MASS LOSS IN M67 GIANTS: EVIDENCE FROM ISOCHRONE FITTING

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ABSTRACT

We present a study of the stellar content of the open cluster M67. We have computed new evolutionary sequences of stellar models with solar abundance that cover all phases of evolution from the Zero-Age Main Sequence to the bright end of the Asymptotic Giant Branch (AGB). The main sequence and giant branch calculations are presented as isochrones, while the later phases of evolution form a set of horizontal branch (HB) and AGB tracks of different envelope masses, i.e. implicitly assuming various degrees of mass loss on the giant branch. The wide agreement on the age (5 Gyr) and metallicity (solar) of this cluster make it an ideal reference standard, and the generally excellent fit of our new isochrones to the M67 color-magnitude diagram (CMD) is consistent with these values. We examine the fit between the calculated and the observed red giant branch (RGB) in particular, and discuss factors that most influence its quality, viz. the mixing-length parameter and the outer boundary conditions used for the models. The distinct color gap between the RGB and the clump giants (i.e., the red HB stars) is compared with the temperature gap between the He-burning tracks and the computed 5 Gyr RGB (where the mass, $M \approx 1.27 M_\odot$). This purely differential approach strongly indicates that the clump giants have $M \lesssim 0.70 M_\odot$, which implies an amount of mass loss ($\approx 0.6 M_\odot$) well in excess of that found in globular cluster stars. Possible interpretations of this result are that mass loss in cool low-mass giants increases either with metallicity or with initial mass. Observational constraints on mass loss processes tend to favor the former explanation, provided a mechanism exists that is much more efficient at solar composition than at the abundances found in metal-rich globular clusters.
1. INTRODUCTION

As part of an ongoing project to calculate synthetic integrated spectra for globular clusters and galaxy nuclei, we have produced a new set of solar abundance isochrones over the range from 4 to 16 Gyr. The isochrones have been calculated following VandenBerg (1983) using similar computational techniques. The evolutionary tracks have been continued up the first-ascent red giant branch (RGB) to the helium flash. A number of post-flash tracks have also been computed in a fully consistent fashion as detailed by Dorman (1992); these comprise the zero-age Horizontal Branch (ZAHB) as well as the subsequent evolution to the asymptotic giant branch (AGB). The (pre-flash) evolutionary tracks have been transformed into isochrones in a straightforward manner, and sampled at narrow intervals of temperature and luminosity. At each of the sampled points we generate a model atmosphere (using MARCS) and then a synthetic spectrum (via the SSG program). In this way we can translate the isochrones directly from the fundamental $T_{\text{eff}} - \log L$ plane to a color-magnitude diagram (CMD).

Proper theoretical modelling of the integrated light from galaxy nuclei will depend crucially on our ability to compute both high-metallicity isochrones and stellar spectra over the temperature and gravity range set by those isochrones. However, the higher the metallicity the more challenging it becomes to compute synthetic stellar spectra accurately because of the great strength of the atomic and molecular features. For this reason we felt it wise to test the isochrones via comparison with the CMD of one of the most well-studied old open clusters in the Galaxy, M67. The age and metallicity of this cluster are regarded as well-determined by recent work using a number of different techniques. In addition, its CMD shows an unusually well-defined RGB and “clump”. This enables us to investigate in some detail one of the more difficult aspects of comparisons between theory and observation, viz. matching the slope of the RGB. Finally, the quality of the data, coupled with accurate cluster membership information and the new helium burning tracks, allows us to estimate the masses of the clump giants and thus deduce the amount of mass lost between the RGB and the He-burning phases.

A detailed description of the calculation of the evolutionary tracks, isochrones, model atmospheres and synthetic spectra are presented in Sec. 2, along with the sources for the M67 observations. In Sec. 3 we show the results of the comparison between the theoretical and observational data. Sec. 4 contains a brief discussion of these results, their uncertainties and the implications for RGB mass loss scenarios. Our conclusions are summarized in Sec. 5.

