FIRST EVIDENCE OF GLOBULAR CLUSTER FORMATION FROM THE EJECTA OF PROMPT TYPE Ia SUPERNOVAE

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ABSTRACT

Recent spectroscopic observations of globular clusters (GCs) in the Large Magellanic Cloud (LMC) have discovered that one of the intermediate-age GCs, NGC 1718, with [Fe/H] $\approx -0.7$ has an extremely low [Mg/Fe] ratio of $\approx -0.9$. We propose that NGC 1718 was formed from the ejecta of Type Ia supernovae mixed with very metal-poor ([Fe/H] $< -1.3$) gas about $\sim 2$ Gyr ago. The proposed scenario is shown to be consistent with the observed abundances of Fe-group elements such as Cr, Mn, and Ni. In addition, compelling evidence for asymptotic giant branch stars playing a role in chemical enrichment during this GC formation is found. We suggest that the origin of the metal-poor gas is closely associated with efficient gas transfer from the outer gas disk of the Small Magellanic Cloud to the LMC disk. We anticipate that the outer part of the LMC disk contains field stars exhibiting significantly low [Mg/Fe] ratios, formed through the same process as NGC 1718.

Key words: galaxies: abundances – galaxies: evolution – galaxies: individual (LMC) – globular clusters: individual (NGC 1718) – stars: abundances

Online-only material: color figures

1. INTRODUCTION

The chemical abundance of stars is a fossil record of how the stars are formed. Thus, we can assess the origin of a globular cluster (GC), which still remains unresolved in spite of many previous observational and theoretical efforts, if we detect some signal characteristic of a specified nucleosynthesis result in the abundances of its member stars. Recently, the GC in the Large Magellanic Cloud (LMC), NGC 1718, is found to exhibit [Mg/Fe] $\approx -0.9 \pm 0.3$ from high-resolution spectra (Colucci et al. 2012). This is indeed a surprising result since no stars with such a low ratio have been found in the Galaxy or the LMC for field or star clusters. Only two stars in the Carina dwarf spheroidal (dSph) galaxy has been detected so far with a similar level of deficiency of Mg ([Mg/Fe] $\approx -0.73 \pm 0.41$, $-0.95 \pm 0.33$) for [Fe/H] $= -1.2$ in the field (Lemasle et al. 2012).

It is well known that the Galactic GCs show the Al–Mg and O–Na anticorrelations and accordingly contain stars with low Mg and O abundances in GCs (e.g., Gratton et al. 2004). However, the Al–Mg abundance range is far smaller than the variation in the Na–O anticorrelation, setting the lowest [Mg/Fe] ratio at $\sim -0.3$ (e.g., Sneden et al. 2004). In addition, a lack of such anticorrelations in young and intermediate-age GCs in the LMC has been reported (Mucciarelli et al. 2011). Figure 1 shows the observed [Mg/Fe] ratios in the LMC together with those in the Galaxy for both GCs and field stars. For GCs which are observed for more than two stars, the [Mg/Fe] ranges are shown for individual GCs. It is evident that the location of the abundance of NGC 1718 in the [Mg/Fe]–[Fe/H] diagram is unusual.

NGC 1718 has an age of $\sim 2$ Gyr (Grocholski et al. 2006) and [Fe/H] $= -0.7$ (Colucci et al. 2012), the lowest among the intermediate-age LMC clusters (a mean [Fe/H] of $\sim -0.5$). In fact, its very low [Mg/Fe] ratio of $\sim -0.9$ together with these two properties give us the theoretical basis to decipher the origin of this cluster. First of all, such a very low [Mg/Fe] is considered to be exclusively associated with nucleosynthesis product from Type Ia supernovae (SNe Ia). Nucleosynthesis in SNe Ia gives [Mg/Fe] $\approx -1.5$ (Iwamoto et al. 1999), while it is hard to predict individual Type II SNe (SNe II) including hypernovae with [Mg/Fe] as small as $\sim -0.2$ (e.g., Kobayashi et al. 2006). Though some low-mass SN II models predict very low [Mg/Fe] ratios down to $\sim -0.6$ (see Gibson 1997), no imprints of these SNe II are seen in the chemical abundances of Galactic halo stars. Therefore, it is expected that [Mg/Fe] $= -0.9$ can be explained by the hypothesis that the stars are born from the ejecta of SNe Ia mixed with the surrounding interstellar matter (ISM) with a moderate [Mg/Fe] ratio (Tsujimoto & Shigeyama 2006).

