Radial Dependence of the Proto-globular Cluster Contribution to the Milky Way Formation

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Abstract

Recent interpretation of the color–magnitude diagrams of the Milky Way (MW) bulge has suggested that the observed double red-clump feature can be a natural consequence of He-enhanced stellar populations in the MW bulge. This implies that globular clusters (GCs), where the He-enhanced second-generation (SG) stars can be efficiently created, are the most likely candidate contributors of He-rich stars to the MW bulge. We extend this idea to the Galactic inner halo and investigate the fraction of the SG stars as a function of the Galactocentric distance. We use bluer blue horizontal branch (bBHB) stars, which are assumed to have originated from He-rich SG populations, as proxies of SG stars, and find that the fraction of bBHB stars increases with decreasing Galactocentric distance. Simulations of the GC evolution in the MW tidal field qualitatively support the observed trend of bBHB enhancement in the inner halo. In these simulations, the increasing tidal force with decreasing Galactocentric distance leads to stripping of stars not only from the outskirts but also from the central regions of GCs, where SG stars are more abundant. We discuss the implication and prospect of our findings concerning the formation history of the bulge and inner halo of the MW.

Unified Astronomy Thesaurus concepts: Computational methods (1665); Milky Way stellar halo (1060); Stellar abundances (1577); Stellar evolution (1599); Horizontal branch stars (746); Globular star clusters (656)

1. Introduction

Understanding the formation history of the Milky Way (MW) is one of the ultimate goals of galaxy formation studies (e.g., Conselice 2014; Somerville & Davé 2015). Various simulations of galaxy formation have revealed that, in addition to the stars that originated in situ, the most plausible candidates for the building blocks of the MW are massive dwarf galaxies and/or massive globular clusters (GCs; e.g., Lada & Lada 1991). Numerous studies on identifying the primary building blocks of the MW have been carried out, but the nature of the building block that played a dominant role in building up the stellar populations of the MW is still under debate. In particular, the Galactic halo has been considered to be a collection of smaller structures such as dwarf spheroidals, and it has been well established that dwarfs are the major constituents of the MW halo via accretion (e.g., Searle & Zinn 1978; Klimentowski et al. 2007). Compared to the dwarf galaxies, the contribution of GCs as building blocks of the MW has been regarded as small because of their lower current mass without dark matter, as well as the small number of GCs (Tolstoy et al. 2009; Deason et al. 2015).

In this context, the discovery of He-enhanced populations in the MW bulge, however, changed the current paradigms on the formation history of the MW. Proto-GCs, where He- and N-enhanced stars can be formed (Martell & Grebel 2010; Martell et al. 2016; Schiavon et al. 2017), are the most likely candidates for the birthplace of bulge He-enhanced stars through the self-enrichment of the first-generation polluters (Kim & Lee 2018), and the observed double red clumps (RCs) in the bulge (resulting from He-rich stars) are crucial evidence for their contribution to the bulge (Lee et al. 2015, 2019; Joo et al. 2017). The recent study on chemical tagging of the double RC in the bulge further strengthens this view by detecting N-enhanced stars in the bright RC (Lee et al. 2018), which implies that almost 50% of stars in the bulge may have originated from second-generation (SG)6 stars. This is in line with a picture of a rapid orbital decay of proto-GCs emerging from N-body models of MW evolution, which suggests that the nuclear star cluster observed in the Galactic center is the result of repeated GC mergers (e.g., Capuzzo-Dolcetta & Miocchi 2008; Abbate et al. 2018). Given the possibility of the significant fraction of GC-origin population in the bulge region, one would expect that the effect of proto-GCs on the formation of the halo should be nonnegligible.

