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MASS LOSS DURING THE RR LYRAE PHASE OF THE HORIZONTAL BRANCH: MASS DISPERSION ON THE HORIZONTAL BRANCH AND RR LYRAE PERIOD CHANGES

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ABSTRACT

Mass loss on the horizontal branch has been invoked in the literature to explain such phenomena as the color (mass) dispersion of the horizontal branch and the observed distribution of period changes in RR Lyrae stars. To test these claims, the Yale stellar evolution code was used to evolve horizontal branch models of masses 0.64, 0.66, 0.68, 0.70, and 0.72 $M_\odot$ with Z of 0.001, core mass of 0.4893, main-sequence helium abundance of 0.23, and constant mass loss rates of 0, 10^{-10}, 5×10^{-10}, and 10^{-9} $M_\odot$ yr^{-1}. Mass loss was assumed to occur only in the instability strip, where a mechanism is most likely to exist. Synthetic horizontal branches, constructed from the models, show that mass loss on the horizontal branch cannot produce the observed color dispersion even for the highest mass-loss rate of 10^{-9} $M_\odot$ yr^{-1}. Mass loss is unlikely to occur at a higher rate without significant effects on the horizontal branch morphology, which would destroy the good agreement between standard synthetic models without mass loss and observed horizontal branches. Periods and period changes were calculated for all models. The period changes are not significantly larger for models with mass loss. The effect of mass loss in clusters of other metallicities is discussed.

Subject headings: stars: horizontal-branch — stars: mass loss — stars: interiors — stars: evolution — stars: variables: other (RR Lyrae)

1. INTRODUCTION

Globular cluster horizontal branches (HB) have colors which imply that HB stars are on the average 0.2 $M_\odot$ less massive than their progenitor stars. This was taken as evidence that stars lose mass on the red giant branch (RGB) even before observations of optical and UV emission lines confirmed that they lose 10^{-8} to 10^{-5} $M_\odot$ yr^{-1} (Cohen 1976; Dupree 1986). The color dispersion of the HB is larger than can be explained by age differences. This color dispersion along the HB is most often accounted for by stochastic variations in the amount of mass lost during the RGB phase. A 10% dispersion in total mass lost is needed to explain the color range (Rood 1973; Lee, Demarque, & Zinn 1990).

The Sun also loses mass, though at the much smaller rate of 2×10^{-14} $M_\odot$ yr^{-1}. Since the Sun is an average star, it is possible that many, if not all, stars lose mass at some rate. Using this reasoning, some authors (e.g., Willson 1988) have suggested that mass loss may be an important factor in other stars, especially those which experience radial pulsations. That we do not see this mass loss may be due to our observational limitations. In this paper, we investigate whether mass loss in RR Lyrae variables on the HB can explain the mass dispersion on the HB and the observed period change distribution of RR Lyrae stars.

Wilson & Bowen (1984, hereafter WB) proposed mass loss during the RR Lyrae phase as a more natural explanation of the range in masses along the HB than a 10% stochastic variation in the amount of mass lost on the RGB. They reasoned that, since mass loss causes RR Lyrae to evolve to bluer colors, it could also force RR Lyrae which would not ordinarily become blue HB stars to emerge on the blue side of the instability strip. This would act to populate both sides of the instability strip and increase the range in masses along the HB. WB suggested that a mass loss rate of 10^{-10} $M_\odot$ yr^{-1} would be sufficient to produce a 10% dispersion in mass along the HB. This hypothesis is tested in § 3.3.

If mass loss occurs in the RR Lyrae phase, it would also have an effect on period changes in RR Lyrae stars. The fundamental period, P_f, of RR Lyrae stars can be calculated using the equation of van Albada & Baker (1971) for nonhomologous stars,

$$\log P_f = -1.772 - 0.68 \log \frac{M}{M_\odot} + 0.84 \log \frac{L}{L_\odot} + 3.48 \log \frac{6500}{T_{\rm eff}} . \quad (1)$$

Periods of RR Lyrae stars will thus change with simple evolution. The period increases as a star evolves redward and decreases as it moves blueward. It has been known for some time (Rosino 1973) that RR Lyrae period changes are not fully explained by evolution. In many cases, observed period changes are a magnitude larger than would be expected from simple stellar evolution (Sweigart & Renzini 1979). There are a number of possible reasons for the discrepancy, including observational errors, noise due to random fluctuations in

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stellar structure, or some other unknown mechanism. Lee (1991) accounted for observational errors in the period changes of 0.07 day Myr^{-1} and found that most period changes are consistent with evolutionary theories. The very large negative changes, however, could not be explained.

