# KINEMATIC DECOUPLING OF GLOBULAR CLUSTERS WITH 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 a 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  $\omega$ 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), have strengthen 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  $\omega$ Cen and M54 have extended horizontal-branch (EHB), with extremely hot horizontal-branch (HB) stars well separated from redder HB (Lee et al. 1999; Rosenberg, Recio-Blanco, & Garcia-Marin 2004). High precision Hubble Space Telescope (HST) photometry (Bedin et al. 2004) has discovered that  $\omega$ Cen also has a curious double main-sequence (MS). Recent studies have shown that both these peculiar colour-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). more, the prediction of the models (Lee et al. 2005; D'Antona et al. 2005) that most of the GCs with 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 signature of the presence of multiple populations in GCs. A significant fraction ( $\sim 30\%$ ) 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 apparently wide spread in iron-peak elements

in most of these GCs, all of these recent developments suggest that GCs with EHB 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 EHB (Lee et al., 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, 5824, 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 as "EHB GCs". Our selection of EHB GCs were based on the reddening independent criteria on CMD in B&V passbands ( $\Delta V_{HB} > 3.5$  for strongly extended HB; either  $3.0 < \Delta V_{HB} < 3.5$  or  $\Delta (B - V)_{HB}$ > 0.78 with clear bimodal colour 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 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 out of 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 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

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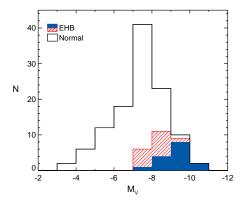


Fig. 1.— The histogram of  $M_V$  for 114 Milky Way GCs (data from Harris 1996). Blue and red are GCs with strongly and moderately extended HBs, respectively. EHB GCs are clearly brighter (more massive) than normal GCs.

existed. This result is perhaps already suggesting 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 previous investigation (Zinn 1993), we have first divided GCs into three subgroups (Fig. 2) based on the HB morphology and metallicity diagram (Lee, Demarque, & Zinn 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  $\sim 1$  Gyr (Rey et al. 2001; Salaris & Weiss 2002). The metal-rich ([Fe/H] > -0.8) GCs are further classified as "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 YH group are in the outer halo (galactocentric distance,  $R_{gc} > 8$  kpc), while the majority (80%) of GCs in OH and D/B groups are in the inner halo  $(R_{gc} < 8 \text{ kpc})$ .

The result of the kinematic analysis based on the constant-rotational-velocity solutions (Zinn 1993; Frenk & White 1980) and the updated database of Harris (Harris 1996) is presented in Table 1. When all the GCs are considered, we are basically confirming the conclusion of the previous work (Zinn 1993). YH group is dominated by random motion with no sign of significant rotation  $(V_{rot})$ , while OH group shows some prograde rotation and a smaller line-of-sight velocity dispersion  $(\sigma_{los})$ . D/B group is mostly supported by rotation with a relatively small  $\sigma_{los}$ . We find, however, EHB GCs, both belonging to 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 OH group show increased rotation (from 1.5 to  $1.8\sigma$  from zero  $V_{rot}$ ) and higher value of  $V_{rot}/\sigma_{los}$ . 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  $V_{rot}$ ). The

TABLE 1 KINEMATICS OF GLOBULAR CLUSTERS BASED ON RADIAL VELOCITY ALONE $^*$ 

Group	N	$V_{rot}$	$\sigma_{los}$	$V_{rot}/\sigma_{los}$
All GCs				
All Halo	71	$25 \pm 27$	$124 \pm 10$	$0.20 {\pm} 0.22$
YH	25	$-18\pm66$	$153 \pm 22$	$-0.12 \pm 0.43$
OH	46	$40 \pm 27$	$104 \pm 11$	$0.38 {\pm} 0.26$
D/B	14	$168 \pm 28$	$65 \pm 12$	$2.57{\pm}0.65$
EHB GCs				
All EHB	24	$10 \pm 32$	$93 \pm 13$	$0.11 \pm 0.34$
OH	18	$4 \pm 35$	$91 \pm 15$	$0.05 {\pm} 0.38$
Normal				
All Halo	48	$32 \pm 39$	$137 \pm 14$	$0.24 \pm 0.29$
YH	20	$-42\pm80$	$162 \pm 26$	$-0.26 \pm 0.49$
OH	28	$70 \pm 39$	$111 \pm 15$	$0.63 \pm 0.36$
D/B	13	$188 \pm 22$	$48 \pm 9$	$3.94 \pm 0.89$
Normal $(M_V < -6)$				
All Halo	39	$37 \pm 44$	$139 \pm 16$	$0.26 {\pm} 0.32$
YH	17	$-69\pm81$	$160 \pm 27$	$-0.44 \pm 0.51$
OH	22	$105 \pm 42$	$103 \pm 15$	$1.02 \pm 0.43$
D/B	11	$195 \pm 27$	$52 \pm 11$	$3.76 {\pm} 0.95$

<sup>\*</sup>For  $R_{qc} < 40$  kpc and excluding GCs with  $(\cos \psi) > 0.2$ 

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 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 metallic-

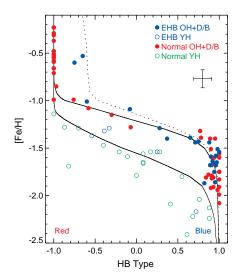


FIG. 2.— The subdivision of GCs in the HB morphology versus metallicity diagram. The filled circles are GCs either in the "old halo (OH)" or metal-rich ([Fe/H] > -0.8) "disk/bulge (D/B)" groups, while open circles are those in the "younger halo (YH)" group. The EHB GCs belong in all three subgroups, but most of them are in OH group. The updated database (Lee et al. 1994) consisting 95 GCs in  $R_{gc} < 40$  kpc zone are compared with model HB isochrones (Rey et al. 2001) in solid lines, the upper being older by 1.1 Gyr. Short dashed line has the same age as the upper solid line, but is for EHB GCs with 15 % of helium enhanced (Y = 0.33) subpopulation (Lee et al. 2005).

