Part III

Planetary Nebulae in the Scheme of Stellar Evolution

PLANETARY NEBULAE: THEIR EVOLUTION AND ROLE IN THE UNIVERSE
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Current Models for the Evolution of AGB Stars

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Abstract. While the basic properties of AGB stellar evolution are well established, comprehensive observational studies of late phases of intermediate mass stars continue to generate puzzles for current stellar models. Here, I review current techniques to model AGB stars, and I discuss important aspects of current research of AGB (and post-AGB) stellar evolution with a particular focus on how these interrelate.

1. Introduction

The final evolution of low and intermediate mass stars proceeds through the Asymptotic Giant Branch (AGB), post-AGB phase and finally the white dwarf phase. The post-AGB phase can be sub-divided according to the evolutionary state of the circumstellar matter into the central star phase of proto-planetary nebulae and planetary nebulae (PNe).

By the early eighties of the last century the dominant aspects of the evolution of low and intermediate mass giant stars had been qualitatively recognized and summarized in the seminal review by Iben & Renzini (1983). These include the first and second dredge-up (DUP), thermal pulses (TP), the relation of core mass, luminosity, metalicity etc., the luminosity variation during a pulse cycle, the main nuclear reactions and element production, hot bottom burning (HBB, called more prosaic *envelope burning* at that time), pulsational properties, mass loss (including the necessity for some kind of *superwind*), the concept of synthetic AGB models, the AGB luminosity function as well as the large potential of pre-solar meteoritic material which originates in the cool outflows of AGB stars. In addition the general picture of the transition from the AGB to the post-AGB, the formation of PNe was established and so were the concept of post-AGB TPs and the nature of the PNe abundances as reflecting the heritage of the progenitor evolution. It was speculated on the role of overshooting from the bottom of the convective envelope and the need for rotationally induced mixing. And already at that time IRC 10+216 had received much attention.

Extensive grids of full stellar evolution models (see Sect. 2.) including the above mechanism in more detail were constructed over the following decade (Lattanzio, 1986; Boothroyd & Sackmann, 1988; Vassiliadis & Wood, 1993; Blöcker, 1995, and related papers by these authors). AGB stars were recognized as the production site for the *s*-process elements, but the dominance of the radiative burning of ^{13}C during the interpulse phase was only discovered later (Straniero et al., 1995; Gallino et al., 1998). In addition a deeper understanding of the third DUP in low mass AGB stars as required by the luminosities of carbon stars in the LMC (Richer, 1981) developed only fairly recently when the dependence on numerical details (Frost & Lattanzio, 1996) and the connection to the treatment of the convective boundaries of *both the bottom of the convective envelope and the bottom of the He-flash convection zone* was recognized (Herwig et al., 1997; Mowlavi, 1999; Herwig, 2000). The more recent efforts in modeling AGB stars were discussed by several authors during the IAU Symp. 191 in Montpellier, France in 1998 (e.g. Blöcker, 1999).

It turns out that we now know much more about the details of AGB stellar evolution, in particular with respect to the nucleosynthesis in these stars (e.g. Forestini & Charbonnel, 1997; Mowlavi & Meynet, 2000; Busso et al., 1999; Marigo, 2001). Degenerate TPs were described by Frost et al. (1998), and extensive computations have explored the evolution of the most massive AGB stars in the initial mass range of 9 to 11 $M_\odot$ (Ritossa et al., 1999, and references therein). The swallowing of planets or brown dwarfs by AGB stars have been investigated by Siess & Livio (1999).

In this paper I will not repeat the basic properties of AGB stars, which are - as mentioned above - well documented in the literature. Instead, I describe in Sect. 2. the different methods currently in use for modeling the interior processes of AGB stars. In Sect. 3. I concentrate on the *various links between the different aspects of the advanced evolution* of low and intermediate mass stars and how these relations offer new diagnostic tools for investigating AGB stars.

2. Modeling AGB stars

Full stellar models In this approach the basic stellar structure equations are solved through the entire star for each time step. The change of abundances due to both mixing and nuclear processing is computed at each time step as well. Mixing is generally treated in some time dependent manner (e.g. by solving a diffusion-like equation for each chemical species), while nucleosynthesis is treated by solving the set of rate equations which describe nuclear production and destruction for each isotope. The evolution is followed consistently from the pre-main sequence through all evolutionary phases up to the TP-AGB, and sometimes continued into the white dwarf stage. Models have high spatial and time resolution. A thermal pulse cycle is resolved by of the order of 5000 models on about 2000 spatial grid points. In particular high resolution is needed in time during the DUP phase ($\Delta t \sim$ weeks) and in space at the core-envelope interface ($\Delta m \sim 10^{-6}\,M_\odot$). Recent computations of such models include those by Straniero et al. (1997), Wagenhuber & Groenewegen (1998) and Heriwg (2000).

