

Why Galaxies Care about AGB Stars: Setting the Stage

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Abstract. In this introduction to the Third Congress of Vienna on AGB stars I first try to highlight why it is so hard to cope with the AGB evolutionary phase. This phase is indeed dominated by three main physical processes concerning bulk motions of matter inside/around stars, namely envelope convection, mixing and mass loss. They are inextricably interlaced with each other in a circular sequence of reactions and counter-reactions which has so far undermined our attempts at calibrating such processes one independent of the other. The second part of this introduction is focused on Globular Clusters, illustrating how they came to be a *new frontier* for the AGB evolution and a new opportunity to understand it.

1. Why We Care

We all know why galaxies care about AGB stars, but it is perhaps worth listing a few items at the beginning of this III Congress of Vienna on AGB stars:

- **The AGB Energetic role in Stellar Populations**, affecting the spectral energy distribution (SED) of galaxies, especially in the near-IR, and consequently the mass and ages derived from SED fits.
- **The Chemical Yields** of several elements, notably He, Li, C, N, O, Ne, Na, Mg, Al, p-process and s-process elements, as they affect the chemical evolution of galaxies.
- **The Dust production**, with carbon-type AGB stars being the source of carbonaceous grains, such as silicon carbide, soot, graphite and perhaps even fullerene; and M-type AGB stars being prime producers of silicate grains. Together, these dust grain obscure galaxies at low and high redshift.
- **The Initial-Mass-Final-Mass Relation**, which is established during the AGB evolution, along with the mass return by dying stars in galaxies.

So, while we all agree that these are the issues at stake, the reason why we are all attending this conference is that AGB evolution is far from being properly understood. In this introductory talk I will try to cursorily illustrate what difficulties one encounters in modeling AGB stars, which explain why we still lack a satisfactory, quantitative understanding of this evolutionary phases, and therefore of the quantities for which galaxies care about.

2. The Three Macrophysics Drivers of AGB Evolution

The *input physics* we use to make stellar evolutionary models comes in two very distinct flavors: *microphysics* and *macrophysics*. The former deals with processes at the atomic and sub-atomic levels, which control three main ingredients in the models: equation of state, opacity, and nuclear reaction rates. Macrophysics instead deals with bulk mass motions inside/around stars, and include convection, rotation, mixing and mass loss. Virtually all the nasty problems in stellar evolution come from macrophysics and in this respect the AGB phase of intermediate mass stars is perhaps the nastier of all evolutionary phases. To simplify the discussion I will neglect rotation and magnetic fields, not because they cannot be important, but because considering just convection, mixing and mass loss makes life already quite complex, as I will try to illustrate. In the next subsections I will discuss them in turn, along with the interactions of each of them with the other two.

The reason why the mentioned macrophysics phenomena are a source of problems in modeling AGB stars is that for them there is no theory from first physical principles. What we are forced to do is to adopt for them some convenient, heuristic parametrization, and try to fix the free parameters by fitting observations. This is where all the problems arise. The considerations that follow are most pertinent for AGB stars that experience the *hot bottom burning* (HBB) process, i.e., those with initial mass above $\sim 2.5 - 3 M_{\odot}$, depending on composition, which are the most difficult to understand and where most of the action actually is taking place.

2.1. Envelope Convection

The envelope of AGB stars is convective and envelope convection is almost universally treated with the mixing-length theory (MLT), with the mixing length as a parameter. This parameter controls the stellar radius and could be fixed by matching stellar radii. However, the same parameter also controls the temperature at the base of the convective envelope: for example, in a $\sim 6 M_{\odot}$ stellar model this temperature can go from ~ 1 to ~ 100 million K just by changing the mixing length by a factor of ~ 2 . Thus, envelope convection controls the onset (and outcome) of the HBB process. In turn, the HBB controls the luminosity of the star, for given mass of its hydrogen-exhausted core. And this is not the end of the consequences, because luminosity and radius control mass loss and the radius affects also the amount of third dredge-up (TDU) at each thermal pulse. So, by just changing one parameter in the models, the mixing length, one affects radius, HBB, luminosity mass loss and TDU. All this might be fine, if we had a perfect theory of convection, but we know that the MLT is not, and therefore we have no assurance that fixing the mixing length by matching one observable all other affected quantities will fall in the right place as well.