2. THE COLOR-MAGNITUDE DIAGRAM

2.1 Theoretical Calculations

We have calculated solar abundance evolutionary tracks for stars having masses between 0.4 and 1.4 $M_\odot$, using the the evolution code described in Dorman (1992). This program is a rewritten version of University of Victoria code described by VandenBerg (1983; 1992) which has been augmented by a detailed treatment of the helium-burning evolutionary phases. The evolution is followed from the pre-main sequence Hayashi track to the zero-age main sequence through central hydrogen exhaustion to the RGB until termination at the He-flash. In addition, we have also generated He-burning tracks for masses between 0.6 and 1.3 $M_\odot$. These begin at the ZAHB (assuming a core mass of 0.469 $M_\odot$) and are allowed to evolve up the AGB until thermal pulses begin to occur, at which point the evolution is terminated. We adopted a metallicity $Z = 0.0169$, a helium fraction $Y = 0.27$, and Los Alamos (Huebner et al. 1977) and Alexander (1975; 1981) low-temperature opacities in these calculations. We have performed a number of experiments with the new OPAL opacities (Iglesias, Rogers, and Wilson 1992) and conclude that their use is unlikely to change the conclusions of this study, although we consider their possible impact later in this paper. The slope of the RGB is, however, significantly affected by the choice of the surface pressure boundary condition. We have adopted the semi-empirical surface pressure grid tables discussed by VandenBerg (1992), which are based on model atmospheres but include empirical corrections designed to improve the agreement with derived IR color-temperature relations for globular clusters. We also conducted a number of trials using other choices for the boundary condition, as we will discuss shortly. The ratio $\alpha$ of mixing length to pressure scale height that best fit the M67 RGB sequence was found to be 1.6, slightly larger than the value used in VandenBerg’s recent work.

The evolutionary tracks (ZAMS through He-flash) have been transformed into isochrones for ages be-
between 4 and 16 Gyr using the usual technique of equivalent-evolutionary points (Prather, 1976; Bergbusch & VandenBerg, 1992). Note that the masses of the RGB stars at 4 and 16 Gyr are \( \approx 1.35 M_\odot \) and \( \approx 0.94 M_\odot \), respectively. Finally, to cover fully the major evolutionary phases found in open and globular clusters, we add to the isochrones our He-burning evolutionary tracks, described above. We emphasize that in every sense possible these post-flash models have been calculated in a fashion consistent with the RGB models. This includes matching \( \alpha \), the pressure boundary condition, opacities and so forth.

The next stage in this exercise is to generate synthetic spectra for stellar models at intervals along the isochrones as well as the subsequent He-burning evolutionary tracks. At each selected \( T_{\text{eff}} - \log g \) point a plane-parallel, flux-constant model atmosphere was calculated using MARCS (Gustafsson et al., 1975), followed by a synthetic spectrum computed using SSG (Bell & Gustafsson, 1978, 1989; Gustafsson & Bell, 1979). The spacing used between flux points was 0.1 Å, and all of the spectra were computed between 3000 and 12000 Å. We point out that for a variety of reasons, models for stars cooler than about 4000 K are still quite uncertain (see Bell & Paltoglou, 1993). One of the main difficulties arises from the dominance and strong temperature sensitivity of the TiO absorption bands. Work is in progress to update the handling of molecular species in the SSG program; for the present paper we have synthesized all of the spectra without using TiO. Note that, for reasonable assumptions about the Initial Mass Function, less than about 7% of the total V-band luminosity in a 5 Gyr old solar abundance cluster will arise from stars cooler than 4000 K.

The last step in the process was to convolve each synthetic spectrum along the isochrones with filter transmission profiles to determine the colors. Though we concentrate here on the broadband colors (using profiles from Bessell 1990) simulated photometry for other color systems (e.g. DDO, Washington) has also been carried out. The colors have been calibrated in a model-independent manner using the Gunn & Stryker (1983) spectrophotometric scans as described in Tripicco & Bell (1991). Absolute magnitudes and bolometric corrections were determined by relating them to our SSG solar model (with \( T_{\text{eff}} = 5770 \) K, \( \log g = 4.44 \), \( (B - V) = 0.64 \)) and adopting the values \( M_V = +4.84 \) and B.C.\( \odot = -0.12 \).