Chung et al. (2016) demonstrated the preferential removal of first-generation (FG) stars from GCs in the outer halo and cautiously suggested that this process may result in the misunderstanding that most of the outer halo consists of the dwarf-origin FG stellar populations. On the other hand, the observed RC stars in the bulge (Lee et al. 2018) may be the simple outcome of full or almost full disruption of GCs at small Galactocentric distances. Therefore, for intermediate Galactocentric distances, one would expect a partial stripping of SG stars, depending on the interplay between the strength of tidal stripping and the amount of confinement of the SG stars in the center of the GC, which in turn depends on the details of SG formation (D’Ercole et al. 2008; Hénault-Brunet et al. 2015; Bastian & Lardo 2018) and dynamical evolution within the host GC (Vesperini et al. 2013; Dalessandro et al. 2014; 6 Throughout this paper, the SG stars indicate all generations of stellar populations enriched by FG stars in proto-GCs.)
Lim et al. 2016). This may lead to a varying fraction between FG and SG stars in the bulge and halo fields.

In this study, we investigate how proto-GC systems, which usually have experienced multiple generations of star formation, have influenced the formation of the MW inner halo. We analyze the number ratio between FG and SG stars as a function of the Galactocentric distance using the ratio of bluer blue horizontal branch (bBHB) to redder blue horizontal branch (rBHB) stars as proxies for each of the populations, respectively. We find a gradient of the bBHB/rBHB ratio with Galactocentric distance, which we interpret in terms of increasing preferential tidal stripping of FG stars as Galactocentric distance increases. This is expected in massive GCs, where relaxation did not have enough time to mix the different stellar generations and SG stars are strongly confined to the central regions of the GC (e.g., see Vesperini et al. 2013). To interpret our results, we additionally run simplified dynamical evolution simulations based on the numerical solution scheme for Hill equations proposed by Quinn et al. (2010) for GCs at different Galactocentric distances.

The paper is organized as follows. Section 2 describes the construction of a population synthesis model and the sample selection. In Sections 3 and 4, we present our new findings together with results from simulations. Section 5 discusses the implications of our results for the formation history of the MW.

2. Population Synthesis Model and Sample Selection

The evolutionary population synthesis (EPS) models presented here are constructed under the same assumptions on the input parameters adopted in Chung et al. (2016). Readers are referred to Chung et al. (2013, 2017) for detailed prescriptions of the EPS models.

Figure 1 presents synthetic horizontal branch (HB) stars and corresponding isochrones from the main sequence to the tip of the red giant branch stars in $(u − g)_0$ and $(g − r)_0$ color–magnitude diagrams (CMDs) at given metallicities and 12 Gyr age. Based on these CMDs, we carefully selected blue colored areas where only bBHBs are located in both colors of $0.8 < (u − g)_0 < 1.1$ and $−0.3 < (g − r)_0 < −0.25$. For rBHB stars, we adopted the selection criteria of Deason et al. (2015). To avoid RR Lyrae contamination in the sample, we took stars with $(g − r)_0 < −0.1$ as rBHB stars. The mean absolute g-band magnitudes ($M_g$) of bBHBs within blue boxes in $(u − g)_0$ and $(g − r)_0$ colors are 0.49 and 0.70 mag, respectively. Given that the mean $M_g$ of bBHBs in the blue box is 0.43 mag, the $M_g$ differences among selection boxes is less than 0.3 mag, which can be used as a distance indicator at a given magnitude. From top to bottom panels, the metallicity of both FG and SG increases and bottom panels show the case of inner halo metallicity and age. This metallicity range clearly shows the drastic morphology change of HB stars that originated from SG populations at the age of 12 Gyr.

We make use of SDSS photometry (York et al. 2000) from DR14 for the halo star census. Our candidate stars are selected from Photoprimary. We are mainly concerned with halo rBHB and bBHB stars at Galactocentric distances from 4 to 50 kpc, which corresponds to the apparent $g$ magnitude of rBHB stars ranging between 15 and 19 mag. We have trimmed the stars below $b = 30^\circ$ to avoid bulge or disk stars, and selected our sample with photometric errors less than 0.05. To see the effect of the population shift in the same halo region with respect to the Galactocentric distance, we choose a rather narrow volume-limited star sample in $−15^\circ < l < 15^\circ$ to meet the above criteria.

