KINEMATIC DECOUPLING OF GLOBULAR CLUSTERS WITH THE EXTENDED HORIZONTAL BRANCH

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ABSTRACT

About 25% of the Milky Way globular clusters (GCs) exhibit unusually extended color distribution of stars in the core helium-burning horizontal-branch (HB) phase. This phenomenon is now best understood as due to the presence of helium-enhanced second-generation subpopulations, which has raised the possibility that these peculiar GCs might have a unique origin. Here we show that these GCs with extended HB are clearly distinct from other normal GCs in kinematics and mass. The GCs with extended HB are more massive than normal GCs and are dominated by random motion with no correlation between kinematics and metallicity. Surprisingly, however, when they are excluded, most normal GCs in the inner halo show clear signs of dissipational collapse that apparently led to the formation of the disk. Normal GCs in the outer halo share their kinematic properties with the extended HB GCs, which is consistent with the accretion origin. Our result further suggests heterogeneous origins of GCs, and we anticipate this to be a starting point for more detailed investigations of Milky Way formation, including early mergers, collapse, and later accretion.

Subject headings: Galaxy: formation — globular clusters: general — stars: horizontal-branch

1. INTRODUCTION

The discovery of multiple stellar populations in the most massive GC ω Cen (Lee et al. 1999), together with the fact that the second most massive GC M54 is a core of the disrupting Sagittarius dwarf galaxy (Layden & Sarajedini 2000), has strengthened the view that some of the massive GCs might be remaining cores of disrupted nucleated dwarf galaxies (Freeman 1993). Among their several peculiar characteristics, both ω Cen and M54 have an extended horizontal branch (EHB), with extremely hot horizontal-branch (HB) stars well separated from the redder HB (Lee et al. 1999; Rosenberg et al. 2004). High-resolution Hubble Space Telescope (HST) photometry (Bedin et al. 2004) has discovered that ω Cen also has a curious double main sequence (MS). Recent studies have shown that both these peculiar color-magnitude diagram (CMD) characteristics are best understood as due to the presence of helium-enhanced second-generation subpopulations (Norris 2004; Lee et al. 2005; Piotto et al. 2005; D’Antona et al. 2005). Furthermore, the prediction of the models (Lee et al. 2005; D’Antona et al. 2005) that most of the GCs with an EHB would have double or broadened MSs are now confirmed by HST ACS (Advanced Camera for Survey) photometry (Piotto et al. 2007). This ensures that EHBs are strong signatures of the presence of multiple populations in GCs. A significant fraction (∼30%) of the helium-enriched subpopulation observed in these peculiar GCs is also best explained if the second-generation stars were formed from enriched gas trapped in the deep gravitational potential well while these GCs were cores of the ancient dwarf galaxies (Bekki & Norris 2006). Despite the lack of an apparently wide spread in iron-peak elements in most of these GCs, all of these recent developments suggest that GCs with EHBs are probably not genuine GCs but might have a unique origin in the formation history of the Galaxy.

In order to test this working hypothesis further, we have carefully surveyed 114 GCs with reasonably good CMDs and found that 28 (25%) of them have an EHB (Y.-W. Lee et al. 2007, in preparation). Their NGC numbers are 2419, 2808, 5139, 5986, 6093, 6205, 6266, 6273, 6388, 6441, 6656, 6715, 6752, 7078, and 7089 for the GCs with strongly extended HB; and 1851, 1904, 4833, 5904, 6229, 6402, 6522, 6626, 6681, 6712, 6723, and 6864 for the GCs with moderately extended HB, including those with bimodal HB distributions. We will collectively call all of them “EHB GCs.” Our selection of EHB GCs was based on the reddening-independent criteria on the CMD in the B and V passbands [ΔV HB > 3.5 for strongly extended HB; either 3.0 < ΔV HB < 3.5 or Δ(B - V) HB > 0.78 with clear bimodal color distribution for moderately extended HB]. But since their appearances on CMDs are distinct enough from GCs with normal HB (Piotto et al. 2002), our selection agrees well with the result based on a smaller sample and other measures of HB temperature extension (e.g., Recio-Blanco et al. 2006). We have then investigated their properties compared to other normal GCs.

