New Insight on the Origin of the Double Red Clump in the Milky Way Bulge

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Abstract
The double red clump (RC) observed in the Milky Way bulge is widely interpreted as evidence for an X-shaped structure. We have recently suggested, however, an alternative interpretation based on the multiple population phenomenon, where the bright RC is from helium-enhanced second-generation stars (G2), while the faint RC is representing first-generation stars (G1) with normal helium abundance. Here, our RC models are constructed in a large parameter space to see the effects of metallicity, age, and helium abundance on the double RC feature. Our models show that the luminosity of RC stars is mainly affected by helium abundance, while the RC color is primarily affected by metallicity. The effect of age is relatively small, unless it is older than 12 Gyr or much younger than 6 Gyr. The observed double RC feature can therefore be reproduced in a relatively large parameter space, once ΔY between G2 and G1 is assumed to be greater than ~0.10. We further show that the longitude dependence of the double RC feature at b ∼ −8°, which was pointed out by Gonzalez et al. as a potential problem of our model, is well explained in our scenario by a classical bulge embedded in a tilted bar.

Key words: galaxies: elliptical and lenticular, cD – galaxy: bulge – galaxy: formation – galaxy: structure – globular clusters: general – stars: horizontal-branch

1. Introduction
Some years ago, the presence of two red clumps (RCs) was discovered in the high-latitude (|b| > 6°) fields of the Milky Way bulge (McWilliam & Zoccali 2010; Nataf et al. 2010). The origin of this double RC, however, is currently under intense debate. It was initially interpreted as evidence for an X-shaped structure that originated from the disk and bar instabilities (McWilliam & Zoccali 2010; Saito et al. 2011; Li & Shen 2012; Wegg & Gerhard 2013). In this picture, the two RCs separated by ~0.5 mag is due to the difference in distance between the two arms of the X-shaped structure. We recently suggested (Lee et al. 2015, hereafter Paper I), however, a drastically different interpretation based on the multiple stellar population phenomenon, which is widely observed in globular clusters (GCs) including metal-rich bulge GCs Terzan 5, NGC 6388, and NGC 6441 (Lee et al. 1999, 2005; Caloi & D’Antona 2007; Yoon et al. 2008; Carretta et al. 2009b; Ferraro et al. 2009; Gratton et al. 2012). In this model, the brighter RC (bRC) is from helium-enhanced second-generation stars (G2), which are intrinsically brighter, while the faint RC (fRC) is originated from the first-generation stars (G1) with normal helium abundance.3

3 As discussed in Paper I, we are not arguing against the bar-dominated bulge in the low-latitude (|b| ≤ 6°) fields. The question is whether this pseudo-bulge characteristic is extended even to the high-latitude region as suggested by the X-shaped structure interpretation of the double RC phenomenon. In our model, low-latitude fields are dominated by the most metal-rich bar population, while relatively metal-poor classical bulge (CB) population becomes more and more important at higher latitudes. While the low-latitude fields show cylindrical rotation, stars in high-latitude fields rotate more slowly (Zoccali et al. 2014). Furthermore, Saha et al. (2012) showed that an initially non-rotating CB could absorb a significant fraction of the angular momentum from the bar within a few Gyr, which suggests that the cylindrical rotation is not necessarily evidence against the coexistence of CB. Zoccali et al. (2014) also pointed out that many early-type galaxies and the bulges originated from clumps (Elmegreen et al. 2008) are fast rotators. Note also that a three-dimensional density map of Wegg & Gerhard (2013) is based on the X-shaped structure interpretation of the double RC. Therefore, whether the high-latitude field is also dominated by the bar population or not depends largely on the interpretation of the double RC.