The isochrones themselves will be presented as part of a larger integrated spectrum array in a forthcoming paper, along with a full set of calibrated integrated light colors in a variety of bandpasses.

### 2.2 M67 Photometry

The primary source for the M67 photometry used in this paper is the tabulation given in Mathieu et al. (1986). They measured precise radial velocities for 170 late-type stars in M67, the sample having been selected on the basis of proper-motion membership probabilities from Sanders (1977). The photometry itself was drawn from a number of sources, including Eggen & Sandage (1964), Racine (1971), and Janes & Smith (1984). Table II(b) of the Mathieu et al. paper lists the full set of photometric references. We have discarded the spectroscopic binaries identified by Mathieu, Latham & Griffin (1990). As the objects of primary concern in this study are the evolved stars, the sample of proper-motion members (mostly restricted to stars brighter than \( V = 12.8 \)) provides an excellent basis for comparison with the theoretical RGB and HB models. In order to demonstrate the fit of our isochrone to the main-sequence and fainter turnoff stars we have also taken data directly from Racine (1971).

In addition to the UBV data discussed above, we use K-band magnitudes for 23 M67 stars published by Cohen, Frogel & Persson (1978) to determine accurate temperatures from the \( (V - K) - T_{\text{eff}} \) relation given in Bell & Gustafsson (1989). We use these data to make a limited comparison between M67 and the isochrones in the fundamental plane, which is presented in the following section.

### 2.3 Properties of M67

A major aim of the present paper is to confirm that our newly computed isochrones are accurate over all phases of stellar evolution, from the unevolved main-sequence to the AGB. M67 provides an appropriate test case as it has been extremely well-studied over the years and there seems to be no major disagreement remaining over its basic properties. Recent studies concur that the metallicity of M67 is virtually indistinguishable from the solar value. The status of the cluster as a fundamental reference standard has been nicely summarized by Janes (1985); other recent direct determinations of the metallicity may be found in Hobbs & Thorburn (1991) who derived \( [\text{Fe/H}] = -0.04 \pm 0.12 \) from high-dispersion spectroscopy, and Nissen et al. (1987) who used \( u\)by photometry to determine a value of \( [\text{Fe/H}] = -0.06 \pm 0.07 \).

The age of a star cluster cannot, of course, be as directly determined as the metallicity. Ages are generally based on isochrone-fitting, which depends on a number of assumed cluster parameters such as reddening, distance, helium abundance as well as on the details of physics underlying the isochrones themselves. Thus,
it is refreshing to note that virtually all of the players in the isochrone-fitting game appear to have reached
a consensus on an age near to 5 Gyr for M67, with uncertainties of only a fraction of a Gyr remaining. A
detailed discussion is presented by Demarque, Green & Guenther (1992). It is worth noting that Hobbs &
Thorburn (1991) use their high-dispersion spectra to determine directly the effective temperature of stars at
the turnoff of M67—their result of 6165 ± 60K leads to an age of 5.2 Gyr ±1.0 based on the Teff(turnoff)-age
relationship from our isochrones. This type of age estimate has the advantage of being independent of cluster
reddening and distance estimates as well as any color-temperature transformations. In summary, it appears
that adopting an age of 5 Gyr for M67 should satisfy our requirements for carrying out this test of our
newly-calculated isochrones, particularly as our emphasis will be on the later phases of evolution where age
effects are minimal.