While most models have been computed using the operator split method in which the treatment of structure, mixing and nucleosynthesis is separately and sequentially treated, there have been efforts to overcome this approximation. Pols & Tout (2002) have computed TP-AGB models with an updated version of the Eggleton code which solves the structure equations and those of composition changes simultaneously. Their results are good and bad news. The good news is that the model properties with this much more computationally demanding strategy is very similar to recent models by Mowlavi (1999) and Herwig (2000) in particular with respect to the amount of third DUP obtained in the models. The bad news is that results are still somewhat dependent on the detailed treatment of mixing at the convective boundary (see the paragraph on the third DUP in Sect. 3.).

Two other variations on the operator split theme have been played. Straniero et al. (1997) have combined the structure and the nuclear burning operator but the implications for the evolution of AGB stars are not immediately clear. More relevant for AGB and post-AGB stars is the combination of the mixing and the nucleosynthesis operator. Such a treatment is needed whenever a relevant nuclear time scale is similar or smaller than the convective turnover timescale, which applies to models of the lithium evolution in HBB stars, zero-metalicity AGB stars as well as the *very late* variant of the post-AGB TP.

Models as described in this category are now outfitted with a description of the effects of stellar rotation. The pilot study by Langer et al. (1999) showed considerable effect both on the structural and the abundance evolution. In particular strong shear mixing induced by a steep angular velocity gradient at the core-envelope interface after the onset of the third DUP is potentially instrumental for the ^{13}C neutron source of the s-process.

Synthetic models The detailed computation of full TP-AGB stellar models has been for a long time too tedious a task to compute complete sets of models for a wide range of mass, metalicity, mass loss and extra mixing prescription, with a sufficiently small spacing in all these parameters and with many isotopic species needed for detailed comparisons with observations. An alternative are synthetic models, which summarize the results of full stellar models through simple analytical relations. This procedure has been initially applied by Iben & Truran (1978) and Renzini & Voli (1981). Such models are useful for other than the AGB evolutionary stages as well (Hurley et al., 2000). Modern synthetic models with a focus on AGB stars have been presented by Groenewegen & de Jong (1993) and Marigo et al. (1996) and subsequent improvements. Most recent models feature a full envelope integration which allows for a mass and metalicity dependent parameterization of the third dredge-up and for a reliable treatment of the HBB burning in massive AGB stars (Marigo, 1998; Mariga et al., 1999). Because it is possible to cover a large parameter space, extensive tables of stellar yields have been computed (van den Hoek & Groenewegen, 1997; Marigo, 2001). These tables also include predictions on the PN composition. In principle, it should be simple to consider the effect of an oxygen enriched intershell, as studied in detail by Herwig (2000).

Post-processing and parametric nucleosynthesis models Most modern stellar evolution codes consider a sufficient number of isotopes in a nuclear network in order to follow the main nuclear processes in some detail. For AGB stellar models these include hydrogen-burning by the CNO cycle, and triple-α and ^{12}C$(\alpha,\gamma)^{16}$O for He-burning. However, AGB stars are interesting because of their large potential of interesting nucleosynthesis. Because of the time consuming nature of computing stellar structure model sequences of AGB stars, the method of post-processing can be employed in order to create detailed nucleosynthesis models of AGB stars with large networks. A post-processing code uses structure output of full stellar evolution models (see above). For a given initial composition (typically the abundance profile of the first post-processed structure

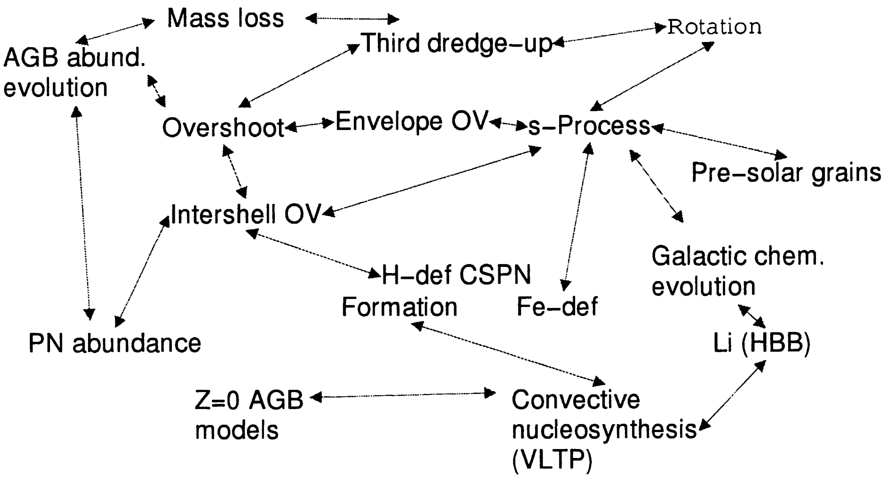

Figure 1. The mind map of advanced evolutionary phases including AGB stars shows associations between their properties and concepts. OV means overshoot.