2.2. Mixing

The discovery by Icko Iben of the TDU has been one of the shining successes of the theory of stellar evolution, explaining the existence of carbon stars which had been a puzzle for over 100 years. Yet, the amount of dredged up material at each thermal pulse is extremely model dependent. This is traditionally indicated as $\lambda = \Delta M_{\text{dredge}} / \Delta M_{\text{H}}$, where ΔM_{dredge} is the mass of the dredged up layers after a thermal pulse and ΔM_{H} is the advancement of the hydrogen burning shell during one interpulse period. The net growth of the stellar core over a full thermal pulse cycle is therefore $(1 - \lambda)\Delta M_{\text{H}}$. Once

more, the problem is that we do not have a theory of how mixing proceed at the edge between the fully convective envelope and the hydrogen-exhausted layers below it. In absence of a physical theory we have used plausible, yet heuristic arithmetical algorithms that may or may not capture reality. Still, the amount of TDU, i.e., λ , controls the evolution of the surface composition, the rate of core mass increase, hence the luminosity evolution which in turn controls mass loss while surface composition controls also radius and again mass loss. So, also the TDU, via λ , controls almost everything else, which in turn will control the TDU itself in a loop that nobody has really explored so far.

It is perhaps worth spending a few more words on the TDU-mass loss connection. For large values of λ (near unity) the core mass increases slowly, hence so does the luminosity, implying modest mass loss and longer AGB lifetimes. With a small λ (say, ~ 0.1) the core mass increases rapidly and so does luminosity whose increase with core mass is extremely steep when HBB is active (Blöcker & Schönberner 1991). Thus, the star soon runs into dramatic mass loss leading to a prompt abortion of the AGB phase. The result is a much different element yield in the two cases, though the final mass of the WD remnant may not be so different after all. In other words, the HBB process works as an amplifier of the mixing-mass loss connection. Worth stressing is that we still have only *heuristic guesses* for the function $\lambda(\text{mass, composition})$.

2.3. Mass Loss

Mass loss from red giants and supergiants, including AGB stars, is another fundamental process for which we don't have a physical theory. We even don't know if dust causes wind or winds cause dust formation (personally, I incline for the second option). So, in AGB models mass loss is introduced via some simple formula giving the mass loss rate as a function of stellar mass, radius and luminosity, plus one adjustable parameter, for example what a long time ago I called η , for efficiency. Not to mention that on top of the regular wind we may also need a *superwind*, bringing in yet another parametrization and another parameter. So, mass loss, via these parameters, controls the mass evolution, hence the radius and the luminosity, which in turn affect the activity of the HBB process and the TDU. Also mass loss is therefore part of this inextricable network of feedbacks and counter-feedbacks.

2.4. Wrup up

Therefore, the *Three Macrophysics Drivers* of AGB evolution are tightly interlaced to each other. This implies that one cannot calibrate each *free parameter* independently of the others. Simple analytical formulations to construct synthetic AGB evolutionary sequences, or transplanted from one series of evolutionary models to another, are bound to miss most of these intricate connections. Only a tiny fraction of the AGB parameter space has been explored so far and the chance of having already found the right combination looks to me vanishingly small. AGB evolution is a particularly nasty puzzle!

Still, the three macrophysics drivers do not complete the list of parametrized processes in constructing AGB evolutionary models. I have mentioned that rotation and magnetic fields are ignored here. Another process that can affect the AGB phase considerably is convective overshooting during the main sequence and pre-AGB evolutionary phases, which is still poorly constrained by observations.

