Nobeyama 45 m Local Spur CO survey. I. Giant molecular filaments and cluster formation in the Vulpecula OB association

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Abstract

We have performed new large-scale $^{12}$CO, $^{13}$CO, and C$^{18}$O $J=1$–$0$ observations toward the Vulpecula OB association ($l \sim 60^\circ$) as part of the Nobeyama 45 m Local Spur CO survey project. Molecular clouds are distributed over $\sim 100$ pc, with local peaks at the Sh 2-86, Sh 2-87, and Sh 2-88 high-mass star-forming regions in the Vulpecula complex. The molecular gas is associated with the Local Spur, which corresponds to the nearest inter-arm region located between the Local Arm and the Sagittarius Arm. We discovered new giant molecular filaments (GMFs) in Sh 2-86, with a length of $\sim 30$ pc, width of $\sim 5$ pc, and molecular mass of $\sim 4 \times 10^4 M_\odot$. We also found that Sh 2-86 contains the three velocity components at 22, 27, and 33 km s$^{-1}$. These clouds and GMFs are likely to be physically associated with Sh 2-86 because they have high $^{12}$CO $J = 2$–$1$ to $J = 1$–$0$ intensity ratios and coincide with the infrared dust cloud.
emission. The open cluster NGC 6823 exists at the common intersection of these clouds. We argue that the multiple cloud interaction scenario, including GMFs, can explain cluster formation in the Vulpecula OB association.

Key words: ISM: H II regions — ISM: clouds — ISM: molecules — stars: formation — ISM: individual objects (Vulpecula OB association, Sh 2-86, Sh 2-87, Sh 2-88, NGC 6823, G59.5+0.1, IRAS 19410+2336)

1 Introduction

Giant molecular clouds (GMCs) are the sites of high-mass star and cluster formation (e.g., Lada, & Lada 2003; McKee, & Ostriker 2007). Their formation and evolution processes have been studied in the Milky Way and Local Group Galaxies (e.g., Blitz et al. 2007; Fukui, & Kawamura 2010; Dobbs et al. 2014). Galactic-plane CO surveys by single-dish radio telescopes have revealed the large-scale distribution of GMCs in the Milky Way (e.g., Combes 1991; Heyer, & Dame 2015). The GMCs exist not only in spiral arms but also in inter-arm regions called 'spurs’, 'branches’ or ‘bridges’ (e.g., Cohen et al. 1980; Dame et al. 1986). In particular, Ragan et al. (2014) reported that filamentary structures, which they named giant molecular filaments (GMFs) exist in the inter-arm regions of the Milky Way. Long filamentary clouds like GMFs often include the dense molecular gas that forms massive stars and clusters (e.g., Jackson et al. 2010; Wang et al. 2020). Thus, their formation and evolution have been investigated by numerical simulations (e.g., Duarte-Cabral & Dobbs 2017) and observations (e.g., Li et al. 2013; Goodman et al. 2014; Zucker et al. 2015; Wang et al. 2015; Abreu-Vicente et al. 2016; Zhang et al. 2019). Recently, a new spur located between the Local Arm and Sagittarius Arm, has been revealed by parallax measurements of maser spots from the very-long-baseline interferometry (VLBI: Xu et al. 2016) and of OB-type stars from Gaia data (Xu et al. 2018; Xu et al. 2021). In this paper, we refer to this spur structure as a "Local Spur” (see Figure 1 in Reid et al. 2016).

GMCs are essential targets for studying star formation in galaxies, but it is not yet clear what processes are responsible for the formation of massive stars and clusters in inter-arm regions. The Local Spur is the best site for investigating these processes, because it is the inter-arm region nearest to the solar system. In this paper, we present high-resolution CO observations toward the Vulpecula OB association, with the goal of investigating the star-formation processes in a GMC in this inter-arm region in the solar neighborhood. This paper is constructed as follows: Section 2 introduces the Vulpecula OB association, Section 3 presents the datasets, and Section 4 gives the results, including the physical parameters of the molecular clouds. In Section 5, we discuss the NGC 6823 cluster-formation scenario, and in Section 6, we summarize this paper.

2 The Vulpecula OB association in the Local Spur

| Name | $l$ | $b$ | Luminosity | Earliest Age | Spectral Type | Age | References |
|------|-----|-----|------------|-------------|--------------|-----|------------|
| Sh 2-86 | 59.36 | -0.18 | $\sim 10^{4}$ | 3 ± 1 Myr | O7V | [1,2,3] |
| Sh 2-87 | 60.88 | -0.13 | $5.0 \times 10^{4}$ | 3-4 Myr | B0 | [4,5,6] |
| Sh 2-88 | 61.47 | 0.10 | $1.3 \times 10^{5}$ | $\sim 2$ Myr | 08.5V-O9.5V | [4, 6, 7, 8, 9] |

[1] Pigulski et al. (2000), [2] Massey et al. (1995), [3] Chapin et al. (2008), [4] Lada, & Lada (2003), [5] Chen et al. (2003), [6] Saito et al. (2007), [7] Deharveng et al. (2000), [8] Marin-Franch et al. (2009), [9] Cappa et al. (2002).

The Vulpecula OB association (hereafter Vul OB1) is a high-mass star-forming region, which was first cataloged by Morgan et al. (1953). It is located at $l \sim 60^\circ$ in the Galactic plane, and it is a nearby (<3 kpc) massive molecular cloud complex in the Milky Way (see Table 3 in Motte et al. 2018). The Vul OB1 GMC contains the three H II regions: Sh 2-86, Sh 2-87, and Sh 2-88 (Sharpless 1959). Figures 1(a) and 1(b) show three-color composite images obtained with the Herschel space telescope (Pilbratt et al. 2010) as part of the Herschel infrared Galactic Plane Survey (Hi-GAL) project (Molinari et al. 2010a). The 70 $\mu$m (blue) and 160 $\mu$m (green) emissions trace the warm dust, whereas the 350 $\mu$m (red) emission traces the cold dust (e.g., Russell et al. 2013). Sh 2-86 has diffuse cold dust emission, whereas Sh 2-87 and Sh 2-88 display compact bright emission regions. The basic parameters of these three H II...
regions are summarized in Table 1.

2.1 Sh 2-86

Figure 1 (b) shows a close-up image of Sh 2-86 obtained by Herschel (see also Figure 2 in Molinari et al. 2010b and Supplemental Figure 5 in Motte et al. 2018). Sh 2-86 is an H II region that includes the open cluster NGC 6823 (=Cr 405: Collinder 1931), which has been studied by optical observations for more than 60 years (e.g., Barkhatova 1957; Erickson 1971; Turner 1979; Sagar, & Joshi 1981; Stone 1988; Guetter 1992; Shi, & Hu 1999; Olmi et al. 2010; Mottram & Brunt 2012). Massey et al. (1995) identified 17 OB-type stars as members of this open cluster (Table 2). Previous studies have estimated the ages of cluster members to lie within the range 1-5 Myr (Riaz et al. 2012; Pigulski et al. 2000; Kumar et al. 2004). The embedded cluster NGC 6820 (=Cr 404, IRAS 19403+2258: Bica et al. 2008), which corresponds to a compact infrared peak in the Herschel image, is located on the western side of Sh 2-86 at \((l, b) \sim (59.14, -0.11)\).

