Mem. S.A.It. Vol. 89, 18
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Formation of globular clusters with multiple stellar populations in the LMC: internal or external gas accretion?

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Abstract. Young stellar objects (YSOs) have been recently discovered in the central region of star clusters (SCs) of the Large Magellanic Cloud (LMC), which strongly suggests that secondary star formation is ongoing in older SCs. We discuss whether these second generation (SG) of stars in these LMC SCs can be formed from gas accretion from AGB stars ('internal accretion' scenario) or from cold molecular hydrogen (H_2) of interstellar medium ('external accretion') using the latest results of numerical simulations of SC formation. We demonstrate that H_2 gas accretion is possible for both low-mass and high-mass SCs only after the intense LMC-SMC tidal interaction in the external accretion scenario. However, a significant fraction of SCs do not accrete H_2 gas, which implies that not all of the LMC SCs can have YSOs. Gas ejected from AGB stars can be accreted onto the LMC SCs after the initial starburst within a fractal molecular cloud (MC), only if the final cluster masses are as large as $10^6 M_\odot$ in the external accretion scenario. Low-mass SCs with masses as low as $10^5 M_\odot$ (i.e., formed from a MC with a mass of $\sim 10^6 M_\odot$) can not form SG stars. We discuss the advantages and disadvantages of these two scenarios in explaining the origin of the LMC SCs with younger stellar populations.

Key words. Stars: abundances – Galaxy: globular clusters – Galaxy: abundances

1. Introduction

Recently 15 YSO candidates in older clusters (400 Myr–1 Gyr) of the LMC have been discovered by For & Bekki (2017), and 7 of them are in the central 1pc (almost center) of the SCs. They adopted the cross-matching method for the positions of YSOs and SCs from the HERITAGE band-matched (Seale et al. 2014) and SC catalogues (Glatt et al. 2010). This discovery of 15 YSOs among 728 SCs using 1025 YSOs in the LMC is quite surprising, because the probability of one YSO being within the central 1 pc of a SC *by accident* is extremely small. This means that these YSOs are physically associated with SCs in the LMC. The left panel of Fig. 1 shows the four examples of YSOs in the central regions of the LMC SCs. For & Bekki (2017) have found that (i) YSOs and SCs are widely distributed across the LMC disk and (ii) such a wide distribution can be seen in SCs with YSOs: no preferred locations of SCs with YSOs. One of the most important results in For & Bekki (2017) is that even low-mass SCs can have YSOs in their central regions. This can provide a strong constraint on

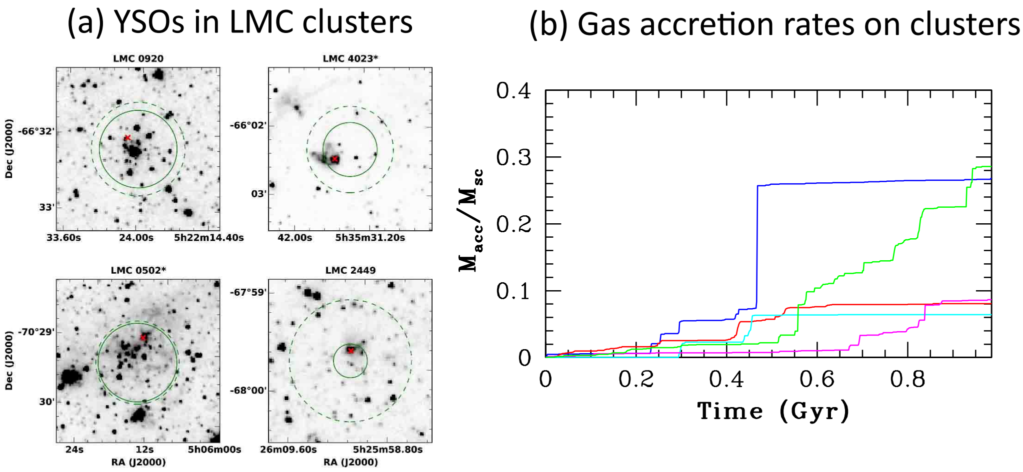

Fig. 1. Left panel (a) shows examples of the LMC SCs with YSOs in their central regions. The red crosses indicate the locations of the central YSOs. The solid and dashed green circles indicate the apparent radii of the SCs and the search radii of 10pc adopted in the cross-matching method for YSO-SC association, respectively. Right panel (b) shows the time evolution of gas mass ($M_{\rm acc}$) accreted onto each SC for representative several SCs (shown in different colors) in the LMC interacting with the SMC. The strong LMC-SMC tidal interaction can occur around $T = 0.2 - 0.4$ Gyr in this model. The accreted gas mass is normalized by initial SC masses ($M_{\rm sc}$) here. Clearly, the intense LMC-SMC interaction triggers the enhanced gas accretion onto some (not all) of existing LMC SCs, in particular, during and after the LMC-SMC interaction.

