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METAL OPACITIES AND CONVECTIVE CORE OVERSHOOTING IN POPULATION I STARS

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ABSTRACT

New stellar opacities computed by Rogers and Iglesias are found to lead to revised evolutionary models for stars of intermediate to high mass that show remarkably close agreement with observed stars, under otherwise standard physical assumptions. Most or all of the earlier discrepancies, except for the problem of predicted apsidal motion constants that are perhaps still too large, appear to have been resolved by using these new opacities with their increased metal line contribution. Thus, the implied interior metallicity of massive stars in the solar neighborhood now becomes "normal." Furthermore, the effective distance of convective overshooting beyond the classical convective core boundary is confirmed to be small and probably less than 0.2 times the local pressure scale height.

Subject headings: convection — opacities — stars: abundances — stars: evolution — stars: interiors

1. INTRODUCTION

The opacity of matter in the stellar interior must be calculated theoretically with the supplementary use of experimental data. Introduced into the structure equations for massive main-sequence stars, these physical opacities have led to stellar models that differ in a small, systematic way from observed stars. Specifically, the astronomically implied opacity is somewhat larger. The deficit in the physical opacity can be made up by adopting an "effective" metals abundance that is about twice the spectroscopically observed value for massive stars in the solar neighborhood (e.g., Stothers 1991).

Recently, Iglesias & Rogers (1991a, b) and Rogers & Iglesias (1991) have convincingly demonstrated that the inclusion of many more metal lines than were previously considered either by the Los Alamos workers (Cox & Stewart 1965, 1970; Huebner et al. 1977) or by Carson et al. (1984) can greatly increase the total opacity at temperatures above 10^5 K. Therefore, this may be the "missing" physical opacity. The astrophysical implications of the new Rogers–Iglesias opacities for the structure and evolution of massive stars are the subject of this paper.

In particular, the important question of convective core overshooting is reassessed in the light of a recent determination, using Cox–Stewart opacities, that a large assumed metals abundance can remove the need for assuming significant convective core overshooting (Stothers 1991). Several other astrophysical tests in the same study indicated that, when the metallicity is unimportant, little or no overshooting is always implied. Therefore, it seems urgent to determine whether the Rogers–Iglesias opacities, which are major improvements over the Los Alamos opacities, lead to the same conclusions and do so for a *normal* metals abundance. A full discussion of earlier work appears in Stothers (1991) and will not be repeated here.

2. STELLAR MODELS

New input physics for the stellar models are mainly the revised opacity tables of Rogers & Iglesias (1991). These tables do not include atmospheric opacities and high-temperature opacities, whose uncertainties have much less influence on stellar models than do the changes of the opacities at intermediate temperatures. Opacities not provided by Rogers & Iglesias (1991) are assumed to be the same as those adopted in our previous work (Stothers & Chin 1973). The initial abundances by mass are taken to be $X_e = 0.700$ (hydrogen) and $Z_e = 0.02$ and 0.03 (metals) for the Anders-Grevesse mixture of metals.

For the still uncertain $^{12}C(\alpha, \gamma)^{16}O$ reaction rate, we have used the largest published rate among all current rate estimates; this is equivalent to adopting $\theta_\alpha^2 = 0.2$ for the reduced α-particle width of the 7.12 MeV level in ^{16}O. In the outer convection zone, the ratio of the convective mixing length to the local pressure scale height is assigned to be $\alpha_P = 1.2$ for $Z_e = 0.02$, and $\alpha_P = 1.4$ for $Z_e = 0.03$. Either of these two combinations leads to an approximate match between predicted and observed effective temperatures for red giants and supergiants that are found in the solar neighborhood. Semiconvection above the hydrogen-burning layers and convective core overshooting are ignored here as probably being unimportant in the stars under consideration (§ 6). Stellar masses chosen as representative are 1.5, 2, 2.5, 3, 4, 5, 6, 7, 10, 15, 25, 30, and 60 $M_\odot$. Stellar wind mass loss is slight enough that it can be neglected for initial masses below 30 $M_\odot$ on the main sequence and below 20 $M_\odot$ off the main sequence. For higher initial masses, it is included by using the parameterized mass-loss rate fitted to observations by Nieuwenhuijzen & de Jager (1990).