Laskarides (1973) suggested that mass loss on the HB might cause large period changes. Mass loss enhances blueward evolution and impedes redward evolution, so a cluster with mass loss should have larger negative period changes and smaller positive period changes than one without mass loss. Laskarides (1974) tested his proposal with theoretical models and found that mass loss rates of 10^{-10} to 3×10^{-10} $M_\odot$ yr^{-1} were sufficient to account for large period changes. Waugh (1985) included mass loss in RR Lyrae models, but found that mass loss did not alter the period change distribution of RR Lyrae. The effect of mass loss on period changes in our models is discussed in § 4.

2. THE MODELS

The Yale rotating stellar evolution code (YREC) in the nonrotating configuration was used to evolve HB models with and without mass loss. Except for the mass-loss routine which was added to the code, the input physics is nearly the same as in Lee & Demarque (1990). Individual subroutines in the evolution code are frequently modified, and improvements in the treatment of the approach to CNO equilibrium are mainly responsible for the differences between the tracks used in this paper and the Lee & Demarque (1990) tables. The effect is at the 10% level for a 0.68 $M_\odot$ star and is similar to the discrepancy between Lee & Demarque and Sweigart (1987). It is consistent with the known sensitivity of HB models to the details of the hydrogen-burning shell (see, for example, Gross 1973; Castellani & Tornambé 1977; Caputo, Castellani, & Tornambé 1978; and Lee & Demarque 1990). Our models are similar to those evolved by Yi, Lee, & Demarque (1993). The agreement between the HB models in four studies is, in fact, quite remarkable, given the sensitivity of theoretical HB evolution.

Models of total masses 0.64, 0.66, 0.68, 0.70, and 0.72 $M_\odot$ were evolved to core helium exhaustion. All models had a core mass of 0.4893 $M_\odot$, a metallicity, Z, of 10^{-3}, and an initial main-sequence helium abundance of 0.23 (see Lee & Demarque 1990). Cox-Stewart opacities (Cox & Stewart 1965, 1970) were used and α, the ratio of mixing length to pressure scale height, was assumed to be 1.4. Mass loss was assumed to occur at a constant rate, and only in the instability strip. The instability strip was defined as the vertical region $3.800 \leq \log T_{\text{eff}} \leq 3.875$ (after Lee 1991), which is a good approximation over the vertical extent of the HB. For this research, mass loss was assumed to be constant throughout the RR Lyrae lifetime, since a more realistic mechanism does not exist. Reimers (1975, 1987) type mass loss, for example, is unlikely to apply to RR Lyrae, since it is based on observations of red giant stars. Four constant mass-loss rates were assumed: 0, 10^{-10}, 5×10^{-10}, and 10^{-9} $M_\odot$ yr^{-1}. No distinction was made between fundamental and first overtone pulsators. Periods at each time step were calculated using equation (1).

2.1. *The Mass-Loss Routine*

A mass-loss routine written into YREC for the modeling of the evolution of massive stars was adapted for use in this research. Because virtually all theoretical models for mass loss are unsatisfactory, mass loss has been incorporated into YREC in a fairly simple manner. Mass is removed from the stellar model during each time step at a rate supplied by the user. The mass-loss procedure starts with a converged model in the evolutionary sequence. Once the mass-loss rate is determined, it is assumed to remain roughly constant for the preceding time step. The total mass lost is calculated by multiplying $\dot{M}$ by the time step. The code then removes mass from some user-specified fraction of the star (typically the outermost 2%–5% by mass). Since YREC models contain two parts (an interior and an envelope), mass is first removed from the envelope such that the ratio $M_{\text{env}}/M_{\text{star}}$ remains constant. Any remaining mass to be lost is divided equally among the shells in the specified outer fraction of the interior and removed. The code also calculates the corresponding energy loss and subtracts it from the energy in the appropriate shells. The model is then allowed to evolve normally with its new mass; once it has converged in the next step in the sequence, the mass-loss rate is recalculated and mass is removed (see also Demarque & Eder 1985).

