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THE COLOR-MAGNITUDE DIAGRAM OF THE GLOBULAR CLUSTER NGC 6362 AND THE CANONICAL TILT OF HORIZONTAL BRANCHES

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ABSTRACT

In this paper we present new and accurate photometry for stars in the Galactic globular cluster NGC 6362. The color-magnitude diagram discloses two peculiarities in the distribution of stars: (1) a slightly tilted horizontal branch (HB) ($\Delta_V^{\rm tilt} = 0.1$ mag) and (2) a clump of stars near the red edge of the HB. We perform a detailed comparison with theoretical stellar models in both the HB and red giant branch (RGB) phases. It appears that in the moderately metal rich NGC 6362 the tilted HB can be explained as a natural product of canonical evolutionary theories, being a consequence of the minimum in the bolometric correction near 7500 K. We also investigate the effect of decreasing the efficiency of convective transport in stars climbing the RGB. Adopting $Z = 0.002$ and $Y = 0.23$, and performing a global fitting with the theoretical isochrones and zero-age HB, an age of 12 ± 1 Gyr is found, together with $(m - M)_V = 14.68$ and $E(B-V) = 0.08$.

Subject headings: globular clusters: individual (NGC 6362) — Hertzsprung-Russell diagram — stars: evolution — stars: horizontal-branch — stars: interiors

1. INTRODUCTION

Galactic clusters have long been the stellar systems most suitable for testing the predictions of stellar evolution theories over the main evolutionary phases of both H- and He-burning structures. In more recent times, the color-magnitude diagrams (CMDs) of Galactic globular clusters (GCs) have become of critical importance in elucidating the early phases of galactic evolution, as well as providing severe constraints to the age of the universe. This has stimulated much effort on both the theoretical (see, e.g., Cassisi et al. 1998 and references therein) and observational fronts.

In a recent paper, Piotto et al. (1999) present a *B*, *V* CMD for the GC NGC 6362 obtained with the *Hubble Space Telescope* (*HST*) Wide Field Planetary Camera 2, and comprising 4104 stars covering the center of the cluster. This CMD is notable for showing a well-defined sequence of blue straggler (BS) stars and a main sequence (MS) that extends almost 2 mag deeper than that shown here, allowing a careful study of the cluster luminosity function. However, due to the small area covered by *HST*, the evolved star sequences, such as the horizontal branch (HB), are not well populated and have lower photometric accuracy than here; thus, the two CMDs to a great extent complement each other.

In this paper we present a new and accurate CMD for stars in the Galactic GC NGC 6362. In § 2 we will discuss the observational data and present CMDs for the cluster stars. We find that NGC 6362 is a further representative of the globular clusters showing a *tilted* HB. In § 3 we discuss this point, showing that (at least in this case) the tilted HB is the natural product of canonical evolutionary theories, without invoking the intervention of more sophisticated mechanisms. In the same section we show that the observed cluster CMD is well fitted by a 12 Gyr isochrone, i.e., the same age already found on the basis of the same theoretical scenario for much more metal poor clusters. A final discussion will close the paper.

2. OBSERVATIONS AND DATA REDUCTION

NGC 6362 lies at $\alpha_{2000} = 17^{\rm h}31^{\rm m}55^{\rm s}$, $\delta_{2000} = -67°02'52''$. With Galactic coordinates ($l = 325.°55$, $b = -17.°57$) and an estimated distance modulus of about 15 mag (Fourcade 1974; Alcaino & Liller 1986), the cluster is placed at the periphery of the Galactic bulge. Zinn & West (1984) find the metallicity of NGC 6362 to be [Fe/H] = -1.08 ± 0.09, and Rutledge, Hesser, & Stetson (1997) give [Fe/H] = -1.18 ± 0.06 on the same scale, or [Fe/H] = -0.99 ± 0.03 on the scale of Carretta & Gratton (1997), who themselves, based on only two stars, find [Fe/H] = -0.96. Suntzeff, Kinman, & Kraft (1991) give [Fe/H] = -1.08. Thus, NGC 6362 is one of the most metal rich clusters known with halo kinematics. Despite the high metallicity, NGC 6362 has an extensive population of RR Lyrae and many blue HB stars. Early reddening estimates range between $E(B-V) = 0.08$ (Fourcade 1974) and 0.12 (Harris & Racine 1979).

