OBSERVATIONAL TESTS FOR OVERSHOOT AND OPACITY ENHANCEMENT BASED ON MASSIVE STARS

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SUMMARY

It is shown that a moderate increase in the opacity due to heavy elements in models of massive stars, incorporating convective overshoot and mass loss by stellar wind, can remove the well known discrepancy between theoretical expectation and observed frequencies of luminous stars in the HR diagram. These models in fact extend their main sequence band far beyond the classical limit.

1. INTRODUCTION

Meylan and Maeder (1982) comparing evolutionary models with observational data for young clusters and associations find that too many stars are observed outside the theoretical main sequence band. The HR diagram of Humphreys (1978) for luminous stars in young galactic clusters and associations shows this same characteristics. In fact the comparison of the relative number of stars in different regions of the HR diagram with the expectation from standard theoretical models reveals that too many stars fall outside the MS band. Unless severe selection effects are present in the star counts for the earliest spectral types (O and B), everything occurs as if the MS band were much wider than predicted, apparently extending up to the spectral type A0. In this paper we aim to show that an increase in the opacity due to heavy elements by a factor 2 to 4 in models with overshoot may significantly improve upon the disagreement. The proposed increase can be physically justified by heavy element opacities in the region around 10^7 K° having been plausibly underestimated by a factor of 2 to 3 (Simon, 1982). Finally it is worth recalling that Carson's (1976) opacities already possessed a similar increase even if it has not received widespread acceptance.

2. MODELS WITH ENHANCED OPACITY

Previous models of massive stars with opacity by heavy elements much higher than the standard value (Carson, 1976) are by Stothers and Chin (1977, 1978). These models however are not useful to our purpose at least for the following reasons: i) the models do not take into account convective overshoot, which on the contrary appears to be very important. ii) When mass loss by stellar wind during the MS phase is considered, too

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high rates of mass loss have been used, which are not supported by current observational information. In the light of this we thought worth recomputing models for a 20 $M_\odot$ star (assumed here as representative of the evolution in the luminosity range $-9 \leqslant M_b \leqslant -7$), in which the opacity enhancement is considered as a free parameter, and in which overshoot is treated according to the formulation of Bressan et al. (1981) with $\lambda = 1$. The opacity of Cox and Steward (1970) has been modified according to the relation

$$\kappa = \kappa_{CS} \left(1 + \chi \exp \left(- 10 \left(5.8 - \mathrm{Log}\, T \right)^4 \right) \right) \quad , \quad (1)$$

where κ_{CS} stands for the Cox-Stewart opacity and χ is an adjustable parameter. From the comparison with the opacity table of Carson the following indicative relation between the metal content Z and the parameter χ can be established, $\chi = Z / 0.005$. It turns out from this that the value $\chi = 1$ is compatible with Z = 0.005 (appropriate for SMC), whereas the value $\chi = 4$ is about right for the galaxy. Evolutionary models computed with the above opacity reveal that: a) the MS band becomes broader and broader at increasing χ, amplitute of the opacity bump, untill when a significant fraction of the core H-burning phase is found to occur in the red supergiant region. b) Indepently of the value for χ, all the models cross the area of the HR diagram comprised between $3.5 < \mathrm{Log}\, Te < 3.9$ to 4.0 on a very short time scale. Models which incorporate oversnoot, opacity bump and mass loss by stellar wind (the last one being important only during the red supergiant phase and at a rate of about 10^{-5} $M_\odot$/yr) may account not only for a substancial broadening of the MS band in the range of luminosity that we are considering, but also for the i) remarkable similarity of the HR diagrams of supergiant stars in galaxies with different metal content, such as SMC, LMC and galaxy , and ii) the observed variation in the relative percentage of WR stars across the galactic disk and from galaxy to galaxy (Maeder et al., 1981).

