Dust Formation and Winds around Evolved Stars: The Good, the Bad and the Ugly Cases

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Abstract. Cool luminous giants, in particular asymptotic giant branch stars, are among the most important sources of cosmic dust. Their extended dynamical atmospheres are places where grains form and initiate outflows driven by radiation pressure, leading to considerable stellar mass loss and the enrichment of the interstellar medium with newly-produced elements. This review summarizes the current understanding of dust formation and winds in such stars, sketching a system of criteria for identifying crucial types of dust grains in the range of possible condensates. Starting with an overview of the specific conditions for dust formation in cool dynamic atmospheres, the role of grains as wind drivers, as well as their influence on observable properties of cool giants and the circum-stellar environment is discussed in some detail. Regarding the literature, special attention is given to current developments, e.g., the debate concerning the Fe-content and size of silicate grains in M-type AGB stars which are critical issues for the wind mechanism, or recent advances in spatially resolved observations and 3D modeling of giants and their dusty envelopes.

1. Introduction

Dust formation in evolved stars is a wide topic with many aspects, and more than a few unknowns, despite several decades of research. It is central to our understanding of the cosmic matter cycle, and, consequently, connected to a range of other astrophysical questions, e.g., the chemical evolution of galaxies, pre-solar dust grains, and the formation of planetary systems. The atmospheres of cool evolved giants and super-giants are sites where newly-produced chemical elements can nucleate into dust grains which, in turn, may drive massive outflows, enriching the interstellar matter with the products of stellar nucleosynthesis. Developments in observational techniques such as space- and ground-based infra-red spectroscopy, sub-millimeter observations and interferometry, combined with laboratory work on grain materials, and progress in numerical modeling have substantially improved the understanding of these processes, but also pointed at gaps in our knowledge regarding micro-physical and chemical aspects of dust formation.

Asymptotic giant branch (AGB) stars, i.e., low- and intermediate mass stars in the final phases of their evolution, have to be counted among the most important sources of cosmic dust, and in particular carbon grains. Mass loss through radiation pressure on dust particles eventually reaches such high rates that a considerable fraction of the stellar mass is blown away, sealing the fate of the star. With decreasing stellar mass, increasing luminosity, and decreasing
effective temperature, mass loss turns into a runaway process where material is transported away from the stellar surface faster than nuclear reactions change the stellar interior. Finally, when the core of the star evolves into a white dwarf, expelled material may briefly become visible as a planetary nebula before it is dispersed into the interstellar medium[1]

Other types of evolved stars, i.e., red giant branch stars and cool supergiants, also show signs of stellar winds. In these cases, however, the role of dust and the actual driving mechanisms of their outflows are more uncertain. In this review the discussion will therefore be centered around AGB stars and structured into the following main areas: First, the stage is set with an overview of the specific conditions for grain formation and growth in the complex environment of cool dynamic stellar atmospheres. Then the role of the newly-formed dust grains as potential wind drivers is discussed in some detail, followed by a brief overview of effects of dust formation and mass loss on the circumstellar and interstellar environment.

2. Dust formation in cool giants: physical and chemical aspects

While dust is an important component of many cool astrophysical environments, some rather specific conditions apply to grain formation in evolved stars. They can roughly be grouped into chemical and dynamical aspects which, combined with prevailing thermodynamic conditions, lead to characteristic properties of the resulting dust particles.

Typical effective temperatures of AGB stars are around 3000 K, i.e. quite low in stellar terms but not low enough to allow for condensation of solids in the photospheric layers of the stars. Therefore, dynamics is commonly assumed to play a key role in the dust formation process. Shock waves – caused by stellar pulsation or large-scale convective motions – propagate outwards through the atmosphere and lift gas above the stellar surface, intermittently creating dense, cool layers where solid particles may form. These dust grains are then accelerated away from the star by radiation pressure (provided that their radiative cross sections are high enough), transmitting momentum to the gas through collisions, and dragging it along. This chain of events supposedly leads to the observed outflows with typical mass loss rates of $10^{-7} - 10^{-4} \text{M}_\odot/\text{yr}$ and wind velocities in the range of 5 – 30 km/s.

2.1. Atmospheric composition and grain materials

The raw material available for condensation of solids comes from two sources, i.e., the original stellar matter – product of previous generations of stars – which made up the star in question at the time of its formation, and the products of nucleo-synthesis of the individual star which are mixed to the surface by convection. As both nucleo-synthesis and convection are ongoing processes, the

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[1] The occurrence of a planetary nebula phase depends on how the timescale for the evolution of the stellar core compares to the expansion of the circumstellar envelope. The lowest mass stars probably evolve so slowly that the wind material is dispersed before it can be ionized.
Figure 1. Schematic picture of atmospheric chemistry in AGB stars: the relative abundances of C and O lead to three different cases due to the high bond energy of CO. The less abundant element is completely bound in CO (cross-hatched area), the excess O (M-stars) or C (C-stars) is available for other molecules and dust grains.

A crucial aspect in AGB stars is that the relative abundances of carbon and oxygen change due to ongoing nuclear burning and dredge-up of processed material, starting out with C/O < 1 and potentially reaching C/O > 1 for stars within a certain initial mass and metallicity range (cf. Lattanzio & Wood 2004 for an overview of stellar evolution on the AGB). The high bond energy of the CO molecule leads to three different types of atmospheric chemistries, corresponding to different spectral types (cf. Fig. 1):

- C/O < 1: all carbon is bound in CO, the excess oxygen is available for the formation of other molecules and dust (M-type);
- C/O ≈ 1: nearly all carbon and oxygen atoms are bound in CO, less abundant elements are crucial for the molecular composition of the gas, no abundant grain-forming materials are available (S-type);
- C/O > 1: all oxygen is bound in CO, the excess carbon is mainly in the form of hydrocarbon molecules and carbon grains (C-type).