model) the abundance changes are computed model by model according to the sequence of stellar structure models. Such a method may be confined only to a particularly interesting section of a star, like the layer including the two burning shells and the intershell in AGB stars. The post-processing method is, for example, routinely used in the combination of the Australian *MSSSP/MOSN* codes (Lattanzio et al., 1996). Gallino et al. (1998) and Goriely & Mowlavi (2000) presented post-processing models for the *s*-process in AGB stars. Here this method is useful because the decisive nucleosynthesis happens only in a tiny mass layer in the star, to which modeling can be confined. In addition small artificial changes can be introduced, which help to overcome certain incapabilities of mixing in full models. Finally, Herwig et al. (2002) used this method in a high resolution variant to study the *s*-process in rotating AGB stars. Since mixing plays an important role in the considered nuclear production site, their fully implicit code also solves for mixing processes according to the input stellar structure models.

3. Making the connection: Concepts across the final stages of evolution

Several concepts and properties of AGB and post-AGB stars and their relations are displayed in Fig. 1. In this section we will discuss the displayed aspects.

How to obtain the third DUP in TP-AGB models has been discussed intensely in recent years. Many models still do not show DUP at low core masses (e.g. Wagenhuber & Groenewegen, 1998). The models by Straniero etal. (1997) feature DUP by using no extra mixing, but they generate carbon stars too luminous to be compatible with the C-star luminosity function (CLF). It is clear now that envelope overshooting improves the models ability to reproduce efficient DUP at low core masses (Mowlavi, 1999), and also the operator split issue plays a role (see Sect. 2.). Nevertheless, also for these models the DUP is probably not compatible with the CLF (although this has not been checked quantitatively), and the same is true for the investigations of the dredge-up law by Karakas etal. (these proceedings; Lattanzio, priv. com.). DUP can however be enhanced beyond the level achieved in the above mentioned models by overshoot from the He-flash convection zone (intershell overshoot, Herwig, 2000). The set of model calculations presented by Herwig et al. (2000) contain carbon stars with the lowest luminosities obtained from full stellar models. However, a quantitative comparison with the CLF has not yet been carried out. Current models of rotating AGB stars (Lanter et al., 1999) do not show enhanced DUP efficiency. The influence of rotation on the *s*-process in AGB stars has been addressed by Herwig, Langer & Lugaro (these proceedings).

The above mentioned intershell overshoot has two side effects which appear to contradict each other. Intershell overshoot increases the temperature at the bottom of the He-flash convection zone and thereby leads to $^{96}\mathrm{Zr}/^{94}\mathrm{Zr}$-ratios incompatible with measurements of mainstream pre-solar SiC grains (Lugaro & Herwig, 2001). In addition intershell overshoot significantly increases the oxygen abundance in that layer. It can not be stressed enough that this is indeed a very desirable feature if one is concerned with the origin of H-deficient post-AGB stars of PG1159 and [WC]-type which are known for some time now to have surface oxygen mass fractions in the range $5\ldots15\%$ (e.g. Hamann, these proceedings). It has been shown by Herwig et al. (1999) that this observed O-abundance can only be reproduced by evolution models of H-deficient post-AGB stars, if the intershell has been pre-enriched with oxygen already on the AGB. So, we are faced here with an interesting *case* in which pre-solar meteoritic grains, the *s*-process, mixing, stellar structure, expanding atmosphere models and spectroscopy are all somehow involved. A systematic study of the implications of a significant oxygen abundance in the intershell remains to be done. It is clear that various aspects of AGB and post-AGB evolution are closely related. Iron-deficiency has now been established in a number of H-deficient post-AGB stars (e.g. Werner, these proceedings) and this may be another example in which the progenitor AGB evolution needs to be carefully included into the interpretation (Herwig, Lugaro, Werner, these proceedings).

H-deficient PN central stars can form as a result of a post-AGB He-flash and in some cases this flash involves convective nucleosynthesis processes where mixing and burning are closely coupled. This has to be reflected by the numerical treatment of this phase (Herwig, 2001). Such a coupled algorithm has of course applications elsewhere, e.g. for the well known Li-production in HBB AGB models (Mazzitelli et al., 1999; Ventura et al., 2000; Blöcker et al., 2000). Unfortunately, galactic chemical evolution models for lithium seem to arrive at antipodal conclusions with respect to the importance of AGB lithium production site (Travaglio et al., 2001; Romano et al., 2001). This may very likely be related to the different treatment of mass loss, in particular during the final tip-AGB evolution (Lattanzio, priv. com.).

