MASSIVE STARS AND GLOBULAR CLUSTER FORMATION

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ABSTRACT

We first present chemodynamical simulations to investigate how stellar winds of massive stars influence early dynamical and chemical evolution of forming globular clusters (GCs). In our numerical models, GCs form in turbulent, high-density giant molecular clouds (GMCs), which are embedded in a massive dark matter halo at high redshifts. We show how high-density, compact stellar systems are formed from GMCs influenced both by physical processes associated with star formation and by tidal fields of their host halos. We also show that chemical pollution of GC-forming GMCs by stellar winds from massive stars can result in star-to-star abundance inhomogeneities among light elements (e.g., C, N, and O) of stars in GCs. The present model with a canonical initial mass function (IMF) also shows a C-N anticorrelation that stars with smaller [C/Fe] have larger [N/Fe] in a GC. Although these results imply that “self-pollution” of GC-forming GMCs by stellar winds from massive stars can cause abundance inhomogeneities of GCs, the present models with different parameters and canonical IMFs cannot show N-rich stars with [N/Fe] ~ 0.8 observed in some GCs (e.g., NGC 6752). We discuss this apparent failure in the context of massive star formation preceding low-mass ones within GC-forming GMCs (“bimodal star formation scenario”). We also show that, although almost all stars (~97%) show normal He abundances (Y) of ~0.24, some stars later formed in GMCs can have Y as high as ~0.3 in some models. The number fraction of He-rich stars with Y > 0.26 is, however, found to be small (~10^-3) for most models. We discuss this result in the context of the possibly large Y-values observed in a few Galactic GCs.

Subject headings: galaxies: star clusters — galaxies: stellar content — Galaxy: halo — globular clusters: general

Online material: color figure

1. INTRODUCTION

Dynamical and chemical properties of globular clusters (GCs) in the Galaxy have been discussed in variously different contexts, such as the Galaxy formation by accretion of low-mass dwarfs (e.g., Searle & Zinn 1978), self-pollution by asymptotic giant branch (AGB) stars within proto-GC clouds (e.g., Cottrell & Da Costa 1981), and the formation process of GCs at high redshifts (e.g., Djorgovski 1993). The observed correlations and anticorrelations in light elements (e.g., C, N, O, Na, Mg, and Al) of stars within GCs have long been considered to provide vital clues for the early formation histories of GCs (e.g., Gratton et al. 2004). Recent observational studies, which have revealed star-to-star abundance inhomogeneity among light elements of stars on the main sequence in the Galactic GCs, have suggested that the observed abundance inhomogeneity is due to the second generation of stars formed from ejecta of the first generation of stars (e.g., AGB and OB stars) within GCs (e.g., Da Costa et al. 2004): proto-GC clouds could be chemically polluted by earlier generations of stars within forming GCs (which is often referred to as “self-pollution”).

It however remains unclear (1) how such self-pollution was possible within proto-GC clouds (e.g., Smith & Norris 1982) and (2) whether massive stars or AGB ones are responsible for the self-pollution processes (e.g., Prantzos & Charbonnel 2006; Smith 2006). Previous studies discuss whether chemical evolution models with canonical initial mass functions (IMFs) and the self-pollution processes by AGB stars could have some problems in explaining the observed large fraction of CN-strong stars (Smith & Norris 1982; Bekki 2006). Decressin et al. (2006) have recently suggested that self-pollution by stellar winds of massive stars with masses of 20–120 M☉ and fast rotation can possibly explain the observed abundance patterns of GCs, such as O-Na and Mg-Al anticorrelations. It is, however, unclear how stellar winds from massive stars influence chemical evolution of forming GCs owing to the lack of extensive chemodynamical simulations of forming GCs.

The purpose of this paper is thus to discuss, for the first time, whether stellar winds from massive stars can be vital in chemical evolution of forming GCs based on chemodynamical simulations of forming GCs within giant molecular clouds (GMCs). We assume that GCs can be formed in GMCs within low-mass galaxies embedded in dark matter halos at high redshifts (z > 6) and thereby investigate the formation processes of GCs within the galaxies. We investigate how stellar winds from massive stars, in particular, those with the masses (m☉) larger than 8 M☉, influence chemical evolution of forming GCs within GMCs. By comparing the observed abundance ratios of [N/Fe] and [C/Fe] and the corresponding simulation results, we raise important questions on IMFs and star formation histories of forming GCs. Since we focus on chemical abundances of GCs, we do not intend to discuss structural properties and scaling relations (e.g., the fundamental plane) of GCs in the present paper. Dynamical properties of GCs with different masses will be discussed in our future papers (K. Bekki & M. Chiba 2007 [hereafter BC07], in preparation). We do not intend to discuss the roles of AGB stars in the chemical evolution of forming GCs in this paper (see Bekki [2006] and Bekki et al. [2007] for the detailed discussions on this matter).

