A Massive Star Odyssey, from Main Sequence to Supernova
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Testing convective mixing in massive stars

Mounib F. El Eid[1] and Philip J. Flower[2]

[1]*Department of Physics, American University of Beirut, P.O. Box 11-236, Beirut, Lebanon*
[2]*Department of Physics and Astronomy, Clemson University, Clemson, SC 29634-1911, USA*

Abstract. Stellar evolution sequences are presented for stars in the mass range 5 - 21 $M_{\odot}$ with initial metallicity $Z = 0.002$ and initial helium abundance $Y = 0.25$ resembling average composition of the Small Magellanic Cloud. The stellar models are calculated with different treatment of convective mixing in regions of varying molecular weight gradient. The stellar sequences are used to study the morphology of the well-observed star cluster NGC 330 in the SMC. We argue that convective mixing should be inhibited in inhomogeneous stellar regions in order to understand the morphology of NGC 330. In other words, our contribution emphasizes the important role of semi-convection in the evolution of massive stars.

1. Introduction

It is well known that star clusters in galaxies are very important for testing the theory of stellar structure and evolution. A particularly interesting case is NGC 330 in the Small Magellanic Cloud, because it has low metallicity and seems to contain massive red supergiants (RSG) and blue supergiants (BSG) (see next section for some more details). The primary aim of this contribution is to use the observational data of NGC 330 to demonstrate how sensitive its morophology is to basic assumptions on convective mixing in the interior of massive stars in particular. More precisely, we can argue that inhibited convective mixing in inhomogeneous stellar layers (those with variable μ-gradient) can initiate or prohibit red-blue loops during the post-main sequence evolution of massive stars in the range 12 to 20 $M_{\odot}$. The morphology of NGC 330 seems to require the existence of such loops at least for stars of masses near to 15 $M_{\odot}$. The sensitivity of such loops to convective instability has been emphasized in many recent works (Stother & Chin 1992; Chiosi *et al.* 1995; El Eid 1995; Langer & Maeder 1995). In this short contribution we can only describe some results of our calculations. Details will be given elsewhere. We hope to indicate the main issue here. In Section 2, we summarize the main observations of NGC 330. In Section 3, some stellar sequences are presented and discussed in connection with NGC 330. Section 4 summarizes some conclusions.

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2. Observations of NGC 330

NGC 330 is one of the brightest and most conspicuous clusters in the SMC galaxy. The color magnitude diagrams (CMDs) presented in many works (Lee 1990; Grebel *et al.* 1997) show similar results: (*i*) MS stars that extend up to $V=14$ ($M_V=-5$); (*ii*) RSGs with color indices ranging from +0.7 to +1.5; and (*iii*) BSGs at $V=13$ ($M_V=-6$) close to the color index of the MS stars.

A subdivision can be made showing the RSGs centered at $(B-V)=+1.30$, but there are also yellow supergiants (YSGs) centered at $(B-V)=+0.80$. If this subdivision is taken at face value, one would have a ratio of BSG/RSG or B/R = 6/11. However, the YSGs are found to be concentrated toward the center and are subject to error in their classification. Counting the YSG to the RSG, a ratio B/R = 13/11 would result in this case. One needs more precise information about this ratio. A straightforward interpretation of this CMD (Carney *et al.* 1985) is that the highest main sequence stars indicate an age of $(1-2)\times10^7$ yr and that the supergiants in NGC 330 are post-main sequence massive stars. We examine this issue in the next section.

3. Stellar models

For the aim to study the morphology of NGC 330, we have constructed evolutionary sequences for stars in the mass range $5-21\,M_\odot$ with initial metalicity $Z=0.002$ and initial helium abundance $Y=0.25$. The metallicity of NGC 330 is not well known, but it seems to lie in the range $Z=0.002$ to 0.004 (see discussion by Stothers & Chin 1992). We have chosen the lowest value in the present calculations, other Z-values will be done later. The evolution code is basically described in its updated version by The, El Eid & Meyer (2000). We have included mass loss according to the compilation by de Jager, Niewenhuijzen & van der Hucht (1988), but scaled with a factor $(Z/Z_\odot)^{0.65}$ according to the stellar wind theory (Kudritzki *et al.* 1987). We note that mass loss has no significant effect on the evolution of the low-metal stars presented here.

