ALMA Observations of Giant Molecular Clouds in M33. I. Resolving Star Formation Activities in the Giant Molecular Filaments Possibly Formed by a Spiral Shock

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Abstract
We report molecular line and continuum observations toward one of the most massive giant molecular clouds (GMCs), GMC-16, in M33 using ALMA with an angular resolution of 0.044 × 0.027 (∼2 pc × 1 pc). We have found that the GMC is composed of several filamentary structures in 12CO and 13CO(J = 2–1). The typical length, width, and total mass are ∼50–70 pc, ∼5–6 pc, and ∼10^2 M☉, respectively, which are consistent with those of giant molecular filaments (GMFs) as seen in the Galactic GMCs. The elongations of the GMFs are roughly perpendicular to the direction of the galaxy’s rotation, and several H II regions are located at the downstream side relative to the filaments with an offset of ∼10–20 pc. These observational results indicate that the GMFs are considered to be produced by a galactic spiral shock. The 1.3 mm continuum and C18O(J = 2–1) observations detected a dense clump with the size of ∼2 pc at the intersection of several filamentary clouds, which is referred to as the “hub filament,” possibly formed by a cloud–cloud collision. A strong candidate for protostellar outflow in M33 has also been identified at the center of the clump. We have successfully resolved the parsec-scale local star formation activity in which the galactic scale kinematics may induce the formation of the parental filamentary clouds.

Unified Astronomy Thesaurus concepts: Interstellar medium (847); Star formation (1569); Giant molecular clouds (653); Triangulum Galaxy (1712); Protostars (1302); Local Group (929)

1. Introduction
Giant molecular clouds (GMCs) are considered to be major sites of high-mass star formation (e.g., Heyer & Dame 2015), and the formed stars eventually regulate the galaxy evolution through their feedback. Understanding of the physical properties of GMCs and their evolution is a challenging study observationally. The sizes of GMCs are as large as >10–100 pc, and a large number of samples are needed to track the continuous evolution. Several comprehensive molecular gas surveys have been carried out toward the Local Group of galaxies, such as the Large Magellanic Cloud (LMC; e.g., Fukui et al. 1999; Kawamura et al. 2009; Wong et al. 2011) and M33 (e.g., Miura et al. 2012; Corbelli et al. 2017). They classified the GMCs into a few groups with different evolutionary stages based on the association of H II regions and young massive star clusters, and then estimated the GMC lifetime as a few ×10 Myr.

Star formation and GMC evolution in the spiral arm are classically considered to be controlled by galactic shock (Fujimoto 1968; Roberts 1969; Shu et al. 1973) caused by “quasi-stationary density waves” (e.g., Lin & Shu 1964). In contrast to this, an alternative model called “dynamic” spiral theory, which involves nonsteady stellar arms, has been proposed (Dobbs & Baba 2014 and references therein). The two models predict qualitatively different gas distributions on the spiral arm. The former produces an apparent offset between parental gas and H II regions, but the latter does not show a clear spatial offset between them (Wada et al. 2011). Although recent observations toward grand design spiral galaxies sometimes prefer to show a sequential distribution of gas and high-mass stars across the spiral arm predicted by galactic shock (e.g., Egusa et al. 2004, 2011; Hirota et al. 2011; Colombo et al. 2014), the actual mechanism to trigger the star formation in the spiral arm is not well constrained by available observations. On spiral arms in galaxies, gas is exposed to many processes in addition to spiral shocks, such as cloud–cloud collision, hydrodynamic instabilities, stellar feedback, and self-gravity (see the review by Dobbs & Baba 2014). In order to understand the mechanism driving GMC and high-mass star formation in spiral arms, it is important to reveal a high-dynamic-range picture from the galactic scale down to filaments/clumps (see the next paragraph) directly leading to star formation.

Molecular gas surveys using CO and its isotopes toward star-forming regions in the solar neighborhood, such as Taurus, revealed that filamentary structures are considered to be fundamental ingredients of molecular clouds (e.g., Mizuno et al. 1995; Onishi et al. 1996; Goldsmith et al. 2008; Hacar et al. 2013) and...
eventually collapse into individual dense cores and protostars. Recent high-resolution dust continuum observations with the Herschel telescope confirmed the quasi-universality of the filamentary structure in molecular clouds extending to the Galactic plane (André et al. 2014 and references therein), and the typical widths of the filament were measured as \( \sim 0.1 \) pc (Arzoumanian et al. 2011, 2019; André et al. 2016). Although the typical length of the abovementioned filaments in the solar-neighborhood star-forming regions are \( \sim 10 \) pc or less, the observations toward the Galactic plane identify much longer filamentary complexes with the length scale of \( \gtrsim 50–100 \) pc, called “giant molecular filaments (GMFs).” One of the most prominent examples is the “Nessie” Nebula (Jackson et al. 2010), which is an infrared dark cloud on the Galactic plane. The long filamentary structure possibly formed by the passage of a spiral shock. One of the most active high-mass star-forming molecular complexes in the Galaxy, W51, also has a filamentary stream with a length of \( \sim 100 \) pc (e.g., Burton & Shane 1970; Moon & Park 1998; Okumura et al. 2001; Fujita et al. 2019). The velocity of this stream is different from that of the main complex of W51, and this excess of the velocity may be due to the streaming motions induced by a spiral density-wave (Burton & Shane 1970; Koo 1999). However, the actual origin of these GMFs/streamer may be hard to understand due to the serious contaminations at the line of sight in the Galactic plane and its edge-on view.