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As part of a program studying the RR Lyrae variables in selected Galactic GC's, 315 CCD frames in the *B*, *V*, and *I* passbands were obtained of a 13'.6 × 13'.6 field centered on NGC 6362 during five observing runs in 1993–1995, with the CTIO 0.9 m telescope and Tektronix 2048 No. 3 CCD. An analysis of the RR Lyrae observations will be given elsewhere (A. R. Walker, in preparation). The clusters NGC 6981 (M72) and NGC 1851 were also observed as part of the same program, and similar observing and reduction techniques were followed for each, as described by Walker (1998).

Photoelectric standards have been observed in the vicinity of NGC 6362 by Alcaino (1970), in *V* and *B* only, and in *UBVRI* by Alcaino & Liller (1986). Many of these latter stars have faint companions, and given the large CCD field here, a new set of local standards was set up. The 21 stars selected have *V* magnitudes between 14.6 and 16.8, and were measured on 36 sets of frames on six fully photometric nights on three different observing runs. During each night many standard stars were observed from Landolt (1992), in order to determine color equations, extinction, and zero points. Reductions for the primary and local standards followed exactly the same procedures, to mitigate the introduction of systematic errors. The rms scatter for the local standards, looking at mean values for each of the six nights, is typically very small, $\ll 0.01$ mag, and thus the error in the magnitude system for the local standards will be dominated by the tie-in to the primary standards and should not be significantly greater than ± 0.01 mag.

Photometry for the stars on the 315 CCD frames utilized the programs DAOPHOT and ALLSTAR (Stetson 1987, 1995), using scripts to efficiently process all the frames. At the completion of the photometry, the lists of stars for each frame were matched and cross-referenced using programs DAOMATCH and DAOMASTER (Stetson 1995). Photometry for the nonvariable stars was combined using the following algorithm, remembering that there are up to 105 measurements in each color. If there were fewer than 20 measurements in each color, the star was rejected. For those remaining, the measurements for each color were sorted, and the median and the lower tenth percentile found. The sorted lists were then clipped both below and above the median using the difference between the median and the lower tenth percentile, on the assumption that most systematic measurement errors (cosmic rays, two stars measured as one, etc.) bias the measured magnitude brighter. The mean of the remaining measurements was then calculated.

The resulting V, $B-V$ and I, $V-I$ CMDs (Figs. 1 and 2) show tightly defined sequences, superimposed on a large field population. The RR Lyrae variables are plotted at their mean magnitude values. The reddening and metallicity can be derived from the CMD by a variety of methods (A. R. Walker, in preparation). Mean values are $E(B-V) = 0.05 \pm 0.02$, rather smaller than the earlier estimates, and $[\mathrm{Fe/H}] = -1.1 \pm 0.1$, in good agreement with values quoted above. This reddening value is in excellent agreement with that obtained by Piotto et al. (1999), $E(B-V) = 0.06 \pm 0.03$, and indeed a careful comparison shows that the two studies are in excellent photometric agreement over the whole CMD, with differences of less than 0.01 mag in V and $B-V$ when fiducials are compared.