However, at the formation epoch of NGC 1718, i.e., $\sim 2$ Gyr ago, an ISM in the LMC is likely to be enriched up to [Fe/H] $\sim -0.5$. When SNe, whether II or Ia, explode in such an enriched ISM, relic of nucleosynthesis in individual SNe is hardly imprinted in stellar abundances since they basically reflect chemical abundances of the ISM (Tsujimoto & Shigeyama 1998). Accordingly, SN Ia explosion in low-metallicity ISM is crucial for the formation of stars with their elemental features characteristic of SN Ia nucleosynthesis. Then, a key question here is how the low-metallicity ISM required for this GC formation was obtained in the LMC that had been already enriched to [Fe/H] $\sim -0.5$ about 2 Gyr ago.

The LMC has a unique history that is different from the Galaxy through interactions with the Small Magellanic Cloud (SMC) and the Galaxy. Bekki & Chiba (2007) and Diaz & Bekki (2012) reveal that the LMC had a close encounter with the SMC about 2 Gyr ago, which led to the disruption of the disk of the SMC, creating the Magellanic Stream (MS), and eventually accreting the gas from the SMC onto the LMC with a total mass of $\sim 10^{8} M_{\odot}$. Since the outer gas-rich disk of the SMC is a major source of the accreting gas, its metallicity is expected to be very low. If we take a look at the abundance of the MS, Fox et al. (2010) deduces [O/H] $= -1.0 \pm 0.13$. For the Magellanic...
Bridge (MB), which shares the same origin with the MS, Rolleston et al. (1999) measure the abundances of young stars residing in the MB, and find ~1 dex lower abundance than the solar value on average, including $\text{[Si/H]} = (-1.23$ to $-1.46) \pm 0.25$ for one star. Moreover, Misawa et al. (2009) claim a large metallicity ($\text{[Fe/H]}$ mixed with the ejecta from a single SN Ia as a function of the mixing of the observed chemical composition within the MB gas. Thus, the accretion of a metal-poor gas that was initially belonging to the SMC could involve gas with a sufficiently low metallicity to meet the condition for this GC formation.

In this Letter, we present a new scenario where the GC NGC 1718 was formed from a metal-poor gas mixed exclusively with SNe Ia ejecta about 2 Gyr ago. In this scenario, the metal-poor gas that was initially in the outer part of the SMC was accreted onto a part of the LMC disk, some regions of which were devoid of chemically enriched ISM like the H1 holes currently observed in the LMC disk (Kim et al. 1999).

We start with the estimate of metallicity and mass of the ISM swept-up by one single SN Ia ejecta, and then with the total number of SNe Ia, required for explaining the observed properties of NGC 1718. Based on these results, a new scenario for the formation of NGC 1718 is presented in detail. Subsequently, we demonstrate that our scenario is consistent with the observed abundances of other elements such as Fe-group and light-odd elements.

2. HOW TO OBTAIN A VERY LOW [Mg/Fe] RATIO

In this section, we estimate the $\text{[Mg/Fe]}$ ratio of the ISM mixed with the ejecta from a single SN Ia as a function of the metallicity ($\text{[Fe/H]}_{\text{ISM}}$) and the total mass of the ISM ($M_{\text{ISM}}$). The $\text{[Mg/Fe]}$ ratio thus obtained corresponds to the stellar $\text{[Mg/Fe]}$ ($\text{[Mg/Fe]}_{\text{star}}$) for stars formed from the final ISM. An SN Ia ejects masses of $0.63 M_{\odot}$ and $8.5 \times 10^{-3} M_{\odot}$ of Fe and Mg, respectively (Iwamoto et al. 1999). These heavy elements are assumed to be well-mixed with the original ISM with $\text{[Fe/H]}_{\text{ISM}}$ and $M_{\text{ISM}}$. From the mixed gas, new stars are eventually born with the chemical feature of $\text{[Mg/Fe]}_{\text{star}}$ and $\text{[Fe/H]} = -0.7$, which is equivalent to the metallicity of NGC 1718. Here we adopt $\text{[Mg/Fe]} = 0$ as a reasonable value of the original ISM, because we consider the situation where the ISM is enriched owing to long-term chemical evolution until ~2 Gyr ago, and thus must involve sufficient contribution from SNe Ia.