3. COMPARISON WITH OBSERVED O- AND B-TYPE STARS

3.1. *ZAMS Stars*

It is well-known that models of main-sequence stars show much greater sensitivity to changes of opacity, or of metals abundance, in the (mass, radius) and (luminosity, effective temperature) diagrams than in the (mass, luminosity) diagram. Figure 1 displays the (mass, radius) diagram for massive members of well-observed detached close binary systems (Hilditch & Bell 1987; Andersen & Clausen 1989). Notice that the lower envelope of observational points, representing mostly unevolved stars, is fitted very well by the new models with $Z_e = 0.02$–0.03. Convective core overshooting, unless it is enormous in extent, has no effect on unevolved stars and so can be ignored as a relevant factor here.

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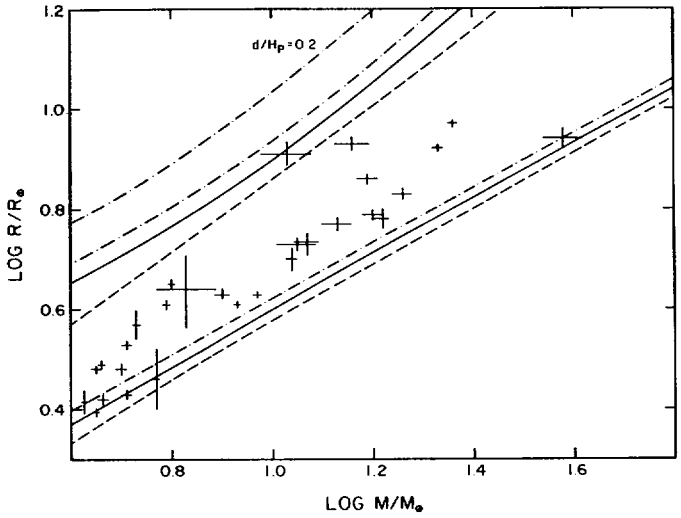

FIG. 1.—Mass vs. radius, for observed members of O- and B-type detached close binary systems. Lines represent (*a*) theoretical ZAMS models without convective core overshooting and (*b*) theoretical TAMS models with and without convective core overshooting. The cases shown refer to the Rogers-Iglesias opacities with $Z_e = 0.02$ (*solid lines*) and $Z_e = 0.03$ (*dash-dot lines*) and to the Cox-Stewart opacities with $Z_e = 0.02$ (*dashed lines*). The parameter d/H_P is the ratio of the convective overshoot distance to the local pressure scale height.

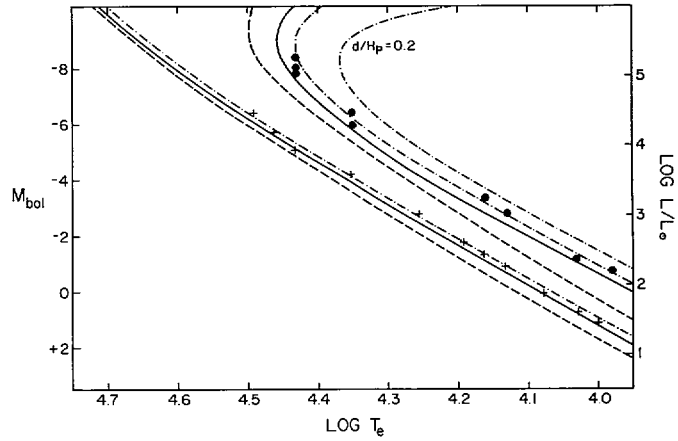

FIG. 2.—H-R diagram for observed O- and B-type stars, showing the standard ZAMS (*plus signs*) and the TAMS based on grouped members of open clusters (*dots*). Theoretical lines have the same meaning as in Fig. 1.

In the (color, magnitude) diagram, the standard zero-age main sequence (ZAMS) for B-type stars has been carefully derived by Blaauw (1963) and Johnson (1963), whose representations of it are almost identical. Crawford's (1978) ZAMS for middle and late B-type stars, as well as other independent evidence (Stothers 1983, § II*a*; Feast 1991, § 3), supports the Blaauw-Johnson ZAMS. To transform this line to theoretical coordinates, we use the Morton & Adams (1968) traditional scale of effective temperature as a function of $B-V$ color for spectral types B5–B9, because the temperature scale in this spectral range has not changed significantly over the years (Gulati, Malagnini, & Morossi 1989). For spectral types B0–B4, the revised scale of Underhill & Doazan (1982, p. 60) will be used here. Bolometric corrections are taken from Flower (1977). The transformed ZAMS is shown on the luminosity, effective temperature) diagram in Figure 2. As expected, the Rogers-Iglesias opacities lead to a good fit with $Z_e =$ 0.02–0.03.

