THE PRESENCE OF TWO DISTINCT RED GIANT BRANCHES IN THE GLOBULAR CLUSTER NGC 1851

SANG-IL HAN1, YOUNG-WOOK LEE1, SEOK-JOO JOO1, SANGMO TONY SOHN2, SUK-JIN YOON1, HAK-SUB KIM1, AND JAE-WOO LEE3

1 Center for Space Astrophysics and Department of Astronomy, Yonsei University, Seoul 120-749, Republic of Korea; ywlee2@yonsei.ac.kr.
2 Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA
3 Department of Astronomy and Space Science, ARCSEC, Sejong University, Seoul 143-747, Republic of Korea

Received 2009 October 5; accepted 2009 November 23; published 2009 December 7

ABSTRACT

There is a growing body of evidence for the presence of multiple stellar populations in some globular clusters, including NGC 1851. For most of these peculiar globular clusters, however, the evidence for the multiple red giant branches (RGBs) having different heavy elemental abundances as observed in ω Centauri is hitherto lacking, although spreads in some lighter elements are reported. It is therefore not clear whether they also share the suggested dwarf galaxy origin of ω Cen or not. Here we show from the CTIO 4 m UVI photometry of the globular cluster NGC 1851 that its RGB is clearly split into two in the \( U-I \) color. The two distinct RGB populations are also clearly separated in the abundance of heavy elements as traced by calcium, suggesting that the Type II supernovae enrichment is also responsible, in addition to the pollutions of lighter elements by intermediate-mass asymptotic giant branch stars or fast-rotating massive stars. The RGB split, however, is not shown in the \( V-I \) color, as indicated by previous observations. Our stellar population models show that this and the presence of bimodal horizontal-branch distribution in NGC 1851 can be naturally reproduced if the metal-rich second generation stars are also enhanced in helium.

Key words: globular clusters: individual (NGC 1851) – stars: abundances – stars: evolution – stars: horizontal-branch

1. INTRODUCTION

The first photometric evidence for the presence of multiple stellar populations in globular clusters came from the discoveries of the discrete distributions of stars on the red giant branch (RGB) and main sequence (MS) of the most luminous globular cluster ω Cen (Lee et al. 1999; Bedin el al. 2004). The fact that the distribution of RGB stars is not just showing a spread but is discrete is compelling evidence for the heavy elements enrichment and the formation of successive metal-enhanced generations of stars in proto-ω Cen. The similarity of this feature to that of the M54, suggested as a nuclear star cluster of the Sagittarius dwarf galaxy (Layden & Sarajedini 1997), together with other peculiarities of ω Cen, has led the community to conclude that ω Cen was once part of a more massive dwarf galaxy that merged with the Milky Way, as the Sagittarius dwarf galaxy is in the process of doing now (Lee et al. 1999; Bekki & Freeman 2003). In recent years, more and more evidence is reported for the presence of double or multiple stellar populations in other globular clusters, such as NGC 2808 (Piotto et al. 2007), NGC 1851 (Milone et al. 2008), NGC 6388 (Moretti et al. 2009), and M22 (Marino et al. 2009; Da Costa et al. 2009). For most of these peculiar globular clusters, however, the evidence for the discrete distribution of heavy elements as observed in the RGB of ω Cen is hitherto lacking, although spreads in some lighter elements (Carretta et al. 2008, and references therein) and helium (Lee et al. 2005; D’Antona et al. 2005; Piotto et al. 2007; Yoon et al. 2008) are reported. Therefore, the case of ω Cen, and now that of M22 (Marino et al. 2009; Da Costa et al. 2009), is still viewed as exceptional, and the presence of chemical inhomogeneity in other globular clusters is largely considered due to the pollution mechanisms expected in normal globular clusters, such as the winds from the intermediate-mass asymptotic giant branch (AGB) stars or fast-rotating massive stars (Ventura & D’Antona 2008; Decressin et al. 2007).

The purpose of this Letter is to report that one of these globular clusters, NGC 1851, is showing a clear split in the RGB from our CTIO 4m UVI photometry. This is compared with the Ca-by photometry (Lee et al. 2009b) to confirm that the two distinct RGB populations are different in the abundance of heavy elements. Stellar population models are then constructed to show that, when the metal-rich second generation stars are also enhanced in helium abundance, the split of the RGB discovered in the \( U-I \) color would not be detected in usual optical colors, such as \( V-I \) used in the Hubble Space Telescope (HST)/ACS survey.

