Formation of Dense Gas and Stars near the End of the Galactic Bar

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Abstract

We carried out H$^{13}$CO$^+$ ($J = 1–0$) observations of a molecular cloud containing a massive star-forming region, G23.44−0.18, using the Nobeyama 45-m radio telescope. We identified three clumps, named Clumps A, B, and C, on the periphery of the H II region in the cloud. The most massive clump, Clump A, has a radius of 0.74 ± 0.20 pc and a mass of $1100^{+800}_{-640} M_\odot$. Both Clumps B and C, however, have much smaller size and mass than Clump A. These three clumps seem not to be virialized. We also found four sub-clumps in Clump A. These sub-clumps may be affected by the strong outflow penetrating Clump A. The star-formation efficiency ($SFE$) of the entire cloud is $\sim 0.4\%$, which is typical for galactic star-forming clouds. The $SFE$ of Clump A is $25^{+14}_{-11}\%$. This value is higher than other embedded cluster-forming clumps, which implies that stars, including massive ones, are formed efficiently and actively in Clump A. The dense gas fraction estimated from H$^{13}$CO$^+$ ($J = 1–0$) and $^{13}$CO ($J = 1–0$) of the cloud are lower than those of other star-forming regions. The results mean that this star-forming region is young, and suggest that the formation of dense gas and stars in the cloud has just begun. Comparing the dynamical age of the H II region with the fragmentation timescale for the collect and collapse process, molecular gas is accumulating through expansion of the H II region in Clumps B and C. Since there are massive young stellar objects (YSOs) in Clump A, we suggest that this clump has already become denser than the other regions in the cloud due to converging flow, or some external factors, such as an old bubble and cloud–cloud interaction.

Key words: ISM: clouds — ISM: individual (G23.44−0.18) — stars: formation

1. Introduction

Bars in disk galaxies play an important role for galaxy evolution. Gas inflow along a bar induces star formation at the leading edge due to shock (e.g., Athanassoula 1992). Around the bar end, the gas density tends to be high because the shear motion is lower than that in a bar. Watanabe et al. (2011) found that the star-formation efficiency ($SFE$) is higher in the bar ends than in the other regions of NGC 3627. They concluded that a plausible reason for the enhanced $SFE$ is that the gravitational instability of an assembly of molecular clouds enhances cloud–cloud collisions and the formation of dense molecular gas. The motive of our study is to investigate what are the causes of the enhanced $SFE$ in the bar ends. However, barred galaxies are too far away to observe molecular emission on the clump scale.

The Milky Way is the ‘nearest’ barred spiral galaxy. Although we can only see an edge-on view of the galaxy, recent studies have inferred its face-on view. One of the most detailed views of the Milky Way has come from Spitzer/Galactic Legacy Infrared Mid-Plane Survey Extraordinaire (GLIMPSE) surveys. Benjamin et al. (2005) analyzed the GLIMPSE Point Source Catalog, and found that the galactic bar has a half-length of $4.4 \pm 0.5$ kpc tilted by $44^\circ \pm 10^\circ$ to the Sun-galactic center line. The best visualization of the face-on view of the Milky Way was presented by Churchwell et al. (2009) (see their figures 15 and 16). Moreover, the galactic structure was inferred from accurate distance measurements to the objects. Trigonometric parallax measurements conducted by the Very Long Baseline Array (VLBA) and the VLBI Exploration of Radio Astrometry (VERA) have determined the distance to the galactic star-forming regions (Reid et al. 2009 and references therein).

Numerical simulations also have revealed the structure and dynamics of the Milky Way (e.g., Wada et al. 1994; Fux 1999). The most detailed structure of the Galaxy was produced by Baba et al. (2010). They reproduced the observed H I and CO longitude-velocity ($l-v$) diagrams of the Milky Way by using a high-resolution, N-body + hydrodynamical simulation in which the multi-phase ISM, star formation, and supernova feedback were taken into account. Their results show clumpy structures as well as large-scale structure. Combined with the Spitzer view, numerical simulations, and a trigonometric-parallel distance, we can determine the relation between the star-forming regions and the galactic structure.

The star-forming region G23.44–0.18 was reported to be located near the end of the galactic bar in the Norma arm; its distance is $5.88^{+1.37}_{-0.93}$ kpc according to Brunthaler et al. (2009). The detection of 6.7-GHz methanol maser emissions in G23.44–0.18 indicates that there are massive young stellar objects (YSOs) in this region (Walsh et al. 1998). One of these methanol maser sources generates strong bipolar outflow (Ren et al. 2011). These observational results show that massive star formation has continued in G23.44–0.18.

We can resolve the molecular cloud containing G23.44–0.18 on the clump scale ($\sim$1 pc) by using the Nobeyama 45-m telescope, and investigate the formation of dense gas and massive stars in the end of the galactic bar. In this paper, we present the results of H$^{13}$CO$^+$ ($J = 1–0$) observations with the Nobeyama 45-m telescope in combination with $^{13}$CO ($J = 1–0$) emission of the Galactic Ring Survey...
The results of data analyses of 13CO in the H\textsc{ii} region, respectively. The H\textsuperscript{13}CO\textsuperscript{+} (J = 1–0) line can trace dense gas regions in molecular clouds because of its high critical density (∼ 8 × 10\textsuperscript{4} cm\textsuperscript{-3}). We can discuss the properties of clumps that directly connect newly formed stars by using the H\textsuperscript{13}CO\textsuperscript{+} emission line. The outline of this paper is as follows. The observation of the H\textsuperscript{13}CO\textsuperscript{+} line and other data are summarized in section 2. The results of data analyses of 13CO and H\textsuperscript{13}CO\textsuperscript{+}, the properties of H\textsuperscript{13}CO\textsuperscript{+} clumps and ionizing source of the H\textsuperscript{ii} region are presented in section 3. We discuss SF\textregistered, the dense gas fraction, the effect of the H\textsuperscript{ii} region and outflow, and the possible formation process of dense clumps in section 4. A summary is given in section 5.