Based on simple analytical calculations, we find the combination of $\text{[Fe/H]}_{\text{ISM}}$ and $M_{\text{ISM}}$ required for the formation of stars with $\text{[Fe/H]} = -0.7$ and a given $\text{[Mg/Fe]}_{\text{star}}$ ratio. The result is presented in Figure 2, showing the relation between $\text{[Mg/Fe]}_{\text{star}}$ and $\text{[Fe/H]}_{\text{ISM}}$. The values of $M_{\text{ISM}}$ are assigned to three cases for $\text{[Mg/Fe]}_{\text{star}} = -0.9, -0.6,$ and $-0.3$. The shaded region corresponds to the range of $\text{[Mg/Fe]}$ ratio for NGC 1718 including an observed error (Colucci et al. 2012). The obtained relation crossing the shaded region leads to the conclusion that a very low $\text{[Mg/Fe]}$ observed in NGC 1718, i.e., $\text{[Mg/Fe]} \lesssim -0.6$, can be achieved only if the metallicity of the ISM that mixed with the SN Ia ejecta is lower than $\text{[Fe/H]}_{\text{ISM}} \sim -1.3$. On the other hand, this ISM with metallicity such as $\text{[Fe/H]}_{\text{ISM}} \sim -0.5$ as expected ~2 Gyr ago in the LMC will completely erase information on the nucleosynthesis of SNe Ia retained inside its ejecta.

3. PROPOSED SCENARIO

From the result on the two required properties of the ISM mixed with the ejecta of SN Ia, i.e., $\text{[Fe/H]}_{\text{ISM}} < -1.3$ and $M_{\text{ISM}} \sim 3000$–$3500 M_{\odot}$, the following two conditions should be set to build NGC 1718 as observed: (1) the ISM that had been already present in the LMC disk was mostly expelled from the vicinity of the future NGC 1718 before the event of a low-metallicity gas accretion to create a new ISM with $\text{[Fe/H]} < -1.3$, and (2) tens of SNe Ia exploded to obtain the observed mass of the GC.

First, we start by discussing the issue of mass budget. The mass of NGC 1718 is estimated to be $6 \times 10^4 M_{\odot}$ (Mackey & Gilmore 2003). Then, it turns out that ~17–20 sequential SN Ia explosions should occur. Here we should highlight recent
results regarding the delay time distribution (DTD) of SNe Ia yielded by the studies on the SN Ia rate in distant and nearby galaxies. These studies dramatically shorten the SN Ia’s delay time, compared with its conventional timescale of ~1 Gyr (Pagel & Tautvaišienė 1995; Yoshii et al. 1996). Mannucci et al. (2006) find that about 50% of SNe Ia explode soon after their stellar birth, and further works reveal that the DTD is proportional to \( r^{-1} \) with its peak at around 0.1 Gyr (Totani et al. 2008; Maoz et al. 2010). Therefore, the phenomenon that numerous SNe Ia sequentially explode after the bursting explosions of SNe II would be realized if a star cluster was formed prior to the formation of NGC 1718.

Let us calculate the mass of the star cluster as a source of numerous SN Ia ejecta that may or may not finally become field stars after its disintegration. From the assumptions that 5\% of stars in the mass range of 3–8 \( M_\odot \) eventually become SNe Ia (Tsujimoto 2012) and the fraction of prompt SNe Ia is 50\% (Mannucci et al. 2006), the mass of ~4 \times 10^4 \( M_\odot \) is deduced. This cluster yields more than 200 SN II explosions in total within a few 10^7 yr prior to the commencement of SN Ia explosions, which is likely to provide sufficient energy to expel the ISM surrounding the star cluster. The resultant structure must be identical to an H i hole that can be ubiquitously seen in the present-day LMC disk (Kim et al. 1999). Then finally, low-metallicity gas from the SMC rains down on this spot, which is followed by sequential SN Ia explosions. Accordingly, our proposed scenario is summarized as follows.

1. At the beginning, a star cluster with the mass of ~4 \times 10^4 \( M_\odot \) is formed.
2. Subsequently, bursting SN II explosions expel the surrounding ISM of this cluster, and create an H i hole.
3. Onto this H i hole, gas with a metallicity of [Fe/H] < −1.3 disrupted from the SMC accretes.
4. Sequential prompt SNe Ia start to explode and multiple ejecta of SNe Ia merge and mix with the new ISM supplied by the accreting metal-poor gas. Finally, NGC 1718 is formed from this mixed gas.

This is the formation process of NGC 1718 that took place about 2 Gyr ago in the LMC.

