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CAPTURE OF FIELD STARS BY GLOBULAR CLUSTERS IN DENSE BULGE REGIONS

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ABSTRACT

The recent detection of a double red giant branch (RGB) in the optical color-magnitude diagram of the bulge globular cluster HP 1—a more populated, metal-poor, steep giant branch corresponding to the cluster itself and another that is metal rich and curved—led us to explore in the present Letter the possibility that field stars are captured by a globular cluster orbiting in dense bulge regions over several gigayears. Analytical arguments, as well as N-body calculations for a cluster model of $10^5\ M_\odot$ in a bulgelike environment, suggest that a significant fraction of cluster stars may consist of captures. Metal-poor globular clusters in the inner bulge, like HP 1, contrasting in Δ[Fe/H] by at least 1.0 dex with respect to the surrounding metal-rich stars, are ideal probes to further test the capture scenario. In turn, if this scenario is confirmed, the double RGB of HP 1 could provide direct estimates of blanketing amounts, which is fundamental for the photometric calibration of metal-rich stellar populations.

Subject headings: Galaxy: kinematics and dynamics — globular clusters: individual (HP 1) — globular clusters: general — methods: analytical — methods: numerical

1. INTRODUCTION

Recently, Ortolani, Bica, & Barbuy (1997, hereafter OBB97) studied V versus $V-I$ diagrams of the inner bulge globular cluster HP 1, which revealed the presence of a double red giant branch (RGB). One RGB is more populated and steep and is accompanied by a well-developed blue horizontal branch (HB), which definitively characterizes HP 1 as a metal-poor globular cluster. The other RGB, observed in an $r \le 23''$ extraction, is curved and extended, characteristic of a nearly solar metallicity stellar population, like that of the globular cluster NGC 6553 or Baade's window itself (Ortolani et al. 1995). OBB97 favored the interpretation of a bulge contamination over that of a merger of two clusters to explain the secondary RGB in HP 1. In the present Letter we explore a scenario in which this contamination may correspond to physical captures of bulge stars.

Van den Bergh (1996) proposed the merger scenario to explain composite (blue and red) horizontal branches for some intermediate- and low-metallicity globular clusters in the Milky Way. For such mergers to occur, individual clusters must have low relative velocities. This condition is matched in dwarf galaxies, where the clusters could have merged in a first step inside the dwarf and subsequently would have been accreted by our Galaxy. As pointed out by van den Bergh (1996), the exceptionally bright globular cluster M54 in the Sagittarius dwarf (Ibata, Gilmore, & Irwin 1994) might be such an example.

The merger scenario would not be appropriate in the case of HP 1 since (1) the bulge velocity dispersion is very high, which makes mergers of globular clusters within the bulge improbable, and (2) the stellar population of the secondary RGB in HP 1 is far too metal rich to have been originated in a dwarf galaxy.

In the present Letter we study, both analytically and with N-body simulations, the possibility that bulge stars are captured by a globular cluster as an alternative explanation for the secondary RGB observed in the color-magnitude diagram (CMD) of HP 1.

2. ANALYTICAL APPROACH

We study the capture scenario of a globular cluster orbiting inside the bulge, assuming for the bulge total mass and mass distribution those values predicted for the Galaxy model of Hernquist (1993; see also Hernquist 1990a). OBB97 derived for HP 1 a distance of ~1.3 kpc from the Galactic center. At this distance the cluster faces a star density of 0.33 $M_\odot$ pc^{-3} (Hernquist 1993). For the remaining cluster parameters, we consider a grid of values that encompasses probable properties for a bulge globular cluster. The rotation of the Galactic bulge (Menzies 1990) implies that globular clusters in the bulge might present considerable amounts of streaming motion. So we consider three possible values for the cluster velocity (v_c): 50, 100, and 160 km s^{-1}. We test cluster diameters of 10, 15, and 20 pc and masses of 10^4, 10^5, and $10^6\ M_\odot$. For these ranges of sizes and velocities, the cluster encounters a total number of bulge stars (N_b) in the range $1.3 \times 10^3 \le N_b \le 7.1 \times 10^4$ during 1 Myr (with 1 $M_\odot$ for bulge stars assumed). Similarly, the size and mass ranges imply cluster escape velocities (v_e) of 3 km s$^{-1} \le v_e \le$ 42 km s^{-1}. The cluster mass is the most

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important parameter determining the escape velocity for the adopted grid.