2. Observation and Data

2.1. H\textsuperscript{13}CO\textsuperscript{+} (J = 1–0) Observation

Observations of the region including G\textsuperscript{23.44–0.18} in H\textsuperscript{13}CO\textsuperscript{+} (J = 1–0) line (the rest frequency 86.754330 GHz) were made with the Nobeyama 45-m telescope in 2011 February and April. We used the 25-Beam Array Receiver System (BEARS; Sunada et al. 2000; Yamaguchi et al. 2000) for the front-end receiver. The half-power beamwidth was 18\textdegree at 87 GHz, and the main beam efficiency was η = 0.51. For the back end, 25 sets of 1024 channel auto-correlators (Sorai et al. 2000) were used. Each of them had a 32 MHz bandwidth and a 37.8 kHz frequency resolution. We carried out observations with the on-the-fly mapping technique, which covered an ∼ 7\textdegree \times 7\textdegree area. The double-sideband system noise temperature was 200–300 K. We checked the telescope pointing through observing an SiO maser source every one hour; the pointing accuracy was better than 5\textdegree.

The observed data were regridded onto the cube data with a spatial grid size of 9" using a Gaussian-tapered 1st-order Bessel function (Sawada et al. 2008). The effective spatial resolution became 23\textdegree.1, corresponding to 0.66 pc at a distance of 5.9 kpc. In order to remove the scanning effect, we combined images that were scanned along both the galactic longitude and latitude directions using the basket-weave algorithm (Emerson & Gräve 1988). Finally, the average rms noise was 0.1 K in T\textsubscript{gb} with 0.52 km s\textsuperscript{-1} velocity resolution.

2.2. 1\textsuperscript{3}CO (J = 1–0), Infrared, and Radio Continuum Data

In addition to the H\textsuperscript{13}CO\textsuperscript{+} (J = 1–0) observation, we extracted 13CO (J = 1–0) data of GRS (Jackson et al. 2006), mid-infrared data from GLIMPSE (Benjamin et al. 2003), and VLA 90-cm radio continuum emission data, which were taken as a part of the observation program for MAGPIS (Helfand et al. 2006).

The GRS was carried out with the Five College Radio Astronomy Observatory (FCRAO) 14-m telescope. The beamwidth and map spacing were 46\textdegree and 22\textdegree, respectively. The survey achieved a mean 1σ rms noise level of T\textsubscript{gb} = 0.13 K per 0.21 km s\textsuperscript{-1} velocity channel. GLIMPSE imaged the region −65\textdegree ≤ l ≤ +65\textdegree, |b| ≤ 1\textdegree using four bands (3.6, 4.5, 5.8, and 8.0 \textmu m) of the Infrared Array Camera (IRAC). We used the mosaicked image and the GLIMPSE 1 Point Source Catalog incorporating the Two Micron All Sky Survey (2MASS) point source catalog. Radio continuum observations at 90 cm were conducted in the C configuration of the VLA. The observation covered an area of 20\degree ≤ l ≤ 33\degree, |b| ≤ 2\textdegree. The data were reduced using a 15\textdegree pixel size, and have a spatial resolution ∼ 70\textdegree.

3. Results

3.1. Structure of the Entire Molecular Cloud

We show the 1\textsuperscript{3}CO (J = 1–0) integrated intensity map of the molecular cloud containing G\textsuperscript{23.44–0.18} in figure 1. Hereafter, we call this the G\textsuperscript{23.4}. The left panel of figure 1 shows an integrated intensity map of 1\textsuperscript{3}CO emission over the velocity range from 85.16 to 114.92 km s\textsuperscript{-1} superposed on an IRAC 8 \textmu m image, which indicates an H\textsuperscript{ii} region (hereafter, G\textsuperscript{23.4} H\textsuperscript{ii} region). In the G\textsuperscript{23.4} cloud there are two intensity peaks at the northern and southern edges of the G\textsuperscript{23.4} H\textsuperscript{ii} region. Contours in the middle and right panels of figure 1 show the integrated intensities of the 1\textsuperscript{3}CO emission from 97.06 to 101.74 km s\textsuperscript{-1} (middle) and from 101.10 to 108.12 km s\textsuperscript{-1} (right). Rathborne et al. (2009) applied the CLUMP\textregistered FIND algorithm to the GRS data, and identified two molecular clouds at (l, b) ~ (23.44, −0.21) with the local standard of rest (LSR) velocity values of 101.1 and 103.7 km s\textsuperscript{-1}. We call these two clouds the 101 km s\textsuperscript{-1} component and the 104 km s\textsuperscript{-1} component, respectively. Figure 1 shows that the northern peak is associated with the 101 km s\textsuperscript{-1} component, and the southern peak with the 104 km s\textsuperscript{-1} component. We did not use the total mass of the G\textsuperscript{23.4} cloud derived by Roman-Duval et al. (2010, 3 \times 10\textsuperscript{5} M\textsubscript{\odot}), which is based on results of Rathborne et al. (2009), but that derived by Heyer et al. (2009, 4 \times 10\textsuperscript{5} M\textsubscript{\odot}), because Roman-Duval et al. (2010) derived molecular gas mass in this region with the assumption that the excitation temperature and optical depth of 13CO emission could be set to zero. The velocity dispersion of the G\textsuperscript{23.4} cloud is σ\textsubscript{v} = 4.6 km s\textsuperscript{-1} (Heyer et al. 2009), corresponding to a linewidth of 10.8 km s\textsuperscript{-1}. This velocity dispersion is about 1.7-times larger than other giant molecular clouds (GMCs) that have almost the same size and mass in Heyer et al. (2009).