4. SN Ia-LIKE ABUNDANCES OF Fe-PEAK ELEMENTS

The unusual elemental feature of NGC 1718 is seen not only in [Mg/Fe] but also in the ratios of Fe-peak elements (Cr, Mn, Ni) to Fe. Figure 3 shows the observed [Cr, Ni, Mn/Fe] ratios of NGC 1718, compared with the LMC and the Galaxy data. We see ratios of NGC 1718 higher than those of other field/cluster stars, in particular for [Cr/Fe]. The reason why these ratios are unusually higher and the deviation of [Cr/Fe] is most significant can be well understood if we compare the observed data with the theoretical nucleosynthesis result of SNe Ia. To consider an uncertainty in nucleosynthesis calculations, the predicted ratios of two models (delayed-detonation models: WDD1, WDD2 in Iwamoto et al. 1999) are shown to each panel of Figure 3. We see good coincidence between the observed ratio for NGC 1718 and the predicted range given by two nucleosynthesis models. This is compelling evidence supporting our scenario because the [Cr, Ni, Mn/Fe] ratios inside the ejecta that eventually give birth to NGC 1718 should basically retain the ratios predicted by nucleosynthesis in SN Ia, with only a small difference of ~0.02–0.1 dex from the pure ejecta case.

5. AGB-LIKE ABUNDANCES OF LIGHT-ODD ELEMENTS

Light-odd elements, Na and Al, are synthesized in asymptotic giant branch (AGB) stars, with a production peak at a ~5 \( M_\odot \) AGB star (e.g., Fenner et al. 2004; Karakas & Lattanzio 2007). Since the lifetime of a 5 \( M_\odot \) star is ~0.1 Gyr, which is nearly equivalent to the major delay time for prompt SNe Ia, the ejecta of prompt SNe Ia might be unavoidably contaminated by the release of Na and Al from mass-losing AGB stars. Indeed, the observed Na and Al abundances of NGC 1718 are not low, i.e.,
[Na/Fe] = +0.05 ± 0.22, [Al/Fe] = +0.15 ± 0.30 (Colucci et al. 2012), though these elements are produced in small amounts in SNe Ia (Iwamoto et al. 1999).

Here we try to make a quantitative estimate of the contribution from AGB stars. Roughly, ∼20 AGB ejecta per one SN Ia are expected from a simple yet reasonable assumption of SNe Ia/AGB ∼0.05%. The AGB yields are updated by several authors (e.g., Fenner et al. 2004; Karakas & Lattanzio 2007; Izzard et al. 2007), and these yields were recently examined to explain the origin of Na–O and Al–Mg anticorrelations observed in the Galactic GCs (Marcolini et al. 2009; Sánchez-Blázquez et al. 2012). If we adopt the mean Na yield averaged over 4–7 $M_\odot$ AGB stars of $7.7 \times 10^{-4} M_\odot$ for the Z = 0.004 model by Karakas & Lattanzio (2007), the ejecta of SNe Ia associated with 20 AGB ejecta results in [Na/Fe] = −0.03, which is in good agreement with the observed ratio. For the Al yield, if we adopt the high yield of $2 \times 10^{-3} M_\odot$, for instance, which is close to the value of $3.5 \times 10^{-3}$ which nicely explains the Al–Mg anticorrelation (Marcolini et al. 2009), we deduce [Al/Fe] = +0.15 for the SN Ia+AGBs ejecta yielding [Mg/Fe] = −0.9.

6. DISCUSSION AND CONCLUSIONS

NGC 1718 is the only GC that has been observed so far to show a very low [Mg/Fe]. However, since a large amount of gas—as much as $10^8–10^9 M_\odot$—is predicted to have accreted onto the LMC from the SMC about 2 Gyr ago (Bekki & Chiba 2007; Diaz & Bekki 2012), there is a potential to detect field stars whose chemical features are identical to NGC 1718 in the LMC disk. The place where these stars populate is likely to be off the central region like the location of NGC 1718 because both the observed distribution of giant H i holes and the predicted spots of accretion are outside the central part. Note that the observed data for the LMC field in Figure 1 is the sample restricted to the inner disk (Pompéia et al. 2008). Therefore, we propose that future spectroscopic observations for the outer disk will detect the stars with unusually low [Mg/Fe] ratios. The level of low Mg/Fe for these individual stars must vary with various [Fe/H] owing to (1) the different number of SN Ia explosions in local regions and (2) the wide range of metallicity of the accreted metal-poor gas.

According to the prediction by Bekki & Chiba (2007), the LMC has experienced another accretion event associated with a large amount of metal-poor gas up to $10^8 M_\odot$ from the SMC about 0.2 Gyr ago. This prediction leads to the possible presence of young GCs and/or field stars exhibiting a low [Mg/Fe] ratio in the proposed scenario. One candidate at the moment is the young cluster NGC 1866 with [Fe/H] = −0.27 and its age of 0.1–0.5 Gyr, which exhibits [Mg/Fe] = −0.27 ± 0.20 (Colucci et al. 2012). It should be, however, noted that other [α/Fe] ratios in this cluster are larger than 0.