In order to predict which types of condensates will be dominant in the different cases, some further aspects have to be taken into consideration: Condensation temperatures of grain materials indicate in which order different types...
of solids may form in response to falling ambient temperatures as gas is moving away from the stellar surface due to shocks or the onset of a wind. Gas densities and element abundances regulate the nucleation and growth timescales of grains, and, consequently the efficiency of condensation. According to these criteria, the most abundant dust types should be those which combine a high condensation temperature with high abundances of their key ingredients. In practice, this means that silicates in the form of olivine-type materials, i.e. Mg$_{2x}$Fe$_{2(1-x)}$SiO$_4$ (with $0 \leq x \leq 1$), and/or pyroxene-type materials, i.e. Mg$_x$Fe$_{(1-x)}$SiO$_3$, should be dominant in M-type AGB stars, while C-stars should mainly produce amorphous carbon grains and some SiC (see Gail 2003 for an in-depth discussion of dust processes in AGB stars). These conclusions fit well with observed features in infrared spectra of AGB stars.

2.2. Dust formation: beyond the simple picture

At this point, we need to add a few caveats which have implications for the following discussion of dust grains as drivers or (by-)products of stellar winds.

Regarding C-stars, it has to be noted that the term amorphous carbon describes a whole class of materials with different microscopic structures. Laboratory studies demonstrate that the ratio of sp$^2$ to sp$^3$ bonds in a specific sample will influence both the optical properties and the bulk density of the grain material (see, e.g., Jäger et al. 1998). This, in turn, affects the dynamic characteristics and observable properties of wind models (cf. Andersen et al. 2003). A further source of uncertainty is the relationship between the SiC component, inferred from the spectral feature around 11 $\mu$m, and the featureless – i.e., observationally not directly accessible – amorphous carbon component which, however, dominates the overall dust opacity and determines the driving force of the wind. At present it is unclear, whether these two types of condensates occur together or separately, with a fixed ratio or not.

Concerning the composition of silicate grains in M-type AGB stars, theoretical considerations favor olivine-type materials over pyroxene-type condensates (e.g., Gail & Sedlmayr 1999, Ferrarotti & Gail 2001) but observations are rather inconclusive on this point. Furthermore, the Mg/Fe ratio of the grains has recently become a matter of debate. From a simple gas kinetic point of view (in contrast to chemical equilibrium condensation which is not applicable in the dynamical atmospheres and winds of AGB stars, see below) one would expect about equal amounts of Mg and Fe to be included in the dust particles, corresponding to their roughly equal abundances (for a solar mixture; cf. Gail & Sedlmayr 1999). This line of reasoning, however, ignores non-grey radiative effects on grain temperature which will strongly favor the Fe-free end members of the olivine and pyroxene sequences (cf. Woitke 2006b).

The core of this issue can be understood with rather simple analytical arguments: The growth and survival of dust particles requires grain temperatures below the stability limit of the respective condensate. The temperature of a grain will be mostly determined by its interaction with the radiation field, and, consequently, a condensation radius $R_c$ can be defined as the distance from the star where the radiative equilibrium temperature of a grain is equal to the condensation temperature $T_c$ of the material, i.e. the closest distance where such grains can exist. Assuming a Planckian radiation field, geometrically diluted
with distance from the star, and a power law for the grain absorption coefficient \( \kappa_{\text{abs}}(\lambda) \) in the relevant wavelength range (near 1 \( \mu \)m, around the flux maximum of the stellar photosphere) the condensation radius can be expressed as

\[
\frac{R_c}{R_*} = \frac{1}{2} \left( \frac{T_c}{T_*} \right)^{-\frac{4+6p}{2}}
\]

where \( \kappa_{\text{abs}} \propto \lambda^{-p} \) (1)

(for details see Höfner 2007 and references therein). Figure 2 shows the condensation distance \( R_c \) (in units of the stellar radius \( R_* \)) as a function of the power law index of the absorption coefficient \( p \) for a range of condensation temperatures \( T_c \) (assuming a stellar temperature of \( T_* = 3000 \) K). For silicates, \( T_c \approx 1000 \) K and \( p \) is strongly dependent on the Mg/Fe ratio. Considering olivine-type material, grains with about equal amounts of Fe and Mg lead to \( p \approx 2 \) for the absorption coefficient of small grains and, consequently, to \( R_c/R_* > 10 \), whereas iron-free particles with a corresponding value of \( p \approx -1 \) can form at typically \( R_c/R_* \approx 2-3 \) (comparable numbers are valid for pyroxene-type particles). For
amorphous carbon grains with $T_c \approx 1500$ K and $p \approx 1$ condensation distances are comparable to Fe-free silicates, i.e., $R_c/R_\star \approx 2 - 3$. Despite the approximations used in these estimates, these numbers compare well with detailed models.

The dependence of condensation distance on grain properties – in particular the strong variation of $R_c$ with Mg/Fe in silicates – may have far-reaching consequences for the role of various dust species as potential wind drivers or by-products of stellar outflows as will be further discussed in the following sections. A few general remarks, however, should be made already at this point.

A decisive but often ignored feature of dust condensation in stellar atmospheres and winds is that low enough temperatures are a necessary condition for the formation or survival of dust grains, but not a sufficient one. Grain formation and growth rates are dependent on prevailing gas densities and element abundances which together affect the collision rates of condensable material in the gas phase with other building blocks and existing grains. These rates have to be compared to the typical dynamical timescales connected with pulsations and outflows in order to determine which types of dust particles will dominate in AGB stars. Dust materials with low condensation rates caused by low abundances of key ingredients or low condensation temperature (synonymous with low gas density in the present context) are unlikely to form in the time-critical environment of a cool giant’s atmosphere or wind. As matter moves away from the star, the temperature decreases which favors condensation. At the same time, however, the nucleation and growth of dust particles turns into a race against falling densities. This results in non-equilibrium compositions of the gas and dust phases and incomplete condensation (dust-to-gas ratios different from chemical equilibrium values) in the outflow (see, e.g., Ferraotti & Gail 2001 for a more detailed discussion). Consequently, the formation probability of grain materials decreases drastically with increasing condensation radius, due to the strong dependence of gas density (and therefore condensation rates) on distance from the star.