Piotto et al. (1999) show that the center of NGC 6362 contains a extensive, narrow sequence of BS stars, but they are not able to determine whether there is any difference in radial distribution of these stars compared to other cluster members. The BS stars are also apparent on our CMD, and they are much more centrally concentrated than the other cluster stars. We quantify this by comparing the number of BS stars as a function of radial distance. For this comparison we use a CMD containing stars with a less stringent error cutoff than the one used for accurately delineating the CMD sequences, containing 8078 stars compared to 4054; many of the extra stars are those measured with higher errors in the crowded central regions of the cluster. We count BS stars in the photometric box $V = 17$–18, $B-V = 0.25$–0.40 and compare to a MS box $V = 18.5$–19.5, $B-V = 0.5$–0.6, and for the inner two annuli, to a box containing RGB stars between $V = 16.5$ and 17.5. The BS box is deliberately chosen to be well separated from the

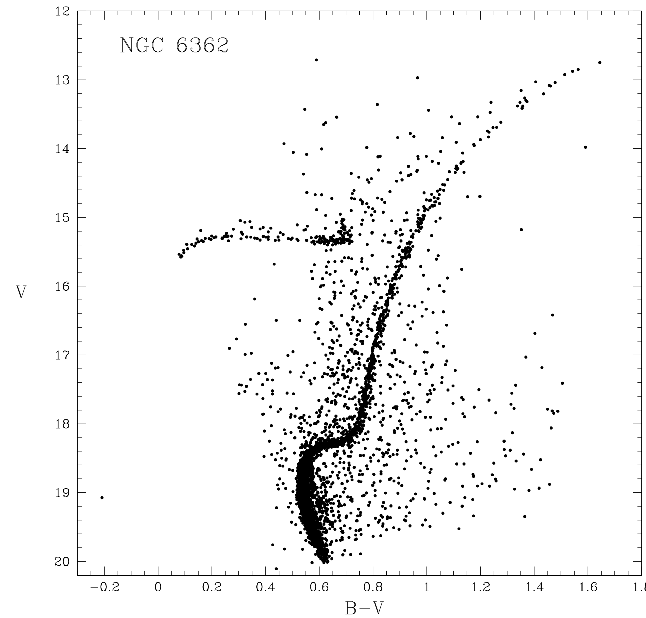

FIG. 1.—V, $B-V$ color-magnitude diagram

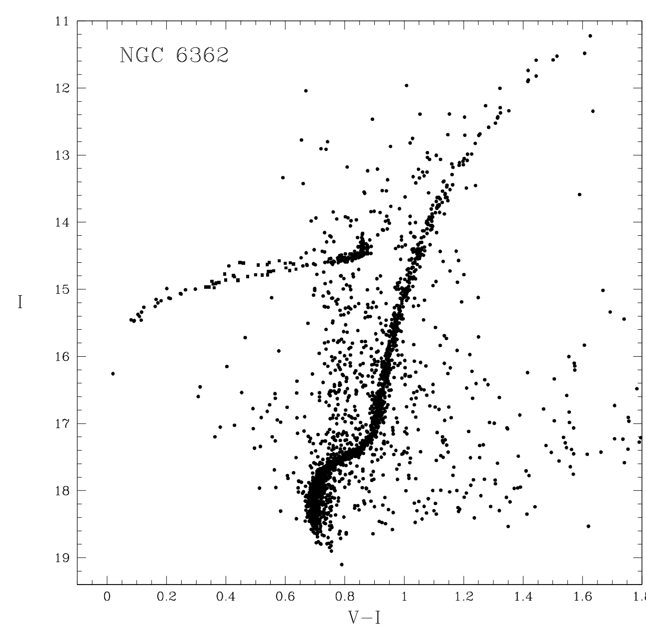

FIG. 2.—I, $V-I$ color-magnitude diagram

cluster MS, so that it will not be contaminated by MS stars with large photometric errors. The results are given in Table 1. These data should not be overinterpreted, since particularly for the inner annulus the incompleteness factor is large and uncertain. For this reason, we compare the BS counts in the inner two annuli with samples both brighter (RGB) and fainter (MS) than the BS sample. Corrections for field star contamination are ascertained from counting stars at a radius greater than 1000 pixels, excluding those that clearly lie on the cluster MS and RGB. The field stars are subtracted off in the "corrected" columns and are seen to be very small. The results show that there are at least a factor of 2 more BS stars than in the MS and RGB samples in the innermost (0–200 pixel) annulus compared to the more distant annuli. Similar selections using Piotto et al. (1999) data provide for BS, MS, and RGB star counts of 12, 712, and 61, respectively, with ratios BS/MS = 0.017 and BS/RGB = 0.20, which can be compared to data in Table 1. These values confirm our results for the bright part of the diagram and show the large incompleteness (crowding) affecting our MS counts in the inner annulus.

