THE SECOND SURVEY OF THE MOLECULAR CLOUDS IN THE LARGE MAGELLANIC CLOUD BY NANTEN. II. STAR FORMATION

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ABSTRACT

We studied star formation activities in the molecular clouds in the Large Magellanic Cloud. We have utilized the second catalog of 272 molecular clouds obtained by NANTEN to compare the cloud distribution with signatures of massive star formation including stellar clusters, and optical and radio H \textsc{ii} regions. We find that the molecular clouds are classified into three types according to the activities of massive star formation: Type I shows no signature of massive star formation; Type II is associated with relatively small H \textsc{ii} region(s); and Type III with both H \textsc{ii} region(s) and young stellar cluster(s). The radio continuum sources were used to confirm that Type I giant molecular clouds (GMCs) do not host optically hidden H \textsc{ii} regions. These signatures of massive star formation show a good spatial correlation with the molecular clouds in the sense that they are located within ∼100 pc of the molecular clouds. Among possible ideas to explain the GMC types, we favor that the types indicate an evolutionary sequence; i.e., the youngest phase is Type I, followed by Type II, and the last phase is Type III, where the most active star formation takes place leading to cloud dispersal. The number of the three types of GMCs should be proportional to the timescale of each evolutionary stage if a steady state of massive star and cluster formation is a good approximation. By adopting the timescale of the youngest stellar clusters, 10 Myr, we roughly estimate the timescales of Types I, II, and III to be 6 Myr, 13 Myr, and 7 Myr, respectively, corresponding to a lifetime of 20–30 Myr for the GMCs with a mass above the completeness limit, 5 × 10^4 M⊙.

Key words: galaxies: individual (Large Magellanic Cloud) – galaxies: star clusters – ISM: clouds – stars: formation

Online-only material: color figures, machine-readable table

1. INTRODUCTION

The Magellanic Clouds can be observed in more detail than any other extra galaxies at any wavelengths because of the proximity. The relatively face-on location of the Large Magellanic Cloud (LMC) enables us to obtain a complete sample of astronomical objects with less contamination compared with the Galaxy. Studies of the LMC provide invaluable information on our understanding of the galaxies in various aspects, including the properties of the interstellar medium (ISM), evolution of molecular clouds, and star formation.

The environments, such as metallicity, in the LMC are different from those in the Galaxy (e.g., Z ∼ 1/2 Z⊙; Dufour 1984 and taking into account the revision of the solar abundance by Asplund et al. 2004). Star formation activities are also different. Stellar clusters called “populous clusters,” which are self-gravitating like Galactic globular clusters, are found by photometric studies (e.g., Hodge 1961; van den Bergh 1981). Their masses are ∼10^4–10^7 M⊙, which are smaller than those of the Galactic globular clusters but larger than those of the Galactic open clusters by an order of magnitude (Kumai et al. 1993; Hunter et al. 2003). It is notable that more than a hundred of the populous clusters are significantly younger, i.e., a few to 100 Myr, than the Galactic globular clusters and some are still forming at present, such as R136 in 30 Dor nebula (e.g., Massey & Hunter 1998). This suggests that the formation process of globular-like rich clusters can be studied through the observations of the young clusters and ISM properties in the LMC. To date, optical indicators of the massive star formation or cluster formation, such as H\textsc{ii} regions and stellar clusters, have been studied in the large area of the LMC (e.g., Henize 1956; Davies et al. 1976, hereafter DEM; Kennicutt & Hodge 1986, hereafter KH; Bica et al. 1996). DEM identified 357 H\textsc{ii} emission nebulae, and KH measured the Hα flux of 240 H\textsc{ii} regions. Regarding the stellar clusters, Bica et al. (1996) cataloged 624 clusters, and classified them into eight types according to their colors.

The first complete map of the molecular gas in the LMC was obtained by Cohen et al. (1988) in 12CO (1−0) with the southern CfA 1.2 m telescope at CTIO. However, the survey was limited by the low spatial resolution, 8′8 corresponding to 130 pc at the distance of the LMC. High-resolution CO observations of selected regions, especially toward well known active star-forming regions (e.g., 30 Dor, N11, N159) by the SEST 15 m telescope have been performed in the LMC (e.g., Israel et al. 1986; Johansson et al. 1994; Caldwell & Kwitter 1996; Kwitter et al. 1997; Johansson et al. 1998; Israel et al. 2003b). These observations revealed detailed structure and properties of the molecular gas of the individual star-forming regions at a linear resolution of less than 10 pc, although they are limited in spatial coverage, about 1 deg^2.

