

CO, HI, recent Spitzer SAGE results in the Large Magellanic Cloud

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Abstract. Formation of GMCs is one of the most crucial issues in galaxy evolution. I will compare CO and HI in the LMC in 3 dimensional space for the first time aiming at revealing the physical connection between GMCs and associated HI gas at a ~ 40 pc scale. The present major findings are 1) [total CO intensity] \propto [total HI intensity]^{0.8} for the 110 GMCs, and 2) the HI intensity tends to increase with the evolution of GMCs. I argue that these findings are consistent with the growth of GMCs via HI accretion over a time scale of a few $\times 10$ Myrs. I will also discuss the role of the background stellar gravity and the dynamical compression by supershells in formation of GMCs.

Keywords. stars: formation, ISM: atoms, evolution, molecules, Magellanic Clouds, galaxies: star clusters

1. Introduction

The Magellanic system including the LMC, SMC, and the Bridge is an ideal laboratory to study star formation and cloud evolution because of its proximity to the sun. In particular, the LMC offers the best site because of its unrivaled closeness and of the nearly face-on view to us. Among the various objects in the LMC, the molecular clouds which are probed best in the millimetric CO emission, provide a key to understand star formation and galaxy evolution. This is because the molecular clouds are able to highlight the spots of star formation due to their highly clumped distribution both in space and in velocity. The situation should be contrasted with atomic hydrogen gas having lower density and more loosely coupled to the star formation spots.

The key issue I would like to focus on in this talk is the formation of giant molecular clouds (GMC) in the LMC. GMCs are the major site of the star formation and the GMC formation must be a crucial step in the evolution of a galaxy. In order to address this issue, I will make (1) a comparison between HI and CO in 3 dimensional space to understand their physical correlation, (2) a comparison between stellar distribution which is dynamically controlling the HI density, and (3) a comparison with some of the most recent Spitzer SAGE results. The contents of sections 3 and 4 are mainly based on the collaboration with Hinako Iritani and Akiko Kawamura of Nagoya University and Tony Wong of ATNF and will be published elsewhere.

2. Three classes of GMCs

The NANTEN CO survey of the LMC has revealed that there are three classes of GMCs according to the association of young objects (Fukui *et al.* 1999; Yamaguchi *et al.* 2001b; Figure 1). Class I has no apparent sign of star formation and Class II is associated with small HII region(s) only but without stellar clusters. Class III is most actively forming stars as shown by huge HII regions and young stellar clusters. This classification was

presented by Fukui *et al.* (1999) based on the first results of the NANTEN survey (see also Mizuno *et al.* 2001; Yamaguchi *et al.* 2001b). The basic scheme of the classification remains valid in the subsequent sensitive survey with NANTEN while the number of GMCs in each class has been increased by a factor of three (Fukui *et al.* 2001; Fukui *et al.* 2006; see also Blitz *et al.* 2006). These Classes are interpreted as an indication of the evolutionary sequence from I to III and the life time of a GMC is estimated to be a few $\times 10$ Myrs in total (Fukui *et al.* 1999). A comparison of physical parameters indicates that size and mass tend to increase from Class I to Class III, and Class III GMC has the largest size and mass among the three. The stage after Class III is perhaps a very violent dissipation of GMCs due to UV photons and stellar winds from formed clusters as seen in the region of 30Dor most spectacularly. More details on this classification are discussed elsewhere in these proceedings (Kawamura *et al.* 2006).

3. HI vs. CO

3.1. 3-D correlation

Previous studies of star formation in galaxies employed 2-D (2 dimensional) projection of HI intensity at large spatial averaging over ~ 100 pc – 1 kpc (e.g., Schmidt 1972). We shall here test a 3-D (3 dimensional) comparison of CO and HI in the LMC where the 3-D datacube has a velocity axis in addition to the two axes in the sky. We use the 3-D datacube of CO with NANTEN (Fukui *et al.* 2006) and of HI with ATCA (Kim *et al.* 2003), where CO traces GMCs and HI less dense atomic gas.

