Stellar structure and evolution to, on and past the AGB

Why Galaxies Care About AGB Stars:
A Continuing Challenge through Cosmic Time
Proceedings IAU Symposium No. 343, 2019
F. Kerschbaum, M. Groenewegen & H. Olofsson, eds.

doi:10.1017/S1743921318007019

AGB Stars: Remaining Problems

John Lattanzio

Monash Centre for Astrophysics
School of Physics and Astronomy, Monash University, 3800, Australia
email: john.lattanzio@monash.edu

Abstract. I present a subjective list of what I think are the most serious problems in the modelling of AGB stars. Because AGB stars represent the last phase of stellar evolution, they suffer from the accumulation of the effects of uncertainties in all the earlier phases. The complexity of AGB evolution adds further uncertainties specific to the evolutionary behaviour of those stars. Most of the problems are associated with mixing, specifically the boundaries of mixed regions. The nature of the "extra-mixing" remains a mystery, let alone how to model it reliably. Other problems are briefly mentioned and I finish with some hopes of making progress in the future.

Keywords. stars: AGB and post-AGB, stars: evolution, stars: interiors, convection, hydrodynamics

1. Introduction

It is useful to periodically review the state of knowledge of a field, with particular emphasis on the impediments to advances. Stellar modelling is no different, of course. If you ask almost anyone who works in the field of theoretical stellar physics "What are the biggest problems?" you will mostly hear "convection" or "turbulence" or "hydrodynamics". While that is largely true, it is still instructive to see how our ignorance of how to model these phenomena manifests itself in the theoretical models. These simple words actually cover a multitude of complex interactions. There are also other problems, of course, but I concentrate on mixing and related phenomena.

The AGB phase is the last nuclear phase of evolution of most stars, say those between about 1 and 8 $M_\odot$. Hence the models of AGB stars have accumulated all uncertainties from earlier evolutionary phases before we even start with AGB evolution. Uncertainty about convective overshoot on the main sequence affects AGB stars through the mass of their H-exhausted cores. Similarly for the core helium burning phase. The so-called "extra-mixing" on the red giant branch does not produce significant structural changes, but it can dramatically alter the surface composition, which is used as a diagnostic for events during the subsequent AGB evolution. Hence we start with a discussion of what I see as the main uncertainties prior to AGB evolution.

2. Previous Evolution

AGB stars began their lives with masses in the range of about 1–8 $M_\odot$. We do not discuss the super-AGB stars, which have been reviewed recently in Doherty *et al.* (2017) and Gil Pons *et al.* (2018). A note on nomenclature is appropriate, with reference to Figure 1. The Schwarzschild criterion gives us the position of neutral *buoyancy*, where the forces balance. A fluid element (if such exists in reality!) has a momentum that will carry it across this border. I shall refer to this as "overshoot", and this is shown schematically in the left panel of Figure 1. Further, at the maximum extent of this overshoot the fluid can "entrain" layers from the radiative region. In some cases, such

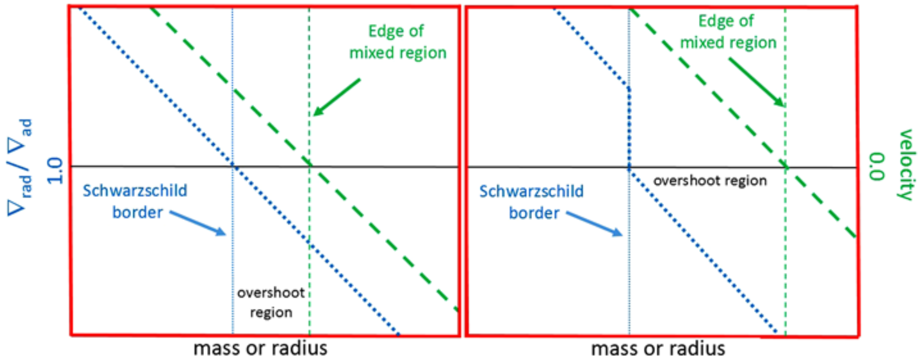

Figure 1. Schematic showing mixed regions in relation to the Schwarzschild criterion.

as core He burning and third dredge-up, there is a discontinuity in the acceleration (due to a discontinuity in composition) and although the Schwarzschild criterion does find a point of zero buoyancy, there is large positive buoyancy on the convective side, rather than a smooth decrease through zero at the border. This is shown in the right panel of Figure 1.

