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Gas and dust from stars

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Abstract. We discuss the yield by stars of various mass, and the modality they pollute the interstellar medium. Massive stars determine an early contamination of their surroundings, in a way depending by the metallicity, but also the treatment of rotation. Stars of intermediate mass pollute the interstellar medium during their asymptotic giant branch phase: stars of mass below $\sim 3M_{\odot}$ eject carbon–rich matter, whereas more massive objects reverse gas with the imprinting of p–capture nucleosynthesis.
We also discuss the dust formed around stars, essentially under the form of carbonaceous particles and silicates grains. We are presently unable to compare on the quantitative side the dust produced by the two groups of stars, owing to the model uncertainties, affecting particularly the higher mass objects.

Key words. Stars: abundances – Stars: abundances – Stars: AGB and post AGB – Supernovae: general

1. Introduction

During their life the stars reverse into the interstellar medium material lost from their outermost layers. This gas can have a chemical composition considerably different in comparison with the cloud from which they formed, thus producing a contamination of the stellar surroundings. The thermodynamical conditions in the outer layers and in the circumstellar envelope may become favourable to condensation of gas molecules into dust.

The evolution of a star is essentially driven by its initial mass, M. The higher is M, the faster is the evolution, owing to the slower core burning phases of lower–mass stars.

We may roughly divide the stars into two subgroups, according to whether the initial mass is larger or smaller than a threshold value[1] $M_{up} \sim 8M_{\odot}$

Stars of mass $M>M_{up}$ experience all the phases of core nuclear burning until an iron core is formed, and eventually explode as type II supernovae. They reverse into the interstellar medium the whole mass outside the iron core (which will be the future remnant, either a neutron star or a black hole). Part of their mass is lost during the pre–explosive phases via stellar winds, the remaining gas is lost during the explosion, and is partly altered by explosive nucleosynthesis. As a consequence of the explosion, a shock wave travels outwards, lifting the density of the outer layers, creating the conditions favourable to dust formation.

[1] The exact value of M depends on the metallicity, and also on the amount of extra–mixing assumed during the core H–burning phase.

Stars of mass below M_{up} evolve differently. Their core becomes degenerate after the helium burning phase, thus preventing the possibility of igniting more advanced nuclear channels. They end their evolution as white dwarfs, either composed of carbon and oxygen, or, when the initial mass is close to M_{up}, of oxygen and neon. These stars loose most of their mass during the Asymptotic Giant Branch (hereinafter AGB) phase. The external regions of AGBs assume an expanded configuration, with temperatures sufficiently low to favour condensation of gas molecules into dust.

In this contribution we present the status of the art of the modelling of the evolutionary history and of the explosion of massive stars, and of the AGB evolution of intermediate masses. We discuss the main uncertainties associated to the physical ingredients used to calculate the models, and try to understand, for the various chemical species, which stars provide the most relevant contribution.

We focus on dust production by massive stars and AGBs, to describe the mass dust produced, and also the grain size distribution expected by the two above categories of objects.

2. Massive stars: evolutionary properties and chemical yields

Stars whose initial mass exceeds $\sim 8M_{\odot}$ experience various phases of nuclear activity in their central regions, until an iron core is formed. The final fate of these objects is the collapse of the core, followed by a type II supernova explosion event, that leaves a central remnant, either a neutron star or a black hole.

The yields from massive stars are composed by a pre–explosive part and by an explosive component. The former is determined essentially by the description of the mass loss mechanism and the efficiency of internal mixing processes, that can alter the surface chemical composition. The quantity of matter ejected during the explosion, as also its chemistry, is sensitive to the chemical stratification in the star at the core collapse: a typical example is shown in the left panel of Fig. 1. Apart from the external, hydrogen–rich regions, we find in more internal layers the residuals of advanced $\alpha-$capture nucleosynthesis.

While the yields of the elements lighter than silicon depend mainly on the stratification present in the star before the explosion, for all the heavier elements the details of the description of the explosion become extremely relevant, particularly the choices of the mass cut, the energy of the explosion, and the explosion mechanism itself.

The pioneering exploration by Woosley & Weaver (1995) set up the framework to simulate the evolution of massive stars until the final explosion, with the description of the different nucleosynthesis channels. The main results of this study, limited to the solar chemistry, are:

i) over–production of $\alpha-$elements;
ii) typical odd–even effect, with underproduction of some odd elements, mainly nitrogen and fluorine;
iii) production of iron–peak elements.