Recently, Fukui et al. (2008, hereafter “Paper I”) made a second survey of the molecular gas in the LMC by a 4 m telescope, NANTEN, at Las Campanas Observatory, Chile. This
survey was carried out in $^{12}$CO (1–0) with resolution of 2 arcmin grid spacing with the half-power beam width of 2.6 and covered $\sim$30 deg$^2$ (Fukui et al. 2008). The resolution of the survey was high enough to resolve giant molecular clouds (GMCs) and enabled us to cover a large region efficiently. The molecular clouds with a completeness limit of $5 \times 10^4 M_\odot$ in mass are identified in nearly the entire region where the current massive star and cluster formation is on-going, and 272 molecular clouds are cataloged.

In this paper, we present the results from comparisons of the GMCs identified by NANTEN (Paper I) with classical H$\alpha$ regions and optically identified stellar clusters and discuss cloud formation. Recent surveys of the Magellanic Clouds by the IR satellites, like Spitzer (e.g., Mexiner et al. 2006, “Surveying the Agents of a Galaxy’s Evolution”) and AKARI (e.g., Ita et al. 2008; Murakami et al. 2007) have been strong tools to identify younger, and lower mass YSOs (Whitney et al. 2008). Comparisons of these YSOs and the GMCs are found elsewhere (Indebetouw et al. 2008; T. Onishi et al. 2009, in preparation).

2. MOLECULAR CLOUDS, H$\alpha$ REGIONS, AND YOUNG CLUSTERS

2.1. Molecular Clouds Identified by the Second NANTEN Survey

A survey of the molecular clouds was carried out in $^{12}$CO ($J = 1–0$) by NANTEN, a 4 m radio telescope of Nagoya University at Las Campanas Observatory, Chile (Paper I). The observed region is about 30 deg$^2$ and covers the region where the CO emission was detected by the NANTEN first survey (e.g., Fukui et al. 1999; Mizuno et al. 2001). The observed grid spacing was 2′, corresponding to $\sim$30 pc at a distance of the LMC, 50 kpc, with a 2′ half-power beam width at 115 GHz. The spectral intensities were calibrated by employing the standard room-temperature chopper wheel technique (Kutner & Ulrich 1981). An absolute intensity calibration was made by observing Orion-KL (R.A. (B1950) = 5°32′47″, decl. (B1950) = $-5°24′21″$) by assuming its absolute temperature, $T_K$, to be 65 K. The rms noise fluctuations were about 0.07 K at a velocity resolution of 0.65 km s$^{-1}$ with about 3 minutes’ integration for an on-position. The typical 3σ noise level of the velocity-integrated intensity was about 1.2 K km s$^{-1}$ (Figure 1).

Fukui et al. (2008) identified 272 molecular clouds of which 230 are detected at more than two observing positions (hereafter “GMCs,” in this paper) by using cloud identifying algorithm, cprops (Rosolowsky & Leroy 2006). The radius and virial mass of the clouds range from 10 to 220 pc, and $9 \times 10^3$ to $7 \times 10^6 M_\odot$, respectively. The CO luminosity and virial mass of the GMCs show a good correlation, and a conversion factor, $X_{CO}$, from a CO intensity to an H$_2$ column density was derived to be $(7 \pm 2) \times 10^{20}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$ by assuming virial equilibrium. The sensitivity in $N$(H$_2$), then, corresponds to $N$(H$_2$) = $8 \times 10^{20}$ cm$^{-2}$ and the range of mass of the GMCs is $2 \times 10^3 M_\odot$ to $7 \times 10^6 M_\odot$, respectively. The details of the observations and the method to identify the GMCs are found in Paper I and Rosolowsky & Leroy (2006).

2.2. Young Astronomical Objects Associated with the Molecular Clouds

In order to identify the current massive star and cluster forming molecular clouds, H$\alpha$ regions and young stellar clusters were searched for in the published catalogs. The association of these objects and the molecular clouds were determined.

Henize (1956) and Davies et al. (1976) cataloged more than 300 H$\alpha$ emission nebulae in the LMC. The estimated diameters of the H$\alpha$ regions range from $\sim$10 pc to $\sim$400 pc. In addition, an extensive H$\alpha$ photometry of the 240 H$\alpha$ regions was carried out by Kennicutt & Hodge (1986). Figure 2 shows luminosity distribution of these H$\alpha$ regions, indicating that the current sample of H$\alpha$ regions includes those with H$\alpha$ luminosities as faint as $\sim 10^{36}$ erg s$^{-1}$ at the faint end. This shows that the sensitivity of the survey is high enough to detect the Orion nebula, $\sim 4 \times 10^{36}$ erg s$^{-1}$, (Gebel 1968) at the distance of the...
3. MOLECULAR CLOUDS IN THE LMC BY NANTEN. II

3. MOLECULAR CLOUDS AND ASSOCIATION WITH H II REGIONS AND YOUNG CLUSTERS

3.1. Overall Distribution of the Molecular Clouds, H II Regions, and Clusters

Figures 1, 3(a), and (b) show the distribution of the H\(\alpha\) emission (Kim et al. 1999), young clusters (younger than 10 Myr), and clusters older than 10 Myr together with the molecular clouds, respectively.
indicate molecular gas dissipation after formation of massive H\textsc{ii} regions. It is also noted that there are several GMCs not associated with H\textalpha\ emission (see also Section 4.1).