ALMA observations with an angular resolution of 0′′.25 (\( \sim 0.06 \) pc) toward GMCs in the LMC have started to resolve \( \sim 0.1 \) pc width molecular filaments (Fukui et al. 2019; Tokuda et al. 2019), possibly formed by a galactic scale flow. Moderate resolution (\( \sim 3'' = 0.7 \) pc) studies in the LMC also provided us hints for understanding the evolution of internal structures of GMCs. For example, Sawada et al. (2018) suggest that the quiescent GMC shows a diffuse emission, whereas the active star-forming ones have highly structured distributions, i.e., filaments and clumps. Wong et al. (2019) measured the linewidth-size relation in several GMCs down to \( \lesssim 1 \) pc and show the velocity dispersion at a fixed size slightly increases as star formation progresses.

The early millimeter/submillimeter observations described in this section suggest that we need at least \( \sim 1 \) pc resolution to understand the internal gas properties of molecular clouds and their kinematics. In addition to this, a birds-eye view is needed to understand the relation between spiral arms and local star formation activities. One of the closest galaxies, the LMC and Small Magellanic Cloud, are not the best targets for this purpose because the irregular galaxies do not have clear spiral arms. The flocculent spiral galaxy M33 is the most unique candidate so far to investigate the effect of the spiral arms on molecular cloud and high-mass star formation at a parsec-scale resolution using ALMA thanks to its proximity (\( \sim 840 \) kpc; Freedman et al. 2001) and favorable inclination (\( i = 51^\circ \); Corbelli & Salucci 2000).

We have performed ALMA observations with a spatial resolution of \( \sim 2 \) pc to 1 pc toward three massive (\( \sim 10^5 M_\odot \)) GMCs (NGC 604-GMC, GMC-8, and GMC-16) in different evolutionary stages identified by the early surveys (Rosolowsky et al. 2007; Onodera et al. 2010; Miura et al. 2012) to investigate the molecular gas structures and star formation activities. In this paper, we present the results of GMC-16 associated with several HII regions and 24 \( \mu \)m sources (Verley et al. 2007). We note that CO(3–2) observations of M33 by Miura et al. (2012) cataloged the present target as two clouds, GMC-2 and GMC-16, which correspond to the cloud numbers 425 and 435 in Corbelli et al. (2017), respectively. Because the two clouds spatially connect each other, we treat these objects as a single molecular cloud system for convenience throughout the manuscript and use the name of GMC-16 as a representative, which is more luminous in CO(3–2) than the other. We describe the detailed results of the other targets in a separate paper for NGC 604-GMC (K. Muraoka et al. 2020, in preparation) and a forthcoming paper for GMC-8.

2. Observations

We performed ALMA Cycle 5 Band 6 (1.3 mm) observations in molecular lines and continuum toward three GMCs in M33 (P.I.: K., Muraoka, #2017.1.00461.S). We used the ALMA main array (the 12 m array) with the configuration of C43-5 as well as the 7 m array of the Atacama Compact Array (ACA; a.k.a. Morita Array). The observations were carried out during 2017 and 2018 October. There were three spectral windows targeting \( ^{12}\text{CO}(J = 2–1) \), \( ^{13}\text{CO}(J = 2–1) \), and \( \text{C}^{18}\text{O}(J = 2–1) \). The bandwidths of the correlator setting were 117.19 MHz with 1920 channels for \( ^{12}\text{CO} \) and 960 channels for \( ^{13}\text{CO} / \text{C}^{18}\text{O} \). We used two spectral windows for the continuum observations with an aggregate bandwidth of 3750 MHz with a channel width of 0.98 MHz.

While we did not change the system calibration provided by the observatory, the data was reprocessed with the Common Astronomy Software Application (CASA) package (McMullin et al. 2007) version 5.4.0 in the imaging process. We used the tclean task with the multi-scale deconvolver. We applied the Briggs weighting with a robust parameter of 0.5 and the natural weighting to the 12 m and 7 m array data, respectively. We used the auto-multithresh procedure (Kepley et al. 2020) in tclean to select the emission mask in the dirty and residual images. We continued the deconvolution process until the intensity of the residual image reached the \( \sim 1\sigma \) noise level. We combined the individually imaged 12 and 7 m array data sets with the feathering task. We also performed the multiple array data combination with an alternative method, in which the visibility data of the 12 and 7 m array were merged together before the tclean task, and then imaged them using the same auto-masking technique as described above. The two different methods reproduce fairly similar results (only \( \lesssim 10\% \) flux difference in rms), and we used the first option in the analysis through the manuscript.

The final processed image qualities are summarized as follows. The beam sizes of the molecular lines (\( ^{12}\text{CO}, ^{13}\text{CO}, \) and \( \text{C}^{18}\text{O} \) and continuum data are 0″.44 \( \times 0″.27 \), corresponding to \( \sim 2 \) pc \( \times 1 \) pc, and 0″.40 \( \times 0″.25 \), respectively. The rms noise levels of the molecular lines at a velocity resolution of \( \sim 0.2 \) km s\(^{-1} \) are \( \sim 4.3 \) mJy beam\(^{-1} \) (\( \sim 0.9 \) K). The sensitivity of the continuum observations is \( \sim 0.02 \) mJy beam\(^{-1} \).