3. RESULTS

3.1. *Tracks*

Figures 1*a* and 1*b* show the smoothed tracks in the H-R diagram for the 0.66 and 0.68 $M_\odot$ stars, respectively. Four mass-loss rates are shown: 0, 10^{-10}, 5×10^{-10}, and 10^{-9} $M_\odot$ yr^{-1}. The complete evolutionary tracks to helium core exhaustion are pictured in Figures 2*a* and 2*b*. In most cases, tracks with mass loss simply extend more to the blue. The track of the 0.68 $M_\odot$ star with 10^{-9} $M_\odot$ yr^{-1} mass loss, however, is significantly altered. The star becomes "trapped" near the blue edge of the instability strip during the initial phases of the redward evolution. In this region, evolution and mass-loss effects are balanced. Every movement to the red caused by evolution is counteracted by a movement to the blue caused by mass loss. The star moves on an almost vertical track (i.e., along the instability strip) in the H-R diagram. Figure 3 shows the region where trapping occurs in the track, with time steps of 10 Myr. The trapping phenomenon was predicted by WB. There are two important effects. First, it is possible for a star which would never have emerged on the blue side of the instability strip without mass loss to become a blue HB star, as proposed by WB. Second, if mass-loss rates are significant, we should observe some effects of the trapping of stars at the blue edge of the instability strip. Some enhancement in stars near the blue edge should be observed. Observations show that some clusters, such as IC 4499, M15, M3, and M68, have double-mode RR Lyrae stars (see Clement et al. 1986 and references therein), which lie near the boundary of the type c and type ab regions in the H-R diagram. This might be a result of trapping as a star moves redward from the first overtone to the fundamental mode. Amplitudes of pulsation are larger in the fundamental mode, so the mass loss may be in reality larger (rather than constant, as we have assumed), and the effect may be similar to our modeling. However, this model must explain why some clusters have more double-mode RR Lyrae stars while others have none.

3.2. *Synthetic HBs*

The tracks described above were used to generate synthetic HBs, following the procedure of Lee et al. (1990). Two parameters, the mass dispersion and $\langle M_{\text{HB}} \rangle$, were varied to obtain the closest resemblance to the morphology and the observed

