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A Revised CO View of the Large Magellanic Cloud with NANTEN: New Deep Observations

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Abstract. I will present a revised CO view of the Large Magellanic Cloud based on the new NANTEN survey, which is ~ 2–3 times more sensitive than the first one.

1. Introduction

The Magellanic Clouds provide an ideal laboratory to study cluster formation thanks to its unrivaled closeness to the solar system. The distance to the Clouds, 50–60 kpc, is far smaller than that of M31 or any other galaxies. In the Clouds we should be able to make a comprehensive study of a whole galaxy at all wavelengths, covering stellar clusters of a variety of ages and giant molecular clouds where clusters are formed.

Regarding cluster formation, the Clouds are particularly important because it includes very young and massive stellar clusters. These are so called populous clusters that resemble globular clusters in their tightly packed spherical morphology. Apparently, populous clusters are gravitationally bound, containing some ten thousands of stars in a cluster, an order of magnitude smaller than a typical globular cluster of the Galaxy (e.g., Hodge 1961). A study by Kumai, Basu and Fujimoto (1993) has shown that the Galaxy and the Large Magellanic Cloud (LMC) exhibit a clear trend of decrease with age in the number of member stars of a cluster over a time scale of 10 billion years. The Galaxy includes very old globular clusters only whose ages are more than 10 billion years. The study of the formation of populous clusters in the LMC may provide a precious clue for inferring the physical conditions in the primordial era of the Galaxy more than 10 billion yrs ago, unique in having been the epoch of the formation of globular clusters.

Theoretical studies (e.g., C. Clarke, in these proceedings) are in progress to model the physical situations where populous/globular clusters are formed. Demands for observational constraints on the formation of gravitationally bound rich clusters are rapidly increasing. The NANTEN survey which focuses on the Magellanic Clouds are producing a complete molecular data set at the highest spatial resolution attainable for a whole galaxy and may help us to make an essential step toward understanding globular cluster formation.

Formation of stars and clusters start from atomic gas that is observed in the 21 cm H I emission. The denser phase, mostly consisting of molecular hydrogen, is tightly connected to star formation and is observable in the rotational spectra

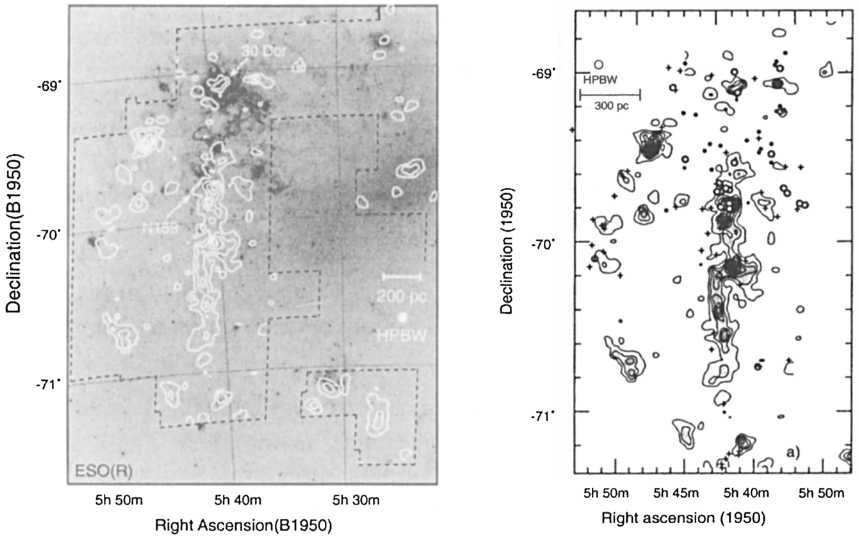

Figure 1. Close up view of the southeastern region of the LMC. The contours are integrated CO($J = 1$–0) image obtained by deep observations with NANTEN. *Left* : The CO clouds overlaid on the ESO(R) plate. The contour levels begins at and increase by step of 1.2 and 2.4 K km s^{-1}, respectively. *Right* : Distribution of CO clouds, H II regions, and stellar clusters. The lowest contours and the separation between contours are each 1.2 K km s^{-1}. The open and filled circles are the clusters of age $\tau < 10$ Myr and $10 < \tau < 30$ Myr, respectively (Bica et al. 1996). The crosses represent the positions of the H II regions (Davies, Elliot, & Meaburn 1976).

