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Trouble and Desire on the AGB ⋆

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Abstract. In this review I will try to summarise the state of our knowledge, and more importantly our lack of knowledge, about nucleosynthesis on the AGB. I will also discuss what we really want from our efforts to understand these stars.

Key words. stellar evolution – AGB stars – nucleosynthesis

1. Introduction

Stars ascending the AGB exhibit many different physical mechanisms and are both challenging and fascinating because of it. The basic evolution is now understood, largely due to the pioneering studies of Icko Iben in the 70s and 80s. This is not to say that there are no quantitative problems: there are. But the main interest these days concerns the nucleosynthesis in AGB stars. Recent studies have shown that AGB stars are far more important that was realised just a few years ago. In this review I will present a summary of the problems that most concern me, as well as what I would like to see us working towards. The view is unapologetically personal and biased. Such is life.

2. Trouble Part I: Structure and Evolution Problems

There are various uncertainties in the evolution and nucleosynthesis of AGB stars that continue to cause us problems. Although its not always easy to separate these into "evolution" and "nucleosynthesis" categories, I will try.

The usual stellar structure caveats apply to AGB stars, perhaps even more so. i.e we ignore rotation and magnetic fields, to our peril. As Peter Eggleton once said: "Nature's ability to generate magnetic fields is matched only by our desire not to acknowledge it." But again, as in most areas of stellar structure, the non-rotating non-magnetic models seem to do pretty well. Are the problems that we now face due to our neglect of these phenomena?

A curious fact is worth remembering. In globular clusters we almost always observe a CN bimodality, with some stars being CN normal and some being CN strong. But the situation on the AGB is confusing at best and perverse at worst. For example, the AGB stars in 47 Tuc and M5 are comprised of mostly CN strong stars. But for NGC6752,

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M4, M13, and M55 the AGB is comprised of mostly (and in some cases *exclusively*) CN weak stars (Campbell, private communication, but see also Smith & Norris 1993). In many cases these conclusions are based on a few AGB stars, and clearly we need to clarify the situation because it could be telling us something about the evolution from the first giant branch to the AGB.

2.1. Convection

If one knows nothing about stellar physics, one can always criticise the models by criticising the theory of convection. Its a cheap shot at an obvious target, but it is a weakness we live with. We expect that the convection theory should tell us about the energy transport in the convective zones, and we saw a presentation at this meeting that warned us of the quantitative effects of using a different theory of convection (see Ventura, this volume). But even more important, in my view, is the determination of the convective boundaries.

The problems with dredge-up are well known: convergence problems are common, and the details of how the mixing is handled in the numerical scheme can cause huge differences in the depth of dredge-up (Frost & Lattanzio 1996). The details of how one implements the Schwarzschild criterion have been the topic of many heated debates, starting at the first Torino workshop, and continuing through to this day (see, for example, Mowlavi 1999). Various authors have various ways of overcoming these problems, but we must be guided by the observations as final arbiters on how we are doing. The standard test is to compare the Carbon Star luminosity function (CSLF) in the Magellanic Clouds with the predictions (as first done by Iben 1981). As is well know, the observations require dredge-up at lower core masses than found in the models, and probably at higher efficiency than found.

This problem still nags at us. Possibly some progress has been made by Stancliffe et al. (this volume). However, we note that Stancliffe et al. (2004) are able to naturally match the CSLF in the LMC but not in the SMC. This is curious, and might indicate that any claims that the problem is solved may be a case of premature explanation.

Closely related to the dredge-up problem(s) is the exact formation mechanism for the ^{13}C pocket. We think that there is some partial mixing of H into the intershell region, at a very low abundance level. So far, four mechanisms have been suggested for this mixing:

1. *Semiconvection:* this was first proposed by Iben & Renzini (1982a,b) who found that, following a pulse, the large expansion of the star could cause cooling to the extent that C recombination occurred. This causes a dramatic increase in the opacity and hence a semiconvective zone mixed small amounts of C outward and H inward. When the star contracts during the following interpulse phase, the protons are captured by the C to form ^{13}C. It must be remembered that this mechanism was **not** found to occur in many models.
2. *Convective overshoot:* Inspired by multidimensional convection calculations, Herwig et al. (1997) included an exponential velocity distribution for matter at the edge of the formal convective zone. This produces a composition gradient at the edge of the convective region rather than a discontinuity. Hence there is a region with a small number of protons, and this will go on to form a ^{13}C pocket.
3. *Rotation:* Calculations of AGB star thermal pulses with rotation included (Herwig et al. 2003) show that shear mixing at the bottom of the convective envelope produces a ^{13}C pocket. But during the interpulse phase the rotational mixing continues so that the ^{13}C pocket and the ^{14}N pocket are mixed together, with protons released by the former being mostly captured by the latter.. The result is that there are almost no neutrons remaining to be captured by the Fe seeds, and hence there is almost no *s*-process (Herwig et al. 2003; Siess et al. 2004). Clearly this is not the case in reality. Perhaps the operation of magnetic fields will brake the rotation soon after dredge-up ceases?

4. *Gravity waves:* Denissenkov & Tout (2003) have proposed that gravity waves could produce the required ^{13}C pocket. Motion in the convective envelope can cause some turbulent mixing which gives approximately the ^{13}C pocket that seems to be required.

All the above mechanisms are open to criticism, all have parameters, and yet all seem to give approximately the correct results. We know that there is a spread in the *s*-process efficiency at a given metallicity: this is required by observations, as shown by Busso et al. (2001). So the mechanism is likely to be stochastic whatever the mechanism turns out to be.

2.2. Rotation

We are just beginning to get some rotating stellar models, as discussed above. It is early days yet and much more remains to be learned. The emphasis so far has been on the dredge-up and ^{13}C-pocket problems, and there are not yet enough models to see how rotation affects other details of the evolution (or nucleosynthesis). At the present, rotation has not helped because it seems to hinder the *s*-process! Work remains to be done here, obviously.

2.3. Magnetic Fields

Someone once said that "magnetic fields are to astrophysics as sex is to psychology." Perhaps this is true. In any event, magnetic fields have been suggested by Lugaro (private communication) as a possible way to modify the effect of rotation, discussed above. It is perhaps a bit early to be discussing magnetic fields, however.

2.4. Mass-Loss

Now we move to a much more serious problem. There is still no formula for mass-loss that is derived from first principles. Rather, we use formulations that are somehow empirical determinations in terms of fundamental stellar parameters, such as mass, radius, luminosity and perhaps pulsation period. The formula used is crucial to the AGB evolution because it is mass-loss that terminates the evolution, by removing the H-rich envelope. This also affects the nucleosynthesis, or more correctly the total yield from a star. The surface composition is a function of time, through dredge-up and perhaps hot bottom burning. The stellar yield then depends on when the mass is removed, so that the mass-loss has a dramatic impact on the final yields. Recent progress on this problem has been discussed by Busso at this meeting.

3. Trouble Part II: Nucleosynthesis Problems

The stellar structure is in some sense the background upon which much of the nucleosynthesis occurs. The two are related, but here we discuss only those nuclear reactions which have a negligible effect on the *structure* of the star.

3.1. Fluorine

A quantitative understanding of fluorine should be within our grasp. The mechanisms for its formation (and destruction!) in AGB stars are known and it remains to simply perform sufficient calculations to determine the yield as a function of mass and composition. This can then be used as input for chemical evolution models, as done by Renda et al. (2004), which showed that AGB stars are crucial to obtaining the Galactic inventory of this element. The size of the ^{13}C pocket is an uncertainty in this work, as are various reaction rates (Lugaro et al. 2005), but in principle we can be doing reasonably good quantitative work on this problem (dredge-up always remains an uncertainty, unfortunately).

3.2. s-process

Again, it is the ^{13}C pocket that is the biggest uncertainty in the *s*-process predictions. It is common to use a small spread in the size of the pocket and this seems reasonable. It might be worth including the *s*-process calculations within the stellar structure calculations, as done by Straniero et al. (see this volume) so that we are not making assumptions about the similarity from pulse to pulse, as is usually done in post-processing codes.

3.3. Reaction Rates

One of the most gratifying areas of recent years has been the now close collaboration between the nuclear physicists determining reaction rates and the astrophysicists using them! This synergy and cross-disciplinary approach helps both fields, and reduces the uncertainties for all workers.