2. LUMINOSITY FUNCTION AND KINEMATICS

First of all, from the luminosity function (Fig. 1), we found that EHB GCs are among the brightest GCs of the Milky Way, including 11 of the 12 brightest GCs (see also Recio-Blanco et al. 2006). It is surprising to see that not a single EHB GC is fainter than $M_V = −7$. Careful inspection of all CMDs confirms that this is not due to the smaller number of HB stars in fainter GCs. Because of a significant fraction (18%–51%) of the helium-enriched bluer subpopulation observed in EHB GCs, its presence on the HB would be reliably detected (>5–10 stars) even in a cluster of $M_V = −6$ or −5 if it existed. This result perhaps already suggests that EHB GCs might have a peculiar origin, as their inferred current stellar mass, which might represent only a small fraction of their original mass, is comparable with that of low-luminosity dwarf galaxies in the Local Group.

Motivated by this, we have investigated the kinematics of EHB GCs, in order to see whether their kinematic properties are also distinct from other normal GCs. Following a previous investigation (Zinn 1993), we have first divided GCs into three subgroups (Fig. 2) based on the HB morphology and metallicity diagram (Lee et al. 1994). Metal-poor ([Fe/H] < −0.8) GCs in the “old halo” (OH) group have bluer HB morphology at a given metallicity, and those in the “younger halo” (YH) group...
have redder HB morphology at fixed metallicity. The OH group, in the mean, is probably older than the YH group by ~1 Gyr (Rey et al. 2001; Salaris & Weiss 2002). The metal-rich ([Fe/H] > −0.8) GCs are further classified as the “disk/bulge” (D/B) group. EHB GCs belong in all three subgroups, although the majority of them are in the OH group. Note also that most (94%) GCs in the YH group are in the outer halo (galactocentric distance, \( R_{500} > 8 \) kpc), while the majority (80%) of GCs in the OH and D/B groups are in the inner halo (\( R_{500} < 8 \) kpc).

The results of the kinematic analysis based on the constant rotational-velocity solutions (Zinn 1993; Frenk & White 1980) and the updated database of Harris (1996) are presented in Table 1. When all the GCs are considered, we are basically confirming the conclusion of the previous work (Zinn 1993). The YH group is dominated by random motion with no sign of firming the conclusion of the previous work (Zinn 1993). The blue 1. When all the GCs are considered, we are basically confirming the conclusion of the previous work (Zinn 1993). The D/B group is mostly supported by rotation with a relatively small \( \sigma_{v_r} \). We find, however, that EHB GCs, belonging to both YH and OH groups, are dominated by random motion and show no signs of rotation. Consequently, when they are excluded from the sample, normal GCs in the OH group show increased rotation (from 1.5 to 1.8 \( \sigma \) from zero \( V_{\text{los}} \)) and higher value of \( V_{\text{los}}/\sigma_{v_r} \). The same trend is also observed in the normal GCs in D/B group, but with much larger uncertainty. When only comparably bright \( (M_V < -6) \) GCs are considered, the differences become significantly larger (2.5 \( \sigma \) from zero \( V_{\text{los}} \)). The above analysis, based only on the radial velocity data, provides good reason to suspect that EHB GCs are kinematically decoupled from other normal GCs, especially in the OH group. Below we investigate this in more detail using the measurements of full spatial motions and orbital parameters now available for 49 GCs in our sample (Dinescu et al. 2003).