We use the color–magnitude diagram (CCD), which is not affected by the distance, to select a clean sample of stars in the same evolutionary stages, i.e., rBHBs and bBHBs, in the halo. Figure 2 shows halo stars selected from the SDSS DR14 in the $(u − g)_0$ versus $(g − r)_0$ plane. We overplot models of synthetic HB stars as well as young turn-off stars on top of the selected halo stars to show how rBHBs and bBHBs are distributed in the CCD. The position of these model HB stars on the CCD are indicated as solid lines with blue and cyan colors for rBHBs and bBHBs, respectively. The adopted metallicities for HB stars in the diagram are the same as models in the bottom panels of Figure 1. In order to show where blue stragglers (BSs) are placed in the CCD, we provide the dashed lines of young main-sequence turn-off points which cross the lower part of the area. Blue and red dashed lines are for the metallicities of [Fe/H] = −1.5 and −1.0, respectively. rBHB stars and some RR Lyraes from metal-poor populations are placed in the curved hook-shaped area in the CCD and sweep the upper edge of the hook-shape. We intend to select rBHBs and bBHBs simultaneously, so we narrowed down our sample using the guidelines of our population model. Among the selected sample, we use 5,942 stars that satisfy our criteria for the analysis in Section 3. The final selection boxes with all samples in the density map are presented in the right panel of Figure 2. The high-density regions in the CCD are shown as dark black colors.

3. The Fraction of the Second-generation Populations in the Inner Halo

Figure 3 shows the selection boxes of rBHBs and bBHBs with respect to the magnitude bin. The bottom left panel shows the location of our volume-limited samples in the heliocentric coordinate. To analyze the population shift with respect to the Galactocentric distance, we divided halo stars into four regions, and those regions are indicated by numbers in the plot. As the magnitude and the Galactocentric distance increase, stars in the bBHB selection box gradually decrease. Following the bBHB/rBHB selection boxes, the fraction of bBHB-to-rBHB decreases with the increasing Galactocentric distance from 1 to 4 regions, implying that the fraction of bBHBs increases with the decreasing Galactocentric distance. The bottom right panel of Figure 3 demonstrates this trend with respect to the Galactocentric distance. There exists an apparent contrast in bBHB/rBHB ratios between the region inside 10 kpc and the region outside. This is consistent with earlier studies based on $B − V$ colors (e.g., Preston et al. 1991) and spectroscopic selection of BHB stars (Santucci et al. 2015).

This result is particularly interesting because it is well established that metallicity of stellar components of the Galactic halo increases as Galactocentric distance decreases (e.g., Layden 1994; Torrealba et al. 2015), which in turn results in more red HBs in the inner halo. Also, the age estimations of the Galactic inner halo in the literature suggest around $\sim 11.5$ Gyr (e.g., Kalirai 2012; Carollo et al. 2016). As presented in Figure 4 of Chung et al. (2017), to reproduce bBHB at halo metallicity without assuming He enhancement, the age of the population would be at least 13 Gyr. Therefore, the age referred to in the literature is not old enough to
reproduce BHBs. Moreover, the age structure of Galactic halo stars shows no radial age gradient \(\text{e.g., Jofré & Weiss 2011; Hawkins et al. 2014}\) or 1 Gyr older ages with the decreasing Galactocentric distance \(\text{e.g., Santucci et al. 2015; Carollo et al. 2016}\), and neither of these is enough to change the morphology of HBs from red to blue type at the given inner halo metallicity \([\text{Fe/H]} \sim -1.4\) see Torrealba et al. 2015\).

According to these, the general trend of halo populations would naturally produce more red HB stars in the central region of the MW \(\text{see, Chung et al. 2013}\). In contradiction to the prediction based on stellar populations reproducing red HB stars at a given mean metallicity of inner halo field, our results show the opposite trend.

In order to explain the increasing fraction of bBHB stars in the Galactic inner halo\(^8\) we need to adopt the He-rich populations usually observed in GCs. Since He-rich stars evolve faster than normal He stars, the He-rich stellar populations that originate

\(^8\) The age and CNO abundance also affect the HB morphology. However, considering the increasing N abundance \(\text{e.g., Martell et al. 2011; Schiavon et al. 2017}\) and small age difference with decreasing Galactocentric distance, bBHBs most likely originated from He-rich populations.