The bulge velocity distribution is assumed to be isothermal (Binney & Tremaine 1987) with a dispersion of 113 km s^{-1} (see, e.g., Sharples, Walker, & Cropper 1991). The number of bulge stars capable of being captured by the cluster must satisfy the following velocity constraints: $|v_c| - |v_e| \leq |v_s| \cos \theta \leq |v_c| + |v_e|$ and $|v_s| \sin \theta \leq |v_e|$, where θ is the angle between the star velocity ($\boldsymbol{v}_s$) and that of the cluster ($\boldsymbol{v}_c$). With a typical mass of 1 $M_\odot$ for bulge stars, the number of stars, N_s, that are captured over 1 Gyr by the cluster can be summarized as follows: (1) for a 10^6 $M_\odot$ cluster with an escape velocity, v_e, of 34 km s^{-1} and a streaming velocity of $v_c = 50$ km s^{-1}, $N_s = 1.2 \times 10^5$, whereas for $v_c = 100$ km s^{-1}, $N_s = 4.1 \times 10^4$. (2) For a 10^5 $M_\odot$ cluster with an escape velocity of 11 km s^{-1} and a streaming velocity of $v_c = 50$ km s^{-1}, $N_s = 5.1 \times 10^3$, whereas for a v_c of 100 km s^{-1}, the captures become negligible. Finally, a 10^4 $M_\odot$ cluster does not capture a significant number of stars. This would set constraints on the mass of a cluster with a secondary RGB, like HP 1.

3. NUMERICAL SIMULATION

In order to further check the capture scenario, we performed an N-body numerical experiment. We used a hierarchical tree algorithm (Barnes & Hut 1986) with the Centro Nacional de Supercomputação da Universidade Federal do Rio Grande do Sul Cray Y-MP2E computer. The algorithm was optimized for vector architectures (Hernquist 1987, 1990b). The adopted tolerance parameter is 0.7, and the calculation includes quadrupole terms.

The globular cluster was modeled with a Plummer polytrope with 10^4 particles, amounting to a mass of 10^5 $M_\odot$. The Plummer cluster cutoff diameter is 15 pc, and the core diameter is 2 pc. The cluster was left to evolve in isolation during one relaxation time (2.8 Myr) to check its stability. Because of computational limitations on the number of particles in the simulation, we adopted 10 $M_\odot$ particles for cluster and field stars. More details on similar star cluster simulations are given in Rodrigues et al. (1994).

The Galactic bulge density at the cluster location adopted is the same as that of the previous section. A cluster with a streaming velocity of 50 km s^{-1} encounters a mass of bulge stars of 2948 $M_\odot$ Myr^{-1}. The bulge stars encountered by the cluster during 10 Myr were placed in a homogeneous sphere with size equal to that of the cluster, as shown in Figures 1*a* and 1*b*. The speed $|v_s|$ of a given star in the bulge sphere was randomly sampled from a Gaussian distribution with $\sigma = 113$ km s^{-1} (§ 2). The Cartesian velocity components were calculated from $|v_s|$ with isotropy assumed.

The simulation begins with spatially coincident cluster and bulge spheres placed to orbit around a massive particle of 7×10^9 $M_\odot$, representing the bulge mass internal to the cluster position (§ 2). The status of the simulation after 10 Myr is shown in Figures 1*c* and 1*d*, respectively, for the cluster and nine bulge particles (equivalent to 90 $M_\odot$) that were captured. In order to further check the capture stability, we let the simulation evolve up to 50 Myr (Figs. 1*c* and 1*d*), and seven particles (70 $M_\odot$) remained trapped. We remind readers that during these supplementary 40 Myr, no new encounters with bulge stars were considered. The capture rate obtained from this numerical simulation implies that about 7000–9000 $M_\odot$ can be captured by a 10^5 $M_\odot$ globular cluster lurking in the bulge during 1 Gyr, a finding in good agreement with the analytical results of § 2.

