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Probing clumpy pasts of galaxies from AGB stars

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ABSTRACT

Recent morphological studies of galaxies by the *Hubble Space Telescope (HST)* have revealed that actively star-forming galaxies at intermediate and high redshifts ($z = 0.5 - 2.0$) have very clumpy and irregular distributions of stars. It is however unclear whether and how these clumpy galaxies evolve into the present spiral and elliptical galaxies with regular shapes. We here propose that spatial distributions of AGB stars, probing the different mean age and metallicity of the underlying stellar population, can provide vital clues to the evolution of these clumpy galaxies, in particular, those at intermediate redshifts. In order to demonstrate this proposal to be quite promising, we show the results of test-particle simulations on the long-term dynamical evolution of unbound groups of AGB stars ("stellar clumps"), which correspond to the successors of star-forming clumps at intermediate redshifts, in isolated and interacting galaxies. We particularly show that azimuthal distributions of AGB stars dispersed from stellar clumps as a result of gravitational interaction with their host galaxies can be still inhomogeneous several Gyrs after stellar clump formation for some models. We also show that the inhomogeneities in the azimuthal distributions of dispersed AGB stars can more quickly disappear in stellar clumps with larger sizes and higher velocity dispersions. These results suggest that if apparently clumpy structures of galaxies at intermediate redshifts are due to stars in unbound or weakly bound clusters, spatial distributions of AGB stars can have fossil records on past clumpy structures of galaxies. As an example, we compare the latest observations on the spatial distributions of AGB stars in the Large and Small Magellanic Cloud (LMC and SMC, respectively) with the corresponding simulations and thereby discuss whether the LMC and the SMC had massive star-forming clumps in their outer disks a few to several Gyrs ago.

Key words: stars: AGB and post-AGB – galaxies: high-redshift – galaxies:evolution – galaxies:structure – galaxies:kinematics and dynamics – galaxies:star cluster

1 INTRODUCTION

Recent morphological studies of galaxies at intermediate and high redshifts ($z = 0.5 - 2.0$) have discovered several kinds of clumpy galaxies, such as "tadpole galaxies", "clump-clusters", and "chain galaxies" (e.g., Cowie et al. 1995; van den Bergh et al. 2006; Reshetnikov et al. 2003; Conselice et al. 2005; Elmegreen et al. 2004a, b, 2005). Recent numerical and theoretical works have suggested that dynamical evolution of massive star-forming clumps in these clumpy galaxies are important for the formation of bulges, thick disks, and their exponential profiles in the present galaxies (e.g., Noguchi 1998). However observational studies on structural and kinematical properties of *the present galaxies* have not yet revealed evolutionary links between these distant clumpy galaxies and the present normal Hubble type ones.

Asymptotic Gian Branch (AGB) stars have been considered to be useful indicators of galaxy structures and kinematics, because they are easily noticed owing to their bright magnitudes and widely distributed across galaxies (e.g., van der Marel et al. 2002; Cioni & Habing 2003). Recent studies on structural properties of nearby galaxies based on spatial distributions of AGB stars (e.g., LMC, SMC, M33, and NGC 6822) have revealed clumpy and asymmetric distributions of stars for age and metallicity ranges (e.g., Cioni & Habing 2003; Cioni et al. 2006a, b). For example, Cioni et al. (2006b) found that (1) the azimuthal distributions of stars with mean ages of 2.0-10.6 Gyr in the SMC are quite inhomogeneous and (2) the distributions depend strongly on ages and metallicities of stars. Although physical origins of the

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Table 1. Model parameters and results

(1) Model no.	(2) r_c (pc)	(3) R_c (kpc)	(4) σ_c (km s^{-1})	(5) f_c
I1	100	5.0	1.0	1.0
I2	500	5.0	1.0	1.0
I3	100	5.0	5.0	1.0
I4	100	5.0	1.0	0.9
I5	100	3.0	1.0	1.0
T1	100	7.0	1.0	1.0
T2	100	5.0	1.0	1.0
T3	100	3.0	1.0	1.0
T4	100	5.0	1.0	0.9
T5	100	3.0	1.0	0.9
T6	100	1.0	1.0	1.0
T7	100	5.0	1.0	0.7