2. THE MODEL

Recent numerical simulations have suggested that high-density gaseous regions within low-mass dwarf galaxies embedded in
dark matter halos at high redshifts ($z$) can be the formation sites of GCs (e.g., Bromm & Clarke 2002). Theoretical studies based on numerical simulations of GMCs with internal turbulent flows suggested that bound star clusters (SCs) can be formed in GMCs with high star formation efficiencies (e.g., Klessen et al. 2000). Guided by these previous studies, we consider that GCs can be formed in turbulent GMCs within low-mass dwarfs at high $z$. Since the details of numerical methods and techniques on chemodynamical simulations using GRAPE5 smoothed particle hydrodynamics (SPH) codes for GC formation are given in BC07, we briefly summarize these in the following.

GMCs with sizes ($r_g$) and masses ($m_g$) are assumed to have homogeneous spherical distributions for most models. We set up the initial velocity fields due to turbulent flows within GMCs in the same way as Mac Low et al. (1998) did. We therefore assume that a turbulent velocity field within a GMC is a Gaussian random field with power spectrum $P(k) = P_0 k^\alpha$, where $\alpha$ is set to be 2.0 for most models and $P_0$ is a parameter controlling the total kinematical energy due to the turbulent flow in the GMC. The virial ratio ($t_v$) of $2T_k/W$, where $T_k$ and $W$ are the total kinematical energy and the absolute magnitude of the total potential energy for a GMC, respectively, is determined by $P_0$ and set to be 0.5 in the present study. Since an isothermal equation of state is suggested to be appropriate for star-forming interstellar clouds of molecular gas (e.g., Mac Low et al. 1998; Klessen et al. 2000), we adopt the equation with the initial temperature of 10 K.

A GMC represented by $10^5$ SPH particles is assumed to be within a low-mass dark matter halo with a mass of $10^8 M_\odot$ and the universal “NFW” radial density profile (Navarro et al. 1996) with the scale length ($r_s$) of 496 pc and the concentration parameter ($c$) of 10. A GMC is assumed to have a circular orbit, and the initial distance from the center of its host’s dark matter halo is a free parameter described by $R_p$. Since GMCs in a halo are influenced strongly by tidal fields of the halo, the formation processes of GMCs within GMCs can be different in different locations within the halo.

Gas particles are assumed to be converted into new stellar particles, if (1) local dynamical timescales are shorter than local sound crossing time and (2) local gas densities exceed a threshold gas density ($\rho_{th}$) of star formation (e.g., Nakasato et al. 2000). Recent high-resolution numerical simulations on the effects of stellar winds from massive stars on the interstellar medium have demonstrated that about 30% of the total energy ($\sim 10^{50}$ ergs) from a massive star can be converted into kinematical energy of gas around the star (e.g., Frey et al. 2003). Guided by these simulations, we consider that one massive star can give its surrounding gas kinematical energy of $3 \times 10^{49}$ ergs in the present study. Stellar particles are assumed to lose their masses gradually ($m_s$) owing to mass loss through stellar winds from massive stars. Since chemical abundances of stellar winds from massive stars are time dependent and quite different in light elements from those of gas from where the stars are born (e.g., Schaller et al. 1992), stars later formed from gas chemically polluted by stellar winds from the first generation of stars in a GMC can show abundances different from those in the first generation.

We use the numerical tables for time-dependent mass-loss rates of nonrotating massive stars and for the chemical yields of the stars shown in Schaller et al. (1992) for a metallicity of $Z = 0.001$ in order to calculate masses and abundances of stellar winds from stellar particles at each time step for a given IMF. This is because these tables are only the ones that show explicitly the time evolution of abundances relevant to the present study (H, He, C, N, and O) for different massive stars. Since chemical yield tables (including Na, Mg, and Al) for rotating massive stars by Decressin et al. (2006) are only for those with a given mass ($m_1 = 60 M_\odot$) and do not show the time-dependent evolution of mass-loss rates and abundances of massive stars, we do not use these tables in the present study. We adopt power-law IMFs $[v(m_i) \propto m_i^{-\alpha}]$ with the slopes of $s$ and an upper and lower mass cutoff($m_u$ and $m_l$); $m_l$ is set to be 0.1 $M_\odot$ for all models, whereas $m_u$ is regarded as a free parameter controlling self-pollution processes by massive stars in the present study. Initial abundances of gas are set to be the same as those used by Schaller et al. (1992) for consistency.

We focus mainly on the observed C-N anticorrelation (e.g., Smith & Norris 1993) that stars with higher [C/Fe] have smaller [C/Fe] in GCs, first because these observations have been extensively discussed in other theoretical papers (e.g., Bekki et al. 2007), and second because [N/Fe] and [C/Fe] can be investigated by the present models based on stellar yield table by Schaller et al. (1992), which does not provide tables for Na, Mg, and Al. We will discuss O-Na and Mg-Al anticorrelations in our future papers, if the tables for time-dependent evolution of Na, Mg, and Al for massive stars with variously different masses and metallicities are available: for this reason, we do not use the latest important work by Maeder & Meynet (2006) for rotating and nonrotating massive stars. It should be stressed here that the observed C-N, O-Na, and Mg-Al anticorrelations can be possibly reproduced by chemical evolution models using stellar yield tables for fast-rotating massive stars (Decressin et al. 2006).