Figure 3(a) shows that young clusters are often found at, or near the peak of the GMCs. Some of the young clusters associated with GMCs are forming groups with a few to ten clusters. These active cluster forming regions, such as N 159, N 11, and N 44, are found especially toward bright H\textsc{ii} regions. Note that a number of clusters in the northeastern region in the LMC and some in the west of 30 Dor are isolated from molecular clouds. These groups of clusters are located inside large cavities of H\textalpha\ emission (see also Figure 1), two of the supergiant shells, LMC 4 and LMC 3, respectively (Meaburn 1980).

Compared with the youngest group of clusters, the older clusters have less degree of association with the GMCs (Figure 3(b)). The second youngest group of clusters, SWB I, is presented in blue crosses in Figure 3(b), showing that the correlation with the molecular clouds is low. Nevertheless there are several regions where the number of SWB I clusters is enhanced, for example, inside a supergiant shell, LMC 4, and the south of 30 Dor. It is interesting to note that the SWB 0 clusters are also gathered in these regions, suggesting that the distribution of SWB 0 and I clusters still retain the information of their formation sites. On the other hand, the older clusters, SWB II–VII, are distributed more uniformly over the galaxy showing no trend of association with the GMCs. It is to be noted here that the older clusters are distributed more widely over the galaxy compared with the region where the current star formation is observed (Bica et al. 1996).

The overall distribution of H\textsc{ii} regions, young clusters, and older clusters indicates that the GMCs are the sites of current massive star formation and of cluster formation. To show the associated object more clearly, we present close-up views of the GMCs and the young objects in Figures 4 and 5(a)–(f) (Figure 4 as a guide). These panels confirm that the H\textsc{ii} regions and young clusters are often associated with molecular clouds well, while the older clusters are distributed randomly.

In the following, we report some individual active star-forming regions in detail. In the N 11 (DEM 41) region, the young clusters are found in a bright, large complex of H\textsc{ii} regions, while they are not exactly found toward the GMCs (Figure 5(a)). Only small clouds are found at the outer edge of N 11 nebulae with young clusters near the edge of the molecular clouds. The cluster at the center of N 11, LH 9, is neither associated with H\textalpha\ emission peaks nor molecular clouds. This suggests that the parent cloud of LH 9 has been dissipated, and that triggered star formation occurred at the outer region as discussed by, for example, Israel et al. (2003a). A group of H\textsc{ii} regions are found near the western edge of the bar in the N 79/N 83 region (Figure 5(b)). In contrast with the N 11 region, young clusters associated with the GMCs and bright H\textalpha\ emission are found near the peak of the GMCs in this region, and the young clusters without a bright H\textsc{ii} region are at the center of diffuse shell-like H\textalpha\ emission. In Figure 5(b), there are a few GMCs
hosting no H II regions, one of which is at the western end of the N79/N 83 region.

Small groups of young clusters are found near the peak of a massive GMC in N 44 (DEM158, 160, 166, 167, 169) as well as small GMCs along the supergiant shell LMC 4 (Figure 5(c)). On the other hand, only one or two clusters are associated with a GMC near the LMC bar (Figure 5(d)). One may speculate that clusters are formed in groups in the massive GMCs of $M \sim 10^6 M_\odot$ near a supergiant shell. It is also noted that a bright H II region, the N 51 complex, is associated with a very small molecular cloud, maybe a remnant of the parent cloud of this bright H II region.

Figure 5(f) shows the 30 Dor (DEM 263) region to the molecular ridge including active star-forming site, N 159 (DEM 271, 272), and the Arc region. The most remarkable feature in Hα emission is a bright complex of H II regions in 30 Dor, while massive molecular clouds are found not exactly toward 30 Dor but extending to the south as already noted by several authors (e.g., Cohen et al. 1988; Indebetouw et al. 2008; Paper I). Most of the youngest clusters of $\tau < 10$ Myr are associated with the GMCs or found near the GMCs. On the other hand, the clusters of $10 < \tau < 30$ Myr are away from the GMCs and mostly found between 30 Dor and N 159 where the bright Hα emission from 30 Dor is extended but only small molecular clouds are detected. The most active current star formation site in this figure is a well known region, N 159, where young clusters as well as a number of H II regions are found at or near the peaks of the molecular ridge. The detailed studies of star formation activities and molecular clouds are carried out by several authors (e.g., Johansson et al. 1998; Minamidani et al. 2008; Indebetouw et al. 2008; Mizuno et al. 2009). In the south of N159, only smaller H II regions are associated with the molecular ridge. These results indicate that the southern region may be younger than the north.

