text{ km s}^{-1} \) GMC G23.0–0.4 (Su et al. 2014). The kinematic signature of the interaction between SNR G22.7–0.2 and the GMC can be seen from the PV diagram of the \(^{12}\text{CO}\) \( (J = 1–0) \) emission (the left panel of
(\text{23.4, 23.1, 22.8, 22.5})$

Figure 8. Left panel: Map of the abundance ratio $X_{\text{C18O}}/X_{\text{C17O}}$ overlaid with the ATLASGAL 870 $\mu$m continuum emission contours (0.2, 1.2, 2.2, and 3.2 Jy beam$^{-1}$). The dense dust clumps (\textcolor{red}{1.2 Jy beam$^{-1}$}) are highlighted with red contours. Right panel: Map of the optical depth of the $^{12}\text{CO}$ ($J = 1-0$) emission. The black boxes, black circles, red circles, blue circles, and blue boxes show the fifteen dust-continuum-identified MC clumps, two 6.7 GHz methanol masers, twelve \text{H\textsc{n}} regions, two \text{H\textsc{n}}/SNR complexes, and two massive star groups, respectively.

Figure 6. On the other hand, the emission of $^{12}\text{CO}$ ($J = 3-2$) is a good tracer of the warm and dense molecular gas associated with star formation. It is also a good tracer of shocked gas (e.g., outflow activity, SNR–MC interaction, and cloud–cloud collision). Unfortunately, the COHRS version 1 only maps a region of $|b| < 0.25$ in the direction (Dempsey et al. 2013), which does not cover the main body of GMC G23.0–0.4. Nevertheless, the available $^{12}\text{CO}$ ($J = 3–2$) data are used to study the molecular gas in the FOV. Some enhanced $^{12}\text{CO}$ ($J = 3–2$) emission in the northern region of SNR W41 is detected in the velocity interval 70–74 km s$^{-1}$ (the blueshift compared to the LSR velocity 77 km s$^{-1}$ of the GMC) when we searched for proof of the SNR–MC interaction (Q. Liu et al., in preparation). This is consistent with the result that SNR W41 lies behind GMC G23.0–0.4 and the remnant is interacting with the GMC (Frail et al. 2013). We hope that the data of the COHRS release 2 will provide further insight into the nature of the warm and dense molecular gas of the overall GMC G23.0–0.4.

There are multiple overlapping \text{H\textsc{n}} regions in the FOV of SNRs G22.7–0.2 and W41 (e.g., Messineo et al. 2010). Even though the velocity of the \text{H\textsc{n}} regions often deviates from that of their parent MCs, we suggest that most regions with a systematic velocity of 70–81 km s$^{-1}$ probably have a similar distance to the 77 km s$^{-1}$ GMC (Su et al. 2014). In the right panel of Figure 8, the positions of twelve \text{H\textsc{n}} regions and two \text{H\textsc{n}}/SNR complexes (Lockman 1989; Kuchar & Clark 1997; Gieven et al. 2005a, 2005b; Helfand et al. 2006; Anderson et al. 2011, 2014) are marked with red and blue circles, respectively. At least six \text{H\textsc{n}} regions (e.g., see Table 6 in Anderson et al. 2014) in the FOV are most likely located at the near distance.

Moreover, the stellar cluster GLIMPSE9 ($l = 22^\circ 756, b = -0^\circ 400$) is also associated with GMC G23.0–0.4 (Messineo et al. 2010; Su et al. 2014). Recently, Messineo et al. (2014) discovered a number of massive stars surrounding GLIMPSE9 in the south of SNR G22.7–0.2 (REG GLIMPSE9Large in their paper) and some massive stars near the center of SNR W41 (REG4 in their paper); early-type stars with K-band extinction from $\sim 1.3$–1.9 mag have spectrophoto-

metric distances consistent with that of the GMC. The two massive star groups, which are most likely associated with the GMC G23.0–0.4 (Messineo et al. 2010, 2014), are also marked with the blue boxes in Figure 8.