Table 2. Lists of OB-type stars in NGC 6823

| Name    | Galactic Longitude [degree] | Galactic Latitude [degree] | Spectral Type |
|---------|-----------------------------|-----------------------------|---------------|
| Erick 93| 59.50                       | -0.21                       | B1 V          |
| Hoag 8  | 59.51                       | -0.19                       | B1.5 III      |
| Hoag 9  | 59.53                       | -0.24                       | B1 V          |
| Hoag 6  | 59.39                       | -0.17                       | B0.5 III      |
| Hoag 2  | 59.40                       | -0.15                       | O7 V((f))     |
| Sharp d | 59.41                       | -0.15                       | B0.5 V        |
| Sharp e | 59.40                       | -0.15                       | B0.5 V        |
| HD 344775| 59.52                      | -0.078                      | B1 III        |
| Sharp n | 59.40                       | -0.14                       | O9.5Ia        |
| HD 344783| 59.37                      | -0.15                       | O9.5Ia        |
| Hoag 10 | 59.38                       | -0.12                       | B2 V          |
| Hoag 7  | 59.41                       | -0.090                      | B1.5 V        |
| HD 344776| 59.51                      | 0.0015                      | B0.5 Ia       |
|         | 59.36                       | 0.016                       | B1.5 V        |

References: Massey et al. (1995)

The hyper-compact H II region IRAS 19410+2336 (GAL 059.7+00.1) is found at \((l, b) \sim (59.78, +0.06)\) about 15 pc from the cluster NGC 6823 (e.g., Chapin et al. 2008). Energetic outflows and maser sources have been reported in this source (e.g., Szymczak et al. 2004; Rodón et al. 2012; Martín-Hernández et al. 2008). Taylor et al. (1992) discovered the supernova remnant (SNR) G59.5+0.1, with a radius of 15' and an age of \(10^3 - 10^4\) yr (Xu et al. 2005). Xu, & Wang (2012) argued that the G59.5+0.1 progenitor may have induced star formation around the SNR.

2.2 Sh 2-87 and Sh 2-88

Sh 2-87 is a massive star-forming region located at \((l, b) \sim (60.88, -0.13)\), and it is composed of compact H II regions. Barsony (1989) reported a molecular outflow from the central embedded source. The Lyman continuum flux derived from observations with the Very Large Array is \(1.9 \times 10^{17}\) s\(^{-1}\), which corresponds to a B0-type exciting star (Barsony 1989).

Sh 2-88 is a compact H II region located at \((l, b) \sim (61.47, 0.10)\), and it is excited by an O8.5V-O9.5V star (Deharveng et al. 2000; Cappa et al. 2002). The compact H II regions Sh 2-88A and Sh 2-88B have been studied by optical, infrared, and radio observations since the 1970s as places where compact H II regions interact with molecular clouds (e.g., Lortet-Zuckermann 1974; Pipher et al. 1977; Deharveng, & Maucherat 1978; Evans et al. 1981).
Fig. 1. (a) Herschel three-color composite image of the Vulpecula OB association. Blue, green, and red represent the Herschel/PACS 70 \( \mu \text{m} \), Herschel/PACS 160 \( \mu \text{m} \), and Herschel/SPIRE 350 \( \mu \text{m} \) distributions, respectively (Molinari et al. 2016). (b) Close up image of Sh 2-86 (see also Supplemental Figure 5 in Motte et al. 2018). The white crosses indicate the OB-type stars in NGC 6823 identified by Massey et al. (1995). The blue dotted circle shows the position of SNR G59.5+0.1 (Green 2019).
2.3 Star formation scenario and distance to the Vulpecula complex

A propagating star formation scenario has been discussed for Vul OB1 (Turner 1986; Ehlerová et al. 2001) based on Elmegreen, & Lada (1977). On the other hand, Billot et al. (2010) excluded the sequential-star-formation scenario because evolutionary stage of the YSO population is homogeneously distributed in the Vul OB1 GMC. In addition, it has been suggested that the clusters in Sh 2-87 and Sh 2-88 may have originated in star formation triggered by clump-clump collisions (Xue, & Wu 2008; Higuchi et al. 2009; Higuchi et al. 2010).

These previous studies suggest that the H II regions and clusters in the GMC have a common distance of 2.0-2.3 kpc (e.g., Billot et al. 2010). In this paper, we adopt 2.0 kpc, which is the mean of the parallactic distances measured by VLBI to the masers in G059.47-00.18 (1.87 kpc: Xu et al. 2016) and G59.7+0.1 (2.16 kpc: Xu et al. 2009). Figure 2(b) shows the position of Vul OB1 in the Milky Way based on trigonometric parallax measurements (Reid et al. 2019; VERA Collaboration et al. 2020).

The molecular clouds in Vul OB1 were discovered in the 1980s using a 1.2 m radio telescope, but their relationship to star formation activity was not clear because of the low 8′ angular resolution of this study (e.g., Dame, & Thaddeus 1985). Studies of star formation were carried out only in the individual H II regions and open clusters, whereas the entire GMC in Vul OB1 has not yet been studied. Therefore, we performed large-scale high-resolution (∼ 20″) CO observations to investigate the relationship of the molecular clouds to star formation in the Vul OB1 GMC.

3 Data sets

Table 3. Observational properties of data sets.

| Telescope/Survey              | Line          | Receiver | HPBW | Effective Resolution | Velocity Resolution | RMS noise† level | References                               |
|------------------------------|---------------|----------|------|----------------------|---------------------|------------------|------------------------------------------|
| Nobeyama 45-m/               | 12CO J = 1–0 | FOREST   | 14″  | ~ 20″                | ~ 0.70 K            | This work        |                                          |
| Local Spur                   | 13CO J = 1–0 | FOREST   | 15″  | ~ 21″                | ~ 0.30 K            | This work        |                                          |
| C18O J = 1–0                 | 15″           | ~ 21″    | 0.5 km s⁻¹ | ~ 0.30 K             | This work          |                  |                                          |
| Osaka Pref. 1.85-m/Galactic Plane | 12CO J = 2–1 | 2′7     | 3′4  | 0.08 km s⁻¹        | 0.50 K              | [1,2,3]          |                                          |

† The value of rms noise levels are for the smoothed (in space and velocity) data sets.

References [1] Onishi et al. (2013),[2] Nishimura et al. (2015), [3] Nishimura et al. (2020) [4] Molinari et al. (2016), [5] Poglitsch et al. (2010), [6] Griffin et al. (2010)

3.1 The Nobeyama 45 m Local Spur CO survey project: 12CO, 13CO, and C18O J =1–0 observations

We carried out CO J = 1–0 observations toward the Vul OB1 GMC from December 2018 to March 2019 using the Nobeyama 45 m telescope. Our data were obtained as part of the Local Spur CO survey (CG181017: PI. A. Nishimura). Figures 2 (a) and 2 (b) show the survey area and a close-up image of Vul OB1 GMC, superposed on a face-on view of the Milky Way. The surveyed area is l = 50°-64°, b = -1°-+1°, and we used the on-the-fly (OTF) scan-mapping mode (Sawada et al. 2008). We observed the Vul OB1 GMC simultaneously in 12CO (115.271 GHz), 13CO (110.201 GHz), and C18O J = 1–0 (109.782 GHz). This CO survey is an extension of the FUGIN CO Galactic plane survey (Umemoto et al. 2017; Torii et al. 2019; Minamidani et al. 2015; Kohno et al. 2018; Torii et al. 2018; Nishimura et al. 2018; Torii et al. 2021; Fujita et al. et al. 2019; Sofue et al. 2019; Torii et al. 2019; Kohno et al. 2021; Nishimura et al. 2021; Nakamichi et al. 2020). More detailed information will be presented in the project overview paper (Nishimura et al. in preparation). The half-power beam width (HPBW) of the 45 m telescope is 14″ in 12CO and 15″ in 13CO and C18O. The effective beam size convolved with a the Bessel-Gaussian function is 20″. We utilized a chopper wheel to convert the raw data to antenna-temperature units (T* a) (Ulich, & Haas 1976; Kutner, & Ulich

1 https://www.nro.nao.ac.jp/~nro45mrt/html/prop/status/Status_latest.html#FOREST_SpW
Local Spur survey
Vul OB1 GMC
R0 ~ 8.0 kpc
d ~ 2.0 kpc
l= 60°
G.C.

