EVOLUTION OF INTERMEDIATE MASS STARS

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Abstract. We summarize the evolution of intermediate-mass stars, calling attention to the uncertainties related to mixing in convectively unstable regions, and to recent developments in the theory of AGB stars with envelope burning. Finally, we briefly report on the distribution of C-stars of the Large Magellanic Cloud in the M_{bol} -log(age) plane.

1. Summary of IMS evolution

Definition. Intermediate mass stars (IMS) are those that ignite helium non degenerately, but following central He-exhaustion develop an electron degenerate C-O core, and as AGB stars experience He-shell flashes or thermal pulses (so-called TP-AGB). This places both the lower limit M_{HeF} (which is also the upper limit for low mass stars) and an upper limit M_{up} on the initial mass of such stars. In classical models $M_{HeF} = 1.8 - 2.2 M_{\odot}$ and $M_{up} = 8 - 9 M_{\odot}$ depending on the chemical composition.

Core and shell H-burning phases. In IMS the core H-burning phase is characterized by the formation of a convective core, a steady increase in luminosity and radius, and a decrease of the T_{eff}. The size of the convective core is customarily fixed by the Schwarzschild criterion $\nabla_R = \nabla_A$ (the so-called classical models). After central H-exhaustion, IMS evolve rapidly to the red giant region, burning hydrogen in a thin shell above a rapidly contracting and heating He core. As they approach the Hayashi line, a convective envelope develops whose base extends inward until it reaches layers in which H has been converted into He and C into N via the CNO cycle (changes in surface abundances, *1st dredge-up*).

Core He-Burning Phase. In IMS core He-burning ignites in non-degenerate conditions. This requires a minimum core mass of 0.33 $M_{\odot}$. Slow core He-burning of IMS takes place in two distinct regions of the HRD, a first near the Hayashi line and a second at higher T_{eff}s and luminosities, therefore extended loops in the HRD may occur, whose precise modelling depends on M, chemical composition, nuclear reaction rates, size of the convective

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core, opacity, mass loss along the RGB, inward penetration of the outer convection during the RGB stages, and other physical details. The blue band of the core He-burning models may intersect the instability strip of the Cepheid stars. The core He-burning phase of IMS (toward the lower mass end) is affected by two types of convective instability: in early stages by a semi-convective mixing (He-semi-convection) similar to that encountered by massive stars (H-semi-convection), and in late stages by the so-called breathing convection. While He-semi-convection has a negligible effect on IMS, breathing convection moderately increases t_{He} (about 20%) but gives origin to much larger C-O cores. After core He-exhaustion, the structure of the stars is composed of a C-O core, a He-burning shell, and an H-rich envelope at the base of which an H-burning shell is active. During the RGB phase, little mass is lost by stellar wind according to current mass loss rates (Reimers 1975).