2. OBSERVATIONS AND COLOR–MAGNITUDE DIAGRAMS

Our observations were performed using the CTIO 4 m Blanco telescope during 2007 November 13–16 and 2008 October 27–31. The telescope was equipped with the Mosaic II CCD Imager consisting of eight 2k × 4k SITe CCDs providing a plate scale of 0.27 arcsec pixel−1 and a field of view of 36 × 36 arcmin2. All of our science frames were obtained under photometric conditions. The total exposure times for UVI were 3990, 676, and 573 s, respectively, split into short, intermediate, and long exposures in each band. NGC 1851 was placed on chip 6, approximately 4.5 arcmin South and 6 arcmin East from the CCD center. Several standard fields (Landolt 1992, 2007) were also observed during our observing runs. The IRAF4 MSCRED package was used for preprocessing including bias correction and flat fielding. Point-spread function (PSF) photometry was then carried out using DAOPHOT II/ALLSTAR (Stetson 1987), and DAOGROW was used for aperture corrections (Stetson 1990).
Figure 1. CMDs for NGC 1851. In both panels, only the stars within an annulus between 3.6 arcsec and 4.5 arcmin from the cluster center and with sep > 1.0 have been plotted. Note the discrete double RGBs in the $U$ vs. $U - I$ CMD. Open circles denote RR Lyrae stars, and the photometric errors are shown.

Figure 1 shows color–magnitude diagrams (CMDs) of NGC 1851 in $(U, U - I)$ and $(V, V - I)$ planes. Stars within 3.6 arcsec and outside of 4.5 arcmin from the cluster center are excluded from the CMDs to reduce blending effects and the field star contaminations, respectively. To examine the CMD features more carefully, we adopted the “separation index” (Stetson et al. 2003) for selecting stars that are relatively less affected by adjacent starlights. All the stars in our CMDs lie well within chip 6, and therefore our CMDs are not subject to any uncertainty stemming from the possible chip to chip variations of the mosaic CCDs. Open circles denote RR Lyrae variables in our program field among those identified by Walker (1998), plotted at a random phase of pulsation. The most remarkable feature of Figure 1 is the presence of two distinct RGBs in the $(U, U - I)$ CMD. The discrete distribution is clear from the sub-giant-branch (SGB) to the tip of the RGB where the mean separation on the RGB is $\sim0.27$ mag in $U - I$. When measured at a given $I$ magnitude, this value is reduced to $\sim0.20$ mag. For the bright RGB stars, some early hints for this feature were noted by Calamida et al. (2007) from the Strömgren $(m1, u - y)$ CMD, and by Lee et al. (2009b) from the $Ca-b$ photometry (e.g., see their Figure 1). Note that Milone et al. (2008) only discovered a split in the SGB, and the split of the RGB we discovered in this paper was not detected in their HST/ACS photometry employing F606W and F814W passbands. Similarly, the RGB split is not apparent in our $(V, V - I)$ CMD (Figure 1(b)). This is most likely because the $U$ band is more sensitive to metal abundance variation than other passbands, as more metal atomic and molecular lines are located in the $U$ band (see Section 3).

Given the small foreground reddening value of $E(B - V) = 0.02$ (Harris 1996) toward NGC 1851, it is very unlikely that the differential reddening has caused the double RGBs. The color difference between the two RGBs in the $U - I$ color, at the given $I$ magnitude of the horizontal-branch (HB) level, is $\sim0.20$ mag, which is about three times larger than the maximum color difference expected in the extreme situation where one group of stars are all reddened by $E(B - V) = 0.02$, while the other group has $E(B - V) = 0.00$. Also, if the observed color difference in the $U - I$ color is due to the differential reddening, it would result in the $V - I$ color difference of 0.10 mag, which would have been detected along the RGB in our $(V, V - I)$ CMD. Similar spatial distributions of stars on the bluer and redder RGBs also indicate that the differential reddening, if any, is not likely the cause of the double RGBs.

