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Current Mysteries of AGB Stars

Christopher A. Tout

Institute of Astronomy, The Observatories, Madingley Road, Cambridge CB3 0HA, England

Abstract. We pay tribute to the memory of Manuel Forestini by recalling his contributions to astronomy and in particular to our understanding of AGB stars. We critically examine the current status of this understanding amongst the community and deduce that major uncertainties arise in the physics of convection, any form of extra mixing beyond convection and the mass loss from the stellar surface. Coupled with these are numerical difficulties associated with the short and similar timescales for structural changes, nuclear burning and convective mixing. We hope that workshops such as this will promote familiarity amongst our diverse international community young and old and so promote effective dialogue that will ultimately lead to solutions to our problems along with the creation of new ones for the future!

Key words. convection – AGB stars – thermal pulses – numerics

1. Manuel Forestini

Just as we were beginning to organize this workshop we heard of the tragic and untimely demise of our much loved colleague Manuel Forestini (Figure 1). He would undoubtedly have contributed a great deal at this meeting and he is sadly missed.

In his all too brief career Forestini managed to make a lasting impact on our theoretical understanding of AGB stars and particularly their associated nucleosynthesis. Indeed his very first scientific paper (Forestini 1989) presented at the 106th IAU Colloquium in Indiana reported on model AGB envelopes in which he had deduced conditions were unfavourable to hot-bottom burning! His conclusion (Lattanzio, Forestini & Charbonnel 2000) had certainly changed by the time of the Third

Fig. 1. Manuel Forestini.

Send offprint requests to: Dr C. A. Tout
Correspondence to: cat@ast.cam.ac.uk

Torino Workshop that he organised for us in Grenoble (Figure 2) in 1998. In the meantime he had made important contributions in star formation (Siess & Forestini 1996) and convection theory (Mowlavi & Forestini 1994) while keeping on top of stellar nucleosynthesis (Forestini & Charbonnel 1997). It was in Grenoble, at that workshop, that this author met Manuel face to face for the first and only time. After that we communicated extensively by email and telephone discussing equations of state (Pols et al. 1995) and though there was always an open invitation to visit Grenoble again I never took it up. Life is short and we must take our opportunities while we can or regret it forever.

At the end Forestini had returned to AGB stars and was investigating those that ignite carbon in their cores, the super-AGB or SAGB stars. This work continues with his last student Gwenaëlle Leclair under the able guidance of Lionel Siess. Regrettably neither could be with us this week but we look forward to hearing from them in the future. Manuel will not be forgotten.

2. Thermally Pulsing AGB Stars

Since Schwarzschild & Härm (1965) identified the instability in thin burning shells we have qualitatively understood the evolution of TPAGB stars and how they become carbon stars and are enriched in *s*-process elements. Figure 3 shows schematically what goes on. The hydrogen- and helium-burning shells are only a few hundredths of a solar mass apart. The thin shell instability develops in the helium-burning shell where the temperature rises, relatively unconstrained by the usual thermostatic controls of stellar evolution. Intershell convection develops and rapidly redistributes the products of helium burning delaying the capture of a fourth α-particle in the $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ reaction. The intershell region is rich in carbon. Ultimately the usual thermostasis returns, the intershell zone expands and cools. Hydrogen burning is extinguished and helium burning drops back to its normal low rate.

At this point the deep convective giant envelope penetrates beyond the dormant hydrogen-burning shell and carries some of the intershell material to the surface, a third dredge-up event. The star then returns to a lengthy quiescent state dominated by hydrogen-shell burning until sufficient helium has accumulated to initiate another pulse. The envelope is gradually enriched in carbon and, when the C/O number ratio exceeds unity, the chemistry of the stellar atmosphere changes distinctively. Rather than showing oxide lines, such as TiO, the spectra become dominated by carbon-rich molecules, such as CN, because it is then all the oxygen rather than all the carbon that is trapped in carbon oxides. The star becomes a carbon star.

Any $^{22}\mathrm{Ne}$ or $^{13}\mathrm{C}$ in the intershell becomes a neutron source as helium burns by $^{22}\mathrm{Ne}(\alpha,\mathrm{n})^{25}\mathrm{Mg}$ and $^{13}\mathrm{C}(\alpha,\mathrm{n})^{16}\mathrm{O}$. Free neutrons are most easily captured by heavy nuclei because they have a larger cross-section while there is no electrostatic repulsion. A series of captures on to existing iron group elements together with β decays leads to a typical *s*-process set of isotopes which are dredged to the surface alongside the carbon at third dredge-up.

Qualitatively models have confirmed these ideas since Iben (1975). But quantitatively models are far from agreeing and it is often quite unclear why they do not.

3. Remaining Mysteries

We report here on some of the fundamental problems that are still to be fixed with AGB star models.