Although we have investigated models with different parameter values, we mainly show the “standard model” with $m_0 = 10^6 M_\odot$, $r_g = 53$ pc, $s = 2.35$, $m_u = 120 M_\odot$, and $R_p = 0.2 r_s = 99$ pc. This is mainly because this model clearly shows how a star-to-star abundance inhomogeneity within a forming GC is achieved during chemodynamical evolution of the GMC with star formation: the details of the parameter dependences of abundance patterns of simulated GCs will be given in BC07. The mass density of the initial GMC in the standard model is much higher than that adopted in the model with $m_0 = 5 \times 10^5 M_\odot$ and

### Table 1: Model Parameters and Results

| Model          | $m_g$ ($10^6 M_\odot$) | $R_p$ (pc) | $s$ | $m_u$ | $\delta Y$ | $\delta [C/Fe]$ | $\delta [N/Fe]$ |
|----------------|-------------------------|------------|-----|-------|------------|-----------------|-----------------|
| Standard       | 1.0                     | 99         | 2.35| 120   | 0.032      | 0.028           | 0.223           |
| Lower mass     | 0.1                     | 99         | 2.35| 120   | 0.026      | 0.023           | 0.189           |
| Lowest mass    | 0.05                    | 99         | 2.35| 120   | 0.032      | 0.028           | 0.222           |
| Nucleus        | 1.0                     | 0          | 2.35| 120   | 0.054      | 0.049           | 0.330           |
| Top-heavy IMF  | 1.0                     | 99         | 1.35| 120   | 0.270      | 0.332           | 0.827           |
| Bottom-heavy IMF | 1.0                 | 99         | 2.35| 40    | $<10^{-5}$ | $<10^{-5}$      | $<10^{-5}$      |
$r_g = 50$ pc by Geyer & Burkert (2002), in which GC formation does not occur owing to low efficiencies of star formation. The mass densities ($n_g$) of the preset models, however, are assumed to roughly follow the observed relation of $n_g = 3400(r_g/1$ pc$)^{-1.1}$ (atoms cm$^{-3}$) by Larson (1981).

We describe only five representative and important models (e.g., standard model) in this paper, and the parameter values and some important results in these models are given in Table 1: $m_g$ (col. [1]), $R_p$ (col. [2]), $s$ (col. [3]), $m_u$ (col. [4]), $\delta Y$ (col. [5]), $\delta(C/Fe)$ (col. [6]), and $\delta(N/Fe)$ (col. [7]); $\delta Y$ ($\delta(C/Fe)$ and $\delta(N/Fe)$) is the difference between the minimum and maximum $Y$ ($[C/Fe]$ and $[N/Fe]$) at $T = 11.0$ Myr. For example, the values shown in the table for the standard model mean that the maximum $Y$, $[C/Fe]$, and $[N/Fe]$ are 0.275, 0.168, and 0.324, respectively, at $T = 11.0$ Myr. $[O/Fe]$ inhomogeneity is not the main focus of this paper, so that it is not so extensively discussed. We however found that (1) $\delta(O/Fe)$ is 0.030 for the standard model, and (2) it is larger for models with larger $\delta(C/Fe)$.

We do not intend to discuss extensively the roles of Type II supernovae (SNe II) in GC formation in the present study, mainly because we confirm that SNe II are not so important for dynamical evolution and star formation in GMCs. Previous simulations by Nakasato et al. (2000) also showed that self-enrichment of heavy elements due to SNe II does not occur so that simulated GCs show homogeneities in Fe-peak elements (which is consistent with most GCs in the Galaxy). We find that if the time delay between star formation and the onset of SNe explosion is similar to a typical lifetime of massive stars ($\sim 10^7$ yr, which corresponds to an average lifetime for stars with $8–120 M_\odot$ in models with $s = 2.35$), SNe II can be important only for expelling the remaining gas of GC-forming GMCs into interstellar regions of low-mass halos. We thus show the results of models including feedback effects of massive stars only for clarity: the roles of SNe II in GC formation will be given in BC07.

Thus, the present study adopts a fundamentally different approach from previous one-zone chemical evolution models (e.g.,...
Bekki et al. 2007), in the sense that not only mixing of stellar ejecta (from massive stars) and the surrounding gas but also star formation from the mixed gas are self-consistency investigated through dynamical simulations with Jeans instability for star formation, kinematical feedback effects of OB stars, and noninstantaneous recycling of stellar ejecta. The present simulations thus enable us to discuss whether the simulated GCs can explain both dynamical properties and chemical ones, although the present models do not allow us to discuss the observed anticorrelations (e.g., C-N, O-Na, and Mg-Al relations) in a self-consistent manner.

