Mem. S.A.It. Vol. 79, 759

Memorie della

M 67: a constraint on $Z_\odot$ and/or on diffusive processes in stellar interiors

D.A. VandenBerg[1], B. Gustafsson[2], B. Edvardsson[2], K. Eriksson[2], and J.W. Ferguson[3]

[1] Dept. of Physics & Astronomy, University of Victoria, Box 3055, Victoria, BC V8W 3P6, Canada, e-mail: vandenbe@uvic.ca
[2] Uppsala Astronomical Observatory, Box 515, SE-751 20 Uppsala, Sweden e-mail: firstname.lastname@astro.uu.se
[3] Dept. of Physics, Wichita State University, Wichita, KS 67260-0032, U.S.A. e-mail: jason.ferguson@wichita.edu

Abstract. The mass of the lowest mass star that has a convective core throughout the main-sequence phase is predicted to be a fairly sensitive function of Z (especially the CNO abundances). The $\sim$ 4 Gyr open cluster M 67 thus provides a constraint on $Z_\odot$ (and the solar metals mix) because (i) it has the same metallicity as the Sun according to high-resolution spectroscopy, and (ii) its turnoff stars have masses just above this lower mass limit. While isochrones computed for $Z = 0.0165$, assuming the Grevesse & Sauval (1998) heavy-element mixture, are able to reproduce the M 67 color-magnitude diagram satisfactorily, those for the solar abundances derived by M. Asplund et al. (implying $Z_\odot = 0.0125$) do not predict a gap near the turnoff where one is observed. These results suggest either that there is a problem with the solar metal abundances derived by Asplund et al. or that the neglect of diffusive processes in the present models is responsible for this difficulty. If the latter is the correct explanation, then M 67 provides an important constraint on the rates of diffusive processes in the deep interiors of stars.

Key words. Hertzsprung-Russell diagram – Galaxy: open clusters (M 67) – Stars: atmospheres – Stars: evolution – Sun: abundances

1. Introduction

From their analyses of the solar spectrum using 3D, non-LTE model atmospheres, Asplund et al. (2006, and references therein) have derived significantly reduced abundances for C, N, O, Ne, and Ar, resulting in $Z_\odot \approx 0.0125$. This metallicity presents a problem for helioseismology; e.g., whereas high-Z (i.e., $Z \gtrsim 0.017$) solar models are able to reproduce the inferred radial dependence of the square of the sound speed from solar oscillations to within $\sim 0.3\%$ (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). This difficulty does not appear to be due to problems with current opacities (Antia & Basu 2005) or with the presently accepted rates of diffusive processes (Guzik 2005). The Asplund et al. abundance determinations are not easily discounted either, given that the model atmospheres that they used have had unprecedented success in

Send offprint requests to: D. A. VandenBerg modelling the solar atmosphere (see Asplund 2005), and the predicted spectral line profiles provide superb matches to the observed line profiles (Asplund et al. 2000).

The mass, $\mathcal{M}_{\rm tr}$, at which a transition is made between stars that have radiative cores during the main-sequence (MS) phase and those possessing convective cores when their central H fuel is exhausted is predicted to depend quite sensitively on Z; see Figure 1. Consequently, M 67 provides a valuable consistency check of the value of $Z_\odot$ because (i) its color-magnitude diagram (CMD) possesses a gap in the vicinity of the turnoff, (ii) its age is such that its turnoff stars have masses just above $\mathcal{M}_{\rm tr}$, and (iii) it has [m/H] = 0.0 ± 0.03 according to the results of high-resolution spectroscopy (see Tautvaišienė et al. 2000, Randich et al. 2006). VandenBerg & Stetson (2004) have already shown that isochrones for $Z \gtrsim 0.017$ provide a good match to the M 67 CMD. Is comparable success possible using models for $Z = Z_\odot = 0.0125$ (as derived by Asplund et al.)?

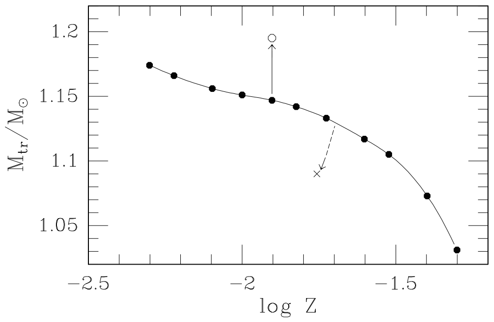

Fig. 1. The filled circles, connected by a solid curve, give the dependence on Z of the mass of the lowest mass star that is predicted to have a convective core at the end of the MS phase: at a given Z, masses below the solid curve have radiative cores. [These results, which are reproduced from VandenBerg et al. (2006), assume $Z_\odot = 0.0188$ and the distribution of heavy element abundances reported by Grevesse & Noels (1993).] The open circle indicates the value of $\mathcal{M}_{\rm tr}$ if $Z_\odot = 0.0125$, assuming the Asplund et al. (2006) metals mixture, whereas the cross indicates the expected effect of diffusive processes on $\mathcal{M}_{\rm tr}$, based on the computations by Michaud et al. (2004). As indicated by the dashed line, diffusive models predict that the metallicity in the surface layers of the Sun will decrease to ≈ 0.0175 at the solar age if $Z \approx 0.02$ initially.

