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MORE MISSING STELLAR OPACITY?

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ABSTRACT

Observational data for Population I stars have shown that blue loops on the H-R diagram form for stellar masses as low as $\sim 4\ M_\odot$. However, current state-of-the-art stellar models, unlike the older ones that were based on smaller opacities, fail to loop out of the red-giant region during core helium burning for masses less than 7 $M_\odot$. A possible explanation is that the currently used Livermore opacities need to be further increased, by at least 70%, at temperatures characteristic of the base of the outer convection zone, around 1×10^6 K. Indeed, no other suggested remedy seems to yield a blue loop at the lowest observed loop luminosities.

Subject headings: atomic processes — stars: evolution — stars: interiors

1. INTRODUCTION

Most yellow giants and supergiants are evolving along blue loops in the Hertzsprung-Russell (H-R) diagram during the phase of core helium burning. Observations of these stars in open Galactic clusters show that their luminosities range downward to log $(L/L_\odot) \approx 2.7$, corresponding to a stellar mass of $\sim 4\ M_\odot$ (Carson & Stothers 1976; Harris 1976; Mermilliod 1981; Schmidt 1984; Evans 1993). For many years, stellar evolution theory has been very successful in reproducing the observed shrinkage of the blue loop with declining luminosity, and therefore in correctly predicting, by and large, the final luminosity cutoff (e.g., Iben 1967; Paczyński 1970; Becker, Iben, & Tuggle 1977; Alcock & Paczyński 1978; Matraka, Wassermann, & Weigert 1982; Bertelli, Bressan, & Chiosi 1985; Maeder & Meynet 1988; Castellani, Chieffi, & Straniero 1990; Chin & Stothers 1991). This success has been generally regarded as a confirmation of the Los Alamos opacities that were employed to calculate the stellar models.

It therefore comes as a surprise that the very recent Livermore opacities, which contain large iron enhancements for which laboratory evidence exists (Da Silva et al. 1992; Springer et al. 1992), completely suppress the blue loops for stellar masses less than 7 $M_\odot$ (Stothers & Chin 1991, 1993; Schaller et al. 1992; Alongi et al. 1993). Paradoxically, this failure accompanies a number of important successes, among which are an improved fitting of the observed main-sequence band, an inference of a realistic interior metals abundance, a reduction of the need for convective core overshooting, and a resolution of the classical Cepheid mass discrepancies (Stothers & Chin 1991; Moskalik, Buchler, & Marom 1992).

What can be done to restore the lost blue loops? After much testing, we have found that a further enhancement of the opacities, in the vicinity of temperatures of 1×10^6 K, appears to be the only feasible solution.

2. INPUT PHYSICS

The following choices have been made for the input physics in our calculation of a new family of stellar evolutionary sequences:

Initial hydrogen abundance by mass: $X_e = 0.650$, 0.700, and 0.750.

Initial metals abundance by mass: $Z_e = 0.015$, 0.02, 0.03, and 0.04.

Iron abundance: normal, $0.07Z_e$; and high, $0.10Z_e$.

Initial stellar masses: 3, 5, and 7 $M_\odot$.

$^{12}C(\alpha, \gamma)^{16}O$ reaction rate: standard (Fowler, Caughlan, & Zimmerman 1975; Buchmann et al. 1993), two times standard (Zhao et al. 1993), and four times standard (Kettner et al. 1982; Redder et al. 1987).

Nonadiabatic convection near the stellar surface has been treated by three different theories of turbulent convection. The first theory is standard mixing-length theory (MLT) (Böhm-Vitense 1958) with the convective mixing length, ℓ, set equal to the local pressure scale height, H_P, multiplied by a constant, α_P. The constant is adjusted so as to achieve agreement between the predicted and observed effective temperatures of red giants. The second convection theory is mixing-length theory with $\ell = \alpha_z z$, where z refers to the geometrical distance below the upper boundary of the convection zone and α_z is an adjustable constant. Third among these theories is a new model incorporating the full spectrum of turbulence (FST) (Canuto & Mazzitelli 1991, 1992), in which $\ell = z$ with no free parameters. Turbulent pressure has been ignored in all of the stellar models calculated here.