of carbon monoxide at 2.6 mm wavelength or shorter. The previous CO maps of the Clouds were either of lower resolution (with a $\sim$ 9 arcmin beam of the 1.2 m telescope, Cohen et al. 1988 and Rubio et al. 1991) or of limited spatial coverage of $\sim$ 1 square degree (with a $\sim$ 0.8 arcmin beam of the 15 m SEST (=Swedish-ESO Submillimetre Telescope) telescope, e.g., Booth et al. 1989). The NANTEN 4m radio telescope moved to Las Campanas in 1996 provides an angular resolution of 2.6 arcmin at the CO wavelength. This corresponds to 40 pc at a distance of the LMC, and is appropriate to resolve typical GMCs (=giant molecular clouds).

2. First NANTEN Results

The first results from NANTEN survey of the LMC has been published by Fukui et al. (1999) (Hereafter, Paper I; see also Mizuno et al. 2001). The survey revealed the first comprehensive view of the giant molecular clouds in a single galaxy at a 2 arcmin grid with a 2.6 arcmin beam. The whole optical galaxy of 36 square degrees (6° × 6°) has been covered with a sensitivity limit of 0.36 K in a 0.1 km s^{-1} resolution.

NANTEN is a 4m mm and sub-mm telescope located at Las Campanas in Chile, 2400 m above the sea level. A 4K cryogenically cooled superconducting mixer receiver provided a system temperature around 250 K in SSB toward the zenith including the atmosphere, one of the best among the existing telescopes.

In total 107 clouds are detected, whose total mass amounts to 4–7$\times10^7$ $M_\odot$. Their distribution is highly clumpy, while some characteristic large scale structures are found. One of such structures is the CO Arc located in the southeast edge of the optical galaxy.

A detailed analysis was made for 55 massive clouds for which fairly reliable physical parameters are derived; virial masses of the GMCs are $< 10^5$–$2\times10^6 M_\odot$ with sizes of 30–100 pc, and the spectral line widths of CO are 4–13 km s^{-1}.

3. New NANTEN Results: Deep Observations

The new survey was started in 1999 April and has covered $\sim$ 70% of the 36 square-degree field (2001 June). It is still ongoing to fully cover the LMC. The survey spends about 4–5 min per pointing, resulting in an improvement in noise fluctuations by a factor of 3 compared to the first one which spent about 40 sec to 1 min per pointing. The typical rms noise level is 0.16 K in a 0.1 km s^{-1} velocity resolution. The present coverage includes 30Dor, N159, the southern large CO complex, N11, N44, the bar, LMC4, and other regions.

The number of clouds detected has been almost doubled by the new survey for a spatial coverage of $\sim$ 70%. We estimate that the new survey is *complete* down to $8\times10^4 M_\odot$, a factor of $\sim$ 3 lower compared to the first one.

Figure 1 shows part of the new survey toward 30Dor and the CO Arc. This clearly illustrates that the new survey has detected weaker CO emission in the periphery of GMCs as well as smaller clouds not seen in the first survey. This improvement generally supports and reinforces the conclusions reached in Paper I, e.g., with respect to clumpiness of the molecular clouds.

Figure 2 compares the cloud mass spectra for the new and first surveys. The new data (upper) shows that the spectral index for 133 GMCs is well approximated by a power law index of -1.9 ± 0.1, somewhat steeper than that of the Galactic GMCs, -1.5 (Solomon et al. 1987). The mass estimate here is based on the correlation between the virial mass and CO luminous mass for GMCs whose mass is larger than $\sim 3 \times 10^5 M_\odot$. The relationship is then extrapolated down to smaller GMCs to produce the mass spectrum. I note here that the distance estimate in the Clouds is much less ambiguous than in the Galaxy and that the present spectral index may be more reliable than that in the Galaxy. It is perhaps premature to say whether the mass spectrum is significantly different between the LMC and the Galaxy. It is certainly worthwhile to reexamine the mass spectrum of the Galactic GMCs based on the improved dataset obtained with most recent CO surveys including that with NANTEN.

Figure 3 shows a plot of $L_{\rm CO}$ vs. $M_{\rm vir}$. The X factor defined as a ratio of the total molecular hydrogen column density $N(\rm H_2)$ to the total integrated intensity of CO emission $W(\rm CO)$, $X_{\rm LMC}$, is estimated to be $\sim 9\times10^{20}$ cm^{-2}/(K km s^{-1}) by using the data in Figure 3, about three times larger than the Galactic X factor. Even including the new data, this result does hold, suggesting that the X factor is actually different in the LMC from the Galaxy.