the theory of SCs in the LMC, because previous models of GC formation with multiple stellar populations did not predict such an observation. The details of the observational results are given in For & Bekki (2017).

The observed presence of YSOs in older SCs suggests that the SCs accreted gas for secondary star formation via some physical mechanisms. There are the following two possibilities. One is that gas ejected from AGB stars in these older SCs have been recently accreted onto the SCs ('internal accretion scenario'). The other is that cold H_2 gas from interstellar medium (ISM) of the LMC has been recently captured by the LMC SCs ('external accretion scenario'). These two scenarios have been previously investigated in our previous works already (e.g. Bekki & Mackey 2009; Bekki 2011). However, Bekki & Mackey (2009) did not model both (i) the dynamical evolution of SCs in the LMC and (ii) the interaction of cold gas and SCs in a self-consistent manner. The GC formation model by Bekki (2011) did not consider the formation of FG stars from giant molecular clouds (GMCs) in the LMC either. Goudfrooij et al. (2014) also adopted the internal accretion scenario and discussed whether the initial gravitational potentials of the LMC SCs with multiple stellar populations (with extended main-sequence-turn-offs) can be deep enough to retain AGB ejecta in their early formation stages. These previous models are oversimplified at some points and thus less useful for physical interpretation of the newly discovered YSOs in the LMC SCs. In this paper, we discuss how much gas can be accreted onto the LMC SCs using realistic hydrodynamical simulations of GC formation based on the two scenarios.

2. The model

2.1. External accretion

We investigate how much H_2 gas of GMCs can be accreted onto existing LMC SCs using our new hydrodynamical simulation code with

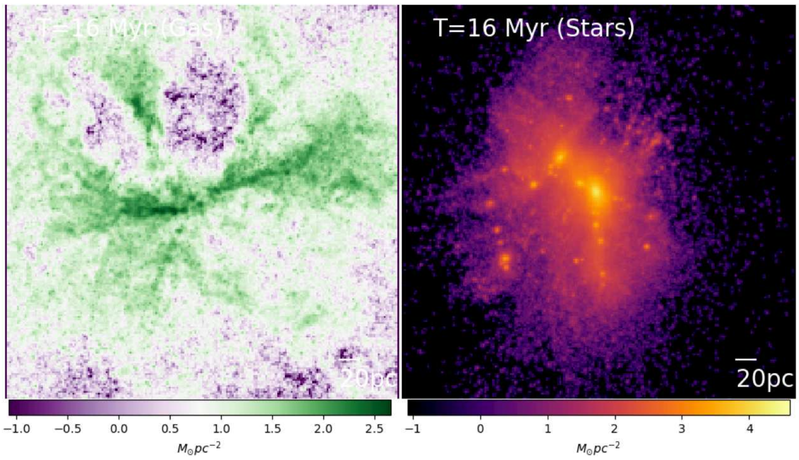

Fig. 2. Left and right panels show the projected mass densities of pristine gas and FG stars, respectively, in a fractal GMC with $M_{\rm mc} = 10^7 {\rm M}_{\odot}$ (i.e., high-mass cluster model) at $T = 16$ Myr. Owing to multiple SNe, most of the remaining gas after FG formation has been blown away from the system by this time step. However, the cold gas that is not influenced by SNe is accreting onto the system along a number of gaseous streams in the left panel. Numerous small sub-clusters can be first formed in the first 10 Myr, and these merge with one another to form a bigger stellar system, as shown in the right panel. The FG system still has many sub-clusters that merge with one another within the next ≈ 20 Myr.