Soon after our suggestion, two counterarguments were presented. First, the longitude dependence of the double RC feature at b ∼ −8° was pointed out by Gonzalez et al. (2015) as a potential problem of our model. Second, by employing the WISE mid-IR image, Ness & Lang (2016) report a direct detection of a faint X-shaped structure in the Milky Way bulge. However, each of them can be rebutted. In a composite bulge, where a CB is embedded in a tilted bar (e.g., Babusiaux et al. 2010; Hill et al. 2011; Saha et al. 2012, 2016; Rojas-Arriagada et al. 2014; Zoccali et al. 2014; Erwin et al. 2015; Saha 2015), we have already shown in Paper I that our models can reproduce the longitude dependence well, which is also discussed in Section 3 of this paper with more realistic treatments. The second argument on the presence of a faint X-shaped structure is highly questioned as well, because when an ellipsoid is subtracted from a boxy structure as has been done by Ness & Lang (2016), an artificial X-shaped structure always remains (D. Han & Y.-W. Lee 2017, in preparation; see also López-Corredoira 2016). Furthermore, if the X-shaped structure is solely responsible for the observed double RC, ~45% of stars in the bulge are predicted to be on the orbits that make this structure (Portail et al. 2015). However, even if real, the stellar density in the claimed X-shaped structure of Ness & Lang (2016) appears to be way too low to be observed as a strong double RC at l = 0°. A crucial evidence against the X-shaped bulge was also presented by López-Corredoira (2016) from the analysis of the main-sequence (MS) stars in the bulge fields. Without critical distance information, therefore, the origin of the double RC phenomenon is still an open question, and the multiple population scenario merits more detailed investigations. The purpose of this paper is to extend the parameter space in our multiple population models to see the effects of metallicity, age, and helium abundance on the double RC feature. We have also used these models to illustrate how the point raised by Gonzalez et al. (2015) can be explained in our scenario.
2. Population Models

The population models presented in this study are based on Paper I and the techniques previously developed by Lee et al. (1990, 1994) and Joo & Lee (2013). As in Paper I, the Yonsei–Yale (Y2) isochrones and horizontal-branch (HB) evolutionary tracks (Yi et al. 2008; Han et al. 2009) were used to construct the models for the normal and helium-enhanced subpopulations, with the assumption of the fixed α-elements enhancement ([α/Fe] = 0.3). Parameters regarding the HB models, such as Reimers (1977) mass-loss coefficient (τ = 0.40) and the mass dispersion on HB stars (σ_M = 0.010M☉), are also identical to those adopted in Paper I. Color–temperature transformation was performed by employing the color table of Green et al. (1987) and the stellar model atmospheres of Castelli & Kurucz (2003). To see the effect of parameter changes on the synthetic RC more clearly, we present only single metallicity models in this paper.

Figure 1 shows our synthetic color–magnitude diagrams (CMDs) for the two RCs at four different metallicity regimes. The iRC stars are produced by G1 with the standard helium-enrichment parameter (ΔY/ΔZ = 2.0, Y_p = 0.23, Y = Y_p + Z(ΔY/ΔZ)), and the bRC is from G2 with the substantially enhanced helium abundance, Y = 0.406. The left panels are almost identical to those presented in Figure 1 of Paper I (Lee et al. 2015), while the helium abundance of G2 was slightly revised from Y = 0.39 to 0.406. Crosses are RR Lyrae variable stars from G2. Panels (b) and (f) represent the “reference models,” with [Fe/H] = −0.1, t = 12 Gyr, and Y = 0.276 (ΔY/ΔZ = 2.0) for G1, and, [Fe/H] = +0.1, t = 10 Gyr, and Y = 0.406 for G2 (see the text).
standard helium-enrichment parameter (i.e., $\Delta Y/\Delta Z = 2.0$, $Y_P = 0.23$, $Y = Y_P + Z(\Delta Y/\Delta Z)$), while G2 is substantially enhanced in helium abundance ($Y = 0.406$). Following Paper I, we have also adopted a 0.2 dex difference in metallicity between G2 and G1, and assumed 12 and 10 Gyrs for the ages of G1 and G2, respectively, with the same population ratio for the two RCs (Nataf et al. 2010; Paper I and references therein).

