A CONSTRAINT ON $Z_{\odot}$ FROM FITS OF ISOCHRONES TO THE COLOR-MAGNITUDE DIAGRAM OF M67

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ABSTRACT

The mass at which a transition is made between stars that have radiative or convective cores throughout the core H burning phase is a fairly sensitive function of $Z$ (particularly, the CNO abundances). As a consequence, the ∼4 Gyr, open cluster M67 provides a constraint on $Z_{\odot}$ (and the solar heavy-element mixture) because (1) high-resolution spectroscopy indicates that this system has virtually the same metal abundances as the Sun, and (2) its turnoff stars have masses just above the lower limit for sustained core convection on the main sequence. In this study, evolutionary tracks and isochrones using the latest MARCS model atmospheres as boundary conditions have been computed for 0.6–1.4 $M_{\odot}$ on the assumption of a metals mix (implying $Z_{\odot} \approx 0.0125$) based on the solar abundances derived by M. Asplund and collaborators using 3D model atmospheres. These calculations do not predict a turnoff gap where one is observed in M67. No such difficulty is found if the analysis uses isochrones for $Z_{\odot} = 0.0165$, assuming the Grevesse and Sauval mix of heavy elements. Our findings, like the inferences from helioseismology, indicate a problem with the abundances of Asplund and collaborators. However, it is possible that low-$Z$ models with diffusive processes taken into account will be less problematic.

Subject headings: Hertzsprung-Russell diagram — open clusters and associations: individual (M67) — stars: atmospheres — stars: evolution — Sun: abundances

1. INTRODUCTION

The metallicity of the Sun (both the mix of heavy elements and the total mass fraction abundance $Z$) is presently a subject of considerable controversy. Until a few years ago, the generally accepted value of $Z_{\odot}$ was $0.017–0.02$, and there was good consistency between the predictions of standard solar models (SSMs) for metallicities within this range (see, e.g., Turcotte et al. 1998; Bahcall et al. 2001) and the measured neutrino flux as well as helioseismological data. However, significantly reduced abundances for several of the most abundant heavy elements (including C, N, O, and Ne), resulting in $Z_{\odot} \approx 0.0125$, have been derived by M. Asplund and collaborators from their analyses of the photospheric spectrum using 3D, non-LTE model atmospheres (see Asplund et al. 2006 and references therein). Whereas high-$Z$ solar models are able to reproduce the inferred radial dependence of the square of the sound speed (down to $R_{\odot}$) from solar oscillations to $\approx$0.3% (see Christensen-Dalsgaard 2002), those computed for the Asplund et al. metallicity are unable to do so to better than $\sim$3% (e.g., Turck-Chièze et al. 2004).

It seems unlikely that this difficulty is due to problems with current opacities (Antia & Basu 2005) or the presently accepted rates of diffusive processes (Guzik 2005). As noted by Montalbán et al. (2006), any substantial increases to the diffusion coefficients that are made in order to recover good agreement with the inferred sound speed profile result in predictions for the surface helium content of the Sun that are below the values obtained by the inversion of solar oscillations. In fact, turbulent mixing processes appear to operate in stellar envelopes to reduce the effects of diffusion on the surface abundances of $\sim$1 $M_{\odot}$ main-sequence (MS) stars (see Korn et al. 2006; Richard et al. 2002).

While the low solar $Z$ derived by Asplund et al. may be erroneous, the 3D model atmospheres used in their studies have had unprecedented success in modeling the properties of the solar atmosphere (see Asplund 2005), and the predicted spectral line profiles based on these atmospheres provide superb matches to the observed profiles (Asplund et al. 2000). In addition, the reduced abundances of the CNO elements are in excellent agreement with the values measured in the interstellar medium (Turck-Chièze et al. 2004) and in solar neighborhood B stars (see Asplund et al. 2005 and references therein). Thus, their findings are not easily dismissed.

There is another, albeit indirect, way of constraining the metallicity of the Sun that has not yet been investigated. The large reduction in the CNO and Ne abundances found by Asplund et al. (relative to previous estimates) affects the mass at which a transition is made between stars that have radiative cores during the MS phase and those possessing convective cores when their central hydrogen fuel is exhausted. Consequently, a cluster like M67, which has $[M/H] \approx 0.0$ and turnoff stars with masses close to the transition mass $M_{tr}$, provides a probe of both stellar physics and the chemical composition of the material out of which the stars formed. As shown by VandenBerg et al. (2006, hereafter VBD06), $M_{tr}$ is predicted to increase with decreasing metal abundance, and to be a fairly sensitive function of $Z$ (see their Fig. 2). Whether or not an old open cluster is expected to have a gap in its distribution of near-turnoff stars on the color-magnitude diagram (CMD) will therefore depend on its metallicity. (A gap is the observational manifestation of the rapid contraction phase that accompanies the exhaustion of hydrogen in stars that have convective cores at the end of their MS lifetimes.)

