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COMPARISONS OF YOUNG CLUSTERS IN THE GALAXY, LMC, AND SMC: THE WAY TO NEW STELLAR MODELS

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RESUMEN

Se revisan brevemente los éxitos y dificultades de los modelos para estrellas de gran masa. En general, estos modelos no reproducen correctamente el crecimiento observado en la relación B/R de supergigantes azules a rojas con la metalicidad Z. Posiblemente el problema esté relacionado a la mezcla. Se muestran los primeros resultados de modelos nuevos y muy detallados para estrellas rotantes. Es interesante notar que, en vista de resultados recientemente obtenidos en las Nubes de Magallanes, se puede sugerir que las estrellas de grandes masas rotan más rápido cuando poseen metalicidades menores, un hecho que podría tener consecuencias importantes para las poblaciones estelares y la nucleosíntesis en galaxias de baja metalicidad.

ABSTRACT

Successes and difficulties of massive star models are briefly reviewed. The observed growth of the ratio B/R of blue to red supergiants with metallicity Z is in general not correctly accounted for. The problem is possibly related to mixing. The first results of new and very detailed models of rotating stars are shown. Interestingly, in view of recent results in the LMC and SMC, we may suggest that massive stars have faster rotation at lower metallicities, a fact which could have major consequences for star populations and nucleosynthesis in low-metallicity galaxies.

Key words: **STARS — STELLAR EVOLUTION — STELLAR ROTATION**

1. INTRODUCTION: SUCCESSES AND FAILURES OF EXISTING MODELS

The existing grids of stellar models, in particular those from our Geneva group (cf. Schaller et al. 1992; Meynet et al. 1994) were extensively compared with observations. These comparisons show a number of satisfactory agreements, but also some difficulties which ask for further progress in stellar models.

Among the points of agreement we may mention the excellent fit of the cluster upper main-sequence (MS) for ages $> 10^7$ yr, the correct prediction of the number of red giants and supergiants in young open clusters of the solar neighbourhood, and the proper account of the properties of WR stars. We may also point out the agreement observed for the surface chemical abundances of WN and WC stars (e.g., Smith & Maeder 1991), for the $M - L - \dot{M} - R - T_{\rm eff}$ relation in WR stars without hydrogen (cf. Schaerer & Maeder 1992), for the number ratios of WR/O stars and WN/WC stars in nearby galaxies of various metallicities Z (cf. Maeder & Meynet 1994), for the distribution of WC subtypes and their relation with luminosities, etc.

The points of disagreement mainly concern the properties of supergiants, in particular the non-occurrence of the blue Hertzsprung gap at the end of the MS, the variations of the ratio B/R of blue to red supergiants between the Milky Way, the LMC, and SMC. Also, supergiants of types B to F show He and N enhancements which are not predicted by the stellar models.

A question arises immediately: how is it possible that things are in better agreement for WR stars than for supergiants, which represent an earlier stage in evolution? The answer is that supergiants are generally in an almost neutral equilibrium between a blue and a red location in the HR diagram, and that their properties critically depend on detailed hydrodynamic processes which are shaping the internal hydrogen profiles. Furthermore, in the WR stage, the huge mass-loss has washed out all initial envelope properties which had so critically affected the supergiants.

2. THE HR DIAGRAMS OF YOUNG CLUSTERS

2.1. The Blue Hertzsprung Gap and the Ledge

The gap predicted for massive stars with $M \geq 15\ M_\odot$ at the end of the MS is not observed, but rather a continuity from MS stars to supergiants. This MS widening, which is likely to extend from the H-burning phase to the right, was noticed by Meylan & Maeder (1982; cf. also Nasi & Forieri 1990; Chiosi, Bertelli, & Bressan 1992). It is also well observable in individual cluster sequences collected by Meynet, Mermilliod, & Maeder (1993). A number of explanations were proposed to account for these facts, for example mass-loss, binarity, opacity effects, semiconvection etc. However, none of these explanations seemed really convincing. In our opinion this is a real problem, and our suggestion is that rotation, which tends to produce a large variety of tracks, might be responsible for this effect (cf. Figure 2).