The mass loss law for AGB stars is still not sufficiently well understood, despite intense theoretical and observational efforts. In particular dynamic wind models which consider in great detail the properties of dust have resulted in theoretical mass loss formulae ready to use in stellar models of carbon stars (Arndt et al., 1997). However, if such a mass loss formula is applied to the AGB evolution sequence of Herwig (2000) when the star has become a carbon star due to DUP the absolute mass loss rate is at that time equivalent to a Reimer's law parameter of $\eta = 0.5$, indicating that many more thermal pulses will occur before the tip of the AGB is reached. In fact, even after about 20 more thermal pulses of the now carbon rich stellar model the mass loss does not pick up very much. Synthetic models (see above) on the other hand have constrained the mass loss parameter η (together with the DUP parameter λ and the minimum core mass for the onset of DUP) by matching observations of Galactic disk and MC AGB stars. In this way van den Hoek & Groenewegen (1997) find $\eta = 4$. For a lower mass loss rate carbon stars become too luminous as the core mass increases from TP to TP over many thermal pulses. We can not expect these two values for η from these totally different approaches to be identical (e.g. because of different temperature dependency of the mass loss laws). The large difference however is indicative that the confrontation of any new mass loss law with the carbon star luminosity function of the clouds within full stellar models with dredge-up is a critical test.

The abundance evolution of AGB models depends critically on mixing processes like overshoot and rotation. The PN abundances are those of the AGB surface during the final tip AGB evolution. The usefulness of synthetic AGB models for predicting abundances has already been emphasized. It should however be noted that these models only contain those effects which have been considered in the underlying full stellar models. From H-deficient models of post-AGB stars it is now known that AGB progenitor models without intershell overshoot (i.e. without intershell oxygen enhancement) are not compatible with observations. An obvious inconsistency would be to compare the oxygen abundance in a PN with a [WC]-type central star to current synthetic AGB models.

Finally, peculiar TPs with ingestion of protons into the underlying He-intershell have been found in zero-metalicity AGB models by Cassisi et al. 1996) and were rediscovered by Chieffi et al. (2001) in zero-metalicity stars. These H-flashes were confirmed by Siess et al.(2002) and by my own computations. However, Marigo et al. (2001) do not mention these convective episodes of the H-shell. As shown by Straka & Tscharnuter (2001) numerical methods for convective nucleosynthesis may have to be applied for Z=0 stellar models, but the importance of this effects remains to be quantified.

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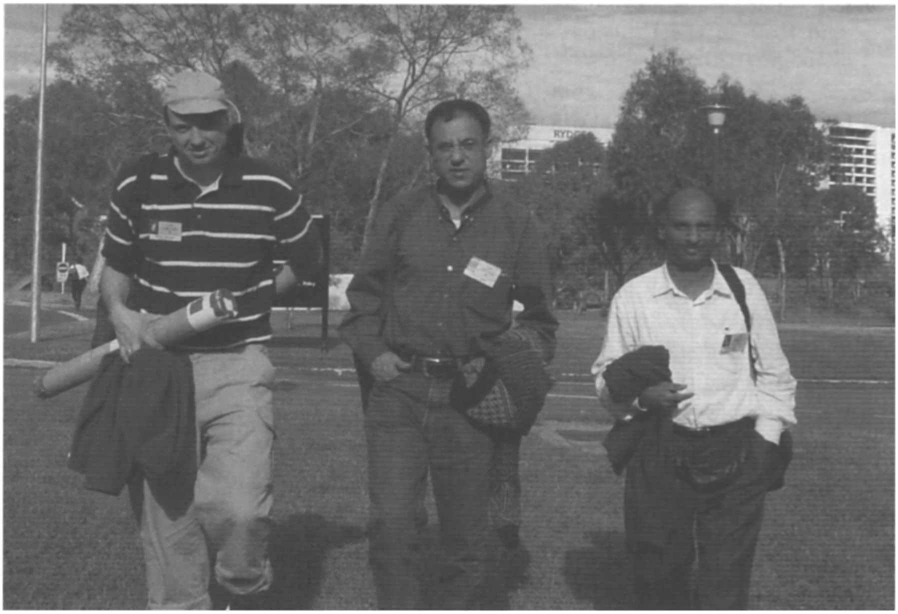

From left to right: Falk Herwig, Noam Soker, Raghvendra Sahai. Photo courtesy of O. de Marco.