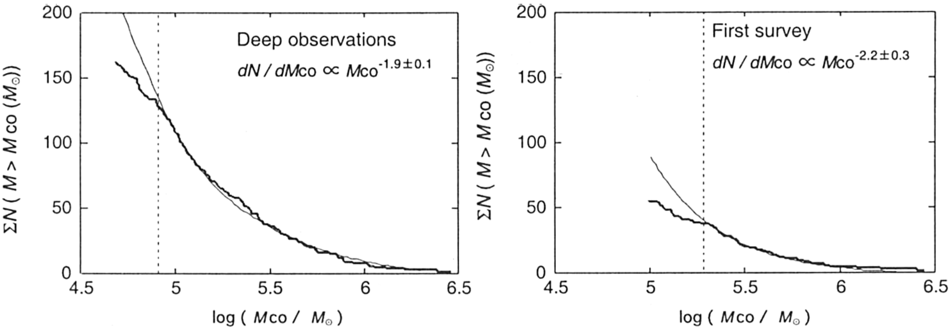

Figure 2. A comparison of cumulative mass spectra of the CO clouds. *Left* : Mass spectrum of the 162 clouds obtained in the deep observations. The slope was obtained by using 133 CO clouds greater than the completeness limits of $8 \times 10^4 M_\odot$ as indicated by the broken line. *Right* : Mass spectrum of the 55 CO clouds in the first survey (Paper I). The fits are newly performed for the 37 CO clouds greater than the completeness limits of $> 2 \times 10^5 M_\odot$.

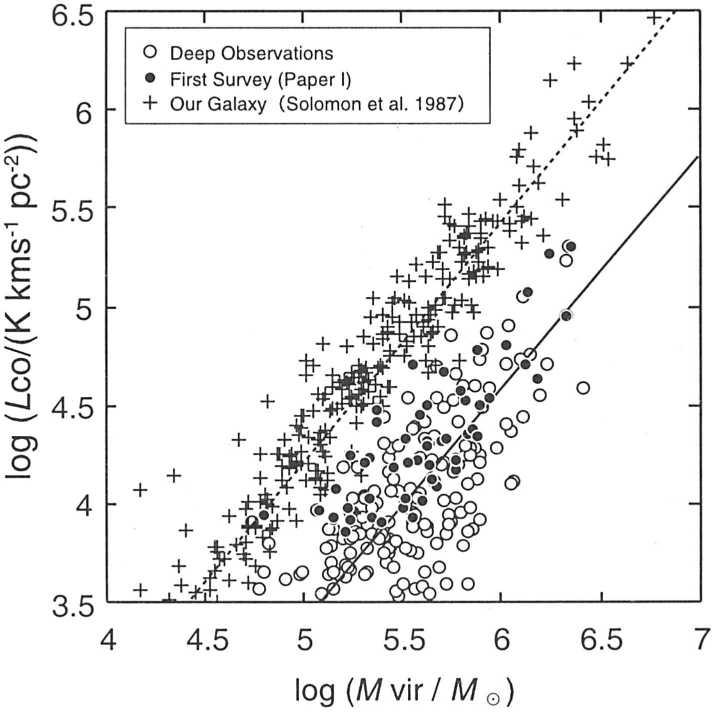

Figure 3. CO luminosity, L_{CO}, plotted against the virial mass, M_{vir}. The open and filled circles are the LMC CO clouds detected in the deep observations and first survey, respectively. The crosses indicate Galactic CO clouds (Solomon et al. 1987).

4. Clusters vs. Giant Molecular Clouds

We for the first time demonstrate in Paper I that the giant molecular clouds in the LMC are the sites of populous cluster formation by showing that about one third of the CO clouds at least are positionally well correlated with the youngest stellar clusters, SWB0. The age of SWB0 is photometrically estimated to be less than 10 Myr (Bica et al. 1996). Even older clusters, SWB1 or later, show little such correlation. This is interpreted as an indication of rapid dissipation of giant molecular clouds in the LMC. The fact that SNRs also show little correlation with GMCs is also consistent with this interpretation.

The mass range of the GMCs shown in Section 3 is similar to that of the Galactic GMCs. In addition, the mass spectrum may be even steeper in the LMC than in the Galaxy (See Fig.2). This leads us to abandon a simple idea that a rich cluster forms in an extraordinarily massive GMC. Instead, the process of mass condensation should be different in forming populous clusters from forming open clusters.