dust physics (Bekki 2013, 2015). The LMC is assumed to consist of dark matter halo with a mass of $10^{11}{\rm M}_{\odot}$, stellar disk with a mass of $2\times10^9{\rm M}_{\odot}$, and gas disk with a mass of $10^9{\rm M}_{\odot}$. The stellar disk has 100 SCs with different masses ($M_{\rm sc}$), and the total mass of gas accreted onto each SC ($M_{\rm acc}$) is investigated using the Bondi accretion formula (Bondi 1952):

$$\frac{dM_{\rm acc}}{dt} = 4\pi {\rm G}^2 M_{\rm sc}^2 \rho_{\rm ism} (v_{\rm rel}^2 + c^2)^{-3/2}, \qquad (1)$$

where G, $\rho_{\rm icm}$, $v_{\rm rel}$, and c are the gravitational constant, the gas density of ISM (which is H_2 gas in the present study), the relative velocity between the ISM and the SC, and the sound velocity of the ISM, respectively. Based on the above equation, we estimate the H_2 accretion rate, i.e., $dm_{\rm acc}/dt$ (at each time step of a simulation), which depends on SC masses ($M_{\rm sc}$) and H_2 gas densities around SCs ($\rho_{\rm ism}$).

2.2. Internal accretion

We consider that the LMC SCs can be formed from fractal GMCs with different initial masses ($M_{\rm mc}$) and sizes ($R_{\rm mc}$). In this paper, we show the results of the models with $M_{\rm mc} = 10^6{\rm M}_{\odot}$ ('low-mass' cluster) and $M_{\rm mc} = 10^7{\rm M}_{\odot}$ ('high-mass') as two representative models which demonstrate gas accretion efficiently dependent on final cluster masses ($M_{\rm sc}$). Since the star formation efficiency in these fractal GMCs is an order of 0.1, the final stellar mass ($M_{\rm sc}$) can be significantly smaller than $M_{\rm mc}$ (i.e., $M_{\rm sc} \sim 0.1 M_{\rm mc}$). A GMC initially has a power-law radial density profile ($\rho_{\rm mc}(r)$) as follows:

$$\rho_{\rm mc}(r) = \frac{\rho_{mc,0}}{(r + c_{\rm mc})^{\beta}}, \qquad (2)$$

where r, $\rho_{\rm mc,0}$, and $c_{\rm mc}, \beta$ are the distance from the MC's center, a constant that is determined by $M_{\rm mc}$ and $R_{\rm mc}$, the core radius of the MC ($c_{\rm mc} = 0.2R_{\rm mc}$), and the power-law slope ($\beta = 1$). The GMC has a fractal gaseous distribution characterized by a fractal dimension D_3 that is set to be 2.6. The details of this fractal GMC model is given in Bekki (2017). Star formation from original pristine gas of a GMC, gas ejection from AGB stars in the FG (first generation) population, and new star formation from AGB ejecta are all incorporated in this study (See Bekki 2017, for the details of the code).

3. Results

3.1. External accretion

The right panel of Fig. 1 shows how the total mass of gas accreted onto a SC can evolve with time during the dynamical evolution of the LMC interacting with the SMC. In this model, the mass-ratio of the SMC to the LMC is set to be 0.1 and the peri-center distance of the SMC is 7.5 kpc. For this set of model parameters, the SMC strongly interacts with the LMC at $T = 0.2-0.4$ Gyr. Owing to this LMC-SMC interaction, the LMC disk is tidally compressed to some extent so that the formation efficiency of H_2 gas on dust grains can be significantly enhanced. As a result of this tidal compression and high H_2 formation rate, the LMC SCs can have a better chance to interact with massive GMCs. Clearly, two SCs shown by blue and green lines have rather high accretion rates and end up with $M_{\rm acc}/M_{\rm sc} \sim 0.3$. These two SCs have $M_{\rm sc} \approx 10^5 M_{\odot}$, which can be responsible for the high gas accretion rates. Other three SCs also show a significant mass increase due to cold gas accretion ($M_{\rm acc}/M_{\rm sc} \approx 0.1$), which is mainly caused by SC-GMC interaction just after the intense LMC-SMC interaction.

The main cause of these efficient gas accretion is the LMC-SMC interaction. Therefore, the present results imply that isolated dwarf disk galaxies are less likely to have SCs with multiple stellar populations. One of key results in this external accretion scenario is that not all of SCs can accrete gas from ISM. Some SCs can not accrete gas at all, because they happen to be away from GMCs during the LMC-SMC interaction. Therefore, if all of the LMC SCs are observed to have multiple stellar populations, then this scenario has a serious problem. For & Bekki (2017) have showed that only 2% of all SCs investigated in For & Bekki (2017) can have younger stellar populations. Therefore, the above results are not inconsistent with these new observations. One of advantages in this scenario is that even low-mass SCs can accrete cold H_2 gas as long as they interact with GMCs during the LMC-SMC interaction. This scenario also predicts that even SCs initially in the outer part of the LMC disk can accrete gas from ISM.