There are several other regions with active star formation in Figure 5(f), N 148, N 180, N 206, and N 214, where groups of H II regions, some of which contain a young cluster, are associated with GMCs. It is interesting to note that these groups of H II regions are mostly found off from the peak of the GMCs. It should be noted that the NANTEN beam is not capable of resolving the individual local peaks of the GMC and the parent core of the group of H II regions may have escaped from detection. Nevertheless, the positional offset of the peak of the GMC and the group of H II regions indicate the dissipation of the molecular gas by active star formation. It is also to be noted that there are several GMCs, especially at southern edge of this figure without significant Hα emission or clusters.

Figure 6 shows the distribution of the projected separations of H II regions and stellar clusters from the nearest CO emission with an integrated intensity above 1.2 K km s$^{-1}$ (3σ noise level). The lines in Figure 6 represent the frequency distribution expected if the same number of the H II regions or clusters are distributed at random in the observed area. It is clearly shown by eye that the distribution of the youngest clusters with an age smaller than 10 Myr, i.e., SWB 0 (Bica et al. 1996), and the H II regions are sharply peaked within 100 pc of CO emission exhibiting strong spatial correlations. On the other hand, the older clusters, SWB I ($\tau > 10$ Myr) or older, show much weaker or no correlation. This figure again indicates that the H II regions and SWB 0 clusters are well associated with molecular clouds as well as that rapid cloud dissipation after cluster formation.
Hereafter, we will focus on the H\textsc{ii} regions and SWB 0 clusters in the discussion and call SWB 0 cluster as “young cluster” unless otherwise stated.

3.2. Determination of Association of Individual Molecular Clouds With H\textsc{ii} Regions and Young Clusters

3.2.1. Determination of association of the H\textsc{ii} regions and young clusters

We have determined the association of individual H\textsc{ii} regions and young clusters with the molecular clouds by the following criteria: (1) for clusters, if the extent of a cluster is overlapped with the boundary of a molecular cloud; and (2) for the H\textsc{ii} regions, if the H\textsc{a}-emitting region is overlapped with the boundary of a molecular cloud.

In total, 97 out of 137 young clusters are found to be associated with the molecular clouds. In addition, those clusters are all associated with H\textsc{ii} regions. These confirm that the clusters associated with the molecular clouds are young and contain massive stars. For reference, we have also determined the association of the SWB I clusters and the molecular clouds. As a result suggests that the molecular clouds start to be dissipated while the clusters are still in the SWB 0 phase. This scenario is consistent with the result from Fukui et al. (1999) and Yamaguchi et al. (2001b).

3.2.2. Determination of Association of Radio Continuum Sources toward the Molecular Clouds without Optically Identified H\textsc{ii} regions

As presented in the previous sections, there are a number of molecular clouds without H\textsc{ii} regions or young clusters. Clusters and H\textsc{ii} regions may be hidden behind the molecular clouds by chance. For the H\textsc{ii} regions, we have also compared the distribution of the molecular clouds and the point sources from the ATCA+Parkes combined continuum emission (Filipovic et al. 1995; Dickel et al. 2005; Hughes et al. 2007) to search for such hidden H\textsc{ii} regions. If an H\textsc{ii} region is behind a GMC, the H\textsc{ii} region cannot be seen optically due to extinction, but should be observed as a radio source.

A mosaic image of the 1.4 GHz continuum emission observed with the Parkes Telescope (Filipovic et al. 1995) and the ATCA are combined to present the thermal and nonthermal radio emission of the LMC covering 10'8 × 12'3 (e.g., Filipovic & Staveley-Smith 1998; Hughes et al. 2007). A catalog of
respectively. These results show that ATCA J054308 at the edge of the GMC 224 and coincides with a radio source, seen at 4.8 GHz and 8.6 GHz, indicating that most of the − only one 1.4 GHz source, ATCA J054308 image near 30 Dor made it difficult to determine the emission of the 72 molecular clouds; ring-like artifacts seen in the 1.4 GHz seventy 1.4 GHz both point-like and extended sources toward any point sources at 1.4 GHz, we searched for corresponding sources identified from this image will be presented elsewhere (M. D. Filipovic et al. 2009, in preparation). In this work, first, 1.4 GHz continuum emission was examined carefully toward the molecular clouds without optical H II region. Then if we see any point sources at 1.4 GHz, we searched for corresponding 4.8 and 8.6 GHz sources (Dickel et al. 2005). We found about seventy 1.4 GHz both point-like and extended sources toward the 72 molecular clouds; ring-like artifacts seen in the 1.4 GHz image near 30 Dor made it difficult to determine the emission toward four molecular clouds. Among these 1.4 GHz sources, only one 1.4 GHz source, ATCA J054308−710409, was also seen at 4.8 GHz and 8.6 GHz, indicating that most of the 1.4 GHz sources in these molecular clouds are background sources or supernova remnants (SNRs).

