Intermediate Mass Stars Massive Stars. A workshop around causes and consequences of differing evolutionary paths

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A workshop around causes and consequences of differing evolutionary paths

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Foreword

The post-main sequence evolution of stars of intermediate or large masses is notoriously complex. In the recent past, a number of workshops and meetings have focused on either the Asymptotic Giant Branch of intermediate mass stars, or the evolution of massive stars. But how well defined is the boundary between these categories of objects defined? How would an observer proceed to classify stars into one or the other category? How do objects near the boundary evolve, die, and contribute to the chemical evolution of their environment?

During this 3-day international workshop[1], 26 high quality presentations were given by specialists in the relevant fields of astrophysics, and stimulating discussions followed. It is technically impossible to provide an exhaustive census of the results and ideas that emerged. In this brief article, we choose to point to key elements of the workshop, some of which are now the topic of new collaborations and will lead to publications elsewhere. For the sake of brevity, we deliberately cite only the contributors to the workshop and no external references. Many bibliographic references can be found in the original presentations, which can be retrieved through: http://astro.u-strasbg.fr/observatoire/obs/stars2009/stars2009.html The programme workshop, which includes the titles of the individual contributions, is provided as an appendix.
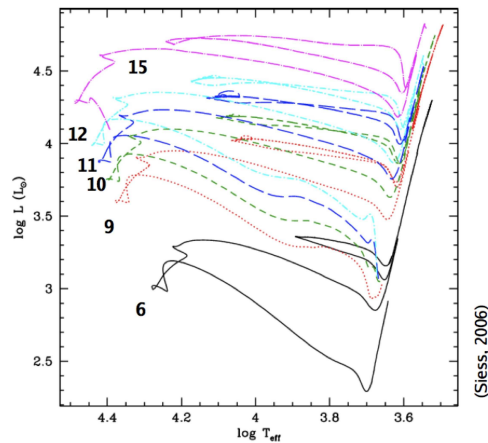

Figure 1: Evolutionary tracks from the STAREVOL code (from *Siess & Palacios*).

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[1] Supported by the PNPS (Programme National de Physique Stellaire, CNRS, France) and ANR (Agence Nationale de la Recherche, France).

1 Definition, mass and impact of super-AGB stars

1.1 The mass domain

"Low-mass" stars end as CO white dwarfs, "massive" stars, which are at the origin of core-collapse type II supernovae (SNe), go through all the nuclear burnings, from H to Si (see Fig. 2 for the fate of massive stars, and *Limongi* for a detailed discussion). In between, one meets a domain of stellar masses, which evolve through the *super asymptotic giant branch* (super-AGB) phase and will end as either ONe white dwarfs or electron capture SNe.
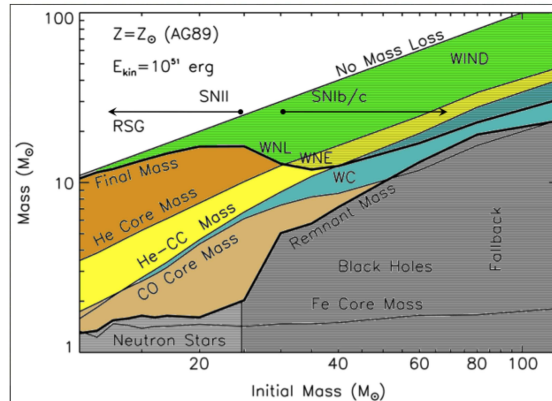

Figure 2: Fate of massive stars (from *Limongi*).

What defines super-AGB stars is what happens in the core. Three critical masses thus have to be determined: the minimum initial stellar mass (referred hereafter as M_{up}) which will allow carbon ignition in the core, the minimum mass M_n for neutron star formation and the limit M_{mas} for type II SN (we adopt here the notation proposed by *Siess & Palacios*; see Fig. 3).