2.1. *Core Hydrogen Burning*

There is now much clear evidence for the existence of convective mixing beyond the Schwarzschild border for main sequence stars with convective cores. Indeed attempts have been made to quantify the required overshoot (Claret & Torres 2016, 2017). This is even more important for the higher masses. The size of the resultant H-exhausted core is critical for later evolution.

2.2. *First Dredge-Up*

The inward march of the convective envelope begins at the base of the giant branch and reaches its maximum extent essentially at the position of the bump in the luminosity function. The discrepancy between the predicted and observed position of the bump is well known now (e.g. see Angelou *et al.* 2015 and references within), and can be alleviated by the inclusion, again, of some overshoot beyond the Schwarzschild border. This affects the composition of the envelope at the end of the giant evolution.

2.3. *Extra-mixing on the Giant Branch*

For decades we have known that standard models do not match the observed abundances for stars beyond the first dredge-up, especially for lithium and carbon. Further, the models do not predict the observed variation with luminosity seen for some species, such as the carbon isotopic ratio. For a recent review see Karakas & Lattanzio (2014). This is very strong evidence for some form of "extra-mixing" connecting the convective envelope to the burning regions. This mixing is "extra" in the sense that it is not included in "standard" or "traditional" models, which only include mixing by convection.

Meridional circulation, caused by rotation, has long been suggested as a possible mechanism for the extra-mixing, but it appears that this phenomenon is not sufficient to explain the observations (Palacios *et al.* 2006). Many other mechanisms have been suggested, such as thermohaline mixing (Eggleton, Dearborn & Lattanzio 2006, 2008; Charbonnel & Zahn 2007) which has received a lot of attention in recent years. However, this mechanism is not free from criticisms, such as those arising from multi-dimensional hydrodynamical

https://doi.org/10.1017/S1743921318007019 Published online by Cambridge University Press

calculations (see Karakas & Lattanzio 2014 for details). Another of the regular suspects is magnetic fields (Busso *et al.* 2007), or a combination of meridional circulation and turbulent diffusion (Denissenkov & Tout 2000), and there have been many others. It is fair to say that none has overwhelming support and even though thermohaline mixing is perhaps the most favoured at present, the modelling of the process in 1D is still under debate, as discussed by Henkel, Karakas & Lattanzio (2017).

2.4. *Core Helium Burning*

Within the constraints of the tradition 1D formalism for convection, the discussion by Castellani, Giannone & Renzini (1971a,b) is still one of the best for explaining the problems that arise during core helium burning. The variation of opacity with temperature, density and composition contrives to produce a minimum in the ratio of the radiative to adiabatic gradients. When this minimum reaches unity then the convective core splits, and we face the problem of dealing with the outer region. This is a classic case of a region that is stable according to the Ledoux criterion but unstable according to the Schwarzschild criterion. Note that the Ledoux criterion includes the variation of composition in the stability condition. Various numerical schemes have been devised to handle this, but in all cases the details of how to handle the mixing are debated. This can produce significant changes in the size of the mixed region.

What is worse is the discovery of "core breathing pulses" where the convective core suddenly, and essentially instantaneously, grows into the semiconvective region. This results in an increase in the central helium content (e.g. see Castellani *et al.* 1985). Debate has raged over whether these are the result of a real instability or a numerical instability. While this behaviour shows many of the signs of a numerical instability, an analytic study by Sweigart & Demarque (1973) showed that there is a genuine physical basis for the instability, and indeed verified that it should only occur when the central He mass fraction reduces below about 0.12. Observations must be the ultimate arbiter, and traditionally this has been investigated by star counts to determine the relative timescales. The core-breathing pulses extend the lifetime of core helium burning because they mix extra helium into the core; they also simultaneously decrease the duration of the early AGB because the stars have removed some helium from the region beyond the core, which is usually burned during the early AGB. It seems that empirically, these pulses are minimal or not existent, as discussed in the recent work of Constantino *et al.* (2016).

The evolution during the core helium burning phase remains one of the last significantly uncertain areas in standard stellar evolution. The lifetime of this phase and, more importantly, the size of the helium exhausted core, are critically dependent on assumptions made for the calculation of mixing during core helium burning. This, in turn, affects the size of the hydrogen exhausted core because it determines how long the shell advances prior to exhaustion of the core helium supply. These are critical to later AGB evolution, with the thermal pulses beginning when the two active nuclear shells move close to each other and the thermal instability can develop. We desperately need more work in this area, such as has been performed by Constantino *et al.* (2015), Constantino *et al.* (2017), Spruit (2015).