3. Globular Clusters: A New Frontier for the AGB

In recent years it became increasingly more likely that the study of globular clusters (GC) may offer an unexpected opportunity for a better understanding of AGB evolution, or at least for setting tighter constraints to it. It was once thought that GCs formed in a single burst, leading to prototypical simple stellar populations (SSP). On the contrary, it now appears that they host multiple stellar generations, with secondary populations characterized by different chemical compositions and our current knowledge can be summarized as follows:

Ubiquity Virtually all GCs that have been studied are composed of distinct stellar populations (at this moment homogeneous data are available for 46 GCs, see Piotto et al. 2014 for a first release of HST Treasury observations), from two in number up to six or more as in the case of NGC 2808 shown in Figure 1. Thus, the production of MPs appears to be inextricably linked to the very formation of a GC.

Enrichment The first-generation (1G) stars have a composition that can be ascribed to the proto-galactic matter out of which they formed, whereas second-generation (2G) stars are depleted in C and O, enhanced in N and Na and can be strongly enriched in helium (e.g., Norris 2004; Piotto et al. 2007; Carretta et al. 2009). This shows that the material out of which they formed was exposed to proton captures at high temperatures (as it happens in AGB stars with HBB). With few exceptions, 2G stars have the same abundances of iron and other heavy-elements as the 1G stars, indicating that their material was not contaminated by supernova products. Even for GCs showing a range of metallicities only a very small fraction of the 1G SN products has been incorporated in 2G stars. Huge cluster-to-cluster differences are also found in the abundance of helium and p-capture elements of 2G stars.

Discreteness One crucial property of MPs is that they split into distinct sequences in color-magnitude diagrams and/or in two-color plots (see Figure 1), as opposed to a continuous spread. This implies that 2G stars formed in a sequence of discrete events, shortly after the formation of 1G stars. Figure 1 shows that UV and UV-optical colors are especially effective in separating MPs, which is so because molecular bands, such as those of OH, NH, CH and CN, fall each in different UV/blue passbands, hence such colors depend on C:N:O proportions.

Figure 1 (from Milone et al. 2014, in preparation) offers a cogent example of these astonishing complexities for the case of the GC NGC 2808, clearly showing how the main sequence, the RGB and the HB split in distinct sequences and in the two color-color plots on the left side one can count at least five distinct populations.

Several tentative progenitors of the 2Gs have been proposed. Massive stars (either fast rotating or in binary systems) have been advocated for being the producers of the raw material out of which later generations formed, but such scenarios have unsurmounting difficulties in explaining how to avoid supernova contamination and how to produce quantized, distinct sub-populations (see Renzini 2008, 2013 for critical reviews). Thus, intermediate-mass stars of the 1G in the mass range $3 \lesssim M \lesssim 8 - 10 M_{\odot}$ are widely regarded as the most plausible (or the least *im-plausible!*) candidates, with their accumulated AGB ejecta then experiencing a series of bursts of star formation.

Also this scenario is facing two main difficulties. First, AGB models do indeed produce helium enriched and oxygen-poor/sodium-rich, *p*-capture material processed through the HBB, but existing AGB models do not quite reproduce the observed O-Na anticorrelation. Second, only $\sim 5\%$ of the 1G mass can be returned to the ISM with the composition one wants for the 2G stars. Since the 2G stars are often as numerous

