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What can pre-solar grains tell us about AGB stars?

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Abstract. The vast majority of pre-solar grains recovered to date show the signature of an origin in asymptotic giant branch (AGB) stars. In AGB stars, the abundances of elements lighter than silicon and heavier than iron are largely affected by proton- and neutron-capture processes, respectively, while the compositions of the elements in between also carry the signature of the initial composition of the star. Dust is produced and observed around AGB stars and the strong mass loss experienced by these stars is believed to be driven by radiation pressure on dust grains. We briefly review the main developments that have occurred in the past few years in the study of AGB stars in relation to dust and pre-solar grains. From the nucleosynthesis point of view these include: more stringent constraints on the main neutron source nucleus, ^{13}C, for the *slow* neutron capture process (the *s* process); the possibility of pre-solar grains coming from massive AGB stars; and the unique opportunity to infer the 'isotopic' evolution of the Galaxy by combining pre-solar grain data and AGB model predictions. Concerning the formation of grains in AGB stars, considerable progress has been achieved in modelling. In particular, self-consistent models for atmospheres and winds of C-stars have reached a level of sophistication which allows direct quantitative comparison with observations. In the case of stars with C/O < 1, however, recent work points to serious problems with the dust-driven wind scenario. A current trend in atmosphere and wind modelling is to investigate the possible effects of inhomogenieties (e.g., due to giant convection cells) with 2D/3D models.

Keywords. nuclear reactions, nucleosynthesis, abundances, stars: AGB and post-AGB, stars: mass loss, stars: winds, outflows

1. Nucleosynthesis in AGB stars and the isotopic compositions of pre-solar grains

Toward the end of their lives stars of masses roughly less than 7 $M_\odot$ go through the asymptotic giant branch (AGB) phase, during which the He- and the H-burning shells are activated alternately on top of a degenerate C-O core and below a large convective envelope. Material in the tiny region between the two shells (intershell) is processed by H-burning and partial He-burning, as well as suffering neutron-capture processes, thus resulting in peculiar nucleosynthesis including the production of ^{12}C, ^{19}F, ^{22}Ne, ^{26}Al as well as of elements heavier than iron such as Zr, Ba and Pb by *slow* neutron captures (the *s* process). This material is mixed to the surface of the star by recurrent episodes of mixing collectively known as the third dredge-up and is thus incorporated into dust grains forming around the star, which are now recovered from primitive meteorites as pre-solar grains.

One of the most important evidences of the origin of pre-solar mainstream SiC grains in AGB stars is the signature of *s*-process nucleosynthesis in all heavy elements analysed to date in these grains, both in bulk, i.e. measurements on a large number of grains, and individually. The main neutron source for the s process in the intershell of AGB stars is the $^{13}C(\alpha, n)^{16}O$ reaction. The production of ^{13}C is possible via the ^{12}C+p reaction, if protons from the envelope diffuse into the ^{12}C-rich intershell. However, it is still much debated by which mechanism the proton diffusion occurs and, hence, the amount of ^{13}C nuclei is treated as a free parameter in the models. A detailed analysis of the composition of Sr, Zr, Mo, and Ba in single SiC grains and in AGB models was presented by Lugaro *et al.* (2003). It was shown that a large spread (factor of 24) in the amount of ^{13}C was needed to cover the SiC data, thus confirming the results obtained by Busso *et al.* (2001) by comparing single-star models to spectroscopic observations of the heavy element distribution in AGB stars at different metallicities.

However, one problem with the SiC data is that it is difficult to exclude or evaluate *a priori* the level of contamination of terrestrial material, which would shift isotopic ratios toward solar composition. This is especially true for elements like Sr and Ba, which are more volatile than Zr and Mo, and thus are present in the grains in lower amounts. Barzyk *et al.* (2006) recently measured the composition of more than one heavy element in single SiC grains, thus making it possible to identify contaminated grains. The uncontaminated grain data could be matched by a much smaller spread (a factor of two) than that used by Lugaro *et al.* (2003), confirming recent results obtained by Bonačić Marinović *et al.* (2007) by comparing stellar population models including the s process to spectroscopic observations.

From the comparison between grain data for heavy elements and s-process models, it is derived that most of the pre-solar grains from AGB stars must have formed around stars of low mass ($M < 3\,M_\odot$). However, a unique pre-solar spinel grain, OC2, has been identified to be the first pre-solar grain to possibly show the signature of nucleosynthesis in intermediate-mass (IM) AGB stars ($4\,M_\odot < M < 7\,M_\odot$), suffering H-burning at the base of the convective envlope (hot bottom burning, HBB). The main hint to such an origin comes from the large observed excesses in the heavy Mg isotopes. Lugaro *et al.* (2007) show that models of IM-AGB stars can reproduce the Mg and O composition of grain OC2 and, within this framework, predictions can be made for the value of the ^{16}O+p and ^{17}O+p reaction rates. Grain OC2, and similar grains that may be recovered in the future, has opened the possibility to derive constraints also on massive AGB models from the study of pre-solar grains.