Figure 2 shows channel maps of 13CO emission. Diffuse and extended components associated with the 101 km s\textsuperscript{-1} component can be seen from the 91.54 to 95.79 km s\textsuperscript{-1} panels. In the 96.85 to 98.98 km s\textsuperscript{-1} maps, the southeast side of the cloud outlines the edge of the G\textsuperscript{23.4} H\textsuperscript{ii} region (thick lines in figure 2), while the opposite side is still diffuse, and elongates to the northwest direction (thin ellipses in figure 2). The outline of the southeast side of the G\textsuperscript{23.4} cloud, however, is much larger than the size of the G\textsuperscript{23.4} H\textsuperscript{ii} region. The G\textsuperscript{23.4} cloud becomes compact around the 102.17 km s\textsuperscript{-1} panel, and the 104 km s\textsuperscript{-1} component can be seen from the 103.23 to 106.42 km s\textsuperscript{-1} panel. In 108.54 to 110.67 km s\textsuperscript{-1} panels, two diffuse components extend toward the north-south direction (pairs of ellipse in figure 2).

Roman-Duval et al. (2009) resolved the kinematic distance ambiguity in the 101 and 104 km s\textsuperscript{-1} components using GRS data and the H\textsc{i} absorption feature. They derived the kinematic distances of 6.43 and 6.65 kpc for the 101 and
Fig. 1. (Left) Integrated intensity map of $^{13}$CO ($J = 1–0$) emission (white contour lines) superposed on the Spitzer IRAC 8 μm image. The velocity range of the integration is from 85.16 to 114.92 km s$^{-1}$. The contour interval is 5 K km s$^{-1}$ from 20 to 55 K km s$^{-1}$. (Middle and Right) Integrated intensity maps of $^{13}$CO from 97.06 to 101.74 km s$^{-1}$ (black contour lines, middle) and from 101.10 to 108.12 km s$^{-1}$ (black contour lines, right) on the total integrated intensity from 85.16 to 114.92 km s$^{-1}$ image (color contour map). Both contours start from 9 K km s$^{-1}$ with intervals of 5 K km s$^{-1}$.

Fig. 2. Channel maps of the $^{13}$CO ($J = 1–0$) emission over the velocity range from 91.54 to 111.73 km s$^{-1}$. The velocity intervals are 1.05 km s$^{-1}$. The values printed at the bottom-left corner denote the LSR velocities. The grey scale images and contours show the $^{13}$CO intensities. The contour levels are from 1 to 8 K in $T_A^*$ with 1 K intervals. The star symbol in each panel shows the location of the G23.4 HII region. In the 96.85 to 98.98 km s$^{-1}$ maps, the thick lines show the southeastern outline of the 101 km s$^{-1}$ component, and the thick ellipses show the diffuse elongated component.
104 km s\(^{-1}\) components, respectively. Compared to the LSR velocity of the methanol maser of 97.6 km s\(^{-1}\) and the distance measured through trigonometric parallax, the maser source G23.44–0.18 is associated with the 101 km s\(^{-1}\) component. The radio recombination-line velocity of the G23.4 H II region is 103 ± 0.5 km s\(^{-1}\) (Lockman 1989). In addition to the LSR velocity, the morphology of the G23.4 cloud, such as the sharp edge of the 101 km s\(^{-1}\) component (thick lines in figure 2) and two peaks in the \(^{13}\)CO integrated intensity map at around the G23.4 H II region, indicate that the structures of the 101 and 104 km s\(^{-1}\) components are affected by the H II region. Hence, we consider that the G23.4 H II region is nearly at the same location as the 101 and 104 km s\(^{-1}\) components. On the other hand, since the H II region and the molecular gas components are located at near the tangent point, these may be unrelated. We discuss the relation among them in subsection 4.3.

### 3.2. Distribution and Physical Properties of \(^{13}\)CO\(^{+}\) Clumps

#### 3.2.1. Overall distribution of the \(^{13}\)CO\(^{+}\) emission

We show the overall distribution of the observed \(^{13}\)CO\(^{+}\) emission. Figure 3 is an integrated intensity map of the \(^{13}\)CO\(^{+}\) emission. The lowest contour level is 5 σ = 0.95 K km s\(^{-1}\). We removed the features with only the single lowest contour because of insufficient integration time. Hence, we identified three clumps with more than two contours. Hereafter, we call these three clumps Clumps A, B, and C in order of the apparent size. Clump A is composed of at least two sub-clumps, since there are two peaks of the integrated intensity map in the clump. We derived the physical properties of these clumps in the next section.