Figure 2 shows an overlay of CO and HI and represents that GMCs are located often towards HI filaments. This shows that the CO emission is certainly located towards HI peaks while there are also many HI peaks or filaments without CO emission,

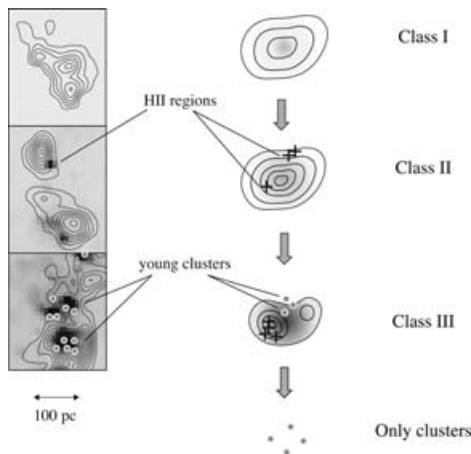


Figure 1. Evolutionary sequence of the GMCs in the LMC. An example of the GMCs and illustration at each class are shown in the left panels and the middle column, respectively. The images and contours in the left panels are $H\alpha$ (Kim *et al.* 1999) and CO integrated intensity by NANTEN (Fukui *et al.* 2006).

suggesting that HI is the placental site of GMC formation (Blitz *et al.* 2006). We should note that this overlay is of the integrated intensities along the line of sight in velocity space. Figure 2 shows typical CO and HI profiles in the LMC, indicating that the CO emission is highly localized in velocity; the HI emission ranges over 70 km s^{-1} while the CO emission has a width less than 10 km s^{-1} . The large velocity dispersion of HI is most likely due to physically unrelated velocity components in the line of sight and the HI gas associated with the CO gas is a small fraction of HI whose velocity is close to that of CO. Previous studies to correlate HI and CO using such velocity integrated 2-D data obviously overestimates the HI intensity.

The present 3-D analysis is able to pick up the HI gas physically connected to the molecular clouds. Accordingly, we expect it reveals the exact connection of the ambient atomic gas to the dense molecular gas. The present HI and CO datasets have a pixel size of 40 pc \times 40 pc \times 1.7 km s^{-1} and consist of

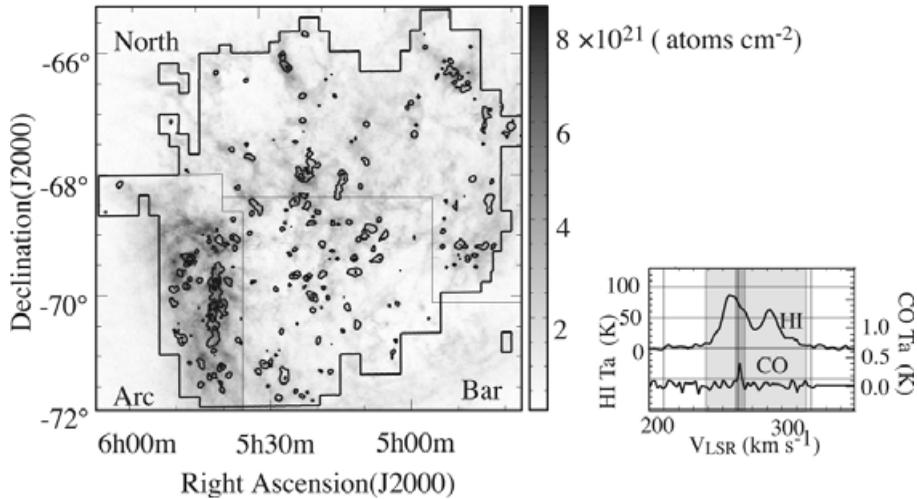


Figure 2. *Left Panel*; HI image (Kim *et al.* 2003) with the CO contours (Fukui *et al.* 2006). The contours are from 1.2 K km s^{-1} with 3.6 K km s^{-1} intervals. The *Right Panel* shows an example of the HI and CO profiles at $\alpha(\text{J2000}) = 5^{\text{h}}35^{\text{m}}42^{\text{s}}$, and $\delta(\text{J2000}) = -69^{\circ}11'$.

~ 2 million pixels. The HI and CO intensities are expressed as averaged T_a (K) in a pixel with the lowest value, the 3σ noise level, in each.