We estimated the missing flux of the interferometric observations toward GMC-16 using the available \( ^{12}\text{CO}(J = 2–1) \) data obtained with the single-dish IRAM 30 m telescope (Druard et al. 2014). We spatially smoothed the 12 m + 7 m data to an angular resolution of 12″, which is the same as the IRAM data and then compared the total flux between the two images. Since the total missing flux of the \( ^{12}\text{CO} 12 m + 7 m \) data in the observed field (Figure 1(a)) is \( \sim 40\% \), we additionally combined the IRAM image with the ALMA data using the feathering technique, and we confirmed that the combined image reproduces the total flux measured with the
IRAM data alone. We assume that the $^{13}$CO, C$^{18}$O, and continuum observations have no significant missing flux, because the distributions of these tracers are more compact than those of $^{12}$CO.

We retrieved the SUBARU H$\alpha$ Supreme-cam image (PI: Arimoto, N.; Proposal IDs: S01B091, S02B105) from the archive and calibrated with a standard manner to investigate the star formation activities in the GMC (see Section 3.1). The absolute astrometry of the original H$\alpha$ image is $\sim$0.2\arcsec, as we align the image using the UBNO-B1 catalog. To confirm the accuracy of the astrometry, a point-source catalog of Gaia Data Release 2 (Bailer-Jones et al. 2018) was used, and thus there is no significant positional error of the H$\alpha$ image over the ALMA beam size.

3. Results

3.1. Spatial Distributions of Molecular Gas of GMC-16

Figure 1 shows the molecular gas distributions in $^{12}$CO and $^{13}$CO($J = 2 – 1$) in GMC-16. The missing flux of the $^{12}$CO toward the southern region where the decl. angle is lower than +30°48′50″ is as small as 10%, indicating that the gas distributions are dominated by compact rather than diffuse gas. This is consistent with an early result that active star-forming GMCs in the LMC are highly structured (Sawada et al. 2018). The previous single-dish studies in CO lines by Tosaki et al. (2011), Miura et al. (2012), and Druard et al. (2014) marginally resolved this GMC into two peaks. The ALMA observations clearly reveal multiple filamentary structures with the length scale of $\gtrsim$50 pc elongated in the north–south direction. The filaments are not randomly distributed but exhibit ordered direction and there are roughly two main filamentary components (Filaments A and B) as indicated in Figure 1(a). In addition to these filaments, there is a relatively “extended gas” (see the final paragraph of this subsection) and a dense clump associated with the 1.3 mm continuum emission (hereafter, MMS, millimeter source) and multiple small filaments (see Section 3.2) at the southern part of the GMC. We estimated the total gas mass and relatively dense gas mass from the $^{12}$CO and $^{13}$CO data, respectively. The first one is derived from the $^{12}$CO data assuming the X$\text{CO}$ factor in M33, $2.0 \times 10^{20}$ cm$^{-2}$/(K km s$^{-1}$)$^{-1}$ (Rosolowsky et al. 2007), and CO($2–1$)/CO($1–0$) ratio of 0.7 (Tosaki et al. 2011; Druard et al. 2014). The mass of higher density regions traced by $^{13}$CO is estimated by the local thermodynamical equilibrium calculation applying the excitation temperature derived from the $^{13}$CO data and the relative abundance of [H$_2$]/[1$^{13}$CO] of 1.4 $\times$ 10$^4$, which is close to an intermediate value adapted in the Galaxy (e.g., Frerking et al. 1982) and the LMC studies (e.g., Fujii et al. 2014; Fukui et al. 2019; Tokuda et al. 2019). The total mass ($^{12}$CO mass) and dense gas mass ($^{13}$CO mass) are $8 \times 10^5 M_\odot$ and $2 \times 10^5 M_\odot$, respectively. The fraction of $^{13}$CO/$^{12}$CO mass is $\sim$0.2, which is consistent with that in the Galactic plane (Torii et al. 2019). The total mass, median (FWHM) width, and length of Filament A/B in the $^{12}$CO map are measured to be $\sim$1 $\times$ 10$^5 M_\odot$, $\sim$5–6 pc, and $\sim$50–70 pc, respectively. These characteristics are comparable to those of GMFs, e.g., the Nessie cloud (Jackson et al. 2010), in the Galaxy.

Figure 2(a) shows that GMC-16 is located at an optical spiral arm in the northern part of M33. Based on the morphology of the spiral arm, the moving direction of the gas (i.e., galactic rotation) is considered to be from east to west. Figure 2(b) shows the comparison between the $^{12}$CO and H$\alpha$ images. There are several bright H$\text{II}$ regions and some of them are outside of the present field coverage with ALMA. Two GMFs

![Figure 1](image1.png)

**Figure 1.** Molecular gas distributions in M33-GMC-16. (a) Color-scale image shows the velocity-integrated intensity map of $^{12}$CO($J = 2–1$) combining the ALMA data (the 12 m + 7 m array) with IRAM 30 m data. The angular resolution is given by the white ellipse in the lower left corner. The cross mark denotes the position of the 1.3 mm continuum peak. Note that the color scale is adjusted to the range from 0 to 100 K km s$^{-1}$ in order to show the diffuse emission and thus the CO peak is saturated in this figure. The white dotted line shows the field coverage of the ALMA observations. (b) Same as (a) but for the $^{13}$CO($J = 2–1$) image obtained by the ALMA 12 m + 7 m array.
Figure 2. (a) The $^{12}$CO($J=2-1$) velocity-integrated intensity map of M33 obtained with the IRAM 30 m telescope (Druard et al. 2014). The transparent white dashed line indicates the optical arm near GMC-16 (Sandage & Humphreys 1980). (b) Color-scale image shows Hα emission obtained by the SUBARU telescope. Contour shows the $^{12}$CO map, which is the same as that in Figure 1(a). The lowest contour level and the subsequent steps are 20 K km s$^{-1}$.