Notes: Cols. (1–5) model parameters: "I" and "T" represent isolated and tidal interaction models, respectively.

observed inhomogeneities in azimuthal distributions of stars remain unclear, it might well be reasonable to consider that AGB stars, which evolve from $0.8-8\mathrm{M}_{\odot}$ stars and therefore are stellar populations suitable for investigating long-term structural evolution of galaxies, can have potentials to probe a possible evolutionary link between nearby galaxies with inhomogeneous spatial distributions of AGB stars and clumpy ones at intermediate redshifts.

The purpose of this paper is to propose that observational studies on spatial distributions of AGB stars for age and metallicity ranges in galactic disks can probe clumpy pasts of galaxies. By using test-particle simulations, we investigate how unbound groups of AGB stars ("stellar clumps") are dispersed into interstellar spaces in galaxies and thereby try to understand how long the initial inhomogeneous distributions of stars survive after the formation of stellar clumps. Since the purpose of this paper is simply to propose the importance of *azimuthal distributions of AGB stars in the present galaxies* in better probing clumpy pasts of the galaxies, we adopt somewhat idealized models. Our more realistic simulations on strongly bound star clusters and stellar clumps in galaxies (e.g., Bekki et al. 2004a; Bekki et al. 2006) will provide the details on more realistic evolution of star clusters and clumps in galaxies.

2 THE MODEL

Previous numerical simulations on disk galaxy formation showed that very massive clumps (m_c) with masses of $10^8-10^9\mathrm{M}_{\odot}$ can spiral into the nuclear regions of galaxies owing to dynamical friction to finally become galactic bulges (Noguchi 1998). Stars initially within these massive clumps are highly unlikely to be within the disk components of the present galaxies. We thus focus on stellar clumps with $m_c \le 10^7\mathrm{M}_{\odot}$ which can be dispersed to become field stellar populations in galaxy (and thus be observed in the present galactic disks). Since we focus on field AGB stars in the present galaxies, we investigate the evolution of unbound stellar clumps that can finally become field stars after dispersal of the clumps: The bound stellar clumps can be observed as star clusters (i.e., not field stars) in the present galaxies after long-term dynamical interaction with their host galaxies. Although we show the evolution of spatial distributions for *all stars* initially within clusters, we consider that the results can be held for spatial distributions for AGB stars.

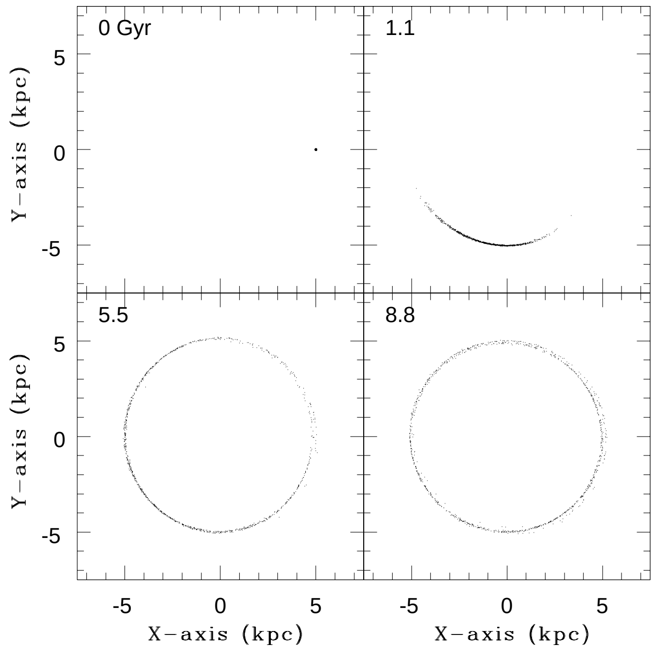

Figure 1. Time evolution of the distribution of stars of an unbound star cluster ("stellar clump") projected onto the x-y plane in the standard model. The numbers indicated in the upper left corner of each panel represent the time (T in units of Gyr) that has elapsed since the simulation starts. The x-y plane corresponds to the galaxy's disk plane, which initially includes orbital planes of stellar clumps.