The M67 CMD (see Montgomery et al. 1993; Sandquist 2004) contains such a gap, and stellar models for $Z \approx 0.017$ have been quite successful in reproducing these data. VandenBerg & Stetson (2004) have shown that a 4.0 Gyr isochrone for $Z = 0.0173$, assuming the Grevesse & Noels (1993) metal abundances, provides a satisfactory match to the cluster CMD, if a small amount of convective core overshooting is assumed (also see VBD06). A nearly identical fit was obtained by Michaud et al. (2004) using diffusive isochrones for 3.7 Gyr and $Z_{\text{init}} = 0.02$, without having to postulate any core overshooting. These
calculations predict that the cluster MS stars have $\sim 6\%-12\%$ surface underabundances of the metals, depending on their temperatures—compared with a $\approx 8\%$ reduction in the case of the Sun (Turcotte et al. 1998), which is much too small to simulate the difference between the Asplund et al. solar composition and that reported by, e.g., Grevesse & Noels.

Given the apparent success of relatively metal-rich models in explaining the CMD of M67, which has very close to the solar metallicity, is it possible for isochrones to provide a comparable fit? This is the question that has motivated the present investigation.

2. STELLAR MODELS FOR SOLAR ABUNDANCES

The evolutionary tracks needed for this investigation have been computed using the Victoria stellar evolution code (see VBD06 and references therein). Model atmospheres produced by the latest version of the MARCS code (e.g., Gustafsson et al. 2003) have been used as boundary conditions. (Differences in the treatment of the surface layers do not alter the tracks for the MS and early subgiant branch [SBG] phases of solar metallicity stars in any significant way if the value of the mixing-length parameter \( \alpha_{\text{MLT}} \) is chosen so that the solar constraint is satisfied [see, e.g., Fig. 3 in the study by VandenBerg et al. 2007]. The assumed value of \( \alpha_{\text{MLT}} \) does affect the predicted location of the red giant branch [RGB], but that is not a concern for the present work.)

The standard abundance distribution reported by Grevesse & Sauval (1998, hereafter GS98) as determined from analyses of solar photospheric spectra and meteoritic data using classical 1D hydrostatic models, was the last such compilation prior to the use of 3D hydrodynamic model atmospheres by Asplund et al. (2004) to determine the solar composition. The GS98 abundances for the 19 metals normally considered in stellar evolutionary computations (because they are the only heavy elements that are taken into account in the calculation of OPAL opacities for stellar interior conditions; see Iglesias & Rogers 1996) are listed in the second column of Table 1. The third column contains the abundance distribution that is obtained when the revised values derived by Asplund et al. for several of the heavy elements are adopted; note that the C and N abundances in Table 1 are 0.02 dex higher than their published 2006 estimates.

OPAL opacities were computed for both heavy-element mixtures using the Livermore Laboratory Web site facility. Because these calculations do not include the contributions from molecular sources or grains, complementary opacity data for \( T \leq 10^4 \) K were computed for the same abundances using the code described by Ferguson et al. (2005). The tabulated values of \( \log N_{\text{H}} \) were obtained from SSMs that were convolved with the code described by Ferguson et al. (2005). The tabulated opacities for the 1.0 \( M_\odot \) models for the GS98 and Asplund et al. abundances required \( \alpha_{\text{MLT}} = 1.84 \) and 1.80, respectively (when MARCS model atmospheres are used as boundary conditions; see VandenBerg et al. 2007).