(Filaments A and B) are located at the eastern side of the H II regions. Although the previous single-dish studies with a spatial resolution of a few $\times$10 pc identified these H II regions inside the molecular cloud, the present observations reveal a clear position offset between ionized and CO gas with a separation of $\sim$10–20 pc.

We made channel maps with a velocity bin of 4 km s$^{-1}$ of the $^{12}$CO($J=2-1$) data to investigate the velocity structure of the GMC (Figure 3(a)). As one can see in the channel maps, there is a velocity gradient along the north–south direction from blueshifted to redshifted velocity. To further illustrate the difference between the individual components, i.e., Filament A, extended gas, and some of the filaments, we made a position–velocity (PV) diagram of $^{13}$CO (Figure 3(b)) along the dotted lines shown in Figure 1(a). We manually selected the analyzed region to avoid the complex hub-filamentary structure (Section 3.2). The velocity width (FWHM) of the filamentary structures is measured as $\sim$3 km s$^{-1}$, in contrast to this, the extended gas shows much wider velocity width, $\sim$6 km s$^{-1}$. The centroid velocity of the extended gas is $\sim$240 km s$^{-1}$, which is apparently redshifted compared to that of Filament A. This difference may be relevant to turbulent dissipation and deceleration by the galactic spiral shock. We discuss this possibility in Section 4.1.

3.2. A Compact Millimeter Source with High-velocity Wing Components in GMC-16

Figure 4 shows a zoomed in view of the $^{12}$CO brightest peak clump in GMC-16. Panel (a) shows the $^{12}$CO distribution and there are several filamentary structures connecting to the central peak. This type of multiple filamentary structure, which is referred to as the “hub filament” (Myers 2009), is found in high-mass star-forming regions in the Galaxy and the LMC (e.g., Peretto et al. 2013; Williams et al. 2018; Fukui et al. 2019; Tokuda et al. 2019). The hub filament in GMC-16 shows an asymmetric distribution, which is extended in a fan shape toward the east direction. The moment 1 map in Figure 4(b) shows that the northern filament has a central velocity of $\sim$248 km s$^{-1}$, which is different from those of the other filaments ($\sim$245 km s$^{-1}$). Note that the hub-filamentary complex is connected to the extended gas (see the moment 0 map (Figure 1) in Section 3.1), but their central velocities are different from each other.

We detected the 1.3 mm continuum source (MMS) as well as the C$^{18}$O emission at the intersection of a few filaments, i.e., the $^{13}$CO peak (Figures 4(a) and 4(d)). If there is a protostellar source inside MMS, the source may contribute to the enhancement of the 1.3 mm flux. This effect is considered to be small, and the continuum flux is mainly arising from the cold dust emission, because the gas mass estimated from the 1.3 mm continuum and that from the C$^{18}$O emission are similar to each other (see the next paragraph). For the same reason, it is likely that the free–free contamination from the H II region next to MMS is also negligible. In fact, the peak position of the hub filament as well as MMS is shifted from that of the Hα emission as shown in Figure 4(c). The Spitzer observations found 24 μm emission around this source with the intensity of 82 mJy, which corresponds to the total infrared luminosity of $\sim$2 $\times$ 10$^6$L$_\odot$ (Verley et al. 2007). Although the brightness of the source suggests the presence of early-O-type stars (Martins et al. 2005; Zinnecker & Yorke 2007), the luminosity is mainly arising from the high-mass stars inside the neighboring H II region.

The deconvolved (FWHM) size of MMS is $(0''.53 \pm 0''.09) \times (0''.27 \pm 0''.06)$, corresponding to $\sim$2.2 pc $\times$1.1 pc. The total mass of MMS ($M_{\text{total}}^{\text{MMS}}$) above the 3σ detection is estimated to be $\sim$2 $\times$ 10$^4$ $M_\odot$, assuming the dust opacity of $\kappa_{\text{1.3 mm}}$ of 1 cm$^2$ g$^{-1}$ for protostellar envelopes (e.g., Ossenkopf & Henning 1994), a dust-to-gas ratio of $\sim$3 $\times$ 10$^{-3}$ (for the LMC-like metallicity; Gordon et al. 2014), and the dust temperature of 20 K. The velocity width (FWHM) of the C$^{18}$O emission in MMS is 6.8 km s$^{-1}$. With a radius of 1.6 pc (=geometric mean of the major and minor axis) the resultant virial mass, $\sim$2 $\times$ 10$^4$ $M_\odot$, is
consistent with the $M_{\text{MMS}}$, indicating that the dense clump is gravitationally bound. Assuming a spherical geometry, the average density of MMS is calculated to be $\sim 2 \times 10^4 \text{ cm}^{-3}$. We note that we could not find any other continuum sources as well as C$^{18}$O emission in the observed field, indicating that the high-density region is localized within a few parsecs with respect to the entire molecular cloud of GMC-16.

Figure 3(a) shows spatial distributions of the high-velocity $^{12}$CO gas toward MMS. The spectra of $^{12}$CO, $^{13}$CO, and C$^{18}$O are shown in panels (e) and (f). The $^{12}$CO profile is slightly asymmetric with a peak velocity of $\sim -245 \text{ km s}^{-1}$. As shown in the $^{13}$CO moment map in Figure 4(b), there are two velocity components toward MMS, and the $^{12}$CO intensity of redshifted gas is stronger than that of the blueshifted gas. The double (or multiple) peaked profile in C$^{18}$O is insignificant at the present sensitivity. Since the $^{13}$CO profile shows a relatively symmetric shape, we use it to estimate the systemic velocity of MMS using Gaussian fitting. The systemic velocity judged from the $^{13}$CO profile is $\sim -246 \text{ km s}^{-1}$ and the maximum relative velocity of the $^{12}$CO red/blueshifted wing components is $\sim 20 \text{ km s}^{-1}$. CO observations in the Galaxy and the LMC often found this type of high-velocity gas toward young stellar objects (e.g., Beuther et al. 2002; Fukui et al. 2015, 2019; Shimonishi et al. 2016; Harada et al. 2019; Tokuda et al. 2019).
The presence of the gravitationally bound dense material toward MMS strongly indicates that there is at least one embedded high-mass protostar and the 12CO high-velocity components originated from its bipolar outflow. This is the first strong candidate for protostellar outflow in M33 as well as the external disk galaxies. We further discuss the reliability of the protostellar outflow in Section 4.2.