AGB Phase. Following the core He-exhaustion IMS evolve through the AGB phase, which splits in two parts: early (E-AGB) and TP-AGB. In brief, the He-exhausted core contracts and heats up while the H-rich envelope expands and cools and the H-burning shell extinguishes. In the HRD the stars evolve running almost parallel to the RGB, and once again the base of the convective envelope penetrates inward. There is a limiting mass above which external convection eventually reaches layers processed by the CNO cycle. This means that fresh helium and fresh nitrogen are brought to the surface (*2nd dredge-up*). Eventually, the expansion of the envelope is halted by its own cooling and the envelope re-contracts, the luminosity decreases, and matter at the base of the convective envelope heats up. Ultimately, the H-burning shell is re-ignited, forcing the envelope convection to move outward in mass ahead of the H-burning shell. This terminates the E-AGB. In the meantime, the matter in the C-O core becomes electrons-degenerate. and nearly isothermal, while neutrino cooling carries away the liberated gravitational energy. Therefore, the temperature in the core tends to equal the temperature of the He-burning shell (about 10^8 K), well below the threshold value for C-ignition. Following the re-ignition of the H-burning shell, nuclear burning in the He-shell becomes thermally unstable. The H- and He-burning shells alternate as the major source of energy. During this phase, material processed into the intershell region can be brought into the outer convective envelope and exposed to the surface. The so-called *3rd dredge-up* can then take place. In AGB stars of large C-O core mass (hence with large initial mass) the dredge-up can occur easily. But in AGB stars of small C-O core mass (hence with small initial mass) this is possible only if extra mixing is forced into the inter-shell region. The goal is achieved either by means of semi-convection (Iben & Renzini 1982) induced by the more opaque C-rich material deposited in the intershell region by the tiny convective shell ahead of the flashing He-burning shell or by crude overshoot of convective elements from the convective shell itself. (Hollowell & Iben 1989). In both cases, C-rich material is deposited in more external layers where it can be easily engulfed by the external convection during the subsequent cycle. This is the basic mechanism to convert an M giant into a C-star. To first approximation, along the TP-AGB phase the luminosity of the star increases linearly with the mass of the H-exhausted core (Paczynski 1970) and the star brightens in M_{bol} at a constant rate (Iben & Renzini 1983). TP-AGB evolution occurs in presence of substantial mass loss terminating the AGB phase. In the classical scenario, the bulk of mass removal occurs via a fast wind (cf. Iben & Renzini 1983 and Chiosi et al. 1992 for all details). C-ignition in highly degenerate conditions requires a C-O core mass of 1.4 $M_{\odot}$ which implies, considering the effect of mass loss, a minimum initial mass of the star, M_W, in the range 4 to 6 $M\odot$. Stars lighter than the above limit will fail C-ignition and, by losing the H-rich envelope will become C-O white dwarfs.

2. Convection: the major uncertainty

Although the above evolutionary scenario substantially agrees with the observational data, a closer scrutiny reveals that there are many points of severe uncertainty, those related to convection in particular. In the classical approach, the Schwarzschild criterion provides the simplest evaluation of the size of the convectively unstable regions and the MLT simplifies the complicated pattern of motions therein by saying that full, and instantaneous mixing of material takes place. In this scheme, well known inconsistencies are known to develop at the border of the convective regions leading to the problems of the He-semi-convection and breathing convection we have already mentioned. Various attempts have been made to cure the above difficulties, among which we recall overshoot and diffusion. Generally speaking the problem is cast as follows:

(1) What determines the extension of the convectively unstable regions (either core or envelope or both) together with the extension of the surrounding regions formally stable but that in a way or another are affected by mixing? In other words how far convective elements can penetrate into formally stable regions (overshoot)?

(2) What is the thermodynamic structure of the unstable and potentially unstable regions?

(3) What is the time scale of mixing? instantaneous or over a finite (long) period of time? What is the mechanism securing either full or partial homogenization of the unstable regions?

Over the past decade different answers to above questions have been suggested and in turn different types of stellar model have been calculated. Among others we recall: (a) The extension of the convective regions is set at the layer where the velocity rather than acceleration of convective elements vanishes. The overshoot region (beyond the Schwarzschild border) is adiabatic, and mixing is instantaneous. The real extension of the overshoot region is a matter of vivid debate. Nowadays it has settled to a sizable fraction of the local pressure scale hight. For the particular case of overshoot from the H-burning convective cores in stars of low mass, the additional (reasonable) assumption is made that it must vanish at decreasing convective core. This is indeed suggested the morphology of the turnoff in the CMD of old clusters (Bertelli et al. 1992). We will refer to stellar models of this type as those with straight overshoot (Bressan et al. 1981, Bertelli et al. 1985). (b) Within the same scheme, the attempt is made to take into account that mixing actually requires a a suitable time scale to occur. To this aim straight mixing is abandoned, and the more appropriate diffusive approach is adopted (cf. Deng et al. 1996). The efficiency of diffusion (or equivalently the time scale of it) seeks to incorporate physical processes known to occur in laboratory hydrodynamics, such as intermittence and stirring, and varies as function of the local properties of the overshoot region. In this context, the thermodynamics structure of these layer plays a secondary role even if a radiative stratification ought to be preferred. Other more physically grounded but by far more complicated formulations of the problem (cf. Xiong 1986; Grossman et al. 1993) have not yet been included in stellar model calculations.