FUGIN survey
(a) (b)
4BHJUUBSJVTBSN
4DVUVNBSN
1FSTFVTBSN
-PDBM	0SJPO
BSN

Fig. 2. Top-view of the Milky Way (NASA/JPL-Caltech/ESO/R. Hurt). (a) The gray and yellow shadows show the survey areas of FUGIN and the Local Spur CO survey project, respectively. (b) The star symbol indicates the position of Vul OB1. The distances to the Galactic Center (R0) and to Vul OB1 (d) are adopted from the VLBI astrometry results: R0 (~ 8.0 kpc) was obtained by the averaged value of Reid et al. (2019) and VERA Collaboration et al. (2020), and d (~ 2.0 kpc) was obtained by the averaged value of Xu et al. (2009, 2016).

1981). We derived the scaling factor by converting T\textsuperscript{\textsc{a}} to the main beam temperature (T\textsubscript{mb}) and comparing it with the FUGIN data for the standard source W51A (Fujita et al. 2021a). The pointing accuracy was checked to be within 2\arcsec~3\arcsec by observing the 43 GHz SiO maser source IRAS 19252+2201 (l, b) = (56\degree 61, 2\degree 47) every 90 min using the H40 high electron mobility transistor (HEMT) receiver. The data were smoothed using a two-dimensional Gaussian kernel function with the full width at half maximum of 36\arcsec to achieve the final resolution of 40\arcsec. In this paper, we analyzed the final cube with the grid size of (l, b, v) = (10\arcsec, 10\arcsec, 1.0 km s\textsuperscript{-1}). The root-mean-square (r.m.s) noise levels are ~ 0.70 K, ~ 0.30 K, and ~ 0.30 K in 12CO, 13CO, and C\textsuperscript{18}O, respectively.

3.2 Osaka Prefecture University 1.85-m radio telescope: CO J =2–1 Galactic plane survey

We utilized 12CO J =2–1 data obtained with the 1.85-m radio telescope installed at the Nobeyama Radio Observatory and operated by Osaka Prefecture University (Onishi et al. 2013; Nishimura et al. 2015; Nishimura et al. 2020). The HPBW is 2.7\arcmin, and the front-end is a 2SB SIS mixer receiver (Hasegawa et al. 2017). The back-end was a digital spectrometer having 16384 channels. The bandwidth and frequency resolutions were 1 GHz and 61 kHz, which correspond to 250 km s\textsuperscript{-1} and 0.08 km s\textsuperscript{-1} in velocity space, respectively. The calibration was performed by observing Orion KL as a standard source (Nishimura et al. 2015). The uncertainty in the data is ~ 10%. More detailed information about the 1.85-m radio telescope is provided by Onishi et al. (2013) and Nishimura et al. (2020). The effective resolution of the cube data is ~ 3\arcmin/4. We analyzed the final 3D cube having a voxel resolution of (l, b, v) = (60\arcsec, 60\arcsec, 0.079 km s\textsuperscript{-1}).

3.3 The Hi-GAL project: Herschel far-infrared archival data for the Galactic plane

We also utilized the dust-continuum data obtained from the Herschel Space Observatory (Pilbratt et al. 2010). The public DR1 fits data were taken from the VIALACTEA web page, which is part of Hi-GAL survey project (Molinari et al. 2010a; Molinari et al. 2010b; Molinari et al. 2016). The far-infrared 70 and 160 \textmu m images were obtained with the Photodetector Array Camera and Spectrometer (PACS). The 350 \textmu m data were obtained with the Spectral and Photometric Imaging REceiver (SPIRE: Griffin et al. 2010). We summarize the basic parameters of the datasets in Table 3.

1 http://www.astro.s.osakafu-u.ac.jp/~nishimura/Orion/
2 http://vialactea.iaps.inaf.it/vialactea/eng/index.php
4 Results

4.1 Large-scale CO velocity distributions in the Local Spur

![Diagram of the Large-scale CO Velocity Distributions in the Local Spur](image)

**Fig. 3.** The large-scale $^{12}$CO $J=1-0$ longitude-velocity diagram obtained with the Nobeyama 45 m telescope. White dotted rectangles in the velocity ranges $0-+15$ km s$^{-1}$ and $15-70$ km s$^{-1}$ show the Vulpecula Rift and Local Spur, respectively. The red dotted circle indicates the Vul OB1 GMC.

Figure 3 shows the $^{12}$CO longitude-velocity diagram for the entire survey area. We find mainly two components in the velocity range $0-+15$ km s$^{-1}$ and $15-70$ km s$^{-1}$ in this longitude range. The former is the Vulpecula Rift, which contains local clouds in the solar neighborhood with distances of $\sim$ 400 pc (e.g., Dame, & Thaddeus 1985; Dame et al. 1987). The latter, which is distributed diagonally in the longitude-velocity diagram, is the Local Spur, which corresponds to the inter-arm region between the Local Arm and Sagittarius Arm (Reid et al. 2016; Xu et al. 2016). This velocity range also corresponds to the terminal velocity in the first quadrant of the Galaxy (e.g., Burton & Gordon 1978; McClure-Griffiths, & Dickey 2016). The GMC associated with Vul OB1 is part of the Local Spur in the velocity range $15-40$ km s$^{-1}$. We also point out another velocity cloud around $(l,v) \sim (53^\circ,23$ km s$^{-1})$. This cloud corresponds to GMF 54.0-52.0 (Ragan et al. 2014). GMF 54.0-52.0 includes dense gas (Wang et al. 2020) and shows signatures of massive star formation in the N115 infrared bubble reported by previous studies (Xu & Ju 2014; Zychová & Ehlerová 2016). A detailed analysis of this cloud will be presented in a separate paper.
4.2 CO spatial distributions in Vul OB1

Figure 4 presents the integrated intensity maps of (a) $^{12}$CO, (b) $^{13}$CO, and (c) C$^{18}$O. The molecular clouds have peaks in the three H II regions. The intensity peaks in Sh 2-86 correspond to IRAS 19410+2336 and NGC 6823. Sh 2-87 and Sh 2-88 have peaks in the centers of the H II regions. The $^{13}$CO molecular gas is distributed within dense regions of $^{12}$CO. The C$^{18}$O emission is hardly detected in the Vul OB1 GMC, and it is localized to a small area within ~1 pc from Sh 2-86, Sh 2-87, and Sh 2-88. In this paper, we have carried out more detailed analyses toward Sh 2-86, where the molecular gas is distributed over ~30 pc.