We note in Paper I that some of the GMCs in the LMC are not associated with any H II regions or young stellar clusters. This conclusion is not affected by the new data even after the weaker, more extended outer skirts of GMCs are detected. If they are not forming stars at all, the GMCs in the LMC may be considerably different from the Galactic GMCs, since all the Galactic GMCs are believed to be forming massive stars except for one: the Maddalena cloud, which is forming low-mass stars only with no H II regions (Maddalena & Thaddeus 1985).

This point perhaps needs further detailed quantitative analyses. We should test how inactive these GMCs are in star formation by taking into account the detection limits in various signs of star/cluster formation, like far infrared emission for embedded sources, for both the Galactic GMCs and those in the LMC. In this respect, some of the apparently starless GMCs like those in LMC4 (see the next section) and in the CO Arc should be of particular interest in our continuing future efforts.

5. Supergiant shells;LMC4 and others

Supergiant shells (SGSs), whose diameter is $\sim$ 1000 pc have been considered as formed by the combined action of stellar winds and supernovae due to the OB stars inside the shell (e.g., Tenerio-Tagle & Bodenheimer 1988). As they grow, they sweep up and accumulate interstellar matter by the pressure of the hot gas. Because of their large volume, they may play an important role in formation of molecular clouds and stellar clusters. In the LMC, Meaburn (1980) identified 9 SGSs with their diameter of $>$ 600 pc. They are characterized by nearly circular regions of filamentary Hα emission. It is intriguing to ask how these SGSs are related to cluster formation.

Among the above SGSs, LMC4 is of particular interest because it is the largest (see, e.g., the H I distribution in Fig.5 including LMC4, LMC5). Hα shells consisting of diffuse filaments and bright H II regions are surrounded by a remarkable H I hole (e.g., Meaburn 1980). The diameters of Hα and H I shells are 1.4 kpc and 1.9 kpc, respectively. In the central region of LMC4, more

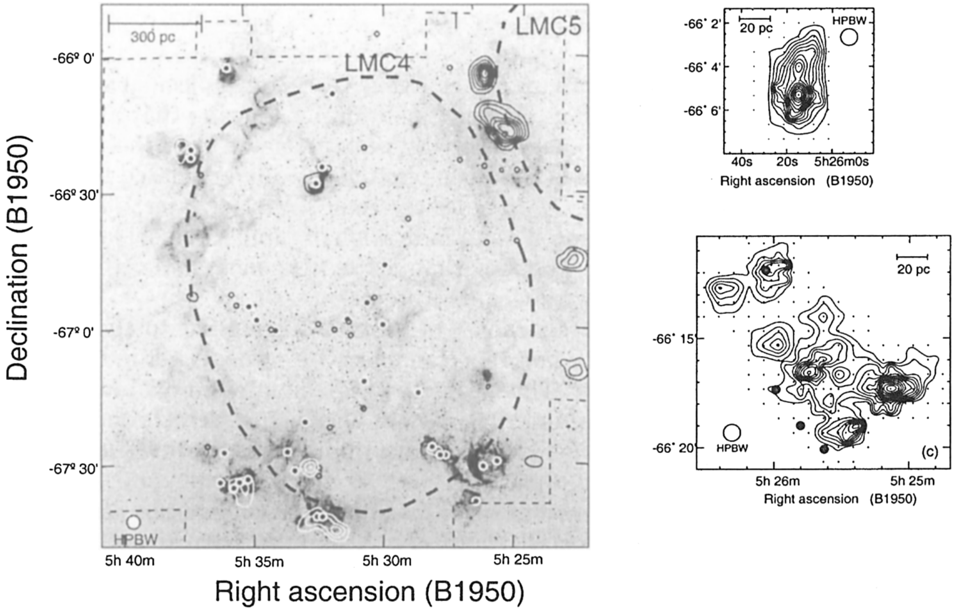

Figure 4. CO distributions in the supergiant shell LMC4 (Paper II). *Left* : CO images superposed on the Hα plate (Kennicutt & Hodge 1986). The filled and open circles are the clusters of $\tau < 10$ Myr and $10 < \tau < 30$ Myr (Bica et al. 1996), respectively. *Right* : High-resolution CO images obtained with SEST. The filled circles are the H II regions (Davies, Elliot, & Meaburn 1976).

than 400 OB stars are found (Meaburn 1980). More recently, stars inside the shell are estimated to be 6–16 Myr old, while those at the rim are ~ 5 Myr old (Braun et al. 1997), suggesting triggered formation of stellar clusters at the rim. Efremov & Elmegreen (1998) discuss triggered star formation in the southern rim of LMC4. Compared with the optical and H I studies, molecular gas in LMC4 as well as other SGSs was only poorly investigated. Previous CO maps were not sensitive enough to resolve individual star forming clouds in LMC4 (e.g., Paper I).