Stellar models with straight overshoot. The core H-burning phase of all stars possessing a convective core on the zero-age main sequence ($M \geq M_{con} \simeq 1.2 M_{\odot}$) is affected by convective overshoot. The models run at higher luminosities and live longer than the classical ones. They also extend the main sequence band over a wider range of T_{eff}s, this trend increasing with stellar mass (e.g. Maeder & Meynet 1991). The over-luminosity caused by overshoot during the core H-burning phase still remains during the shell H- and core He-burning phases because of the larger size of the He-exhausted core. As a consequence of it, t_{He} gets shorter in spite of the larger mass of the convective core. This, combined with the longer H-burning lifetime, t_H, makes the ratio t_{He}/t_H fairly low (from 0.12 to 0.06 when the stellar mass varies from 2 $M_{\odot}$ to 9 $M_{\odot}$). The lifetime ratio is about a factor of 2 to 3 lower than in classical models of the same mass. Models with core overshoot alone produce luminosity functions of main sequence stars that agree much better with the observational data for rich clusters (Chiosi et al. 1989), however they hardly match the extension of the blue loops observed in the same clusters because they possess less extended blue loops in the HRD (Alongi et al. 1993). However extended loops are reinstated when the effect of overshoot from the bottom of the convective envelope during the RGB phase is taken into account (Alongi et al. 1991). Convective envelopes extending deeper inside a star than predicted by the classical models are also suggested by the surface abundances of RGB stars, and the bump in the RGB luminosity function. Finally, Due to the larger masses of the He and C-O cores left over at the end of core H- and He-burning phases, respectively, the critical masses M_{up} and M_{HeF} are about 30% smaller than in classical models (Barbaro & Pigatto 1984; Bertelli et al. 1985; Bertelli et al 1986).

Stellar models with diffusion. Diffusive models of IMS have been recently calculated by Deng et al. (1996). These models share the properties of the classical semi-convective models and those with straight overshoot. In brief, the more extended convectively unstable cores yield lifetimes, lifetime ratios, and limiting masses M_{up} and M_{HeF} much alike to those of the straight overshoot models, whereas the partial diffusive mixing in the overshoot regions induces very extended loops in the the HRD. These models have not yet been applied to studies of the CMD and luminosity functions of real star clusters.

3. Why different kinds of mixing ? Observational hints

The many uncertainties in extant theories of convective overshooting and mixing reflect onto the variety of solutions and evolutionary models that have been proposed over the years, and has spurred many studies aimed at assessing the soundness of the proposed alternative by comparing parameterized models with observations. Among the various tests, three of them are particularly relevant.

Old open clusters. As first pointed out by Barbaro & Pigatto (1984), the interpretation of the CMD of old open clusters (e.g. M67, NGC 2420, NGC 3680, IC 4651) in terms of the classical models encounters some difficulties that can be solved by invoking a certain amount of convective overshoot during the main sequence core H-burning phase and hence older ages with respect to those from classical models. The main signatures are the detailed shape of the main sequence turnoff, the shape of the RGB, the clump of red stars (most likely core He-burners), and the number of stars brighter than the main sequence at the beginning of the subgiant branch with respect to the main sequence stars. Another type of evidence comes from small samples of stars for which good determinations of mass, radius, luminosity, and abundances are available (Andersen et al. 1990; Napiwotzki et al. 1991; Nordstrom et al. 1996), falling near the turnoff of some of these clusters. It seems that their position in the CMD is best accounted for by models with significant overshoot.

Young LMC clusters. The young rich clusters of the Large Magellanic Cloud (LMC) are classical templates to which the results of stellar evolution theory for intermediate-mass stars are compared. A powerful workbench is NGC 1866, which is well populated throughout the various evolutionary phases, exhibits an extended loop of giant stars, and is rich in Cepheids (Mateo et al. 1990). For the observed luminosity of the giants, there are too many stars above the predicted main sequence turnoff, whose number is a significant fraction of the number of giant stars. Furthermore, he predicted ratio of post main sequence stars to the main sequence stars is about four times the observed one. Making use of the integrated luminosity function of the main sequence stars normalized to the number of giants (NILF), which simply reflects the ratio of core He- to H-burning lifetimes, Chiosi et al. (1989) showed that models with substantial core overshoot reproduced the observed NILF, whereas classical models failed. Similar studies by Vallenari et al. (1992) on other clusters of the LMC reached the same conclusions.