Except for NGC 1718, two stars are found in the Carina dSph to have very low [Mg/Fe] ratios less than −0.7 (Lemasle et al. 2012). In addition to them, Venn et al. (2012) find the star (Car-612) with [Mg/Fe] = −0.5 ± 0.16 at [Fe/H] = −1.3 in the Carina, and discuss its origin as a pocket of SN Ia enriched gas (see also Marcolini et al. 2009; Sánchez-Blázquez et al. 2012). Note that this star’s [Mg/Fe] is measured to be −0.9 by Koch et al. (2008). The presence of these stars may suggest that in dwarf galaxies, stars that formed from the ejecta of SNe Ia can retain its relic thanks to the low-metallicity environment with [Fe/H] ≪ −1.3, though iron-peak elements of Car-612 do not show SN Ia-like abundances as discussed in Section 4 such that [Cr/Fe], [Mn/Fe], [Ni/Fe] are −0.20, −0.51, −0.46, respectively. Since the Galactic halo is considered to be formed from the ancient destruction of dwarf galaxies, there may exist halo stars with unusually low [Mg/Fe] that originated from the SNe Ia ejecta in dwarf galaxies. The newly identified halo stars by Evans et al. (2003), i.e., BD +80°245, G4–36, and CS 22966–043 with [Mg/Fe] = −0.22, −0.19, and −0.65, respectively, are promising candidates.

Here we present a bigger picture for the GC formation; past gas accretion events triggered the formation of young and intermediate-age GCs in the LMC. This view could provide a clue to the origin of the age-gap problem, i.e., the observed fact that almost all GCs in the LMC are either very old (like the Galactic GCs) or younger than a few Gyr (e.g., Da Costa 1991). Since most GCs are formed from the mixture of enriched ISM and accreted metal-poor gas, their chemical abundances are predicted to be similar to those in the ISM at their birth epoch. It is already claimed that the strong LMC–SMC interaction is responsible for the onset of GC formation in the LMC disk (Bekki et al. 2004). Its outcome, gas accretion, could also be a driver of the GC formation in the LMC.

In this Letter, we have shown that an unusually low [Mg/Fe] ratio recently found for one intermediate-age GC in the LMC enables us to assess its unique origin. Since its extremely low ratio (−0.6) is outside any observed Al–Mg anticorrelations (>−0.3) as well as by the prediction from nucleosynthesis calculations on any SNe II (>−0.2, though there is room for the possibility of lowering this limit in some low-mass SN II models), a birthplace of this GC is narrowed down to the ejecta of SNe Ia. However, in general, an already chemically enriched ISM, e.g., with [Fe/H] ≈ −0.5, eventually changes the chemical abundances inside the ejecta from those determined by the chemical pollution by SN explosions to those similar to the ISM, because the total amount of metals ejected by SNe is much smaller than that contained in the ISM. Therefore, the formation of the GCs showing characteristics of SN nucleosynthesis at moderate metallicity is possible only under two physical conditions: (1) there are some local regions devoid of H i gas in the galaxy, and (2) the galaxy experiences accretion of very metal-poor gas. The LMC is one of those galaxies where these two conditions can be satisfied.

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REFERENCES

Bekki, K., & Chiba, M. 2007, MNRAS, 381, L16
Bekki, K., Couch, W. J., Beasley, A., et al. 2004, ApJ, 610, L93
Bensby, T., Feltzing, S., Lundström, I., & Ilyin, I. 2005, A&A, 433, 185
Colucci, J. E., Bernstein, R. A., Cameron, S. A., & McWilliam, A. 2012, ApJ, 746, 29
Da Costa, G. S. 1991, in IAU Symp. 148, The Magellanic Clouds, ed. R. Haynes & D. Milne (Dordrecht: Kluwer), 183
Diaz, J. D., & Bekki, K. 2012, ApJ, 750, 36
Fenner, Y., Campbell, S., Karakas, A. I., Lattanzio, J. C., & Gibson, B. K. 2004, MNRAS, 353, 789
Fox, A. J., Wakker, B. P., Smoker, J. V., et al. 2010, ApJ, 718, 1046
Gibson, B. K. 1997, MNRAS, 290, 471
Gratton, R., Sneider, C., & Carretta, E. 2004, ARA&A, 42, 385
Gratton, R. G., Carretta, E., Claudel, R., Lucatello, S., & Barbieri, M. 2003, A&A, 404, 187