3. RESULTS

Figure 1 describes how the star formation rate within a GMC evolves with time in the standard model. First stars are formed within a GMC at $T = 2.4\, \text{Myr}$ when the turbulence within the GMC has decayed significantly to form local high-density gaseous regions ($\rho_g \geq 10^3\, \text{atoms cm}^{-3}$). The star formation reaches its maximum rate ($0.32\, M_\odot\, \text{yr}^{-1}$) at $T = 5.0\, \text{Myr}$, and suddenly declines and finally stops completely until $T = 8.0\, \text{Myr}$ owing to (1) feedback effects of massive stars (i.e., the momentum input) on the remaining gas and (2) stripping of the gas by the background tidal field of the dark matter halo. Almost $90\%$ of initial gas is converted into new stars within a timescale of $\sim 5\, \text{Myr}$ to form a number of SCs.

Figure 2 shows the final spatial distribution of SCs at $T = 43.5\, \text{Myr}$, which corresponds to one orbital rotation after most stars are formed within the GMC. The largest SC shows a size of $10.6\, \text{pc}$, an appreciably flattened shape, two companion SCs, and a total stellar mass (including field stars and the companions) of $8.3 \times 10^5\, M_\odot$ within $50\, \text{pc}$ from the SC’s center. The two small, low-mass, and bound SCs survived from tidal destruction by their host halo may well be identified as low-mass open clusters (OCs). Field stars that are diffusely distributed within the halo were initially weakly bound or unbound star-forming complexes. These results imply that not only a GC (and OCs) but also field stars can be formed from a single high-density GMC with a mass of $\sim 10^6\, M_\odot$.

Figure 3 shows that (1) the standard model can reproduce a C-N anticorrelation that stars with smaller $[\text{C}/\text{Fe}]$ have larger $[\text{N}/\text{Fe}]$ in the simulated GC at $T = 11.0\, \text{Myr}$, and (2) the star-to-star abundance spread in $[\text{C}/\text{Fe}]$ and $[\text{N}/\text{Fe}]$ is about $0.03$ and $0.22$, respectively. However, it cannot explain the existence of very low N/Fe stars.

![Normalized cumulative number distribution](image)

Fig. 4.—Normalized cumulative number distribution (in log scale) of He $[F_Y(>Y); \text{left}]$ and $[\text{N/Fe}]$ $[F_{\text{N}(>\text{N/Fe})}; \text{right}]$ for stars (solid lines) and gas (dotted lines) in the standard model. For comparison, the observed range of $0.26 < Y < 0.29$ for He-rich stars consisting of about $30\%$ of the entire stellar population in NGC 2808 (D’Antona et al. 2005) are shown by two dashed lines in the left panel. The observed range of $0.0 < [\text{N/Fe}] < 0.8$ for AGB stars in NGC 6752 (Smith & Norris 1993) is shown by two dashed lines in the right panel. Note that the number fraction of He-rich stars with $Y > 0.26$ is very small ($\sim 10^{-3}$).
N-rich stars with $[\text{N/Fe}] \sim 0.8$ observed in NGC 6752 (Smith & Norris 1993). It should be noted here that the gaseous components show high $[\text{N/Fe}]$ ($\sim 0.8$) and low $[\text{C/Fe}]$ ($\sim -0.2$). These results imply that although chemical pollution of gas by massive stars earlier formed does occur, stars cannot form efficiently from the polluted gas later because the gas is dispersed into the interstellar space to have a lower density due both to feedback effects of massive stars and to tidal stripping.

Figure 4 shows that the simulated number fraction of N-rich ($[\text{N/Fe}] > 0.2$) stars is small ($\sim 10^{-2}$). This result is inconsistent with observations that show the number fraction of CN-strong stars, which are considered to be N-rich stars, is as large as 0.5 in some GCs (e.g., NGC 6752; Smith & Norris 1993). This inconsistency results from the fact that only a very small fraction of chemically polluted gas is converted into new stars after the final burst of star formation ($T = 6.0$ Myr). It should be noted here that the number fraction of N-rich components ($[\text{N/Fe}] > 0.2$) in the gas is relatively high ($\sim 10^{-1}$). These results imply that if a GC is formed from a GMC that evolves in isolation (i.e., without interacting with other GMCs in the halo) and has a canonical IMF, self-pollution by stellar winds of massive stars can hardly explain the large fraction ($>0.1$) of CN-strong (i.e., N-rich, C-depleted) stars observed in some Galactic GCs. It should be noted, however, that the observed fraction of N-rich stars is quite diverse (e.g., Norris 1988); some GCs with very low fraction of N-rich stars could be consistent with some of the present models.