2. Stellar models and application to M 67

To answer this question, grids of evolutionary tracks were computed (see VandenBerg et al. 2007), using the Victoria stellar evolution code (see VandenBerg et al. 2006, and references therein), for $Z = 0.0125$ and $Z = 0.0165$, assuming the Asplund et al. (2006) and Grevesse & Sauval (1998) heavy-element mixtures, respectively. Both sets of models were properly normalized so as to satisfy the solar constraint (by assuming, in each case, the appropriate values of $Y_\odot$ and the mixing-length parameter, $\alpha_{\rm MLT}$). Fully consistent MARCS model atmospheres (see, e.g., Gustafsson et al. 2003) were used as boundary conditions.

As mentioned, M 67 has [m/H] = 0.0 ± 0.03 according to high-resolution spectroscopy. There is, in particular, no evidence that the cluster CNO abundances differ significantly from the solar values; e.g., Randich et al. (2006) obtained [O/Fe] = -0.01 ± 0.03. Insofar as the reddening and distance are concerned, $E(B-V) = 0.038$ and $(m-M)_V = 9.70$ are arguably current best estimates (see the discussion by VandenBerg et al. 2007). On the assumption of these values, the isochrone that best reproduces the cluster subgiants is found to have an age of 3.9 Gyr, if $Z = 0.0165$, or 4.2 Gyr, if $Z = 0.0125$ — as shown in Figure 2. Whereas the former provides a good match to the M 67 CMD all the way from the zero-age MS to the lower giant branch, including the location of the gap near the turnoff, the latter fails to predict the observed gap, despite providing a comparably good fit elsewhere. [As shown in Fig. 2, a 3.6 Gyr isochrone for the Asplund et al. metal abundances is morphologically very similar to the 3.9 Gyr, $Z = 0.0165$ isochrone. However, fitting the M 67 CMD to the former would require $E(B-V) \approx 0.065$ and $(m-M)_V \approx 9.90$, which are well outside the ±0.01 and ±0.10 mag uncertainties associated with the adopted reddening and distance modulus, respectively.]

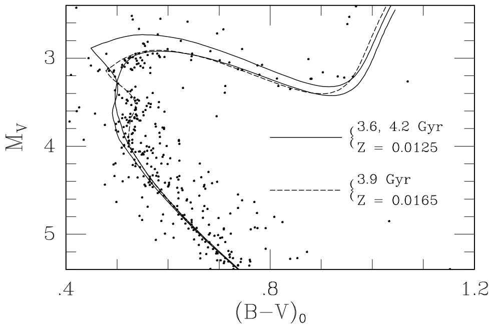

Fig. 2. Comparison of isochrones for the indicated ages and metallicities with the Montgomery et al. (1993) CMD of M 67, assuming $E(B-V) = 0.038$ and $(m-M)_V = 9.70$. The vertical line bounded by short horizontal lines, located just to the left of the turnoff, indicates our estimate of the gap location. Only the dashed isochrone has a blueward hook in the same magnitude range. The 3.6 Gyr isochrone for $Z = 0.0125$ has a very similar morphology to the dashed isochrone, but the predicted location of the gap (the blueward hook) is significantly too bright if best estimates of the reddening and distance are assumed.

3. Conclusions

Isochrones for the Asplund metallicity thus appear to pose similar difficulties for our understanding of M 67 as for helioseismology, in the sense that *stellar models with higher values of $Z_\odot$ are better able to explain the observations*. However, it is possible that models with diffusive processes taken into account will not suffer from the same difficulties as the present computations, which neglect this physics. As indicated in Fig. 1, $\mathcal{M}_{tr}$ is reduced by ~ 0.03–$0.04\ \mathcal{M}_\odot$ when diffusion is treated. This possibility needs to be investigated. It would be a remarkable result if consistency between the M 67 CMD and the Asplund et al. solar abundances can be obtained *only* if the effects of diffusion are taken into account, not only at the surfaces of stars but also in their deep interiors.

Acknowledgements. This work has been supported by an NSERC Discovery Grant to DAV, by grants from the Swedish Research Council to BG, BE, and KE, and by NSF grant AST 02-39590 to JWF.

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