The new deep observations offer useful data to answer the following questions (Yamaguchi et al. 2001a; hereafter, Paper II); 1) does LMC4 contain a sufficient amount of molecular gas to form stars? 2) are stars and clusters being formed at present and/or for the future? 3) is star formation triggered at present? We also used SEST to map the two molecular clouds to reveal their distributions at a higher spatial resolution in NANTEN results.

In the new survey, we have found clumpy molecular clouds along LMC4 (Fig.4a). We have identified 18 molecular clouds, 12 of which are newly found. The clouds tend to be small and clumpy except for the clouds between LMC4 and LMC5. The masses of the clouds, M_{CO}, are 10^4 to 8×10^5 $M_\odot$. The total molecular mass is 3×10^6 $M_\odot$, ~ 25% of that of the H I mass (Dopita et al. 1985).

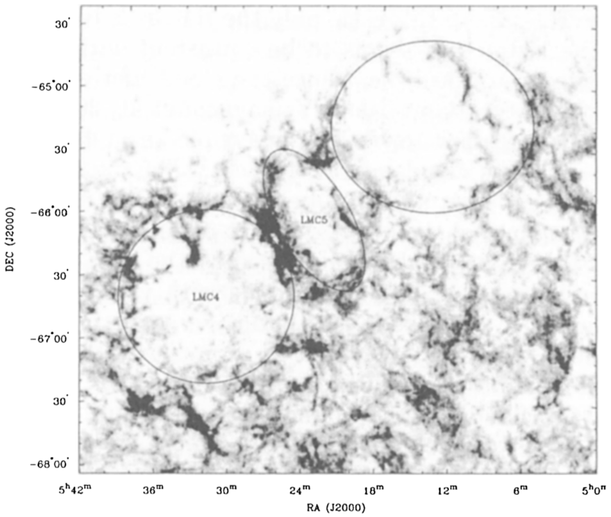

Figure 5. The H I distribution around the supergiant shells LMC4 and LMC5 obtained with ATCA (=Australia Telescope Compact Array). (Kim et al. 1997).

No apparent expansion is found as is consistent with the fact that the clouds are along the projected boundary but not inside the shell.

Figures 4b–4c are the detailed CO maps of the two clouds between LMC4 and LMC5, and were obtained with SEST (Paper II). 11 dense clumps are within NANTEN distributions.

In order to study the relationship between the molecular clouds and H I gas, the distributions of H I gas (Kim et al. 1997) is shown in Figure 5. The molecular clouds coincide well with the H I clumps (see also Paper II). No H I and molecular gas are found inside the shell, except for the cloud LMC/M53221−6828, which appears to be inside the shell. A H I tail is found to the northeast (see Fig. 5), which extends outward from the shell center. The H I gas shows uniform velocity distribution similar to the cloud. These suggest that the cloud is left inside the shell, being dynamically affected by the expanding shell.

We have found two massive clouds between the LMC4 and LMC5. The total mass of these clouds is $\sim 1.5\times10^6 M_\odot$, which is $\sim$ 50% of the cloud mass detected in the present observations of LMC4. A dense H I ridge is seen in this part (see Fig. 5), and the clouds are in the ridge. This suggests that the H I gas swept up by the expanding shells accumulates between the two shells, and the clouds are formed within the dense H I cloud.

LMC4 is likely to be expanding according to H I observations (e.g., Dopita et al. 1985; Kim et al. 1999). The molecular clouds, thus, are probably affected by the expanding shell. We suggest two effects of the expanding shell on molecular gas. One is formation of molecular clouds due to the expanding shell. The expanding shell accumulates H I gas, and the molecular clouds are formed in the dense parts of the H I gas. The other is compression of pre-existent molecular clouds. Since the molecular clouds are denser than the H I gas, they are less affected than the H I gas. In this case, only the H I gas is likely to be accelerated by the shell. The latter case seems to be consistent with the present results, although both effects are possible. Since the cloud lifetime is estimated to be several Myr in the LMC (Paper I and Yamaguchi et al. 2001b; hereafter Paper III), and LMC4 is suggested to be 10–20 Myr old (e.g., Braun et al. 1997), it is too long to regard the clouds as pre-existent. The molecular clouds may be formed in dense H I gas first, and then become dense and massive enough not to be swept by the expanding shell. The present results strongly suggest that the molecular clouds are dynamically compressed by the expanding shell.