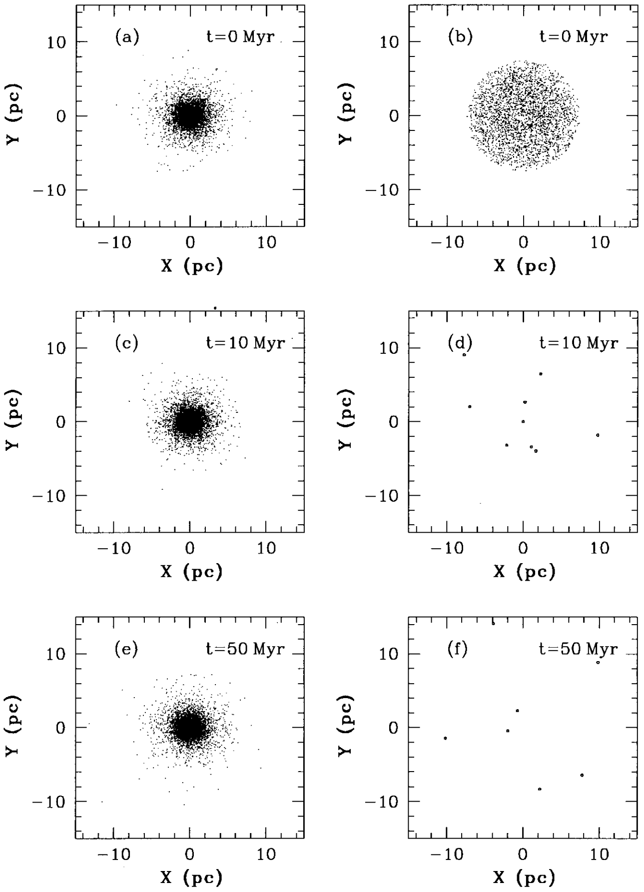

FIG. 1.—Initial distribution of (*a*) cluster and (*b*) bulge particles encountered during 10 Myr, (*c*) the cluster and (*d*) nine bulge particles (90 $M_\odot$) captured after 10 Myr, and (*e*) cluster and (*f*) capture stability for further 40 Myr.

4. DISCUSSION AND CONCLUDING REMARKS

In the present Letter we proposed a capture mechanism to explain a metal-rich secondary RGB in the CMD of the bulge metal-poor globular cluster HP 1. So far, the proposed mechanisms affecting the number of stars in globular clusters are the escape of stars by evaporation (see, e.g., Spitzer & Thuan 1972) and ejection (see, e.g., Hénon 1969). Evaporation is by far the most important escape mechanism: typically, a globular cluster with 10^6 $M_\odot$ should be stable during a Hubble time, whereas one with 10^5 $M_\odot$ should lose an important fraction of its mass. The disk-shocking process (Ostriker, Spitzer, & Chevalier 1972; see also Binney & Tremaine 1987) is another possible loss mechanism caused not only by the disk but also by the bulge itself in such central regions. The presently proposed accretion mechanism for bulge globular clusters would balance such losses, allowing those with $\sim 10^5$ $M_\odot$ to survive in the bulge.

Depending on the cluster mass and the evaporation and capture rates, it is possible to envisage changes of the cluster stellar population content over a Hubble time. A very massive cluster, initially metal poor, would conserve this character and add a secondary metal-rich component to its CMD, as might be the case for HP 1. On the other hand, a less massive, initially metal-poor cluster might recycle its stellar content, if capture outweighs evaporation effects, so that its CMD would become similar to that of the bulge. In this case, metal-poor evolutionary sequences like blue HB and vertical RGB would become relatively less populated. *Hubble Space Telescope* color-magnitude diagrams of metal-rich bulge clusters would be important in investigating this scenario.