Convective overshooting from the classical Schwarzschild boundary where the radiative and adiabatic temperature gradients formally become equal can be parameterized in terms of a nondimensional quantity that is simply the overshoot distance for efficient mixing of material divided by the local pressure scale height. For the convective core, this quantity is denoted d/H_P; for the outer convective envelope, penetrating downward, it is D/H_P. We set both d/H_P and D/H_P independently equal to 0, 0.2, and 0.4.

Opacities are the new Livermore opacities (Iglesias, Rogers, & Wilson 1992), supplemented by standard Cox-Stewart opacities for $T < 6 \times 10^3$ K and $T > 10^8$ K, since the Livermore opacity tables cover only the intermediate temperature range. As an alternative for $T < 6 \times 10^3$ K, we have used a formula fit to the mean values of the low-temperature opacities published by Alexander, Johnson, & Rypma (1983), Alexander, Augason, & Johnson (1989), and Sharp (1992), which include molecular sources that Cox & Stewart (1965, 1970) omitted. The formula fit has been published elsewhere (Stothers & Chin 1993). Since scattering by free electrons dominates the total opacity for $T > 10^8$ K at the densities of our stellar models, the uncertainty of the high-temperature opacities is comparatively unimportant. Arbitrary modifications to the intermediate-temperature opacities have been made for a number of the evolutionary sequences calculated here; these critical changes will be described below.

3. THEORETICAL RESULTS

The basic set of physical input parameters was taken to be $X_e = 0.700$, $Z_e = 0.02$, normal iron abundance, the large $^{12}C(\alpha, \gamma)^{16}O$ reaction rate, standard mixing-length theory, $\alpha_P = 1.8$, no convective overshooting, and molecular sources included in the opacities. Variations were then made around this standard theme, by using the parameter choices listed in § 2. In all, 16 evolutionary sequences were computed for 5 $M_\odot$, with less extensive surveys conducted at 3 and 7 $M_\odot$.

No matter how we varied the disposable parameters (Table 1), no blue loop ever appeared for 5 $M_\odot$. Nor was there any sign of incipient evolutionary instability appearing at the bottom of the red-giant branch during the late stages of core helium burning, at a time when a blue loop would potentially form.

The only possible remedy that we have come up with is to raise the opacity at a temperature around 1×10^6 K. This is the temperature of the base of the outer convection zone when it is deepest, at the top of the red-giant branch. If the local radiative temperature gradient is steepened by a significant opacity increase, convection will be driven deeper into the envelope. The hydrogen-burning shell, marching outward, will then merge with the base of the convectively mixed outer region before the end of core helium burning. A merger of this kind generally produces a blue loop (Lauterborn, Refsdal, & Roth 1971; Carson & Stothers 1976).

Accordingly, we have modified the intermediate-temperature opacities by multiplying them by a trapezoidal ramp function centered at log $T = 6.0$. This function equals unity for log $T < 5.4$; runs up linearly to a value of p at log $T = 5.8$; equals p for $5.8 < \log T < 6.2$; declines linearly to unity at log $T = 6.4$; and again equals unity for log $T > 6.4$. If $p > 1.7$, we find that a blue loop develops for 5 $M_\odot$. Such a minimal increase in opacity is not unreasonable, being comparable to or less than the average difference between the Livermore opacities and the Los Alamos opacities at the relevant temperatures and densities (Rogers & Iglesias 1992, Fig. 21). Our specific modification of the Livermore opacities is shown in Figure 1 in the typical case of $R = \rho/(10^{-6}\ T)^3 = 10^{-3}$, where the units of temperature, density, and opacity are K, g cm^{-3} and cm^2 g^{-1}, respectively.