We have compared the molecular clouds with young objects, such as the H II regions (Kennicutt and Hodge 1986) and the young clusters of $\tau < 30$ Myr (Bica et al. 1996). We have found that 11 clouds are associated with the H II regions, and that 8 clouds are associated with the clusters. Out of the 15 clusters associated with the clouds, 14 are younger than 10 Myr, indicating that these clusters have been just formed in the clouds. Figure 4a shows a distribution of the clouds superposed on the Hα. The clouds are distributed along the Hα shell. The H II regions and clusters are found on the side of the clouds facing to the shell center.

The SEST observations more clearly show that H II regions are located inside of the clumps. Massive stars and clusters are being formed on the inner side of the clouds facing to the shell center. This suggests that star formation has been triggered by LMC4. The clump separation is typically $\sim$ 30 pc, similar to the cluster separation of the young clusters associated with molecular clouds (Paper III). This suggests that these clumps are likely to form a group of clusters for the future. According to the optical observations (e.g., Braun et al. 1997), the clusters at the central region of LMC4 are older by $\sim$ 5 Myr than those at the rim. Star formation is likely to be triggered at the southern arc (Efremov & Elmegreen 1998). The clusters of $\tau < 10$ Myr inside the shell are not associated with the Hα emission and molecular gas, indicating that the parent molecular clouds have been completely dissipated. The clusters at the rim are associated with the molecular clouds, indicating that the cluster formation occurs at present. Clusters may be also formed for the future. From these results, we infer that LMC4 grow larger due to the star formation activity at the rim. To summarize the results, massive stars and/or clusters are actively being formed in the molecular clouds at the boundary of LMC4.

6. Summary

I give a summary of this contribution as follows;
1) Giant molecular clouds in the LMC are identified as the formation sites of populous clusters.
2) GMCs are similar to those in the Galaxy, in mass, line width, etc., provided that the X factor is different. This suggests that the way of gas condensation is different in forming populous clusters from forming open clusters.
3) Supergiant shells are triggering cluster formation. The stars and clusters tend to form on the side facing to the shell center, suggesting that the star formation is triggered at the shell boundary.

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Discussion

P. Goudfrooij: Do you have information from more density-sensitive molecular lines such as CS to check whether the star-forming molecular clouds in the LMC are actually denser than the non-star-forming molecular clouds? This would be a good check of the molecular cloud evolution scenario you presented.

Y. Fukui: Such observations have been made with the SEST 15m telescope for a quite limited number of GMCs. It is certainly interesting to use the other tracers of high density in mapping the NANTEN GMCs.

J. Melnick: The mass spectrum for GMCs you find is exactly what you expect if the ISM has a fractal structure of any dimension. This reinforces the modern view of GMCs as highly turbulent fluctuations of the ISM that change with time. In that case, the size of a GMC is determined entirely by the resolution of your telescope.

L. Vanzi: Could you comment more on the X=H_2/CO ratio observed in the LMC?

Y. Fukui: This ratio should be a result of rather complicated inner structure of a cloud. The cloud surface is more ionized than the inner part, and this results in a strong dependence of the ratio on the cloud ionization structure. At the moment, our knowledge on this is quite limited. We need a careful study of the cloud structure in order to reach a convincing view.

J. Hesser: Do we have any information on the magnetic fields in those regions?

Y. Fukui: Unfortunately, no. ALMA, for instance, is definitely usable in such studies in the future.

C. Clarke: How does the fraction of GMCs not forming stars compare with this number in the Milky Way? Here, only one GMC, the Maddalena, is apparently non-star forming.

Y. Fukui: This is a very interesting issue. I added some comments in this contribution. In our first paper, I show that 12 clouds are starless among the 55 clouds in total (Paper I). The ratio becomes 22%, certainly larger than what we know in the Galaxy, where only the Maddalena Cloud is starless (for massive young stars). Nevertheless we perhaps need to worry about the detection limits for young objects at 50 kpc before taking this difference very seriously.