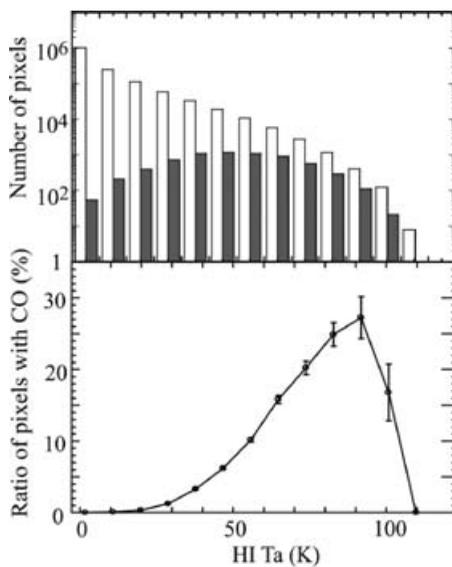


Figure 3. (*Upper Panel*) Distribution of HI integrated intensity in 3-dimension. Distribution of the HI integrated intensity where the significant CO emissions are detected is also shown in gray. (*Lower Panel*) The ratio of the HI pixels with and without CO emission.

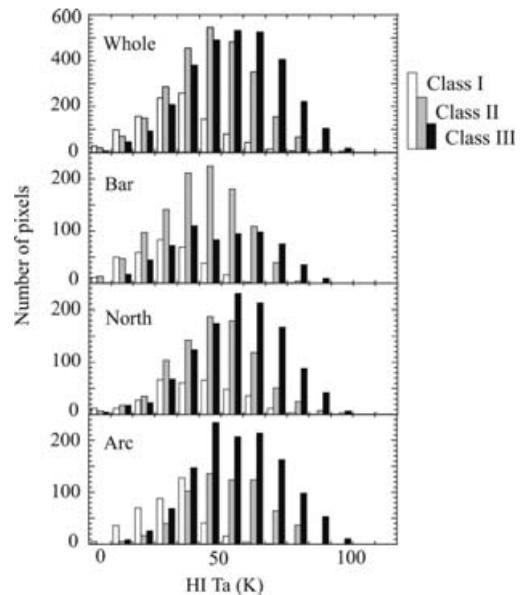


Figure 4. Distribution of the HI antenna temperature (T_a) associated with the GMCs in the entire galaxy, the arc, the bar, and the north regions from the top. Each panel indicates the HI intensity distribution associated with the GMC Class I (white), Class II (gray), and Class III (black).

Figure 3 shows a histogram of the HI integrated intensity in 3-D and the pixels with the significant CO emission (greater than 0.7 K km s^{-1}) are marked. This histogram

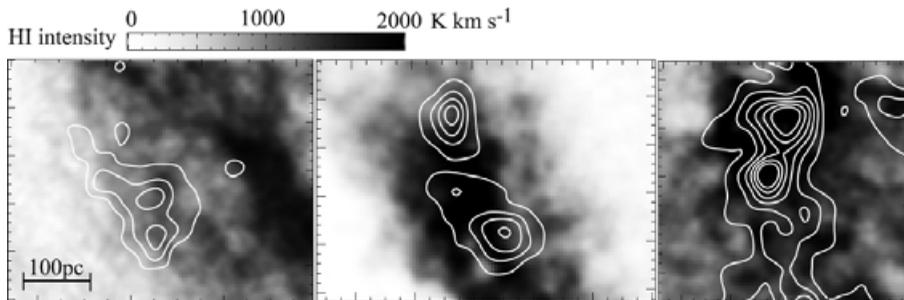


Figure 5. Examples of the HI and CO distributions of the GMC Class I (Left), II (Middle), and III (Right), respectively. Gray images are HI integrated intensity maps; velocity is integrated over the range where the significant CO emissions are detected. The contours are CO integrated intensities from 1.2 K km s^{-1} with 1.2 K km s^{-1} intervals (Fukui *et al.* 2006).

shows that the CO fraction increases steadily with the HI intensity, suggesting the HI provides a necessary condition to form GMCs. About one third of the pixels exhibit CO emission near $T_a(\text{HI})$ of $\sim 90 \text{ K}$ and it seems that there is no sharp threshold value for GMC formation with respect to the HI intensity.

Figure 4 shows a histogram of the HI intensity for the three GMC Classes. This clearly shows that the HI intensity tends to increase from Class I to Class III while the dispersion is not so small. The average HI intensity over the whole LMC is $34 \pm 16 \text{ K}$, $47 \pm 17 \text{ K}$ and $56 \pm 19 \text{ K}$ for Class I, II and III, respectively. The HI intensity surrounding GMCs becomes greater with the GMC evolution and star formation. In order to test the variation within the galaxy, we shall divide the galaxy into three regions, i.e., Bar, North and Arc (see the left panel of Figure 2). Histograms for each shown in the lower three panels of Figure 4 again indicate the same trend.