It is evident from these models that in the metal-rich population like the bulge, highly helium-enhanced stars ($Y \approx 0.40$) are not placed on the very blue HB as in the metal-poor GCs, but are instead placed on the bRC. We refer the reader to Section 2 of Paper I for a detailed description of the RC features of our models at four different metallicity regimes in Figure 1. Here, we note from the $(V-I, I)$ CMDs that the variation of the overall RC features on metallicity is similar to that in $(J-K, K)$ CMDs. Panel (f) in $(V-I, I)$ CMD can also naturally reproduce the observed double RC feature, i.e., $\sim 0.5$ mag difference with almost negligible color difference between the two RCs, as is the case in panel (b) in $(J-K, K)$ CMD. Hereafter, we refer to these models in panels (b) and (f) constructed at $\langle [\text{Fe/H}] \rangle = 0.0$ as “reference models,” to distinguish them from the models with different input parameters presented below. The CMDs for these reference models, down to the MS luminosity level, are further presented in Figure 2. This figure confirms that, in the position and width of the lower red-giant-branch (RGB) and main-sequence turn-off (MSTO), our models are not inconsistent with the observed CMDs of bulge population by Clarkson et al. (2008, 2011) and Brown et al. (2010).

While helium abundance was fixed for G2 ($Y = 0.406$) in the models in Figure 1, a more realistic case, in terms of the chemical evolution, would be that the helium content varies with metal abundance following a certain value of $\Delta Y/\Delta Z$. Models in Figure 3 were constructed with this hypothesis, adopting $\Delta Y/\Delta Z = 6.0$ for G2. The models for G1 are identical to those in Figure 1 following $\Delta Y/\Delta Z = 2.0$. Note that the reference models in panels (b) and (f) of Figure 3 are still identical to those in Figure 1. As the metallicity decreases from panels (b) and (f) to (c) and (g), magnitude differences between the two RCs decrease drastically, and in the bottom panels, the two RCs are almost merged into one. This is due to the strong decrease in helium abundance for G2 following $\Delta Y/\Delta Z = 6.0$. Compared to the models in Figure 1, where the helium abundance of G2 is fixed, the bRC stars in lower panels in Figure 3 are confined in the RC region rather than shifted to the bluer HB regime. Consequently, in both cases (i.e., Figures 1 and 3), no double RC is predicted by our models in the metal-poor regime, although the HB morphologies produced by G2 are significantly different in the two cases (see also Paper I). According to the chemical evolution models (e.g., Bekki & Norris 2006; Romano et al. 2007), helium abundance of G2 cannot increase beyond $Y_{\text{max}} \approx 0.41$; therefore, we adopted this value for G2 in the most metal-rich models in panels (a) and (e). Accordingly, the magnitude differences between the two RCs decrease again in these panels.

To see the individual effects of age, helium abundance, and metallicity on the double RC feature, in Figures 4–7, we have constructed the RC models under different assumptions on these parameters for G1 and G2. In these figures, luminosity functions are also presented on the right-side of each CMD, which were derived from $\sim 10,000$ stars for G1 and G2 respectively to minimize a stochastic effect. In Figure 4, we first investigate the effect of age variation on G2 from the reference models. From top to bottom panels, the age for G2 is decreased from 12 to 6 Gyrs, while the age for G1 is fixed (12 Gyr), so that the age difference between G1 and G2 ($\Delta t_{G1-G2}$) increases from 0 to 6 Gyrs. The helium abundance and metallicity are also fixed for both G1 and G2 as in the reference models. In the top panels, where the age for G2 is increased by 2 Gyr from the reference models in panels (b) and (f), it is evident that some significant portion of bRC stars are shifted to the blue HB, making the bluer mean color for the bRC stars compared to the stars in fRC. As such, this could be
considered as a reasonable upper limit for the age of G2, at the adopted metallicity and helium abundance. When the age of G2 is decreased by $2\text{–}4\text{ Gyr}$ from the reference models, however, as shown in the four bottom panels, the overall bRC feature is not remarkably changed, implying an insensitivity of the bRC morphology in this age range. Compared to the reference models in panels (b) and (f), the stars in bRC in the bottom panels are $\sim0.2\text{ mag}$ brighter and $\sim0.1\text{ mag}$ redder, while the age of G2 is decreased by 4 Gyrs, which would give a lower limit for the age of G2.