The compositions of elements such as Si, Ti, Ca and Fe in pre-solar grains from AGB stars are determined by the initial composition of the parent star and by the nucleosynthesis occurring within it. By combining a large amount of Si data from SiC grains of mainstream, Y and Z populations to a variety of detailed models of the nucleosynthesis in AGB stars of different masses and metallicities down to $\sim 1/10\,Z_\odot$, Zinner *et al.* (2006) were able to infer the Galactic chemical evolution of the Si isotopes. The evolution based on the grain data predicts much higher ^{29}Si and ^{30}Si abundances at low metallicities than calculated by the models of Timmes & Clayton (1996). This indicates perhaps a low-metallicity source for these isotopes not considered so far, or some other problems with the Galactic chemical evolution model. This kind of work can be extended to other intermediate-mass elements, making pre-solar grains an ideal tool to study the evolution of isotopic abundances in the Galaxy.

2. The role of grains in atmospheres and winds of AGB stars

For a long time, dust has been treated as just another opacity source in models of atmospheres and winds, in order to provide radiation pressure for driving the wind, or

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fitting observed spectra. Detailed studies of the actual grain formation process in the atmospheres of AGB stars are a rather recent development, especially in the context of self-consistent, time-dependent dynamical models. Such models have become more and more sophisticated during the past decade, and, in some cases, they have reached a level where a direct quantitative comparison with observations becomes possible (see recent reviews, e.g., by Woitke (2003) and Höfner (2005), for an overview of historical developments and a discussion of modelling methods).

The latest generation of models for atmospheres and winds of C-rich AGB stars by Höfner *et al.* (2003), combining a frequency-dependent treatment of radiative transfer with time-dependent hydrodynamics and a detailed description of dust formation, compares nicely with various types of observations, such as low-resolution NIR spectra (Gautschy-Loidl *et al.* 2004) or profiles of CO vibration-rotation lines (Nowotny *et al.* 2005ab). The combination of dynamics, taking into account effects of pulsation and shock waves, and frequency-dependent radiative transfer, accounting for molecules and dust, turns out to be crucial for a reasonably realistic description of AGB atmospheres, and thus for modelling the conditions in the zone where the dust grains are formed. With these non-grey dynamical models it is possible for the first time to simultaneously reproduce the time-dependent behavior of fundamental, first and second overtone vibration-rotation lines of CO, features originating in the outflow, dust formation region, and pulsating atmosphere, respectively, probing the dynamics from the photosphere out into the wind.

Such detailed models, however, rely on fundamental physical and chemical data for dust grain materials measured in the laboratory, and in particular optical properties. Andersen *et al.* (2003) studied the effects of microphysical grain properties in the context of detailed dynamical models for atmospheres and winds of C-stars as described above, using data obtained by Jäger *et al.* (1998). It is commonly assumed that grains in C-stars mostly consists of amorphous carbon, a term that actually covers a variety of materials with varying ratios of sp^2 to sp^3 hybridization of the C atoms. The microphysical structure of the grain material, however, will lead to different optical properties in the near IR, with sp^3-rich material showing a much steeper dependence on wavelength than sp^2-rich material. In non-grey wind models, these differences in the optical properties of the grains influence both the flux-integrated opacity relevant for driving the wind and the grain temperature, and therefore the actual dust formation process.

While recent advances in modelling, in particular the inclusion of frequency-dependent radiative transfer, have lead to a better agreement between models and observations of C-rich AGB stars, the opposite seems to be true for the O-rich case. Jeong *et al.* (2003) presented wind models for M-type stars, combining a detailed description of dust formation with time-dependent dynamics and grey radiative transfer. The combinations of stellar parameters used in this study may be considered as somewhat on the extreme side (high luminosities and low effective temperatures), but their models lead to reasonable wind velocities and mass loss rates. Recent work by Woitke (2006b) and Höfner (2006), including frequency-dependent radiative transfer for gas and dust, however, points to a serious problem with the dust-driven wind scenario. The higher the Fe-content of grains, the steeper the slope of the opacity as a function of wavelength, and thus the higher the radiative equilibrium temperature of the grains. In practice, this means that the Fe-content of silicate grains will be very low, in order to allow for condensation reasonably close to the star. This, in turn, leads to a low flux-integrated opacity of the grains which is not sufficient to drive a stellar wind for typical stellar parameters. At present it seems that alternative wind scenarios for M-type stars should possibly be considered.

Another new development is 2D/3D models of atmospheres and circumstellar envelopes around AGB stars. The computational effort behind such models is considerable, and a number of simplifications have to be introduced in the physics, compared to the detailed spherical models discussed above. In the light of recent interferometric observations which indicate deviations from spherical symmetry, however, it seems necessary to spend some effort testing possible causes and consequences for dust formation and winds. Woitke (2006a) presented 2D (axisymmetric) dust-driven wind models, including time-dependent dust formation and grey radiative transfer, and studied how instabilities in the dust formation process (originally found in earlier spherical models) create intricate patterns in the circumstellar envelope. These models, however, exclude the central star and its pulsation. Freytag & Höfner (2003, 2006), on the other hand, developed complementary 3D RHD 'star-in-a-box' models (including time-dependent dust formation) to investigate the effects of giant convection cells and of the resulting shock waves in the atmosphere on dust formation. The atmospheric patterns created by convective motions are found to be reflected in the circumstellar dust distribution, due to the strong sensitivity of grain formation to temperatures and gas densities.

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