The value of the *core* mass corresponding these different transition masses seems rather well determined by theory: 1.05 $M_o dot$ is the minimum core mass for carbon ignition, above 1.37 $M_o dot$ the (degenerate) neon-oxygen core is massive enough to activate electron capture (EC) reactions leading to the formation of a neutron star and if the core mass at the end of He-burning exceeds the Chandrasekhar mass (1.44 $M_o dot$), then the star will proceed through all nuclear burning stage and end up as a core collapse SN (SNII or SNIbc depending on the initial mass and mass loss). But going back to initial masses is more problematic. Treatment of (semi-)convection (and associated overshooting and dredge-up), mass loss and carbon burning are among the most influential ingredients. While the differences between critical masses are reasonably robust against the input physics (e.g. adopted nuclear rates) and models, at least for *single* star evolution ($M_{mas} - M_{up} \approx 2$ M$_\odot$, $M_{mas} - M_n \approx 0.25$ M$_\odot$ at solar metallicity; *Weiss, Pols*), their absolute values are quite controversial.

Straniero presented a new study of the ^{12}C(^{12}C, p)^{23}Na rate (with the discovery of two new resonances) which reduces M_{up} by 2 M$_\odot$, from 8 to 6 M$_\odot$. Taking into account overshooting has a a similar impact (*Siess & Palacios*). And the uncertainty on the evolution of massive stars is still largely dominated by the poor kowledge of the ^{12}C(α, γ)^{16}O cross section (*Limongi*).

1.2 Constraints from white dwarfs and supernovae

Observational constraints on the limiting masses are thus required. In principle, they can be obtained from the observation of white dwarfs (WD) in open clusters (*Meynet, Kalirai, Williams*). This method goes through several steps: based on atmosphere models, determination of WD effective temperature and gravity; from a mass-radius relation, estimation of WD masses; from theoretical isochrones, estimation of the age of the cluster. Since the age of the cluster is also the sum of nuclear lifetime of
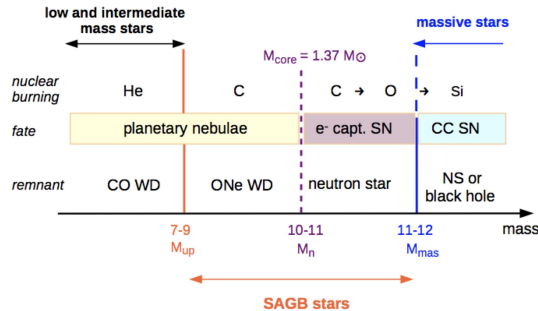
Figure 3: Definition of the threshold masses (from *Siess & Palacios*).

the progenitor of the white dwarf and its cooling age, one deduces the nuclear lifetime of the progenitor, and thus its initial mass. Obviously, all these steps require theoretical inputs ... so the results are model dependent! Given the Main Sequence lifetime of a 8 $M_\odot$ ($\sim$ 40 Myrs), this method requires the study of open clusters with an age of a few 10 Myrs. *Williams* obtained a *lower limit* on M_{mas} of 6.3-7.1 $M_\odot$.

The knowledge of the chemical composition of white dwarfs is crucial for determining the cooling rate and the progenitor mass. Strong mass loss on the red giant branch may lead to a bypass of the AGB, and thus the formation of a He white dwarf, which will cool 3 times more slowly than a CO white dwarf. This could explain the apparent discrepancy between Main Sequence turnoff age and white dwarf cooling age for some clusters (*Kalirai*). Hot DQ white dwarfs may be the progeny of 9-11 $M_\odot$ stars, and thus have a ONe core. This could be tested with asteroseismology (*Williams*).

The study of type II-P SNe and the identification of their progenitors (mostly red supergiant stars) should constrain M_{mas} (*Smartt, Eldridge*). A lower limit of 8.5 (+1/-1.5) $M_\odot$ is found. Recent observations of possible electron-capture supernovae such as supernova 2008S and the WD masses of Kurtis et al. *Eldridge* estimated that $M_{mas} - M_n = 1.1 M_\odot$.