4. Discussions

4.1. Possible Origins of the GMFs

We discuss the formation mechanism of the GMFs in GMC-16. Early molecular gas surveys in the Galaxy speculated that this type of long filamentary structure is supposed to be formed by galactic spiral shocks (e.g., Burton & Shane 1970; Jackson et al. 2010). Alternative ideas have also been proposed; for example, the streamer in W51 can be regarded as a part of the expansion ring based on its velocity structure (Moon & Park 1998). Our extragalactic view of GMC-16 with a resolution similar to that of the Galactic single-dish studies allows us to address the origin of the GMFs. The morphology of the GMFs in GMC-16 shows a relatively straight shape, and the sizes of the HII regions are small compared to those of the GMFs. Based on their morphologies, it is unlikely that the GMFs are part of the ring-like structure associated with the HII regions. As shown in Section 3.1, we find clear position discrepancies between the GMFs and the HII regions. This type of spatial offset is sometimes seen in nearby grand design spiral galaxies (Hirota et al. 2011; Colombo et al. 2014), although the separations are more than a few ×10 pc, which is much larger than the present case. The authors suggest that high-mass star formation activities are triggered by the density-wave driven galactic spiral shocks. The sequence of the GMFs and HII regions in GMC-16 is consistent with the propagation direction of the spiral arm. According to the steady-state density-wave theory (Lin & Shu 1964), the interstellar medium is decelerated and compressed at the bottom of the stellar potential, i.e., the...
shock front (Fujimoto 1968; Roberts 1969). If we adopt a rotation velocity of the interstellar medium, \(\sim 80 \text{ km s}^{-1}\) at 2 kpc from the galactic center (Corbelli et al. 2014), and a pattern speed, \(\Omega_p\), of \(\sim 25 \text{ km s}^{-1} \text{ kpc}^{-1}\) (Newton 1980), the timescale of the propagation of the H II regions from the possible shock front traced by the CO filaments is calculated to be \(\sim 1 \text{ Myr} (=20 \text{ pc}/(80–50) \text{ km s}^{-1})\) assuming that the GMFs and the H II regions are located at the same height in the galactic disk. This is consistent with the age of the HII regions (see Section 4.3).

We found a central velocity difference between the extended gas component (\(\sim –240 \text{ km s}^{-1}\)) at the eastern (upstream) side of GMC-16 and the filamentary structures (\(\sim –245 \text{ km s}^{-1}\)), as shown in Figure 3 and Section 3.1. Based on the \(\sim 40 \text{ pc}\) resolution measurements in CO and HI by Gratier et al. (2010), the velocity gradient along the north–south direction of the GMC is \(\leq 0.1 \text{ km s}^{-1} \text{ pc}^{-2}\), which is mostly arising from the galactic rotation. The rotational motion alone may not simply explain the velocity offset \(\sim 5 \text{ km s}^{-1}\) in the PV diagram (Figure 3(b)), which is extracted perpendicular to the large-scale gradient direction. In addition to this, the velocity width of the extended gas is larger than that of the filamentary clouds. These velocity features can be qualitatively explained by the dissipation of turbulent energy and the deceleration of the gas at the shock front. The idea that filamentary structure can be seen as a consequence of turbulent dissipation has been proposed in various scales of interstellar medium (e.g., Padoan et al. 2001; Inoue et al. 2018; Tokuda et al. 2018). In addition to this, our observations toward GMC-8, which is a quiescent GMC, show fewer filamentary structures and a large velocity dispersion compared to the GMFs in GMC-16 (forthcoming paper). In summary, our indirect evidence suggests that the galactic spiral shock compresses a turbulent diffuse cloud to form filamentary structures.

In flocculent spiral galaxies like M33, it may be hard to realize strong spiral shocks compared to grand design galaxies (Egusa et al. 2011, 2017; Hirota et al. 2011; Colombo et al. 2014). Wada et al. (2011) proposed that the complex spiral structures found in M33 are explained by the nonsteady stellar arms rather than the conventional density-wave picture. The galactic shear motion can elongate GMCs over an \(\sim 100 \text{ pc}\) scale (Wada 2008; Miyamoto et al. 2014). The nonsteady stellar arm model predicts that there is no clear spatial offset between the gas spiral arm and young stars across the galaxy. Further statistical studies to investigate the position discrepancies between molecular clouds and H II regions based on observations toward similar targets in M33 with a similar angular resolution will allow us to draw a comprehensive picture of the relation between the galactic kinematics and GMF formation.