#### 3.2.2. Physical properties of clumps

In this section, the physical properties (radius, linewidth, mass, and virial mass) of the \(^{13}\)CO\(^{+}\) clumps are derived. We summarized these quantities of clumps in table 1. We defined the apparent clump radius, \(R_{\text{obs}}\), as

\[
R_{\text{obs}} = \frac{10}{\text{arcmin}} \times \text{arcmin}
\]
Assuming optically thin emission and local thermal equilibrium (LTE), we can evaluate the mass of the clump using the following equation:

$$M_{\text{clump}}(M_\odot) = 142 \left( \frac{X_{\text{H}^{13}\text{CO}^+}}{5.6 \times 10^{-11}} \right)^{-1} T_{\text{ex}} \exp \left( \frac{4.16}{T_{\text{ex}}} \right) \times \left( \frac{D}{5.9 \text{kpc}} \right)^2 \left( \frac{R_{\text{clump}}}{10''} \right)^2 \left( \frac{\eta}{0.51} \right)^{-1} \times \int T_A^* dv \left( \frac{\text{K km s}^{-1}}{\text{K km s}^{-1}} \right),$$

(4)

where $X_{\text{H}^{13}\text{CO}^+}$ is the fractional abundance of H$^{13}$CO$^+$ relative to H$_2$ (Aoyama et al. 2001), $T_{\text{ex}}$ the excitation temperature, $D$ the distance to the G23.4 cloud, $R_{\text{clump}}$ the radius of a clump in arcsecond, and $\int T_A^* dv$ the total integrated intensity of the clump. Taking into account other observations of OMC-2/3 in the Orion A GMC by Aso et al. (2000) and a radiative transfer model of Goicoechea et al. (2009), we adopted $X_{\text{H}^{13}\text{CO}^+} = 3.6 - 6.5 \times 10^{-11}$ in the G23.4 cloud. The uncertainty of $X_{\text{H}^{13}\text{CO}^+}$ is included in the errors listed in table 1. In order to derive the excitation temperature of H$^{13}$CO$^+$, we used the NH$_3$ observational data taken with the Tomakomai 11-m telescope (Ohishi et al. in preparation). We calculated $M_{\text{clump}}$ with $T_{\text{ex}} = T_{\text{rot}} = 17$ K, where $T_{\text{rot}}$ is the rotation temperature of NH$_3$. 

$$R_{\text{obs}} = \left( \frac{A}{\pi} \right)^{1/2},$$

(1)

where $A$ is the projected area of the H$^{13}$CO$^+$ clump. In order to derive $A$, we counted the pixel numbers bounded by a 5 $\sigma$ contour and an error of $A$, evaluated from the semimajor and semiminor axes of the clumps. The radius of a clump, $R_{\text{clump}}$, corrected a broadening effect of the beam, and is given by

$$R_{\text{clump}} = \sqrt{R_{\text{obs}}^2 - (\theta_{\text{beam}}/2)^2},$$

(2)

where $\theta_{\text{beam}}$ is the effective beam size (23'.1). Since the size along the galactic longitude of Clump B and the radius of Clump C are less than the effective beam size, a column in table 1 shows the upper limits.

We derived the velocity widths in FWHM of a clump, $\Delta V_{\text{clump}}$, as follows. The observed velocity widths, $\Delta V_{\text{obs}}$, were estimated by fitting the total H$^{13}$CO$^+$ ($J = 1$–0) spectra summed up over the entire clump with a single Gaussian function. Then, $\Delta V_{\text{clump}}$ is described by

$$\Delta V_{\text{clump}} = \sqrt{\Delta V_{\text{obs}}^2 - \Delta V_{\text{1ch}}^2},$$

(3)

where $\Delta V_{\text{1ch}}$ is a velocity resolution of 0.52 km s$^{-1}$ of our 4-ch bind-up spectra. The LSR velocity of each clump shows that Clump A is associated with the 101 km s$^{-1}$ component and Clumps B and C are with 104 km s$^{-1}$ component. 

**Fig. 4.** Channel maps of H$^{13}$CO$^+$ ($J = 1$–0) emission (white contour lines) in Clump A. The background image is an integrated intensity map of H$^{13}$CO$^+$; black contour lines show the lowest level of the integrated intensity ($5\sigma = 0.95$ K km s$^{-1}$). Red circles are the positions of massive YSOs. The eastern YSO is GLIMPSE 023.4401–00.1830 and the western one is GLIMPSE 023.4363–00.1842. The dashed line in each panel is the direction of an outflow (Ren et al. 2011). The white arrow in the 99.46 km s$^{-1}$ panel shows a sliced line for the P–V diagram; the direction of the arrow indicates the positive direction of the horizontal axis in figure 5.

$$R_{\text{clump}} = \left( \frac{D}{5.9 \text{kpc}} \right)^2 \left( \frac{R_{\text{clump}}}{10''} \right)^2 \left( \frac{\eta}{0.51} \right)^{-1} \times \int T_A^* dv \left( \frac{\text{K km s}^{-1}}{\text{K km s}^{-1}} \right),$$

(4)
The virial mass for a uniform sphere is derived as

$$M_{\text{vir}}(M_\odot) = 209 \left( \frac{R_{\text{clump}}}{\text{pc}} \right) \left( \frac{\Delta V_{\text{clump}}}{\text{km s}^{-1}} \right)^2.$$  \hspace{1cm} (5)

We neglected the external pressure here (see discussion in subsection 4.2). All three clumps seem not to be virialized, although both the LTE mass and the virial mass of Clumps B and C are given by the 5σ upper limit.

3.2.3. Internal structure in Clump A

As can be seen in the previous section, Clump A consists of some internal sub-clumps. Figure 4 shows channel maps of H13CO+ emission in Clump A. In figure 5 there are four emission peaks in the position-velocity (P–V) diagram. We assumed that each peak corresponds to each sub-clump.

To identify sub-clumps, we extracted H13CO+ spectra from the cube data, and fitted them using multiple Gaussian functions. The spectra were split into some components whose LSR velocity corresponds to that in the P–V diagram (that is, 99, 101, and 103 km s\(^{-1}\) in figure 5). The detection limit of the components is 3σ = 0.3 K in \(T_A^*\). Since Subs 2 and 3 are in approximately the same velocity range, we split them using a contour map of the integrated intensity, which is summed up from 100.50 to 101.54 km s\(^{-1}\), like the CLUMPFIND method. After identification, we combined each split Gaussian function, and made one spectrum of each sub-clump. The physical properties of sub-clumps were derived by applying the method in sub-subsection 3.2.2 to these combined spectra. The results are also given in table 1.