Figure 4 shows that although stars show the He abundance spread, the number fraction of moderately high He-rich ($Y > 0.26$) stars is very small ($\sim 10^{-3}$): this model is reasonable for GCs with "normal" $Y$. Accordingly this model cannot reproduce the high fraction ($\sim 30\%$) of He-rich ($0.26 \leq Y \leq 0.29$) stars observed for NGC 2808 (D’Antona et al. 2005) and for NGC 6441 (Caloi & D’Antona 2007), which implies that models with canonical IMFs are not reasonable for some GCs with high fractions of He-rich stars. Although $Y$ of gaseous particles range from 0.24 to 0.57, new stars cannot form from He-rich gas with $Y > 0.3$: the origin of stars with possibly very high $Y > 0.3$ in NGC 2808 (D’Antona et al. 2005) cannot be explained by self-pollution processes of GC-forming GMCs in the standard model with a canonical IMF. Although He-rich gaseous components can be finally formed, the local densities of these components become too low when they are formed in the standard model. This is why the number fraction of He-rich stars is very small in this model. Figure 5 shows that abundance inhomogeneity in $[\text{O/Fe}]$ is much less significant in comparison with $[\text{N/Fe}]$. The simulated results are not so consistent with the observations of GCs stars, where a great reduction of the surface oxygen abundance is observed in the most polluted objects.

Dependences of the results on model parameters are described as follows. Although all four models with different $m_2$ and $R_p$ and a canonical IMF with $s = 2.35$ (i.e., the Salpeter IMF) clearly show C-N anticorrelations and star-to-star abundance spread in He, C, and N, they cannot show very N-rich stars with $[\text{N/Fe}] \sim 0.8$ observed for CN-strong AGB stars in NGC 6752 (Smith & Norris 1993); $\delta [\text{N/Fe}]$ ranges from 0.19 to 0.33 (corresponding to $0.1 \leq [\text{N/Fe}] \leq 0.43$) in these models (see Table 1). The “nucleus” model shows a slightly larger degree of abundance inhomogeneity in the simulated GC, because gas ejected from massive stars cannot be blown away so effectively owing to the deep gravitational potential of the host halo: the chemically polluted gas can be used for further star formation. The number fractions of stars with $Y > 0.26$ (or with $[\text{N/Fe}] > 0.2$) are mostly $\sim 10^{-3}$ in these models with $s = 2.35$.

The “top-heavy IMF” model shows the presence of stars with very high $Y$ ($\sim 0.5$), because stellar winds of stars with $m_1 = 120 M_\odot$, and thus with $Y = 0.72$ in their later wind phases, can more effectively pollute the GC-forming GMC. Figure 6, however, shows that the fraction of Y-rich stars with $Y > 0.4$ is very small ($\sim 10^{-3}$). Figure 6 also shows that the number fraction of N-rich stars with $[\text{N/Fe}] > 0.2$ is 0.06, which is more consistent with the observed fraction of CN-strong stars in NGC 6752 (Smith & Norris 1993) than the standard model. We confirm that the fraction of N-rich stars can be as high as 0.4, if we adopt the top-heavy IMF models with initial isothermal radial density profiles $[\rho(r) \propto r^{-2}]$ of GMCs for which stellar winds of massive stars can more effectively pollute GC-forming GMCs in the very early phases.
stage of star formation. Thus, the present models with smaller \( s \) can better explain stellar abundances of GCs with larger degrees of abundance inhomogeneities in \( Y, [C/Fe] \), and \([N/Fe] \).

Although the above five models with \( m_0 = 120 \, M_\odot \) clearly show abundance spread among stars within the simulated GCs, the “bottom-heavy IMF model” with \( m_u = 40 \, M_\odot \) shows a very small degree of the abundance inhomogeneity; \( \delta Y, \delta [C/Fe], \) and \( \delta [N/Fe] \) are all less than \( 10^{-3} \). We confirm that (1) this result does not depend on \( m_g \), and (2) \( m_0 \geq 60 \, M_\odot \) is required for the simulated GCs to show star-to-star abundance inhomogeneities. These results imply that total numbers of massive stars with \( m_1 = 60 - 120 \, M_\odot \), which are determined by \( m_b \) for a given \( s \) (and \( m_0 \)), are important determinants controlling whether GCs can show observable star-to-star abundance inhomogeneities.

4. DISCUSSIONS

4.1. Problems Related to the Stellar Wind Scenario

Recent observations have reported that star-to-star abundance inhomogeneity can be seen in less evolved stars on the main sequence and subgiant branch (e.g., Cannon et al. 1998 for 47 Tuc), for which deep mixing is highly unlikely to occur: the self-pollution scenario might well be more promising than the mixing one. The present numerical simulations have first demonstrated that star-to-star abundance inhomogeneity is possible within GC-forming GMCs being polluted by stellar winds of massive stars (from now on this scenario is referred to as the stellar wind scenario, just for convenience).

However, the simulated fractions (\( \sim 10^{-2} \)) of N-rich ([N/Fe] > 0.2) stars for the adopted canonical IMF are too small to be consistent with the observed one for some GCs (e.g., NGC 6752; Smith & Norris 1993). This inconsistency implies either that stellar populations other than massive stars (e.g., AGB stars) could be responsible for the observed abundance patterns of GCs, or that the present models did not include important ingredients of GC formation processes (and thus failed to explain the observations). Since abundance inhomogeneity due to AGB stars were already discussed in previous papers (Cottrell & Da Costa 1981; Bekki et al. 2007), we focus on the later implication below.