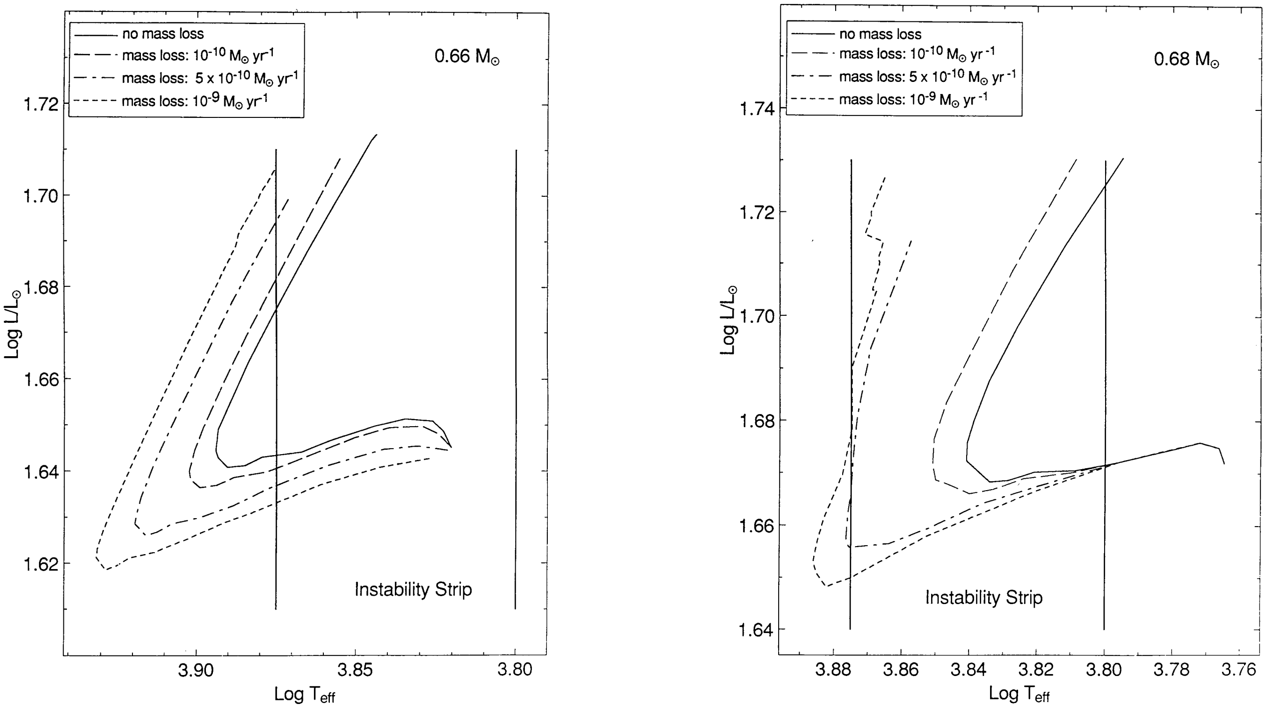

FIG. 1*a* FIG. 1*b*

FIG. 1.—Smoothed evolutionary tracks of (*a*) 0.66 $M_\odot$ and (*b*) 0.68 $M_\odot$ stars for mass-loss rates of 0, 10^{-10}, 5×10^{-10}, and 10^{-9} $M_\odot$ yr^{-1}