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**Figure 1.** Synthetic color–magnitude diagrams (CMDs) of proto-GCs with FG and SG populations. The left and right panels are \((u - g)_0\) and \((g - r)_0\) CMDs at 12 Gyr, respectively. Red and blue colors depict the FG and SG populations at given metallicities, respectively. The metallicities of SGs are set as 0.1 dex higher than those of FGs. Crosses between \(-0.1 \leq (g - r)_0 \leq 0.3\) and \(1.0 \leq (u - g)_0 \leq 1.3\) represent RR Lyrae stars. Blue boxes indicate bBHB selection criteria at a given color, while red boxes in the right panels indicate where rBHBs are located in the CMDs.
from GCs could reproduce more bBHB stars at younger ages with a high metallicity in the inner halo (Chung et al. 2011, 2017). Figure 1 displays this effect by showing the population synthesis model of simple stellar populations under different assumptions on the initial He abundance. BHBs are naturally reproduced even at the intermediate metallicity of \([\text{Fe}/\text{H}] \approx -0.7\).

Chung et al. (2016) used BSs and BHBs as proxies for FG and SG populations, respectively, and explained that the low BHB-to-BS ratio in the outer halo of the MW is caused by the preferential removal of the normal He FG stars from proto-GCs while He-rich SG stars remain inside of the proto-GCs. If this is universal regardless of the Galactocentric distance of the proto-GCs, the fraction between FG and SG, which can be estimated using rBHBs and bBHBs, should remain constant regardless of the Galactocentric distance. However, our result shows that the preferential disruption of GC-like systems in the inner halo regime of the MW halo becomes ineffective as the Galactocentric distance decreases but rather the disruption of both FG and SG stars is preferred due to the stronger tidal force of the MW.

The result may lead us to a comprehensive interpretation of the early formation of the MW. The contribution of disrupted proto-GCs to the MW bulge and halo. The preferential removal of the FG stars within the proto-GCs is a function of the Galactocentric distance, and this becomes stronger as the proto-GCs reside in the outer part of the MW halo. However, for the proto-GCs located in the inner part of the MW, both FG and SG populations are affected by the disruption, leading the increasing SG population in the field with the decreasing Galactocentric distance. In this sense, the double red clump phenomenon of the MW bulge is the natural outcome of effective removal of the He-rich SG stars from their host GCs.

### 4. Dynamical Evolution Models of Proto-GCs

The observed trend can be explained by a couple of galaxy formation scenarios. One such possibility includes a gradual age shift (Santucci et al. 2015; Carollo et al. 2016). In this Letter, we propose that it can also be plausibly explained by disruption of massive GCs by tidal force, and subsequent ejection of He-enriched SG stars with systematically bluer colors.

We use our C implementation of the symplectic, time-reversible second-order integrator introduced by Quinn et al. (2010) to compute the orbits of stars in a Plummer potential (representing the GC) in a circular orbit around a point-mass galaxy (representing the MW). The forces acting on each star include tides and the Coriolis force, which, being velocity-dependent cannot be treated correctly with simpler integration schemes such as standard leapfrog (Rein & Tremaine 2011).

We generate stars with an initially multivariate normal distribution with standard deviation equal to \(a/\sqrt{3}\) along the \(x\), \(y\), \(z\) coordinates, where \(a\) is the Plummer scale radius, and equal to \(v_c/\sqrt{3}\) along the \(v_x\), \(v_y\), \(v_z\) where \(v_c\) is the equilibrium circular velocity at the scale radius. We then tag as SG the stars located within distance \(ka\) from the GC center, where \(k\) is allowed to vary over different simulations from 0.4 to 1 corresponding to an initial SG fraction between \(\approx 10\%\) and \(60\%\). The orbits are evolved from these initial conditions for 1000 crossing times and considered escapers if their final position is further than 100\(a\) from the center of the GC. Over our set of simulations, we change the ratio of the revolution time (around the Galactic center) to the crossing time by several orders of magnitude. This corresponds to changing the ratio of the Plummer scale radius to the Galactocentric distance.