3. COMPARISON WITH THEORETICAL PREDICTIONS

Inspection of the CMDs reveals that in the V, $B-V$ plane the HB of NGC 6362 does not show a continuously decreasing V magnitude when moving from the cool toward the hot portion of the branch, and indeed the HB is brightest around $B-V = 0.2$. An additional very interesting feature, seen in both the V, $B-V$ and I, $V-I$ diagrams, occurs at the red boundary of the HB, where a clump of stars extends over some tenths of a magnitude in brightness at near constant color.

Figures 3 and 4 show the observed distribution of HB stars in the V, $B-V$ and I, $V-I$ CMDs. According to data in Figure 3, it is apparent that NGC 6362 appears as a representative of globular clusters with a tilted HB, to be added to NGC 1851 (Walker 1998) and perhaps NGC 6229 (Borissova et al. 1997, 1999) and the extreme cases of NGC 6388 and NGC 6441 (Piotto et al. 1997; Rich et al. 1997; Layden et al. 1999). This feature, appearing in the $B-V$ color, is not seen in the I, $V-I$ diagram of NGC 6362 (Fig. 4).

In the case of NGC 6362 (and also in NGC 1851) the tilt is of the order of $\Delta_V^{\rm tilt} = 0.1$ mag, where $\Delta_V^{\rm tilt}$ is a measurement of the luminosity increase occurring from the red side to the blue, i.e., the maximum luminosity distance of the HB from a straight line drawn at the lower level of the red HB, while in the two clusters NGC 6441 and NGC 6388 it is $\Delta_V^{\rm tilt} \sim 0.5$ mag. The matter has been recently discussed by Sweigart & Catelan (1998), who suggest that such a severely tilted HB should be regarded as evidence for the occurrence

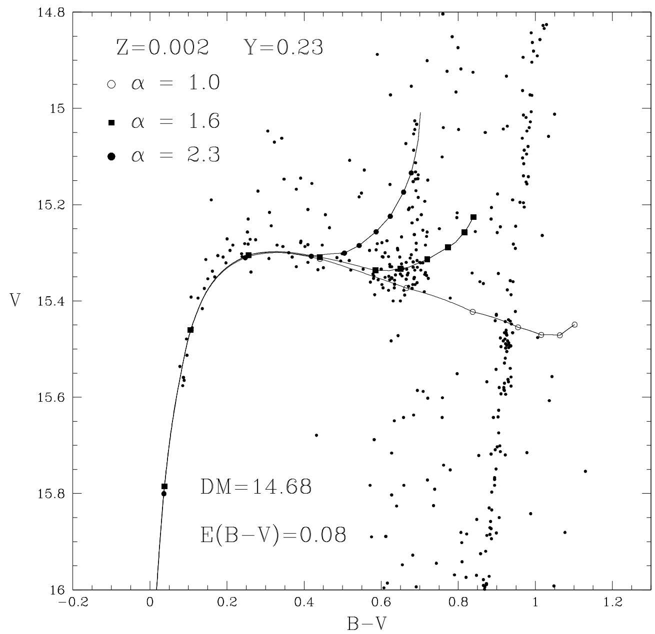

FIG. 3.—Observed distribution of HB stars in the V, $B-V$ plane, plotted together with the theoretical ZAHBs calculated for three different values of the mixing length. Symbols mark the location of stars with mass 0.80, 0.75, 0.70, 0.67, 0.65, 0.64, 0.63, 0.62, 0.61, and 0.60 $M_\odot$.

of some unusual mechanism, such as rotation or differential He enrichment of the external layers. However, one should note that the occurrence of a tilted HB is not ignored by available theoretical predictions concerning canonical HB sequences, as already presented in the current literature. For example, by looking, e.g., at Figures 8 and 9 in Castellani, Chieffi, & Pulone (1991), one finds that in the V, $B-V$ diagram, a very metal poor HB ($Z = 0.0001$) has a luminosity that regularly slopes down when the temperature is increasing, while by $Z = 0.001$ the HB starts to tilt up. Thus, metal-rich GCs are theoretically expected to have a tilted HB.