Although the observed ZAMS for O-type stars is still not well defined in luminosity, the new stellar models are successful in reproducing the observed effective tmperature range of 30,000–50,000 K.

3.2. *TAMS Stars*

Cluster observations, despite their many problems, most adequately furnish the location of the terminal-age main sequence (TAMS) in the (color, magnitude) or (spectral type, magnitude) diagram. Figure 2 shows the transformed data for five individual clusters with reliably determined early B-type main-sequence turnups (Stothers 1991) and for four large groups of clusters with known middle to late B-type main-sequence turnups (Maeder & Mermilliod 1981). In the case of the latter clusters, we have shifted the Maeder & Mermilliod (1981) TAMS absolute magnitudes to values fainter by 0.16 mag, because they adjusted the cluster distance scale based on B-type stars upward by this amount to allow for a revised Hyades distance modulus— an adjustment that we (and Feast 1991) believe is unnecessary.

Stellar models constructed with the Rogers-Iglesias opacities and without convective core overshooting produce an excellent fit to the observed TAMS for $Z_e = 0.02$–0.03. On the other hand, nonovershooting stellar models based on the Los Alamos opacities—even for Z_e as large as 0.044—cannot accommodate the full observed extension of the main-sequence band (Maeder & Mermilliod 1981; Bertelli, Bressan, & Chiosi 1985; Doom 1985; Grenier et al. 1985; Stothers & Chin 1985; Mermilliod & Maeder 1986; Maeder & Meynet 1989; Wolff 1990; Napiwotzki, Schönberner, & Weidemann 1991; Stothers 1991).

The observed TAMS at still higher luminosities appears to bend back toward later spectral types after reaching subtype B1 (Andrews 1968; Humphreys 1978). Corresponding to $\log T_e \approx 4.43$, this hottest point is predicted very well by nonovershooting stellar models based on the Rogers-Iglesias opacities, although the switchback as a qualitative feature is caused chiefly by stellar wind mass loss.

Finally, the new models lead to isochrone ages for young clusters that are ~15% smaller than before (Stothers 1991).

3.3. *Apsidal Motion Stars*

In a close binary system, the tidal and rotational distortion of the stellar components causes the orbital line of apsides to advance. Apsidal motion constants, k_2, which are related to the interior density distributions inside the stars, have been calculated for several of our new stellar models. The evolutionary trend of k_2 as a function of the changing surface gravity g is shown in Figure 3 for stellar masses of 10 and 25 $M_\odot$. Comparison trend lines based on the Cox-Stewart opacities are also displayed. An increased metals abundance in either of the opacity sets lengthens the trend line without otherwise displacing it significantly.

Observed apsidal motion constants have tended to be systematically smaller by 0.1–0.2 in $\log k_2$ than the theoretically computed values. The new Rogers-Iglesias opacities go in the right direction for reducing the discrepancy, but obviously not nearly far enough. Nor can the assumption of convective core overshooting solve the problem (compare Fig. 8*b* of Claret &

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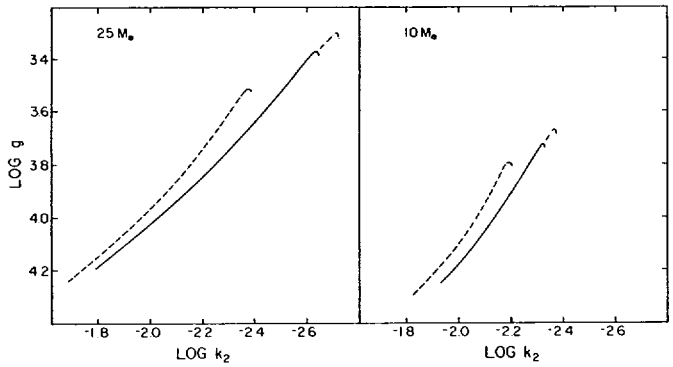

FIG. 3.—Theoretical apsidal motion constant, k_2, as a function of surface gravity, g, for stars of 10 and 25 $M_\odot$ during the main-sequence phase of evolution without convective core overshooting. Same notation as for Fig. 1.

