OPEN CLUSTERS AS TESTS OF STELLAR EVOLUTION

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1. INTRODUCTION

The HR diagram (HRD) of clusters constitutes an especially sensitive test of physical processes in stellar interiors. Let us remember that the picture of inhomogeneous stellar evolution imposed itself by the fact that the cluster sequences turn to the right in the HRD (cf. Schwarzschild, 1958).

The HRD of clusters bears the signatures of many other facts, for example:

the shape of the sequence and star number in phases just after the end of the core hydrogen-burning phase are very sensitive to the size of the convective core;

the existence of a gap at that stage is evidence of central mixing, thus the identification of gaps in the oldest clusters may have some relevance to the solar neutrinos problem;

the blue loop for red giants closely depends on the shape of the H-profile in the stars;

for massive stars, several indications of mass loss exist (see §2).

Two examples from this non-exhaustive list are discussed below.

2. CHANGE IN THE RATIO OF NUMBERS OF RED TO BLUE SUPERGIANTS IN THE GALAXY

Very young groups studied by Humphreys (1978, 1979) in the Galaxy and LMC show important observational facts: a) the decrease in luminosity with increasing T_{eff} of the envelope in the HRD for O-type stars; b) lower luminosity (by 2^m) of the red supergiants in relation to the blue supergiants (RSG and BSG respectively); c) the strong increase in the number of RSG to BSG with distance from the galactic centre: by a factor of at least 2, between the Sagittarius-Carina and Perseus arms.

James E. Hesser (ed.), Star Clusters, 215–220.

Difficulties in studying this ratio have been emphasised by Lamb (1978, where further reference may be found).

Grids of models with mass loss from the MS to advanced nuclear burning phases are at present being made (Maeder, in preparation). The location of the upper envelope of the MS band for massive stars is very sensitive to the mass loss rate $\dot{M}_{MS}$ (cf. Chiosi *et al.*, 1978; see also figure 1). Feature a) above has thus been used for fixing coefficients in mass loss parametrisation. Feature b) results from the fact that the most massive models (e.g. 120 and 60 $M_\odot$ in figure 1) with mass loss do not reach the RSG region. Due to mass loss, the stellar core soon represents a large fraction of the total stellar mass and the star has its equilibrium position in the blue region (e.g. Weigert, 1969). On the other hand, the 15 $M_\odot$ model burns its helium as a RSG for the adopted mass loss rate. The 30 $M_\odot$ (cf. figure 1) is in an intermediate situation: according to the value of $\dot{M}_{MS}$, it spends more or less time in the red position. If N represents the star numbers in the respective stages, there is thus a relation $\dot{M}_{MS} \uparrow \rightarrow (N_{RSG}/N_{BSG}) \downarrow$. It is noted that $\dot{M}_{MS}$ results (at least in part) from the transfer of momentum in lines of the CNO ions (cf. Castor *et al.*, 1975), thus the greater the metal content Z, the greater the $\dot{M}_{MS}$, giving

$$Z \uparrow \quad \rightarrow \quad \dot{M}_{MS} \uparrow \quad \rightarrow \quad (N_{RSG}/N_{BSG}) \downarrow$$