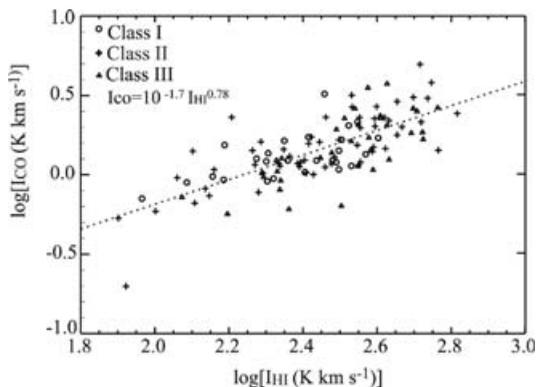


Figure 6. Correlation diagram between HI and CO intensities. Open circles, crosses and open triangles represent GMC Class I, Class II, and Class III, respectively. The dotted line shows the regression line of $I_{\text{CO}} = 10^{-1.7} I_{\text{HI}}^{0.78}$.

in the sky and estimated L_{CO} in the velocity range where CO is detected. Then we divide the L_{CO} by the apparent size of a GMC. This gives an average CO intensity. For each GMC we chose the pixels where the CO emission is significantly detected and tested HI and CO correlation (Figure 6), where only the HI pixels with CO are counted.

Three images in Figure 5 show the HI distribution associated with GMCs of the three Classes. The CO distribution has detailed structures of $\sim 100 \text{ pc}$ or less and the HI seems to be associated with the GMC at a scale of $50\text{--}100 \text{ pc}$. The HI is not always isotropic with respect to a GMC but indicates close spatial correlations so that the HI is more or less enveloping a GMC. The typical HI velocity width associated is estimated to be $\sim 10\text{--}14 \text{ km s}^{-1}$, and beyond this velocity span the associated HI peaks generally becomes much weaker or disappear.

We have chosen 110 GMCs with five or more pixels in the two axes

The regression shown in Figure 6 is well fitted by a power law with an index of ~ 0.8 , indicating a nearly linear correlation between CO and HI in a GMC. We shall note that this index should become larger as ~ 1.5 if we use 2-D correlation because the velocity integrated HI intensity has large offsets unrelated with CO.

3.2. Dressed GMCs; growth of GMCs via HI accretion

The dependence of HI intensity on Class of GMC indicates that the surroundings of a GMC change appreciably depending on the Class at a length scale of 40–100pc. The HI intensity is generally a product of the spin temperature and the optical depth, and the correlation indicates the temperature and/or density is dependent on Class. The spin temperature of HI is generally estimated to be ~ 100 K in the Milky Way. Since the HI spin temperature may be higher in the LMC where UV is more intense and dust opacity is less than in the Milky Way. The typical HI intensity less than 100 K suggests that the HI emission is optically thin. If so, the HI intensity should represent HI density. We therefore infer that GMCs are “dressed” in HI and that the “HI dress” grows in time.

The correlation between HI and CO is nearly linear (Figure 6). This alone does not provide a strong constraint on the formation of a GMC. Nonetheless, the apparent association of HI with GMCs suggests that the HI is enveloping each GMC and the HI density increases with the cloud evolution. We infer that this represents the enveloping HI gas is accreting onto GMCs and is converted into H_2 due to increased optical depth. This leads to increase the molecular mass of GMC, i.e., the observed mass increase from Class I to III (see section 2). The timescale of the GMC evolution is ~ 10 Myrs and the increased molecular mass is in the order of $10^6 M_\odot$. Namely, a mass accretion rate of $\sim 10^{-1} M_\odot \text{ yr}^{-1}$ is required. We roughly estimate that this rate is consistent with that calculated for a spherical accretion of the HI gas having $n(\text{HI}) \sim 10 \text{ cm}^{-3}$ at an infall speed of $\sim 7 \text{ km s}^{-1}$.

4. Stellar gravity and triggering in GMC formation

We shall examine two effects which may be important in converting HI to H_2 : one is the stellar gravity and the other supershells driven by OB stars and/or SNRs.