The 1.4 GHz source, ATCA J054308−710409, is found just at the edge of the GMC 224 and coincides with a radio source, LMC B0543−7105, identified at 4.75, 4.85, and 8.85 GHz by Filipovic et al. (1995). Because it lies at the edge of the GMC, the absence of Hα emission toward the source is not perhaps due to the extinction by the molecular cloud. We estimated a spectral index of this source, α, defined as \( S_{\nu} \sim \nu^{\alpha} \), where \( S_{\nu} \) is the integrated flux density at frequency, \( \nu \), to be \( \alpha \sim -0.4 \). Filipovic et al. (1998) studied the spectral index of radio sources detected with the Parkes telescope and found that the known H II regions have rather flat spectra with a spectral index of \( \alpha = -0.15 \pm 0.31 \), and the SNRs and background sources have steeper spectra, \( \alpha = -0.43 \pm 0.19 \) and \( \alpha = -0.59 \pm 0.48 \), respectively. These results show that ATCA J054308−710409 is also unlikely to be a hidden H II region and is more likely to be an SNR.

This comparison of the ATCA 1.4 GHz and the molecular clouds indicates that hidden H II regions of this size are unlikely to exist. Since all the young clusters found in the molecular clouds are associated with the H II regions, these results suggest that the hidden clusters are also unlikely to exist.

### 3.3. Molecular Cloud Types

It was shown in Fukui et al. (1999) that the GMCs can be classified into three groups based on a sample of 55 GMCs with a mass ranging from \( 2 \times 10^{5}M_{\odot} \) to \( 3 \times 10^{6}M_{\odot} \): (1) starless GMCs; (2) those with small H II regions whose Hα luminosity is less than \( 10^{37} \) erg s\(^{-1} \); and (3) those with stellar clusters and large H II regions of Hα luminosity greater than \( 10^{37} \) erg s\(^{-1} \).

The current comparison of the molecular clouds with the clusters and H II regions gives a consistent result. Here we classify the molecular clouds into three types: Type I, Type II, and Type III.

It should be noted that ”starless” here means without star-forming activities with stars more massive than early O star capable of ionizing H II regions, and it does not exclude the possibility of associated young low-mass stars. Comparisons of the GMCs with young, low or intermediate mass stars are now possible by using recent results by the IR satellites, like Spitzer (e.g., Mexiner et al. 2006, “Surveying the Agents of a Galaxy’s Evolution”) and AKARI (e.g., Ita et al. 2008; Murakami et al. 2007). Comparisons of these YSOs (Whitney et al. 2008) and the GMCs are found elsewhere (Indebetouw et al. 2008; T. Onishi et al. 2009, in preparation).

Table 2 lists the associated H II regions and young clusters for each molecular cloud. Out of 272 molecular clouds, 72, 142, and 58 are found to be Type I, II, and III, respectively (see also Table 3). Figures 7–9 present the examples of the molecular clouds of each type. Examples are chosen from the most massive clouds from each type. It is interesting to note that the most massive Type I molecular clouds have similar size and mass to those of Type II, while the number of massive Type I is less. To study the physical properties of the molecular clouds, one has to keep in mind that the completeness limit of the NANTEN survey of \( M_{\text{CO}} = 5 \times 10^{4}M_{\odot} \). Table 3 also summarizes a number of GMCs with \( M_{\text{CO}} \geq 5 \times 10^{4}M_{\odot} \) for each type. Out of 191 GMCs, 46, 96, and 49 GMCs are found to be Type I, II, III, showing that about a half of them are Type II, and a quarter is Type I and Type III, respectively.

### 3.4. Distribution of the Molecular Clouds

Figures 10(a)–(f) show the radial distribution of CO emission; the number and the surface density, Σ, of the molecular clouds with Types I, II, and III, respectively. The surface density, Σ, is derived by integrating the CO luminosity within annuli spaced by 4′ and then divided by an area of the annuli. The center used is \( \alpha(J2000)=5^{h}17^{m}6^{s}, \delta(J2000)=-69^{\circ}2^{\prime} \) determined from the kinematics of the H I observations by Kim et al. (1998). To see the angular distribution of the CO emission, the distribution of the clouds and the surface density, Σ, for each molecular cloud type are also presented in Figures 11(a)–(f). Here, the
Figure 5. (Continued)

| Distance (pc) | (a) HII regions | (b) SWB 0 | (c) SWB I | (d) SWB II - VII |
|--------------|----------------|----------|-----------|-----------------|
| 0            | 10             | 15       | 20        | 20              |
| 10           | 15             | 15       | 15        | 10              |
| 20           | 10             | 10       | 10        | 10              |
| 30           | 5              | 5        | 5         | 5               |
| 40           | 2              | 2        | 2         | 2               |
| 50           | 1              | 1        | 1         | 1               |
| 60           | 1              | 1        | 1         | 1               |
| 70           | 1              | 1        | 1         | 1               |
| 80           | 1              | 1        | 1         | 1               |
| 90           | 1              | 1        | 1         | 1               |
| 100          | 1              | 1        | 1         | 1               |