We investigate ~ 9 Gyr evolution of azimuthal distributions ($N(\theta)$) of stars initially in stellar clumps with different masses (m_c), numbers of stars (n_c), sizes (r_c), internal velocity dispersion (σ_c), and orbits with respect to the centers of their host galaxies. The initial position ($\mathbf{x}$) and velocity ($\mathbf{v}$) of a clump with respect to the center of its host galaxy are $(x,y,z) = (R_c, 0, 0)$ and $(v_x,v_y,v_z) = (0, f_cV_0, 0)$, respectively, where f_c and V_0 are parameters determining the orbit and the circular velocity at $R = R_c$, respectively (R is the distance from the galaxy center). Each clump is assumed to have a Plummer density profile (e.g., Binney & Tremaine 1987) and an isotropic velocity dispersion.

We construct models with parameters consistent with physical properties of the LMC to compare the results with observations for the LMC (Cioni et al. 2006a). We adopt the same gravitational potential as used in previous simulations of the LMC with the total mass of $2\times10^{10}\mathrm{M}_{\odot}$ (e.g., Murai & Fujimoto 1980) and thereby investigate the evolution of stars represented by test-particles under the gravitational field both for "isolated" models and "tidal interaction" ones. The total number of AGB stars observed (e.g., Cioni & Habing 2003) for the LMC is an order of 10^4 (~ 30000), which means that the total number of AGB stars used for each radial bin in estimating azimuthal distributions of stars is an order of 10^3. We accordingly show the results with the models with $n_c = 10^3$. Since we investigate test-particle simulations, the essential results do not depend on n_c.

We mainly investigate the isolated models in which stellar clumps can be influenced only by gravitational fields of their host galaxies for $\sim$ 9 Gyr. For the tidal interaction models, we use the same model as used by Bekki et al. (2004b) and Bekki & Chiba (2005) in which orbital evolution of the LMC and the SMC during the LMC-SMC-Galaxy interaction is investigated for the last $\sim$ 9 Gyr. Since the typical age of AGB populations is several Gyrs (Cioni & Habing 2003), we mainly discuss the distributions of stars at $T = 5.5$ Gyr, where T represents the time that has elapsed since the simulation starts.

We mainly show the results of the standard isolated model (referred to as "the standard model" just for convenience) with $r_{\rm c}$ = 100pc, $\sigma_{\rm c}$ = 1 km s^{-1}, $R_{\rm c}$ = 5 kpc, and $f_{\rm c}$ = 1. Considering that (i) stellar clumps are born embedded within giant molecular clouds (GMCs) (e.g., Lada & Lada 2003) and (ii) there is an observed relationship ($m_{\rm GMC} \propto {r_{\rm GMC}}^2$) between their masses ($m_{\rm GMC}$) and sizes ($r_{\rm GMC}$) by Larson (1981), we adopted the above $r_{\rm c}$ corresponding to the sizes of GMCs with the masses of $10^6 - 10^7 {\rm M}_{\odot}$. The adopted $\sigma_{\rm c}$ corresponds to a typical velocity dispersion of open clusters (e.g., Binney & Tremaine 1987). We shows the results of the 12 models, for which the parameter values are given in Table 1. We try to quantify the degrees of inhomogeneities in the azimuthal distributions of stars by introducing a parameter σ_θ, which is a dispersion in N_θ (i.e., ${\sigma_\theta}^2 = \Sigma {N_\theta}^2/N_{\rm bin} - (\Sigma N(\theta)/N_{\rm bin})^2$, where $N_{\rm bin}$ is the total bin number used in the present study) for a given radius in a galaxy: The larger (smaller) σ_θ mean higher (lower) degrees of inhomogeneities. We note that the σ_θ statistic is only intended to quantify the azimuthal asymmetry in these simplified models. For real data, a method such as tracing the mean metallicity as a function of position (Cioni et al. 2006a) should be used.