### 4.2. High-velocity Wing Components as Strong Candidates for Protostellar Outflow

We found the redshifted and blueshifted wing features at MMS (Section 3.2). According to the Galactic studies of high-mass star-forming regions (e.g., Beuther et al. 2002), such high-velocity wings with a maximum velocity of \(\sim \pm 20 \text{ km s}^{-1}\) or even much smaller velocities are normally interpreted as protostellar outflows. The typical size of outflow lobes in the Galaxy (e.g., Beuther et al. 2002) and the LMC (e.g., Fukui et al. 2019; Tokuda et al. 2019) is less than 1 pc. To demonstrate compactness of the possible outflow, we made the velocity profile maps around the MMS’s location in \(^{12}\text{CO}\) and \(^{13}\text{CO}\) (Figure A1 in the Appendix) with a grid size of \(0.93 \times 0.961\), which corresponds to \(\sim 3.7 \text{ pc} \times \sim 2.5 \text{ pc}\). We could not find similar high-velocity wing emission except in the middle panel, i.e., at the location of MMS. These observational results strongly suggest that the high-velocity \(^{12}\text{CO}\) emission at MMS is a protostellar outflow.

We briefly mention the limitations of the present observations. As seen in Figure 4, there is no significant spatial offset between the red and blue velocity components. Because protostellar outflows are as compact as \(\leq 1 \text{ pc}\) as mentioned in the previous paragraph, this feature is mostly due to the lack of spatial resolution. For example, a low-resolution study toward the Galactic high-mass protostellar object AFGL 2591 identified the molecular outflow without a clear offset between the red- and blueshifted components (Lada et al. 1984). Subsequently, Mitchell et al. (1991) clearly revealed its bipolar nature with a finer resolution measurement. A pole-on configuration is another possibility to interpret our data at MMS, in which case the accretion disk may be observable as face-on. However, the sizes of such disks associated with high-mass protostars are as small as \(\leq 1000 \text{ au}\) (e.g., Motogi et al. 2019), which is much smaller than outflow lobes, and thus it is also impossible to resolve it with this measurement. The present elongation of MMS in the north–south direction is arising from the combination of the beam swelling effect and its filamentary nature.

Although we need much higher angular resolution observations to reveal the actual distribution of the outflow and its age, the current data tell us that the dynamical time (=size/velocity) is as young as \(\sim (5–8) \times 10^5 \text{ yr}\) depending on the assumption of the inclination angle (45°–60°). Considering the fact that the high-mass stars are frequently formed in binary or multiple manners (e.g., Massey 2003), MMS may be composed of unresolved multiple protostellar sources. Future high-resolution infrared and long-baseline ALMA observations will elucidate further details regarding the nature of the source.

#### 4.3. A Possible Trigger of the High-mass Star Formation in GMC-16

In Section 4.1, we suggest that the galactic shock may be a plausible mechanism to explain the GMF formation. However, the high-mass star formation activity itself is localized within a few parsec scales rather than the entire \(\sim 50 \text{ pc}\) scale filament. Although Filament B has a \(^{13}\text{CO}\) peak at the edge of the filament (Figure 1), we could not detect any dense gas tracers, \(^{13}\text{CO}\), and 1.3 mm continuum so far. With respect to the H II regions, which represent the recent star formation activities (Figure 2(b)), their distributions are discrete rather than continuous. These facts indicate that an additional factor may also be needed to trigger the high-mass star formation.

One possible mechanism to trigger the high-mass star formation in MMS is “collect and collapse” (Elmegreen & Lada 1977; Dale et al. 2007) driven by the expansion of the nearby H II region (Figure 4(c)). However, the velocity gradient traced by the \(^{13}\text{CO}\) emission (Figure 4(b)) does not follow the direction of the expanding motion judged from the distribution.
of the H\textsc{ii} region. It is unlikely that the second generation star formation in MMS of GMC-16 was triggered by the expanding motion.

The moment 1 map shows a drastic velocity change at the boundary between the northern and eastern filaments as mentioned in Section 3.2. This type of velocity difference is often seen in high-mass star-forming filamentary clouds in the LMC at a subparsec resolution (Fukui et al. 2015; Saigo et al. 2017; Harada et al. 2019; Nayak et al. 2019), and its interpretation is that collision between two or several filaments triggers high-mass star formation. More recently, the follow-up observations toward some of the targets with a spatial resolution of \(\lesssim 0.1\) pc resolved further complex substructures composed of many filaments, which are difficult to explain by a coalescence process of individual components (Fukui et al. 2019; Tokuda et al. 2019). Nevertheless, because the orientation of filaments in the two different high-mass star-forming regions separated by over 50 pc is roughly aligned, they concluded that a tidally driven galactic scale colliding flow (see Fukui et al. 2017; Tsuge et al. 2019) induced the formation of the fan-shaped hub filaments as precursors of high-mass stars following the propagation direction of the flow. Such a hub filament is also reproduced by numerical simulations of cloud–cloud collision (Inoue et al. 2018).

In GMC-16, as shown in Figures 4(a)–(c), the hub–filamentary structure extends toward the eastern direction, which is considered to be the upstream side in the spiral shock. Although the large-scale spiral shock may form the GMFs with a length of \(\gtrsim 50\) pc as discussed in the Section 4.1, the formation of the small-scale hub filament may not be explained by the spiral shock alone. An additional factor, such as a collision between the GMF and a preexisting small cloud, is needed to interpret the localization of the hub–filamentary dense clump leading to high-mass star formation. We note that a similar hub-like molecular complex is also found in NGC 604-GMC (K. Muraoka et al. 2020, in preparation). According to the galactic scale numerical simulations, cloud–cloud collisions frequently occur around the galactic potential where interstellar media are concentrated (e.g., Dobbs & Baba 2014). Sano et al. (2019) found a high-mass star-forming clump possibly formed by a collision between two clouds in the central region in M33, suggesting that cloud–cloud collision is not a rare event in M33 (see also, Tachihara et al. 2018; K. Muraoka et al. 2020, in preparation). The Galactic high-mass star-forming regions NGC 6334 and NGC 6357 (Persi & Tapia 2008) are also good counterparts to consider the high-mass star formation activities analogous to GMC-16. The regions contain several bright infrared sources with a total luminosity of \(>10^5 L_\odot\) along the molecular filament with a length of \(\sim 100\) pc. Fukui et al. (2018) concluded that a cloud–cloud collision promoted over a 100 pc scale mini-starburst in the NGC 6334 and NGC 6357 regions. Our GMC-16 studies may be equivalent to observations of such Galactic high-mass star-forming regions from outside the Galaxy.