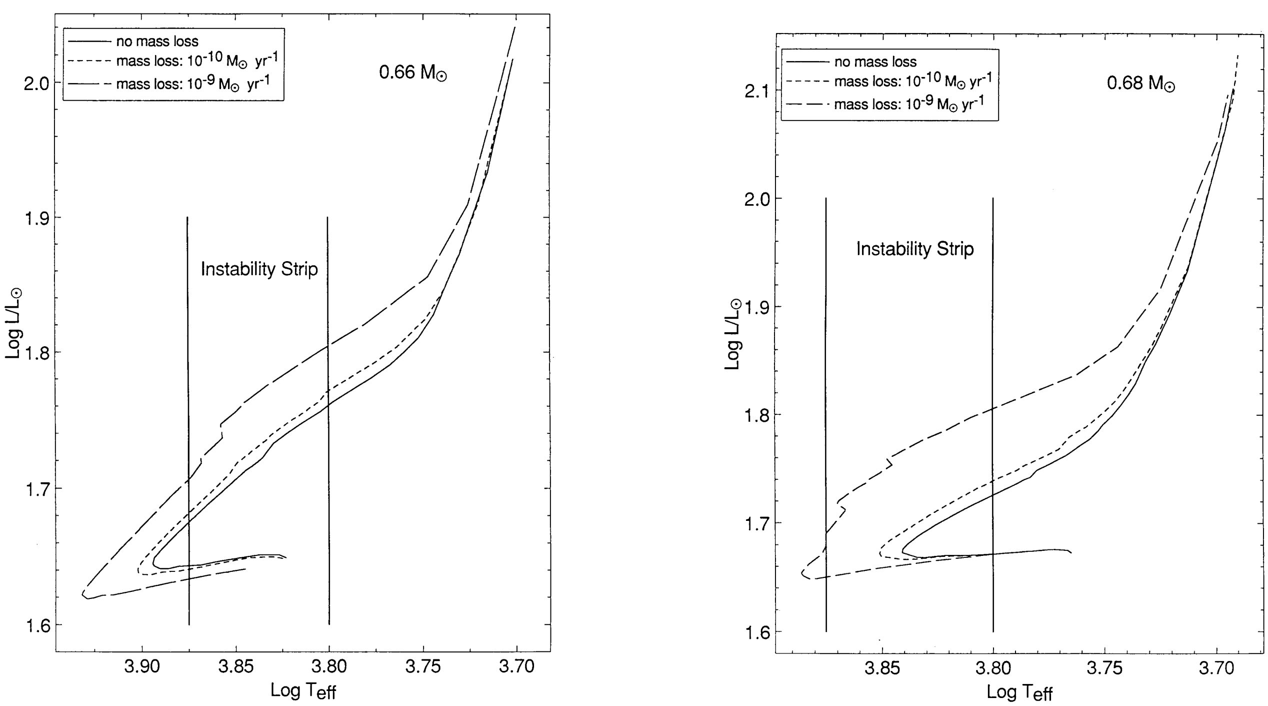

FIG. 2*a* FIG. 2*b*

FIG. 2.—The evolution of the AGB for the (*a*) 0.66 $M_\odot$ and (*b*) 0.68 $M_\odot$ stars for mass-loss rates of 0, 10^{-10}, and 10^{-9} $M_\odot$ yr^{-1}

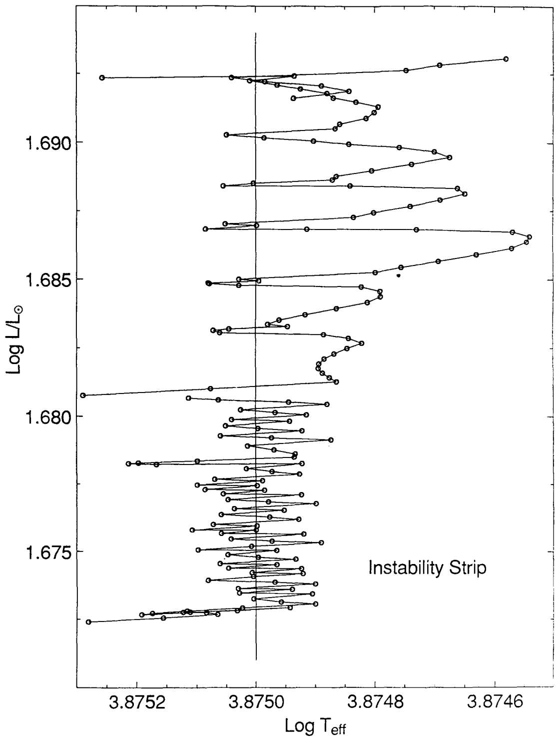

FIG. 3.—The track in the H-R diagram of a 0.68 $M_\odot$ star losing mass at the rate 10^{-9} $M_\odot$ yr^{-1} near the instability strip boundary. The instability strip is indicated.

ratio of blue:variable:red stars (the B:V:R ratio) in M3.[1] Figure 4*a* shows the synthetic HB calculated from our tracks with no mass loss. An added mass dispersion of $\delta_M = 0.02$ $M_\odot$ and a $\langle M_{\rm HB} \rangle$ of 0.665 best matched the observed morphology of M3 (see, for example, M3 in Fig. 3 of Lee et al. 1990). The B:V:R ratio of the synthetic HB was 0.33:0.40:0.27, close to the observed B:V:R ratio of 0.33:0.42:0.25.

The synthetic HBs pictured in Figures 4*b* and 4*c* were computed from our tracks with a mass-loss rate of 10^{-9} $M_\odot$ yr^{-1}. The $\langle M_{\rm HB} \rangle$ for these HBs was 0.681, which produced the best models for M3 with this mass loss. No mass dispersion was added to the synthetic HB in Figure 4*b*. The color spread in this HB is totally due to the effects of mass loss. The spread is larger than in the case of an HB with no mass loss, but the HB does not resemble the observed in morphology or in the B:V:R ratio of 0.29:0.47:0.24. The number of blue stars and variables is enhanced relative to red stars (due partially to the trapping of stars near the blue edge). WB predicted that a mass loss rate of 10^{-10} $M_\odot$ yr^{-1} in RR Lyrae stars could explain the morphology of the HB without the need to introduce a dispersion in mass loss on the RGB. Based on Figure 4*b*, a mass-loss rate of 10 times this value does not seem capable of solving the mass dispersion question. Higher rates of mass loss might increase the dispersion, but would produce HBs very different in morphology from those observed.