In Figure 3, we have plotted kinematic parameters obtained from full spatial motions as a function of metallicity, which show more directly the systematic differences between EHB and normal GCs. In Figure 3, EHB GCs have diversity in kinematics and show no correlations with metallicity (correlation coefficient, \( r \), of −0.02 to −0.31 with high \( p \)-values of \( 0.25-0.94 \)). Normal YH GCs, mostly in the outer halo, show kinematically hot signatures (high \( E_{\text{rot}} \), \( Z_{\text{max}} \), eccentricity, and large velocity dispersion; see also Mackey & Gilmore 2004).

To our surprise, however, when EHB GCs are excluded, most normal GCs with prograde rotation in OH and D/B groups (red

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**TABLE 1**

| Group   | Number | \( V_{\text{los}} \) | \( \sigma_{v_r} \) | \( V_{\text{los}}/\sigma_{v_r} \) |
|---------|--------|----------------------|-------------------|-----------------------------|
| All GCs |        |                      |                   |                             |
| All     | 71     | 25 ± 27              | 124 ± 10          | 0.20 ± 0.22                 |
| YH      | 25     | -18 ± 66             | 153 ± 22          | -0.12 ± 0.43                |
| OH      | 46     | 40 ± 27              | 104 ± 11          | 0.38 ± 0.26                 |
| D/B     | 14     | 168 ± 28             | 65 ± 12           | 2.57 ± 0.65                 |
| All EHB | 24     | 10 ± 32              | 93 ± 13           | 0.11 ± 0.34                 |
| OH      | 18     | 4 ± 35               | 91 ± 15           | 0.05 ± 0.38                 |
| Normal  |        |                      |                   |                             |
| All     | 48     | 32 ± 39              | 137 ± 14          | 0.24 ± 0.29                 |
| YH      | 20     | -42 ± 80             | 162 ± 26          | -0.26 ± 0.49                |
| OH      | 28     | 70 ± 39              | 111 ± 15          | 0.63 ± 0.36                 |
| D/B     | 13     | 188 ± 22             | 48 ± 9            | 3.94 ± 0.89                 |
| Normal  |        |                      |                   |                             |
| All     | 39     | 37 ± 44              | 139 ± 16          | 0.26 ± 0.32                 |
| YH      | 17     | -69 ± 81             | 160 ± 27          | -0.44 ± 0.51                |
| OH      | 22     | 105 ± 42             | 103 ± 15          | 1.02 ± 0.43                 |
| D/B     | 11     | 195 ± 27             | 52 ± 11           | 3.76 ± 0.95                 |

Note.—For \( R_{500} < 40 \) kpc and excluding GCs with cos \( \psi > 0.2 \).
filled circles) show clear signs of dissipational collapse, $E_{\text{int}}$, $Z_{\text{max}}$, $W$ velocity, and perhaps orbital eccentricity are all decreasing with increasing metallicity, among which the “chevron” shape of $W$ velocity distribution is most impressive. Rotational velocity, however, is increasing with metallicity, and $L_Z$ appears to be conserved. The orbital properties of NGC 6528 are known to be highly affected by the potential of the bar because of its proximity (Dinescu et al. 2003). Thus, excluding this one deviant point in Figures 3d and 3e, we obtain strong correlations for $E_{\text{int}}$, $Z_{\text{max}}$, $|W|$, $\Theta$, and eccentricity ($r = -0.58, -0.71, -0.95, 0.89$, and $-0.77$, respectively) with small p-values ($0.05, 0.01, 3.1 \times 10^{-6}, 0.0002$, and $0.005$, respectively). In other words, the correlations are highly significant at the level of 95%, 99%, 99.999%, 99.98%, and 99.5%, respectively. As expected, however, correlation is low ($r = 0.17$) for $L_Z$ with a high $p$-value of 0.59.