The reason for the canonical tilt appears to be rather obvious: whereas theoretical luminosities decrease when the temperature of zero-age HB (ZAHB) stars is increasing, the bolometric corrections have a minimum around $T_e =$ 7500 K. As a consequence, the bolometric correction (BC) tends to push toward a brighter V magnitude around this temperature. At lower metallicities, the resulting HB magnitude is dominated by the slope of the theoretical luminosity-temperature relation, and theory predicts that the V magnitude will continuously increase from the red to the blue side of the branch. However, for higher metallicities the theoretical slope decreases, and a minimum V appears

TABLE 1

NUMBER OF STARS IN THE SELECTED EVOLUTIONARY PHASES

Annulus Radii (pixels)	BS	MS	RGB	BS_{corr}	MS_{corr}	RGB_{corr}	BS_{corr}/MS_{corr}	BS_{corr}/RGB_{corr}
0–200..........	12	230	63	11.9	229	62	0.052	0.19
200–300.......	4	336	46	3.85	334	46	0.012	0.08
300–400.......	4	456	36	3.8	454	36	0.008	0.10
400–500.......	1	428	26	0.75	425	26	0.002	0.03
>1000........	1	88	10	0	77	5	...	...

NOTE.—Subscript "corr" indicates the correction for the field star contamination.

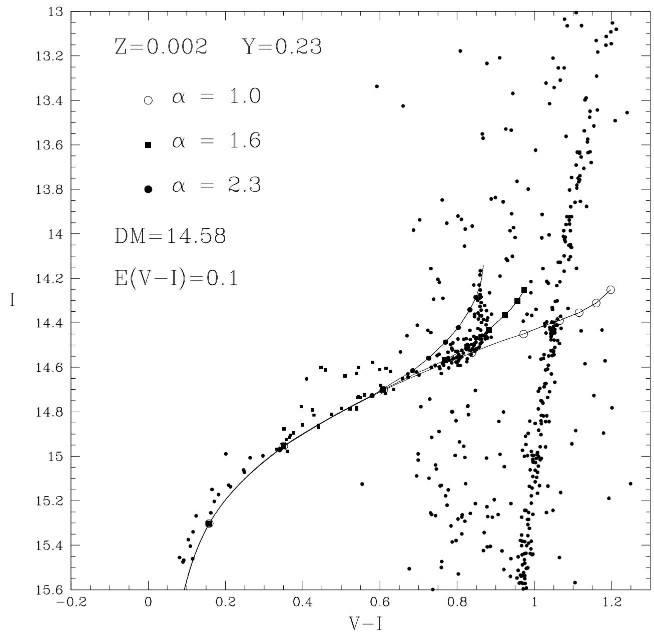

FIG. 4.—As in Fig. 3, but in the I, $V-I$ plane. Symbols mark the location of stars with mass 0.80, 0.75, 0.70, 0.67, 0.65, 0.64, 0.63, 0.62, and 0.61 $M_{\odot}$.

within the HB. This is not the case for the I magnitude, since in that case the BC is much less dependent on the stellar temperature.