Perhaps mass loss is occurring in RR Lyrae stars, even though it is not causing the mass dispersion along the HB. A limit on the amount of mass loss which can occur can be obtained by adding a mass dispersion to the synthetic HB produced using the 10^{-9} $M_\odot$ yr^{-1} tracks. This synthetic HB is shown in Figure 4*c*. The best fit to the observations was obtained using $\delta_M = 0.015$ $M_\odot$. This mass dispersion is somewhat smaller than that required in Figure 4*a*, a direct effect of the increased spread in color due to mass loss. There are, however, significant differences in morphology and B:V:R ratio between this synthetic HB and observed HBs. On the basis of this diagram, we can limit the mass loss rate present in RR Lyrae stars to less than 10^{-9} $M_\odot$ yr^{-1}.

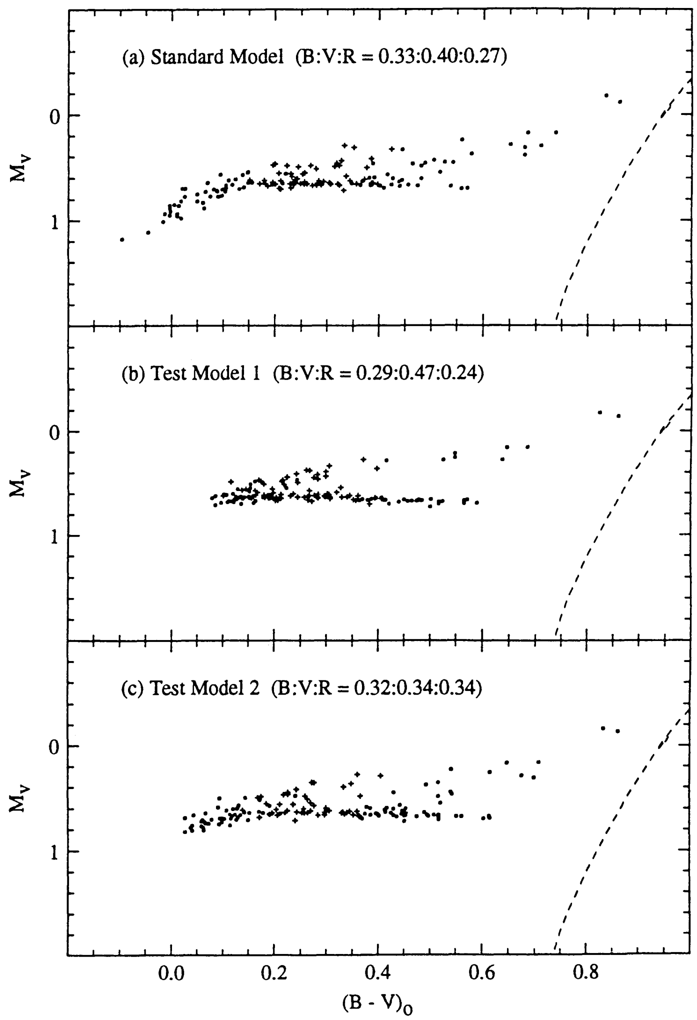

FIG. 4.—(*a*) A synthetic HB calculated using the 0 mass loss tracks, assuming a 0.02 $M_\odot$ dispersion. (*b*) The synthetic HB in the case of RR Lyrae which lose 10^{-9} $M_\odot$ yr^{-1}. No mass dispersion is included. (*c*) The synthetic HB in the case of RR Lyrae which lose 10^{-9} $M_\odot$ yr^{-1}. A mass dispersion of 0.015 $M_\odot$ is included.

[1] A more suitable comparison cluster would have been M4, which has the same metallicity as our models. Unfortunately, differences in reddening across the cluster field cause large observational errors in M4's HB. M3 is a well-observed cluster, but with a lower metallicity ($Z = 0.0004$). However, recent observations (e.g., Sneden et al. 1992) indicate that stars in M3 are enhanced in oxygen (and other α-elements) with respect to scaled solar composition. These enhancements would have a net effect similar to increasing the total Z in scaled solar composition tracks (see Chieffi, Straniero, & Salaris 1991). Thus M3 may be more appropriate to compare with our models, which use a scaled solar composition. Note also that any determination of Z is also subject to zero-point uncertainties and observational error.