In Figure 5, we examine the case where the age of G1 also varies from 14 to 6 Gyrs, from the top to bottom panels, while the ages for G2 are identical to those in Figure 4. Again, panels (b) and (f) present the reference models. In the top panels, where the age of G1 is increased by 2 Gyrs from the reference models, no obvious changes are noticed in the fRC morphology, while the mean luminosity of fRC stars is slightly decreased ($\lesssim0.05\text{ mag}$) in both $K$ and $I$-bands. Similarly, when the age of G1 is decreased to be 2–6 Gyrs younger than that of the reference model, in the four bottom panels, no apparent changes in the color of the fRC stars are detected, while their luminosity is slightly increased. Consequently, in all panels, the fRC stars are confined to the RC region, even if they are as old as 14 Gyrs, illustrating that the color of the fRC is almost completely insensitive to the age variation in this high-metallicity regime. The luminosity of the fRC stars is also
not seriously affected by the age changes, although they become slightly brighter as age decreases. From Figures 4 and 5, we can therefore conclude that the possible ranges for age are $12 \gtrsim t \gtrsim 6$ Gyr for G2 and $t \gtrsim 6$ Gyr for G1. It should be noted that these age estimations are affected by the current uncertainty in the stellar mass-loss on the RGB. For example, if we increase the Reimers (1977) mass-loss coefficient, $\eta$, from 0.40 to 0.50, these ages are decreased by $\sim 1.0-1.5$ Gyr.

The effect of helium abundance is illustrated in Figure 6. In these models, helium mass fraction for G2 is varied from 0.41 to 0.35, while all the other parameters are fixed as in the reference models. The difference in helium abundance between the two RCs ($\Delta Y_{G2-G1}$) is then decreased from 0.13 to 0.07. The most prominent feature in this figure is that the magnitude difference between the two RCs decreases substantially as $\Delta Y_{G2-G1}$ decreases, from top to bottom panels. It is therefore clear from the luminosity functions that the observed separation in magnitude is reproduced in the top four panels, but not in the bottom four panels. The color of the bRC stars, on the other hand, is less affected by the variation in helium abundance, though they are somewhat redder than the fRC stars in the bottom four panels. This is because G2 in our models are more metal-rich than G1, and thus the helium effect is mostly canceled out by the metallicity effect in this metal-rich regime (see Section 1 in Paper I). Our simulations also suggest that if the helium abundance for G2 is allowed to increase beyond the upper limit ($Y_{\text{max}} = 0.41$) adopted in our models, the colors of the bRC can be bluer than those in the top panels.
Consequently, the strong dependence of the double RC feature on the helium abundance of G2 clearly suggests that the $\Delta Y_{G2-G1}$ would be within the range of $0.10 - 0.13$, to reproduce the observation in our scenario.

Figure 7 explores the cases where the metallicity difference between G2 and G1 ($\Delta [\text{Fe}/\text{H}]_{G2-G1}$) is different from our standard assumption, $\Delta [\text{Fe}/\text{H}]_{G2-G1} = 0.2$ dex. From the top to bottom panels, metallicity for G2 is increased from $[\text{Fe}/\text{H}] = -0.1$ to $+0.5$, so that $\Delta [\text{Fe}/\text{H}]_{G2-G1}$ increases from 0.0 to 0.6 dex. The other parameters are fixed as in the reference models presented in panels (b) and (f). The most notable feature from these models is that the color of bRC considerably shifts from blue to red in both $J - K$ and $V - I$ colors as metallicity for G2 increases. It is therefore clear that the difference in color between the two RCs changes substantially with $\Delta [\text{Fe}/\text{H}]_{G2-G1}$. Some decrease in luminosity of bRC is also shown in panels (a), (g), and (h), but the magnitude difference is not seriously affected by the metallicity variation in other panels. From these, we conclude that the $\Delta [\text{Fe}/\text{H}]_{G2-G1}$ would be no more than $\sim 0.3$ dex to reproduce the observed double RC with negligible color difference. Note that this is consistent with the metallicity difference ($\Delta [\text{Fe}/\text{H}] = 0.12 - 0.23$ dex) between the two RCs inferred from the spectroscopic observations (De Propris et al. 2011; Ness et al. 2012; Uttenthaler et al. 2012).