3. AGB Evolution

So we come to AGB evolution itself. Again, the main uncertainties are associated with the convective phases, but this time we are concerned with those convective zones that develop during a pulse cycle.

https://doi.org/10.1017/S1743921318007019 Published online by Cambridge University Press

3.1. *Depth of Third Dredge-Up*

The composition discontinuity that results during third dredge-up produces a discontinuity in the ratio of the gradients, as shown in the right panel of Figure 1 (only here the situation is reversed left-right, as the convection is in the outer regions of the star). Hence we have the usual uncertainties of how to calculate the extent of the mixing. Almost every person makes different assumptions for this phase, and hence the resultant depth of dredge-up is very dependent on how the calculations are performed (e.g. Frost & Lattanzio 1996; see also Kamath, Karakas & Wood 2012). There is very little reliability in the calculations for this phase, sadly.

3.2. *The Carbon Pocket*

AGB stars are powerhouses of s-process nucleosynthesis. It is well established that this is dependent upon a partially mixed region, at the bottom of the convective envelope, which mixes small amounts of protons into the carbon-rich intershell. These are then turned into ^{13}C by the first reaction in the CN cycle, and when the region later heats enough for α-capture we get neutrons produced by $^{13}C(\alpha,n)^{16}O$. The details of the formation of this so-called carbon pocket remain a mystery. How are the protons added? Is it simply partial mixing? Is it entrainment at the bottom of the convective envelope? Are magnetic fields implicated? Could it be shear instabilities from rotation? Gravity waves? In each case the proton profile is different, and there is an industry trying to work backwards from the resultant s-processing to determine constraints on the proton profile and hence mixing. The details remain unknown.

3.3. *Extra-mixing on the AGB*

Earlier we discussed extra-mixing on the first giant branch. There are similar reasons for thinking that some form of extra-mixing may occur during the AGB phase. The evidence appears to be contradictory. For example, Busso *et al.* (2010) argue for extra-mixing based on oxygen and aluminium isotopes in pre-solar grains as well as other evidence. In contrast Karakas, Campbell & Stancliffe (2010) argue that the C/O and carbon isotope ratios do not require extra-mixing. Interestingly, if one does not include extra-mixing on the first giant branch then the predictions for compositions on the AGB are incompatible with the models. But the real stars do have some extra-mixing on the first giant branch. If this is included then the models are more in accord on the AGB. In short, the situation is still uncertain.

3.4. *Overshoot inward from the Intershell Convective Zone*

For a convective core the only overshoot possible is outward, and for a convective envelope the only possible overshoot is inward. But for the intershell convective region that develops during a thermal pulse we have the possibility of overshoot at either (or both) edges of the convective region. It has been suggested by Herwig (2000) that overshoot inwards might mix carbon and, more importantly, oxygen into the intershell convective zone. This region usually has a negligible oxygen content, and yet there are indications that observations require some oxygen to be added to the envelope of AGB stars. In particular, this might explain the observed abundances in PG-1159 stars.

While one can easily apply an algorithm to force overshoot according to your favourite prescription, the true situation is far from understood. Lattanzio *et al.* (2017) attempted to model the proposed overshoot inward into the dense CO core, and found the extent of the overshoot to be negligible. At present there is no resolution to this conflict, except to allow that the mixing may exist, but may be produced by some mechanism other than traditional convective overshoot – something like a shear instability or another hydrodynamical instability.

4. Proton Ingestion Episodes

Low mass AGB stars, in particular, suffer "proton ingestion episodes" where a convective region, typically burning helium, makes contact with a hydrogen-rich region. These are sometimes called "convective-reactive" events (Jones *et al.* 2015), because the convective timescale is similar to the nuclear reaction timescale. I will use the term PIE for "proton ingestion episodes". These can occur during both core flashes and AGB thermal pulses, especially for the lower metallicities. Clearly the assumptions used in the mixing-length theory are inappropriate for such events, and indeed it seems very unlikely that the simple Schwarzschild (or Ledoux) criterion will be reliable either. Let me also warn against doing the mixing in such regions with a diffusion approximation, as is done almost universally in evolutionary calculations.

Interest in these events has grown following the recent work of Hempel *et al.* (2016). It seems that PIEs can produce a neutron density that is intermediate between that of the s- and r-processes (Campbell, Lugaro & Karakas 2010). The resultant neutron capture nucleosynthesis appears to produce an abundance pattern that matches the so-called CEMP-s/r stars.

5. Progress

After that depressing list of problems, let me end with something much more promising. I think that true progress is around the corner, finally. This progress answers to the names of "asteroseismology" and "hydrodynamical simulations". Neither of these will provide the full answer in the short term. But both are starting to yield true insights. Progress has been slow but the pace has accelerated in the last decade and there is room for optimism. Let us hope that at the next IAU General Assembly we can report some substantial progress on the problems outlined in this paper.