5. Summary

We have performed ALMA observations of one of the most massive GMCs in M33, GMC-16, associated with a few H\textsc{ii} regions. The spatial resolution is \(\sim 1\) pc, which is the highest angular resolution molecular gas survey in M33 (see also K. Muraoka et al. 2020, in preparation). We have spatially resolved \(>50\) pc scale GMFs with a mass of \(\sim 10^6 M_\odot\) along with the spiral arm in M33. One of the most striking features is a \(\sim 10–20\) pc scale offset between the GMFs and H\textsc{ii} regions, suggesting that the density-wave driven galactic shock may convert the diffuse interstellar gas into the filamentary structures and promote the subsequent high-mass star formation. At the southern part of the GMC, the 1.3 mm continuum and C\textsuperscript{18}O observations have found a \(\sim 1\) pc scale dense clump (MMS) with an average number density of \(\sim 10^4\) cm\(^{-3}\) at the intersection of the hub–filamentary cloud possibly formed by a cloud–cloud collision. We found a promising candidate for protostellar outflow at one of the GMFs, indicating that high-mass star formation is still ongoing in MMS.

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Software: CASA (v5.4.0; McMullin et al. 2007), Astropy (Astropy Collaboration et al. 2018), APLpy (v1.1.1; Robitaille & Bressert 2012).

Appendix

Figure A1 shows \(3 \times 3\) profile maps in \(^{12}\)CO and \(^{13}\)CO toward MMS. The map grid size of each panel is \(0''.93 \times 0''.61\), which corresponds to \(\sim 3.7\) pc \(\times \sim 2.5\) pc.
Figure A1. Velocity profile maps in $^{12}$CO and $^{13}$CO centered at the position of MMS. The black, blue, and red dotted lines are the same as those in Figures 4(e), (f).

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References

André, P., Di Francesco, J., Ward-Thompson, D., et al. 2014, in Protostars and Planets VI, ed. H. Beuther et al. (Tucson AZ: Univ. Arizona Press)
André, P., Revéret, V., Könyves, V., et al. 2016, A&A, 592, A54
Arzoumanian, D., André, P., Könyves, V., et al. 2019, A&A, 621, A42
Astropy Collaboration, Price-Whelan, A. M., Sipőcz, B. M., et al. 2018, AJ, 156, 123

Bailer-Jones, C. A. L., Rybizki, J., Fouesneau, M., et al. 2018, AJ, 156, 58

Beuther, H., Schilke, P., Sridharan, T. K., et al. 2002, A&A, 383, 892

Burton, W. B., & Shane, W. W. 1970, in IAU Symp. 38, The Spiral Structure of Our Galaxy, ed. W. Becker & G. I. Kontopoulos (Dordrecht: Reidel), 397

Colombo, D., Meidt, S. E., Schinnerer, E., et al. 2014, ApJ, 784, 4

Corbelli, E., Braine, J., Bandiera, R., et al. 2017, A&A, 601, A146

Corbelli, E., & Salucci, P. 2000, MNRAS, 311, 441
Corbelli, E., Thilker, D., Zibetti, S., et al. 2014, A&A, 572, A23

Dale, J. E., Bonnell, I. A., & Whitworth, A. P. 2007, MNRAS, 375, 1291

Dobbs, C., & Baba, J. 2014, PASA, 31, e035

Druard, C., Braine, J., Scuflaire, K. F., et al. 2014, A&A, 567, A118

Egusa, F., Koda, J., & Scoville, N. 2011, ApJ, 726, 85

Egusa, F., Mentuch Cooper, E., Koda, J., & Baba, J. 2017, MNRAS, 465, 460

Egusa, F., Sofue, Y., & Nakanishi, H. 2004, PASJ, 56, L45

Elmegreen, B. G., & Lada, C. J. 1977, ApJ, 214, 725

Freedman, W. L., Madore, B. F., Gibson, B. K., et al. 2001, ApJ, 553, 47

Fraternali, F., Aumer, M. E., Langer, W. D., & Wilson, R. W. 1982, ApJ, 262, 590

Fujii, K., Minamidani, T., Mizuno, N., et al. 2014, ApJ, 796, 123

Fujimoto, M. 1968, in IAU Symp. 29, Non-stable Phenomena in Galaxies (Cambridge: Cambridge Univ. Press), 453