3. Z-INDEPENDENT MORPHOLOGY OF HR DIAGRAMS AND THE EFFECT OF Z ON WR FORMATION AND STATISTICS

The HR diagrams of supergiant stars in our own galaxy and two Magellanic Clouds show nearly identical morphologies in spite of the diverse metal content. In all the three galaxies there is a continuous distribution of stars up to Log Te = 4.0 to 3.9, a few objects in the range 4.0 to 3.9 $> \mathrm{Log}\, Te > 3.7$ and a clump of red supergiants. Evolutionary computations for a 20 $M_\odot$ star with Z = 0.005 and X = 0.765 (pertinent to the case of SMC), moderate mass loss rates during the early phases, overshoot with $\lambda = 1$ and opacity bump with $\chi = 1$ can explain this important feature. In fact: i) the core H-burning band extends also in this case up to Log Te = 4.08, therefore the observed distribution of O to A type stars in SMC is reproduced; ii) the phase of core He-burning takes place in the red region of the HR diagram. If mass loss by stellar wind occurs at a rate similar to that of galactic red supergiants (about 10^{-5} $M_\odot$/yr) these models cannot lose the whole H-rich envelope before completing core He - burning and will likely terminate their evolution as red supergiants. In this scheme the formation of single WR stars is unlikely. On the contrary, stars with normal metal content, say about 0.02, may reach the red supergiant stage while still burning H in the core, due to the high bump in the opacity as a consequence of the high metallicity. Owing to the much longer lifetime now available in the red supergiant region, the entire H-rich envelope can be lost even before central He-burning ignition. These stars go back to higher effective temperatures and appear as WR 's. In this scheme, the gradient in the number of WR with respect of red supergiant stars acroos the galactic plane should be attributed to both the gradient in progenitors and to the gradient in metallicity, which by increasing the opacity would determine longer lifetimes for the post red supergiant stages, and in consequence favour the number of WR stars with respect to supergiants at increasing Z.

4. COMPARISON OF THE MODELS WITH STAR COUNTS AND CONCLUSIONS

The Table below shows the relative number of stars in each spectral type falling in the luminosity range $-9 \leqslant M_b \leqslant -7$ and within 2.5 Kpc from the sun. To cope with the incompleteness of the Humphreys catalogue that we have used to derive the data of the Table, we have multiplied the number of stars derived from the Humphreys catalogue by a filling factor estimated from the ratio of the number of O type stars in the catalogue of Garmany et al. (1982), which is known to be complete, to the number of the same stars in the list of Humphreys. In addition to this, when performing star counts we have also included the number of WR stars falling within the same are. The first column of the Table gives the number of stars falling within the main sequence band of models with overshoot and no opacity bump. It is evident that about 30% of stars fall beyond the limit of the MS band, contrary to the expectation of less than 10%.

Table

SP	O-B1	B2-B9	A	F-G	K-M	OB*	WR	Note
N/N_t	0.71	0.12	0.02	0.01	0.07		0.05	Humphreys
t/t_{tot}	0.69	0.10	0.01	0.01	0.09	0.04	0.06	Models

The second row of the Table gives the relative lifetime spent in the various spectral types by the 20 $M_\odot$ star computed with the following prescription: $\dot{M}_b = 0$, $\dot{M}_r = 10^{-5}$, $\dot{M}_{WR} = 0.5\ 10^{-5}\ M_\odot/yr$, $\lambda = 1$ and opacity with $\chi = 4$. It is soon evident that these new models almost entirely eliminate the disagreement between theory and observation. They spent in fact 69% and 10% of their life in the spectral range O to B1 and B2 to B9 respectively as it is required by the star counts. Another interesting feature is that about 9% and 4% of the core H-burning lifetime is spent by the models while appearing as red red supergiants and O type stars with low H content at the surface (indicated as OB* in the Table). Furthermore the whole core He-burning lifetime is now available to the WR phase, thus easily accounting for the relative percentage of WR stars in the solar vicinity. More details on this problem are reported in Bertelli et al. (1983). *As a major conclusion, we argue that opacity changes of the order we have used in models with overshoot and mass loss by stellar wind can reconcile theory and observations, and explain the major properties of supergiant and WR stars at the same time.*

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DISCUSSION

Brunish: What was the hydrogen-burning lifetime and how did the increased opacity affect the lifetime? (i.e. what was t_{tot} in years in both cases)?

Bertelli: The opacity bump characterized by $\chi = 4$ produces only a small increase in the total lifetime ($\sim 5 \cdot 10^5$ y.) if compared to the case in which Cox-Stewart opacities are adopted. In the case of evolution with opacity bump the total lifetime is $1.11 \cdot 10^7$ years.

Jeffery: On increasing the CNO opacity, did you find convective instability in the envelope?

Bertelli: No.

Maeder: Did you check the consequences of your assumed opacity bumps in the solar model? In other words, are you able to get the proper solar luminosity after 4.6 billion years for the standard solar chemical composition?

Bertelli: In the case of the sun the problem does not exist. In fact the opacity bump (due to the ultimate ionization of the CNO elements) could appear only around $T \simeq 10^6$K and for low values of density, and these conditions are never met simultaneously inside low mass stars.

Roxburgh: Of course you can make the solar model with the opacity bump. There are enough free parameters in a solar model that a small change in say the ^{4}He abundance will give a model with the solar luminosity at the solar age.