It is also interesting to see that the double RC feature in panels (c) and (g) of Figure 7 are qualitatively similar to that of Terzan 5, a metal-rich GC in the bulge (Ferraro et al. 2009; D’Antona et al. 2010; Origlia et al. 2011). This suggests that a larger difference in metallicity between the two RC populations is
mainly responsible for the color difference between the two RCs in this GC (see also Paper I), while a larger age difference (Ferraro et al. 2009) would also help to increase the color difference. Recently, Ferraro et al. (2016) have shown that the age of G2 in Terzan 5 is only \sim 4.5 Gyr from the detection of brighter MSTO stars, in addition to the faint majority MSTO stars of G1 with an old age (\sim 12 Gyr). In their comparison with stellar models, however, Ferraro et al. (2016) adopted \Delta [M/H] = 0.51 dex between G2 and G1, which is too large considering the observed difference (0.3 dex) in [\alpha/Fe] between G1 and G2. When this difference in [\alpha/Fe] is taken into account, \Delta [M/H] must be reduced to \sim 0.29 dex. Although G2 in Terzan 5 is much younger, the observed differences in age and metallicity are then not sufficient enough to reproduce the observed double RC as illustrated by our models in Figure 8. We still need a large difference in helium abundance (\Delta Y = 0.07). Therefore, Terzan 5 is qualitatively similar to our multiple population model for the double RC in the bulge. Because G2 in Terzan 5 is much younger, they are more affected (diluted) by SNe Ia, which would explain lower helium abundance (0.33 versus 0.39) and [\alpha/Fe] (0.0 versus 0.2) compared with bulge field stars in our scenario. In any case, Terzan 5 shows directly that multiple populations can produce a double RC.

In the metal-poor populations like the Milky Way GCs, the HB morphology is well known to be crucially influenced by all the three parameters (age, helium abundance, and metallicity) explored above (e.g., Lee et al. 1990, 1994). Our model simulations indicate, however, that in the metal-rich regime
(\(\text{[Fe/H]} \approx 0.0\)), the HB stars are mostly confined in the RC region, where the effects of these parameters are either qualitatively or quantitatively different from the metal-poor cases. The luminosity of RC stars is mainly affected by helium abundance, while the RC color is primarily affected by metallicity. The effect of age is relatively small within the age range of \(12 \gtrsim t \gtrsim 6\). From our models, we can suggest the possible ranges of parameters required to reproduce the observed double RC feature: \(\Delta t_{\text{G1-G2}} \approx 0-6\text{ Gyr}\), \(\Delta Y_{\text{G2-G1}} \approx 0.10-0.13\), and \(\Delta \text{[Fe/H]}_{\text{G2-G1}} \approx 0.0-0.3\text{ dex}\). It should be noted, however, that these three parameters are not independent from each other but degenerated. For example, Figure 9 illustrates how the different combinations of parameters could reproduce the observed double RC feature.

From the top to bottom panels, we increased the metallicity of G2 from \(\text{[Fe/H]} = -0.1\) to \(+0.2\), so that the metallicity difference between G2 and G1 increases from \(0.0\) to \(0.3\) dex. All the other parameters are fixed as in the reference models in panels (b) and (f).

**Figure 7.** Similar to Figure 4, but for the effect of \(\Delta \text{[Fe/H]}\) variation between G2 and G1. From top to bottom panels, \(\text{[Fe/H]}_{\text{G2}}\) is increased from \(-0.1\) to \(+0.5\), while \(\text{[Fe/H]}_{\text{G1}}\) is fixed at \(-0.1\), and thus, \(\Delta \text{[Fe/H]}_{\text{G2-G1}}\) varies from 0.0 to 0.6 dex. All the other parameters are fixed as in the reference models in panels (b) and (f).
3. Longitude Dependence at $b \approx -8^\circ$