4.1. Stellar gravity

We shall here use the K-band image of 2MASS which represents relatively old stellar population dominating the gravity (Sergei *et al.* 2000). This will allow us to test the effects of stellar gravity on GMC formation. The young stars associated with GMCs are small in mass and are not important in such gravity.

Figure 7 shows a histogram of CO clouds vs. K-band stellar density. We find that the number density of CO clouds increases with the increase of the stellar density. It seems that there is a threshold value at ~ 1.0 in $\log(\text{number of stars}/4 \text{ arcmin}^2)$ for the HI - H_2 conversion where the number density of CO clouds increases beyond $\sim 5\%$ of the pixel number.

Wong and Blitz (2002) argue that the pressure exerted on HI gas may play a role in converting HI to H_2 . They studied several spiral galaxies to show that the HI gas is associated with CO only in the inner part of galaxies where the stellar gravity is strong. The pressure should be basically dominated by the stellar gravity as long as the stars are the dominant source of gravity and the present result on the LMC supports that the pressure plays a role in converting HI into H_2 .

4.2. SAGE results

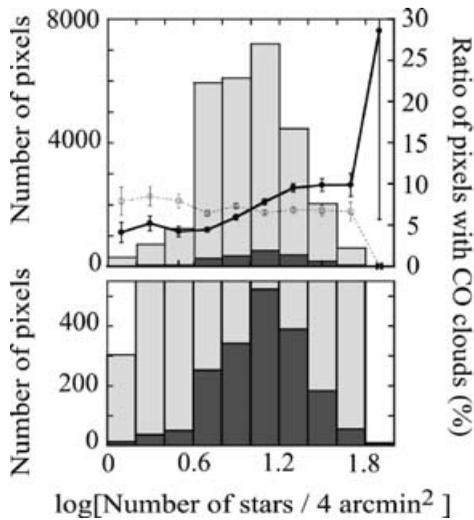


Figure 7. Distribution of the stellar density derived from the 2MASS K band sources. The histogram in dark gray shows the stellar density distribution where the significant CO emissions are detected. Thick line indicates the ratio of the pixels of the stellar density with and without CO emissions. Thin line shows the ratio as for the thick line but obtained by assuming the CO emissions are distributed randomly. The Lower Panel is an enlargement of the Upper Panel.

GMCs may be associated with supergiant shells. Since more candidates may be identified from the SAGE image, triggering of GMC formation by supershells may be more important than previously thought by Yamaguchi *et al.* (2001a).

5. Summary

I shall summarize this contribution as follows;

- 1) 3-D comparison between CO and HI has revealed GMCs are associated with HI gas at a ~ 40 pc scale; these are “HI dressed GMCs”.
- 2) There is a clear increase of the HI intensity around GMCs from GMC Class I to Class III. Growth of GMCs in mass via HI accretion has been suggested over a time scale of a few times 10 Myrs.
- 3) This correlation has a form, $[\text{CO intensity}] \propto [\text{HI intensity}]^{0.8}$, for selected 110 major GMCs.
- 4) The background stellar gravity and dynamical compression by supershells may be important in converting HI into H_2 , i.e. in GMC formation.

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The Spitzer satellite has been used to make an extensive study of the LMC at infrared wavelengths from $3.6\text{--}160\mu\text{m}$. This is the SAGE project headed by M. Meixner. Figure 8 shows the $3.6\text{--}24\mu\text{m}$ 3-color composite image ($3.6\mu\text{m}$, $8.0\mu\text{m}$ and $24\mu\text{m}$ in blue, green, and red) from the SAGE project (NASA/Caltech-JPL/Meixner STScI and the SAGE Legacy Team) with NANTEN CO distribution (Fukui *et al.* 2006). This presents that CO clouds are well correlated with the far-infrared distribution and future comparisons should reveal considerable details of the dust-gas relationship quantitatively.