We find two expected trends in the results of our simulations: First, the fraction of escapers at the end of the simulation is higher in GCs that are nearer to the Galactic
center with respect to those that are further away from it. This is clearly a direct effect of tidal stripping. Second, we find that SG stars that are confined within a sphere around the center in the initial conditions of our simulations are less likely to be escapers than the average star. This latter result holds at any Galactocentric distance but is more pronounced far from the Galactic center, where the Hill sphere of the cluster is larger, and stars located centrally are even more unlikely to escape. In Figure 4, we plot the fraction of SG escapers over FG escapers as a function of Galactocentric distance. Simulations with different initial ratios of SG stars over the total number of stars are shown in different colors. The behavior is essentially the same, with almost full stripping at low Galactocentric radii corresponding to a fraction of SG stars among the escapers equal to the initial fraction. As Galactocentric distance increases, only the stars that were initially unbound and the outermost parts of the GC are stripped, so that comparatively fewer SG stars escape.

5. Discussion and Conclusion

We have found a population gradient in the inner halo of the MW as shown by the decreasing fraction of bBHB-to-rBHB stars with increasing Galactocentric distance based on SDSS photometry. He-rich SG stellar populations that originated from proto-GCs can explain this trend if the fraction of SG tidal stripping increased as Galactocentric distance decreased. We provide simplified models of two-generation GC evolution in a tidal field, showing that this is indeed the case, at least for dynamically unrelaxed GCs where the SG stars are mostly confined to the GC center. This suggests that, rather than the contribution of dwarf galaxies only with red HBs, a significant fraction of the halo stellar population originated from GCs, which built up the MW inner halo during its early formation stages. The contribution of SG populations in proto-GCs to the halo assembly depends on the Galactocentric distance of the proto-GCs. Martell et al. (2016) already began to discover CN-strong SG stars in the halo, and many more discoveries will be followed based on larger spectroscopic data sets, shortly.

The simulations we use to reproduce the overall behavior of SG stripping with the Galactocentric radius are greatly simplified. The most important ingredient, which is absent in our models but might affect their outcome, is collisional dynamical relaxation, which may lead to a mixing of the SG stars.
and FG stars on the relaxation timescale of the cluster (see, e.g., Vesperini et al. 2013). We expect this mixing to increase the fraction of SG stars that become tidally stripped, but extensive, direct N-body simulations are required to estimate its full effect (U. N. Di Carlo et al. 2019, in preparation).

Our discovery leads to fundamental questions about how the MW has formed because the mass fraction of presently remaining GCs seems to be too small to be the primary building blocks of the MW. Additional building blocks are still needed to explain the mass of the MW halo and bulge (excluding the disk and bar components). The recent discovery of clumpy disk galaxies at high redshift (e.g., Dessauges-Zavadsky et al. 2017; Cava et al. 2018) may shed light on the formation history of our MW. If these clumps contain 10–100 proto-GCs, the total mass of several clumps observed in high-z galaxies is comparable to the mass of the galaxy itself. Inside of these clumps, proto-GCs are provided and they would have experienced chemical evolution similar to the GCs we now observe. Through this mechanism, the Galactic bulge and halo can be created (Elmegreen et al. 2008). In this way, the significant fraction of the bulge and halo stellar mass can be explained by the contribution of proto-GCs in clumps, also without conflicting with the chemical enrichment scenario of Kim & Lee (2018), which can reproduce multiple generations of stellar populations without losing enriched gas from the previous generation of stars.

If our hypothesis is correct, we would expect to observe different FG and SG ratios in the present-day GCs with respect to their Galactocentric distance. However, as shown in Milone et al. (2017), GCs with multiple populations do not show such trends significantly as a function of Galactocentric distance. This might be explained by the very low surviving rate of proto-GCs, and this makes it hard to find trends in the present GCs with different Galactocentric distances.