Simple estimates based on gas kinetics as presented in Gustafsson & Höfner (2004) show that the timescales for the growth of carbon grains close to the condensation radius are on the order of a year, i.e. comparable with the pulsation period of the star, and increasing outwards with falling density. This is in good agreement with detailed numerical models which tend to show mean degrees of condensation well below unity (typically 0.3-0.5), and a rather limited zone of grain growth.

3. Dust as a wind driver

3.1. Basic principles

In order to illustrate the interplay between atmospheric dynamics and dust grains, the following simple model is adopted: The dynamical evolution of a single mass element is described from an instant when it has just been accelerated outwards by a passing shock wave to the point where it is accelerated beyond the escape velocity, or starts falling back towards the stellar surface. Assuming that gravity and radiation pressure are the only relevant forces (which is a reasonable
approximation between shocks), the equation of motion can be written as

\[
\frac{du}{dt} = -g_0 \left( \frac{r_0}{r} \right)^2 (1 - \Gamma) \quad \text{with} \quad \Gamma = \frac{\kappa_H L_\ast}{4 \pi c G M_\ast}
\]  

(2)

where \( r \) is the distance from the stellar center, \( u = dr/dt \) the radial velocity, \( g_0 = GM_\ast/r_0^2 \) denotes the gravitational acceleration at \( r_0 \), \( \kappa_H \) the flux mean opacity, and \( M_\ast \) and \( L_\ast \) are the stellar mass and luminosity, respectively (\( c = \) speed of light, \( G = \) gravitation constant). Atmospheric shocks due to stellar pulsation or large-scale convective motions enter the picture by setting the initial velocity \( u_0 \) of the matter element.

After the passage of a shock, the mass element first follows a ballistic trajectory (since \( \Gamma \ll 1 \) in the hot dust-free gas close to the photosphere), slowing down gradually due to gravity. If no (or very little) dust is forming, \( \Gamma \) will stay close to zero and the matter will reach a maximum distance \( r_{\text{max}} \) according to its initial velocity \( u_0 \) given by

\[
\frac{r_0}{r_{\text{max}}} = 1 - \left( \frac{u_0}{u_{\text{esc}}} \right)^2 \quad \text{where} \quad u_{\text{esc}} = \sqrt{\frac{2GM_\ast}{r_0}}
\]  

(3)

(\( u_{\text{esc}} = \) escape velocity at \( r_0 \)) and then fall back towards the stellar surface.

As the formation and survival of dust grains requires temperatures below the condensation temperature of the respective material, grains will not exist closer to the stellar surface than their corresponding condensation distance \( R_c \) (cf. Sect. 2). If the initial velocity imparted on the gas element by the passing shock is high enough that the material reaches distances beyond \( R_c \), grain formation and growth may set in, causing \( \kappa_H \) and thereby \( \Gamma \) to increase. In this case, we can distinguish several scenarios:

- If \( \Gamma > 1 \), \( du/dt \) is positive, the matter is accelerated away from the star.
- If \( \Gamma = 1 \), the r.h.s of the equation of motion vanishes. The matter element continues to move at a constant velocity.
- If \( 0 < \Gamma < 1 \), the final fate of the matter element (escape or fall-back) depends on the velocity at which it is moving when it reaches the dust formation zone. As a positive value of \( \Gamma \) can be interpreted as a reduction of the effective gravitational acceleration, the corresponding local escape velocity is smaller than in the dust-free case, leading to a narrow regime where the combined momentum transferred by the shocks and the radiation pressure on dust drive the matter away from the star (cf. Höfner 2007 for a more detailed discussion).

Figure 3 illustrates the different scenarios (for stellar parameters \( M_\ast = 1 M_\odot \), \( L_\ast = 7000 L_\odot \), \( T_\ast = 2700 \text{K} \), and initial conditions \( r_0 = R_\ast \), \( u_0 = 0.8 u_{\text{esc}} \)).

\[2\] In the discussion here we assume that the velocity of the mass element is below the escape velocity before the material reaches the dust condensation zone. Otherwise it would be misleading to talk about a dust-driven wind.
Figure 3. A toy model for atmospheric dynamics, showing the location of a matter element (i.e., its distance from the stellar center) as a function of time. The velocity is determined by assuming a distance-dependent $\Gamma$ (ratio of radiative acceleration to gravitational acceleration) in the equation of motion, i.e., $\Gamma = 0$ for $r < R_c$ (no dust), and $\Gamma = \text{constant}$ at distances beyond $R_c$. Both, the value of $\Gamma$ (varied in upper panel, for constant $R_c$) and the condensation distance $R_c$ (varied in lower panel, for constant $\Gamma$) play a crucial role for the onset of a stellar wind. See text for details.
assuming that $\Gamma = 0$ for $r < R_c$ (no dust), and $\Gamma =$ constant at distances beyond $R_c$. This is, of course, a simplification of the real situation where dust formation and grain growth are spread out over a range of distances (see Höfner 2008b for a more elaborate toy model including grain growth), and, in addition, the resulting flux mean opacity may vary due to other factors than the changing amount of material condensed into grains\footnote{Note that the optical depth of the circumstellar envelope at wavelengths around the stellar flux maximum may have a critical influence on the flux mean opacity $\kappa_H$ and, consequently, on the variation of $\Gamma$ with distance from the star. As the optical depth approaches unity, a matter element moving outwards will be increasingly shielded from the direct stellar radiation, and will instead be exposed to the flux emitted by the inner layers of the circumstellar envelope, with the flux maximum shifting to larger wavelengths, corresponding to lower temperatures. In a case where the dust opacity decreases with increasing wavelength (e.g., for small amorphous carbon grains in the near infrared) this will lead to a decrease of $\Gamma$ with distance. As a high optical depth of the circumstellar envelope is connected to high opacities and/or high densities, the shielding effect will not be significant in winds close to the threshold for dust-driven mass loss, but it may regulate the terminal velocity of outflows corresponding to the highest mass loss rates. Also, it should be noted that this is mostly relevant for C-rich AGB stars (amorphous carbon grains), while envelopes of M-type objects usually have comparatively low optical depths in the near infrared.}. The simple toy model, however, makes it easy to demonstrate that both, the total opacity of the dust grains (i.e. the resulting $\Gamma$) and the condensation distance $R_c$ play a crucial rule for the onset of a stellar wind (see Fig. 3, upper and lower panel, respectively). Even a small difference in $R_c$ for different grain materials can have a dramatic effect on their potential as a wind drivers.