To examine this problem in more detail, we used our updated evolutionary code (see Cassisi et al. 1998) to compute a set of evolutionary sequences, taking into account element diffusion and for an original chemical composition that should be suitable for NGC 6362, namely, $Z = 0.002$, $Y = 0.23$. Figure 5 shows theoretical predictions concerning the ZAHB luminosity, as derived for three different assumptions about the mixing length parameter,

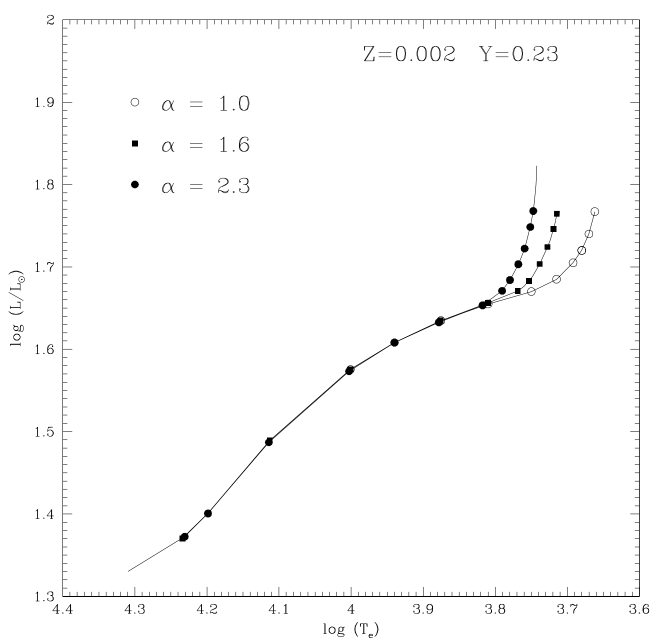

FIG. 5.—Theoretical ZAHBs as derived for the labeled values of the mixing length. Symbols mark the location of stars with mass 0.80, 0.75, 070, 0.67, 0.65, 0.64, 0.63, 0.62, 0.61, 0.60, 0.58, 0.56, and 0.55 $M_{\odot}$.

which governs the efficiency of the external convection that affects the envelopes of the cooler stars. Figure 3 shows the same theoretical result, but translated into the V, $B-V$ diagram, adopting model atmospheres from Castelli, Gratton, & Kurucz (1997) and best fitted to the observation with the labeled value of the cluster reddening and distance modulus. In all cases, one finds that theoretical predictions appear to be in reasonable agreement with observations and, in particular, that the theory shows a minimum V magnitude at $B-V \simeq 0.3$. The assumption about the efficiency of superadiabatic convection plays a relevant role in governing the predicted location of the HB red portion. Thus, the tilt observed in NGC 6362 must be regarded as a natural expectation from canonical theories.

Turning now to the clump of stars at the cool end of the red HB, we first note that Fusi Pecci et al. (1992) predict that this location is close to where blue straggler descendants should be found, which is relevant since NGC 6362 appears to be fairly rich in blue stragglers. However, the Piotto et al. (1999) data do not show an excess of stars clumped near the red HB, which would be expected given the large number (~ 30) of BS stars, thus apparently ruling out this possibility. In addition, this feature disappears in the field population (i.e., for stars at radius greater than 1000 pixels); thus, it is not due to a chance superimposition of field stars. Therefore, we suggest that either we are facing evolutionary effects (see, e.g., the synthetic HB of Catelan et al. 1998 and Brocato et al. 1999) on a clump of red ZAHB stars with mixing length parameter $\alpha = 1.0$, or the ZAHB follows the $\alpha = 1.6$ predictions but with a disagreement between theory and observations of the order of 0.05 mag.

By relying again on Castelli et al. (1997) model atmospheres and adopting the above reported values for the cluster reddening and distance modulus, one can translate the theoretical results onto the observational I, $V-I$ diagram. We adopted $E(V-I) = 1.25E(B-V)$ from Bessell & Brett (1988), and thus $\delta I = 1.75E(B-V)$. The fitting, as shown in Figure 4, appears quite satisfactory.

The theoretical scenario has finally been used to derive cluster isochrones for a suitable range of ages. According to the discussion given in Brocato et al. (1998), the cluster reddening and distance modulus can be firmly established by fitting the HB. Following the quoted procedure, we derive $(m-M)_V = 14.68 \pm 0.05$ and $E(B-V) = 0.08 \pm 0.02$, in good agreement with De Santis & Cassisi (1999). The reddening is slightly higher than the value obtained in § 2, but the observational and fitted values do agree within their estimated uncertainties. Figures 6 and 7 show that with the already given values of DMs, $E(B-V)$, and $E(V-I)$, stars at the cluster turnoff and along the subgiant branch appear very nicely fitted by the 12 Gyr isochrone, with $\alpha = 2.3$.