3. RESULTS

3.1 Theoretical H-R Diagram

Figure 1 compares the post-turnoff portion of our 5 Gyr solar abundance isochrone with a number of
evolved M67 stars in the H-R diagram. Temperatures have been computed from (V − K) colors as described
in the previous section. The luminosities are based on an apparent distance modulus (m − M)V = 9.55 and a
functional relationship between bolometric correction and Teff from our set of models. The M67 giants (up to
log L/L⊙ = 2.1) are nicely matched by the isochrone calculated with VandenBerg’s semi-empirical tables for
the surface pressure boundary condition. Alternative choices for this boundary condition are also indicated
in Figure 1. Using a scaled-solar T-τ relation results in a considerably cooler (and slightly flatter) RGB,
partly due to overestimated low-temperature opacities. If used without modification, the ‘pure’ (MARCS)
model atmospheres produce somewhat bluer giant branches, but the RGB becomes progressively flatter
toward increasing luminosities. It was precisely this tendency which led VandenBerg (1992) to modify the
MARCS-based pressure boundary conditions so as to match globular cluster RGBs (see his Fig. 6 and Sec.
4). The latter are, of course, much older and generally more metal-poor than the present case. All of the
RGB tracks indicated in Figure 1 were calculated using an adopted value of 1.6 for α; a change to α = 1.5
results in a displacement of the track to the right in the theoretical HR diagram, with the RGB becoming
nearly 100K cooler at a given luminosity.

3.2 Color-Magnitude Diagram

In Figure 2 we compare our solar abundance isochrones with the color-magnitude diagram of M67. The
adopted reddening (E(B-V)=0.032) matches the value found by Nissen, Twarog, & Crawford (1987) to
provide the best fit to their uvbyβ photometry. (They also provide a useful discussion of their reddening
estimate in the context of previous results and find it to be consistent.) Figure 2 shows our 5 Gyr isochrone to
provide quite a good fit to the whole of the M67 data for an apparent distance modulus of (m − M)V = 9.55.
The RGB slope is clearly less than perfect, but the detailed shape is a function of numerous free parameters.
For example, as outlined in the previous section the choice of α and the surface pressure boundary condition
strongly affect the position of the RGB. Fig. 1 suggests that these parameters have been well-chosen (note,
however, that the brightest M67 giants plotted there are approximately one magnitude fainter than those
in Fig. 2). But transformation to the color-magnitude plane imposes additional uncertainties. At a given
temperature and surface gravity, the resulting spectrum (and thus the colors) can be a non-negligible function
of the strength of particular spectral features. This is most significant for the coolest giant stars, once
absorption from the TiO bands begins to dominate (at temperatures below about 4000 K or (B − V) ≥ 1.4).
Close to the tip of the RGB, mass loss may also play a role. Constant-mass giant branches move to the red
with decreasing mass, with the tip cooling by about 100K for each 0.10 M⊙ lost. This effect will modify the
slope of the upper RGB, but will leave the color (B − V)0.9 of the giant branch at the HB level unchanged.
In the next section we will argue that a significant fraction of the stellar mass is evidently lost prior to the
stars’ arrival on the core-helium burning branch.

3.3 Clump Giants

The five M67 clump giants with (V-K)-based temperatures are plotted along with our He-burning
evolutionary tracks in Figure 3. The diagram is essentially an expanded version of Fig. 1; the position of
the 5 Gyr RGB is indicated, as is the ZAHB for masses between 0.60 and 1.30 M⊙. The post-ZAHB tracks
are plotted for four representative masses, showing the manner in which the stars are predicted to rise off
the ZAHB, first cooling slightly and then evolving to higher temperatures. After approximately 70 Myr of
rather steady evolution, the tracks turn sharply back to the red. The late HB evolution is characterized by a contracting core and evolution toward the AGB, which is reached after the core is exhausted and the helium-burning shell has gained nuclear equilibrium (cf. Dorman et al. 1993 and references therein).