Stars in other building block candidates such as dwarf galaxies, mostly consisting of FG populations, show slightly different abundance patterns compared to the Galactic inner halo (Tolstoy et al. 2003). This implies that the Galactic inner halo could be less affected by the satellite dwarfs observed now. The closest example M31 halo also has enhanced α-elements, which are similar to the abundance patterns of the MW halo (Vargas et al. 2014). Proto-GCs are enriched in α-elements fed by SNe type II and they were disrupted to form the halo of the MW rather than present-day dwarf satellites. This may be yet another manifestation that the primary building blocks of the inner halo are proto-GCs.

Interestingly, recent abundance analyses of early-type galaxies support our predictions of the increasing SG population with the decreasing Galactocentric distance. As shown, e.g., in Milone et al. (2017) and generally regarded as well established, the enhancement of several elements, such as N and Na, would usually accompany He enhancement. van Dokkum et al. (2017; see their Figure 10) directly confirmed our hypothesis of the galaxy formation by showing enhanced Na abundance and depleted O abundance with decreasing radius of early-type galaxies, which is the same behavior of early-type galaxies support our predictions of the increasing SG population with the decreasing Galactocentric distance. As shown, e.g., in Milone et al. (2017) and generally regarded as well established, the enhancement of several elements, such as N and Na, would usually accompany He enhancement. van Dokkum et al. (2017; see their Figure 10) directly confirmed our hypothesis of the galaxy formation by showing enhanced Na abundance and depleted O abundance with decreasing radius of early-type galaxies, which is the same behavior of early-type galaxies support our predictions of the increasing SG population with the decreasing Galactocentric distance. As shown, e.g., in Milone et al. (2017) and generally regarded as well established, the enhancement of several elements, such as N and Na, would usually accompany He enhancement. van Dokkum et al. (2017; see their Figure 10) directly confirmed our hypothesis of the galaxy formation by showing enhanced Na abundance and depleted O abundance with decreasing radius of early-type galaxies, which is the same behavior of early-type galaxies support our predictions of the increasing SG population with the decreasing Galactocentric distance. As shown, e.g., in Milone et al. (2017) and generally regarded as well established, the enhancement of several elements, such as N and Na, would usually accompany He enhancement. van Dokkum et al. (2017; see their Figure 10) directly confirmed our hypothesis of the galaxy formation by showing enhanced Na abundance and depleted O abundance with decreasing radius of early-type galaxies, which is the same behavior of
elements that originated from GCs. If the dominant fraction of SGs causes this result, the assertion related to the bottom-heavy initial mass function, usually suggested and supported by strong Na absorptions (e.g., van Dokkum & Conroy 2010), is not valid, but the effect of SG stars that originated from GCs is more viable. We will discuss this issue in the upcoming paper regarding the initial mass function of early-type galaxies (C. Chung et al. 2019, in preparation).