If IMFs of forming GCs are significantly top-heavy (i.e., much smaller \( s \)), the observed large fraction of N-rich stars can be reproduced (Smith & Norris 1982; see also Prantzos & Charbonnel 2006, in the context of the observed O-Na anticorrelation). Although our top-heavy IMF model with \( s = 1.35 \) can show a large fraction of N-rich stars, the stellar wind scenario with a top-heavy IMF has serious problems, as described below. If we adopt the Salpeter IMF with \( m_1 = 0.1 \, M_\odot \) and \( m_0 = 120 \, M_\odot \), the mass fraction of massive stars with masses ranging from \( 8 \) to \( 120 \, M_\odot \) is about 0.84. Since the vast majority (\( \sim 90\% \)) of gas of these massive stars can be expelled from GC-forming GMCs via SNe II (owing to very shallow gravitational potentials of GMCs), the total masses of GCs can dramatically decrease after their formation. Previous theoretical works demonstrated that if self-gravitating SCs like GCs lose more than 50% of their original masses, they soon become disintegrated (e.g., Hills 1980). Furthermore, dynamical models of GCs with top-heavy IMFs demonstrated that GCs losing a significant fraction of their masses can be disintegrated during their dynamical evolution around the Galaxy (e.g., Chernoff & Weinberg 1990). Thus, we think that top-heavy IMFs in forming GCs cannot be plausible.

We can provide the following two possible solutions for the above inconsistency in the stellar wind scenario. First, most massive stars in GMCs are first formed before the major epoch of low-mass star formation so that their stellar winds can chemically pollute a large fraction of remaining gas from which low-mass stars are later formed. This time delay between the major epoch of massive star formation and that of low-mass one was not modeled properly in the present simulations for which stellar particles (“stars”) have almost identical masses. In this second solution, a large fraction of low-mass stars can be formed from N-rich gas well polluted by massive stars formed earlier: a larger degree of abundance inhomogeneity can be seen in GCs. It is, however, currently unclear in what physical conditions of GMCs massive stars can be formed earlier than low-mass ones: more quantitative discussions on this solution are given in § 4.2, just for convenience.

Second, GMCs forming GCs were chemically polluted not only by stars within the GMCs but also by those outside the GMCs (e.g., field massive stars): “external pollution” by field massive stars is required to explain the large fraction of N-rich stars. Owing to the lack of extensive simulations on this external pollution processes, it is unclear whether and how this process can occur in GMCs with low-mass galaxies at high redshifts. Thus, we cannot determine whether the first or the second solution is more reasonable and realistic until we perform new sets of simulations on time delay between low- and high-mass star formation and on the above external pollution processes.

Recent photometric observations of stars in \( \omega \) Cen have discovered a double main sequence (DMS) in the color magnitude diagrams (CMDs) of its stellar populations (e.g., Bedin et al. 2004). One of the most promising interpretations is that stars on the bluer main sequence (bMS) of the DMS represents a very helium-rich (\( Y \geq 0.3 \)) population (e.g., Norris 2004). Although the present chemodynamical simulations have first demonstrated that the formation of stars with moderately high \( Y > 0.26 \) is possible in GMCs chemically polluted by stellar winds from massive stars, the derived number fraction of He-rich stars (\( Y > 0.26 \)) is too small (\( \sim 10^{-3} \)) to be consistent with the observed one (e.g., 0.3 for the bMS in \( \omega \) Cen). Bekki & Norris (2006) suggested that \( \omega \) Cen was a nucleus of an ancient dwarf galaxy where He-rich gas could be efficiently transferred into its nucleus and consequently used for star formation to form the bMS.

4.2. Twofold Star Formation: Massive Stars First and Low-Mass Ones Second?

We have suggested above that if the vast majority of massive stars (“polluters” of star-forming GMCs) are formed well before the formation of low-mass ones, the fraction of N-rich stars can be significantly increased to be consistent with the observed one. In order to discuss this point in a quantitative way, we here assume that (1) a GC-forming GMC has two major epochs of star formation, (2) the total gas mass consumed for the formation of the first (second) generation of stars is \( M_1 (M_2) \), (3) the slope of the power-law IMF of the first (second) generation is \( s_1 (s_2) \), (4) the initial mass fraction of N in the GMC is \( 7 \times 10^{-5} \) (from the table by Schaller et al. [1992] for \( m_1 = 120 \, M_\odot, Z = 0.001 \), and \( T = 0 \) yr), and (5) the mass fraction of N in the winds of stars in the first generation is \( 7 \times 10^{-4} \) (from the table by Schaller et al. [1992] for \( m_1 = 120 \, M_\odot, Z = 0.001 \), and \( T = 3.1 \times 10^8 \) yr). For a given \( M_1, s_1, \) and \( s_2 \) (fixed at 2.35), we search for parameter values of \( M_2 \) for which \( [N/Fe] \) between the first and the second generations is as large as 0.8 observed for NGC 6752 (Smith & Norris 1993). In these models, the vast majority of massive stars (polluters) are formed in the first epoch of star formation owing to the adopted top-heavy IMF (\( s_1 < 2.35 \)), whereas most low-mass stars are formed in the first and second epochs.
models based on the bimodal star formation scenario are promoting massive stars. We thus suggest that future chemodynamical studies in the bimodal star formation scenario with stellar yields from rotating massive stars for different masses and (2) N abundances for these stars shown in Decressin et al. (2006). In order to answer this question, we investigate dependences of the GC-forming GMC needs to be consumed for the first-generation massive stars. Figure 7 also shows that N2/N1 can be as large as 1.0 (i.e., as observed in NGC 6752) for the models with very top-heavy IMFs of s1 < 1.2. This result implies that top-heavy IMFs in the first epochs of massive star formation are essential for explaining the observed large (>1) fraction of CN-strong stars in some GCs.