The mismatch between theory and observation in the upper portion of the RGB may be due to the adopted color temperature relation being incorrect, as discussed by Lejeune, Cuisinier, & Buser (1997). An alternative explanation is that the efficiency of convective transport is progressively decreasing with respect to the predictions of evolution with a constant value for the mixing length, in the sense that a lower value of the mixing length is needed in order to fit the observations. To explore this possibility, we computed evolutionary models in which we progressively varied the α parameter, i.e., the mixing length, as stars start [log $(L/L_{\odot}) \geq 0.5$] to climb the RGB. We parameterize the

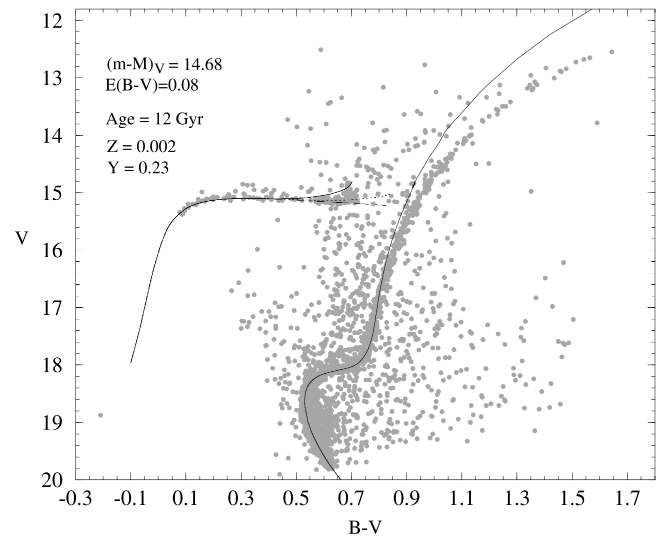

FIG. 6.—Fit of the NGC 6362 data to the theoretical isochrone aged 12 Gyr.

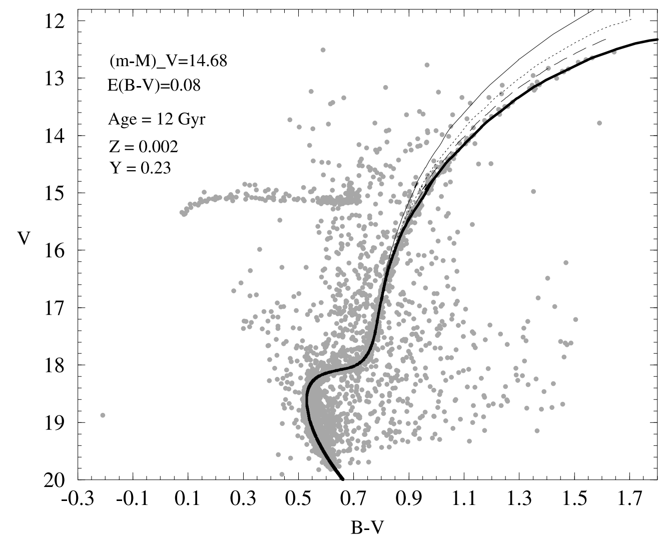

FIG. 8.—Effect of different decreasing rates of the α parameter. The thin solid line corresponds to a constant value ($\alpha = 2.3$), as in Fig. 6; dotted line corresponds to $\beta = 0.10$, and long-dashed line to $\beta = 0.15$. The best fit is performed with $\beta = 0.20$ (*thick solid line*).

mixing length as a linear function of the stellar luminosity: $\alpha = \alpha_0 - \beta \log (L/L_\odot)$, where α_0 is the usual value and β is the decreasing rate that needs to be calibrated. The best fits are obtained by adopting a decreasing rate of $\beta = 0.20$, as shown in Figures 8 and 9, where we also plot the isochrones derived with $\beta = 0.10$ and $\beta = 0.15$.