Comparison of the position of the M67 clump giants with the theoretical tracks in Fig. 3 immediately suggests a mass of approximately $0.70 M_\odot$ for these stars, compared with $\sim 1.27 M_\odot$ for the giants. The straightforward interpretation is that the stars suffer a larger amount of mass loss before the helium burning stages than do those in globular clusters. Basing this on an absolute comparison (such as is shown in Fig. 3) would not be conclusive, as the derived temperatures depend sensitively on such things as the accuracy of the $(V - K) - T_{\text{eff}}$ calibration, as well as the detailed position of the theoretical tracks. In fact, while VandenBerg (1985) seems to have suggested years ago that an unusually large amount of mass loss may have occurred in the M67 clump stars, the systematic effects referred to above prevented him from calling this result more than “a very uncertain prognostication”. However, because the RGB and HB tracks tend to respond nearly identically to small changes in these adopted parameters, the observed color gap can be used in a purely differential sense to estimate the clump giant masses.

Inspection of Fig. 2 shows that the clump in the color-magnitude diagram of M67 is separated from the RGB by 0.10 mag in $(B - V)$. This color gap is obviously independent of the choice of reddening or other cluster parameters and can be accurately measured because of the clean separation between the clump and RGB, a result of the richness of M67 and of the membership criteria firmly established by both proper motion and radial velocity techniques. Next, relative comparison between model spectra in the proper temperature and gravity regime indicates that $\Delta(B - V) = 0.10$ corresponds to $\Delta T_{\text{eff}} = 250K$. This again is quite insensitive to the details of the temperatures, gravities, or metallicities of the models used. The effective temperature gap between the 5 Gyr RGB and the He-burning tracks of various masses (at the same luminosity) have been calculated and are shown in Table 1. These are tabulated at three representative points along the tracks: zero-age, $T_{\text{eff}}$-minimum and $T_{\text{eff}}$-maximum. The differential comparison illustrated by Table 1 suggests that a temperature gap of 250K can only be explained if the clump giants have lost nearly half of their mass before helium burning commences. Note that this result is insensitive to the adopted cluster age, as the RGB shifts quite slowly with age (about 25K/Gyr in this age range).

4. DISCUSSION

The notion that a significant quantity of mass is lost between the red giant and horizontal branch stages of evolution is well-established in stellar evolution theory. Mass loss must be inferred to explain the color spread in observed globular cluster CMDs, but it cannot be so large as to inhibit the helium burning phases of evolution altogether (see, e.g., Renzini 1981). More direct evidence for mass outflows from cool giants has been available for some time (see Dupree 1986 and references therein), from which mass loss rates are computed. It is difficult or impossible, however, to quantify how much mass is actually lost during the giant-branch evolution: in the globular clusters, this can be inferred from comparisons between the observed horizontal-branch morphology and theoretical models. This is exactly the methodology of the present study. The metallicity and age of M67 are well-established, and we have shown that an isochrone calculated for those parameters provides a good fit to the whole of the cluster CMD. Recall that the age estimate is grounded not in the fit to the giant branch in the CMD but to the main-sequence turnoff region (as well as in the spectroscopically-derived temperature of the turnoff). Thus the RGB mass is thought to be $\approx 1.27 M_\odot$: an initial mass as low as $1.20 M_\odot$ (corresponding to a cluster age $\geq 6.2$ Gyr) is probably ruled out by these constraints. The mass of the clump giants is somewhat more difficult to establish, but the purely differential approach adopted here, based on the excellent data on one hand and a consistent set of evolutionary computations on the other, points strongly toward a mass of $0.70 M_\odot$ or less.

Recent observations may actually show the signature of mass outflow in progress in this cluster. KPNO 4-m echelle spectra at the Ca II (H & K) lines of red giants in M67 show asymmetries in the emission cores that indicate outflow from the brightest stars. This outflow is clearly present down to $V = 9.69$ but appears to vanish by around $V = 10$ (Dupree, 1993). More quantitative conclusions await a full analysis of these new data but it is extremely suggestive that the mass loss we have proposed here may in fact be observable as it happens. Simply pinpointing where on the RGB the signature of mass loss first appears will provide important constraints on the future modelling of the underlying mechanism.