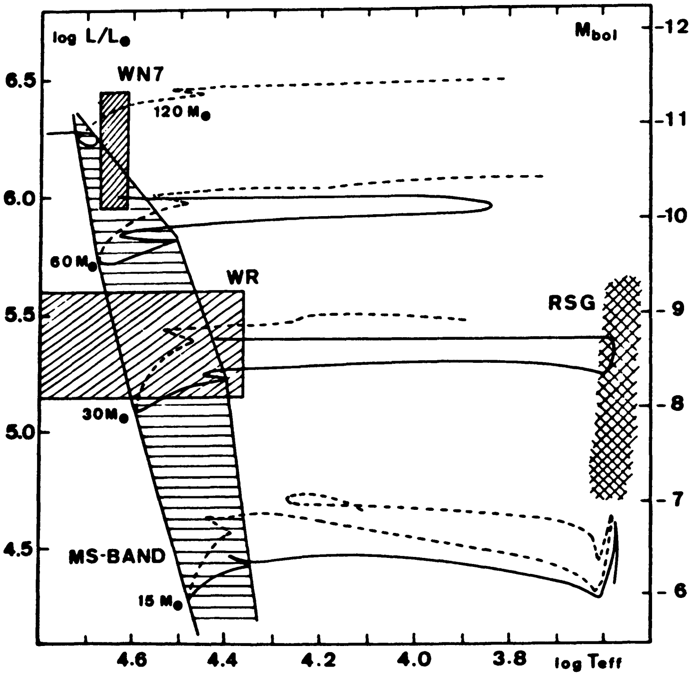

Fig. 1 Evolutionary tracks with mass loss (continuous lines) and without mass loss (broken lines). The location of WR stars comes from Conti (1976) and of red supergiants (RSG) from Humphreys (1979a). The width of the MS band with mass loss is indicated.

As the metal content increases towards the galactic centre (e.g. Peimbert, 1977), it follows that we may understand qualitatively why the ratio of red to blue supergiants is smaller in the direction of the galactic centre than towards the anticentre. Models now in progress will allow a quantitative theoretical calibration of the ratio

$$\frac{\Delta\log\ (N_{RSG}/N_{BSG})}{\Delta\log\ (\mathrm{Fe/H})}\quad \text{which empirically is about } -2.5.$$

For large $\dot{M}_{MS}$, massive stars ($M \gtrsim 30\ M_\odot$) spend most of their core He-burning phase in the blue, where they may be observed as WR stars. Thus the stronger concentration towards the galactic centre of some WR stars (mostly WC9, WC7, WN6; cf. Smith, 1968, 1973) could also be connected with the influence of the chemical composition on the rate of mass loss.

3. COMPARISON OF MODELS AND CLUSTER SEQUENCES IN THE AGE RANGE OF HYADES TO PLEIADES

A large amount of photometric material for 41 clusters in this range of ages has been collected and carefully discussed for homogeneity

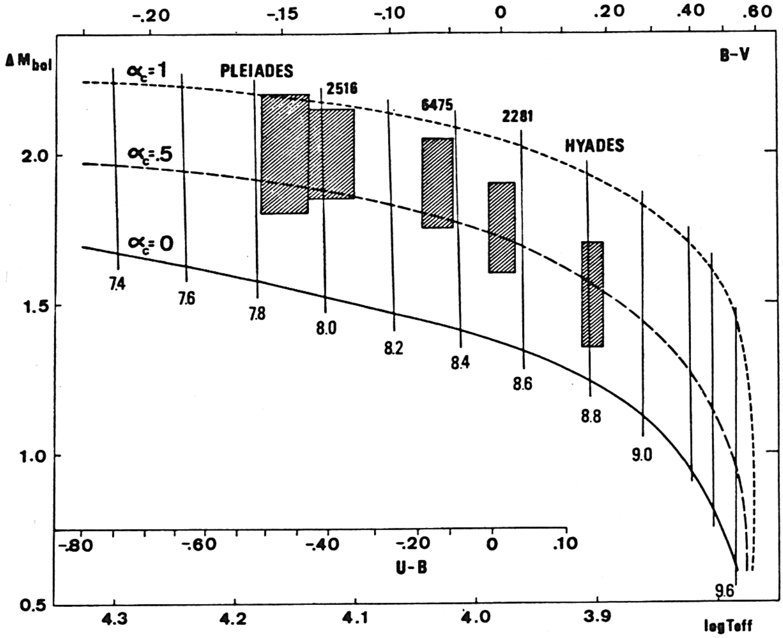

Fig. 2 Relation between the deviation ΔM_{bol} and log T_{eff} for composite clusters and for evolutionary models. ΔM_{bol} is the deviation of the end of the core hydrogen-burning phase from the zero-age main sequence. The models with α_c=0 correspond to the case calculated with Schwarzschild's criterion (see also Maeder, 1976).

of the data: distance, reddening, and when possible for membership, binarity and peculiarity (Mermilliod, in preparation). From this, composite sequences have been obtained which allow accurate comparisons of models and sequences, much less subject to uncertainties due to the sparseness of stars on the upper MS and red giant branch.