4. FINAL REMARKS

In this paper we have shown that the occurrence of tilted HBs, at least up to $\Delta_V^{\rm tilt} = 0.1$ mag, is a natural prediction of current evolutionary theories for old GC's with moderate to large metallicities. The fitting between theory and observations of stars in NGC 6362 appears quite satisfactory, predicting a cluster age of about 12 Gyr. Such an age is similar to the ages derived adopting the same theoretical scenario for other Galactic globular clusters with much lower metallicity, such as M68 ($Z = 0.0004$, $t \simeq 11$ Gyr; Cassisi et al. 1999), so that no evidence can be found here to support a possible correlation between age and metallicity. Note also that similar ages have also been measured for old globular clusters in the Large Magellanic Cloud (Brocato et al. 1996; Olsen et al. 1998).

However, the explanation for the clumping of stars at the red boundary of the HB remains an open question, for which we have only suggested some possible alternative explanations.

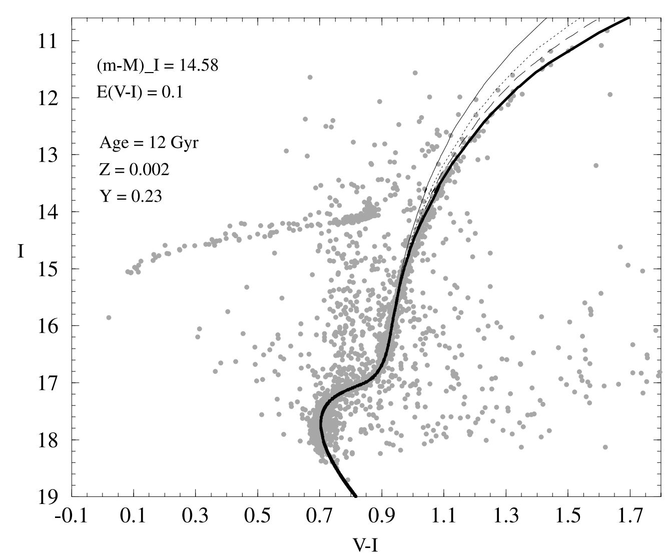

FIG. 9.—As in Fig. 8, but in the I, $V-I$ plane. The thin solid line corresponds to a constant value ($\alpha = 2.3$), as in Fig. 7; the dotted line corresponds to $\beta = 0.10$, and the long dashed line to $\beta = 0.15$. The best fit is performed with $\beta = 0.20$ (*thick solid line*).

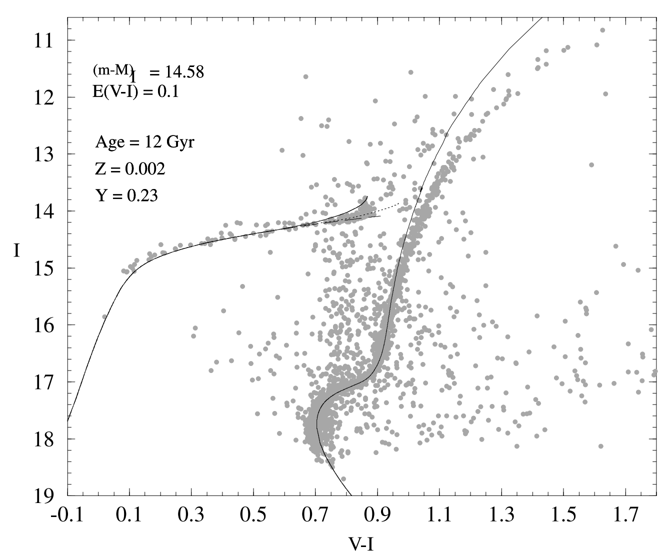

FIG. 7.—Fit of the NGC 6362 data to the theoretical isochrone aged 12 Gyr.

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