3.2. Internal accretion

Fig. 2 shows how a LMC SC consisting of FG stars can be formed from a fractal MC in the high-mass cluster model with $M_{\rm mc} = 10^7 M_{\odot}$ and $R_{\rm mc} = 200$ pc. The projected mass densities for pristine gas (left) and FG stars (right) clearly show that numerous small gaseous and stellar clumps can be developed from local gravitational instability within the MC. These stellar clumps of FG stars can merge with one another to form a a single FG stellar system over the timescale of 10^8 yr. Star formation can proceed also in massive long filaments developed during the dynamical evolution of the fractal MC. Multiple SN explosion can occur well before most of the cold gas is consumed by star formation and thus cold H_2 gas that was not converted into FG stars before SN explosion can be brown away from the MC. However, a small amount of cold gas that was distant from these SNe can be accreted onto the forming FG stellar system along the long gaseous stream in this Fig. 2. The formation processes of FG stars in the low-mass cluster model with $M_{\rm mc} = 10^6 M_{\odot}$ are essentially the same as the model with $M_{\rm mc} = 10^7 M_{\odot}$.

However, physical roles of feedback effects of AGB stars of FG population in the evolution of AGB ejecta are quite different in different models with different $M_{\rm mc}$. As a result of this the formation processes of SG stars are strongly dependent on $M_{\rm mc}$ (thus $M_{\rm sc}$). Fig. 3 shows the snapshots for AGB ejecta (left) and new stars formed from AGB ejecta (right) for the two models. It is clear in Fig. 3 that