The crucial point in our study is the choice of the criterion for convection in inhomogeneous stellar layers. Any text on stellar structure and evolution (*e.g.*, Kippenhahn & Weigert 1990) introduces the *Schwarzschild* criterion and the *Ledoux* criterion for convective instability. The latter includes the effect of the μ- gradient which inhibits convection but not necessarily prevents it.

Figure 1a (top left) shows evolutionary sequences which are calculated beyond core helium burning and are obtained by adopting the Schwarzschild criterion everywhere in a stellar model. In this case, the red-blue loops disappear when the initial mass exceed $12\,M_\odot$. Figure 1b (top right) displays another set of evolutionary sequences in the same mass range, but this time the Ledoux criterion is adopted only in inhomogeneous layers to determine whether a layer is convective or not. With this treatment, the evolutionary tracks start to deviate from those in Figure 1a for initial masses in the range $12-20\,M_\odot$. This remarkable difference in this mass range will be below related to the structure of the hydrogen profile and its effect on the the hydrogen-burning shell.

We emphasize that by adopting the Ledoux criterion as described above we do not exclude the role of semi-convection . We just minimize its efficiency

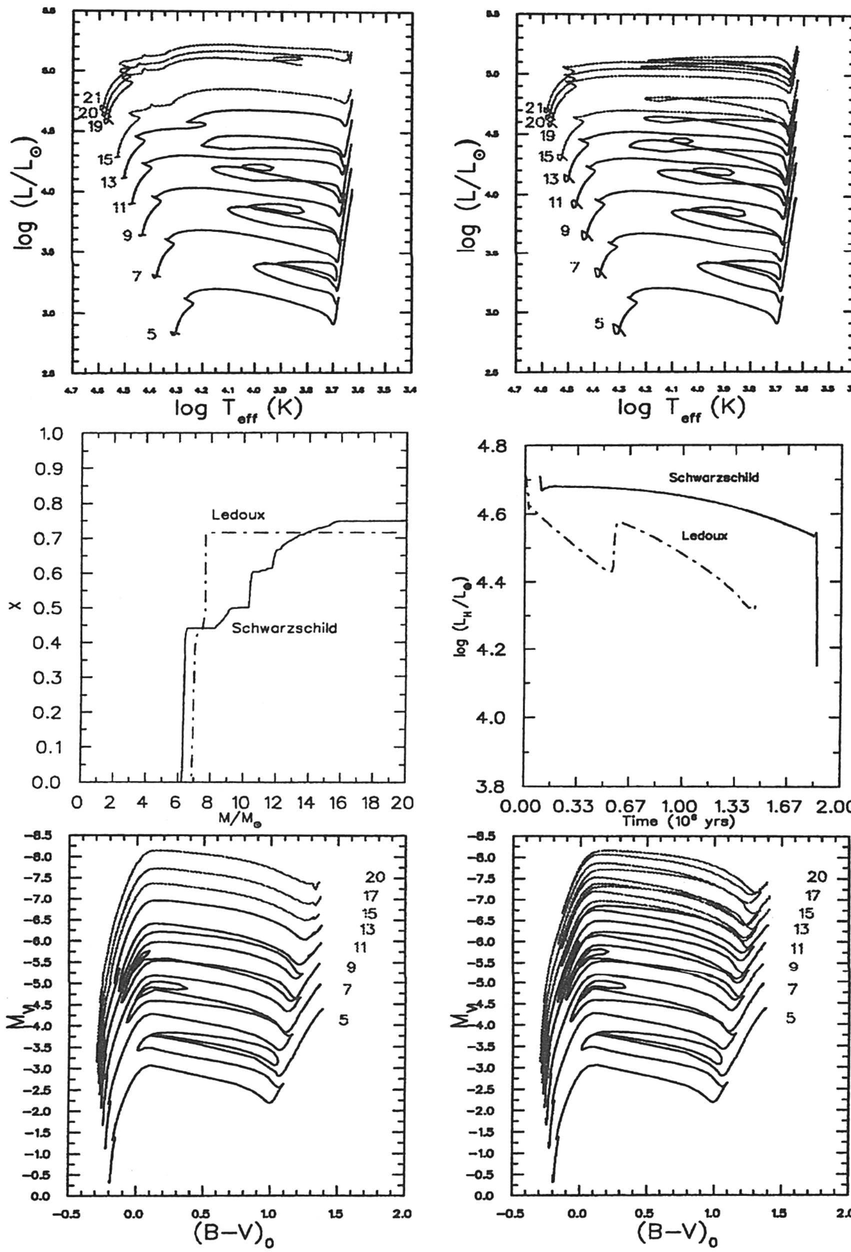

Figure 1. The figures are in the text labelled 1a, 1b, 1c, 1d and 1e, 1f from top left to bottom right. Figure 1e correspond to Figure 1a and Figure 1f corresponds to Figure 1b.

which is not known *a priori* and therefore it is usually parameterized (Langer 1991; El Eid 1995). We note that a test for semi-convective mixing would be an accurate value for the B/R ratio, because semi-convective mixing influences the timing at which the red-blue loop occurs.

We can understand the different behavior of the red-blue loops in Figure 1a and Figure 1b in terms of the hydrogen profile formed at the end of the main sequence phase. Figure 1c (middle left) shows a snapshot of the hydrogen profiles (or H-profile) as they develop near the end of core helium burning for a $20\,M_\odot$, resembling the behavior of the stars in the range specified above. The solid curve, obtained with the Schwarzschild criterion, shows a broad inner convective zone that developed immediately after the main sequence phase. This zone creates a discontinuity in the H-profile such that the H-burning shell encountering this profile delivers rather high luminosity that decreases only gradually as seen in Figure 1d by the solid curve. A stellar sequence with such H-profile evolves gradually to the red supergiant branch and cannot develop a red-blue loop. In contrast, the H-profile represented by the dashed-dotted curve obtained by using the Ledoux criterion in the way described above does not show any broad convective zone. What happened in this case is that the H-burning shell encounters a shallow H-profile created