A drop-off in the distribution of LMC supergiants in the HR diagram to the right of an oblique line between $\log T_{\rm eff} = 4.2$ and 3.9 was noticed by Fitzpatrick & Garmany (1990), who called this drop-off "the ledge". Due to statistical effects it is possible that this ledge is not as significant as claimed. Anyway, most stellar models predict a rapid evolution below $\log T_{\rm eff} \simeq 4.0$, and therefore, problems related to this feature do not seem particularly critical.

2.2. Blue and Red Supergiants

It is a basic fact that for young clusters of ages around 10^7 yr the ratio B/R of blue to red supergiants varies strongly from the Milky Way to the LMC and the SMC. This is nicely illustrated in Fig. 1 which shows two clusters of about the same age, one in the Milky Way and one in the SMC. We clearly notice many more RSG in NGC 330 than in NGC 4755. Table 1 from Langer & Maeder (1995) further confirms this growth of the B/R ratio with increasing metallicity Z (SN refers to solar neighbourhood). We might emphasize that the change of the B/R ratio with Z is of major importance for the study of the integrated colours of galaxies from UV to IR and that, as long as no explanation has been found, we shall have difficulties in the interpretation of the spectra of young galaxies and starbursts.

TABLE 1

THE B/R RATIO IN GALAXIES. UNLESS SPECIFIED, B MEANS O, B, AND A STARS.

Z		SMC .002	LMC .006	outer MW .013	SN .02	inner MW .03
Stars	$M_{\rm bol} < -7\overset{\rm m}{.}5^a$	4	10	14	28	48:
Associations	$M_{\rm bol} < -7\overset{\rm m}{.}5^a$	4	10	14	30	89:
Clusters	$M_{\rm V} < -2\overset{\rm m}{.}5^b$	2.5	6.7	7.7		20
Counting only B supergiants						
NGC 330		0.5...0.8				
Young clusters					3.6	

[a] Humphreys & McElroy (1984).
[b] Meylan & Maeder (1982).

All existing models have difficulties to account for the B/R ratios *at all metallicities*. In general, they are only able to reproduce the B/R ratio at one Z value only (cf. Langer & Maeder 1995). The Geneva models, for example, reproduce quite well the number of red giants and supergiants at solar Z (cf. Meynet 1993). However, the models do not show the large number of red stars observed at low Z. Neither do other sets of models done with Schwarzschild's criterion and overshooting (Bressan et al. 1993). It is interesting to note that models with semiconvection (cf. Arnett 1991; Brocato & Castellani 1993) predict a better B/R ratio at low Z with the right amount of red supergiants. These models, however, generally fail to reproduce observations at solar Z.

Langer & Maeder (1995) have shown that observations at solar Z tend to support models with extended convection, while observations at low Z support restricted convection. This undoubtedly shows that the B/R problem has something to do with the extent of the internal mixing.