Figure 5 shows $^{12}$CO velocity channel maps of Sh 2-86. We find a filamentary cloud (Filament A) that is elongated from east to west in the velocity range 21.5-25.5 km s$^{-1}$, and the CO peaks correspond to the infrared source IRAS 19410+2336. In the velocity range 23.5-26.5 km s$^{-1}$, we discovered a filamentary cloud (Filament B) that extends over ~40 pc from north to south. We also find a filamentary cloud (Filament C) in the velocity range 26.5-29.5 km s$^{-1}$. Filament C has a length of ~30 pc, and it is extended in the direction of Galactic longitude. The CO peaks correspond to NGC 6823 and to the embedded cluster NGC 6820. We point out that Filament B and C are likely to be comparable to the GMFs in the Milky Way reported by Ragan et al. (2014).

On the other hand, there is also a round-shaped cloud in the velocity range 31.5-34.5 km s$^{-1}$ that is distributed over ~10 pc around the cluster NGC 6823. We also present $^{13}$CO and C$^{18}$O velocity channel maps of Sh 2-86 in the Appendix (see Figures 11 and 12).
Fig. 4. Integrated intensity maps of (a) $^{12}$CO, (b) $^{13}$CO, and (c) C$^{18}$O $J=1$–0 for Vul OB1. The yellow dotted boxes show the area presented in the velocity-channel maps in Figure 5. The map resolution after convolution is 40″. Pixels of the C$^{18}$O map are blanked if the line intensity is less than 1.0 K.
Fig. 5. Velocity-channel map of the $^{12}\text{CO } J = 1-0$ emission with velocity steps of 1.0 km s$^{-1}$. The plots are the same as in Figure 1(b). The map resolution after convolution is 40$''$. The 1$\sigma$ noise level is $\sim 0.7$ K km s$^{-1}$ for the velocity interval of 1.0 km s$^{-1}$. 
Fig. 5. (Continued.)
4.3 CO velocity distributions and the three velocity components in Sh 2-86

Figure 6 presents the $^{12}$CO (a) intensity-weighted velocity map (first-moment) and (b) velocity dispersion (second-moment) maps. We calculated the intensity-weighted velocity ($V_c$) and velocity dispersion ($\Delta V$) given by

$$V_c = \frac{\int T_B(v) \, dv}{\int T_B(v) \, dv} \text{[km s}^{-1}]$$

$$\Delta V = \left\{ \frac{\int T_B(v) (v - V_c)^2 \, dv}{\int T_B(v) \, dv} \right\}^{1/2} \text{[km s}^{-1}]$$

where $T_B(v)$ and $v$ are the brightness temperature and radial velocity, respectively. The velocity field (Figure 6a) extends $\sim 20$ km s$^{-1}$ around IRAS 19410+2336, and $\sim 28$ km s$^{-1}$ near the cluster NGC 6823. A large velocity dispersion of $\sim 5$ km s$^{-1}$ (Figure 6b) exists at the open cluster NGC 6823, which also corresponds to the intersection of Filament B and Filament C.

Figure 6 (c), (d) show the CO spectra near the NGC 6823 cluster at the position A and B. We find the three velocity components at 22, 27, and 33 km s$^{-1}$. Blue, green, and red shadow area indicate the integrated velocity range of each component in this paper.

We performed a detailed analysis of these multiple velocity components with the goal of determining the relationship between these molecular filaments and cluster formation in Sh 2-86.

4.4 $^{12}$CO $J=2-1/1-0$ intensity ratio and comparison to the Herschel dust-continuum images

We performed detailed analyses of the $^{12}$CO $J=2-1/1-0$ intensity ratio (hereafter $R_{2-1/1-0}$) and compared it with the infrared image toward these velocity components. Figures 7(a), (b), and (c) show the $R_{2-1/1-0}$ maps of the 22, 27, and 33 km s$^{-1}$ components, respectively. The $^{12}$CO $J=1-0$ data were smoothed to 3.4, which corresponds to the effective resolution of the $^{12}$CO $J=2-1$ data. Pixels are blanked if the integrated intensity is less than 5 K km s$^{-1}$ ($\sim 5\sigma$) for each integrated velocity range. The intensity ratio of the different CO rotational levels is useful for investigating the excitation states of the molecular clouds. The 22 km s$^{-1}$ components has a high-intensity ratio ($R_{2-1/1-0} \sim 0.8 - 1.0$) at NGC 6820 and on the eastern side of IRAS 19410+2336. The 27 km s$^{-1}$ components has a high ratio ($R_{2-1/1-0} \sim 0.9 - 1.0$) at NGC 6823 and NGC 6820. The 33 km s$^{-1}$ components has $R_{2-1/1-0} \sim 0.9 - 1.0$ around NGC 6823. These values are higher than the typical value of $R_{2-1/1-0} \sim 0.6$ in the Galactic plane (e.g., Yoda et al. 2010) and in external spiral galaxies (e.g., Yajima et al. 2021). The value of $R_{2-1/1-0}$ depends on the kinematic temperature of the molecular gas and the number density of hydrogen molecules, assuming the large-velocity-gradient model (e.g., Goldreich & Kwan 1974). Therefore, a high-intensity ratio indicates the presence of dense or warm gas associated with massive stars in these molecular clouds. Figures 7(d), (e), and (f) show the spatial distributions of the three clouds (contours) superposed on the Herschel 160 $\mu$m image. We find that the CO peaks in each velocity component correspond morphologically to the infrared peaks of IRAS 19410+2336, NGC 6823, and NGC 6820. From these results, we suggest that these three components, which have the velocity separations of 5-6 km s$^{-1}$ are likely to be physically associated with Sh 2-86.
Fig. 6. (a) The $^{12}$CO first-moment (velocity-field) map for Sh 2-86. (b) The $^{12}$CO second-moment (velocity dispersion) map. The adopted velocity range extends from 19 to 34 km s$^{-1}$. The crosses and dotted circles are the same as in Figure 1(b). Pixels are blanked if the line intensity is less than 3.5 K ($\sim 5\sigma$). The map resolution after convolution is $40''$. (c) and (d) The CO spectra observed at two positions indicated by the white circles in panel. Short black arrows show the three velocity components at 22, 27, and 33 km s$^{-1}$. Blue, green, and red shadows show the integrated velocity range of each velocity component in this paper.
Fig. 7. The $^{12}$CO $J = 2-1/1-0$ intensity ratios of the (a) 22 km s$^{-1}$, (b) 27 km s$^{-1}$, and (c) 33 km s$^{-1}$ components in Sh 2-86. The map resolution after convolution is 3.4′, which corresponds to the effective resolution of the $^{12}$CO $J = 2–1$ data. Pixels are blanked if the integrated intensity is less than 5 K km s$^{-1}$ ($\sim$ 5σ) for each integrated velocity range. The lowest contour levels and the contour intervals are 5.0 K km s$^{-1}$. The integrated intensities (contours) of the three components are superposed on the Herschel 160 μm continuum image (Molinari et al. 2016) for the (d) 22 km s$^{-1}$, (e) 27 km s$^{-1}$, and (f) 33 km s$^{-1}$ clouds. The lowest contour levels and the contour intervals are 8.0 K km s$^{-1}$ and 15.0 K km s$^{-1}$ for (d), 13.0 K km s$^{-1}$ and 15.0 K km s$^{-1}$ for (e), and 10.0 K km s$^{-1}$ and 15.0 K km s$^{-1}$ for (f). The crosses and dotted circles are the same as in Figure1(b).
4.5 Physical parameters of the molecular gas