Figure 6. Frequency distribution of the projected distances of (a) the H II regions, (b) SWB 0 clusters ($\tau \lesssim 10$ Myr), (b) SWB I clusters (10 Myr $\lesssim \tau \lesssim 30$ Myr) and SWB type II to VII clusters (30 Myr $\lesssim \tau$, Bica et al. 1996) from the nearest molecular cloud (Paper I), respectively. Lines show the frequency distribution of the distance when the H II regions and clusters are distributed randomly.

Figure 10 shows that the radial profile of the surface density decreases moderately along the galactocentric distance for Type II as is also seen in the nearby spiral galaxies (e.g., Wong & Blitz 2002), while those for Types II and III are rather flat with respect to the radial distance. It is interesting to note that the number distribution and surface density show different radial profiles for Type I; the number increases at large radial distances but the surface density is relatively constant. This indicates that the more massive Type I GMCs are found at the large radial distances. It is also notable that there is a sharp enhancement of the number of the clouds around 1.5 kpc for Types II and III. This enhancement is due to the molecular ridge, N11, and N44. This enhancement is also seen in the angular distribution, especially at about 120° due to the molecular ridge.
4. DISCUSSION

4.1. GMC Type I: GMCs Without Massive Star Formation

Almost all the GMCs in the solar vicinity are forming massive stars actively as indicated by associated H\(\text{ii}\) regions and/or OB associations in addition to a number of young low-mass stars (Dame et al. 1987; Blitz 1993 and references therein). There are only two GMCs which show no signs of massive star formation in the solar neighborhood among \(\sim 20\) GMCs; the Maddalena’s cloud (Maddalena & Thaddeus 1985) and ON-1 cloud complex (Israel & Wootten 1983). The reason for not forming massive stars may be either it is at a very young stage prior to massive star formation (Maddalena & Thaddeus 1985; Israel & Wootten 1983) or that it is in a late stage after active star formation (Lee et al. 1994).
Figure 7. Examples of GMCs without massive star formation (GMC Type I). The eight most massive GMCs are shown in contours superposed on the DSS2 images. The contours are from 1.2 K km s\(^{-1}\) with 1.2 K km s\(^{-1}\) intervals. The crosses indicate the position of the GMCs as in Table 1 of Paper I.
Figure 8. Examples of the molecular clouds associated with H ii regions but not with young clusters (GMC Type II). The six most massive GMCs are shown in contours superposed on the DSS2 images. The contours are from 1.2 K km s$^{-1}$ with 1.2 K km s$^{-1}$ intervals except for (a) GMC 216; the contours are from 1.2 K km s$^{-1}$ with 2.4 K km s$^{-1}$ intervals for (a). The crosses indicate the positions of the GMCs as in Table 1 of Paper I.

A large number of starless GMCs in the LMC suggests that the timescale in star formation is significantly longer in the LMC than in the Galaxy. The ionization degree in a molecular cloud is likely determined by the far-ultraviolet (FUV) photons of stellar radiation fields (McKee 1989; Nozawa et al. 1991). In the LMC, the FUV flux is several times higher (Israel et al. 1986) and the dust extinction is smaller by a factor of 3–4 for a given gaseous column density (Koornneef 1982). Since the timescale of the diffusion of magnetic field is proportional to the ionization degree (Spitzer 1978), the contraction of cloud may be slowed down by the magnetic field. In addition, the cooling rate via molecular and dust emission is expected to be
Figure 9. Examples of the molecular clouds associated with H\textsc{ii} regions and young clusters (GMC Type III) in (a) the N 11 region, (b) the N 44 and N 51 regions, (c) the N 206 region observed, and (d) the 30 Dor and N 159 regions. Left panels: distribution of the molecular clouds by NANTEN (Paper I) is superposed on the H\textsc{α} image (Kim et al. 1999). Right panels: distribution of the NANTEN molecular clouds (Paper I, contours), H\textsc{ii} regions (yellow circles by Henize 1956 and red circles by Davies et al. 1976), and youngest clusters identified as SWB type 0 (Bica et al. 1996, crosses), respectively. The contours shown are from 1.2 K km s$^{-1}$ with 1.2 K km s$^{-1}$ intervals.

(A color version of this figure is available in the online journal.)
smaller in the LMC than in the Galaxy, helping star formation activity to slow down. Higher ionization degree and smaller cooling rate are basically the consequences of lower metallicity in the LMC (Dufour 1984) and are both likely to support for the retarded star formation.