The sum of these sub-clump mass is as large as the total mass of Clump A. The reason for the upper limit of the radius of Sub 4 is the same as in Clump C. Considering the margin of the errors for \(M_{\text{clump}}\) and \(M_{\text{vir}}\) of Sub 2, it might be virialized, but other sub-clumps are not. The most interesting feature can be seen in the 101.02 km s\(^{-1}\) panel of figure 4. It looks like the strong bipolar outflow observed by Ren et al. (2011) passes through between Subs 2 and 3. The relations among sub-clumps, massive YSOs, and outflow are discussed in subsection 4.4.

3.3. Properties of Ionizing Star

In this section, we estimate the properties of the exciting star(s) using the 90-cm radio continuum emission and the infrared data (figure 6), since there is no cataloged O star in the G23.4 H\(\text{\textsc{ii}}\) region, and it is impossible to observe in optical wavelength. We used the total number of UV photons emitted by star(s) per unit time given by Chaisson (1976),

$$N_{\text{UV}}(s^{-1}) = 0.76 \times 10^{47} \left( \frac{T}{10^4 K} \right)^{-0.45} \left( \frac{\nu}{\text{GHz}} \right)^{0.1} \times \left( \frac{S}{\text{Jy}} \right) \left( \frac{D}{\text{kpc}} \right)^2,$$  \hspace{1cm} (6)

where \(T\) is the electron temperature, \(\nu\) the frequency, \(S\), the total flux density, and \(D_{\text{kpc}}\) the distance. We assumed the electron temperature is \(T = 10^4 K\) (Reynolds 1985; Alves et al. 2010). Since the 90-cm continuum emission from SNR W 41, which is located in front of the G23.4 cloud, overlaps the emission from the H\(\text{\textsc{ii}}\) region, we had to subtract the average flux density of W 41 from the total emission. The total flux density from the G23.4 H\(\text{\textsc{ii}}\) region, which is subtracted the emission from SNR, is 4.9 Jy. The total number of photons
Based on calculations of the parameters of O and early-B stars (e.g., Vacca et al. 1996; Martins et al. 2005), we estimated the spectral type of the ionizing star to be between B0.5V and O9.5V stars.

In order to determine the mass and location of the ionizing star, we fitted its SED using an on-line fitting tool developed by Robitaille et al. (2007). Before fitting SEDs, we removed any extragalactic contamination from the GLIMPSE Point Source Catalog using the criteria of Gutermuth et al. (2008). We then found 80 stellar sources in and around the G23.4 H II region. We estimated the interstellar extinction from $^{13}$CO ($J = 1–0$) data. The interstellar extinction, $A_V$, can be calculated using $N(H)/A_V = 1.9 \times 10^{21}$ cm$^{-2}$ mag$^{-1}$ and $N(H) = N(H_1) + 2N(H_2)$, where $N(H)$ is the total hydrogen column density, $N(H_1)$ the column density of atomic hydrogen of $1.0 \times 10^{21}$ cm$^{-2}$, and $N(H_2)$ the column density of hydrogen molecules derived by $^{13}$CO (Bohlin et al. 1978). The derived extinction is between 10 and 100 mag. We selected the point sources with a best-fit $\chi^2/N_{data}$ as well-fit ones, where $N_{data}$ is the number of input data of flux or magnitude (Povich et al. 2009).

We found two YSO candidates (GLIMPSE 023.4288–00.2183 and 023.4286–00.2309), and no massive main-sequence stars that could be fitted by only the stellar photosphere model in the G23.4 H II region. We show the results of the SED fitting for these YSO candidates in figure 7. According to Robitaille et al. (2006), stage I YSOs are those that have $M_{env}/M_* > 10^{-6}$ yr$^{-1}$; stage II are those with $M_{disk}/M_* > 10^{-6}$ and $M_{env}/M_* < 10^{-6}$ yr$^{-1}$; and stage III are those with $M_{disk}/M_* < 10^{-6}$ and $M_{env}/M_* < 10^{-6}$ yr$^{-1}$. GLIMPSE 023.4286–00.2309 is categorized as stage I, indicating that it is too young to produce a pc-scale H II region. The properties of GLIMPSE 023.4288–00.2183 are as follows: the mass of the star is $M_* = 14.6 M_\odot$, the surface temperature of the star $T = 31000$ K, the circumstellar disk mass $M_{disk} = 9.0 \times 10^{-9} M_\odot$, and the envelope accretion rate $M_{env} = 0$, and $\chi^2/N_{data} = 0.42$. This YSO is categorized as stage III, and the spectral type is between B0V and O9.5V (Panagia 1973), which is consistent with the result of radio continuum emission at 90 cm. Hence, we conclude that GLIMPSE 023.4288–00.2183 is a good candidate of the ionizing star in the G23.4 H II region.