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References
Abbate, F., Mastrobuono Battisti, A., Colpi, M., et al. 2018, MNRAS, 473, 927
Bastian, N., & Lardo, C. 2018, ARA&A, 56, 83
Battaglia, G., North, P., Jablonka, P., et al. 2017, A&A, 608, A145
Capuzzo-Dolcetta, R., & Micocchi, P. 2008, MNRAS: Letters, 388, L69
Carollo, D., Beers, T. C., Placco, V. M., et al. 2016, NatPh, 12, 1170
Cava, A., Schaerer, D., Richard, J., et al. 2018, NatAs, 2, 76
Chung, C., Lee, Y.-W., & Pasquato, M. 2016, MNRAS: Letters, 456, L1
Chung, C., Yoon, S.-J., Lee, S.-Y., & Lee, Y.-W. 2013, ApJS, 204, 3
Chung, C., Yoon, S.-J., & Lee, Y.-W. 2011, ApJL, 740, L45
Chung, C., Yoon, S.-J., & Lee, Y.-W. 2017, ApJ, 842, 91
Conselice, C. J. 2014, ARA&A, 52, 291
Dalessandro, E., Massari, D., Bellazzinni, M., et al. 2014, ApJL, 791, L4
Deason, A. J., Belokurov, V., Kosopov, S. E., & Lancaster, L. 2018, ApJL, 862, L1
Deason, A. J., Belokurov, V., & Weisz, D. R. 2015, MNRAS: Letters, 448, L77
D’Ercole, A., Vesperini, E., D’Antona, F., McMillan, S. L. W., & Recchi, S. 2008, MNRAS, 391, 825
Dessauges-Zavadsky, M., Schaerer, D., Cava, A., Mayer, L., & Tamburello, V. 2017, ApJL, 836, L22
Elmegreen, B. G., Bournaud, F., & Elmegreen, D. M. 2008, ApJ, 688, 67
Hawkins, K., Jofré, P., Gilmore, G., & Masseron, T. 2014, MNRAS, 445, 2575
Helmi, A., Babusiaux, C., Koppelman, H. H., et al. 2018, Natur, 563, 85
Hénault-Brunet, V., Gieles, M., Agertz, O., & Read, J. I. 2015, MNRAS, 450, 1164
Jofré, P., & Weisz, A. D. 2011, A&A, 533, A95
Joo, S.-J., Lee, Y.-W., & Chung, C. 2017, ApJ, 840, 98
Kalirai, J. S. 2012, Natur, 486, 90
Kim, J. J., & Lee, Y.-W. 2018, ApJ, 869, 25
Kalirai, J. S. 2012, Natur, 486, 90
Kim, J. J., & Lee, Y.-W. 2018, ApJ, 869, 25
Kim, J. J., & Lee, Y.-W. 2018, ApJL, 862, L8
Lee, Y.-W., Joo, S.-J., & Chung, C. 2015, MNRAS, 453, 3906
Lee, Y.-W., Kim, J. J., Johnson, C. I., et al. 2019, ApJL, 878, L2
Lim, D., Lee, Y.-W., Pasquato, M., Han, S.-I., & Roh, D.-G. 2016, ApJL, 832, 99
Martell, S. L., & Grebel, E. K. 2010, A&A, 519, A143
Martell, S. L., Shetrone, M. D., Lucatello, S., et al. 2016, ApJ, 825, 146
Martell, S. L., Smolinski, J. P., Beers, T. C., & Grebel, E. K. 2011, A&A, 534, A136
Milone, A. P., Piotto, G., Renzini, A., et al. 2017, MNRAS, 464, 3636
Preston, G. W., Shectman, S. A., & Beers, T. C. 1991, ApJ, 375, 121
Quinn, T., Perrine, R. F., Richardson, D. C., & Barnes, R. 2010, AJ, 139, 803
Rein, H., & Tremaine, S. 2011, MNRAS, 415, 3168
Santucci, R. M., Beers, T. C., Placco, V. M., et al. 2015, ApJL, 813, L16
Schiavon, R. P., Zamora, O., Carrera, R., et al. 2017, MNRAS, 465, 501
Searle, L., & Zinn, R. 1978, ApJ, 225, 357
Somerville, R. S., & Davé, R. 2015, ARA&A, 53, 51
Tolstoy, E., Hill, V., & Tosi, M. 2009, ARA&A, 47, 371
Tolstoy, E., Venn, K. A., Shetrone, M., et al. 2003, AJ, 125, 707
Torrealba, G., Catelan, M., Drake, A. J., et al. 2015, MNRAS, 446, 2251
van Dokkum, P., Conroy, C., Villumme, A., Brodie, J., & Romanowsky, A. J. 2017, ApJ, 841, 68
van Dokkum, P. G., & Conroy, C. 2010, Natur, 468, 940
Vargas, L. C., Gilbert, K. M., Geha, M., et al. 2014, ApJL, 797, L2
Vesperini, E., McMillan, S. L. W., D’Antona, F., & D’Ercole, A. 2013, MNRAS, 429, 1913
York, D. G., Adelman, J., Anderson, J. E. J., et al. 2000, AJ, 120, 1579

Deason, A. J., Belokurov, V., & Weisz, D. R. 2015, MNRAS: Letters, 448, L77
Deason, A. J., Belokurov, V., & Weisz, D. R. 2015, MNRAS: Letters, 448, L77