While grain temperatures and, consequently, condensation distances are determined by the respective absorption cross sections, the opacities relevant for radiative pressure are a more complex topic. The corresponding grain cross sections are given by a combination of absorption and scattering, i.e.

$$C_{\text{rp}} = C_{\text{ext}} - g_{\text{sca}} C_{\text{sca}} = C_{\text{abs}} + (1 - g_{\text{sca}}) C_{\text{sca}}$$

where $C_{\text{abs}}$, $C_{\text{sca}}$ and $C_{\text{ext}}$ denote the cross sections for absorption, scattering and extinction, respectively, $g_{\text{sca}}$ is the asymmetry factor describing deviations from isotropic scattering ($g_{\text{sca}} = 0$ for the isotropic case, $g_{\text{sca}} = 1$ corresponding to pure forward scattering, i.e., no momentum being imparted on the grain due to scattering; see, e.g., Krügel 2003), and $C_{\text{rp}}$ may depend severely on grain size, as well as on material properties.

In order to compute the total flux mean opacity $\kappa_H$, determining the radiation pressure and, consequently, $\Gamma$, it is necessary to know the combined opacity (cross section per mass) of all grains of a certain size (i.e., radius $a_{\text{gr}}$, for spherical particles) in a matter element (with a total mass density $\rho$),

$$\kappa_{\text{rp}}(\lambda, a_{\text{gr}}) = C_{\text{rp}}(\lambda, a_{\text{gr}}) n_{\text{gr}} \frac{1}{\rho}$$

($n_{\text{gr}} =$ number density of grains of radius $a_{\text{gr}}$) at all relevant wavelengths $\lambda$. Introducing the efficiency $Q_{\text{rp}} = C_{\text{rp}}/\pi a_{\text{gr}}^2$ (radiative cross section divided by geometrical cross section) which can be calculated from refractive index data
using Mie theory (cf., e.g., Bohren & Huffman 1983) the dust opacity defined above can be reformulated as

$$\kappa_{rp}(\lambda, a_{gr}) = \pi a_{gr}^2 Q_{rp}(\lambda, a_{gr}) \frac{1}{\rho} = \frac{\pi}{\rho} \frac{Q_{rp}(\lambda, a_{gr})}{a_{gr}} a_{gr}^3 n_{gr}$$

where $a_{gr}^3 n_{gr}$ represents the volume fraction of a stellar matter element which is occupied by grains, apart from a factor $4\pi/3$. This quantity can be rewritten in terms of the space occupied by a monomer (basic building block) within the condensed material, $V_{mon}$, times the number density of condensed monomers in the matter element under consideration, $n_{mon}$, i.e.,

$$a_{gr}^3 n_{gr} = \frac{3}{4\pi} V_{mon} n_{mon} = \frac{3}{4\pi} \frac{A_{mon} m_p}{\rho_{grain}} f_c \varepsilon_c n_H$$

where the monomer volume $V_{mon}$ has been expressed in terms of the atomic weight of the monomer $A_{mon}$ and the density of the grain material $\rho_{grain}$ ($m_p =$ proton mass). Assuming, for simplicity, that all grains at a given location have the same size, the number density of condensed monomers $n_{mon}$ has been rewritten as the product of the abundance of the key element of the condensate $\varepsilon_c$, the degree of condensation of this key element $f_c$, and the total number density of H atoms $n_H$. Using $n_H = \rho/(1 + 4\varepsilon_{He}) m_p$ (where $\varepsilon_{He}$ denotes the abundance of He), we obtain

$$\kappa_{rp}(\lambda, a_{gr}) = \frac{3}{4} \frac{A_{mon}}{\rho_{grain}} \frac{Q_{rp}(\lambda, a_{gr})}{a_{gr}} \frac{\varepsilon_c}{1 + 4\varepsilon_{He}} f_c.$$ 

This way of writing the dust opacity which may seem unusual at first has the advantage of distinguishing between material properties (constants and optical properties) and the chemical composition of the atmosphere/wind, and allows to take into account that $Q_{rp}(\lambda, a_{gr})/a_{gr}$ becomes independent of grain size for particles much smaller than the wavelength $\lambda$. For a given grain material and stellar element abundances, the only unknown quantity in this expression of the opacity is the degree of condensation $f_c$ (i.e. the fraction of available material actually condensed into grains). As dust formation in AGB stars usually proceeds far from equilibrium, $f_c$, in general, needs to be calculated with detailed non-equilibrium methods such as those described by, e.g., Gail & Sedlmayr (1988, 1999). Assuming a reasonable value for $f_c$, however, this equation allows to estimate which grain types can, in principle, drive an outflow, and which alternatives can be ruled out for this purpose based on too small radiative pressure.

Taking amorphous carbon as an example ($A_{mon} = 12$), the optical properties according to Rouleau & Martin (1991) give $Q_{rp}(\lambda, a_{gr})/a_{gr} \approx 2 \cdot 10^4 [1/cm]$ at $\lambda \approx 1 \mu m$ (near the stellar flux maximum) in the small particle limit, with a corresponding density of the grain material $\rho_{grain} = 1.85 [g/cm^3]$. Assuming C/O = 1.5 at solar metallicity, leading to $\varepsilon_c = 3.3 \cdot 10^{-4}$ (abundance of excess carbon not bound in CO), together with complete condensation of all available carbon ($f_c = 1$), $L_\star = 5000 L_\odot$ and $M_\star = 1 M_\odot$, results in $\Gamma \approx 10$. This is clearly more than enough for driving the wind of a typical AGB star, and even a small fraction of the available carbon being condensed into grains (about 10-20 percent in this case) will be sufficient to cause an outflow.
3.2. Detailed dust-driven wind models and observations

Radiation pressure on dust grains has long been suspected to be the driving force behind the slow, massive outflows observed in cool giants, in particular for carbon stars (see, e.g., Dorschner 2003 or Habing and Olofsson 2004 for historical overviews), but early modeling attempts had to rely on crude assumptions regarding dust properties and dynamics (not to mention radiative transfer and molecular opacities) due to a lack of input data and insufficient computational resources. Time-dependent dynamical models of pulsating atmospheres and dust-driven winds where pioneered by Wood (1979) and Bowen (1988), taking the effects of atmospheric shock waves due to pulsation into account but reducing the description of dust to simple parameterized opacities, without a treatment of grain formation and destruction. Consequently, these models could only predict mass loss rates and other wind characteristics but they allowed no conclusions about grain types and dust yields.