Gonzalez et al. (2015) pointed out that our multiple population models for the double RC cannot explain the longitude dependence of the RC luminosity function at high Galactic latitude, $b \approx -8^\circ$. As shown in their Figures 1 and 2, the population in bRC becomes more prominent toward the positive longitudes, while the fRC population becomes more dominant in the negative longitudes. If this high-latitude field is dominated by the CB population with negligible contribution from the bar component, as argued by Gonzalez et al. (2015), it would be challenging for our models to reproduce the longitude dependence. However, in the case where the bar component is still not negligible over $b \approx -8^\circ$, our models can reproduce such lateral variations by a combination of the CB and bar populations, as shown in Figure 4 of Paper I. To investigate this effect in a composite bulge in more detail, we further conduct Monte-Carlo simulations for the three-dimensional density distributions of the CB and the bar components. For the CB component, we adopt the spatial density distribution of bulge RR Lyrae stars, $\rho \propto r^{-2.5}$, from Pietrukowicz et al. (2015), and assume a simple spherical shape (Dékány et al. 2013). Following Gardner & Flynn (2010) and Romero-Gómez et al. (2011), the bar component is modeled by a simple Ferrers ellipsoid (Ferrers 1877) with a density function of $\rho \propto (1 - m^2)^n$, where $m^2 = x^2/a^2 + y^2/b^2 + z^2/c^2$ and $n = 1$ when $m < 1$ ($\rho$ becomes 0 when $m > 1$). We assume the COBE/DIRBE bar with the axis ratio of $a:b:c = 10:4:3$ (Weiland et al. 1994; Freudenreich 1998; Gerhard 2002), and the position angle of the major axis with respect to the Galactic Center-Sun line as $30^\circ$ (López-Corredoira et al. 2005; Romero-Gómez et al. 2011).

Figure 10 shows density maps of our simulations for the two component bulge model, where the CB, the bar, and the sum of these two components are displayed from the top to bottom panels. Because we adopted a simple Ferrers bar, our composite model (the bottom right panel) may appear not as boxy as the observed bulge (e.g., López-Corredoira et al. 2005). Note, however, that our models are not for the detailed comparison with the observed density map, but to illustrate the variation of the population ratio between the CB and the bar components with Galactic longitude and latitude, and the corresponding changes in the RC luminosity function. As illustrated by our simulations, if the CB component has a spheroidal shape, the stellar density monotonically decreases with increasing distance from the Galactic center, while the density of the bar mostly depend on the distance above the Galactic plane. Therefore, at fixed latitude, the CB to bar population ratio would reach the maximum at minor axis ($l=0^\circ$) and decrease as longitude ($|l|$) increases.

In Figure 11, we present this effect on the RC luminosity function at $b \approx -5$ and $-8^\circ$ based on the stellar density distributions in Figure 10. For the direct comparison with Figure 2 of Gonzalez et al. (2015), we chose three fields at Galactic latitudes of $l = +2^\circ$, $0^\circ$, and $-2^\circ$. For the luminosity function of the CB component, we adopt $\Delta K \approx 0.6$ mag between the two RCs, and a Gaussian noise is added to reflect the differential reddening (Gonzalez et al. 2012) and other minor effects at chosen fields for both CB and bar components ($\sigma_K = 0.05$ for $b = -8^\circ$).
The large dispersions in RC luminosity functions are mainly due to the magnitude differences that come purely from distance differences of each star from the Sun. In our model, the RC luminosity function would be the sum of the CB component with double RC and the bar component with a single RC. The double RC in the lower middle panel is due to the majority CB population, while the longitude variations of the RC luminosity function, in the left and right panels, are mostly produced by the distance effect of the minority population of the tilted bar, where the bar component is placed at the near (far) side of the bulge toward positive (negative) longitude. This effect is more evident in the fields at $b = -5^\circ$, where the contribution of the bar population is stronger. The magnitude difference due to the distance effect is about $\Delta K \approx 0.09$ mag between the near and far sides of the bar component. This leads to the skewed distribution of RC luminosity function as the longitude $|l|$ of the field increases (see the top panels of Figure 11). In addition, when the tilted bar is projected on the sky, the near-side of the bar at positive longitude would appear larger than the far-side component at negative longitude (see the middle right panel in Figure 10). Therefore, at the same latitude, toward the positive longitude, we would observe the bulge field at a lower distance above the plane, where the stellar density is expected to be higher, and consequently, the bar contribution would be more prominent in the positive longitude compared to the negative longitude. This effect is also included in Figure 11. Note also that the luminosity