| Table 4. Excitation temperature, optical depth, and column density of molecular clouds in Vul OB1. |
|-----------------------------------------------|
| Name             | $T_{ex}$  | $\tau_{13}$ | $\tau_{18}$ | $N^{12}_{X\ max}$ | $N^{12}_{X\ mean}$ | $N^{13}_{LTE\ max}$ | $N^{13}_{LTE\ mean}$ | $N^{13}_{LTE\ max}$ | $N^{13}_{LTE\ mean}$ |
|------------------|---------|------------|-------------|-----------------|-------------------|----------------------|---------------------|----------------------|----------------------|
| (1)              | (2)     | (3)        | (4)         | (5)             | (6)               | (7)                  | (8)                 | (9)                  | (10)                 |
| Sh2-86           | 10      | 0.38       | 0.13        | $4.4 \times 10^{22}$ | $8.0 \times 10^{21}$ | 1.1 $\times 10^{23}$ | 1.1 $\times 10^{22}$ | 7.4 $\times 10^{22}$ | 1.6 $\times 10^{22}$ |
| 22 km s$^{-1}$   | 10      | 0.38       | 0.13        | $2.9 \times 10^{22}$ | $5.3 \times 10^{21}$ | 1.0 $\times 10^{23}$ | 1.1 $\times 10^{22}$ | 7.4 $\times 10^{22}$ | 1.7 $\times 10^{22}$ |
| 27 km s$^{-1}$   | 10      | 0.38       | 0.1         | $2.2 \times 10^{22}$ | $4.6 \times 10^{21}$ | 7.0 $\times 10^{22}$ | 7.5 $\times 10^{22}$ | 5.3 $\times 10^{22}$ | 1.6 $\times 10^{22}$ |
| 32 km s$^{-1}$   | 8.8     | 0.41       | 0.19        | $1.2 \times 10^{22}$ | $2.8 \times 10^{21}$ | 1.8 $\times 10^{22}$ | 2.4 $\times 10^{21}$ | 1.7 $\times 10^{22}$ | 1.0 $\times 10^{22}$ |
| Sh2-87           | 18      | 0.27       | 0.04        | $6.0 \times 10^{22}$ | $2.0 \times 10^{23}$ | $3.7 \times 10^{22}$ | $8.0 \times 10^{22}$ | $3.4 \times 10^{22}$ |  |
| Sh2-88           | 13      | 0.39       | 0.09        | $6.4 \times 10^{22}$ | $1.2 \times 10^{22}$ | $2.7 \times 10^{23}$ | $2.7 \times 10^{22}$ | $1.5 \times 10^{23}$ | $2.6 \times 10^{22}$ |

Note: The mean values were adopted within the cloud surface area ($S$). Columns: (1) Name. (2) The mean excitation temperature obtained from the $^{12}$CO peak intensity. (3) The mean optical depth obtained from $^{12}$CO. (4) The same as (3), but for C$^{18}$O. (5) The peak H$_2$ column density derived from $^{12}$CO assuming the X-factor. (6) The mean H$_2$ column density calculated from $^{12}$CO assuming the X-factor. (7) The same as (6), but for $^{13}$CO assuming LTE. (8) The same as (6), but for $^{13}$CO, assuming LTE. (9) The same as (7), but for C$^{18}$O (10) The same as (8), but for C$^{18}$O.  

| Table 5. Size and molecular mass in Vul OB1. |
|-----------------------------------------------|
| Name             | $D_{12}$ | $M_{\odot}^{12}$ | $D_{13}$ | $M_{\odot}^{13}$ | $D_{18}$ | $M_{\odot}^{18}$ |
|------------------|---------|-----------------|---------|-----------------|---------|-----------------|
| (1)              | (2)     | (3)             | (4)     | (5)             | (6)     | (7)             |
| Sh2-86           | 43      | $8.0 \times 10^{4}$ | 15      | $4.3 \times 10^{4}$ | 3.5     | $3.4 \times 10^{4}$ |
| 22 km s$^{-1}$   | 31      | $2.9 \times 10^{4}$ | 10      | $1.7 \times 10^{4}$ | 3       | $1.8 \times 10^{4}$ |
| 27 km s$^{-1}$   | 34      | $4.5 \times 10^{4}$ | 13      | $2.3 \times 10^{4}$ | 2       | $3.3 \times 10^{4}$ |
| 32 km s$^{-1}$   | 22      | $1.4 \times 10^{4}$ | 10      | $4.1 \times 10^{3}$ | 0.7     | 78              |
| Sh2-87           | 7.4     | $6.5 \times 10^{3}$ | 3.6     | $8.4 \times 10^{3}$ | 1.1     | $7.8 \times 10^{2}$ |
| Sh2-88           | 15      | $1.1 \times 10^{3}$ | 4.9     | $1.1 \times 10^{3}$ | 1.6     | $1.2 \times 10^{3}$ |

Note: The physical parameters were calculated using the data points above 5$\sigma$ ($\sim 3.5$ K for $^{12}$CO and 0.90 K for $^{13}$CO and C$^{18}$O $J=1-0$). Columns: (1) Name. (2) The $^{12}$CO cloud diameter within 10% of the peak integrated intensity. (3) The total molecular mass estimated from $^{12}$CO. (4) The same as (2), but for $^{13}$CO. (5) The same as (3), but for $^{13}$CO. (6) The same as (2), but for C$^{18}$O. (7) The same as (3), but for C$^{18}$O.  

We derived the physical parameters of the molecular clouds in Vul OB1 following a procedure that uses the X-factor and assumes local thermal equilibrium (LTE), which is described by Pineda et al. (2008); Wilson et al. (2013), and Sofue & Kohn (2020).

The brightness temperature $T_B(\nu)$ can be expressed in terms of the excitation temperature $T_{ex}$ and the optical depth $\tau(\nu)$, and it is given by

$$T_B(\nu) = T_0 \left( \frac{1}{\exp(T_0/T_{ex}) - 1} - \frac{1}{\exp(T_0/T_{bg}) - 1} \right) \left( 1 - \exp(-\tau(\nu)) \right),$$

where $T_0$ is the Planck temperature defined as $T_0 = \frac{h\nu}{k}$, with $k$ and $h$ being the Boltzmann and Plank constants, respectively, and $T_{bg}$ is the black-body temperature of the cosmic microwave background: $T_{bg} = 2.725$ K.

If we assume that the $^{12}$CO $J=1-0$ line is optically thick ($\tau \to \infty$), the excitation temperature is given by

$$T_{ex} = 5.53 \left[ \frac{1}{\ln \left( 1 + \frac{5.53}{T_B(^{12}\text{CO})_{max}/K + 0.836} \right)} \right] [K],$$

where $T_B(^{12}\text{CO})_{max}$ is the peak brightness temperature. This yields mean values $T_{ex} \sim 10 \sim 18$ K in Vul OB1 and in each H II region.