In connection with the GMC formation, we note that the SAGE image indicates numerous good candidates for apparently swept-up matter perhaps by supershells owing to the better angular resolution. Yamaguchi *et al.* (2001a) made a comparison between $\text{H}\alpha$ supershells and CO and concluded that $\sim 30\%$ of the

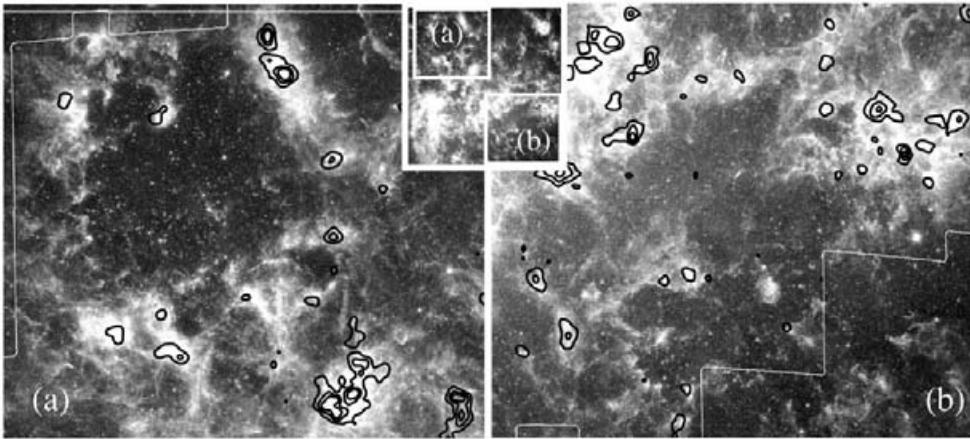


Figure 8. 3.6–24 μm 3-color composite image (3.6 μm , 8.0 μm and 24 μm in blue, green, and red, respectively) from the SAGE project (NASA/Caltech-JPL/Meixner STScI and the SAGE Legacy Team) of the LMC (*Middle inset*); Overlays with CO contours are shown (a) toward LMC 4, and (b) LMC 7 and 8. The CO contours are from 1.2 K km s⁻¹ with 2.4 K km s⁻¹ intervals from the CO survey by NANTEN (Fukui *et al.* 2006). The regions of (a) and (b) are indicated by white boxes in the inset.

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Discussion

KRUMHOLZ: You mentioned that $\sim 1/3$ of GMCs in the LMC show clusters or HII regions, but in the Milky Way we see almost no starless clouds. How can we understand that? Two possibilities: first we have only a poor view of GMCs in the Milky Way, so the statistics may be bad. Second, GMCs in the LMC may evolve more slowly than those in the Milky Way for some unknown reason.

FUKUI: Regarding your first suggestion: the reasonably studied GMCs in the Milky Way are only 30 and are restricted to within a few kpc of the sun because of confusion and extinction in the disk. And for the second point: this remains an interesting possibility.

TAN: If GMCs form quickly from HI, their angular momentum vector directions should be correlated with those of the surrounding HI gas. Do you see this?

FUKUI: This sounds like an interesting work to do. We will try. Thank you for the suggestion.

ZINNECKER: I have not understood what you meant by your concept of “stellar gravity” compression of the GMCs?

FUKUI: The stellar gravity is kpc scale as probed by 2MASS K band image. This gravity confines the HI gas and regulates the pressure in it. This produces higher pressure to help GMC formation.

VAZQUEZ-SEMADENI: How can you tell whether a larger mass of stars is a cause rather than a consequence of the larger gas mass?

FUKUI: The stellar mass I showed is by 2MASS K band data. These stars must be much older and more massive than the gas. So, the stellar gravity potential is a given condition for the HI gas that evolves into H α in ~ 10 Myr. The newly formed stars must be much less than that K band image shows.

DICKEY: Years ago Ulrich Mebold and I did a survey of 21 cm absorption in the LMC. We found many absorption lines, but none so optically thick that the absorption would obscure any HI emission. For this reason, you can measure the HI column density directly from the 21 cm brightness temperature, without worrying about the excitation temperature of HI. Most of the HI in the LMC is very warm, hundreds to thousands of K.

FUKUI: Thank you, I agree with that.

ELMEGREEN: You are saying there is an evolutionary sequence going from no star formation in low mass clouds to high star formation in high mass clouds, and you interpret this as a result of accretion. But couldn't it also be that there are clouds of all masses and the low mass clouds are not sampling far into the IMF so there are no massive stars and they are not sampling vary far into the cluster mass function so there are no massive clusters? There could be low mass stars and low mass clusters in these low mass clouds.

FUKUI: The lowest mass class of GMCS, Class 1, is already fairly massive, \sim several $\times 10^5 M_{\odot}$ to more than $10^6 M_{\odot}$. In the Milky Way, these mass range of GMCs are almost all forming high mass stars. So, a simple different in IMF is not a good explanation for the difference in star formation among the three classes of GMCs.