3.4. There is more than just Carbon

It is perhaps due to the fact that C stars are very easily distinguished from O-rich stars that we have so much data concerning the luminosity function of C stars. However, the AGB models are now much better and we should be looking at the distribution of many other elements such as Li, N, O, F, Na, Mg etc among the AGB stars.

4. Desire

A wise man once said “There is only trouble and desire.” We have dealt with the trouble, but what do we desire? This is a serious question. I mean, at what stage would we say that we have enough understanding of AGB stars? What are we working toward?

My feeling is that the ultimate goal is to fully understand all stellar populations. From the structure and evolution point of view, this means being able to determine all of the observable characteristics of a star, from its birth to death, for stars of any mass and composition. A tall order. And recall that this must include single as well as binary stars.

We have spent the 20th century on single stars, with some forays into binarity[1] and we have various codes for the simulation of stellar populations (especially at Cambridge!). I believe that this is the future goal.

Some work toward this goal has recently been completed by Izzard (see this volume) and I think we have reason for optimism. The advent of massively parallel fast computers means that it is possible to consider calculations of stellar populations (including evolution, nucleosynthesis and dynamics) which were not possible just a few years back. Things will only improve. The future is, I believe, quite bright.

4.1. The Missing Stars

There are a couple of areas where we need better models. These are the so-called “Super-AGB stars”, discussed in this volume by Eldridge, and the post-AGB stars, Some work was done on Super-AGB stars by Ritossa et al. (1996a,b, 1997a,b, 1999) but these stars have been largely ignored. Leclaire and Siess (private communication) and Doherty (private communication) are also working in this area now, and we can expect to soon have some quantitative models.

Post-AGB stars are an area where we need some advances. This includes stars showing late thermal pulses, which can involve the mixing of cold fuel into hot regions. This means implementing a time-dependent burning and mixing algorithm. Its not trivial but it can be done.

At the moment the data for post-AGB stars well outweighs the models, and this should be addressed. It is an area desperately needing attention from theorists.

5. Conclusions

It has been very interesting to see how our understanding of AGB stars has grown and meandered during my career. From the first exploratory models by Iben (and co-workers like Becker and Hollowell) and the work of Wood, the basic physics was determined. The nucleosynthesis goes hand in hand, and the revolution caused by pre-solar grain data has

[1] I must say that I agree with Drs Tout and Izzard that “binarity” as a word does not exist, and that the correct word is “duplicity”; however to be practical, the latter word has a second meaning which is all too common and which will preclude it ever being used instead of the newly invented word “binarity”.

meant that theoretical models these days include about 100 species rather than the typically 5-10 needed to get the structure correct.

The models became more quantitative, AGB stars became tools used for probing other physics and even other stellar populations (due to their brightness). But for those attending the Torino Workshops, the stars themselves remain the main fascination. And rightly so.

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References

Busso M., Gallino R., Lambert D. L., Travaglio C., Smith, V. V., 2001, ApJ, 557, 802
Denissenkov P. A., Tout C. A., 2003, MNRAS, 340, 722
Frost C. A., Lattanzio J. C., 1996, ApJ, 473, 383
Herwig F., Blöcker T., Schönberner D., El Eid M., 1997, A&A, 324, L81
Herwig F., Langer N., Lugaro M., 2003, ApJ, 593, 1056
Iben I. Jr., 1981, ApJ, 246, 278
Iben I., Jr., Renzini A., 1982, ApJ, 259, L791
Iben I. Jr., Renzini A., 1982, ApJ, 263, L231
Lugaro M., et al., 2005, ApJ, in press.
Mowlavi N., 1999, A&A, 344, 617
Renda A., et al., 2004, MNRAS, 354, 575
Ritossa C., Garcia-Berro E., Iben I. Jr., 1996, Mem.S.A.It., 67, 675
Ritossa C., Garcia-Berro E., Iben I. Jr., 1996, ApJ, 460, 489
Ritossa C., Garcia-Berro E., Iben I. Jr., 1997, ApJ, 487, 765
Ritossa C., Garcia-Berro E., Iben I. Jr., 1997, ApJ, 489, 772
Ritossa C., Garcia-Berro E., Iben I. Jr., 1999, ApJ, 515, 381
Siess L., Goriely S., Langer N., 2004, A&A, 415, 1089
Smith G. H., Norris J. E., 1993, AJ, 105, 173
Stancliffe R. J., et al., 2004, MNRAS, in press.