Figure 9. Similar to Figure 4, but here the models are constructed with different combinations of parameters to reproduce the double RC feature. While the model parameters for G1 are fixed as in the reference models, $[\text{Fe}/\text{H}]_{G2}$ is increased from $-0.1$ to $+0.2$, from top to bottom panels, so that $\Delta [\text{Fe}/\text{H}]_{G2-G1}$ varies from 0.0 to 0.3. The helium abundances and ages of G2 are then adjusted until we get reasonable agreements with the reference models in panels (c) and (g). The adopted values are denoted in the bottom left corner of each panel. Note that, in all panels, $Y_{G2}$ is significantly enhanced ($Y_{G2} > 0.1$).
The function of the bar component at \( b = -8^\circ \) is shifted toward the brighter side, which is because the line of sight passes through the near boundary of the Ferrers bar. It is encouraging to see that the observed RC luminosity functions presented in Figure 2 of Gonzalez et al. (2015) are better explained by our simulations than their X-shaped bulge model, especially at \( l = -2^\circ \).

There are at least two possible alternative effects that can also help to explain the longitude dependence at \( b \approx -8^\circ \). The first effect comes from the recent analysis of RR Lyrae variable stars in the Galactic bulge by Pietrukowicz et al. (2015, see their Figure 6), which shows that even the CB component is elongated in the inner region with the shape of a triaxial ellipsoid following the bar structure, while the outer region shows more spherical distribution. The RR Lyrae luminosity function in Figure 6 of Pietrukowicz et al. (2015) shows some hint of asymmetric distribution in the luminosity function with longitude dependence.

The other effect is from the possible metallicity variation with longitude at \( b \approx -8^\circ \). According to the metallicity map of Gonzalez et al. (2013), the double RC is best reproduced when \( \Delta Y/\Delta Z \) is adopted to be 8.0 for G2 and ages for G1 and G2 are assumed to be 11 and 9 Gyrs, respectively. From the top to bottom panels, we have then decreased the metallicity by 0.1 dex with the other parameters held fixed, which would mimic the metallicity variation from \( l = 0^\circ \) to \( -4^\circ \). Similarly to the metallicity dependence presented in Figure 3, the luminosity of bRC stars decreases rapidly with decreasing metallicity, and, with the metallicity change of only \( \Delta[Fe/H] = 0.2 \) dex, the RC split disappears as shown in panels (c) and (g). As discussed above, this drastic change of the bRC luminosity is mostly due to the large variation of helium abundance according to the high value of \( \Delta Y/\Delta Z \) parameter. Therefore, if the metallicity variation is confirmed, this effect would also help to reproduce the longitude dependence of the RC luminosity function on the negative longitude side. On the positive longitude side, the stronger peak at the bRC would be explained by the projection effect discussed above. The point raised out by Gonzalez et al. (2015) is therefore not necessarily a potential problem in our models, since our multiple population models can equally reproduce the observed variation of luminosity function with longitude at \( b \approx -8^\circ \).
4. Discussion

In the multiple population paradigm, we have shown that the magnitude difference between the two RCs is mostly affected by the difference in helium abundance between G2 and G1, and the observed double RC feature can be reproduced if \( \Delta Y_{G2-G1} \approx 0.10 - 0.13 \) at around solar metallicity. As illustrated in Figure 3, this is obtained if the helium abundance for G2 increases with metallicity following a helium-enrichment parameter \( \Delta Y/\Delta Z = 6.0 \), while G1 follows a standard value \( \Delta Y/\Delta Z = 2.0 \). Chemical evolution models (J. Kim & Y.-W. Lee, 2017, in preparation) confirm that this trend for G2 is predicted if the gas that formed G2 was locally enriched within the protogalactic subsystems by the winds of massive stars and the winds and ejecta from low and intermediate mass asymptotic-giant-branch stars. Disruption of these “building blocks” in a hierarchical merging paradigm would have provided stars (G1 and G2) to form a CB component in the early stage of the Milky Way formation. One crucial condition required to obtain this result is to assume that most of the supernova ejecta could escape from these relatively less massive systems without expelling the pre-enriched gas inside (see, e.g., Romano et al. 2010; Tenorio-Tagle et al. 2015). Because of the strong metallicity dependence of helium yield from the winds of massive stars (Maejer 1992; Meynet et al. 2008), helium abundance of G2 in these models would then increase rapidly with metallicity.