Cepheids. The above arguments in favour of convective overshoot were also reinforced by the study of the Cepheid stars in the LMC cluster NGC 2157 by Chiosi et al. (1992), where it was shown that the use of overshoot models brings into agreement the evolutionary and pulsational mass of these stars. See also Wood (1997, this conference).

4. Mass loss from RGB and AGB stars

Mass loss during the RGB and AGB phases bears very much on the evolution of IMS. In RGB stars the question is whether or not the mass loss rate depends on the metallicity Studying the stars in the red clump of the old open cluster M67 with nearly solar metallicity, Tripicco et al. (1993) argue that the mass of these stars in much lower than commonly assumed and that the rate of mass loss along the RGB increases with the metallicity above the value holding for Globular Clusters and predicted by the classical Reimers (1975) relation. Their conclusion has been questioned by Carraro et al. (1996) who showed that fits of the CMD of M67 (and position of the clump stars in particular) are possible, in which the classical value of the mass for the stars in question is recovered.

In AGB stars, it is long known that the classical Reimers (1975) mass loss rate does not remove sufficient mass as suggested by the properties of PN stars. In the past, the discrepancy has been cured invoking the occurrence of superwind during the latest TP-AGB stages (cf. Iben & Renzini 1983). In recent models of TP-AGB stars (see below), the semi-empirical formalism of Vassiliadis & Wood (1993) is used to evaluate the mass-loss rate by stellar wind as a function of the pulsation period of variable AGB stars. It is derived from observational determinations of mass-loss rates for

Mira variables and pulsating OH/IR stars both in the Galaxy and LMC. The notable feature of this prescription is the onset of superwind which develops naturally on the AGB, instead of the artificial sudden transition that is needed if a Reimers-like law is used.

5. AGB & Carbon stars: recent results

The most recent studies of these topics are by Marigo et al. (1996a,b; 1997) who have investigated the TP-AGB phase of low and IMS with the aid of a semi-analytical model following the TP-AGB evolution from the first pulse till the complete ejection of the envelope by stellar wind (cf. also Renzini & Voli 1981, Groenewegen & de Jong 1993), paying particular attention to the changes in the chemical composition of the envelope due to (a) inter-shell nucleosynthesis and convective dredge-up; (b) envelope burning in the most massive AGB stars ($M \geq 3 - 4M_{\odot}$); (c) mass loss by stellar wind.

Third dredge-up. The analytical treatment of the 3rd dredge-up involves two parameters: M_c^{min}, the minimum core mass for convective dredge-up, and λ the fractionary core mass increment during the previous interpulse period dredged up to the surface. The calibration ($M_c^{min} = 0.58M_{\odot}$ and $\lambda = 0.65$) is constrained on the luminosity function of C-stars in the LMC.

Envelope burning. In agreement with previous studies (Boothroyd & Sackmann 1992 and references therein), in massive TP-AGB stars ($M \geq 3 - 4M_{\odot}$) with deep and hot-bottom convective envelopes ($T_{\rm B} \geq 60 - 100 \times 10^6 K$) the evolution of the core is not de-coupled from that of overlying layers. At high luminosities, the standard core mass - luminosity ($M_{\rm c} - L$) relation breaks down and the stars rapidly get much higher luminosities. This would anticipate the onset of the super-wind phase, thus favouring the ejection of the residual envelope.

Chemical abundances. As far as the chemical surface abundances are concerned, the rapid conversion of ^{12}C into ^{13}C and then into ^{14}N via the first reactions of the CNO cycle, can delay and even prevent the formation of C-stars. Moreover, the production of ^{7}Li possibly occurs by means of electron captures on ^{7}Be nuclei convected from the hot regions of the envelope into cooler layers ($T < 3 \times 10^6 K$) before the reaction $^{7}{\rm Be}(p,\gamma)^{8}{\rm B}$ proceeds.