Progress in computational resources and new data from laboratory studies of dust materials eventually made it possible to adopt a more detailed, time-dependent description of the dust component, including nucleation, growth and destruction of grains, in dynamical models of C-type AGB stars (using methods developed by, e.g., Gail & Sedlmayr 1988 and Gauger et al. 1990). At first, the application of this improved dust treatment was restricted to stationary winds (e.g. Dominik et al. 1990). Soon after, however, models combining grain formation, growth and evaporation of particles with time-dependent dynamics were developed (e.g. Fleischer et al. 1991), which allowed to study the interaction of pulsation-induced shock waves and dust. As mentioned above, dust processes depend critically on ambient temperatures and densities. This sensitivity to thermodynamical conditions in combination with the feedback of the dust component into gas dynamics and the radiation field may lead to the formation of discrete dust shells (e.g. Fleischer et al. 1992), dynamical instabilities (e.g. Fleisher et al. 1995, Höfner et al. 1995), multi- or non-periodic behavior of the circumstellar envelope (e.g. Winters et al. 1994, Höfner & Dorfi 1997), and incomplete condensation (low dust-to-gas ratios). Another topic investigated with this type of models is the role of grain drift relative to the gas which may modify grain growth rates and the efficiency of wind acceleration (e.g. Sandin & Höfner 2004), as well as causing flow instabilities which may explain large-scale patterns in circumstellar envelopes (Simis et al. 2001) as observed around IRC+10216 (Mauron & Huggins 1999, 2000).

Mass loss rates predicted by such wind models have been used in theoretical studies of AGB evolution (e.g. Schröder et al. 1999, 2003, Wachter et al. 2002, 2008), and synthetic IR colors have been applied to the interpretation of photometric observations characterizing stellar variability and dust-driven mass loss (e.g. Winters et al. 1997, 2000, Le Bertre & Winters 1998). A closer comparison of model-based spectra and observations, however, revealed some serious shortcomings of this first generation of dusty dynamical models. The crude, grey treatment of radiative transfer and opacities in the dynamical computations proved to be a major drawback, resulting in unrealistic atmospheric structures, and thereby influencing the conditions for dust formation and the observable properties predicted by the models.
As a consequence, a new generation of dynamic atmosphere and wind models was developed, featuring a frequency-dependent treatment of radiative transfer which includes detailed molecular and grain opacities. A well-tested example are the models for C-rich AGB stars by Höfner et al. (2003). They compare favorably with such diverse observable properties as low-resolution spectra covering about two orders of magnitude in wavelength, with features formed at different depths in the atmosphere and wind (Gautschy-Loidl et al. 2004), and high-resolution spectra showing variations of molecular line profiles which probe the dynamics of atmospheric shocks and wind acceleration (Nowotny et al. 2005ab). Mattsson et al. (2007, 2008) have applied these models to investigate the formation of detached shells in connection with a He-shell flash, and the dependence of mass loss on metallicity.

The development of similar detailed models for winds of M-type AGB stars has proved more difficult than in the C-rich case, not the least due to a more complex chemistry of dust formation. Recently, new models by Woitke (2006b) demonstrated that silicate grains condensing in M-type atmospheres have to be basically Fe-free, since even a low Fe-content will lead to much higher grain temperatures, and, consequently, large condensation distances (see discussion in Sect. 2). Without the inclusion of Fe in olivine- or pyroxene-type grains, however, radiative pressures are too low for driving a wind, as long as the grains are small compared to the relevant wavelengths. For clarity, it has to be mentioned in this context, that this problem was not apparent in earlier models with grey radiative transfer, e.g., by Jeong et al. (2003). Such grey models will severely underestimate the temperature of silicate particles which include Fe and give condensation distances comparable to C-rich models, resulting in marginally sufficient radiative driving (note that grey models correspond to $p = 0$ in Fig. 2).

As a possible solution of this problem, Höfner (2008a) investigated the viability of driving winds with micron-sized Fe-free olivine-type grains (forsterite), instead of small particles. For wavelengths corresponding to the flux maximum of AGB stars, the radiative pressure experienced by a given total amount of Fe-free olivine-type material is strongly dependent on particle size, potentially exceeding the gravitational force for grain radii just below 1\(\mu\)m at typical stellar parameters (cf. Fig. 1 in Höfner 2008a). The strong variation with grain size is a consequence of the shifting relative contributions of absorption and scattering to the total cross section for radiative pressure (cf. Eq. 4). For particles which are small compared to the wavelengths under consideration, scattering is negligible and this cross section will be dominated by absorption which is very low for Fe-free olivine-/pyroxene-type materials around wavelengths $\lambda \approx 1\mu$m. The relative contribution of scattering, compared to absorption, however, increases steeply with particle radius, and starts to dominate the radiative pressure for this dust type long before the grain radius approaches the wavelength, possibly bringing up the cross section for radiative pressure to values required for driving an outflow.