In our models, the helium abundance of G2, following \( \Delta Y/\Delta Z = 6.0 \), would be relatively low \( Y \approx 0.24 - 0.25 \) at metal-poor regime (i.e., halo GCs), while it is very high \( Y \approx 0.40 \) at solar metallicity where the double RC is observed (see Figure 11 of Lee & Jang 2016). Therefore, G2 in our models would correspond to “Na-intermediate” population defined by Carretta et al. (2009a). Very Na-rich and O-poor stars (“Extreme” population) are defined as G3 (3rd and later generations) in our models, which, if any, are more likely to be trapped in bulge GCs as in the metal-poor halo GCs (D’Ercole et al. 2008), and thus we do not expect many of them in the bulge fields. Nevertheless, at around solar metallicity, some significant spread in [Na/Fe] \( \Delta [\text{Na/Fe}] \approx 0.4 - 0.5 \) dex is observed in the bulge (see Figures 15 and 16 of Johnson et al. 2014; Figure 7 of Lecureur et al. 2007), which is clearly larger than that of the disk \( \Delta [\text{Na/Fe}] \approx 0.1 \) dex and halo \( \Delta [\text{Na/Fe}] \approx 0.25 \) dex field populations (see Figure 11 of Villanova et al. 2017), suggesting that the bulge contains more stars from G2 and later generations. Lecureur et al. (2007) even reports some indication of Na-O anticorrelation, although this has not been confirmed by Johnson et al. (2014).

In the relatively metal-poor regime ([Fe/H] \approx -1.1) of the Milky Way bulge, Pietrukowicz et al. (2015) discovered two sequences of RR Lyrae stars on the period-amplitude diagram. Recently, Lee & Jang (2016) suggested a common origin for this phenomenon and the double RC observed in the metal-rich regime of the bulge. They have shown that the period-shift between these two populations of RR Lyrae stars is due to a small difference in helium abundance \( \Delta Y \approx 0.01 \) between the first- and second-generation stars. As discussed above, this is expected because \( \Delta Y \) between G2 and G1 would be an order of magnitude smaller amount at this low metallicity regime compared to the metal-rich bulge where the double RC is observed. Therefore, it appears quite possible that the two populations of RR Lyrae stars and the double RC observed in the Milky Way bulge might be different manifestations of the same multiple population phenomenon in the metal-poor and
metal-rich regimes respectively. It is important to note that the double RC originated from multiple population phenomenon is also observed in a metal-rich bulge GC Terzan 5 (Ferraro et al. 2009). In Figure 8, we estimate a helium difference of $\Delta Y \approx 0.07$ between the two RCs in Terzan 5, which is roughly consistent with the value expected from a $\Delta Y / \Delta Z = 6.0$ trend at the metallicity of this GC ([Fe/H] = $-0.2$; Harris 1996). At lower metallicity, $\Delta Y$ between G2 and G1 would be smaller and consequently the magnitude separation between the two RCs would be also narrower, or the two RCs could be merged into one with a vertically extended feature (see Figure 3).

Interestingly, the RC part of the HB in NGC 6441, another bulge GC with [Fe/H] = $-0.5$ (Piotto et al. 2002; Harris 1996), shows just this feature, and Caloi & D’Antona (2007, see their Figure 6) indeed estimate a smaller $\Delta Y$ between G2 and G1 ($\Delta Y \approx 0.05$) from the RC luminosity function.

As stressed in Paper I, Gaia trigonometric parallax distances can soon provide a crucial test as to the origin of the double RC observed in the Milky Way bulge. This will in turn reveal whether a non-negligible fraction of the CB population is embedded in a bar structure of the Milky Way or not. Since the stellar populations in the CB component of the Milky Way are
considered the nearest example of those in elliptical galaxies, this will also severely impact our understanding of stellar populations and formation of early-type galaxies.

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Figure 13. Same as Figure 12, but for \((V - I, I)\) CMDs and \(I\)-band luminosity functions.
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