3.1. Numerical Difficulties

The evolution of thermally pulsing AGB stars is difficult for two reasons. First, the action is taking place in a very small region of the star and on a very short timescale. Indeed a standard relaxation evolution code can easily jump over thermal pulses if the resolution in either space or time is not fine enough. The need to move to smaller timesteps carries with it difficulties of stability (Sugimoto 1970)

Fig. 2. Manuel Forestini admires Dr Lattanzio's tie during the Third Torino Workshop held in Grenoble. This was the only occasion on which the author had the honour of meeting Forestini in the flesh.

which are overcome by various researchers in various different ways that are never clearly stated. One of the major advantages of these small workshops is the opportunity to discuss such details with the users of various independent and not so independent codes. Secondly, stellar structure changes, nuclear burning and mixing are all taking place on similarly short timescales. In particular, during third-dredge up, it is critical to keep track of the movement of the base of the convective envelope while its composition is changing due to both dredge up and hot-bottom burning, the process by which partial hydrogen burning takes place at the very hot base of the convective envelope. It is still the case that many codes solve for the structure and burning first, find the convective boundaries and then subsequently fully mix. Attempts to overcome this were first presented by Pols & Tout (2000) at the Fourth Torino Workshop in Rome. Since then we have made a great deal of progress with Richard Stancliffe (Stancliffe, Tout & Pols 2004). We find that our models have deeper and earlier dredge up than others and as such can account for the Carbon Star Luminosity function of the Large Magellanic Cloud (Stancliffe, Izzard & Tout 2004; Stancliffe et al. 2004).

3.2. The ^{13}C Pocket

By definition the *s*-process is a chain (or path) of consecutive neutron captures by heavy nuclides, starting from the iron peak elements,

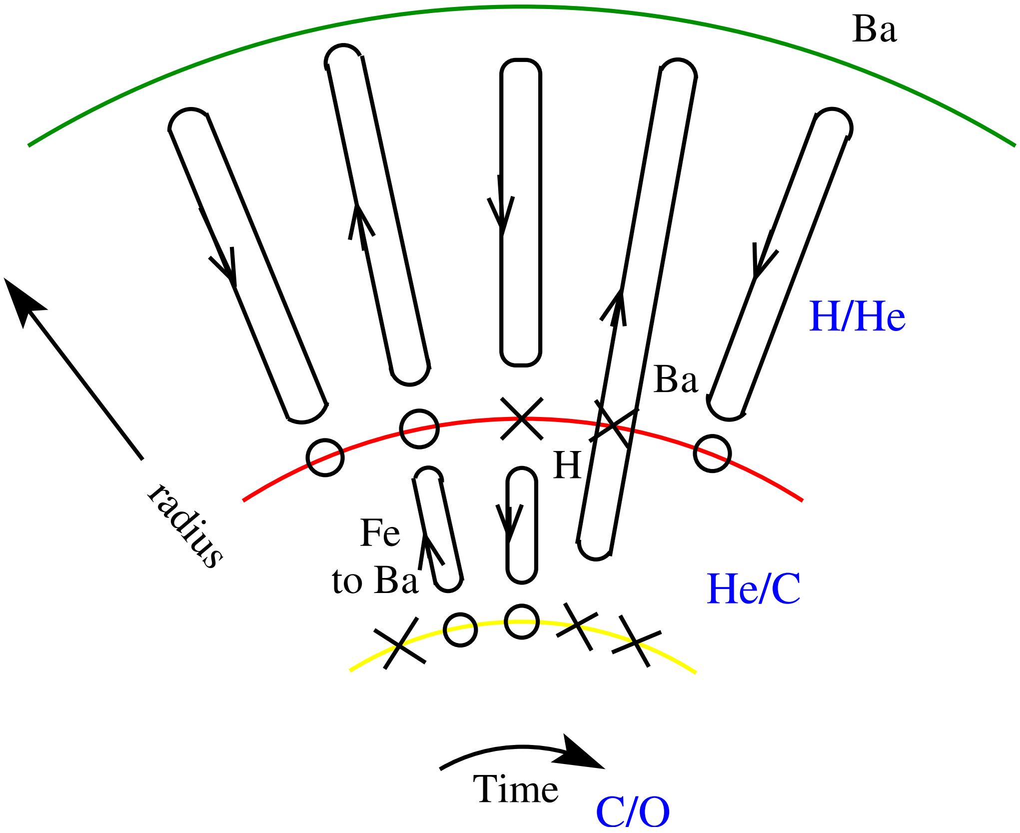

Fig. 3. Schematic diagram of a thermal pulse.

which are slow enough for any β-unstable nuclei and which have a half-lives of the order of hours within a factor of a thousand or so, met on this path to experience β-decay rather than to capture another neutron. In low-mass TPAGB stars neutrons necessary for the *s*-process are released by the reaction $^{13}C(\alpha,n)^{16}O$. In order to reach neutron number densities sufficient for the *s*-process a large initial ^{13}C abundance is required. The H-burning shell is known to reshuffle almost all the CNO-nuclei into ^{14}N and to leave behind too little ^{13}C. So another source of ^{13}C has to be found. To solve this problem it has been hypothesized that during the TDU, which lasts for about 50 yr, some *partial mixing* ingests protons from the H-rich envelope into the He- and C-rich layers beneath its base. The first physical mechanism for this mixing, semiconvection caused by an opacity increase due to the partial recombination of C, was proposed by Iben & Renzini (1982) but has since proved incapable especially at higher metallicities.