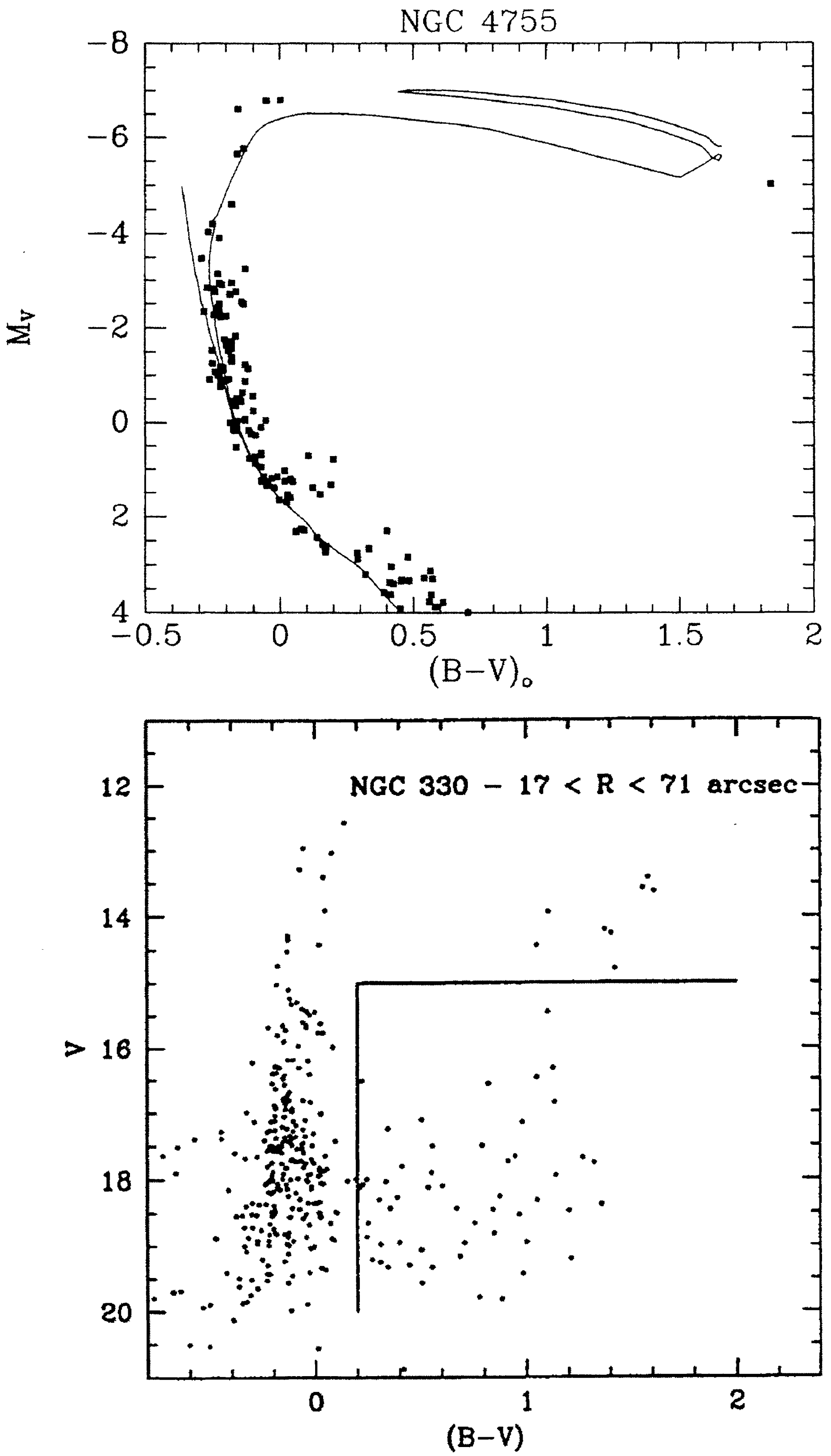

Fig. 1. Colour-magnitude diagram of NGC 4755 in the Milky Way (age $1-2\cdot10^7$ yrs) from Meynet, Mermilliod, & Maeder 1993. The same for NGC 330 in the SMC (age $1-2.5\cdot10^7$ yrs) from Chiosi, Bertelli, & Bressan 1995.

2.3. The Role of Mass-Loss

We may also think of mass-loss as being responsible for the observed problem. Indeed, for a 30 $M_\odot$ star without mass-loss we have no red supergiant phase. For growing $\dot{M}$ rates the R/B ratio increases up to a maximum, then decreases again and the star enters the WR phase earlier. From the SMC to the Galaxy the situation would well correspond to this descending part of the R/B ratio after the maximum. The problem is, however, that the necessary $\dot{M}$ rates ought to be much higher than the observed ones. Thus, although mass-loss may largely change the B/R or R/B ratio, the rates necessary to account for the observations are too high.