The value of \( M_{\text{tr}} \) is a function of \( Z \) (especially the CNO abundances; see below). The transition occurs when the CNO cycle becomes an important source of nuclear energy production, and since both the decrease in the abundances of the CNO elements and the concomitant reduction in opacity will serve to reduce the rate of the CNO cycle, the minimum mass for sustained core convection on the MS is higher in stars of lower \( Z \). By trial and error, \( M_{\text{tr}} \) was found to be 1.195 \( M_\odot \) if \( Z = 0.0125 \) (Asplund et al. mix), whereas 1.155 \( M_\odot \) is obtained if \( Z = 0.01165 \) (GS98 metal abundances). (The transition mass also depends on the adopted helium content; e.g., \( M_{\text{tr}} = 1.181 \) \( M_\odot \) if \( Z = 0.0125 \) and the value of \( Y \) required by an SSM for \( Z = 0.01165 \) is assumed [i.e., \( Y = 0.2676 \); see Table 1].)

Indeed, the character of the tracks changes abruptly when core convection persists until H exhaustion. This is shown in Figure 1, which plots the evolutionary tracks for 1.0–1.4 \( M_\odot \) that were computed for the two values of \( Z \), including, in particular, sequences for \( M_{\text{tr}} \) and \( (M_{\text{tr}} + 0.001) M_\odot \). Each of the higher mass tracks possesses a blueward hook, which arises when a star contracts following the depletion of hydrogen in a convective core in order to ignite H burning in a shell around the He core. This morphology is not seen in the lower mass tracks because the central regions are radiative when hydrogen is exhausted and there is a smooth transition to H shell burning. A difference of 0.04 \( M_\odot \) in \( M_{\text{tr}} \) is surprisingly large given that VBD06 found an increase of only 0.009 \( M_\odot \) when \( Z \) was decreased from 0.0173 to 0.0125. However, the latter calculations assumed the same relative abundances of the metals (those given by Grevesse & Noels 1993), whereas the tracks plotted in Figure 1 assume two very different heavy-element mixtures. Indeed, a large reduction in the CNO abundances is mainly responsible for the downward revision of the solar value of \( Z \) from 0.0165 (GS98) to 0.0125 (Asplund et al.)—which demonstrates that \( M_{\text{tr}} \) is a strong function of the abundances of the CNO elements.

An increase in \( M_{\text{tr}} \) from 1.155 to 1.195 \( M_\odot \) will be accompanied by a decrease in the maximum age at which a gap near the turnoff is expected in an observed CMD. Figure 1 shows that the biggest differences between the two models occur at masses of \( \approx 1.2 \) \( M_\odot \). Because \( M_{\text{tr}} \) is lower in the case of the GS98 computations, and because the amount of overshooting in stars of mass \( M > M_{\text{tr}} \) is assumed to vary directly with \( M - M_{\text{tr}} \) (see VBD06), the tracks represented by the dashed curves for masses of 1.2–1.4 \( M_\odot \) have larger

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**Table 1**

| ELEMENT | Grevesse & Sauval (1998) | Asplund et al. \(^a\) |
|---------|-------------------------|-----------------------|
| H       | 12.00                   | 12.00                 |
| He       | 10.9738                 | 10.9487               |
| C        | 8.52                    | 8.41                  |
| N        | 7.92                    | 7.80                  |
| O        | 8.83                    | 8.66                  |
| Ne       | 8.08                    | 7.84                  |
| Na       | 6.33                    | 6.33                  |
| Mg       | 7.58                    | 7.58                  |
| Al       | 6.47                    | 6.47                  |
| Si       | 7.55                    | 7.51                  |
| P        | 5.45                    | 5.45                  |
| S        | 7.33                    | 7.33                  |
| Cl       | 5.50                    | 5.50                  |
| Ar       | 6.40                    | 6.18                  |
| K        | 5.12                    | 5.12                  |
| Ca       | 6.36                    | 6.36                  |
| Ti       | 5.02                    | 5.02                  |
| Cr       | 5.67                    | 5.67                  |
| Mn       | 5.39                    | 5.39                  |
| Fe       | 7.50                    | 7.45                  |
| Ni       | 6.25                    | 6.25                  |
| He mass fraction (Y) | 0.2676 | 0.2559 |
| Metallicity (Z) | 0.0165 | 0.0125 |

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\(^a\) Abundances for C, N, O, Ne, Si, Ar, and Fe were provided by M. Asplund (2004, private communication); Grevesse & Sauval (1998) abundances are assumed for all other elements heavier than helium.

\(^b\) Determined from standard solar models.