after the main sequence phase, such that its luminosity is much lower than in the previous case (see dashed-dotted curve in Figure 1d). The consequence of the weak shell source is that the stellar sequences evolve directly to the red supergiant branch. The ensuing evolution is characterized by the development of a convective envelope that penetrates deep enough to modify the H-profile in such a way that a step-like structure results (see dashed-dotted curve in Figure 1c). When the H-burning shell encounters the discontinuity it becomes stronger (as seen by the dashed-dotted curve in Figure 1d), and a red-blue loop is initiated at this time.

In summary, the structure of the H-profile which develops at the end of the main sequence evolution phase, and its modification by the treatment of convective mixing, is crucial for the occurrence of the red-blue loops during the core helium burning of massive stars of masses in excess of $12\,M_\odot$. In a detailed forthcoming work, we will show that this feature is also found at higher metallicity than used here.

We have done preliminary calculations for NGC 330 to obtain synthetic CMDs using the CMDs shown in Figure 1e and 1f, which are obtained by transforming the stellar evolution tracks according to the $T_{\rm eff}$ - $(B-V)$ scale as discussed by Flower (1996).

To construct a synthetic CMD, an age of the cluster is assigned with an age spread. The stellar masses are randomly distributed according to a Salpeter-like initial mass function (IMF). For each star in the IMF, the CMD is obtained as described above. In addition, a systematic error is introduced for each star by using a Gaussian distribution following the way described by Robertson (1974). Our results so far indicate that the evolutionary tracks with the Ledoux criterion are the only consistent with the morphology of NGC 330. Especially, we can reproduce a ratio B/R near one and obtain a reasonable age of $16 \pm 2 \times 10^6$ yr.

4. Concluding remarks

In this short contribution, we have concentrated on the main properties of the star cluster NGC 330 in the SMC to study the influence of convective mixing

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on its morphology. Our main conclusion is that mixing in inhomogeneous layers in stars in the mass range 12 - 20 $M_\odot$ seems to be less efficient than the Schwarzschild criterion for convection predicts. Semi-convective mixing is important in such layers and may not be ignored. The properties of star clusters of low metallicities represent a powerful tool for testing this issue. Of course, one should ask about the role of rotation in this context (see Maeder, these Proceedings). Are stellar sequences with rotation able to reproduce the morphology of a cluster like NGC 330? We think that semi-convection and rotation should be considered together to have a unified picture about convective mixing in massive stars.

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