The grain size dependence of optical properties is illustrated by Fig. 4, showing the efficiency factors for absorption, scattering and radiative pressure, $Q_{\text{abs}}$, $Q_{\text{sca}}$ and $Q_{\text{rp}}$, respectively, as a function of grain radius (cf. Sect. 3 for definitions). The quantities are calculated using Mie theory for spherical particles (program BHMIE from Bohren & Huffman 1983, modified by B.T. Draine).
Figure 4. Optical properties of dust particles at wavelength $\lambda = 1\,\mu\text{m}$ as a function of grain radius: $\log(Q_{\text{rp}})$ (solid lines), $\log(Q_{\text{abs}})$ (dashed), $\log(Q_{\text{sca}})$ (dotted) and $\log(g_{\text{sca}})$ (dash-dotted), based on Mie theory for spherical grains. Upper panel: forsterite particles ($\text{Mg}_2\text{SiO}_4$). Lower panel: amorphous carbon grains. See text for details.
Figure 5. Mass loss rate vs. wind velocity for M-type AGB stars: crosses mark observations by Olofsson et al. (2002) and González Delgado et al. (2003), circles correspond to detailed RHD models by Höfner (2008a) where the winds are driven by micron-sized Fe-free silicate grains.

Note that the behavior displayed by the silicate material (upper panel; Mg$_2$SiO$_4$, refractive index data taken from Jäger et al. 2003) differs crucially from the case of amorphous carbon (lower panel; data of Jäger et al. 1998, sample cel1000) where absorption dominates radiative pressure for particles of sizes up to about 1 µm (due to the much higher level of $Q_{\text{abs}}$), and the dependence of $Q_{\text{rp}}$ on grain size is much less pronounced.

The detailed frequency-dependent atmosphere and wind models of Höfner (2008a) which include a time-dependent treatment of forsterite grains demonstrate that radiation pressure on such particles is sufficient to drive outflows if prevailing conditions allow grains to grow to sizes in the micro-meter range. The resulting combinations of mass loss rates and wind velocities compare rather well with observations of M-type AGB stars (cf. Fig. 5) and preliminary test of synthetic spectra show reasonably good agreement with observed near- and mid-IR spectra (Lederer et al., in prep.).

4. Dust as a (by-) product: features, patterns and yields

In the previous section, the discussion has been focused on the dominant dust species and their potentials as wind drivers. Now we will take a look at other
aspects of dust in evolved stars, i.e., the influence of grains on observable properties of these objects, and estimated contributions from cool giants to interstellar dust.

The progress of space-based infrared spectroscopy achieved in recent years, in particular at mid- and far-IR wavelengths, has had a dramatic influence on our understanding of cool stellar winds. Simultaneous coverage of a wide spectral range with the instruments aboard the Infrared Space Observatory (ISO) has allowed an analysis of molecular features originating in different layers of stellar atmospheres and outflows, an unprecedented tool for studying their structure and dynamics. A large variety of dust features has been discovered in the infrared spectra of evolved stars, some expected, some surprising (see, e.g., Dorschner 2003 or Molster & Waters 2003 for an overview). Examples include the well-studied SiC feature at 11 μm in C-type AGB stars, and the characteristic features of silicates at about 10 μm and 18 μm (Si-O stretching and O-Si-O bending modes), as well as more controversial cases like the 13 μm feature in M-type AGB stars which was first attributed to corundum (Al₂O₃; Vardy et al. 1986, Onaka et al. 1989, Begemann et al. 1997) but later more convincingly identified with spinel (MgAl₂O₄; Posch et al. 1999, Fabian et al. 2001). Some of the species discovered or predicted theoretically are too rare or have too low opacity to contribute as wind drivers. But certain high-temperature condensates, even if they are rare due to low abundances of their key ingredients, may play an important role as seed nuclei for olivine/pyroxene condensation in M-type AGB stars (see, e.g., Gail & Sedlmayr 1999, Jeong et al. 2003, Nuth & Ferguson 2006). Another interesting aspect is the discovery of Mg-rich crystalline silicates (Molster et al. 2002abc) in addition to their more abundant amorphous counterparts, since a highly ordered microscopic structure of the condensate hints at a formation at high temperature, close to the condensation limit.

In addition to spectroscopy, new ways of studying circumstellar dust shells have become available through interferometry and imaging. Present-day interferometers achieve resolutions down to the scales of stellar radii, allowing detailed investigations of the innermost parts of circumstellar envelopes and wind acceleration regions. Certain features seen in near-IR spatial intensity distributions have been interpreted as dense molecular layers in the upper atmospheres and wind acceleration regions, probably related to shock waves, based on their variations with wavelengths and phase (e.g., Tej et al. 2003, Weiner 2004, Woodruff et al. 2008, Wittkowski et al. 2008). The inner edges of circumstellar dust shells seem to be located at a few stellar radii (e.g., Danchi et al. 1994, Tevousjan et al. 2004) while SiO masers are observed at somewhat closer distances (e.g., Boboltz & Wittkowski 2005, Wittkowski et al. 2007), in agreement with theoretical models. All interpretations of such data in terms of radii/distances (with or without limb darkening) should however be regarded with caution since many observations indicate non-spherical stellar shapes or brightness variations across the stellar surface (possibly due to large-scale convective motions), as well as complex structures in the circumstellar envelopes close to the star (e.g., Weigelt et al. 1998, 2002, Hofmann et al. 2000, Monnier et al. 2004, Ragland et al. 2008, Tatebe et al. 2008).

Such spatially resolved observations have stimulated the development of 2D/3D dynamical models for AGB stars and their circumstellar environments.
The computational effort behind such models is considerable, and, consequently, examples are a lot less numerous than the spherically symmetric atmosphere and wind models discussed above. There is a severe trade-off between generalized geometry and physical/chemical approximations necessary in the models, as well as serious limitations regarding the spatial ranges and time spans covered by the 2D/3D simulations. Nevertheless, investigations of the effects of intrinsically three-dimensional phenomena, like convection or flow instabilities, on dust formation and mass loss seem necessary in view of interferometric results, and the simulations performed so far have provided valuable insights, despite their limitations. Woitke (2006a) constructed 2D (axisymmetric) dust-driven wind models with time-dependent dust formation and grey radiative transfer. With these models, he investigated how intrinsic instabilities in the dust formation process create complex patterns in the circumstellar envelope (without taking the pulsation of the central star into consideration). Freytag & Höfner (2008) on the other hand, studied the effects of large-scale convective motions and of the resulting shock waves in the atmosphere on time-dependent dust formation in the framework of 3D radiation-hydrodynamical 'star-in-a-box' models. The atmospheric patterns resulting from convection are found to be reflected in the circumstellar dust distribution, due to the strong sensitivity of grain formation to temperatures and gas densities.