4. Discussion

4.1. Star-Formation Efficiency and Dense Gas Fraction

In this section we discuss the current star-formation activity and evolutionally stage of the G23.4 cloud and Clump A. SFE is defined as
$SFE = \frac{M_{\text{star}}}{M_{\text{star}} + M_{\text{gas}}}.$  \hspace{1cm} (7)

where $M_{\text{star}}$ is the total stellar mass and $M_{\text{gas}}$ is the total molecular gas. To estimate the total stellar mass, we considered two massive YSOs (GLIMPSE 023.4401–00.1830 and 023.4363–00.1842) in Clump A (red circles in figure 4). We also fitted their SEDs in the same way in subsection 3.3. The results of the fitting are shown in figure 7. The errors of the fit are rather large, and the best-fit $\chi^2$ is $\approx 27 > 5N_{\text{data}}$. GLIMPSE 023.4401–00.1830 (eastern circle in figure 4) has $\approx 9 M_\odot$, and GLIMPSE 023.4363–00.1842 (western circle in figure 4) has $\approx 27 M_\odot$. They are categorized as stage I, and their age is $\approx 10^3$ yr. Furthermore, the G23.4 cloud has two other diffuse HII regions, found by the Green Bank Telescope HII Region Discovery Survey (HRDS; Bania et al. 2010). The HRDS source G023.389–0.148 has a 9-GHz continuum flux of $1200 \pm 120$ mJy, and G023.458–0.179 has $1080 \pm 80$ mJy. We calculated the number of UV photons with equation (6), and found that each diffuse HII region has one B0.5V star. Assuming the Salpeter initial mass function (IMF) with a mass range of $0.1–27 M_\odot$ and the total number of ionizing sources and YSOs in the mass range between $14$ and $27 M_\odot$ to be four, the total stellar mass is estimated to be $\approx 1780 M_\odot$. Here, we exclude GLIMPSE 23.4401–00.1830, which have less than $14 M_\odot$, because we fitted only massive sources, and there may be other YSOs with $\approx 8–10 M_\odot$ in the GLIMPSE Point Source Catalog. Using the molecular gas mass derived by Heyer et al. (2009), the SFE of G23.4 cloud is derived to be $\approx 0.4\%$. This SFE is a recent one because we counted only the number of young stars. The typical SFE of the galactic star-forming region is from $1\%$ to $5\%$ (e.g., Duerr et al. 1982; Myers et al. 1986). The G23.4 cloud has a normal SFE.

The SFE of the H$^{13}$CO$^+$ clump is $25^{+11}_{-14}\%$, which we derived from the total stellar mass of $\approx 370 M_\odot$ and $M_{\text{clump}}$ of Clump A. This value implies active star formation in Clump A. Higuchi et al. (2010) have suggested that SFE is an indicator of the evolutionary stage in cluster-forming regions. According to their morphological classification, Clump A is classified as type A because the massive YSOs are embedded in the clump, while its SFE is larger than that of type A clumps in Higuchi et al. (2010) and as large as the one of type B or C, which are more evolved cluster-forming clumps. Hence, active star formation occurs in Clump A.

In order to investigate the dense gas-formation activity in the 101 and the 104 km s$^{-1}$ components, we compared the integrated intensity ratio of H$^{13}$CO$^+$ and $^{13}$CO, $I(\text{H}^{13}\text{CO}$)$^+$/I($^{13}$CO). The ratio is $0.25 \pm 0.02$ for 101 km s$^{-1}$ and $<0.45$ for 104 km s$^{-1}$, which indicates that the dense gas-formation activity in both the 101 and 104 km s$^{-1}$ components seems to have no difference. We also derived the dense gas fraction for the G23.4 cloud to be 0.2$\%$–0.5$\%$, which is defined as the fraction of $M(H_2)$ derived from H$^{13}$CO$^+$ to $M(H_2)$ derived from $^{13}$CO. We estimated the dense gas fraction in Clump A to be 21$\%$ from Ikeda, Sunada, and Kitamura (2007) and references therein. We also estimated the fraction of AFGL 5142 to be 18$\%$ using the results of Higuchi et al. (2010) and Kawamura et al. (1998). Yonekura et al. (2005) observed $\eta$ Carinae in $^{12}$CO, $^{13}$CO, C$^{18}$O ($J = 1\rightarrow 0$), and H$^{13}$CO$^+$ ($J = 1\rightarrow 0$). Although H$^{13}$CO$^+$ emission was not observed over the region, the dense gas fraction is $>3.3\%$. The dense gas fraction in the G23.4 cloud is lower than that in these star-forming regions. No evidence of SNR in the cloud and the low dense gas fraction suggest that dense gas formation and massive star formation have just begun in G23.4 cloud.

4.2. Star Formation Triggered by the HII Region?

As mentioned in subsection 3.1, there is a possibility that the G23.4 HII region and the 101 and 104 km s$^{-1}$ components are unrelated. However, if these components are related to each other, the 101 and 104 km s$^{-1}$ components are affected by the HII region. In this section we verify whether the collect and collapse process triggers star formation or not in the G23.4 cloud. This model was first proposed by Elmegreen and Lada (1977). Then, Whitworth et al. (1994) estimated the timescale until the layer swept up by an HII region becomes gravitationally unstable. Recently, Iwasaki, Inutsuka, and Tsuribe (2011) investigated the gravitational fragmentation of expanding shells using three-dimensional simulation codes. Hosokawa and Inutsuka (2006) calculated the time evolution of an HII region, photodissociation regions (PDRs), and swept-up shells. We compared our results to these theoretical studies.

The dynamical age of the HII region at a given radius, $R$, is estimated by the model of Dyson and Williams (1980) as

$$t(R) = \frac{4R_S}{c_s} \left[ \left( \frac{R}{R_S} \right)^{7/4} - 1 \right],$$

(8)

where $R_S$ is the Strömgren radius, and $c_s$ is the sound speed in ionized gas ($c_s = 10$ km s$^{-1}$). The Strömgren radius is given by $R_S = [3N_{\text{UV}}/(4\pi n_0^2\alpha_B)]^{1/3}$, where $N_{\text{UV}}$ is the total number of ionizing photons per unit time emitted by the central star(s), $\alpha_B = 2.6 \times 10^{-13}$ cm$^3$ s$^{-1}$ is the hydrogen recombination coefficient to all levels above the ground state, and $n_0$ is the ambient density. We assumed $n_0 = 10^3$ cm$^{-3}$, which is the typical density of $^{13}$CO clouds. As derived in subsection 3.3, $N_{\text{UV}} = 1.8 \times 10^{47}$ s$^{-1}$. The approximate radius of the HII region is $1'–1.5'$, which corresponds to 1.7–2.6 pc at a distance of 5.9 kpc. Hence, the dynamical age of the G23.4 HII region is $0.5$–$1$ Myr.