3. DISCUSSION

We have shown that the RGB of NGC 1851 is split into two distinct subpopulations. The fact that the distribution of RGB stars does not just show a spread but is discrete can naturally eliminate the possibilities such as (1) star formation from inhomogeneous interstellar matter that is not mixed well, (2) differential reddening (see also Section 2), and (3) photometric errors, as all of these would produce a spread in color rather than a discrete distribution. Consequently, the most plausible interpretation for the double RGBs is that the NGC 1851 underwent metal enrichment in its early stage of evolution and successively formed metal-enhanced second generation stars. Spectroscopic observations show star-to-star abundance variations of the lighter elements (elements lighter than Si, such as N, O, Na, and Al) in NGC 1851 (Hesser 1982; Yong & Grundahl 2008; Yong et al. 2009). This is generally interpreted as a result of pollution from winds of intermediate-mass AGB stars (Ventura & D’Antona 2008) or fast-rotating massive stars (Decressin et al. 2007). Based on the elemental abundances observed by Yong & Grundahl (2008) and Yong et al. (2009) for eight bright RGB stars, we can estimate the differences in the lighter elements between the two RGB populations. Analysis of these data by Lee et al. (2009b), see their Figure 3) indicates that, while N, Na, and Al are all enhanced in redder RGB ($\Delta[N/Fe] \approx 0.47$, $\Delta[Na/Fe] \approx 0.53$, $\Delta[Al/Fe] \approx 0.20$), O is depleted ($\Delta[O/Fe] \approx -0.45$), and no significant variation is shown in $[C/Fe]$.

In order to investigate the effect of these elemental variations in the $(U - I)$ color, in Figure 2, we have computed the differences in fluxes between two synthetic spectra using the spectral-synthesis program SPECTRUM (Gray & Corbally 1994), one without and the other with these enhancements (and depletion for O) in lighter elements (panels (a) and (b)). Also shown in Figure 2 are the two additional cases where (1) CNO and Na are enhanced by 0.3 dex while heavier elements are fixed (panels (c) and (d)), and (2) elements heavier than Al are enhanced by 0.3 dex while lighter elements are fixed (panels (e) and (f)). These simulations demonstrate that small variations either in lighter or heavier elements could cause significant change in $(U - I)$ color. The observed variations in the lighter elements alone, however, would cause relatively small line blanketing equivalent to $\Delta(U - I) \approx 0.079$ in terms of color difference. Despite uncertainties, taken at face value, this is only $\sim41\%$ of the observed color difference $[\Delta(U - I) = 0.195 \pm 0.011]$ at given $I$ magnitude and suggests that other


Figure 2. Differences in fluxes between two synthetic spectra of RGB stars at the HB level. (a), (b) For the observed variations in lighter elements ($\Delta[N/Fe] \approx -0.47$, $\Delta[Na/Fe] \approx 0.53$, $\Delta[Al/Fe] \approx 0.20$, and $\Delta[O/Fe] \approx -0.45$). (c), (d) CNO and Na are enhanced by 0.3 dex, while heavier elements are fixed. (e), (f) Elements heavier than Al are enhanced by 0.3 dex, while lighter elements are fixed. Panels (g) and (h) are normalized responses for CTIO-4m U and I filters, while the dashed lines are for the Johnson filters (see text).

Figure 3. Same as Figure 1, but zoomed around the SGB and RGB regions in $U$ vs. $U-I$ CMD. Denoted by blue and red dots are, respectively, “Calcium-normal” and “Calcium-rich” stars from Lee et al. (2009b). Note that two discrete RGB sequences are well separated in calcium abundance.

Indeed, recent Ca-by photometry (Lee et al. 2009a) shows that besides lighter elements variations, RGB stars of NGC 1851 also show bimodal distribution in Ca, which can only be supplied by Type II supernovae (SNe II; Timmes et al. 1995). In Figure 3, we show in our $(U, U-I)$ CMD the “Ca-normal” and “Ca-strong” stars from Lee et al. (2009b). The Ca-strong stars lie well on the redder RGB sequence, whereas the Ca-normal stars are on the bluer RGB. According to Lee et al. (2009a), the difference in Ca abundance is estimated to be $\Delta[Ca/H] \approx 0.15$ dex, and other heavy elements, albeit small, are similarly enhanced in redder RGB population. We conclude therefore that the redder RGB population is richer in metallicity, but not in helium enhancement in N, but only negligible effect in the HR diagram morphology at globular cluster ages.

Comparison of the number ratio between the two subpopulations suggests that bluer RGB, brighter SGB, and redder HB are associated with one subpopulation, which we refer to as “Pop-1,” while the redder RGB, fainter SGB, and bluer HB are associated with the other subpopulation, which we refer to as “Pop-2.” Pop-1 comprises about 75% of the total population, while Pop-2 takes about 25% of the whole population. The $U$ flux is very sensitively affected by CN and NH bands, and therefore by N abundance. In order to reflect this effect in the $(U, U-I)$ CMD of the second generation population (redder RGB), we are also including the effects of the additional line absorptions from the enhancements in N and other lighter elements as discussed above, again by using SPECTRUM. More rigorous modeling should include the effects of these lighter elements enhancements in the construction of stellar evolutionary tracks, but we note that Dotter et al. (2007) found that the enhancement in N has only negligible effect in the HR diagram morphology at globular cluster ages.