The existence of two SNRs, several \text{H\textsc{n}} regions, and a number of massive stars associated with GMC G23.0–0.4 show the energetic star-formation activity in the region. The natal GMCs of these objects are very likely destroyed by the process of the photoevaporation of the \text{H\textsc{n}} regions (McKee & Ostriker 2007). On the other hand, the supernova explosions will remove a significant fraction of the cloud mass if their massive progenitors did not run far away from their parent GMCs (Iffrig & Hennebelle 2015). However, these energetic processes have a limited influence on the nearby dense gas of the filamentary GMC G23.0–0.4. For example, SNR G22.7–0.2, which has a center about 18 pc away from the dense filamentary GMC, has only $3.3 \times 10^4 M_\odot$ km s$^{-1}$ momentum and $5 \times 10^{48}$ erg kinetic energy injection to GMC G23.0–0.4 (Su et al. 2014). The dense gas within GMC G23.0–0.4 still keeps the filamentary structure, which is roughly parallel to the Galactic plane.

The formation of GMCs along the spiral arms is believed to be related to the spiral shocks (e.g., Dobbs et al. 2006; Dobbs & Bonnell 2007). Assuming that GMC G23.0–0.4 and the ambient GMCs, which are the natal places of the massive progenitors of the SNRs, formed simultaneously in the region of the FOV, the age of GMC G23.0–0.4 is $\gtrsim 10$ Myr (the typical lifetimes of B1–O9 stars). In this timescale, the natal GMCs of SNRs G22.7–0.2 and W41 and the \text{H\textsc{n}} regions (Su et al. 2014) had been destroyed by the violent massive star formation therein (e.g., Section 3.2.2 in McKee & Ostriker 2007). But these energetic processes outside GMC G23.0–0.4 have a limited influence on the dense gas of the GMC. On the other hand, the strong massive star-forming activities are ongoing along the filamentary GMC G23.0–0.4 (see Section 4.3), which will exhaust and dissipate the molecular gas of the GMC in several future Myr. Part of the dense gas has actually been destroyed by the \text{H\textsc{n}}/SNR complex G022.760–0.485 (FP2 in Figure 9, Section 4.3). In the region of the \text{H\textsc{n}}/SNR complex G022.760–0.485, the $^{18}\text{O}$ ($J = 1–0$) emission is very weak (see the region of 06 in Figure 8 of Su et al. 2014), which is probably due to the stellar feedback of the massive star therein. Accordingly, the lifetime of the dense filamentary GMC should be about 10–20 Myr, which is consistent with the result of the 1–3 free-fall time of massive GMCs (Murray 2011).

4.3. Fragmentation of the Giant Filament

4.3.1. Fragmentation on Large Scale

$^{18}\text{O}$ ($J = 1–0$) emission is not a good tracer for very high-density molecular gas ($\gtrsim 10^5$ cm$^{-3}$) due to its relatively low
critical density. Other high-density tracers such as HCN or N$_2$H$^+$ are helpful in investigating conditions within high-density regions of the GMC ($\sim$10$^2$–10$^4$ cm$^{-3}$). In our study, we use the bright dust emission to reveal the dense, massive structures within GMC G23.0–0.4. The strong dust emission is labeled on red contours in the left panel of Figure 8. These dense molecular clouds, together with massive star-formation regions, probably represent the molecular gas concentration along the dense filament.