An alternative idea to explain starless GMCs is that the GMCs in the LMC are of very recent formation, a situation possibly similar to the Maddalena’s clouds and ON-1 cloud complex. It is well known that the LMC has a number of supershells expanding to accumulate the interstellar matter (Meaburn 1980; Oey 1996; Kim et al. 1999). Yamaguchi et al. (2001a) investigated the possible correlation between GMCs and supergiant shells and concluded that one third of GMCs may be located toward the shell boundaries, suggesting that a significant number of GMCs may have been formed under the triggering by expanding shells. The spatial distribution of the starless GMCs is however fairly random, showing little correlation with supergiant shells. It seems therefore the retarded star formation in the LMC is not due to some local environment or dynamical activities.

Finally, we shall comment on a possible link between Type I GMCs and the formation of populous stellar clusters. It is tempting to speculate that there is a link between populous clusters and the Type I GMCs. A possible explanation is that a longer timescale of star formation allows the formation of protocluster molecular condensations as massive as $10^5 M_\odot$, which can lead to form populous clusters. This will never happen in the Galaxy because of the star formation immediately after formation of protocluster condensations having mass of $10^5 M_\odot$.

4.2. Evolution of the GMCs

The molecular clouds are considered to be formed in neutral gas, and as they evolve, they form stars and clusters, being dissipated by stellar winds or UV radiation from the massive stars or supernova explosions. At the end of their life, the newly formed stars and clusters remain. The process is, however, still unclear quantitatively, because we need a complete data set of molecular clouds to estimate the evolutionary timescale statistically. In our Galaxy, it is difficult to obtain such a complete sample due to the heavy contamination toward the Galactic plane. On the other hand, a face-on galaxy like the LMC is suitable for collecting a complete sample, which enables us to investigate the evolutionary process more quantitatively. By using the complete data set of the GMCs for a whole galaxy, we shall estimate their evolutionary timescale. In this section, only the GMCs with mass $M_{\text{CO}} > 5 \times 10^4 M_\odot$ are considered.

The evolutionary sequence of the GMCs is schematically drawn in Figure 13 together with examples of the GMCs corresponding to each stage. In the first stage, the GMC Type I, the GMCs show no sign of massive star formation. The second stage, the GMC Type II, is the GMCs associated only with H ii regions. They are forming massive stars, but clusters have not appeared yet. The third, the GMC Type III, is the GMCs associated with both H ii regions and clusters. They are actively forming clusters. Molecular gas around newly formed clusters is partly dissipated, but the GMCs are still massive as is seen in Figure 12. The last is when the GMCs have been completely dissipated and only the young clusters and/or SNRs are found.
Figure 10. (a), (c), and (e): Frequency distribution of the cloud distances from the center $\alpha_{J2000}=5^h 17^m 6, \delta_{J2000}=-69^\circ 2^\prime$ determined from the kinematics of the H\textsc{i} (Kim et al. 1998). (b), (d), and (f): Distribution of the surface mass density along the distances from the center $\alpha_{J2000}=5^h 17^m 6, \delta_{J2000}=-69^\circ 2^\prime$. (a) and (b), (c) and (d), and (e) and (f) present those of the GMC Type I, Type II, and Type III, respectively. Dashed lines (red in electric version) present those of the GMCs without small clouds. The region within 1.7 kpc from the center (dotted lines) is completely covered (Paper I).

If we assume that the GMCs and clusters in the LMC are being formed nearly steadily, we can estimate each evolutionary timescale according to the above classification. First, we shall estimate the timescale of the cloud dissipation. We found that $\sim 66\%$ of the youngest clusters of $\tau < 10$ Myr are associated with the GMCs (see Section 3.2). If we assume that the clusters in the LMC are being formed nearly steadily in the past 10 Myr, this result means the GMCs can survive during $\sim 66\%$ of the cluster age, 10 Myr, and are dissipated in a few Myr after formation of clusters due to the UV photons from the clusters. The timescale for the GMC Type III is thus considered to be $\sim 7$ Myr. If we further assume that the massive star formation and cluster formation occur nearly steadily, the timescale for each stage is proportional to the number of the GMCs. Accordingly, the timescales for the GMC Type I and II are estimated to be 6 Myr and 13 Myr, respectively. As a result, the typical lifetime of the GMCs, corresponding to the total lifetime of the GMC from Type I to III, is roughly $\sim 30$ Myr.

Fukui et al. (1999) and Yamaguchi et al. (2001b) made a comparison of 55 GMCs with mass above $2 \times 10^5 M_\odot$ from the NANTEN first survey with the young objects. Their result shows that 6 GMCs show no sign of massive star formation, 9 are associated with H\textsc{ii} regions, and 28 with young clusters, indicating that the population of Type III GMCs is the highest.
Figure 11. (a), (c), and (e): frequency distribution of the position angle of the clouds with respect to the center $\alpha (J2000) = 5^h 17^m 6, \delta (J2000) = -69^\circ 2'$. (b), (d), and (f): distribution of the surface mass density along the position angle of the clouds with respect to the center $\alpha (J2000) = 5^h 17^m 6, \delta (J2000) = -69^\circ 2'$. (a) and (b), (c) and (d), and (e) and (f) present those of the GMC Type I, II, and III, respectively. Dashed lines (red in electric version) present those of the GMCs without small clouds. The region within 1.7 kpc from the center (dotted lines) is completely covered (Paper I). (A color version of this figure is available in the online journal.)