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\(^4\) See http://www-phys.lnl.gov/Research/OPAL.
masses (in solar units). The sequences for 1.155 and 1.156 \\
(Many of the stars just brighter than the gap, at , are \\
cluding, in particular, the location of the gap near the turnoff. \\
vides a good match to the morphology of the M67 CMD all \\
isochrone for each value of that provides the best fit to the \\
presumably binaries, given that M67 is known to have an un-
convective cores during MS evolution, and cooler blueward 
hooks at H exhaustion, than those plotted as solid curves. Such 
 differences will impact the isochrones (computed in this study 
using the interpolation software described by VBD06) and the 
degree to which they are able to reproduce the M67 CMD.

3. APPLICATION TO THE M67 CMD

According to high-resolution spectroscopy, M67 has [Fe/H] = 
0.0 ± 0.03 (see Tautvaisienė et al. 2000; Randich et al. 2006). 
For the cluster reddening, we have adopted E(B − V) = 0.038 
mag, as found from the Schlegel et al. (1998) dust maps; this 
estimate is probably accurate to within ±0.01 mag, given that it 
agrees so well with the values derived using alternative methods 
(see Nissen et al. 1987; Sarajedini et al. 1999). As far as the 
distance is concerned, the modulus that is obtained from a main-
sequence fit of the dereddened photometry to the lower MS 
segments of our isochrones should also be quite accurate (prob-
able to within ±0.1 mag) because the model temperatures satisfy the 
solar constraint and the adopted color transformations (by 
VandenBerg & Clem paper) are in very good agreement with the 
empirical relations derived by Sekiguchi & Fukugita (2000) from 
their study of solar neighborhood stars having well-determined 
properties (see the VandenBerg & Clem paper). The application of 
the MS-fitting technique yields (m − M)ν = 9.70.

With these choices for the basic parameters of M67, the 
isochrone for each value of Z⊙ that provides the best fit to the 
subgiant is readily identified. As shown in Figure 2, the 3.9 
Gyr isochrone for Z = 0.0165 (GS98 metal abundances) pro-
vides a good match to the morphology of the M67 CMD all 
the way from the ZAMS to the base of the giant branch, in-
cluding, in particular, the location of the gap near the turnoff. 
(Many of the stars just brighter than the gap, at Mν ≈ 3.1, are 
presumably binaries, given that M67 is known to have an un-
usually large binarity fraction—at least 63%, according to 
Montgomery et al. [1993]. The ≈0.06 mag offset in color at a 
given Mν along the lower RGB is discussed by VandenBerg et al. [2007].) In stark contrast with this, the 4.2 Gyr isochrone 
for Z = 0.0125 (the Asplund et al. metallicty) fails to repro-
duce the location of the near-turnoff stars of M67, despite 
providing a comparably good fit to the ZAMS and the SGB. 
This isochrone shows no indication at all of a blueward hook 
feature, and thus it does not predict a gap in the distribution of 
stars near the turnoff where one is observed.5

The oldest isochrone in the Z = 0.0125 set that has the 
required turnoff morphology is one for an age of 3.6 Gyr, and 
indeed, it provides a satisfactory fit to the CMD of M67 if 
E(B − V) ≈ 0.065 and (m − M)ν ≈ 9.90. However, such a high 
reddening seems to be ruled out and it is doubtful that the 
model colors are in error by as much as 0.03 mag. Isochrones 
for the Asplund metallicity thus appear to pose difficulties for 
our understanding of M67 similar to those for helioseismology, 
in the sense that stellar models with higher values of Z⊙ are 
better able to explain the observations.