Combining these theoretical and "observational" results may lead to inconsistencies. Apart from improvements in models and interpretation of observations, one should consider the possible effects of binarity. Indeed, as emphasised by *Pols*, merging in close binaries leads to a decrease of effective mass limit.

Finally, one should keep in mind that these threshold masses depend on metallicity, as illustrated in Fig. 4 (extracted from *Siess & Palacios*).

1.3 Stellar populations and yields

How important are super-AGB stars for stellar populations and Galactic chemical evolution?

Most evolutionary tracks available for population synthesis purposes are still incomplete at the masses relevant to super-AGB stars, lacking the latest, reddest and also brightest phases of evolution. This may lead to unrealistically blue colours for synthetic populations at ages around 100 Myr.

Despite the relatively narrow mass interval ($\Delta M = 2$ $M_\odot$), a Salpeter-like Initial Mass Function gives a number of stars with $M_{up} < M < M_{mas}$ which is about 2/3 that of the stars with $M > M_{mas}$ (the progenitors of core collapse SNe), and these may thus play an important role in chemical evolution.

Super-AGB stars are the most massive stars which experience the second dredge-up (*Siess & Palacios*), but maybe no third dredge-up. Hot Bottom Burning is thus a key-ingredient in determining the super-AGB yields and these stars may be strong contributors of early ^{14}N and ^{13}C enrichment (up to Z = 10^{-4}; *Chiappini*). Such yields may explain the chemically anomalous second generation of stars
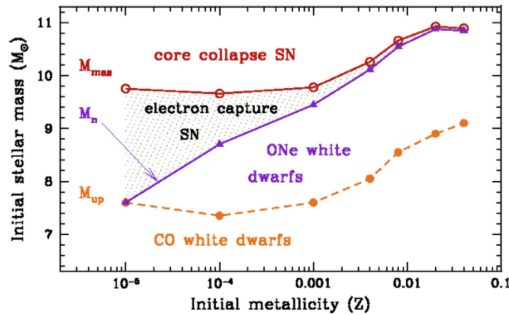
Figure 4: Evolution of threshold masses as a function of metallicity (from Siess & Palacios).

in globular clusters (*d'Antona*), although this remains a matter of debate, and more massive rotating stars are an alternative favoured by some (*Decressin*).

Concerning elements heavier than Fe, the timescale and importance of neutron exposure in super-AGB stars are small, and the main neutron source is $^{22}Ne(\alpha,n)^{25}Mg$. This leads to significant production of a limited number of elements, around Z=40, such as Rb (*Straniero, Frishknecht*).

Many open questions remain. In particular, what are the final C/O ratio in super-AGB stars. Is it possible to find carbon-rich super-AGB stars ? If yes, at which metallicities ?

2 Identification of super-AGB stars: atmospheric properties

2.1 Atmospheres and spectral classification

If one excepts asteroseismology, still applicable to a limited number of stars, only the atmosphere of stars are observable, so diagnostics on their nature rely on our ability to interpret their spectra. The most widely used models (e.g. MARCS or PHOENIX) are based on "classical" approximations: 1D, static atmospheres, LTE, mixing length theory for convection, a depth-independant microturbulent velocity. From such models, it is noticeable that red supergiant stars and AGB stars with same luminosity and temperature, thus differing only by their masses (and thus their surface gravity), have a different thermal structure, and different emerging spectra (*Plez*). However, pulsations and/or convection, probed by photometric and line profile variability, make the validity of the classical approximations questionable. 3D models are under development, but still need improvements (temperature profiles are too shallow, velocity fields are too small; *Plez*). In parallel, progress in full NLTE 3D radiative transfer aims at producing more reliable diagnostics (*Hauschildt*).