The present study may well represent the first evidence, albeit indirect, for the amount of mass lost to
stars of approximately solar mass and metallicity, which differ from the stars of Galactic globular clusters (GCs) both in age and in metallicity. Our result allows two different interpretations, i.e. that the higher degree of mass loss in M67 giants implies (a) a dependence of mass loss on metallicity or (b) higher degrees of mass loss in more massive stars. We consider other evidence and implications of both of these suggestions.

Any change to the models that tends to increase the intrinsic gap between the giant branch and the red end of the HB would, of course, weaken our conclusion. It is, however, difficult to destroy it altogether because HB models with \( M > 1 M_\odot \) are also significantly (0.25\% \( ^m \)) brighter, with zero-age locations on the upper branch of the ZAHB sequence illustrated in Figure 1. Recall that for the mass lost to be similar to that inferred from globular clusters, the mean mass of the clump stars should be about 1.1 \( M_\odot \). We have experimented with fitting the observed points with the more massive models along the upper branch but in that case one cannot achieve an acceptable fit to the turnoff region regardless of the age of the isochrone used.

The HB models themselves are of course sensitive to changes in composition, input physics and input parameters, notably the core mass \( M_c \). The composition is, however, well-constrained by observation to be greater than \([\text{Fe}/\text{H}] = -0.1\). We have not attempted a detailed match to isochrones of lower metallicity. However, models of significantly lower abundance that are otherwise consistent with the solar metallicity isochrones (i.e., \([\text{Fe}/\text{H}] = -0.23, \alpha = 1.6, Y = 0.27\)) will move the red end of the HB to approximately the same color as the observed clump giants. The corresponding giant branch will also be bluer, though by somewhat less than the ZAHB, so that in order to reproduce the gap the data must again be fitted away from the coolest HB stars, implying \( M < 0.9 M_\odot \). Thus even for an extreme choice of the metallicity for this cluster, the mass of the clump giants would appear to be significantly lower than the giant branch.

An increase in \( M_c \) at the helium flash tends to shift the HB evolutionary tracks for a given mass blueward. However at the red end of the sequence the dominant effect is to raise the luminosity of the models. Increasing \( M_c \) by 0.01 \( M_\odot \) shifts our 0.70 \( M_\odot \) sequence blueward by about 20K, and to a luminosity 0.05\% greater. Of course, this would require slight adjustment to the derived distance modulus and/or the isochrone fit. The derived mass of the clump giants would increase slightly; however we would argue that a much larger change in \( M_c \) would be required to invalidate our conclusions. The new OPAL opacities imply a slightly higher value for the solar helium abundance and a different choice for the mixing length. The effect – a change in \( Y \) from 0.27 to about 0.28 – may produce a reduction in the core mass (the increased luminosity resulting from higher helium will be offset by the larger opacity) which would tend to strengthen the conclusions of this study. In sum, the conclusion we have is robust partly because the match to the isochrones implies that the data are too faint for the ‘upper’ branch of the ZAHB sequence, and it is difficult to see how any of the factors that can shift the theoretical models can alter this fact.

Simulations of GC horizontal-branch (HB) morphology usually invokes a mass loss formula proposed by Reimers (1975),

\[
\dot{M} = -4 \times 10^{-13} \eta \frac{L}{gR} M_\odot \text{ yr}^{-1},
\]