The $^{13}$CO and C$^{18}$O optical depths can be derived from the brightness temperatures and the excitation temperature, and they are given by

$$\tau_{^{13}} = - \ln \left[ \frac{1}{T_B(^{13}\text{CO})_{max}} \left\{ \frac{1}{\exp(\frac{2.29 \text{ K}}{T_{ex}}) - 1} - 0.168 \right\}^{-1} \right]$$

and

$$\tau_{^{18}} = - \ln \left[ \frac{1}{T_B(C^{18}\text{O})_{max}} \left\{ \frac{1}{\exp(\frac{2.29 \text{ K}}{T_{ex}}) - 1} - 0.168 \right\}^{-1} \right]$$
\[ \tau_0^{18} = -\ln \left[ 1 - \frac{T_{\text{mb}}(^{18}\text{O})_{\text{max}}}{5.27 \text{ K}} \right] \left( \frac{1}{\exp\left( \frac{5.27 \text{ K}}{T_{\text{ex}}} \right) - 1} - 0.169 \right)^{-1} \], \text{respectively.} \tag{6} \]

The values \( \tau_0^{13} \) and \( \tau_0^{18} \) at the peak intensity were thus found to be \( \sim 0.3-0.4 \) and \( \sim 0.04-0.19 \), respectively, for each \( \text{H II} \) region. In terms of the brightness temperature and the velocity width (dv), the \(^{12}\text{CO}\) and \(^{18}\text{O}\) column densities are given by

\[
N(^{13}\text{CO}) = 2.42 \times 10^{14} \frac{T_{\text{ex}}/K}{1 - \exp\left( - \frac{5.27 \text{ K}}{T_{\text{ex}}} \right)} \int z^{13}(v) \, dv
\]
\[
\sim 2.42 \times 10^{14} \frac{\tau_0^{13}}{1 - \exp\left( - \tau_0^{13} \right) \left[ 1 - \exp\left( - \frac{5.27 \text{ K}}{T_{\text{ex}}} \right) \right]} \int T_{\text{mb}}(^{13}\text{CO})(v) \, dv \, [\text{cm}^{-2}],
\]

\[
N(^{18}\text{O}) = 2.52 \times 10^{14} \frac{T_{\text{ex}}/K}{1 - \exp\left( - \frac{5.27 \text{ K}}{T_{\text{ex}}} \right)} \int z^{18}(v) \, dv
\]
\[
\sim 2.52 \times 10^{14} \frac{\tau_0^{18}}{1 - \exp\left( - \tau_0^{18} \right) \left[ 1 - \exp\left( - \frac{5.27 \text{ K}}{T_{\text{ex}}} \right) \right]} \int T_{\text{mb}}(^{18}\text{O})(v) \, dv \, [\text{cm}^{-2}],
\]

where we use the relationship \( T_{\text{ex}} \int \tau(v)dv \sim \frac{\tau_0^{13}}{1 - \exp\left( - \tau_0^{13} \right) \left[ 1 - \exp\left( - \frac{5.27 \text{ K}}{T_{\text{ex}}} \right) \right]} \int T_{\text{mb}}(v)dv \) and assumes the optically thin case quoted from Wilson et al. (2013).

The \( \text{H}_2 \) column density is derived from the \(^{12}\text{CO}\) integrated intensity using the X-factor \( (X(^{12}\text{CO})) \). The \(^{13}\text{CO}\), and \(^{18}\text{O}\) column densities are calculated from the isotopic abundance ratios using the following formulas:

\[
N_{X}^{12} (\text{H}_2) = X(^{12}\text{CO}) \int T_{\text{mb}}(^{12}\text{CO}) \, dv, \tag{9}
\]

\[
N_{\text{LTE}}^{13} (\text{H}_2) = Y(^{13}\text{CO}) \times N(^{12}\text{CO}), \tag{10}
\]

\[
N_{\text{LTE}}^{18} (\text{H}_2) = Y(^{18}\text{O}) \times N(^{12}\text{CO}), \tag{11}
\]

We used \( 2.0 \times 10^{20} \, [\text{K} \text{ km s}^{-1}]^{-1} \, \text{cm}^{-2} \) as the X-factor whose uncertainty is 30%. (Bolatto et al. 2013). The adopted CO conversion factors for \( Y(^{13}\text{CO}) \) and \( Y(^{18}\text{O}) \) are \( 7.7 \times 10^9 \) and \( 5.6 \times 10^9 \), respectively. These values are calculated from the isotopic abundance ratios \( [^{12}\text{C}] / [^{13}\text{C}] = 77 \) and \( [^{16}\text{O}] / [^{18}\text{O}] = 560 \) (Wilson, & Rood 1994), and \( \text{H}_2 \) abundance ratio \( [^{12}\text{CO}] / [\text{H}_2] = 10^{-4} \) (e.g., Frerking et al. 1982; Pineda et al. 2010). The peak column densities obtained from \(^{13}\text{CO}\) are \( > 10^{23} \, \text{cm}^{-2} \), which is larger than that estimated from \(^{12}\text{CO}\). This tendency is consistent with the other GMCs in the Milky Way (e.g., Sofue & Kohno 2020).

We estimated the diameter \( D \) of each molecular cloud using the equation

\[
D = 2 \sqrt{\frac{S}{\pi}}, \tag{12}
\]

where \( S \) is the cloud area within 10% of the peak integrated intensity. The resulting diameters of the clouds in Sh 2-86, Sh 2-87, and Sh 2-88 obtained by \(^{12}\text{CO}\) are \( \sim 40 \, \text{pc}, \sim 7 \, \text{pc}, \text{ and } \sim 15 \, \text{pc}, \text{ respectively.} \)

The total molecular mass is given by

\[
M = \mu_{\text{H}_2} m_{\text{H}} d^2 \sum_i \Omega N_i (\text{H}_2), \tag{13}
\]

where \( \mu_{\text{H}_2} \sim 2.8 \) is the mean molecular weight of a hydrogen molecule including contribution of helium (e.g., Appendix A.1. of Kauffmann et al. 2007), \( m_{\text{H}} = 1.67 \times 10^{-24} \, \text{g} \) is the proton mass, \( d \) is the distance to the Vul OB1 GMC, \( \Omega \) is the solid angle of the map pixel, and \( N_i (\text{H}_2) \) is the molecular column density of the i-th pixel. The total mass of Sh 2-86, Sh 2-87, and Sh 2-88 are \( 8.0 \times 10^4, 6.5 \times 10^4, \text{ and } 1.1 \times 10^4 \, M_\odot \) derived by \(^{12}\text{CO}\). The mass derived from \(^{12}\text{CO}\) and \(^{13}\text{CO}\) is consistent with this within a factor of 2-3. On the other hand, the mass derived from \(^{18}\text{O}\) is about smaller than one order of magnitude. This difference causes the \(^{18}\text{O}\) line to be optically thin and trace the dense region in the Vul OB1 GMC. These results are consistent with molecular clouds in the Galactic Plane revealed by the FUGIN CO survey (see Figure 13 of Torii et al. 2019). We summarize the physical parameters of molecular clouds in Vul OB1 in Table 4 and 5.
5 Discussion