Looking, quite literally, at the dust and gas flowing from the star into the surrounding environment, the question of yields comes to mind. Compared to the task of determining the total amount of newly-produced elements fed into the interstellar medium by AGB stars, the problem of computing reliable dust yields has an extra layer of complication. It is not sufficient to follow the evolution – in terms of nucleo-synthesis and stellar parameters – of a likely population of stars, including a realistic description of mass loss. In addition, the fractions of elements condensing into various types of dust grains have to be calculated along the evolution tracks using a detailed time-dependent method since dust formation proceeds far from equilibrium. The most comprehensive modeling in this area so far has been done by Ferrarotti and Gail (2006). They combined synthetic stellar evolution models with a non-equilibrium dust formation description for the most abundant grain materials in M-, S- and C-type AGB stars. Their dusty outflow models, however, suffer from two major drawbacks. The mass loss rate is an input parameter of their dynamical models, not a result, and the flows are assumed to be stationary, neglecting the effects of shock waves. A follow-up study with more realistic dynamical wind models is far from trivial but urgently needed to provide reliable input for models of the interstellar medium.

5. Summary and conclusions

If one would try to characterize the topic of dust formation in evolved stars with one word the choice would probably fall on ‘complex’. At a first glance it seems that there is an almost infinite spectrum of possibilities to build solid particles from the chemical elements available in cool giants, and have them interact with dynamical and radiative processes in stellar atmospheres and winds.
Fortunately, there is a system of criteria which helps to sort materials, processes and interactions according to relevance for the problem at hand, in particular when it comes to investigating wind mechanisms. Abundances of chemical elements determine, in principle, which types of condensates should be expected at a given stage of stellar evolution. Dynamical processes like convection, pulsation, shocks, and outflows, on the other hand, will often determine, in practice, which of the possible grain types will actually form, as dynamics is setting the timescales available for condensation and causing deviations from chemical equilibrium. Regarding potential wind drivers, the need for high flux mean opacities directs the search towards condensates with high radiative cross sections in the wavelength range around the stellar flux maximum, but also high abundances of the constituents to speed up condensation, and arrive at sufficient total opacities. Furthermore, by definition, a wind driver must be able to form close to the stellar photosphere to accelerate the gas away from the star, which requires grain materials with high condensation temperatures.

Looking at the most abundant condensible elements, the high bond energy of the CO molecule – blocking the less abundant of the two elements – leads to a convenient dichotomy in molecular and dust chemistry for M- and C-type AGB stars. In the latter case, the excess carbon will start forming amorphous carbon particles at high temperatures, resulting in efficient radiative driving of an outflow. For M-type stars with C/O \(< 1\), on the other hand, the excess oxygen needs to combine with elements of lower abundances to form high-temperature condensates. Using the criteria summarized above, silicates (olivine- and pyroxene-type materials) suggest themselves as candidates, and seem to be consistent with observed mid-IR spectral features. Specific points are, however, still debated, e.g., if non-grey effects on grain temperatures and condensation distances will suppress the inclusion of Fe in silicate grains (cf. Woitke 2006b), if Mg-rich end members of the olivine-/pyroxene-type material sequences provide sufficient radiative pressure for driving an outflow (cf. Höfner 2008a), to which degree the condensates are crystalline or amorphous, or what particles are the seed nuclei for silicate condensation.

In contrast to the more or less satisfactory cases of C- and M-type AGB stars, the enigmatic S stars still present a challenge to the understanding of dust formation and outflows. Observations indicate that these objects have wind characteristics which are similar to the other two types (e.g. Ramstedt et al. 2006) but the lack of abundant dust-forming elements in S-type giants (with both C and O locked up in CO) makes it difficult to envision an efficient driving mechanism, on par with, e.g., radiative pressure on amorphous carbon grains. Various dust species have been suggested (cf. Ferrarotti & Gail 2002, 2006) but no detailed self-consistent dynamical models are currently available.

The discussion of S-type AGB stars leads naturally into a topic that could be called minor dust species, defined as the types of grains that are no viable wind drivers due to low abundances or low opacity. A considerable number of potential dust materials has been inferred from the rich variety of features discovered in IR spectra of cool giants but dynamical models are usually concentrating on a handful of dominating species for computational reasons. Nevertheless, some rare or low-opacity high-temperature condensates may play a crucial role in the important process of grain nucleation which is not well understood at present.
(see, e.g., Gail & Sedlmayr 1999, Nuth & Ferguson 2006, Patzer 2007, and references therein).

Having listed some present concerns about our understanding of dust in evolved stars, the great progress achieved in recent years through a combination of high-quality IR observations, laboratory work on dust analogues, and detailed numerical modeling should not be underestimated. A consistent, reasonably realistic description of dust-driven mass loss of AGB stars seems within reach, both for C- and M-type objects, providing urgently needed input for models of stellar and galactic chemical evolution. Furthermore, the exploration of intricate structures in circumstellar envelopes is gaining momentum, both regarding interferometric observations and 3D modeling, promising interesting new insights.