In order to better understand the origin of the RGB color difference in $(U-I)$, and to place stronger constraints on the chemical combinations of the two subpopulations, we have constructed stellar population models based on the updated version of the Yonsei-Yale (Y$^2$) isochrones (S. Yi et al. 2010, in preparation) and HB evolutionary tracks (S.-I. Han et al. 2010, in preparation). Readers are referred to Yoon et al. (2008) and references therein for the details of our model construction. Figure 4 presents our synthetic CMDs for NGC 1851 in $(U, U-I)$ and $(V, V-I)$ planes. Our models are constructed under two different assumptions regarding the chemical enrich-

5 We have compared the ratio of the two subpopulations with samples selected in different manners (e.g., entire sample and a sample selected with various separation indices) and for all cases, the ratio comes out to be similar. This is also more or less consistent with the population ratio based on the SGB stars reported in Milone et al. (2009).
producing the observed HB bimodality. At the same time, the increase in helium abundance in Pop-2 moves RGB slightly bluer and this effect cancels out the metallicity effect in \((V, V − I)\) CMD, making apparently single and narrow RGB. Also, the model (Figure 4(b), inset) is in better agreement with the observed SGB split (Milone et al. 2008). The \(U\) band is much more sensitive to metal line blanketing, and therefore the increased helium has relatively small effect on the \(U − I\) color of RGB. One caveat to this helium enhanced scenario is that the blue HB in our model appears to be slightly brighter (−0.05 mag) than the observation in the \(U\) band, although this could be due to the uncertainty in bolometric correction of the \(U\) band.

The apparent helium enhancement in the second generation subpopulation in NGC 1851 is reminiscent of the cases of other globular clusters with multiple populations, including \(ω\) Cen (Norris 2004; Lee et al. 2005; Piotto et al. 2005), NGC 2808 (Lee et al. 2005; D’Antona et al. 2005), NGC 6388, and NGC 6441 (Caloi & D’Antona 2007; Decressin et al. 2007). In the case of NGC 1851, given the enhancements both in the lighter (such as \(N\)) and heavy (such as \(Ca\)) elements in the second generation population (Pop-2), all of the mechanisms seem to be responsible for the helium enhancement. A possible scenario is that, soon after the formation of the first generation stars (Pop-1), numerous SNe II explosions enriched both metal and helium of the leftover gas in the proto-NGC 1851. Winds and ejecta from the intermediate-mass AGB stars or fast-rotating massive stars (Ventura & D’Antona 2009; Decressin et al. 2007). In the case of NGC 1851, given the enhancements both in the lighter (such as \(N\)) and heavy (such as \(Ca\)) elements in the second generation population (Pop-2), all of the mechanisms seem to be responsible for the helium enhancement. A possible scenario is that, soon after the formation of the first generation stars (Pop-1), numerous SNe II explosions enriched both metal and helium of the leftover gas in the proto-NGC 1851.
High resolution spectroscopy of stars in the two distinct groups is also needed to confirm the small difference in the abundance of heavy elements.

We thank the referee Luigi Bedin for a number of helpful suggestions. Support for this work was provided by the Creative Research Initiatives Program of the Korean Ministry of Education, Science & Technology and KOSEF, for which we are grateful. S.-J. Y. acknowledges support from KOSEF/MEST grant (2009-0080851). J.-W. L. acknowledges support from KOSEF to ARCSEC. This material is based upon work supported by AURA through the NSF under AURA Cooperative Agreement AST 0132798, as amended.