Grids of evolutionary models from 0.85 to 9 $M_\odot$ (X=0.7, Z=0.03), which incorporate the effects of non-local convection in stellar cores, have been constructed for three values of the mixing-length in the core. Detailed comparisons which take into account binaries and star numbers show that the observed MS bands of clusters extend much further (by about $0\overset{m}{.}5$) than expected from standard models, and this confirms the results found for older clusters (cf. Maeder, 1974, 1976), i.e. the presence of some mixing process, such as overshooting, in a small zone above the core (about 15% of a mixing length with $\alpha \simeq 0.5$).

It may also be noted that for much younger clusters, the effects of mass loss which, if moderate, extend the width of the MS band, are similar to those due to overshooting.

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DISCUSSION

ROSSI: I agree quite well with you, when invoking diffusion as a mechanism which should be present in star evolution. With regard to your talk, I have one thing to ask. Your conclusions are referred to evolutionary tracks with Y=0.27. Since helium changes will shift the tracks vertically, how can you take into account the uncertainty in the experimental helium abundance determination?

MAEDER: Surely one has to discuss the position of the isochrones according to the composition, and this has been done by several authors. If there are less metals, the difference will be increased; it would be necessary to go to a very small helium content, incompatible with current data, in order to explain the observed differences only by helium content.

CHIOSI: I want to report briefly on recent work that we have done on the problem of mass loss in stars in the Small Magellanic Cloud. The idea is twofold, in the sense that we want, first, to reproduce the observations of the most luminous stars in the Small Magellanic Cloud. Second, to interpret the sequence of Wolf-Rayet and the sequence of morphological features that are observed in the Wolf-Rayet stars in the Small Magellanic Cloud, Large Magellanic Cloud, and our own Galaxy. The results that we have obtained are in agreement with the idea that the effect of mass loss systematically varies from galaxy to galaxy and we are able to reproduce, at least qualitatively, the observed trend of different classes of Wolf-Rayet stars in the three galaxies.

RENZINI: It has been shown that the extension of the loops during the core helium burning phases is extremely sensitive to the details of the hydrogen profile left during the core hydrogen burning phase. Lauterborn and others showed this several years ago. Did you compute your models past the helium ignition phase to see whether you're able to produce with your hydrogen profiles the Cepheids, for instance?

MAEDER: This is a very good question, as Cepheid loops are extremely sensitive to hydrogen distribution. The trouble is that you do not know the mixing-length ratio for both the core and envelope, and that more than one parameter is involved in the description of the loop. I think that when one looks at the Cepheid band with such models we might obtain a more definite answer. A larger core will also modify the Cepheid relations and one might examine the so-called mass discrepancy problem for the Cepheids in this connection.

DEMARQUE: I might add one point which actually adds support to your view. It concerns the binary α Virginis, for which we have apsidal motion, and I should indicate that the standard models have two small a convective core to agree with observations. With somewhat larger convective cores, the apsidal motion would be in agreement. It has been a thorn in the side of stellar interiors for several years that we have tended to ignore. So your model would help.

CANNON: It seemed to me in doing a detailed comparison between the evolutionary tracks and the cluster observations you really need to make isochrones and look at the whole diagram and not just look at the track going through one part of the diagram.

MAEDER: Oh, no. The tracks are complete, but for the purpose of presentation I concentrate on the piece of interest. The Mermilliod sequences are complete and the isochrones go up to the red giant tip.