One of possibly serious problems in this “bimodal star formation” scenario is that the second generation of stars in a GC-forming GMC needs to be formed well before the SNe explosion of the first: otherwise, the GC shows abundance spreads in Fe-peak elements, which are not observed for typical GCs. This problem would not be so serious if stellar winds from the first can trigger star formation of the second. It is, however, theoretically unclear in what physical conditions star formation of the second can be triggered by stellar winds of the first owing to the lack of numerical simulations on these processes. Another problem is that a significant amount of mass loss (more than 90%) due to (1) top-heavy IMFs and (2) M1 much larger than M2 can lead to rapid disintegration of forming GCs. We thus suggest that the proposed bimodal star formation scenario would not be so convincing without solving the above disintegration problem due to the assumed top-heavy IMFs.

Then is the above IMF problem also serious for models in which chemical yield tables for rotating massive stars are used? In order to answer this question, we investigate dependences of N2/N1 and M2/M1 on s1 by using (1) final mass fraction of stellar winds for rotating massive stars with different masses and (2) N abundances for these stars shown in Decressin et al. (2006). Figure 8 shows that for slightly flatter IMFs (i.e., s1 ≥ 1.85), N2/N1 can be as large as ~1 (e.g., N2/N1 = 1.2 for s1 = 1.85) and the required M2/M1 is significantly larger (>0.3), which suggests that the above disintegration problem is much less serious in the bimodal star formation scenario with stellar yields from rotating massive stars. We thus suggest that future chemodynamical models based on the bimodal star formation scenario are promising in terms of explaining the observed spread in N abundances of GCs.

4.3. Relations to the Galactic Open Clusters and Halo Field Stars

We have shown that the models with m0 = 40 M⊙ show a very small degree of the abundance inhomogeneity; δY, δ[C/Fe], and δ[N/Fe] are all less than 10⁻⁵. These results imply that (1) it depends on m0 of GC-forming GMCs whether the GCs show abundance inhomogeneities, and (2) the observed differences in the degree of abundance inhomogeneities in the Galactic GCs can also be due to the differences in the number fraction of very massive stars formed in GC-forming GMCs. The fraction of N-rich stars in a GC can be observationally quantified by an “r” parameter by counting the number fraction of CN-strong stars versus CN-weak stars (Norris 1988), and the values of these r-parameters are observed to be different between the Galactic GCs (Norris 1988). We suggest that the observed difference of r is due to the difference in m0 and the number fraction of very massive stars between GC-forming GMCs.

Although the Galactic GCs show abundance inhomogeneities, the old Galactic OCs do not show significant abundance inhomogeneities (e.g., De Silva et al. 2006). One of the possible explanations for OCs without abundance inhomogeneities is that massive stars with m1 = 60–120 M⊙ could not be formed in GMCs of OCs for some physical reasons. For the Salpeter IMF, the total number of massive stars with m1 = 60–120 M⊙ is just 0.3 (i.e., less than 1) for low-mass OCs with masses (M⊙) of 1000 M⊙. This means that the probability of low-mass OCs having very massive stars with m1 = 60–120 M⊙ is very low (owing to small-number statistics). We thus suggest that the origin of the observed lack of abundance inhomogeneities in the Galactic old OCs can be understood in terms of incapability of their host GMCs to form massive stars with m1 = 60–120 M⊙.

The vast majority (90%) of stars are observed to form in SCs embedded within GMCs (Lada & Lada 2003): strongly bound SCs can finally evolve into GCs or OCs, whereas weakly bound, low-mass ones can be disintegrated into field stars in galaxies. Previous simulations (Bekki & Chiba 2000, 2001) showed that the Galactic stellar halo can be formed by both dissipative and dissipationless merging of subgalactic clumps and their resulting tidal disruption in the course of gravitational contraction of the Galaxy at high redshift (z > 1): the halo field stars were initially field stars originating from low-mass, unbound (or weakly bound)
SCs formed from GMCs not polluted by massive stars in high-z building blocks of the Galaxy. These previous results combined with the present ones therefore imply that there can be significant differences in abundance patterns of light elements between the Galactic halo field stars and stars within the GCs.