As the CNO elements play such a key role in the interpre-

5 Although one might question the reality of the gap in the Montgomery et 
al. (1993) CMD, there is no doubt about its existence (in the same magnitude 
range as that indicated in Fig. 2) in the CMD published by Sandquist (2004) for 
the high-probability single-star members. Moreover, the observed distribution of 
single stars along the cluster fiducial sequence (see Sandquist’s Fig. 14) is very 
reminiscent of that predicted by best-fitting isochrones (see Fig. 14 in the study 
by Michaud et al. 2004). [The CMD obtained by Sandquist is not used here 
because he did not provide BV photometry (only VI), and his V − I colors, but 
not his V magnitudes, are at odds with other measurements (see the discussion 
by VandenBerg & Stetson 2004). Perhaps the main advantage of using BV data 
in our analysis is that, as mentioned above, the (B − V)−Teff relations that have 
been used to transpose the models to the observed plane appear to be especially 
reliable.]
tation of the cluster data, one must first consider whether their abundances, relative to iron, are higher in M67 than in the Sun. An increase in the abundances of C, N, and O by \( \sim 0.1 \) dex (or more, if the increase is limited to one or two of these elements) may be enough to reconcile the predicted and observed CMDs. However, while a true cosmic spread among solar metallicity disk stars with an abundance of about 0.1 dex in [C/Fe], [N/Fe], and [O/Fe] cannot be excluded (see the recent surveys by Reddy et al. 2003 and Eclivillon et al. 2006), the abundance analysis of M67 main-sequence stars carried out by Randich et al. (2006) does not support the possibility that M67 has [CNO/Fe] \( \geq 0.1 \). These authors derived a mean oxygen abundance corresponding to [O/Fe] = \(-0.01 \pm 0.03\), which agrees well with the findings of Tautvaišiene et al. (2000) for cluster giants. The latter also derived C and N abundances; however, in the case of giant stars, they are expected to have been altered by CN burning and the first dredge-up. They find that [C/H] and [N/H] are typically \(-0.2 \) and \( +0.2 \), respectively, which is roughly consistent with initial C and N abundances slightly lower than solar. In fact, Friel & Boesgaard (1992) found a mean [C/H] of \(-0.09 \pm 0.03\) for three F dwarfs of M67. (Based on the work of Nissen et al. [2002], we find that the expected differential effects due to the use of 3D model atmospheres in the determination of [O/Fe] in the cluster turnoff stars, like those analyzed by Randich et al., would amount to \(+0.03 \) dex relative to the solar value.) Thus, it seems improbable that the CNO abundances relative to iron are enhanced in the cluster with respect to the Sun by as much as 0.1 dex. We also note that an increase of the Ne abundance, which has been suggested (by Bahcall et al. 2005) to solve the discrepancy between solar oscillation data and the Asplund et al. abundances, would not resolve the M67 conundrum.

Although our present understanding of diffusive processes precludes the possibility that there is a large difference between the interior and photospheric metallicities of the Sun, Michaud et al. (2004) have found from their calculations for \( Z > 0.0175 \) that the lowest mass diffusive model with a convective core on the MS is \( \approx 1.1 \, M_\odot \), as opposed to \( 1.4 \, M_\odot \) in the case of non-diffusive models. The difference in mass is comparable to the difference in \( M_\odot \), predicted by our calculations when the assumed value of Z is increased from 0.0125 (Asplund et al.) to 0.0165 (GS98). Consequently, it seems quite possible that low-Z diffusive models (with or without some core overshooting) may be able to satisfy the M67 constraint. Further investigation is needed. However, even if this leads to a consistent explanation for both the Asplund et al. solar abundances and the M67 CMD, the large discrepancies with helioseismology would remain.

4. CONCLUSIONS

The new Asplund et al. metallicity for the Sun presents some difficulties for fits of solar abundance models to the M67 CMD, in that they do not predict a gap near the turnoff where one is observed. Whether or not stellar models predict a gap at the observed \( M_f \) in this open cluster depends quite sensitively on the assumed CNO abundances, and it is mainly the revision of these elemental abundances (along with that of Ne) that is responsible for the decrease in \( Z_\odot \) from 0.0165 (GS98) to 0.0125. Isochrones for the higher value of Z are able to reproduce the detailed CMD morphology of M67 in the vicinity of the turnoff without apparent problems. Interestingly, it is primarily the reduction in the abundances of CNO that has resulted in substantial difficulties for helioseismology, e.g., an increase from \(-0.3\%\) to \(-3\%\) in the differences between the predicted and inferred sound speed squared profiles. Are solar oscillation studies and our investigation of M67 telling us that the low solar Z determined by Asplund et al. is wrong?

Not necessarily. It is possible, judging from the work of Michaud et al. (2004), that models which take diffusive processes into account may not have the same difficulties as the models used in this study, which neglect such processes. That is, if the Asplund et al. solar abundances are correct, only those low-Z models that treat diffusion may be able to reproduce the M67 CMD. This possibility, which would not resolve the quandary presented by solar oscillations, needs to be carefully studied. Diffusion clearly adds another level of complexity to the problem since, e.g., the initial abundances of the gas out of which the Sun and M67 formed would have been somewhat different, if they have the same abundances today, because the Sun is up to 1 Gyr older than M67. Importantly, MS stars in M67 should show systematic variations in their surface metallicities as a function of \( T_{\text{eff}} \), due to the operation of diffusive processes (see Michaud et al.).

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