REFERENCES

Baumgardt, H., Kroupa, P., & Parmentier, G. 2008, MNRAS, 384, 1231
Bedin, L. R., Piotto, G., Anderson, J., Cassisi, S., King, I. R., Momany, Y., & Carraro, G. 2004, ApJ, 605, L125
Bekki, K., & Freeman, K. 2003, MNRAS, 346, 11
Calamida, A., et al. 2007, ApJ, 670, 400
Caloi, V., & D’Antona, F. 2007, A&A, 463, 949
Carretta, E., Bragaglia, A., Gratton, R. G., & Lucatello, S. 2008, arXiv:astro-ph/0811.3591
Cassisi, S., Salaris, M., Pietrinferni, A., Piotto, G., Milone, A. P., Bedin, L. R., & Anderson, J. 2008, ApJ, 672, L115
Da Costa, G. S., Held, E. V., Saviane, I., & Gullieuszik, M. 2009, ApJ, 705, 1481
D’Antona, F., Bellazzini, M., Caloi, V., Pecci, F. F., Galleti, S., & Rood, R. T. 2005, ApJ, 631, 868
Decressin, T., Meynet, G., Charbonnel, C., Prantzos, N., & Ekström, S. 2007, A&A, 464, 1029
Dopita, M. A., & Smith, G. H. 1986, ApJ, 304, 283
Dotter, A., Chaboyer, B., Ferguson, J. W., Lee, H. -c., Worthey, G., Jevremović, D., & Baron, E. 2007, ApJ, 666, 412
Gray, R. O., & Corbally, C. J. 1994, AJ, 107, 742
Green, E. M., Demarque, P., & King, C. R. 1987, The Revised Yale Isochrones & Luminosity Functions (New Haven, CT: Yale Univ. Obs.)
Harris, W. E. 1996, AJ, 112, 1487
Hesser, J. E., Bell, R. A., Harris, G. L. H., & Cannon, R. D. 1982, AJ, 87, 1470
Landolt, A. U. 1992, AJ, 104, 340
Landolt, A. U. 2007, AJ, 133, 2502
Layden, A., & Sarajedini, A. 1997, ApJ, 486, L107
Lee, J.-W., Kang, Y.-W., Lee, J., & Lee, Y.-W. 2009a, Nature, 462, 480
Lee, J.-W., Lee, J., Kang, Y.-W., Lee, Y.-W., Han, S.-I., Joo, S.-J., Rey, S.-C., & Yong, D. 2009b, ApJ, 695, L78
Lee, Y.-W., Demarque, P., & Zinn, R. 1994, ApJ, 423, 248
Lee, Y.-W., Gim, H. B., & Casertani, C. D. 2007, ApJ, 661, L49
Lee, Y.-W., Joo, J.-M., Sohn, Y.-J., Rey, S.-C., Lee, H.-c., & Walker, A. R. 1999, Nature, 402, 55
Lee, Y.-W., et al. 2005, ApJ, 621, L57
Marino, A. F., Milone, A. P., Piotto, G., Villanova, S., Bedin, L. R., Bellini, A., & Renzini, A. 2009, A&A, 505, 1099
Milone, A. P., Stetson, P. B., Piotto, G., Bedin, L. R., Anderson, J., Cassisi, S., & Salaris, M. 2009, A&A, 503, 755
Milone, A. P., et al. 2008, ApJ, 673, 241
Moretti, A., et al. 2009, A&A, 493, 539
Norris, J. E. 2004, ApJ, 612, L25
Piotto, G., et al. 2005, ApJ, 621, 777
Piotto, G., et al. 2007, ApJ, 661, L53
Pryor, C., & Meylan, G. 1993, in ASP Conf. Ser. 50, Structure and Dynamics of Globular Clusters, ed. S. G. Djorgovski & G. Meylan (San Francisco, CA: ASP), 357
Reimers, D. 1977, A&A, 57, 395
Salaris, M., Cassisi, S., & Pietrinferni, A. 2008, ApJ, 678, L25
Stetson, P. B. 1987, PASP, 99, 191
Stetson, P. B. 1990, PASP, 102, 932
Stetson, P. B., Bruntt, H., & Grundahl, F. 2003, PASP, 115, 413
Timmes, F. X., Woosley, S. E., & Weaver, T. A. 1995, ApJS, 98, 617
Ventura, P., & D’Antona, F. 2008, MNRAS, 385, 2034
Ventura, P., & D’Antona, F. 2009, A&A, 499, 835
Walker, A. R. 1998, AJ, 116, 220
Yong, D., & Grundahl, F. 2008, ApJ, 672, L29
Yong, D., Grundahl, F., D’Antona, F., Karakas, A. I., Lattanzio, J. C., & Norris, J. E. 2009, ApJ, 695, L62
Yoon, S.-J., Joo, S.-J., Ree, C. H., Han, S.-I., Kim, D.-G., & Lee, Y.-W. 2008, ApJ, 677, 1080