Whitworth et al. (1994) obtained the time at which fragmentation in the swept-up layer starts. Iwasaki, Inutsuka, and Tsuribe (2011) showed the relation between the ambient density, $n_0$, $N_{\text{UV}}$, and the time, $t_{\text{bgm}}$, when gravitational instability begins to glow (figure 12 in their paper). The analytic formula of $t_{\text{bgm}}$ is written as

$$t_{\text{bgm}} \text{(Myr)} = 0.6 \left( \frac{N_{\text{UV}}}{10^{47} \text{ s}^{-1}} \right)^{-0.11} \left( \frac{T}{10 K} \right)^{0.375} \times \left( \frac{n_0}{10^3 \text{ cm}^{-3}} \right)^{-0.45},$$

where $T$ is the temperature of the ambient cold gas; we assumed $T = 10$ K. Using this formula, the gravitational instability started at $\approx 0.9$ Myr ($n_0 = 10^3$ cm$^{-3}$) after the G23.4 HII region was formed.

The dynamical expansions of the HII region and PDR were analyzed by Hosokawa and Inutsuka (2006). They solved the UV and FUV radiation transfer and the thermal and chemical...
processes. The models S19 (the mass of central star is $19 M_\odot$) and the number density of ambient gas is $10^3 \text{cm}^{-3}$) and S12 ($11.7 M_\odot$ and $10^4 \text{cm}^{-3}$) are similar to the G23.4 H II region, which has a central star of $14.6 M_\odot$; the gravitational instability occurred at $\sim 0.5\text{Myr}$ and $\sim 1\text{Myr}$ after the G23.4 H II region was formed, respectively. Comparing the dynamical age of the H II region with $b_{\text{dyn}}$ of Iwasaki, Inutsuka, and Tsuribe (2011) and Hosokawa and Inutsuka (2006), the gravitational fragmentation may have started in a swept-up shell in the case of an ambient density of $n_0 = 10^3 \text{cm}^{-3}$.

All three $^{13}\text{CO}^+$ clumps seem to be non-virialized, as mentioned in sub-subsection 3.2.2. We neglected external pressure for deriving the virial mass. Nakamura and Li (2011) showed that most cores in their simulation are out of equilibrium with the external pressure due to ambient outflow-driven turbulence, and suggested that the core evolution is controlled by the outflow-driven turbulence. Because there is no evidence of massive star formation in Clumps B and C, which is inferred from no compact H II regions and no massive YSOs from SED fittings, the external pressure due to outflow may not be effective. Hence, neglecting the external pressure is plausible, and we considered that Clumps B and C are not virialized. The timescale for the gravitational fragmentation discussed above and the non-virialised condition of clumps suggest that in Clumps B and C, molecular gas is accumulating due to expansion of the G23.4 H II region. For Clump A, however, there is some evidence of newly formed massive stars. Hence, the star formation in Clump A cannot be explained only by expansion of the H II region.

If the molecular gas is denser, $n_0 = 10^4 \text{cm}^{-3}$, the dynamical age is $t \sim 2.6\text{Myr}$ and $b_{\text{dyn}} \sim 0.3\text{Myr}$. This is consistent with Clump A. On the other hand, if the ambient gas is less dense, $n_0 = 10^2 \text{cm}^{-3}$, the dynamical age becomes $\sim 0.2\text{Myr}$ and gravitational fragmentation began at $\sim 2.6\text{Myr}$ after the H II region was formed. This is inconsistent with the existence of a massive YSO in Clump A. These two cases imply that the precursor of Clump A was denser than other regions in the G23.4 cloud.

4.3. Spatial Relation among the G23.4 H II Region and the Molecular Gas Components

Since the G23.4 cloud and the G23.4 H II region are located at near the tangent point, there is a possibility that these components are unrelated, even if they have nearly the same LSR velocity. In this section we discuss the relation of each component and star formation. The H II region is supposed to be associated with its parental molecular cloud, since the dynamical age (0.5–2.6 Myr) is not very old. Moreover, as mentioned in subsection 3.1, the LSR velocity of the radio recombination line of the G23.4 H II region is $103 \pm 0.5 \text{ km s}^{-1}$ and that of the $^{13}\text{CO}$ line of $104 \text{ km s}^{-1}$ is $103.7 \text{ km s}^{-1}$. Hence, we assumed that the H II regions are associated with the $104 \text{ km s}^{-1}$ component, and the $108 \text{ km s}^{-1}$ components are unrelated to other components.

First, we considered the case where the $101 \text{ km s}^{-1}$ component is not related to the H II and $104 \text{ km s}^{-1}$ components. In this case, the spectral type of the ionizing star must change, depending on the distance. Since Clump A has not been affected by the expansion of the H II region, we required other mechanisms of massive clump formation. For example, turbulent converging flow (e.g., Banerjee et al. 2009; Gong & Ostriker 2011) or external factors, such as an old bubble (Povich et al. 2009). If Clump A formation is caused by an old bubble, the large outline of the $101 \text{ km s}^{-1}$ component mentioned in subsection 3.1. may be explained.