The fragmentation points (FPs) 1–5 along GMC G23.0–0.4 are shown in Figure 9. The properties of these FPs are summarized in Table 3. FP1 contains a millimetric radio source BGPS G022.548–00.525 (Rosolowsky et al. 2010), in which region the emission from the 870 µm ATLASGAL data is also bright (G022.5483–0.5225, 3.68 Jy; Csengeri et al. 2014). The mass of the dense molecular gas in the region of 1.5 × 1.5 estimated from the C$^{18}$O ($J = 1$–0) emission is $\sim$4 × 10$^3$ $M_\odot$. Assuming that the dust can be characterized by a single temperature of 15 K in the region (see Figure 3), we calculate the isothermal mass of $\geq$6 × 10$^2$ $M_\odot$ in the region of 0.5 × 0.5 based on the dust-continuum data. The high-surface density ($\geq$10$^3$ $M_\odot$ pc$^{-2}$) implies the potential star formation in the region of FP1. FP2 is an H II/SNR complex region (Lockman 1989; Kucharcz & Clark 1997; Helfand et al. 2006; Anderson et al. 2011, 2014) that is associated with the GMC G23.0–0.4 (Messineo et al. 2010, 2014; Su et al. 2014). FP3 and FP4 contain the 6.7 GHz methanol masers G23.01–0.41 and G23.19–0.38, respectively, which are good tracers of massive star formation (Szymczak et al. 2002; Brunthaler et al. 2009). In the two regions, the 1.1 mm (Rosolowsky et al. 2010) and 870 µm (Csengeri et al. 2014) emission are very bright (e.g., BGPS G023.012–00.410 and ATLASGAL G023.0063–0.3991 (3.79 Jy), and G023.0082–0.4092 (12.76 Jy) in FP3; BGPS G023.208–0.0378 and ATLASGAL G023.2056–0.3772 (11.30 Jy) and G023.2122–0.3726 (1.34 Jy) in FP4). The nature of FP5, where a millimetric radio source BGPS G023.368–0.0290 is placed (Rosolowsky et al. 2010), is similar to that of FP1 (see Table 3). The emission from the 870 µm ATLASGAL data is also bright (G023.3652–0.2887, 4.93 Jy; Csengeri et al. 2014) and many young stellar objects (YSOs) are distributed in the vicinity of FP5 (Ragan et al. 2009).

We also showed the abundance ratio distribution between $^{13}$CO and C$^{18}$O, $X_{^{13}$CO}/$X_{C^{18}$O}$ for the 77 km s$^{-1}$ molecular gas in the left panel of Figure 8. We found that the abundance ratio $X_{^{13}$CO}/$X_{C^{18}$O}$ becomes lower (similar to the value of 5.5 in the solar system, see Table 4 in Wilson & Rood 1994) in the regions of the bright dust-continuum emission (the red contours in the left panel of Figure 8), which probably indicates the high-density regions for star formation. The difference between the abundance ratios in the bright dust emission regions (e.g., $\sim$5 for FPs 1, 3, 4, and 5) and the other region (e.g., $\sim$10 for FP 2) very likely represents the evolutionary sequence of the dense molecular gas in the GMC. The abundance ratio will be relatively higher when the dense molecular cores are chemically influenced by the far-ultraviolet (far-UV) radiation from the massive stars embedded in the GMC (van Dishoeck & Black 1988). In other words, the photodissociation rate of the C$^{18}$O molecule is larger than that for $^{13}$CO, which leads to the higher abundance ratio $X_{^{13}$CO}/$X_{C^{18}$O}$ in the massive star’s UV radiation field. This is consistent with the result that part of the dense gas in GMC G23.0–0.4 has been destroyed by the H II/SNR complex G022.760–0.485 (see Section 4.2). In contrast, the lower abundance ratio represents the earlier stage of dense MCs, which are either not or less affected by massive star formation. The low abundance ratio in the bright dust emission regions is also consistent with the result that most of cold dust emission is from 77 km s$^{-1}$ GMCs (see Figure 8). We find that the distribution of the dust clumps/cores (the fifteen black boxes in Figure 8) is coincident with that of the C$^{18}$O emission. In the FOV, 11 of 15 dust clumps are associated with GMC G23.0–0.4. The distance of these dust-continuum-identified MC clumps (Ellsworth-Bowers et al. 2013) is therefore consistent with that of the 77 km s$^{-1}$ MCs.

The mean column density from C$^{18}$O ($J = 1$–0) emission is 0.5–1.5 × 10$^{23}$ cm$^{-2}$ for the regions of FP1, FP3, FP4, and FP5, in which regions the column density from NH$_3$ emission are all higher than 1 × 10$^{23}$ cm$^{-2}$ (Wienen et al. 2012). FP1, FP3, FP4, and FP5 show the densest regions along the filament (see the red contours in the left panel of Figure 8); whereas the dense molecular gas in FP2 is exhausted and dissipated by the very strong star-formation activities there. The abundance ratio $X_{^{13}$CO}/$X_{C^{18}$O}$ is higher than 10 in the region of FP2, which is consistent with the result that the abundance ratio becomes higher in the mature H II region within the GMC.