We mainly shows the results of the models in which only a stellar clump is orbiting a galaxy. This is because we intend to show more clearly the essential ingredients of the evolution of N_θ. Several stellar clumps with almost identical ages and metallicities at a given radius can be formed in real galaxies. Since different clumps can have different N_θ, it is possible that the integrated N_θ of these multiple clumps can not clearly show an inhomogeneity. We have investigated a model ("multiple clump model") in which (i) five clumps, one of which has the same mass and the size of the clump used in the standard model, are initially located at the same distance from a galaxy yet at different azimuthal angles, (ii) the mass distribution follows a canonical luminosity function of the Galactic globular cluster (Harris 1991), and (iii) other model parameters are the same as those in the standard model. We have confirmed that since the integrated N_θ of the five clumps is mostly determined by the stellar distribution of the dominant (the most massive) clump, an inhomogeneity in N_θ can be seen in the multiple clump model.

3 RESULTS

Fig. 1 shows that the initial compact distribution of the stellar clump in the standard model (I1) is transformed into a "crescent-shaped" one ($T = 1.1$ Gyr) through phase mixing of stars. As dynamical evolution proceeds, the azimuthal distribution of stars becomes more circular and less inhomogeneous ($T = 5.5$ and 8.8 Gyr). Fig. 2 shows that although the azimuthal distribution of stars projected onto the x-y plane appears to be more homogeneous at $T = 5.5$ Gyr (Fig. 1), $N(\theta)$ clearly shows a high degree of inhomogeneity: There is a factor of $\sim$ 5 difference between the minimum and the maximum $N(\theta)$. σ_θ is 0.27, 0.26, and 0.13 for T = 1.1 Gyr, 5.5 Gyr, and 8.8 Gyr, respectively, which clearly indicates that the degree of inhomogeneity in the azimuthal distribution of stars lessens owing to phase mixing. These results demonstrate that the initial inhomogeneous distribution of stars ($\sigma_\theta > 0.2$) can be maintained in the galaxies for several Gyrs in this model. These results thus suggest that inhomogeneous azimuthal distributions of stars observed in the present galaxies can probe the past clumpy stellar distributions of the galaxies several Gyr ago.

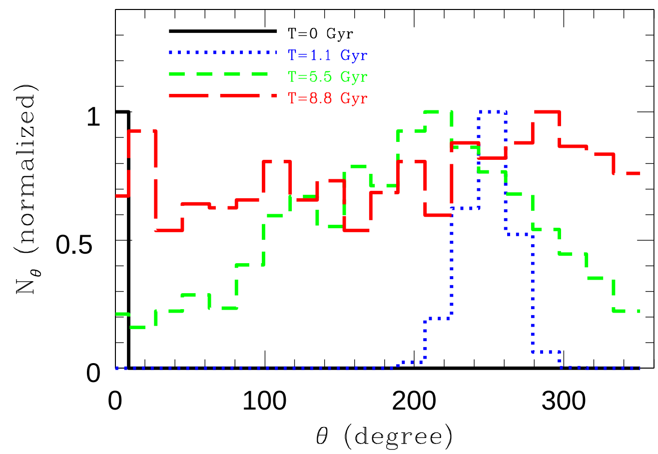

Figure 2. The azimuthal distributions ($N(\theta)$) of stars at four different epochs, T = 0 Gyr (black solid), T = 1.1 Gyr (blue dotted), $T = 5.5$ Gyr (green short-dashed), and $T = 8.8$ Gyr (red long-dashed), for the standard model. For convenience, all stars at $T = 0.0$ Gyr are assumed to be in the first θ bin (i.e., $\theta \le 10°$).