The description of the evolution of massive stars has changed considerably in the last 10 years, when different research groups started to consider the effects of rotation. This latter mechanism not only determines a purely structural effect, via distortion of the stellar configuration, but also favours internal mixing, by means of meridional circulation and shear mixing (Meynet & Maeder 2002a,b; Meynet et al. 2006, 2008; Limongi & Chieffi 2012, 2003).

The combination of these processes naturally favours mixing of the internal core with the external regions, thus smoothing the chemical profiles normally found at the border of the central nuclear burning regions.

The right panel of Fig. 1 shows the effects of rotation on the yields of massive star models of various metallicities. The results are averaged over a Salpeter IMF. Among the effects introduced by rotation, we stress the differences concerning the predictions for nitrogen and fluorine: outwards mixing from the He–burning core favours primary carbon to be transported outwards, where it produces fresh nitrogen via proton capture. This freshly synthesized nitrogen starts a series of reactions leading to the production of fluorine, and also

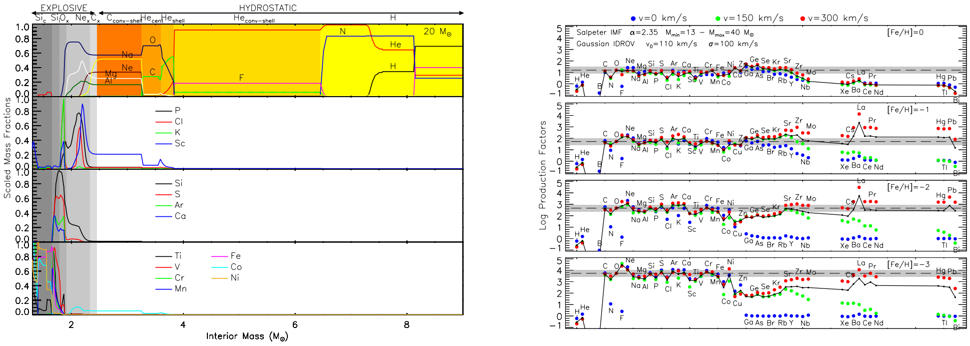

Fig. 1. Left: Internal chemical stratification of a 25M$_\odot$ model in the phases preceeding the core–collapse; Right: Yields from massive stars of various metallicities and rotation rates. The results are averaged over a Salper IMF with index α = 2.35. The solid lines in the various panels connect points corresponding to a gaussian distribution of rotational velocities, peaked around 110 Km/s.

of neutron–rich species (Meynet & Maeder 2002a; Limongi & Chieffi 2003).

Note that the effects of rotation are more important at the small metallicities, owing to the stronger meridional currents in these stars.

3. Pollution by intermediate mass stars

The stars of mass in the range 1M$_\odot$ <M<8M$_\odot$, after the end of core He–burning, enter the AGB phase, experiencing a series of thermal pulses, with periodic ignitions of helium in a thin layer above the degenerate core. For most of the time the energy is supplied by a CNO burning region (Herwig 2005).

AGBs finally evolve as White Dwarfs, after loosing their whole external mantle, leaving only the compact, degenerate core.

It is during the AGB phase that these stars pollute the interstellar medium, with gas contaminated by nuclear and internal mixing processes.

The surface chemical composition of AGBs is altered by two mechanisms: Third Dredge–Up (hereinafter TDU) and Hot Bottom Burning (HBB). The former is the inwards penetration of the base of the convective mantle in the evolutionary phases following each thermal pulse: surface convection reaches stellar regions previously touched by 3α nucleosynthesis, with the progressive enrichment in carbon of the surface zones. HBB is achieved when the base of the convective envelope becomes sufficiently hot to trigger an advanced p–capture nucleosynthesis (Renzini & Voli 1981; Blöcker & Schönberber 1991): the surface chemistry will be consequently changed, according to the equilibria of the nucleosynthesis experienced.

Fig. 2 shows the yields of AGB stars of various mass and metallicities in terms of the abundance of carbon, nitrogen and oxygen in the ejecta (Ventura et al. 2013a).