Observational studies have extensively discussed similarities and differences in abundances between the Galactic halo field stars and the GCs (e.g., Frogel 1993; Sneden 2005). For example, Suntzeff (1993) showed that (1) the Galactic halo field stars show an apparently unclear O-Na anticorrelation, (2) oxygen abundance is relatively constant at [O/Fe] ~ 0.5 for the halo field stars with [Fe/H] < -1, and (3) these two properties of the halo field stars are thus in a striking contrast with those of the GCs. We suggest that these differences reflect the fact that only GCs originate from strongly bound, massive SCs formed in GMCs polluted by stellar winds of very massive stars in low-mass subhalos: although both the halo field stars and the GCs were initially “clusters” within low mass building blocks of the Galaxy at high-z and later stripped to become the halo populations, the differences in physical properties of their parent SCs/GMCs result in the differences of abundances between the two halo populations.

5. CONCLUSIONS

We have first investigated the influences of stellar winds of massive stars on early chemical evolution of GC-forming GMCs based on GRAPE SPH chemodynamical simulations. In our numerical models, GCs form in turbulent, high-density giant molecular clouds (GMCs), which are embedded in a massive dark matter halo at high redshifts. We have focused on the chemical evolution of GC-forming GMCs in the present study. We summarize our principal results of the models as follows.

1. Chemical pollution of GC-forming GMCs by stellar winds from massive stars can result in star-to-star abundance inhomogeneities among light elements (e.g., C, N, and O) of stars in GCs. The present model with a canonical IMF (\(s = 2.35\)) also shows a C-N anticorrelation that stars with smaller [C/Fe] have larger [N/Fe] in a GC. These results imply that “self-pollution” of GC-forming GMCs by stellar winds from massive stars can cause abundance inhomogeneities of GCs.

2. The present models with different parameters and canonical IMFs (\(s = 2.35\)), however, cannot show N-rich stars with [N/Fe] ~ 0.8 observed in some Galactic GCs (e.g., NGC 6752). The simulated number fraction of N-rich ([N/Fe] > 0.2) stars is small (~10^-2) in most models with \(s = 2.35\). The clear bimodality in [N/Fe] cannot be seen in the models, mainly because the stellar winds of the first generation of stars cannot trigger a strong burst of star formation for the second generation in the present models with a single, structureless GMC. Models with top-heavy IMFs (\(s = 1.35\)) show a significantly larger fraction (~0.1) of N-rich stars. Although models with top-heavy IMFs are more consistent with observations, GCs in these models are suggested to be disintegrated soon after GC formation.

3. Although almost all stars (~97%) show normal He abundances (\(Y\)) of ~0.24, some stars later formed in GMCs can have \(Y\) as high as ~0.3 in some models. The number fraction of He-rich stars with \(Y > 0.26\) is, however, found to be small (~10^-3) for most models. These results imply that (1) the Galactic GCs can have \(Y\) abundance inhomogeneities, and (2) the degree of inhomogeneities can depend on IMFs and \(m_{\text{up}}\) of GC-forming GMCs.

4. The present models with canonical IMFs can hardly explain the observed large fraction of CN-strong stars in NGC 6752 and the large fraction of He-rich stars in NGC 2808. We therefore discussed these apparent failures in the context of massive star formation preceding low-mass one within GC-forming GMCs (i.e., the bimodal star formation scenario) and the new external pollution scenario. The formation of the second generation of stars needs to be triggered by the stellar winds of the first ones to explain the observed very small spread in [Fe/H] in the bimodal star formation scenario. The above IMF problem is, however, demonstrated to be much less severe in the bimodal star formation scenario with stellar yield tables for rotating massive stars.

5. The origin of the observed differences in abundance patterns of light elements (e.g., C, N, and O) between the Galactic halo field stars and the GCs can reflect the fact that the field stars originate from low-mass, unbound SCs formed in GMCs not polluted by stellar winds of very massive stars with \(m_{\text{up}} \geq 60 M_{\odot}\). Although both the halo field stars and the GCs were initially in the low mass subhalos and later stripped to become the halo populations, only GCs originate from strongly bound, more massive SCs formed within GMCs polluted efficiently by stellar winds of very massive stars.

Thus, the present chemodynamical simulations, which first have investigated self-consistently star formation histories and time evolution of He, C, N, and O within GC-forming GMCs, have shown that the observed abundance inhomogeneities of GCs cannot be explained on the basis of the stellar winds by massive stars, if a realistic IMF and the yields by Schaller et al. (1992) are used. In the present paper, we have not considered the self-pollution of GC-forming gas clouds by ejecta of AGB stars, for which top-heavy IMFs are required to explain the observed large fraction of N-rich stars in some GCs (e.g., Smith & Norris 1982; Bekki et al. 2007). If a top-heavy IMF is the only way to explain the observed degrees of abundance inhomogeneities of GCs both in the stellar wind scenario and in the AGB one, and if...
GCs with top-heavy IMFs inevitably disintegrate soon after their formation, the external pollution scenario discussed briefly in this paper needs to be investigated by chemodynamical simulations in a more quantitative way both for the two scenarios. We have also suggested that different IMFs in two major epochs of star formation for GC-forming GMCs need to be explored in future chemodynamical models, in particular, with chemical yield tables for rotating massive stars.

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