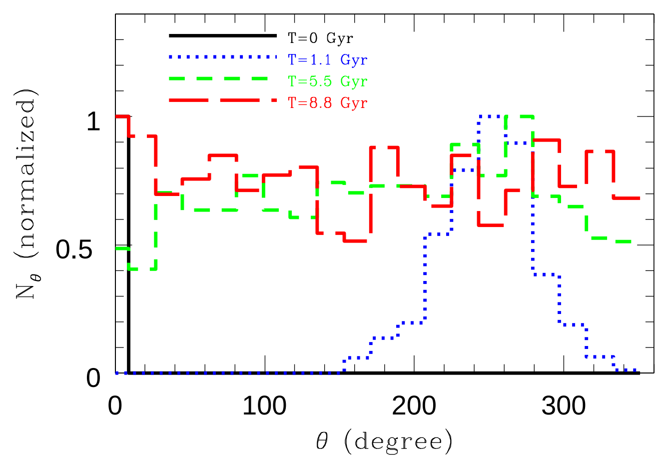

Figure 3. The same as Fig. 2 but for the model I2.

Fig. 3 shows that the initial inhomogeneous distribution can much more quickly disappear in the model I2 with a larger size of the stellar clump owing to the more efficient phase mixing. $N(\theta)$ is more homogeneous and thus has a smaller σ_θ (0.13) at $T = 5.5$ Gyr in comparison with the standard model. Considering the $m_{\rm GMC} - r_{\rm GMC}$ relation (i.e., $m_{\rm GMC} \propto {r_{\rm GMC}}^2$) of GMCs from where stellar clumps are assumed to form, this result implies that initial inhomogeneities in the azimuthal distributions of stars can more quickly disappear for more massive stellar clumps. This dependence of the results on r_c does not depend on other parameters such as σ_c,R_c, and f_c.

We find the following parameter dependences for the isolated models: (i) the initial inhomogeneous distribution of stellar clumps can more quickly disappear in the models with larger σ_c ($\sigma_\theta = 0.10$ at $T = 5.5$ Gyr in I3), (ii) the models with smaller f_c (i.e., more elongated orbit) show larger σ_θ (e.g., 0.30 and 0.20 at $T = 5.5$ Gyr and $T = 8.8$ Gyr, respectively, in I4), and (iii) the final σ_θ at $T = 8.8$ Gyr does not depend so strongly on R_c (e.g., 0.14 in I5). These results suggest that it depends on initial properties of stellar clumps how quickly the initial inhomogeneous distributions ($\sigma_\theta > 0.2$) disappear owing to phase mixing in disk galaxies. These furthermore imply that the spatial distribution of field stars with a given age and metallicity has a potential to probe the initial conditions of a stellar clump from which the stars originate.

Fig. 4 shows that stellar clumps with different initial parameters have different spatial distributions of stars at $T = 5.5$ Gyr because of (i) different initial conditions of the clumps (e.g., R_c) and (ii) different strength of tidal force that the clumps feel from the Galaxy and the SMC. Fig. 5 clearly indicates that each clump has an inhomogeneous $N(\theta)$, though the degree of inhomogeneity (σ_θ) is different between them. The synthesized azimuthal distribution for all stars from the seven models also show a significant inhomogeneity ($\sigma_\theta = 0.22$). These results imply that inhomogeneous azimuthal distribution of stars due to dispersal of stellar clumps can last several Gyrs in strongly interacting galaxies like the LMC and the SMC.

It is highly likely that different stellar clumps initially have different ages and metallicities in the LMC. The above results in Figs. 4 and 5 accordingly imply that a stellar clump with a metallicity formed about several Gyr ago in the LMC can be probed by an inhomogeneous azimuthal distribution of field stars with the same metallicity as obtained from the K_s magnitude distribution of AGB stars. These results also imply that field stars for different metallicity ranges in the LMC have fossil information of different clumps formed several Gyr ago.