3. THE CASE WITH ROTATION

3.1. On Some Remarkable Observational Results on Rotation at Low Z

Massive stars generally rotate fast and thus various effects of rotation can be expected. Over recent years a dozen of compelling observational evidences suggesting some additional mixing, particularly for massive stars, have been found (cf. Maeder 1995). In this context a major question arises: is rotation in massive stars the same at all Z? It has been known for long that NGC 330 contains many Be stars (cf. Grebel, Richtler, & de Boer 1992). Additional studies by the same authors (Grebel et al. 1994; Grebel, Roberts, & Brandner, 1996) have confirmed this fact. The SMC cluster NGC 330 contains many blue giants of type Be near the cluster turnoff. Spectral studies by Mazzali et al. (1996) clearly confirm the Be phenomenon in NGC 330, related to fast rotation, the Be emission being due to a circumstellar disk resulting from fast rotation. Mazzali et al. find that about 60 to 70% of all B stars are in fact Be stars in the spectral interval O9 to B3, while the percentage of Be stars in Milky Way clusters represents only some 10 to 20%. The fast rotation observed in NGC 330 may not be due to an alignment effect, as sometimes suggested (cf. Grebel et al. 1996), because for B-type stars the fraction of Be stars is the same as for the Milky Way. Thus we may wonder whether NGC 330 is a peculiar case or whether there is a general trend for faster rotation at low Z. The fact that some clusters like NGC 1818, NGC 2004, and NGC 2100 in the LMC also show some relatively high proportions of Be stars (up to about 40%) clearly points in favour of a cosmogonic effect, possibly associated to star formation processes which are leading **to faster rotation in massive stars at lower Z.** This working hypothesis, if confirmed, would have major consequences for stellar evolution and nucleosynthesis.

3.2. New Models of Massive Stars with Rotation

New sets of models with rotation and mass loss are now under construction. The treatment of the basic physical effects is based on the results by Zahn (1992), with further developments made according to more recent works (cf. Meynet & Maeder 1997; Maeder 1997). Globally the effects of rotation accounted for are summarized in Table 2.

We notice that shear instabilities and meridional circulation produce a flattening of the μ-gradient and a mild transport of products of the CNO-burning to the surface.

The first results of models done by Meynet & Maeder (1999) show that massive star evolution is a function of mass (M), metallicity (Z), and angular velocity (Ω). The effects are larger for larger masses. This results from the fact that shear mixing which is the main effect is proportional to the thermal diffusivity $K = 4\,ac\,T^3/(3\,\kappa\rho^2\,C_{\rm P})$ which is much larger in more massive stars. Fig. 2 shows some first results for a 40 $M_\odot$ star with solar composition (cf. Meynet 1998). Models without rotation were computed with Ledoux criterion, which produces a very restricted core and an evolutionary track with very little extension. Here are some first results:

1. With increasing rotation the model star becomes overluminous with respect to its mass. Furthermore, towards the end of the MS it becomes redder, but with increasing rotation turns bluer due to surface enrichment in helium which lowers the surface opacity. Models with rotation velocities above some limiting value experience an essentially homogeneous evolution, their evolutionary tracks tending to move leftwards. These effects cause an important widening of the MS, which eventually suppresses the blue Hertzsprung gap immediately after the MS. They also broaden the mass-luminosity relation such that it is no longer possible to derive an accurate mass of a star from its location in the HR diagram.

2. Another effect is an increase of the MS lifetime. In the example of Fig. 2, for a rotational velocity equal to 30% of the critical angular velocity, the MS lifetime increases by about 35%. Let us mention that the theoretical initial break-up velocity for a 40 $M_\odot$ star is about 800 km s^{-1} and 670 km s^{-1} for a 20 $M_\odot$ star.

TABLE 2

EFFECTS OF ROTATION CONSIDERED IN THE NEW MODELS

– Shellular rotation	
– Internal hydrostatic effects	
– Surface effects:	distortion change of g and $T_{\rm eff}$ effects on $\dot{M}$
– Shear instabilities with:	thermal losses μ-gradient horizontal turbulence thermal transport by shear
– Meridional circulation with:	general equation of state μ-gradient horizontal turbulence
– Transport of the elements X_i by:	convection semiconvection shears meridional circulation
– Transport of angular momentum:	by the above effects