Second, we assumed that the H II region, 101, and $104 \text{ km s}^{-1}$ components are related to each other. We interpreted the structure as an embedded H II region in a GMC and three dense clumps at its periphery. The effect of the H II region is discussed in subsection 4.2. Moreover, interactions between the 101 and $104 \text{ km s}^{-1}$ components may occur. In numerical simulations in the Milky-Way-like disk galaxy of Tasker and Tan (2009), the cloud collision time is found to be $\sim 1/5$ of the galactic orbit time. Their results have shown that cloud–cloud collisions occur frequently in the galactic disk. In the bar end, molecular clouds tend to gather due to crowded orbits (e.g., Athanassoula 1992), and the clouds may collide with each other much more frequently than those in the disk. Furthermore, both the outline of the $101 \text{ km s}^{-1}$ component and the large linewidth of the cloud can be explained by cloud–cloud interactions (e.g., Habe & Ohta 1992). In either case, to distinguish how these components relate to each other, precise distance measurements are necessary for the star-forming regions, especially located near the tangent point.

4.4. Outflow in Clump A

Ren et al. (2011) found strong bipolar outflow from the massive YSO GLIMPSE 23.4363$-$00.1842. The apparent size of the extended outflow is about $0.68 \text{ pc}$, which is comparable to the radius of Clump A. Ren et al. (2011) observed C$^{18}$O ($J = 2$–1) emission and 1.3-mm continuum emission of G23.44$-$0.18; they also found dense cores associated with massive YSOs (MM1 associated with GLIMPSE 023.4401$-$0.1830 and MM2 with GLIMPSE 023.4363$-$00.1842). Neither MM1 nor MM2 has radio continuum emission, which indicates that both cores are prior to forming an ultra-compact H II region. Since the LSR velocities of the cores are $102.2 \text{ km s}^{-1}$ for MM1 and $99.8 \text{ km s}^{-1}$ for MM2, the former can be associated with Sub 3 and the latter with Sub 1 in Clump A. As mentioned in subsection 3.2.3, the outflow passes through between Subs 2 and 3, which indicates that it separates one sub-clump into two sub-clumps, Subs 2 and 3. In addition to MM1 and MM2, a shock region has been found by Ren et al. (2011) along the redshifted side of the outflow. The LSR velocity of this shock region is $102$–$103 \text{ km s}^{-1}$. Since the LSR velocity of Sub 4 is $103 \text{ km s}^{-1}$, the interaction between the outflow and Sub 4 is consistent with these velocity structures.

Three-dimensional simulations of massive star formation in dense, turbulent, parsec-scale clumps of cluster star formation was carried out by Wang et al. (2010). For parsec-scale clumps of $\sim 10^3 M_\odot$, they proposed an outflow-regulated clump-fed massive star-formation scenario. The virial ratio, $M_{\text{vir}}/M_{\text{clump}}$, is $> 1.5$ in Sub 1, $1.9^{+1.2}_{-0.5}$ in Sub 2, and $2.6^{+1.8}_{-1.4}$ in Sub 3, respectively. Although we cannot analyze detailed properties, such as the density profile and the velocity structure of sub-clumps in Clump A, because of a lack of spatial resolution, these high virial ratios can be explained by large
turbulence induced by the outflow. Detailed observations of Clump A will provide an important key to verify the outflow-regulated clump-fed massive star-formation scenario.

5. Summary

We carried out observations of the G23.4 cloud in $^{13}\text{CO}^+ (J = 1\rightarrow 0)$ emission using the Nobeyama 45-m telescope. In addition to $^{13}\text{CO}^+$ data, we used the GRS $^{13}\text{CO} (J = 1\rightarrow 0)$, GLIMPSE, and MAGPIS 90-cm data.

1. We found three clumps around the G23.4 H II region. Clump A, the most massive clump, has a size of $0.74 \pm 0.20$ pc and a mass of $1100^{+660}_{-640} M_\odot$ and consists of four sub-clumps, while Clumps B and C are less intense. We derived only the upper limit of their mass. Compared with the $^{13}\text{CO}$ emission data, Clump A is associated with the 101 km s$^{-1}$ component and Clumps B and C with the 104 km s$^{-1}$ component.

2. $\text{SFE}$ of the G23.4 cloud is estimated to be 0.4%, which is typical of the galactic star-forming region. $\text{SFE}$ of Clump A is $25_{-11}^{+14}$%, which is larger than that of other cluster-forming clumps categorized as the youngest evolutionally stage. The result suggests that the star formation in Clump A is both active and efficient. We derived a dense gas fraction in the G23.4 cloud to be 0.2%--0.5%, indicating a very low, dense gas fraction. These results suggest that dense gas formation and star formation have just begun in the G23.4 cloud.

3. We compared the dynamical age of the H II region with the fragmentation timescale for the collect and collapse process. We found that molecular gas is now accumulating in Clumps B and C. On the other hand, since there are massive YSOs in Clump A, the formation process of the clump cannot be explained only by the expansion of the H II region; also, the precursor of Clump A might be denser than the other region in the G23.4 cloud.

4. If the 101 km s$^{-1}$ component is not related to the G23.4 H II region and 104 km s$^{-1}$ km s$^{-1}$, the formation processes, except for collect and collapse, are required for Clump A. On the other hand, if the H II region and molecular components are related each other, the clumps are affected by the H II region. Moreover, the cloud-cloud interaction may occur because the cloud is located near the end of the galactic bar. In any case, precise distance measurements are necessary for the star-forming region located at the tangent point.

5. The outflow originating from a massive YSO may penetrate Clump A. We predict that the sub-clumps must be affected by the outflow, but we cannot analyze them in detail because of a lack of resolution. Interferometric observations are needed to verify the outflow-regulated clump-fed star formation.

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