Giménez 1991). Perhaps the stellar radius observations still require some small systematic correction, which could greatly affect the observed apsidal motion constants because $k_2 \propto R^{-5}$. Axial rotation in the stellar models would also lower the predicted k_2.

4. COMPARISON WITH OBSERVED A- AND F-TYPE STARS

Blaauw's (1963) ZAMS for A-type stars, which agrees very well with Johnson's (1963) and Crawford's (1979), has been transformed to theoretical coordinates by using the conversion relations provided by Flower (1977). It is shown in Figure 4 and appears to be matched closely by the new theoretical ZAMS for $Z_e = 0.02$–0.03. However, in the mass range of A-type stars, the revised Los Alamos opacities (but not the Cox-Stewart opacities) also lead to a similarly close fit (Andersen, Nordström, & Clausen 1990).

On the other hand, the TAMS for A-type stars is fitted rather poorly by any version of the Los Alamos opacities if convective core overshooting is slight or absent, because an unexpectedly large number of observed stars lie outside the predicted main-sequence band (Maeder & Mermilliod 1981; Grenier et al. 1985; Lemke 1989; Maeder & Meynet 1989; Andersen et al. 1990). Employing the same published data for 11 "evolved" main-sequence A- and F-type components of detached close binary systems that were used by Andersen et al. (1990), we show in Figure 4 the positions of these stars with respect to the new theoretical TAMS. Nearly all the stars now lie acceptably within the predicted main-sequence band for $Z_e = 0.02$–0.03 without any convective core overshooting. A (mass, radius) diagram gives the same result. Likewise, cluster and field star data, although they are somewhat less accurate and are not shown in Figure 4, exhibit an equally good fit with respect to the new models. The three significant outliers in Figure 4 actually confirm the new models, because within the total sample of 56 main-sequence stars from which the "evolved" members were drawn one would expect to find two or three stars evolving rapidly away from the main-sequence band.

5. COMPARISON WITH EVOLVED GIANTS AND SUPERGIANTS

Over the mass range 3–15 $M_\odot$, the main-sequence evolutionary tracks have been continued to a terminal stage close to the end of core helium burning. Tracks for $Z_e = 0.02$ exhibit no prominent blue loops during core helium burning except at a mass of 10 $M_\odot$, while those for $Z_e = 0.03$ display long blue loops at all masses above 6 $M_\odot$ (Fig. 5). We have also computed a parallel series of tracks with Cox-Stewart opacities, $Z_e = 0.03$, and other input physics the same (Fig. 5). The Rogers-Iglesias opacities, being larger than the Cox-Stewart opacities, are found to lead to slightly fainter and cooler stellar models at nearly all stages. In particular, the blue edge connecting the tips of the blue loops is cooler by 0.06 in log T_e at a fixed luminosity. Observationally, these temperature shifts are

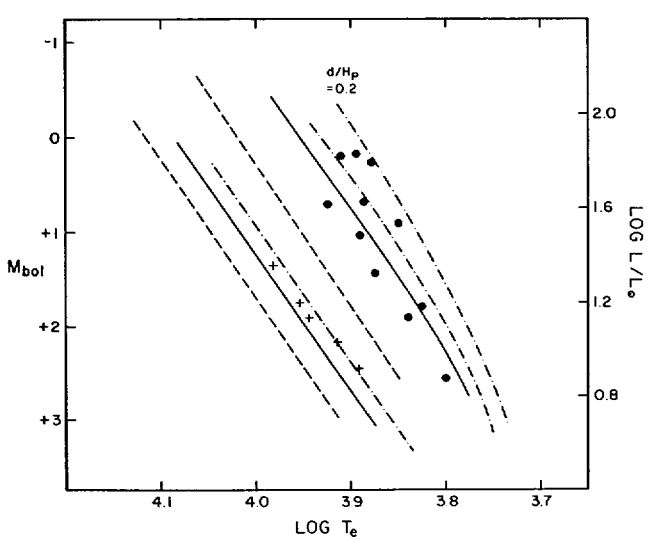

FIG. 4.—H-R diagram for observed A- and F-type stars, showing the standard ZAMS (*plus signs*) and the TAMS based on individual members of detached close binary systems (*dots*). Theoretical lines have the same meaning as in Fig. 1.