3. In Fig. 2 some values of the helium surface mass fraction $Y_{\rm s}$ are indicated. The initial value is $Y_{\rm s} = 0.30$. We see that when rotation is large enough, i.e., $\Omega/\Omega_{\rm c} > 20\%$, values of $Y_{\rm s} \geq 0.40$ can be reached during the MS phase. At the same time the N/C ratio increases. In the latter case the N/C ratio would be above 3 for $\Omega/\Omega_{\rm c} > 20\%$ compared to an initial value of 0.3. For a 20 $M_{\odot}$ star surface enrichments for $\Omega/\Omega_{\rm c}$ values lie above 0.3. These results are to be compared with the surface enrichments observed during the MS phase as well as in B-supergiants (cf. Gies & Lambert 1992; Lennon 1994; Venn 1996). It is to be recalled that He- and N/C-enrichments seem to be the rule among B-supergiants.

4. The formation of WR stars is favoured by rotational mixing. It is, nevertheless, possible that stars with masses above 40 $M_{\odot}$ and rotational velocities 30% above the critical value may enter the WR stage already before the end of the MS phase, due to the combination of rotation and mass loss effects.

These various examples show some major consequences of rotation in massive stars. As a cautionary measure we have to mention that our results are preliminary. Additional, thorough investigations are under way.

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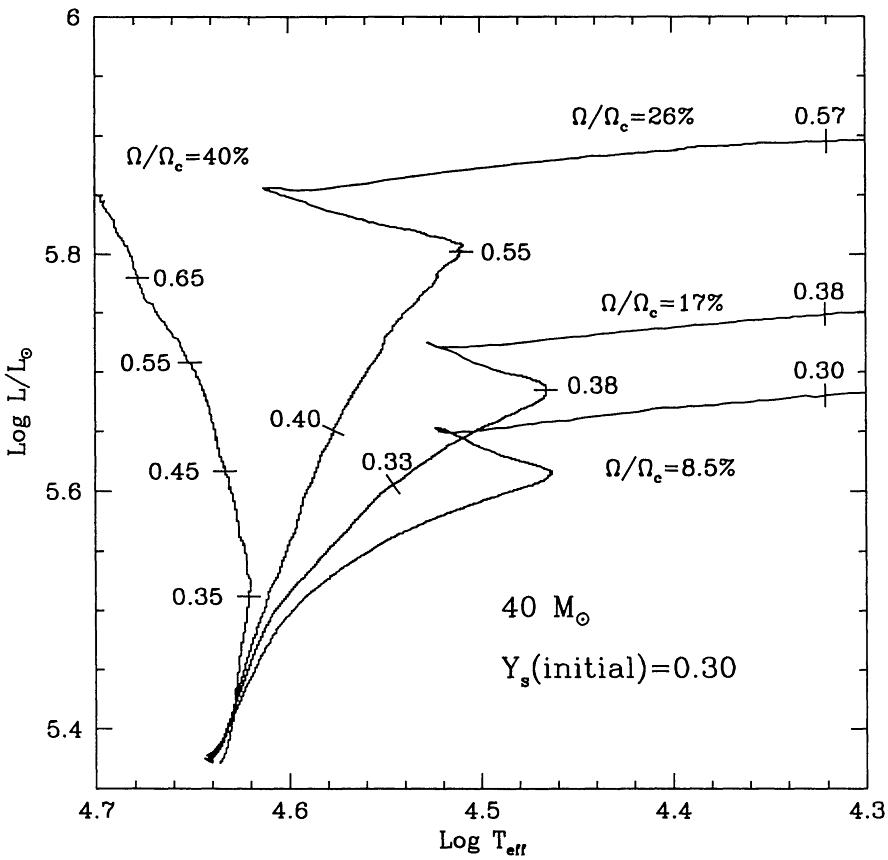

Fig. 2. Evolutionary tracks of an initial $40\,M_\odot$ star for different rotational velocities. Ω/Ω_c is the fractional value of the break-up angular velocity, the value being taken on the zero age sequence. Labels on the tracks also give the mass fraction Y_s of helium at the stellar surface. The model with zero rotation is very close to that with $\Omega/\Omega_c = 0.085$.

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