(\( L, g \) and \( R \) expressed in solar units), in which \( \eta \) is a free parameter whose value is constrained by observation. This formula was originally derived (with \( \eta = 1 \)) from observations of cool Population I giants using dimensional analysis. For GC stars with \( M < 0.9 M_\odot \), comparison of the HB morphology with theoretical tracks implies values of \( \eta \) quite tightly constrained, i.e. \( \eta = 0.4 \pm 0.2 \), with the range generously estimated. The upper bound comes from the estimate of Renzini (1981) that a value for \( \eta \) as large as 0.6 would suppress helium-burning evolution altogether, i.e. globular clusters would have no horizontal branch stars at all. However, integrating the Reimers formula along our (constant-mass) evolutionary tracks – which should give a fair approximation to a self-consistent calculation in which the mass is actually removed from the model – yields much smaller cumulative mass loss than is implied by our differential comparisons. Importantly, one infers that more massive stars lose less mass than the GC stars. Figure 4 demonstrates these points. We show here the estimated total mass lost by a model during the ascent to the RGB tip as a function of stellar luminosity for four different masses: 0.9, 1.2, 1.3, and 2.0 \( M_\odot \). We have calculated \( \dot{M}_{\text{Reimers}}(L) \) here with the choice \( \eta = 1 \). This choice strips sufficient mass from the 0.9 \( M_\odot \) sequence – corresponding roughly to an 18 Gyr isochrone – that the helium burning phases would be suppressed. However, even with this relatively large value for \( \eta \), the total mass lost from the 1.3 \( M_\odot \) sequence is only about 0.3\% \( M_\odot \). The 2.0\( M_\odot \)
track loses much less mass because it reaches the helium core flash at significantly lower luminosity, and is somewhat hotter during its evolution. Indeed, if the mass loss were included consistently rather than by post hoc estimation then there would be even greater difference in the predicted mass loss as a function of mass.

Of course, Reimers’ formula is not the only mass loss ‘law’ proposed, nor is it based on a physical model of the processes that result in mass outflows. Chiosi and Maeder (1986) have tabulated empirical mass loss formulæ, and include several different relations for cool giants. Dupree (1986) notes that still other empirical formulæ fit the observational database equally well. She also provides a useful summary of the observational constraints upon mass loss from cool stars. Those that apply directly to such ‘parametrized mass loss’ relations are (i) that it increase with decreasing $T_{\text{eff}}$ and (ii) that it increase with $L$. Neither of these will predict a significant increase in mass loss with mass at fixed composition; on the contrary, both imply a variation in the same sense as the Reimers formula.

One obvious inference is that mass loss is a significant function of composition. A current idea is that molecular or dust opacity might allow radiatively driven winds in cool stars in similar fashion to the UV resonance lines that drive winds from massive stars (see Holzer & MacGregor 1985; MacGregor & Stencel 1992). The record from the globulars provides no strong evidence for variation in the masses of HB stars with metallicity: of course, this issue is strongly tied to the infamous ‘Second Parameter’ problem. However, it is possible that the responsible mechanism may possess a ‘threshold’ effect, in which mass loss becomes more efficient below a certain $T_{\text{eff}}$. This seems plausible for a process that involves grain formation or line-driven winds. The fact that none of the observed metal-rich globular clusters show evidence of strong RGB mass loss (in the form of populations of RR Lyrae stars or blue HB stars) would imply that the threshold metallicity lies in the range $-0.5 < [Fe/H] < 0$.

The idea that mass loss is enhanced in metal-rich stars has some important implications for the interpretation of galaxy spectra. In particular, sufficient mass loss from giants in evolved populations may produce hot helium-burning stars. Increasing mass loss with metallicity would enhance this effect, producing a positive correlation between UV output and metallicity, as has been observed (see Burstein et al. 1988 for observational data; for an extensive theoretical exploration, see Greggio and Renzini 1990). On the other hand, if the mechanism for ‘slow’ stellar winds in red giants indeed operates less efficiently in metal-poor systems, then the later stages of evolution for stars in intermediate-age clusters might be different. In particular, the core helium burning stars should be more massive. Since the hydrogen fuel consumption will be larger, they should produce more massive post-AGB remnants, which implies brighter planetary nebulae. Finally, the mass of white dwarfs may be somewhat greater.

The other hypothesis, that mass loss in cool giants actually might increase with the initial mass of the giant, appears to run opposite to the observational constraints noted above. If this were indeed the case, however, it would imply that the global stellar properties do not predict mass loss rates - an uncomfortable conclusion for future understanding in this field. It is, however, intriguing that we may infer that whatever process is responsible tends to reduce the size of the stellar envelope to rather than by a constant amount of mass. This inference is of course highly speculative, unless confirmed by further studies on similar open clusters. In this regard, the mass of clump giants is perfectly consistent with the data on Pop. I white dwarf masses, but implies low-mass or non-existent planetary nebula ejecta from stars with initial mass $\lesssim 1.3M_\odot$. This cannot be ruled out, but it seems safe to adopt the more conservative assumption that we have evidence for increasing mass loss with metallicity.