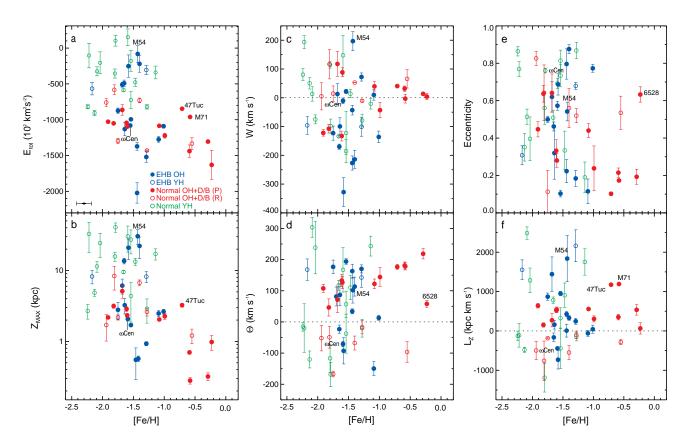


FIG. 3.— The relationship between kinematics derived from full spatial motions and metallicity. From (a) to (f), total orbital energy  $(E_{tot})$ , maximum distance perpendicular to the Galactic plane  $(Z_{max})$ , velocity component perpendicular to the plane (W), rotational velocity  $(\Theta)$ , orbital eccentricity, and the angular momentum component associated with  $\Theta$  ( $L_Z$ ) are plotted as a function of metallicity (Zinn 1993), respectively. Red filled circles are normal GCs with prograde rotation in OH and D/B groups. All of them are in the inner halo. Red open circles are normal GCs with retrograde rotation in OH and D/B groups. Only 3 of them are in the inner halo.

ity, which shows more directly the systematic differences between EHB and normal GCs. In all panels of 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 to 0.94). Normal YH GCs, mostly in the outer halo, show kinematically hot signatures (high  $E_{tot}$ ,  $Z_{max}$ , & eccentricity, and large velocity dispersion) (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 filled circles) show clear signs of dissipational collapse.  $E_{tot}$ ,  $Z_{max}$ , 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 panels (d) and (e), we obtain strong correlations for  $E_{tot}$ ,  $Z_{max}$ , |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

All of these trends observed for normal GCs with pro-

grade rotation in OH and D/B groups are fully consistent with the model first envisioned by Eggen, Lynden-Bell, & Sandage (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 behaviours 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, (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 relicts of primeval starforming subsystems that first formed the nucleus (EHB GCs with low  $E_{tot}$  and  $Z_{max}$ ) and halo (EHB GCs with high  $E_{tot}$  and  $Z_{max}$ ) of the Galaxy through both dissipational and dissipationless mergers, as has been predicted by recent  $\Lambda$ CDM simulations for "high- $\sigma$  peaks" (e.g., Diemand, Madau, & Moore 2005; Moore et al. 2006). As described above, a significant fraction of the helium enriched subpopulation also favours 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 the Sagittarius, were merging with the Milky Way. The GCs with EHB 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 inhomogenity 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 originated from the subsystems with retrograde rotation. Interestingly, their relatively confined distributions both in 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,  $\omega$ Cen and/or NGC 6723 (Lee et al., in preparation). Their distribution in velocity space is also well consistent with the model prediction of the tidal debris from  $\omega$ Cen's parent dwarf system (Mizutani, Chiba, & Sakamoto 2003), which was presumably formed in the outer halo and accreted to the inner halo. Note that a similar minor merging of subsystem with the thin disk (Quinn, Hernquist, & Fullagar 1993) could have also changed some of the original kinematic properties of two disk GCs in Figure 3 (47Tuc and M71).

## 3. DISCUSSION

The clear differences in kinematics and mass between GCs with and without 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 assem-

bled 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 eventually formed the Galactic disk (Eggen et al. 1962), and (3) genuine GCs formed in the outskirts of outlying building blocks that later accreted to the outer halo of the Milky Way (Searle & Zinn 1978). In this picture, relicts of first building blocks that formed the flattened nucleus (Kravtsov & Gnedin 2005; Moore et al. 2006) are now observed as relatively metal-poor EHB GCs (e.g., NGC 6266, 6522, and 6626) having low  $E_{tot}$  and  $Z_{max}$  near the centre. Formation of the slowly-rotating 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, search for the tidal streams that might be associated with EHB GCs, dark matter search in the outlying EHB GCs where preferential disruption of dark matter halo (Saitoh et al. 2006) might be less severe, kinematics analyses of extragalactic GC systems along with the ultraviolet survey for EHB GC candidates, together with more detailed high resolution  $\Lambda$ CDM simulations.

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