Thus, both isolated and tidal interaction models show that significantly inhomogeneous azimuthal distributions of stars due to dispersal of unbound stellar clumps can last several Gyrs, though the timescales (T_{sur}) for the inhomogeneities to disappear depend strongly on physical properties of the clumps. The self-gravity of the clumps, which is not included in the present simulations, is highly likely to extend the survival timescales T_{sur}. We therefore suggest that the time evolution of $N(\theta)$ is slower in real stellar clumps than in the simulated ones.

4 DISCUSSIONS AND CONCLUSIONS

We have shown that stellar clumps formed about several Gyr ago in the LMC's disk can leave inhomogeneous azimuthal distributions of field stars in the present LMC even after strong tidal interaction between the LMC, the SMC, and the Galaxy. This result strongly suggests that although the *integrated* distribution of field stars with different ages and metallicities in the LMC can be relatively homogeneous, the azimuthal distributions of the stars *for a given age and metallicity range* (thus stars from a specific stellar clump) can be significantly inhomogeneous ($\sigma_\theta > 0.2$). In the real LMC, field stars for a given radius (R) originate from different stellar clumps formed with different masses and metallicities at different epochs. The characteristic azimuthal distribution at a given radius in the LMC accordingly would be determined by the stars originating from the most massive stellar clump ever formed around the radius.

Cioni et al. (2006a) reported that (1) mean ages of stars are different in different regions of the LMC and (2) mean ages of stellar populations can be younger in the northern

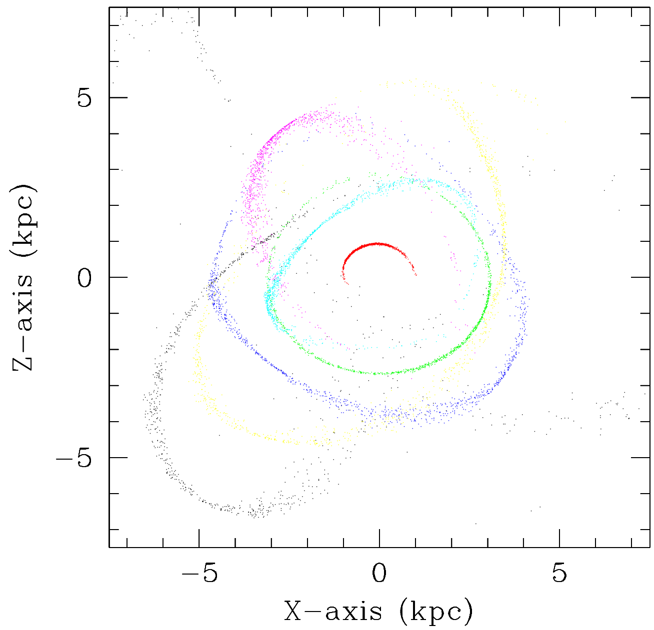

Figure 4. Distributions of stars originating from different stellar clumps projected onto the x-z plane for the tidal interaction models T1−T7. Different colors show different models: black, yellow, green, blue, cyan, red, and magenta represent T1, T2, T3, T4, T5, T6, and T7, respectively. The initial disk defined by orbital planes of stellar clumps in this interaction models is inclined so that the configuration of the disk including clumps' orbital plane (in the sky) is consistent with observations (Bekki & Chiba 2005). The distribution projected onto the x-z plane is similar to that viewed from the face-on of the LMC.

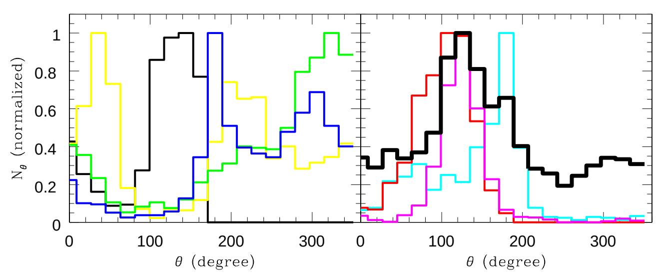

Figure 5. The azimuthal distributions ($N(\theta)$) of stars at $T = 5.5$ Gyr for the tidal interaction models T1−T7. Different colors show different models: black, yellow, green, blue, cyan, red, and magenta represent T1, T2, T3, T4, T5, T6, and T7, respectively. For comparison, $N(\theta)$ for all stars from the seven models is shown by a thick black line.