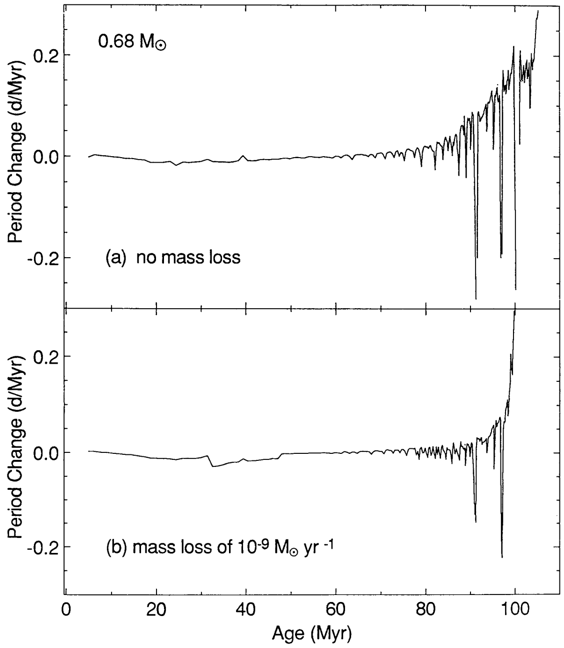

FIG. 5.—(*a*) The variation in period change over the lifetime (since the ZAHB) of a 0.68 $M_{\odot}$ HB star without mass loss. Large dips are caused by semiconvection instabilities (see text). (*b*) The variation in period change of a 0.68 $M_{\odot}$ HB star which loses 10^{-9} $M_{\odot}$ yr^{-1} during the RR Lyrae phase.

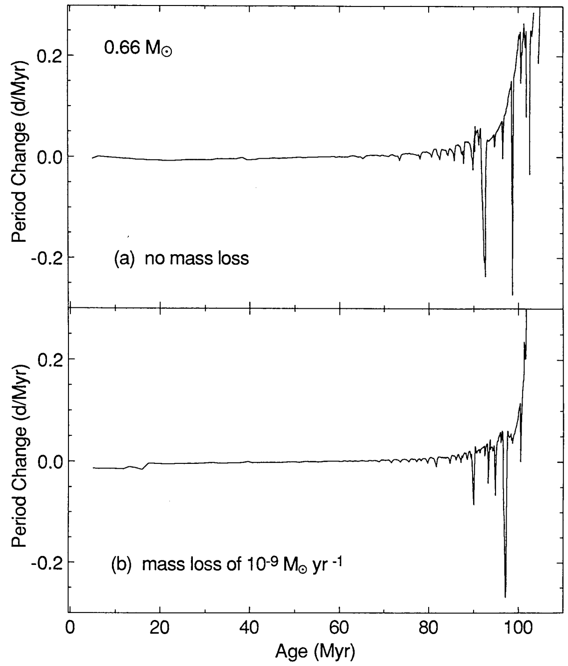

FIG. 6.—(*a*) The variation in period change over the lifetime of a 0.66 $M_{\odot}$ HB star with no mass loss during the RR Lyrae phase. (*b*) The variation in period change over the lifetime of a 0.66 $M_{\odot}$ HB star which loses 10^{-9} $M_{\odot}$ yr^{-1}.

4. PERIOD CHANGES

Periods and period changes were calculated using equation (1). If mass loss affects the distribution in period changes, it should act to reduce the magnitude of positive period changes and to increase the magnitude of negative period changes. Mass loss causes a star to be drawn toward the blue in an H-R diagram, so that it aids evolution when the star evolves to the blue and impedes evolution when the star moves redward. We find that the blueward evolution of HB stars is so slow that mass loss does not greatly speed the blueward trend. Positive period changes in models with mass loss have somewhat smaller magnitudes, as shown in Figures 5 and 6. In short, we find that the magnitude of period changes in stars without mass loss is similar to those with mass loss. We do not find large period changes attributable to mass loss even in the case of our most extreme mass-loss rate, 10^{-9} $M_{\odot}$ yr^{-1}. The run in unsmoothed period changes is contrasted for models with and without mass loss in Figures 5 and 6.