Meanwhile, the use of classical models encountered success, such as the new determination of effective temperatures of red supergiant stars for different metallicities (*Levesque*). Remarkably, this new calibration agrees well with independent determinations, based e.g. on interferometric measurements (*Gray*). It also shows a better agreement with evolutionary tracks (Geneva model) ... which may be partly fortuitous. (The end points of the STARS models extend to cooler temperatures than the Geneva models and also the observed positions of Galactic RSGs. However it is important to compare models which end at the same burning stage to ensure reliable physical comparisons. Also models spend more time at the bottom of their RSG track and accelerate up it, spending more time in the region of the HR diagram inhabited by observed RSGs; *Smartt & Eldridge*). Let us recall that the effective temperature at the red supergiant stage depends on the ratio of the mixing length to the pressure scale height, which is a free parameter in general adjusted using solar models. Combination of realistic stellar atmospheres and evolutionary models, to obtain reliable predictions of effective

temperatures, are needed, but this is far from being an easy task... Another improvement of both atmospheric and evolutionary models would concern the treatment of convection, based in both cases on the mixing length theory (MLT). The used α parameter is widely that calibrated with the Sun. To what extent is it applicable to red (super-)giant stars? Is MLT itself appropriate?

The spectral classification of M-type stars relies on the *absolute* strength of TiO bands, and are thus metallicity dependent (*Gray*). To overcome this problem and obtain a univocal correspondence between spectral type and effective temperature, a possibility could be to define a spectral classification based on atomic line or molecular band ratios. Is such a revision in spectral classification desirable?

In the context of (super-)AGB stars, an extension of the calibration of effective temperatures toward lower mass/luminosity, longer wavelengths (infrared) and lower metallicities is highly desirable. Static models seem to reproduce satisfactorily the spectra of the warmer stars ($T_{eff} \gtrsim 3500$ K) but, as one goes toward lower temperatures, one is confronted with inconsistencies between the visible and the infrared parts of the spectra (*Lançon*). Finally, the link between the empirical concept of luminosity class and stellar mass or evolutionary models is pending.

As mentioned above, another approach to determine fundamental stellar parameters consists in the interpretation of interferometric observations. Realistic (1D) hydrodynamic models now allow to interpret consistently such observations, without invoking *ad-hoc* structures such as "molspheres" (*Wittkowski, Sacuto*). They indeed show how extended the atmospheres of (super-)giant stars are. In return, this renders the concept of effective temperature less clear for observers, as it cannot be considered as a "surface" temperature.

2.2   Pulsations, mass loss and circumstellar envelopes

Apart from complicating the building of reliable stellar atmosphere models, stellar pulsations are interesting for themselves. In particular, the apparent universality (i.e. metallicity independent) of the period-luminosity relations is remarkable (*Schultheis*). There remains work to do. The origin of the variability of some classes of objects (in particular the sequence "D") remain mysterious. A complete census of semi-regular variables in the solar neighbourhood is still missing, and would bring important constraints for stellar evolution models.

Pulsation is a key-ingredient in the mass-loss process of AGB stars, together with radiation on dust. From Hydrodynamical Dust driven wind models, it appears that abundances are also important. As metallicity increases, similar mass-loss rate, larger wind velocity and dust-to-gas ratio are predicted for a given C/O value, while mass-loss rate, wind velocity and dust-to-gas ratio all increase with C/O (*Groenewegen*). High angular resolution observations also point toward the need of 3D models, as it appears that asymmetries in the wind of AGB stars develop very early (*Chesneau*).

A good understanding of the mass-loss process, and a proper determination of the total mass-loss rate, is fundamental to predict initial-final mass relations. Intermediate-mass stars are supposed to experience stronger winds and have thus larger amounts of circumstellar material, compared to more massive stars. Then how many evolved intermediate mass stars are missed because of extinction? What place do OH/IR stars occupy in the context of intermediate mass star and super-AGB evolution?