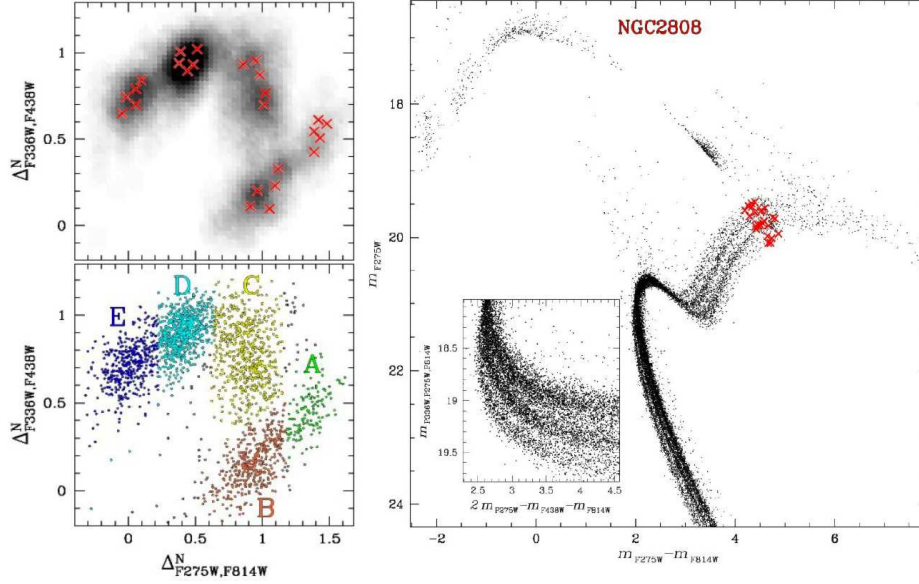


Figure 1. Right panel: the HST color-magnitude diagram of the globular cluster NGC 2808 combining the UV filter F275W of WFC3-UVIS with the near-IR F814W filter of ACS. Several discrete components are recognizable in all evolutionary sequences with the insert zooming on the main sequence turnoff and using a multicolor combination. Left panels: a combination of four filters is used to split the red giant branch in at least five distinct stellar populations. Each clump corresponds to a population with a distinct pattern of He, C, N, O and Na abundances. Red crosses show stars being now observed with FLAMES at the VLT for their spectroscopic chemical characterization (from Milone et al. 2014, in preparation).

as the 1G stars (or even more so), the immediate consequence is that the 1G ought to be at least 10 – 20 times more massive than it is today (e.g., D’Ercole et al. 2008). Still, this assumes a 100% efficiency in the gas-to-star conversion, hence 1G had to be even much more massive than that if the 2G star-formation efficiency was closer to a canonical 10%. This puts the formation of GCs into a scale never conceived before: the progenitors of today’s GCs with mass of a few times 10^5 to a few times $10^6 M_{\odot}$, might have been stellar systems in the $10^7 - 10^8 M_{\odot}$ mass range, or even more. With GCs being the remnants of much bigger objects, the notion is also currently entertained that the majority of 1G stars, once tidally stripped off, made a major, if not dominant contribution to the formation of the Galactic halo.

Thus, if multiple populations are formed out of AGB ejecta, then the puzzling formation of GCs and AGB evolution become just one problem and the same. Spectroscopic observations are going to be used to further characterize each sub-population in terms of chemical composition, such as especially [O/Fe] and [Na/O] ratios. Main sequence splits will allow us to quantify differences in helium content as small as $\Delta Y = 0.02$. The full body of resulting compositions will then represent an **extensive random sampling of AGB ejecta**, whose analysis will allow us to make progress in understanding AGB evolution, a challenging but not impossible puzzle to assemble. Out of this it should be possible to assess whether AGB models can be tuned to produce the

observed composition patterns and, if so, one will have placed the tightest constraints on AGB evolution itself, including lifetimes and fuel consumptions as a function of stellar mass. This is indeed what is urgently needed to calibrate synthetic stellar population models which are commonly used to estimate stellar masses and luminosity-weighted ages of distant galaxies, but where the AGB contribution to near-IR light is radically different from one set of models to another, leading to systematic differences which depend on age and are especially relevant for high redshift galaxies (see e.g., Pforr, Maraston & Tonini 2012).

4. Conclusions

So, many are the things we would like to know about AGB Stars, such as their yields of He, Li, C, N, O, Ne, Na, Mg, Al, s-process, the mass of hydrogen and helium burned during the AGB phase, hence the AGB contribution to the light (SED) of stellar populations, the time spent and maximum luminosity reached on AGB, and all this as a function of initial stellar mass and composition. Stellar models can “predict” these quantities as functions of various, arbitrary input parameters, but almost certainly they are all *wrong* as so far only a tiny fraction of the parameter space has been explored. “All theories [of AGB evolution] are wrong, but –as one participants said at the meeting – some theory is more useful than others”. Mine indeed is not a plea against making AGB models. I would advocate that at this stage we may learn more on AGB evolution by *measuring* the just listed quantities on the multiple populations of globular clusters in the Milky Way and looking at the SED of low- and high-redshift galaxies, especially those dominated by ~ 1 Gyr old stellar populations. Then, by all means, we should try to see if the models can be forced to do what we see.

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