Acknowledgements

I would like to thank Peta Nocon for providing important and valuable distraction, both when requested and at less opportune times.

References

Angelou, G. C., *et al.* 2015, *MNRAS*, 450, 2423
Busso, M., Wasserburg, G. J., Nollett, K. M., & Callandra, A., 2007, *ApJ*, 671, 802
Busso, M., *et al.* 2010, *ApJ* (Letters), 717, L47
Campbell, S. W., Lugaro, M., & Karakas, A. I., 2010, *A&A*, 522, 6
Castellani, V., Chieffi, C., Pulone, L., & Tornambé, A., 1985, *A&A*, 296, 204
Castellani, V., Giannone, P., & Renzini, A., 1971a, *Ap&SS*, 10, 340
Castellani, V., Giannone, P., & Renzini, A., 1971b, *Ap&SS*, 10, 355
Charbonnel, C., & Zahn, J. P., 2007, *A&A*, 467, L15
Claret, A., & Torres, G., 2016, *A&A*, 592, A15
Claret, A., & Torres, G., 2017, *ApJ*, 849, 18
Constantino, T., Campbell, S. W., Christensen-Dalsgaard, J., & Lattanzio, J. C., 2015, *MNRAS*, 452, 123
Constantino, T., Campbell, S. W., Lattanzio, J. C., & van Duijneveldt, A., 2016, *MNRAS*, 456, 3866
Constantino, T., Campbell, S. W., & Lattanzio, J. C., 2017, *MNRAS*, 472, 4900
Denissenkov, P., & Tout, C. A., 2000, *MNRAS*, 316, 395
Doherty, C. L.. Gil-Pons, P., Siess, L., & Lattanzio, J. C., 2017, *PASA*, 34, 56

Eggleton, P. P., Dearborn, D. S., & Lattanzio, J. C., 2006, *Science*, 314, 1508
Eggleton, P. P., Dearborn, D. S., & Lattanzio, J. C., 2008, *ApJ*, 677, 581
Frost, C. A., & Lattanzio, J. C., 1996, *ApJ*, 473, 383
Gil-Pons, P., Doherty, C. L., Gutiérrez, J. L., Siess, L., Campbell, S. W., Lau, H. B., & Lattanzio, J. C., 2018, *PASA*, in press, arXiv:1810.00982
Hempel, M., Stancliffe, R. J., Lugaro, M., & Meyer, B. S., 2016, *ApJ*, 831, 171
Henkel, K., Karakas, A. I., & Lattanzio, J. C., 2017, *MNRAS*, 496, 4600
Herwig, F., 2000, *A&A*, 360, 952
Karakas, A. I., Campbell, S. W. & Stancliffe, R. J., 2010, *ApJ*, 713, 374
Kamath, D, Karakas, A. I., & Wood, P. R., 2012, *ApJ*, 746, 20
Karakas, A. I., & Lattanzio, J. C., 2014, *PASA*, 31,30
Lattanzio, J. C., Tout, C. A., Neumerzhitckii, E. V., Karakas, A. I., & Lesaffre, P., 2017, *MemSAIt*, 88, 248
Palacios, A., Charbonnel, C., Talon, S., & Siess, L., 2006, *A&A*, 453, 261
Jones, S., *et al.*, 2015, *MNRAS*, 455, 3848
Spruit, H., 2017, *A&A*, 582, 2
Sweigart, A. V., & Demarque, P. 1973, in IAU Colloq. 21, Astrophysics and Space Science Library, Variable Stars in Globular Clusters and in Related Systems, Vol. 36, ed. J. D. Fernie, D. Reidel Publishing Co, Dordrecht, 221

Discussion

Question: Do you have a comment on late thermal pulse stars having C/O $<$ 1 and high Ne abundances; neither of those match observations.

Lattanzio: These are very complex stars, probably involving burning from a thermal pulse and mixing into the very thin envelope, and probably on similar timescales.

Sahai: Has there been any progress in understanding J-type Carbon stars, where the $^{13}C/^{12}C$ is quite low ($\lesssim$5), although in general C stars have much higher ratios ($\gtrsim$30)(as per your talk)?

Lattanzio: I am not aware of anything recent. The last I recall was that J-star properties were probably consistent with being evolved R stars; the latter being merged binaries.

Question: What do you mean by an i-process?

Lattanzio: Something between the r- and s-processes. These are two convenient extremes, but nature need not follow these two extremes, and it looks like there may well be something with a neutron density somewhere between the two.