Our models do predict some large negative period changes, though these are unrelated to mass-loss effects. HB models often have sudden blueward loops in their evolution, due to semiconvection instabilities, which have been described in several papers (Sweigart & Demarque 1973; Sweigart & Renzini 1979). An example of such a loop is pictured in Figure 1 of Sweigart & Demarque (1973). Whether these instabilities are physical or numerical in nature is still a matter of debate. (See Sweigart 1990 for a review.) These instabilities were therefore removed in the smoothing of the tracks described above, but are included in the period change plots (Figs. 5 and 6). These loops occur whether a model includes mass loss or not. If these loops are real, they may explain the presence of some large negative period change variables (see Lee 1991).

An interesting question is how the period changes of RR Lyrae are affected while in the trapped zone. The change in period with time is shown in Figure 7. The largest period changes are due to semiconvection instabilities. Period change magnitudes are not significantly larger in the trapped region.

5. CONCLUSIONS AND DISCUSSION

Based on the above evidence, we conclude that constant mass loss in the instability strip of the HB is incapable of fully explaining either the mass dispersion along the HB or the RR Lyrae period change distribution. If constant mass loss is a good approximation to any mass loss occurring on the HB, mass loss probably is not a significant factor in HB evolution,

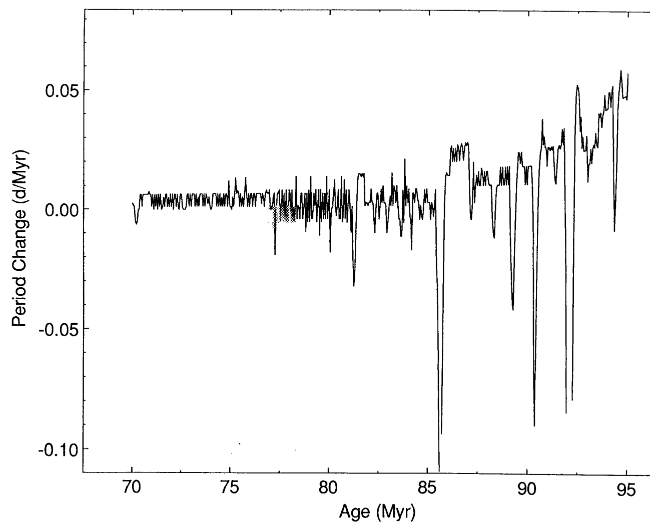

FIG. 7.—The variation in period change with time in the region of the instability strip for the 0.68 $M_{\odot}$ star which loses 10^{-9} $M_{\odot}$ yr^{-1}.

though it may be a small contributing factor to the observed mass dispersion. We can limit the constant mass-loss rate along the HB to $10^{-9}\ M_{\odot}\ \mathrm{yr}^{-1}$ based on the synthetic HBs. More would destroy the good agreement between theoretical and observed HBs.

Mass loss, of course, is not likely to be constant in the RR Lyrae phase. The amplitude of the pulsations presumably causing the mass loss is certainly different along the instability strip. We also make no distinction between the fundamental and first overtone pulsators. It is possible, for example, that mass loss is quiet over much of the instability strip, but larger in certain regions. If this were the case, one might expect to see erratic changes in RR Lyrae periods. However, one might also expect to see evidence for trapping in these regions, which does not seem to be observed. Erratic period changes instead appear to be randomly scattered in the H-R diagram. Erratic mass loss behavior also has less time to remove mass from a star compared to constant mass loss, and therefore is unlikely to explain the mass dispersion across the HB. Finally, it is possible that mass loss also occurs outside the instability strip. This was not tested, since mass loss there is likely to be a small effect compared to that in the radially pulsating RR Lyrae phase.

The above results were based on analysis of a cluster with a Z of 0.001. Models were not computed for clusters of different metallicities, but several inferences can be drawn. Metal-rich clusters ($Z \geq 0.0004$) are known to require a larger added mass dispersion (on average, 0.03 $M_{\odot}$) than metal-poor clusters (on average, 0.01–0.02 $M_{\odot}$), as discussed in Lee et al. (1990). It might therefore seem possible that mass loss could have a stronger effect on metal-poor clusters. However, metal-poor clusters have many blue HB stars, which pass through the instability strip only in the late stages of core-helium burning. If significant mass loss occurs only in the instability strip, as is assumed in this paper, the stars in metal-poor clusters would lose less mass over their lifetimes than those in metal-rich clusters. Mass loss would thus have a small effect on both the color dispersion and period distribution in low-metallicity clusters.

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