5. CONCLUSIONS

We have performed a comparison between the color-magnitude diagram of M67 and a new set of theoretical evolutionary models which include all phases from the unevolved main-sequence through core-helium burning (horizontal branch) and onto the asymptotic giant branch. We find that:

(1) Our 5 Gyr solar abundance isochrone yields an excellent fit to the whole of the M67 color-magnitude diagram. The model parameters adopted were $Z = 0.0169$, $Y = 0.27$, and $\alpha = 1.6$. Values of $(m - M)_V = 9.55$ and $E(B - V) = 0.032$ for M67 provide the best fit.

(2) A differential technique that compares the gap in color between clump giants and normal red giants on one hand with the temperature gap between core He-burning tracks and first-ascent RGB tracks on the other, strongly indicates that the clump giants in M67 have masses $\approx 0.70\,M_\odot$ or less. The extremely large amount of mass loss that we deduce in this study ($\approx 0.6\,M_\odot$) is well in excess of that found for
globular cluster stars.

(3) Possible resolutions of this problem are that degree of mass loss increases with total stellar mass, or with metallicity. The observational evidence on mass loss rates appears to favor the latter choice, since parametrized mass loss formulae such as the Reimers ‘law’ predict a decrease rather than an increase in the mass loss with total mass. This appears to be the case for any such formula that obeys the observational constraints on mass loss rates.

In either case, this study represents the first evidence for enhanced mass loss in solar-type stars. We are investigating other open clusters in an effort to identify other good examples of this phenomenon. It seems unlikely, however, that many more cases as robust as the present one can be found in which the cluster age and metallicity are as well determined, and for which such high-quality photometry and membership data exist.

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**FIGURE CAPTIONS**

Fig. 1.— Comparison between our 5 Gyr solar abundance isochrone and M67 subgiants and giants in the fundamental plane. The parameters used in computing the isochrones are given in the text. We illustrate the results for three different choices for the surface pressure boundary condition in the calculation of the giant branch evolutionary tracks. A value of 1.6 for the convective parameter \( \alpha \) was used in all of these cases. The semi-empirical tables described by VandenBerg (1992) yield the best fitting models for the evolved stars in M67. The zero-age horizontal branch for masses 0.6 to 1.3M\(_\odot\) (also calculated with the semi-empirical boundary condition) is also indicated.

Fig. 2.— The color-magnitude diagram of M67 is compared with our isochrones. The apparent distance modulus and reddening adopted for the cluster are listed. Filled symbols indicate radial velocity members of M67, while open symbols refer to photometry taken directly from Racine (1971) for stars whose membership is based only on proper motion criteria. The full 5 Gyr solar abundance isochrone (plus zero-age horizontal branch) is plotted, along with the main-sequence through turnoff portions of the 4 and 8 Gyr isochrones from the same set.
Fig. 3.— Similar to Fig. 1, but concentrating on the He-burning evolutionary phases. Open circles represent the 5 M67 clump giants with (V-K)-based temperatures. The zero-age horizontal branch (ZAHB) is plotted as a sequence of connected filled circles for the range of total masses as indicated. The evolution from the ZAHB onto the asymptotic giant branch is indicated by the dashed lines for 0.6, 0.7, 0.9 and 1.3 M⊙.

Fig. 4.— The cumulative mass loss predicted by the Reimers formula with η = 1.0. Results are plotted for four representative solar abundance mass tracks. Note that the total mass lost prior to the onset of He-burning decreases with increasing initial mass and should not exceed ≈ 0.3M⊙ in a 5 Gyr old cluster (where the giants begin with masses near 1.27 M⊙) even for such a large value for η.
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