We see a trend with mass: low–mass stars (M< 3M$_\odot$), that experience only TDU, produce carbon, whereas higher mass objects, whose surface chemistry is dominated by HBB, eject carbon–poor matter, because the surface carbon is destroyed by proton capture reactions. The increase in the carbon content is more evident in lower metallicity stars, be-

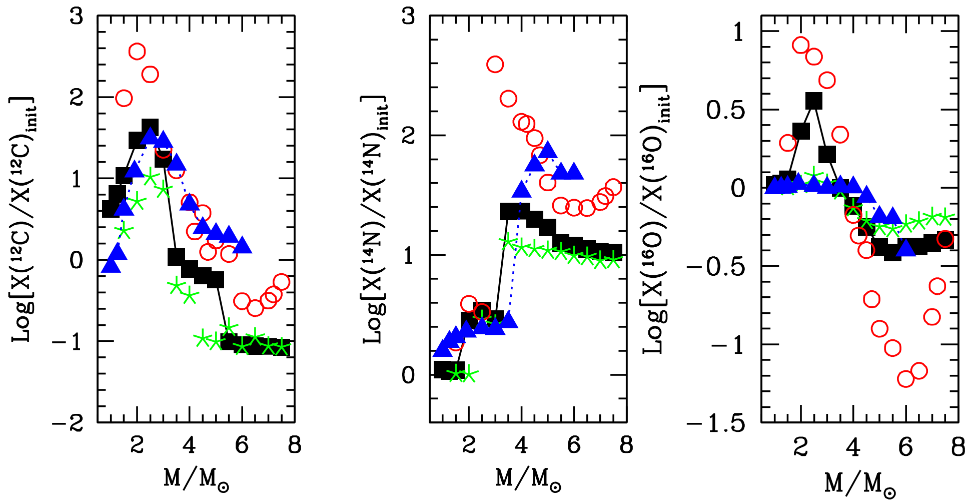

Fig. 2. Average abundance of carbon (left panel), nitrogen (middle), oxygen (right) in the ejecta of AGB stars of various metallicity as a function of the initial mass of the star. On the ordinate we show the ratio between the average mass fraction of the individual elements in the ejecta and the initial abundance. The meaning of the symbols is as follows: red, open circles: $Z = 3 \times 10^{-4}$ models; black, full squares: $Z = 4 \times 10^{-3}$; green crosses: $Z = 8 \times 10^{-3}$. These models are published in Ventura et al. (2013a). The blue, full triangles indicate $Z = 4 \times 10^{-3}$ models by Karakas (2010).

cause they experience a deeper TDU, and also, for a given quantity of carbon dredged–up to the surface, the percentage increase is higher.

Nitrogen is produced in the range of masses where HBB is active. In stars with mass $\sim 3M_\odot$, just above the threshold for HBB ignition, that also experience some TDU, great amounts of primary nitrogen are produced, owing to the conversion of carbon transported to the surface by TDU.

Oxygen is scarcely changed in low–mass stars, whereas it is destroyed in higher mass models, owing to the effects of full CNO cycling.

4. Dust production by stars

Type II supernovae and AGB stars are the major contributors of dust in the Universe. In both kinds of stars the conditions in the regions surrounding the stars are suitable to condensation of gas molecules into dust.

4.1. Dust from supernovae

Dust formation is predicted to occur after the shock wave following the explosion, propagating outwards, lifts the outermost regions, creating the conditions favourable to dust condensation.

The pioneering exploration by Todini & Ferrara (2001) depicted a two–step process, with the formation of graphite grains and corundum (Al_2O_3) particles in a first phase ($\sim$ 300 – 400d after the explosion), followed by the formation of silicates ($\sim$ 600d) and magnetite (Fe_3O_4).

The formation of solid carbon particles is extremely efficient, and practically all the carbon available is absorbed in this formation process; in this scenario, carbon grains grow until reaching dimensions of the order of $a_{car} \sim 0.03\mu$m.

Corundum formation is also highly efficient, although the scarcity of aluminium available limits the growth of Al_2O_3 grains to

$a_{Al_2O_3} \sim 0.002\mu$m, similar to the size reached by silicates and magnetite particles.

The total mass M_d of dust produced turns out to be dependent on the metallicity. SNe of primordial metallicity with masses in the range $12M_\odot < M < 40M_\odot$ produce a mass $M_d \sim 0.1-0.3M_\odot$, these values increasing by a factor ~ 3 for solar metallicity SNe.

These results seem to overestimate by at least two orders of magnitude the condensation efficiencies derived from IR observations, which indicate typical dust masses of the order of $M_d \sim 0.02M_\odot$ (Green at al. 2004).

To understand whether the dust yields by Todini & Ferrara (2001) are overestimated, Bianchi & Schneider (2007) reconsidered the model proposed by Todini & Ferrara (2001), accounting also for the effects of a reverse shock: these conditions are seriously hostile for the already formed dust grains, owing to the impact of gas particles, that transfer thermal and kinetic energy, thus eroding the dust grains present.