The metallicity distribution of the Galactic globular clusters is skewed toward high metallicities, or perhaps it is bimodal (Zinn 1980) and cannot be described by a one-zone metal enrichment model (Bica & Pastoriza 1983). The above-described scenario of bulge star captures by globular clusters and recycling of their stellar population provides a natural way of creating an asymmetrical histogram of cluster metallicities from an initially Gaussian distribution. It is possible to speculate about the existence of two families of metallic clusters: (1) genuine ones formed from enriched gas and (2) recycled ones that were initially metal poor and, over a Hubble time, developed CMD sequences like those of Baade's window by means of captures.

The relative loci of evolutionary sequences in the H-R diagram for globular clusters of different metallicities are fundamental for the calibration of stellar population parameters. Da Costa & Armandroff (1990) studied metal-poor globular clusters together with 47 Tucanae, whereas Bica, Barbuy, & Ortolani (1991) studied those of nearly solar metallicity. The HP 1 CMD containing combined metal-poor and metal-rich stellar populations could provide a means of directly measuring relative blanketings, independent of stellar atmosphere and spectral models. We show in Figure 2 the CMD of the spatial extraction for $r \leq 23''$ from OBB97, where, in addition to the mean locus of a metal-poor globular cluster (NGC 6752 with $[Z/Z_\odot] = -1.54$) fitted to the sequences of HP 1 itself, we also superpose that of the nearly solar metallicity globular cluster NGC 6553 (Ortolani et al. 1995). This HP 1 CMD was built from images obtained at the ESO New Technology Telescope 3.55 m telescope and was reduced with the DAOPHOT II package, with particular attention to crowded field extractions and calibrations (Ortolani et al. 1996; OBB97).

We illustrate relative measures of reference points in the CMD. The magnitude difference between the metal-poor and metal-rich horizontal branches is $\Delta V_{\rm HB} \approx 0.55$ mag, which has important implications for the relative distances of globular clusters (see, e.g., Jones et al. 1992). The magnitude difference between the brightest giants (BGs) in the metal-poor and metal-rich RGBs is $\Delta V_{\rm BG} \approx 1.75$ mag. However, if the tips of the metal-poor and metal-rich giant branches correspond to a similar stellar temperature, the difference could be as large as $\Delta V_{\rm TIP} \approx 3.6$ mag, because of blanketing effects. Finally, the color difference could be as large as $\Delta(V - I)_{\rm TIP} \approx 2.2$ mag. Such magnitude and color differences are fundamental quantities for blanketing calibrations of metal-rich stellar populations.

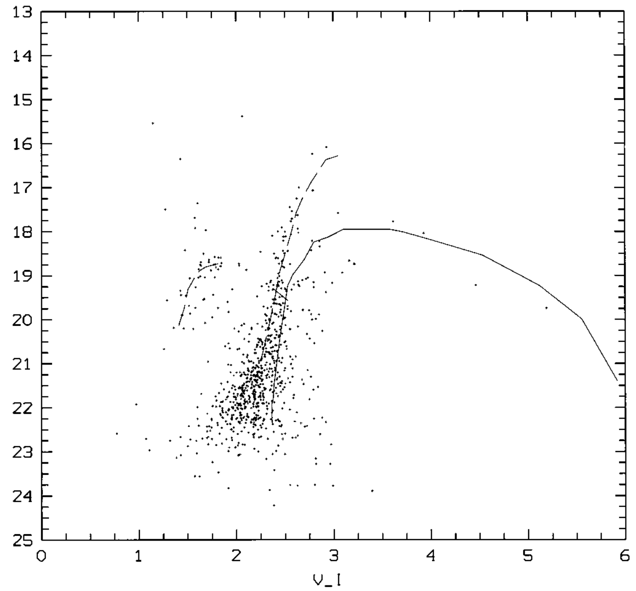

FIG. 2.—Color-magnitude diagram of HP 1 from OBB97. In addition to the mean locus of NGC 6752 (*dashed line*), we superposed that of NGC 6553 (*solid line*), which fits the metal-rich sequences.

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