AGB & C-stars in LMC. Examining the available data for AGB stars in the LMC clusters, Marigo et al. (1996b) address the question about the mass interval of low- and intermediate-mass stars which eventually evolve into C-stars during the TP-AGB phase. They combine the data compiled by Frogel et al. (1990) – near infrared photometry and spectral classification for luminous AGB stars in clusters – with the ages for individual clusters derived from independent methods (Girardi et al. 1995). The resulting distribution of C-stars in the $M_{\rm bol}$ – log(age) plane evidences that the upper and the lower limits of the mass range for the formation of C-stars cannot be derived from cluster data. The explanation of this resides in the presence of two different periods of quiescence in the cluster formation history of the LMC, shaping the age (and progenitor mass) distribution of C-stars. The most recent of these quiescence episodes could also explain the lack of very luminous AGB stars (with $-6 > M_{\rm bol} > -7$) in the clusters, contrary to what observed in the field. Finally, they compare the distribution of C-stars in the $M_{\rm bol}$ – log(age) diagram with models of AGB evolution which were previously constrained to reproduce the observed luminosity function of C-stars in the field. These models provide a good description of the relative frequency of M- versus C-stars.

References

Alongi M., Bertelli G., Bressan A., Chiosi C., 1991, A&A, 244, 95
Alongi M., Bertelli G., Bressan A., et al., 1993, A&AS, 97, 851
Andersen J., Nordstrom N., Clausen J.V., 1990, ApJ 363, L33
Barbaro G., Pigatto L., 1984, A&A, 136, 355
Bertelli G., Bressan A., Chiosi C., 1992, ApJ
Bertelli G., Bressan A., Chiosi C., 1985, A&A, 150, 33
Bertelli G., Bressan A., Chiosi C., Angerer K., A&AS, 66, 191
Bressan A., Bertelli G., Chiosi C., 1981 A&A, 102, 25
Boothroyd A.I., Sackmann I.J., 1992, ApJ 393, L21
Carraro G., Girardi L., Bressan A., Chiosi C., 1996, A&A 305, 849
Chiosi C., Bertelli G., Bressan A., ARA&A, 30, 235
Chiosi C., Bertelli G., Meylan G., Ortolani S., 1989, A&A 219, 167
Chiosi C., Wood P.R., Bertelli G., Bressan A., Mateo M., 1992, ApJ, 385, 205
Deng L., Bressan A., Chiosi C., 1986, A&A, 313, 145; 159
Frogel J.A., Mould J., Blanco V.M., 1990, ApJ, 352, 96
Girardi L., Chiosi C., Bertelli G., Bressan A., 1995, A&A, 298, 87
Groenevegen M.A.T., de Jong T., 1993, A&A, 267, 410
Grossman S.A., Narayan R., Arnett D., 1993, ApJ, 407, 284
Iben I.Jr., Renzini A., 1982, ApJ 259, L79
Iben I.Jr., Renzini A., 1983 ARA&A 21, 271
Hollowell D.E., Iben I.Jr., 1989, ApJ 340, 966
Maeder A., Meynet G., 1991. A&AS, 89, 451
Marigo P., Bressan A., Chiosi C., 1996a, A&A, 313, 545
Marigo P., Bressan A., Chiosi C., 1996b, A&A, 316, L1
Marigo P., Bressan A., Chiosi C., 1997, A&A, to be submitted
Mateo M., Olszewski E.W., Madore B., 1990, ApJ 107, 203
Napiwotzki R., Schoenberner D., Weidmann V., 1991, A&A 243, L5
Nordstrom B., Andersen J., Andersen M.I., 1996, A&AS, 118, 407
Paczynski B., 1970, Acta Astron. 20, 47; 287
Reimers D., 1975, Mem. Soc. R. Sci. Liege, 6 (8), 369
Renzini A., Voli M., 1981, A&A 94, 175
Tripicco M.J., Dorman B., Bell R.A., 1993, AJ, 106, 618
Vallenari A., Chiosi C., Bertelli G., Meylan G., Ortolani S., 1992, AJ, 104, 1100
Vassiliadis E., Wood P.R., 1993, ApJ, 413, 641
Xiong D.R., 1986, A&A 167, 239

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