5.1 Comparison of the H$_2$ column density with YSO distributions

Figure 8(a) shows the spatial distribution of the YSOs cataloged by Billot et al. (2010) superposed on the H$_2$ column density map derived from the $^{12}$CO $J = 1$–$0$ integrated intensity using the X-factor $X$(CO) = 2.0 × 10$^{20}$ [K km s$^{-1}$] cm$^{-2}$] (Bolatto et al. 2013). The column density is high (> 1.0 × 10$^{22}$ cm$^{-2}$) near IRAS 19410+2336 and NGC 6823. Figure 8(b) presents the surface density of YSOs and OB-type stars (red contours) superposed on the H$_2$ column density map. We calculated the surface density of stars at each point of a 10" grid using the nearest neighbor method (Chavarría et al. 2008; Billot et al. 2010). The equation of the surface density ($\sigma_{\text{star}}$) is given by

$$\sigma_{\text{star}} = \frac{N}{\pi r_N^2} \text{[stars pc}^{-2}],$$

where $r_N$ is the distance to the nearest neighbor. In this paper, we adopted $N = 5$, the same as Billot et al. (2010). The surface density map was convolved to 1" with a Gaussian kernel function. We point out that the YSOs and OB-type stars are concentrated around the NGC 6823 cluster. Billot et al. (2010) argue that each YSO-population class is homogenously distributed in Vul OB1, and they were unable to determine the age sequence. Hence, they excluded the propagating star formation scenario proposed by Ehlerová et al. (2001). However, we note that the YSOs around SNR G59.5+0.1 may have been induced by the stellar wind from the G59.5+0.1 progenitor, as suggested by Xue, & Wu (2008). Based on our observational results and previous studies, we discuss the cluster formation scenario in NGC 6823 in the following subsection.
Fig. 8. (a) The YSO distributions superposed on the $\text{H}_2$ column density maps derived from the $^{12}\text{CO} \ J=1-0$ data. The contour levels for the column density are $1 \times 10^{22}, 2 \times 10^{22}, 3 \times 10^{22},$ and $4 \times 10^{22} \text{ cm}^{-2}$. Red, green, and blue circles indicate the class 0/I, class II, and class III objects, respectively, as identified by Billot et al. (2010). The yellow crosses indicate the OB-type stars in NGC 6823 identified by Massey et al. (1995). The blue dotted circle shows the position of SNR G59.5+0.1 (Green 2019). (b) The surface density of YSOs and OB-type stars (red contours) superposed on the $\text{H}_2$ column density map. The red contours were convolved to 1' with a Gaussian kernel function. The contour levels for the surface density are 0.01, 0.05, 0.1, 0.5, 1, 2, and 3 stars pc$^{-2}$. The column density map resolution after convolution is 40''.
5.2 The interpretations of the three velocity components associated with Sh 2-86

Figure 9 presents the $^{12}$CO $J = 1$-0 integrated intensity maps for the two overlapping clouds associated with Sh 2-86. The 27 km s$^{-1}$ cloud has peaks at the southern side of the cluster, corresponding to the intensity depression of the 22 km s$^{-1}$ cloud (Figure 9a). That shows anti-correlated spatial distributions. The NGC 6823 cluster members are found to be the overlap region between the 33 km s$^{-1}$ cloud and 22, 27 km s$^{-1}$ components (Figure 9b, c). These components are also connected in the position-velocity diagram (see Figure 10).

Molecular clouds associated with massive star-forming regions often compose of multiple velocity components. They are interpreted as the expansion by stellar wind (e.g., Deharveng et al. 2010), oscillation of a single cloud (e.g., Lada et al. 2003), infall motion of a massive cloud (e.g., Shimoikura et al. 2016; Shimoikura et al. 2018), and a cloud-cloud collision (e.g., Kohno et al. 2021a, 2021b). To investigate the origin of three velocity components in detail, we made the position-velocity diagram along with
the elongation of Filament B and C as shown in Figure 10(a) and (b), respectively. Billot et al. (2010) and Chapin et al. (2008) pointed out that the ionization feedback by the stellar wind from the OB-type stars in the NGC 6823 cluster affects the parent molecular cloud of Sh 2-86. The two cavity structures having $<5$ pc exist at $\sim 31$ km s$^{-1}$ presented in Figure 10(b). We suggest that they were formed by the ionization effect of the NGC 6823 cluster. On the other hand, the 22 km s$^{-1}$ component exists 5 km s$^{-1}$ apart from the cavity velocity and distributes at the blue-shifted side of the 27 km s$^{-1}$ component. The 22 km s$^{-1}$ component also has an intensity peak at IRAS 19410+2336, which is located $\sim 15$ pc away from the NGC 6823 cluster (Figure 9a). Therefore, we suggest that the effect of stellar feedback by the NGC 6823 cluster toward the 22 km s$^{-1}$ component is limited.

Shimoikura et al. (2016) reported the two velocity components having the velocity separation of $\sim 1$ km s$^{-1}$ associated with the massive clump of S235 AB. They showed symmetrical two peaks with the clump center at the position-velocity diagram taken along its major axis (see Figure 3b in Shimoikura et al. 2016). The authors argued that their velocity distribution is interpreted as the infall motion of a single massive cloud with rotation based on the model of single protostars presented by Ohashi et al. (1997) (see also Type 2 massive clumps presented by Shimoikura et al. 2018). In the case of Sh 2-86, we find the inverted V-shaped structure (Figure 10a) and three intensity peaks (Figure 10b) on the position-velocity diagrams along with Filament B and Filament C, respectively. These features are different from the velocity gradients reported by Shimoikura et al. (2016). Hence, we suggest that the infall motion with rotation of the GMC scale is unlikely to explain our observational results.

Lada et al. (2003) proposed that the oscillation of a single cloud can explain the origin of the velocity gradient in the molecular cloud associated with the starless core Barnard 68. If the cloud has oscillation, we are likely to find the velocity pattern like the sine wave on the position-velocity diagram along the filament (e.g., Figure 6 in Liu et al. 2019). However, we cannot find them on the position-velocity diagram in Sh 2-86. Thus, we suggest that it is difficult for the cloud oscillation (pulsation) to explain the origin of the three independent velocity components associated with Sh 2-86.

Based on our CO data, we show the connecting the three velocity components in the position-velocity diagram, V-shape structure, complementary spatial distributions, and high-intensity ratio around the NGC 6823 cluster. We propose that these observational signatures show the evidences of cloud-cloud collisions (see also the review paper by Fukui et al. 2021). Numerical simulations of cloud-cloud collisions reproduced the (inverted) V-shaped structures (see Figure 5 middle panel in Haworth et al. 2015), and anti-correlated spatial distributions of different velocity channels (Matsumoto et al. 2015). Arzoumanian et al. (2018) also argue that V-shaped structure shows the shock compression for the filament formation by colliding flows. Theoretical studies have also demonstrated that cloud-cloud collisions can set up the initial conditions for massive cluster star formation (e.g., Habe & Ohta 1992; Inoue & Fukui 2013; Inoue et al. 2018; Takahira et al. 2014; Wu et al. 2015). The radio observations were also suggested that cloud-cloud collisions (e.g., Sagittarius B2: Hasegawa et al. 1994, M20: Torii et al. 2011, RCW 38: Fukui et al. 2016, IRAS 05358+3543: Yamada et al. 2021) and filament-filament collisions (e.g., Serpens South: Nakamura et al. 2014, Cygnus OB 7: Dobashi et al. 2014) as a trigger of massive stars and cluster formation in the Milky Way. These results were also supported by the recent observational studies of Large Magellanic Cloud (e.g., Fukui et al. 2015; Saigo et al. 2017; Fukui et al. 2019; Tokuda et al. 2019), M33 (e.g., Sano et al. 2021) and Antennae Galaxies (e.g., Tsuge et al. 2021; Tsuge et al. 2021).
Xue, & Wu (2008) and Higuchi et al. (2010) argue that the clump-clump collision triggered the cluster formation of Sh 2-87 and Sh 2-88 in Vul OB1. In the case of Sh 2-86, it is excited by the 17 OB-type stars in the NGC 6823 cluster (see Table 2). This H II region is also the most active star-forming site in Vul OB1 (Billot et al. 2010). We suggest that multiple collisions between molecular cloud and GMFs having high peak column density \( \sim 1 \times 10^{23} \text{ cm}^{-2} \) obtained by \(^{12}\text{CO}\) are likely to explain the origin of the multiple OB-type star formation in Vul OB1. The dynamical collision timescale is estimated to be 20-30 pc/ (5 km s\(^{-1}\)) ∼ 3-4 Myr, assuming a viewing angle of 45°. This value is roughly consistent with the cluster age of NGC 6823 (3 ± 1 Myr: Pigulski et al. 2000). Therefore, we propose multiple cloud collisions are the most plausible hypothesis to explain the origin of the three velocity components and OB-type stars in Sh 2-86. To advance our current understanding in Vul OB 1, additional molecular line observations using shock tracers, such as SiO (Fujita et al. 2021b; Cosentino et al. 2020) and dense gas tracers (Priestley & Whitworth 2021), are helpful, leading the dynamical state as a consequence of the molecular cloud collisions.