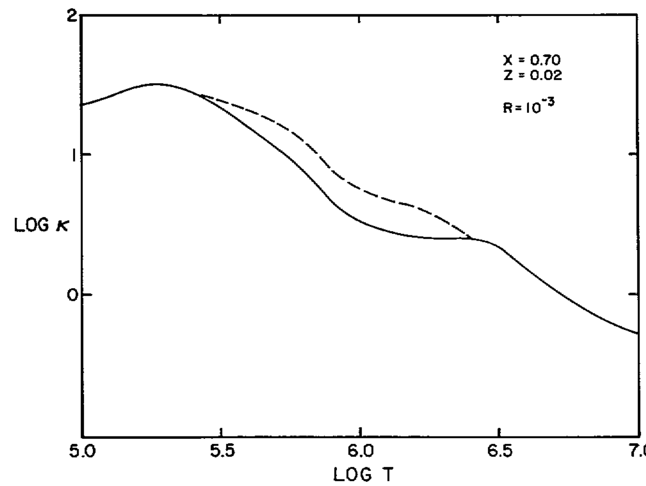

FIG. 1.—New Livermore opacities (Iglesias et al. 1992) as a function of temperature, for $X = 0.70$, $Z = 0.02$, $R = 10^{-3}$. The dashed line represents our suggested modification of the opacities between log $T = 5.4$ and log $T = 6.4$ (see text).

On the other hand, if the large opacity peak due to strong iron-line absorption around log $T = 5.3$ is artificially enhanced in the same way, no blue loop is triggered, because this temperature domain lies in the adiabatic part of the convective envelope, which is insensitive to opacity. We have also tested the effect of increasing the much smaller iron-line opacity peak around log $T = 6.3$, but this peak lies too far below the base of the convective envelope to make a significant difference.

Our selected evolutionary track for the case $p = 1.75$ is shown in Figure 2. (Tracks for p up to at least 2.5 differ negligibly from the track actually displayed.) The blue loop stretches between log $T_e = 3.67$ and log $T_e = 3.80$, and evolution along it occurs everywhere on the nuclear timescale of the core. The cause of the blue loop is the downward penetration of the outer convection zone, whose base reaches $1.1 H_P$ deeper than the greatest depth achieved in the standard sequence. The base

TABLE 1

EVOLUTIONARY SEQUENCES FOR 5 $M_\odot$ WITH UNMODIFIED LIVERMORE OPACITIES

X_e	Z_e	Iron	Molecular Opacities	Convection Theory	ℓ	D/H_P	d/H_P	Rate $^{12}C(\alpha, \gamma)^{16}O$
0.650	0.020	Normal	No	MLT	$1.4H_P$	0.0	0.0	Large
0.700	0.015	Normal	No	MLT	$1.4H_P$	0.0	0.0	Large
0.700	0.020	Normal	No	MLT	$1.4H_P$	0.0	0.0	Large
0.700	0.020	High	No	MLT	$1.4H_P$	0.0	0.0	Large
0.700	0.020	Normal	Yes	MLT	$1.8H_P$	0.0	0.0	Large
0.700	0.020	Normal	No	MLT	$1.5z$	0.0	0.0	Large
0.700	0.020	Normal	Yes	MLT	$1.7z$	0.0	0.0	Large
0.700	0.020	Normal	Yes	FST	z	0.0	0.0	Large
0.700	0.020	Normal	Yes	FST	z	0.4	0.0	Large
0.700	0.020	Normal	No	MLT	$1.4H_P$	0.2	0.0	Large
0.700	0.020	Normal	No	MLT	$1.4H_P$	0.0	0.4	Large
0.700	0.020	Normal	Yes	MLT	$1.8H_P$	0.0	0.0	Standard
0.700	0.030	Normal	No	MLT	$1.4H_P$	0.0	0.0	Large
0.700	0.030	High	No	MLT	$1.4H_P$	0.0	0.0	Large
0.700	0.040	Normal	No	MLT	$1.4H_P$	0.0	0.0	Large
0.750	0.020	Normal	No	MLT	$1.4H_P$	0.0	0.0	Large