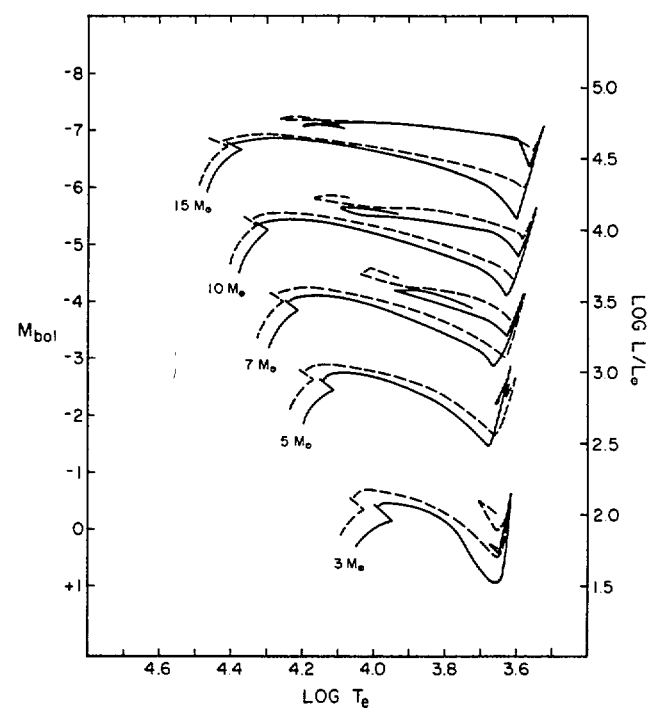

FIG. 5.—Theoretical H-R diagram showing evolutionary tracks running from the ZAMS stage to the end of core helium burning without convective core overshooting. The initial metals abundance is $Z_e = 0.03$. The opacities used are Rogers-Iglesias (*solid lines*) and Cox-Stewart (*dashed lines*).

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too small to detect with present data. On the other hand, it has been relatively easy to discern observationally that blue loops do not exist below 4 or 5 $M_\odot$. Although our theoretically predicted cutoff mass of 6 $M_\odot$ is a little high, the blue loop is known to be very sensitive to variations in the physical input parameters. A blue loop at 5 $M_\odot$, for example, has been very easily triggered by introducing a small amount of downward convective envelope overshooting. For either set of opacities, the predicted blueward extensions of the loops, when the loops are actually formed, agree excellently with the available observations (Stothers 1991).

Implications of the results based on the Rogers-Iglesias opacities for the evolutionary (mass, luminosity) relation of classical Cepheids are as follows. Using our evolutionary tracks for a star of 5 $M_\odot$ on its second crossing of the instability strip, the dependence of the luminosity on metallicity is found to be $\delta \log (L/L_\odot) \approx -12\delta Z_e$, which is identical to the relation derived with the older opacities (Stothers 1988). The shift in luminosity by switching from Cox-Stewart to Rogers-Iglesias opacities is $\delta \log (L/L_\odot) = -0.19$, -0.12, -0.07, and 0.00 for masses of 5, 7, 10, and 15 $M_\odot$, respectively. This corresponds to a change in the (mass, luminosity) relation from $L \propto M^{3.6}$ to $L \propto M^{4.0}$. Revisions as minor as this should have little effect on the theoretical pulsational properties of classical Cepheid models.

6. CONCLUSION

Stellar models constructed with conventional physical assumptions plus the new Rogers-Iglesias opacities are so successful in matching observed stars of intermediate to high mass that little room is left now for the possibility of significant convective core overshooting. Previously, the best evidence for such convective overshooting was the apparently extended main sequences of stars in the Hertzsprung-Russell diagram (§§ 3.2 and 4). That evidence has now essentially vanished. The present, greatly improved opacities, together with the assumption of a reasonable, solar-like initial metals abundance of $Z_e = 0.02$–0.03, have also resolved, in essence, all of the long-standing classical Cepheid pulsational mass discrepancies without the need for convective core overshooting to raise the stellar luminosities, as Moskalik, Buchler, & Marom (1991) have recently shown.

Assuming that the new opacities are close to the true stellar opacities, our new results confirm a recently derived upper limit for the overshoot parameter: $d/H_P < 0.2$, where d is the distance of effective convective overshooting beyond the classical convective core boundary and H_P is the local pressure scale height (Stothers 1991). To illustrate this point for the TAMS, we show in Figures 1, 2, and 4 the theoretical TAMS line for $d/H_P = 0.2$ in the case of a metals abundance of $Z_e = 0.03$. It is obvious that the derived limit $d/H_P < 0.2$ is in fact very conservative.

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