It is also worth noting that the column density of FP1 derived from the C$^{18}$O emission is comparable to that from the 870 µm dust emission. According to Kauffmann & Pillai (2010), both FP1 and FP5 are potentially dense enough ($m_{\text{clump}} > m_{\text{min}}[r] = 870M_\odot [r/pc]^{1.3}$) to form massive stars. On the other hand, the 870 µm fluxes of FP1 (3.68 Jy) and FP5 (4.93 Jy) are close to the conservative criterion of 5 Jy at 4.5 kpc, which is the flux limit at the distance to potentially form high-mass stars (Csengeri et al. 2014).

Therefore, two dense clumps potentially sustain high-mass star formation (FP1 and FP5), two ongoing massive stars (FP3 and FP4), and one mature H II/SNR complex region (FP2), which are all the dense gas concentrations associated with the filament, can well represent the fragmentation on large scales ($\sim$10 pc) along the dense filamentary GMC G23.0–0.4.

### 4.3.2. Turbulence Dominates the Large-scale Fragmentation

We presented the main physical properties of the dense filament GMC G23.0–0.4 in Section 3.1. The large-scale fragmentation of the dense gas along the filament was discussed in Section 4.3.1. In this section, we investigate the stability of the dense filament.

If we regard the dense gas traced by the C$^{18}$O ($J = 1$–0) emission as a whole, the stability of the filamentary GMC...
can be described by the virial parameter $\alpha = \frac{M_{vir}}{|M|} = 2\sigma_v^2 l / GM$ (Bertoldi & McKee 1992; Fiege & Pudritz 2000), where $\sigma_v = \Delta v_{180}/2.355$, $l$, and $G$ are the average velocity dispersion of $^{13}$CO ($J = 1-0$), the length of the dense filament, and the gravitational constant, respectively. The virial parameter $\alpha$ is thus estimated to be 0.27, which indicates that the dense filament is gravitationally bound. Thus, the dense GMC is unstable and will collapse on a free-fall timescale if no other supporting mechanisms are included in the whole system.

In the above calculation, we take the long dense GMC as a symmetrical cylinder. The parameters of the cylinder (~$66' \times 66' \times 6'$) can be obtained from the CO observations (see Section 3.1.1 and Table 2). The ~$66'$ length of GMC G23.0–0.4 can be obtained from the $^{13}$CO emission (~1.2 K cutoff of $^{13}$CO emission; see the second contour level in the middle panel of Figure 6). Assuming the length of the $^{13}$CO emission of ~$66'$, the mean width of the dense filament is Area ($^{12}$CO)/length ~$6'$. The morphology of the dense filament can also be seen in Figures 4 and 8, which clearly show the boundary of the GMC. We also note that the virial parameter of the GMC from the $^{13}$CO emission is similar to that from the $^{12}$CO emission. This is normal because the value of the length, velocity dispersion, and total mass of the GMC from $^{13}$CO and $^{12}$CO are similar (see Table 2).

Moreover, we can estimate the fragmentational separation within the large-scale filamentary structure to determine the character of the gaseous cylinder. Adopting $10^5$ cm$^{-3}$ as the mean density of the GMC (Table 2), the filament scale height $H = \sigma_v (4G\pi M)^{-0.5}$ is about 0.8 pc due to the sausage instability of a self-gravitating fluid cylinder (Chandrasekhar & Fermi 1953; Inutsuka & Miyama 1992). In the above calculation, we use the mean full width at half-maximum (FWHM) of $^{18}$O ($J = 1-0$) emission ($\Delta v_{180} = 3.5 \text{ km s}^{-1}$) in the GMC to estimate the velocity dispersion of the turbulence (Fiege & Pudritz 2000). This leads to a spacing of $22 H \sim 17 \text{ pc}$ (~$0.22$ at $4.4$ kpc) between the fragmentation clumps, which results in good agreement with the observations of the fragmentation spacing $0.18-0.26$ along the dense filamentary GMC G23.0–0.4 (see Figure 9). This indicates that the non-thermal turbulent pressure dominates over thermal pressure, which is consistent with other works (e.g., Jackson et al. 2010; Kainulainen et al. 2013). In this case, the turbulence seems to control the fragmentation of the dense gaseous filament on a large scale.