50%, and Type II and I are 21% and 14%, respectively. The higher sensitivity of the second survey made us possible to obtain a sample of the GMCs with mass as small as $5 \times 10^4 M_\odot$. This provides us with a complete sample of the GMCs, which are massive enough to produce massive stars. The numbers of Type I and Type II GMCs are increased in the current work compare to the first survey more than that of the Type III, because the mass of the Type I and Type II are smaller than the mass of the Type III, and thus, the higher sensitivity of the survey increased the number of Type I and Type II more. As a consequence of it, the estimated timescale of the a GMC now becomes longer from the previous result.

We summarize the evolutionary timescale of the GMCs in Table 3. The GMCs form massive stars, and H II regions appear after $\sim 6$ Myr from their birth. After 13 Myr, clusters start to be formed, then also start dissipating the surrounding molecular gas. The GMCs continue to form clusters actively, being dissipated by the UV photons and stellar winds from the clusters. After $\sim 7$ Myr, the GMCs have been almost dissipated by the newly formed clusters, and eventually, by supernova explosions. The above time estimation should include an error. The age determination for the clusters contains uncertainty, but this changes only the absolute timescale for each stage. Other errors are possible due to a simple assumption of the
constant formation rate for the clusters and the GMCs. Our estimation, nevertheless, shows a typical evolutionary sequence of the GMCs. Further quantitative detailed studies, such as a comparison with Hα flux, determining the age and mass of the clusters, and observations at higher resolution, will lead us to better understandings of star formation processes and the cloud dissipation in the LMC. Furthermore, detailed comparisons of the molecular clouds with H I give us a clue to understand the molecular clouds formation. These studies are found in elsewhere (e.g., Wong et al. 2009; Fukui et al. 2009).

5. SUMMARY

We summarize our results obtained by comparing the molecular clouds from the second NANTEN survey (Paper I) with the young stellar clusters and H II regions.

1. We made a positional comparison of the molecular clouds with classical H II regions and clusters. It is indicated that the youngest group of the clusters, SWB 0 type, with an age of \( \tau < 10 \) Myr and H II regions show a significant correlation with the GMCs, while the clusters older than 10 Myr show little or no correlation.

2. The molecular clouds are classified into three types; Type I shows no signature of star formation, Type II is associated with relatively small H II region(s), and Type III with both H II region(s) and young stellar cluster(s). Out of 272 molecular clouds, 72, 142, and 58 are found to be Types I, II, and III, respectively. The radio continuum sources were used to confirm that Type I molecular clouds do not host optically hidden H II regions.

3. It is found that there is no significant difference in the distribution of the line widths and sizes of the GMCs among the three types for those with a mass above the completeness limit, \( 5 \times 10^4 \) M\(_\odot\), while the mass distribution of the Type III GMCs is different from those of Type I and II. The mass distribution of Type I and II shows a peak at \( M_{\text{CO}} \sim 10^5 \) M\(_\odot\), while that of the Type III is rather flat.

4. We interpret that these Types represent the evolutionary sequence; i.e., the youngest phase is Type I followed by Type II and the last phase is Type III where most active star formation takes place leading to cloud dispersal. The number of the three types of GMCs should be proportional to the timescale of each evolutionary stage if a steady state is a good approximation. By adopting the timescale of the
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Figure 13. Evolutionary sequence of the molecular clouds. The left panels are examples of GMC Type I (GMC 215, LMC N J0544-7127 in Table 1), Type II (GMC 135, LMC N J0525-6609), and Type III (the northern part of GMC J0540-7008) from the top panel, respectively. Each panel presents Hα images from Kim et al. (1999) with GMCs identified by NANTEN (Paper I) in contours: The contour levels are from 1.2 K km s$^{-1}$ with 1.2 K km s$^{-1}$ intervals. Open circles indicate the position of young clusters (Bica et al. 1996). The middle panels are illustration for each evolutionary stage. Open circles and filled circles in red represent young clusters and HII regions, respectively. (A color version of this figure is available in the online journal.)

youngest stellar clusters, 10 Myr, we roughly estimate the timescales of Types I, II, and III to be 6 Myr, 13 Myr, and 7 Myr, respectively, for those with a mass above the completeness limit, $5 \times 10^4 M_\odot$. This corresponds to a lifetime of the GMC of 20–30 Myr.