Since then three physical phenomena have been discussed as potential mechanisms for partial mixing in AGB stars, convective overshooting (Herwig et al. 1997), rotation-driven instabilities (Langer et al. 1999) and gravity waves excited at the convective boundary (Denissenkov & tout 2003). Overshooting is most probably unable to generate a thick enough ^{13}C pocket if at all and rotational mixing spreads the ^{13}C pocket over a wide mass interval which results in too weak a neutron flux. By contrast internal gravity waves, excited by turbulent motions near the base of the convective envelope, appear to be free of the shortcomings afflicting the above three mechanisms: *(i)* its operation does not seem to depend on metallicity, *(ii)* with appropriately chosen, physically reasonable parameters it can generate a ^{13}C pocket thick enough for the *s*-process to go, and *(iii)* immediately after the TDU, the region where internal gravity waves produce efficient mixing recedes outwards leaving the ^{13}C pocket in its original form for subsequent *s*-processing. However further modelling is required before we can fully understand the formation of the pocket.

3.3. Mass Loss

The end of the life of a stars is determined by the competition between nuclear burning, with the growth of its core, and mass loss, with the removal of its envelope. In stars of less than 8 $M_\odot$ it is the mass loss that dominates, at least at the very end. By its very nature dredge up slows core growth and may also enhance mass loss by changing the chemistry of the atmosphere.

Theoretically we have very little understanding of what drives AGB star winds. A deep convective envelope and rotation can lead to a strong magnetic dynamo and hence coronal heating (Tout & Pringle 1992) that may launch a wind. If this is the case then AGB stars that are spun up by a binary companion would have stronger winds. Once launched the wind may be radiatively accelerated particularly as dust grains condense.

For the present we rely on empirical calibrations based on observation. But included in these is the expectation that planetary nebulae are the products of AGB stars and so there must be a superwind at the end of their lives to eject sufficient mass fast enough to form the relatively dense envelope around the hot subdwarf. Indeed, if this is so planetary nebulae are the envelope material of the very last stages of the AGB star's life and reflect its composition after many dredge-up episodes.

However there is increasing evidence that all planetary nebula nuclei are relatively close binary stars (De Marco et al. 2004). In fact the companion to the hot subdwarf is too close for the giant to have evolved without engulfing it and this points to the fact that all planetary nebulae are actually the material expelled during a common envelope phase of evolution (Paczyński 1971). In which case they represent giants at all phases of evolution and any analysis of their composition must be very carefully considered.

3.4. Super AGB Stars

At the top end of the mass range for AGB stars are those that ignite carbon in their cores. Early work by Garcia-Berro & Iben (1994) has set the scene for some very exciting evolution indeed. However it is all too clear that they also present some very exciting numerical challenges (Eldridge & Tout 2004).

4. Conclusions

We need much more work and more meetings such as this where we can discuss the finer details of our models. We hope we have made significant progress over the week.

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References

De Marco O., Bond H. E., Harmer D., Fleming A. J., 2004, ApJ, 602, 93L

Denissenkov P. A., Tout C. A., 2003, MNRAS, 340, 722

Eldridge J. J., Tout, C.A. 2004, these proceedings

Forestini M., 1989, in Evolution of Peculiar Red Giant Stars, eds. Johnson H. R., Zuckerman B., CUP, Cambridge, 236

Forestini M., Charbonnel C., 1997, A&AS, 123, 241

Garcia-Berro E., Iben I. Jr., 1994, ApJ, 434, 306

Herwig F., Blöcker T., Schönberner D., El Eid M., 1997, A&A, 324, L81

Iben I. Jr., 1975, ApJ, 196, 525

Iben I. Jr., Renzini A., 1982, ApJ, 263, L23

Langer N., Heger A., Wellstein S., Herwig F., 1999, A&A, 346, L37

Lattanzio J., Forestini M., Charbonnel C., 2000, MemSAI, 71, 737
Mowlavi N., Forestini M., 1994, A&A, 282, 843
Paczyński B., 1971, ARA&A, 9, 183
Pols O. R., Tout C. A., 2000, MemSAI, 71, 753
Pols O. R., Tout C. A., Eggleton P. P., Han Z., 1995, MNRAS, 274, 964
Schwarzschild M., Härm R., ApJ, 1965, 142, 855
Siess L., Forestini M., 1996, A&A, 308, 472
Stancliffe R. J., Izzard, R.G., Tout C. A., 2004, MNRAS, in press (astro-ph/0410227)
Stancliffe R. J., Izzard, R.G., Tout C. A., Pols, O. R., 2004, these proceedings
Stancliffe R. J., Tout C. A., Pols O. R., 2004, MNRAS, 352, 984
Sugimoto D., 1970, ApJ, 159, 619
Tout C. A., Pringle J. E., 1992, MNRAS, 256, 269