Fujita, S., Torii, K., Kuno, N., et al. 2019, PASJ, in press

Fukui, Y., Harada, R., Tokuda, K., et al. 2015, ApJL, 807, L4

Fukui, Y., Kohn, M., Yokoyama, K., et al. 2018, PASJ, 70, S41

Fukui, Y., Mizuno, N., Yamaguchi, R., et al. 1999, PASJ, 51, 745

Fukui, Y., Tokuda, K., Saigo, K., et al. 2019, ApJ, 886, 14

Fukui, Y., Tsuge, K., Sano, H., et al. 2017, PASJ, 69, L5

Goldsmith, P. F., Heyer, M., Narayanan, G., et al. 2008, ApJ, 680, 428

Gordon, K. D., Roman-Duval, J., Bot, C., et al. 2014, ApJ, 797, 85

Gratier, P., Braine, J., Rodriguez-Fernandez, N. J., et al. 2010, A&A, 522, A3

Hacar, A., Tafalla, M., Kaufmann, J., et al. 2013, A&A, 554, A55

Harada, R., Onishi, T., Tokuda, K., et al. 2019, PASJ, 71, 44

Heyer, M., & Dame, T. M. 2015, ARA&A, 53, 583

Hirota, A., Kuno, N., Sato, N., et al. 2011, ApJ, 737, 40

Inoue, T., Hennebelle, P., Fukui, Y., et al. 2018, PASJ, 70, 553

Jackson, J. M., Finn, S. C., Chambers, E. T., et al. 2010, ApJL, 719, L185

Kawamura, A., Mizuno, Y., Minamidani, T., et al. 2009, ApJS, 184, 181

Kepley, A. A., Tsutsu, T., Brogan, C. L., et al. 2020, PASP, 132, 024505

Koo, B.-C. 1999, ApJ, 518, 760

Lada, C. J., Thronson, H. A., Smith, H. A., et al. 1984, ApJ, 286, 302

Lin, C. C., & Shu, F. H. 1964, ApJ, 140, 646

Martins, F., Schaerer, D., & Hillier, D. J. 2005, A&A, 436, 1049

Massey, P. 2003, ARA&A, 41, 15

McMullin, J. P., Waters, B., Schiebel, D., et al. 2007, in ASP Conf. Ser. 376, Astronomical Data Analysis Software and Systems XVI, ed. R. A. Shaw, F. Hill, & D. J. Bell (San Francisco, CA: ASP), 127

Mitchell, G. F., Maillard, J.-P., & Hasegawa, T. I. 1991, ApJ, 371, 342

Miura, R. E., Kim, K., Sano, H., & Egusa, F. 2019, ApJ, 876, L25

Myers, P. C. 2009, ApJ, 700, 1609

Nakayama, O., Meixner, M., Siewalo, M., et al. 2019, ApJ, 877, 135

Newton, K. 1980, MNRAS, 190, 689

Okumura, S.-I., Miyawaki, R., Sorai, K., et al. 2001, PASJ, 53, 793

Onishi, T., Mizuno, A., Kawamura, A., Ogawa, H., & Fukui, Y. 1996, ApJ, 465, 815

Onodera, S., Kuno, N., Tosaki, T., et al. 2010, ApJL, 722, L127

Ossenkopf, V., & Henning, T. 1994, A&A, 291, 943

Padoan, P., Puget, M., & Goodman, A., et al. 2001, ApJ, 553, 227

Peretto, N., Fuller, G. A., Duarte-Cabral, A., et al. 2013, A&A, 555, A112

Persi, P., & Tapia, M. 2008, in Handbook of Star-forming Regions, Vol II: The Southern Sky, ed. B. Reipurth (San Francisco, CA: ASP), 397

Robitaille, T., & Bressert, E. 2012, APLy; Astronomical Plotting Library in Python, Astrophysics Source Code Library, ascl:1208.017

Roussel, W. 1969, ApJ, 158, 123

Robitaille, T., & Bressert, E. 2012, APLy; Astronomical Plotting Library in Python, Astrophysics Source Code Library, ascl:1208.017

Rosolowsky, E., Keto, E., Matsushita, S., & Willner, S. P. 2007, ApJ, 661, 830

Salo, K., Onishi, T., Nayak, O., et al. 2017, ApJ, 835, 108

Sandage, A., & Humphreys, R. M. 1955, ApJ, 121, 417

Sano, H., Tsuge, K., Tokuda, K., et al. 2019, arXiv:1908.08404

Sawada, T., Koda, J., & Hasegawa, T. 2018, ApJ, 867, 166

Shimomori, T., Onaka, T., Kawamura, A., et al. 2016, ApJ, 827, 72
Shu, F. H., Milione, V., & Roberts, W. W. 1973, ApJ, 183, 819
Tachihara, K., Gratier, P., Sano, H., et al. 2018, PASJ, 70, S52
Tokuda, K., Fukui, Y., Harada, R., et al. 2019, ApJ, 886, 15
Tokuda, K., Onishi, T., Saigo, K., et al. 2018, ApJ, 826, 8
Torii, K., Fujita, S., Nishimura, A., et al. 2019, PASJ, 71, S2
Tosaki, T., Kuno, N., Onodera, S. M., et al. 2011, PASJ, 63, 1171
Tremblin, P., Anderson, L. D., Didelon, P., et al. 2014, A&A, 568, A4
Tsuge, K., Sano, H., Tachihara, K., et al. 2019, ApJ, 871, 44
Verley, S., Hunt, L. K., Corbelli, E., et al. 2007, A&A, 476, 1161
Wada, K. 2008, ApJ, 675, 188
Wada, K., Baba, J., & Saitoh, T. R. 2011, ApJ, 735, 1
Williams, G. M., Peretto, N., Avison, A., Duarte-Cabral, A., & Fuller, G. A. 2018, A&A, 613, A11
Wong, T., Hughes, A., Ott, J., et al. 2011, ApJS, 197, 16
Wong, T., Hughes, A., Tokuda, K., et al. 2019, ApJ, 885, 50
Zinnecker, H., & Yorke, H. W. 2007, ARA&A, 45, 481