The regions of the five FPs represent the nodes of the filamentary GMC, which features regions that have a large amount of molecular gas fragments that assemble into cores of subsequent protostars (see the sketch of Figure 2 in Jackson et al. 2010). If these cores are massive and dense enough to form high-mass stars, the stellar feedback such as outflows, UV radiation field, stellar winds, and supernova explosions within the dense filament will dramatically affect the surrounding molecular gas. FPs 2–4 in GMC G23.0–0.4 probably represents this case. The mass in these regions is massive enough to form massive stars. FP2, with its mature H II/SNR complex region, represents a slightly older generation than FP3 and FP4. The dense molecular gas in the region of FP2 is now exhausted, whereas the dense molecular gas in regions of FP3 and FP4 is still plentiful (Figures 8 and 9). Recent massive star formation is ongoing in FP3 and FP4, which is revealed by the 6.7 GHz methanol masers (Szymczak et al. 2002). FPs 1 and 5, which are at both ends of the dense filament, are also massive and dense enough to form massive stars (Section 4.3.1).

5. SUMMARY

We have presented a detail CO line study of the dense filamentary GMC G23.0–0.4. Combining the molecular line observations and the 870 $\mu$m dust-continuum emission, the main results are summarized as follows:

1. GMC G23.0–0.4 with LSR velocity of 77 km s$^{-1}$ displays a filamentary structure roughly along the Galactic plane, which also shows hierarchical branch structure in $^{18}$O ($J = 1-0$) emission. Some slim filaments and pc-scale dense clumps are distributed along the main body of the GMC.

2. The optical depth of $^{13}$CO ($J = 1-0$), $\tau_{13}$, is higher than 0.5 in the dense parts of the giant molecular filament, whereas $\tau_{13}$ is only close to 0.2 in the same regions. This indicates that $^{13}$CO is optically thin in the dense regions of the GMC. The dense parts of the GMC are readily seen in $^{18}$O ($J = 1-0$) emission, which is also the good tracer of the high-density molecular gas ($\gtrsim 5 \times 10^{22}$ cm$^{-3}$ in our case, see Figure 9).
3. The mass of the dense part of GMC G23.0–0.4 is \( \sim 5 \times 10^5 M_\odot \) in the region of \( \sim 84 \times 15 \) pc, while the total mass of the GMC is probably close to \( 1.2 \times 10^6 M_\odot \).

4. GMC G23.0–0.4, which has a distance of 4.4 kpc, is probably located at the near side of the Scutum-Centaurus arm in the inner Galaxy. The long structure at \( b \sim -0.4 \), which is traced by \(^{13}\)CO (\( J = 1-0 \)) emission along the longitude, is probably related to the density wave of a spiral arm of the Milky Way.

5. There are at least two SNRs, several H\( \pi \) regions, and many massive stars associated with the \( 77 \) km s\(^{-1}\) molecular gas, indicating that massive star formation occurred several Myr ago in the region. The natal GMCs of these objects have probably been destroyed by the strong stellar feedback. Meanwhile, these energetic sources are interacting with the nearby GMC G23.0–0.4.

6. The distribution of the abundance ratio \((X_{\text{CO}})/X_{\text{CO}0})\) is coincident with the distribution of the cold dust emission along the dense filamentary GMC G23.0–0.4. The giant filament is massive and dense enough to form high-mass stars. Massive star formation is ongoing in the nodes of the giant filament, which is also traced by the bright dust-continuum emission, the 6.7 GHz methanol maser, and H\( \pi \)+H\( \text{II} \)/SNR complex associated with the dense GMC. The fragmentation with spacing \( \sim 0.22 \) along the filamentary GMC G23.0–0.4 also can be explained by the sausage instability of the cylinder.

7. The turbulence seems to control the fragmentation process of the dense gaseous filament on a large scale. Combining the millimeter and IR data set, we show that massive star formation is ongoing at the fragmentation points with the periodic spacing along the entire filament. The massive stellar feedback near the dense filament has little influence on the evolution of the filamentary GMC G23.0–0.4. On the contrary, the evolutionary processes of the massive stars within the massive filament dominate the fate of the dense GMC.

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