5.3 The origin of the filamentary clouds in the Local Spur of the Milky Way

| Name | Length \([\text{pc}]\) | Width \([\text{pc}]\) | \(v_{\text{FWHM}}\) \(\text{km s}^{-1}\) | \(N(H_2)_{\text{peak}}\) \(\text{cm}^{-2}\) | Total mass \(M_\odot\) | \(M_{\text{line}}\) \(M_\odot/\text{pc}\) | Reference |
|------|----------------|------------|-----------------|-----------------|-----------------|-----------------|------------|
| Filament C in Sh 2-86 | \(\sim 30\) | \(\sim 3\) | \(1 \times 10^{22}\) | \(\sim 4 \times 10^4\) | \(\sim 1 \times 10^4\) | This work |
| HVS in W51\(^\dagger\) | \(\sim 90\) | \(\sim 5\) | \(2 \times 10^{22}\) | \(\sim 3 \times 10^5\) | \(\sim 3 \times 10^5\) | Fujita et al. (2021a) |
| Filament B in GMC-16 \(^\dagger\) | \(\sim 70\) | \(\sim 4\) | \(5 \times 10^{22}\) | \(\sim 4 \times 10^5\) | \(\sim 6 \times 10^5\) | Tokuda et al. (2020) |

\(^\dagger\) The parameters of the W51 GMC was taken from the FUGIN CO survey data (Umemoto et al. 2017; Fujita et al. 2021a; URL: https://nro-fugin.github.io).

In particular, Filament C in the 27 km s\(^{-1}\) cloud is distributed along the Galactic plane. This feature is common to the high-velocity stream (HVS) in the W51 GMC (Fujita et al. 2021a). A galactic spiral density wave has been suggested as the origin of the HVS (e.g. Burton 1970; Carpenter & Sanders 1998; Koo 1999; Kumar et al. 2004). Recently, Tokuda et al. (2020) discovered the GMFs associated with the high-mass star-forming region in the external spiral galaxy M33. The authors suggested that a Galactic spiral shock had formed these GMFs. Table 6 shows the comparison of Filament C with the physical parameters of GMFs as sites of a cloud-cloud collision. Filament C has \(\sim 1/2-1/3\) length comparing with HVS and GMC-16. This value is also smaller than other GMFs identified by previous studies with \(\sim 100\) pc in the Galactic plane (e.g., Jackson et al. 2010; Ragan et al. 2014). The total mass is \(\sim 1/10\) of HVS and GMC-16. Therefore, we suggest that Filament C at the Local spur of the Milky Way is the smaller scale GMF than reported by previous studies.

On the other hand, based on the observations of the external spiral galaxy M51 (e.g., Koda et al. 2009; Miyamoto et al. 2014), it has been suggested that filamentary clouds in inter-arm regions can be produced by galactic shear motions. Numerical simulations by Wada & Koda (2004) and Dobbs & Bonnell (2006) have reproduced such filamentary structures in inter-arm regions. Hence, we suggest that they are formed by galactic-scale dynamics like spiral shocks or shear motions. More detailed analyses are necessary to confirm the origins of the GMFs in Sh 2-86. With such detailed considerations, we will argue the separated paper.

6 Summary

The conclusions of this paper are as follows:

1. We have performed large-scale \(^{12}\text{CO}, \(^{13}\text{CO}, \text{and C}^{18}\text{O J}=1-0\) observations toward the Vulpecula OB association (\(l \sim 60^\circ\)) as a part of the Nobeyama 45 m Local Spur CO survey project, with the goal of determining the cause of cluster formation in an inter-arm region of the Milky Way.

2. The molecular clouds are distributed over \(\sim 100\) pc, and they have peaks at the HII regions Sh 2-86, Sh 2-87, and Sh 2-88 in Vul OB1. The whole of Vul OB1 is located in the Local Spur between the Local Arm and the Sagittarius Arm of the Milky Way.

3. We discovered new GMFs in Sh 2-86, which have a length of \(\sim 30\) pc, width of \(\sim 5\) pc, and mass of \(\sim 4 \times 10^4\) \(M_\odot\) obtained by...
$^{12}$CO.

4. Sh 2-86 contains three velocity components at 22, 27, and 33 km s$^{-1}$. These clouds have high intensity-ratios around high-mass stars, and they coincide with the infrared dust emission. Therefore, we conclude that the multiple velocity components are likely to be physically associated with Sh 2-86.

5. The OB-type stars in the open cluster NGC 6823 are located at the intersection of three clouds. From these observational results, we suggest that the cloud-cloud collision scenario can explain the origin of cluster formation in the Vul OB1 GMC.

6. We propose that the GMFs in Vul OB1 were produced by galactic-scale dynamics like spiral shocks or shear motions.

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Software: We utilized Astropy, a community-developed core Python package for astronomy (Astropy Collaboration et al. 2013; Astropy Collaboration et al. 2018), NumPy (van der Walt et al. 2011), Matplotlib (Hunter 2007), IPython (Perez, & Granger 2007), APLpy (Robitaille & Bressert 2012), Miriad (Sault et al. 1995), and Montage software (Berriman & Good 2017).

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Appendix 1 $^{13}$CO and C$^{18}$O velocity channel maps of Sh 2-86

We present the velocity channel maps of the $^{13}$CO and C$^{18}$O J = 1-0 emissions toward Sh 2-86 in the Appendix 1 (see Figures 11 and 12)

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Fig. 11. Velocity-channel map of the $^{13}$CO $J = 1-0$ emission with a velocity step of 1.0 km s$^{-1}$. The crosses and dotted circles are the same as in Figure 1(b). The map resolution after convolution is 40″. The 1σ noise level is $\sim 0.3$ K km s$^{-1}$ for the velocity interval of 1.0 km s$^{-1}$. 
Fig. 11. (Continued.)
Fig. 12. Same as Figure 11, but for C$^{18}$O $J=1$–0
Fig. 12. (Continued.)