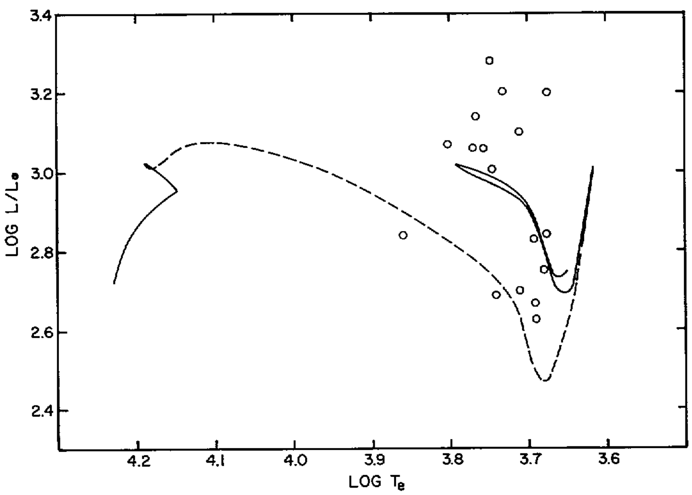

FIG. 2.—Theoretical H-R diagram showing the modified evolutionary track for a star of 5 $M_\odot$ from the zero-age main sequence to the end of core helium burning. The dashed segment represents the very rapid phase of envelope expansion after central hydrogen exhaustion. Schmidt's (1984) observations of yellow giants and supergiants in open clusters are shown as open circles.

temperature is 1.5×10^6 K, or slightly hotter than 1.1×10^6 K in the standard case.

For comparison, we have plotted Schmidt's (1984) observational data for 17 yellow giants and supergiants with $\log (L/L_\odot) < 3.3$ belonging to Galactic open clusters. Two probable nonmembers of NGC 2546 (Sowell 1987) and a probable red giant (star 21 in NGC 2287) have been omitted. Notice that the observed range of $\log T_e$ is identical to the range predicted by our models for 5 $M_\odot$, except for one relatively hot star which is probably on its first approach to the red giant region before core helium depletion begins. This interpretation is strongly supported by Evans's (1993) observational data for yellow supergiants in binary systems, none of which is hotter than $\log T_e = 3.80$.

Nine cluster members lie in the cooler half of the predicted $\log T_e$ range, and seven in the hotter half. Normalized to the same total number of stars, 10 stars and six stars, respectively, would be expected from our models. This remarkable agreement between theory and observation perhaps lends support to our proposed method of achieving the blue loop.

We should mention that the suggested opacity increase is sufficiently localized in temperature that it produces little other effect on the star's evolution. If it were very much broader in temperature, its effect would be tantamount to an increase of Z_e and would therefore not have the desired outcome. In addition, it produces no blue loop at 3 $M_\odot$, and also scarcely affects the already existing blue loop at 7 $M_\odot$, except to increase the loop lifetime somewhat, because the loop now starts at an earlier stage of core helium burning. Therefore, our proposed opacity modification accommodates the observations satisfactorily.

In the case of the Sun, the base of the solar convection zone occurs at a temperature of 2.0×10^6 K, and so would not be much affected. The pulsationally inferred masses of classical Cepheids would be expected to rise slightly (e.g., Vemury & Stothers 1978; Simon 1982), which would reduce by a small amount their inferred luminosities at a fixed mass.

4. CONCLUSION

A long record has been compiled on the subject of "missing opacity" in stellar structure (e.g., Eddington 1926; Simon 1982; Stothers 1991). This latest instance suggests that the currently best opacities may still be too small, by at least 70%, for temperatures around 1×10^6 K. The detailed shape of our suggested modification in Figure 1 is unimportant, although the increase near and just above 1×10^6 K is critical. The necessary increase seems very modest in comparison with the factor of ~ 3 increases already obtained at both lower and higher temperatures, due to the better treatment of iron (Rogers & Iglesias 1992; Iglesias et al. 1992) than was used in the older Los Alamos work. It may be that further improvements in stellar opacity calculations for the most abundant heavy ions, which still retain several electrons, could raise the total opacity sufficiently. Perhaps the relative abundances of some of these elements could also be improved. Inclusion of more lines would certainly only increase the opacity.

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Note added in proof.—Very recently Bressan et al. (Bressan, A., Fagotto, F., Bertelli, G., & Chiosi, C., A&AS, 100, 647 [1993]) have published an evolutionary track for 5 $M_\odot$ with input parameters that are almost identical to our standard set. A normal blue loop appears. The reason for the difference from our track is not known.