and southern parts of the inner disk in comparison with the western part of the inner disk and the northern east part of the outer disk. We suggest that this observed inhomogeneity can be caused by the combination of inhomogeneous distributions of field AGB stars originating from massive stellar clumps formed at different epochs: The observed inhomogeneity suggests that the LMC had a significantly clumpy distribution of stars about several Gyr ago. The observed inhomogeneity in the azimuthal distribution of metallicities of stars (Cioni et al. 2006a) might well be closely associated with dispersal of stars originating form stellar clumps with different metallicities. It is however unclear whether the LMC several Gyr ago was so clumpy as to be identified as clump-clusters (or chain galaxies).

Harris & Zaritsky (2004) reported that the SMC has a ring-like structure of stars with metallicities of $Z = 0.004$ and ages of about 2.5 Gyr. The present study has demonstrated that ring-like structures or crescent-shaped ones can be formed from stellar clumps owing to phase mixing. This suggests that the observed ring-like structure in Harris & Zaritsky (2004) is due to the dispersal of a massive stellar clump(s) formed about 2.5 Gyr ago: The observed large-scale (i.e., kpc-scale) annular structure does not necessarily mean that the *initial* distribution of new stars in the SMC about 2.5 Gyr was similar to a ring.

Cioni et al. (2006a) proposed that star formation histories of AGB populations can be investigated by comparing the observed K_s magnitude distributions of AGB stars with the corresponding theoretical predictions based on population synthesis models (See also Cioni et al. 2003 for the details of metallicity determination of AGB stars). Cioni et al. (2006b) investigated the K_s magnitude distribution of carbon stars in the SMC and thereby found a "broken-ring" with a larger degree of inhomogeneity in age distributions of field stars: They confirmed the presence of the ring reported by Harris & Zaritsky (2004). They also found that the stellar population becomes increasingly more metal-rich from southern east (SE) to northern west (NW) with increasing mean age within the ring. The present study suggests that the locations of the peak stellar densities of stellar clumps being dispersed (to become field stars) in the azimuthal direction for a given radius are different between different clumps (with different masses, sizes, and metallicities). We thus suggest that the observed inhomogeneous age and metallicity distributions within the ring of the SMC can be due to the dispersal of multiple clumps with different metallicities and ages formed at the radius where the ring is now observed. It is however unclear how the observed SE-NW age and metallicity gradients were formed in the SMC and what is the effect of the orientation of the SMC on these findings.

Massive, strongly bound stellar clumps with $m_\mathrm{c} = 10^8 - 10^9 \mathrm{M}_\odot$, which could be responsible for the clumpy appearances of galaxies such as clump-clusters at intermediate and high redshifts (e.g., Elmegreen et al. 2005), are suggested to spiral into the central regions of galaxies to become galactic bulges (e.g., Noguchi 1998). Therefore, the presence of such very massive clumps in these distant galaxies can be difficult to be probed by inhomogeneous azimuthal distributions of AGB stars in *disk components* of the present galaxies. The present study thus suggests that the clumpy appearances of distant galaxies caused by less massive clumps can be probed by inhomogeneous azimuthal distributions of AGB stars in the present galaxies.

AGB stars are just one of stellar populations that are formed within star clusters, and accordingly other stellar populations (e.g., planetary nebulae) can also probe the clumpy pasts of galaxies. Owing to the bright magnitudes of AGB stars, the AGB population is the most promising in probing the clumpy pasts not only for galaxies in the Local Group but also for nearby ones outside the Local Group in future observational studies. Clumpy structures due to the presence of bound and unbound star clusters have significant influences on dynamical evolution of galaxies such as thick disk formation (e.g., Kroupa 2002). Thus probing clumpy pasts of galaxies from AGB stars can be important for better understanding long-term dynamical evolution of galaxies.

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