3   The future

Super-AGB stars represent a real challenge for stellar physics. More generally, intermediate mass stars, and super-AGB stars in particular, play an important role in "the Bigger Picture" (*Kalirai*). The evolution in different environments, such as the correlation between mass loss and metallicity (i.e. how extinct extra-galactic super-AGB stars may be?), the metallicity of bulge stars, are key-ingredients for the interpretation of light from distant galaxies, or our understanding of the Milky Way formation.

From an observer's point of view, upcoming facilities will help clarify some of the questions raised above. Important projects mentioned during this workshop include: the LSST (Large Synoptic Survey

Telescope, e.g. HR diagrams of clusters), ALMA (Atacama Large Millimetre Array, mass loss in the Magellanic Clouds as a test dust driven wind theory), second generation of VLTI instrumentation (wind aymmetries), GAIA (survey of long period variables to constrain pulsation properties in the Milky Way better).

We thus hope and believe that this workshop will be followed by other ones. Keep in touch!

Programme of the workshop

Day 1 - Monday, February 9, 2009:
Topics:
- AGB stars, super-AGB stars and related objects. Definitions. Which evolutionary path to each of these categories?
- Predicted properties from evolutionary models. Model assumptions and their effects.

- Achim Weiss - Review about location in the theoretical diagram, lifetimes, surface abundances and the like

- Oscar Straniero - Around Mup : energy generation, energy sink and nucleosynthesis

- Ana Palacios - Nucleosynthesis and the fate of super-AGB stars

- Georges Meynet - Mass transition between white dwarf progenitors and neutron stars progenitors - Present status and perspectives

- Onno Pols - Effects of binaries on the transition mass and on the occurrence of electron-capture supernovae

- Steve Smartt - Observational constraints on the progenitors of type II-P supernovae

- J. Eldridge - Constraints from combining SN-progenitors, white dwarf masses & stellar models

- Workshops and discussion

  1. Comparisons between spectral models
  2. Spectral typing of model spectra
  3. Do we know the mass-cut between WD and NS progenitors?
  4. Comparisons between evolutionary models

- Marco Limongi - massive stars : pre-SN evolution, explosion, nucleosynthesis

- Jason Kalirai - Initial-final mass relations

- Kurtis A. Williams - Observations of white dwarf remnants of intermediate mass stars

Day 2 - Tuesday, February 10, 2009:
Topics:
- Predicted and observed atmospheric properties. Comparisons with observations.

- Bertrand Plez - Differences between atmospheres of intermediate mass stars and of massive stars, recent model developments

- Richard Gray - Spectral types in the upper right of the HR diagram known relations to physical properties, known problems; the future of spectral types

- Peter Hauschildt - Lessons from 3D simulations, views on micro/macroturbulence

- Workshops and discussion

- Emily Levesque - Modelling the physical properties of red supergiants

- Ariane Lançon - Near-IR spectra of luminous red stars. Data versus models.

- Eric Josselin - Water and other molecules. Observational evidence for molecular layers.

- Mathias Schultheis - Period-luminosity relations on the AGB

- Markus Wittkowski - Interferometric data compared to model atmospheres

- Olivier Chesneau - Constraints from interferometry in the mass range of interest to the workshop

- Séphane Sacuto - Hydrodynamic interpretation of AGB stars observed at high angular resolution.

Day 3 - Wednesday, February 11, 2009:
Topics:
- Chemistry, yields, contributions to the chemical evolution of galaxies
- Summary of the sub-workshops

- Martin Groenewegen - Mass loss from AGB stars and red supergiants in the Magellanic Clouds.

- Cristina Chiappini - Chemical evolution of galaxies with and without AGB stars or super-AGB stars

- Thibaut Decressin - The role of super-AGB stars and related objects in the self-enrichment of star clusters.

- Francesca D'Antona - A dynamical model for the formation of multiple populations in globular clusters, and the role of super-AGBs.