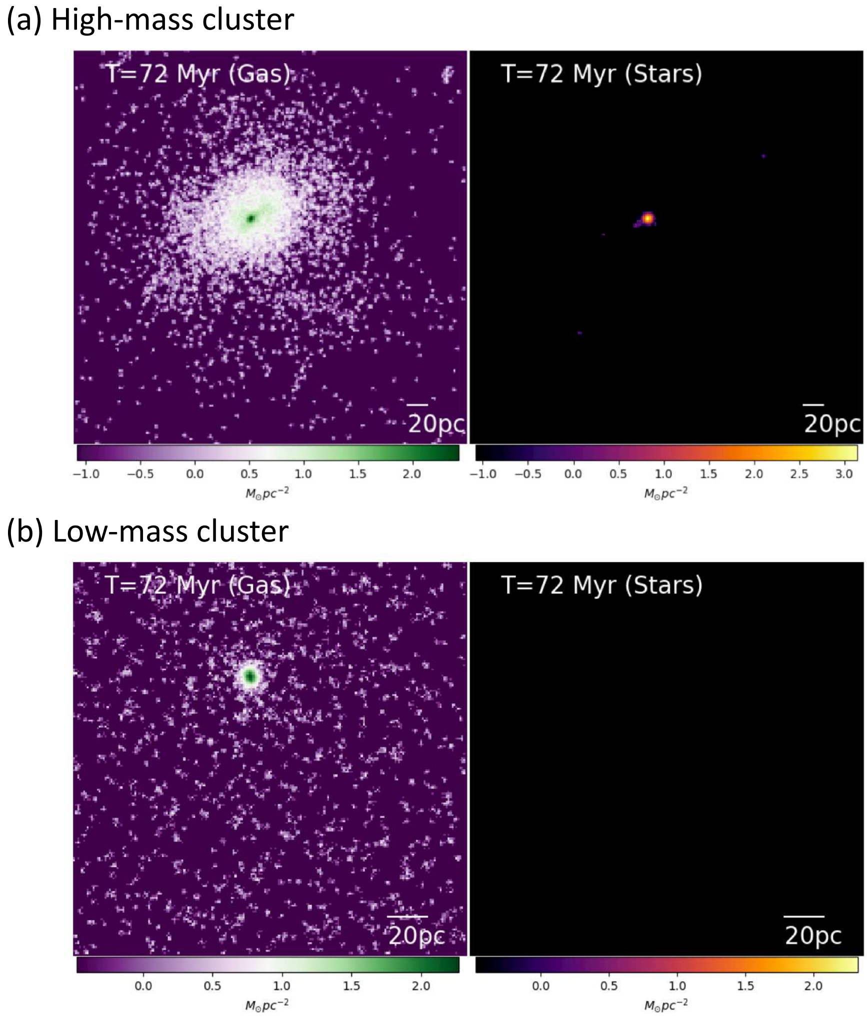

Fig. 3. Left and right panels show the projected mass densities of AGB ejecta and SG stars formed from AGB ejecta, respectively, in fractal GMCs with $M_{\rm mc} = 10^7 {\rm M}_\odot$ ((**a**) high-mass cluster; upper two) and $M_{\rm mc} = 10^5 {\rm M}_\odot$ ((**b**) low-mass cluster; lower two) at $T = 72$ Myr. This time step is well after the completion of the FG system formation in these models. By this time step, a larger amount of gas has been ejected from intermediate-mass AGB stars. Even after the formation of SG stars in the high-mass model, the density of AGB ejecta can be high, which implies that AGB ejecta can be efficiently accreted onto the existing FG system. On the other hand, the low-mass cluster model does not show any SG formation, mainly because most of the AGB ejecta is escaped away from the system owing to the shallow gravitational potential. This result implies that the low-mass LMC SCs can not accrete gas ejected from AGB stars: this internal accretion scenario appears to be inconsistent with the observed YSOs in the low-mass LMC SCs with $M_{\rm sc} < 10^5 {\rm M}_\odot$ (For & Bekki 2017).

SG stars can be formed efficiently only in the high-mass cluster model (i.e., upper two models) with higher surface mass density of AGB ejecta. A small amount of AGB ejecta can be accumulated in the potential well of the forming SC for the low-mass model, however, the mass density can not be high enough to trigger star formation (i.e., gas density can not be so high as $\sim 10^5$ atoms cm^{-3}). Given that the final total mass of the SC (FG+SG stars) for the low-mass model is $\approx 10^5 M_\odot$, this result implies that only the LMC SCs with the total masses significantly higher than $10^5 M_\odot$ can accrete gas for secondary star formation. This further implies that the presence of SCs with lower masses in For & Bekki (2017) is inconsistent with the internal accretion scenario.

4. Discussion

These results based on the internal and external accretion scenarios suggest that the presence of YSOs in low-mass and high-mass SCs (For & Bekki 2017) is more consistent with the external accretion scenario. However, the spatial distribution of SCs with YSOs and the frequency of SCs with YSOs among all LMC SCs have not been predicted in the external accretion scenario. Although the external accretion process has been investigated in the present simulations, conversion from H_2 gas to SG stars has not been investigated yet. It could be possible that gas accreted from ISM in a SC can not be efficiently converted into new stars, if the gravitational potential of the SC is shallow (i.e., if the SC mass is not so high). Therefore, it is premature for the present study to make a robust conclusion on the validity of the external accretion scenario. Furthermore, other physical processes, which are not explored in the present study, might be responsible for the origin of YSOs in the LMC SCs. Thus, it remains unclear how YSOs can be formed from cold gas within the LMC SCs with older ages (0.1 − 1 Gyr old).

5. Conclusions

Recent discovery of YSOs in 15 LMC SCs has provided valuable information on the origin of younger stellar populations in the older LMC SCs. Using new hydrodynamical simulations with H_2 formation on dust grains and H_2 accretion onto existing clusters, we have demonstrated that cold gas accretion onto SCs is possible for different SC masses. However, some SCs can not accrete cold gas at all, which implies that multiple stellar population phenomenon is not universal in the LMC SCs. On the other hand, internal accretion from AGB stars in existing SCs is not efficient at all for SCs with the total masses less than $10^5 M_\odot$. This internal accretion scenario is inconsistent with the presence of YSOs in low-mass LMC SCs (For & Bekki 2017). An alternative scenario is merging between SCs with different ages in the LMC, and this SC merging scenario is currently being investigated. In conclusion, it remains unclear:

(i) why both high-mass and low-mass LMC SCs can have YSOs,
(ii) why only 2% of them can have YSOs.

Acknowledgements. I am grateful to P. Kroupa, T. Jerabkova, and T. Tsujimoto for extensive discussion on the origin of GCs in galaxies.

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