References

Andersen A.C., Höfner S., Gautschy-Loidl R., 2003, A&A, 400, 981
Begemann B., Dorschner J., Henning Th., et al. 1997, ApJ 476, 199
Boboltz D., Wittkowski M., 2005, ApJ 618, 953
Bohren C.F., Huffman D., 1983, *Absorption and scattering of light by small particles*, John Wiley, New York
Bowen G.H. 1988, ApJ 329, 299
Danchi W.C., Bester M., Degiacomi C.G., et al. 1994, AJ 107, 1469
Dominik C., Hail H.P., Sedlmayr E., Winters J.M. 1990, A&A 240, 365
Dorschner J. 2003, in: *Astromineralogy*, LNP 609, ed. Th. Henning, Springer, p.55
Ferrarotti A.S., Gail H.-P., 2001, A&A 371, 133
Ferrarotti A.S., Gail H.-P., 2002, A&A 382, 256
Ferrarotti A.S., Gail H.-P., 2006, A&A 447, 553
Fleischer A.J., Gauger A., Sedlmayr E. 1991, A&A 242, L1
Fleischer A.J., Gauger A., Sedlmayr E. 1992, A&A 266, 321
Fleischer A.J., Gauger A., Sedlmayr E. 1995, A&A 297, 543
Freytag B., Höfner S. 2008, A&A 483, 571
Gail H.-P. 2003, in: *Astromineralogy*, LNP 609, ed. Th. Henning, Springer, p.55
Gail H.-P., Sedlmayr E. 1988, A&A 206, 153
Gail H.-P., Sedlmayr E. 1999, A&A 347, 594
Gauger A., Gail H.-P., Sedlmayr E. 1990, A&A 235, 345
Gautschy-Loidl R., Hörn S., Jörgensen U.G., Hron J., 2004, A&A, 422, 289
González Delgado D., Olofsson H., Kerschbaum F., et al., 2003, A&A 411, 123
Habing H.J., Olofsson B. 2004, in: *Asymptotic Giant Branch Stars*, Habing H.J., Olofsson H. (eds.), Springer, p.149
Hofmann K.-H., Balega Y., Scholz M., Wiegert G. 2000, A&A 353, 1016
Höfner S., 2007, ASP Conf. Ser. 378, p. 145
Höfner S., 2008a, A&A, 491, L1
Höfner S., 2008b, Phys. Scr., T133
Höfner S., Dorfi E.A. 1997, A&A 319, 648
Höfner S., Feuchtinger M., Dorfi E.A. 1995, A&A 297, 815
Höfner S., Gautschy-Loidl R., Aringer B., Jørgensen U.G., 2003, A&A, 399, 589
Jäger C., Dorschner J., Mutschke H., Posch Th., Henning Th., 2003, A&A, 408, 193
Jäger C., Mutschke H., Henning Th., 1998, A&A, 332, 291
Jeong K. S., Winters J. M., Le Bertre T., Sedlmayr E. 2003, A&A, 407, 191
Krügel E., 2003, *The Physics of Interstellar Dust*, IoP
Lattanzio J.C., Wood P.R. 2004, in: *Asymptotic Giant Branch Stars*, Habing H.J., Olofsson H. (eds.), Springer, p.23
Le Bertre T., Winters J.M. 1998, A&A 334, 173
Mattsson L., Höfner S., Herwig F., 2007, A&A 470, 339
Mattsson L., Wahlin R., Höfner S., Eriksson K., 2008, A&A, 484, L5
Mauron N., Huggins P.J. 1999, A&A 349, 203
Mauron N., Huggins P.J. 2000, A&A 359, 707
Molster F.J., Waters L.B.F.M. 2003, in: *Astromineralogy*, LNP 609, ed. Th. Henning, Springer, p.121
Molster F.J., Waters L.B.F.M., Tielens A.G.G.M. 2002a, A&A 382, 222
Molster F.J., Waters L.B.F.M., Tielens A.G.G.M, Barlow M.J. 2002b, A&A 382, 184
Molster F.J., Waters L.B.F.M., Tielens A.G.G.M. et al. 2002c, A&A 382, 241
Monnier J.D., Millan-Gabet R., Tuthill P.G., et al. 2004, ApJ 605, 436
Nowotny W., Aringer B., Höfner S., et al. 2005a, A&A, 437, 273
Nowotny W., Lebzelter T., Hron J., Höfner S. 2005b, A&A, 437, 285
Nuth J.A., Ferguson F.T. 2006, ApJ 649, 1178
Olofsson H., González Delgado D., Kerschbaum F., Schöier F. L., 2002, A&A 391, 1053
Onaka T., de Jong T., Willems F.J. 1989, A&A 218, 169
Patzer A.B.C., 2007, ASP Conf. Ser. 378, p. 181
Posch T., Kerschbaum F., Mutschke H., et al. 1999, A&A 352, 609
Ragland S., Le Coroller H., Pluhžnik E., et al., 2008, ApJ 679, 746
Ramstedt S., Schüier F. L., Olofsson H., Lundgren A. A., 2006, A&A, 454, L103
Rouleau F., Martin P.G. 1991, ApJ 377, 526
Sandin C., Höfner S. 2004, A&A 413, 789
Schröder K.-P., Wachter A., Winters J. M. 2003, A&A 398, 229
Schröder K.-P., Winters J. M., Sedlmayr E. 1999, A&A 349, 898
Simis Y.J.W., Icke V., Dominik C. 2001, A&A 371, 205
Tatebe K., Wishnow E. H., Ryan C. S., et al. 2008, ApJ 689, 1289
Taj A., Lançon A., Scholz M. 2003, A&A 401, 347
Tevonsjan S., Abdeli K.-S., Weiner J. et al. 2004, 611, 466
Vardy M.S., De Jong T., Willems F.J. 1986, ApJ 304, L29
Wachter A., Schröder K.-P., Winters, J. M., et al. 2002, A&A 384, 452
Wachter A., Winters, J. M., Schröder K.-P., Sedlmayr, E. 2008, A&A 497, 504
Weigelt G., Balega Y.Y., Blöcker T., et al. 1998, A&A 333, L51
Weigelt G., Balega Y.Y., Blöcker T., et al. 2002, A&A 392, 131
Weiner J. 2004, ApJ 611, L37
Winters J.M., Fleischer A.J., Gauger A., Sedlmayr E. 1994, A&A 290, 623
Winters J.M., Fleischer A.J., Le Bertre T., Sedlmayr E. 1997, A&A 326, 305
Winters J.M., Le Bertre T., Jeong, K.S., Helling C., Sedlmayr E. 2000, A&A 361, 641
Wittkowski M., Boboltz D. A., Driebe T., et al. 2008, A&A 479, L21
Wittkowski M., Boboltz D. A., Oshara K., et al. 2007, A&A 470, 191
Woitke P. 2006a, A&A, 452, 537
Woitke P. 2006b, A&A, 460, L9
Wood P.R. 1979, ApJ 227, 220
Woodruff H.C., Tuthill P.G., Monnier J.D., et al. 2008, ApJ 673, 418