All of these trends observed for normal GCs with prograde rotation in OH and D/B groups are fully consistent with the model first envisioned by Eggen et al. (1962), where metal enrichment went on as dissipational collapse continued. Although these results are based on relatively modest numbers of GCs with full spatial motion information, their coherent behaviors in all panels of Figure 3, together with statistically significant correlations, confirm that we are detecting real signatures. Also, these results are consistent with the kinematics solution obtained from radial velocity alone (Table 1), which is based on a larger sample of GCs. We argue, therefore, that (1) EHB GCs in our sample are indeed kinematically decoupled from most of the normal GCs in OH group, and (2) when EHB GCs are excluded, we are detecting clearer signatures of dissipational collapse in the inner halo, which apparently led to the formation of the Galactic disk (Zinn 1993; Mackey & Gilmore 2004). The kinematics of EHB GCs, which are not following the dissipational collapse, are more consistent with what one would expect among the relics of primeval star-forming subsystems that first formed the nucleus (EHB GCs with low $E_{\text{int}}$ and $Z_{\text{max}}$) and halo (EHB GCs with high $E_{\text{int}}$ and $Z_{\text{max}}$) of the Galaxy through both dissipational and dissipationless mergers, as has been predicted by recent ΛCDM simulations for “high-σ peaks” (e.g., Diemand et al. 2005; Moore et al. 2006). As described above, a significant fraction of the helium-enriched subpopulation also favors the building block origin of EHB GCs. Normal YH GCs in the outer halo share their kinematic properties with the outlying EHB GCs, which is consistent with the view (Searle & Zinn 1978) that they were originally formed in the outskirts of isolated building blocks and later accreted to the outer halo of the Galaxy when their parent dwarf galaxies, like Sagittarius, were merging with the Milky Way. The GCs with EHBs also tend to show more extended Na-O and Mg-Al anticorrelations (Gratton 2007). Therefore, the suggested connection between some of these GCs with strong chemical inhomogeneity and orbital parameters (Carretta 2006) might be due to the diversity of kinematics among EHB GCs.

According to the present picture, most of the normal GCs with retrograde rotation in OH and D/B groups could have also orig-
inated from the subsystems with retrograde rotation. Interestingly, their relatively confined distributions in both the angular momentum phase space (Helmi et al. 1999) and velocity space are not inconsistent with the possibility that some or most of them were former members of parent dwarf galaxies hosting two EHB GCs, ω Cen and/or NGC 6723 (Lee et al. 2007, in preparation). Their distribution in velocity space is also well consistent with the model prediction of the tidal debris from ω Cen’s parent dwarf system (Mizutani et al. 2003), which was presumably formed in the outer halo and accreted to the inner halo. Note that a similar minor merging of subsystems with the thin disk (Quinn et al. 1993) could have also changed some of the original kinematic properties of two disk GCs in Figure 3 (47 Tuc and M71).

3. DISCUSSION

The clear differences in kinematics and mass between GCs with and without an EHB are strong evidence that they have different origins. Our results suggest present-day Galactic GCs are most likely an ensemble of heterogeneous objects originated from three distinct phases of the Milky Way formation: (1) remaining cores or central star clusters of building blocks that first assembled to form the nucleus and halo of the proto-Galaxy (Bromm & Clarke 2002; Santos 2003; Bekki 2005; Kravtsov & Gnedin 2005; Moore et al. 2006), (2) genuine GCs formed in the dissipational collapse of a transient gas-rich inner halo system that later collapsed in phase (2) is still most unclear, but it is attractive to speculate that leftover gas from “rare peaks” (building blocks hosting EHB GCs) in the inner halo and gas from continuously falling “less rare peaks” (Moore et al. 2006) led to the formation of this structure, perhaps with the aids of some heating feedbacks (e.g., Schawinski et al. 2006) soon followed by cooling. Several lines of further study will certainly help to shed more light into the picture briefly sketched here, for example, a search for the tidal streams that might be associated with EHB GCs, a dark matter search in the outlying EHB GCs where preferential disruption of dark matter halo (Saitoh et al. 2006) might be less severe, and kinematics analyses of extragalactic GC systems along with the ultraviolet survey for EHB GC candidates, together with more detailed high-resolution ΛCDM simulations.

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