This process favours the formation of smaller particles, with the total mass of dust formed decreasing by one–two orders of magnitude, depending on the density ρ_{ISM} of the interstellar medium: the higher is ρ_{ISM}, the faster travels the reverse schock, which increases the efficiency of the sputtering process, and the erosion of dust grains.

4.2. Dust from AGBs

The regions surrounding AGBs are extremely favourable to dust formation. This is because these stars evolve at low photospheric temperatures, thus their winds are sufficiently cool to allow condensation of gaseous molecules in regions not too far from the surface of the star, where the densities are large enough to allow a substantial growth of the size of dust grains (Ferrarotti & Gail 2001, 2002, 2006).

The dust formation process is also enhanced by the large mass loss rates experienced, that increase the density in the wind, thus allowing more and more gas molecules to imping on the already formed grains, favouring their further growth.

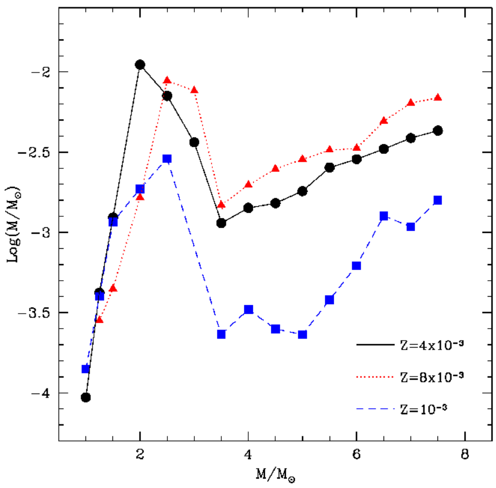

Fig. 3. The mass of dust produced by AGB stars of various mass and metallicity, taken from Ventura et al. (2013b). Stars of mass M> 3M$_\odot$ produce silicate–type dust, whereas stars of smaller mass produce carbonaceous particles.

The dust formed exhibits a well defined trend with mass and metallicity (Ventura et al. 2013b), as shown in Fig. 3, that reports the mass of dust formed for models of various initial masses and metallicities.

Stars with mass below ~ 3M$_\odot$ form mainly carbon type dust, owing to the effects of TDU, which gradually increases the surface carbon, leading to the formation of a carbon star. These stars produce $10^{-3} - 10^{-2}$M$_\odot$ of dust, essentially under the form of solid carbon. These numbers are almost independent of metallicity, because the carbon transported to the surface of the star is of primary origin, being synthesized in the internal helium–burning shell.

More massive stars produce silicate–type dust. The reason is that these stars experience HBB, thus their surface carbon is destroyed by p–capture reactions. The amount of silicates formed increases with the initial mass of the star, because the higher is the mass, the stronger is the HBB experienced, the larger is the rate at which they loose the external envelope: this increases the density of the wind, enhancing the condensation efficiency.

Unlike their lower mass counterparts, in this case the mass produced depends on metallicity. Solar metallicity models produce 10^{-3} – $10^{-2}M_{\odot}$ of dust, comparable to the lower mass stars; M_d scales in an approximately linear way with Z, because the amount of silicon available is also proportional to the metallicity.

5. Conclusions

The pollution by stellar sources is mainly determined by its initial mass, but also depends on the metallicity.

Stars initially more massive than $\sim 8M_{\odot}$ undergo core–collapse, and contaminate their surroundings mainly with material exposed to advanced $\alpha-$ capture nucleosynthesis. The yields exhibit a characteristic odd–even effects.

The yields from these sources depend on the description of rotation, which enhances the internal mixing processes, and change the predictions concerning some elements, particularly nitrogen and fluorine.

Intermediate mass stars pollute the interstellar medium via stellar winds during the AGB phase. The yields are different from their more massive counterparts: no element more massive than silicon is changed, the most significant changes involving the CNO elements. The yields of stars with mass below $\sim 3M_{\odot}$ are dominated by the Third dredge–up, and are extremely enriched in carbon. Higher masses undergo Hot Bottom Burning: their yields show up the signature of p–capture nucleosynthesis, thus being enriched in nitrogen, and depleted in their carbon and oxygen content.

Both groups of stars are efficient dust producers, mainly under the form of carbonaceous dust, silicates and corundum. The size of the grains formed, however, are different: while SNe produce dust particles of dimension 10^{-3} – $10^{-2}\mu$m, in the circumstellar envelopes of AGBs silicates and carbon grains reach dimensions of the order of 0.1μm.

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