DUST FORMATION AND MASS LOSS IN EVOLVED STARS

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Abstract. The problem of dust formation in the circumstellar envelopes of Asymptotic Giant Branch stars is addressed. We summarize the basic thermodynamic prerequisites necessary to enable the formation and growth of solid particles from the gas phase and draw some conclusions on the evolution of the emergent dust component. In a circumstellar environment the dust grains interact with the stellar radiation field, which leads to a strong coupling among the local thermodynamic conditions and the dust formation process itself. By a consistent treatment of the physics describing the dust forming circumstellar shells of evolved stars we demonstrate, that the non–linear interaction among the dust formation process and the hydrodynamic and thermodynamic conditions of the dust forming system leads to a complex dynamical structure of these shells. Some observable consequences resulting from corresponding model calculations are given.

1. Introduction

Most of the dust present in our Galaxy is produced in the circumstellar shells around evolved stars, located on the Asymptotic Giant Branch (AGB) in the HR diagram (e.g. Gehrz 1989). During this evolutionary phase, a star is unstable against pulsation driven by the κ mechanism; therefore these objects are large amplitude, long period variable stars. Caused by the pulsation, shock waves are created which propagate through the atmosphere, leading to an enhancement of the density compared to a hydrostatic situation. In the cooling outflow, a complex chemistry develops, which in a certain region of the circumstellar shell allows solid particles to form. Once these particles are present, they severely influence the hydrodynamic and thermodynamic structure of the shell. Due to their huge absorption cross section for short wavelength photons, the grains effectively transfer the photon energy to the infrared spectral range, leading to the observed infrared excess of these objects and to a pronounced heating of the surrounding gas. The absorbed photon momentum causes an effective outward directed acceleration of the grains, which by momentum coupling to the ambient gas molecules also drag the gas outwards: a low velocity, massive wind develops, carrying mass loss rates up to $10^{-4}M_{\odot}\mathrm{yr}^{-1}$ at a velocity of the order of 15 kms^{-1} (e.g. Loup et al. 1993).

2. Dust nucleation, growth, and evaporation

2.1. BASIC THERMODYNAMIC PREREQUISITES

In order to enable the formation of solid particles out of the gas phase three basic conditions have to be fulfilled:

- The chemistry must provide abundant molecular species which can form high temperature condensates
- The trajectory of the dust forming system has to reach temperatures low enough that the small aggregates formed by collisions between the dust forming molecules are stable against decay
- Simultaneously, the density of the dust forming species has to be high enough, that a sufficient number of collisions between the growing dust particles and the growth molecules can occur during the lifetime of the system to form macroscopic particles. Typically, some 10^9 collisions are required to build up a 0.1μm sized particle

A closer inspection of the problem reveals, that dust formation may be conceived as a two–step process:

i) **Formation of the critical cluster**, which serves as the seed particle for further grain growth. By definition, the critical cluster consists of N_* constituents, where N_* results from the requirement, that the enthalpy change ΔG for formation of an N-cluster from the gas phase has its maximum value at N_* for given temperature and density. Therefore, the critical cluster separates the region of thermally unstable aggregates ($N < N_*$) which preferentially will evaporate, from the thermally stable aggregates ($N > N_*$) which preferentially will grow. Therefore, the number density of clusters f(N) attains a minimum at the critical size N_*, expressing the fact, that the constructive and destructive rates are nearly out-balanced for clusters of size N_*. In order to form these clusters in a finite time, a considerable supersaturation of the condensing species is required. Therefore, the nucleation rate, i.e. the net growth–rate of the critical cluster, strongly depends on temperature. Under astrophysical conditions, the typical size of the critical cluster is of the order of $N_* \approx 10$, which approximately also gives the number of chemical reactions necessary to form this aggregate. Since the chemical time scale in the nucleation region of stellar outflows generally is small compared to the thermodynamic and hydrodynamic time scales, the nucleation process usually can be described by a stationary approach (cf. Gail & Sedlmayr 1988).

ii) **Growth of the critical clusters to macroscopic grains.** Once the seed particles are formed, they might grow to macroscopic sizes if the dust forming gas element remains for a sufficiently long time at sufficiently high densities. Since grain growth is governed by chemical reactions with the condensing molecules, the growth rate mainly depends on the local particle density of these species. Depending on the molecular composition of the dust forming gas element and the thermodynamic conditions encountered, different grain structures and chemical compositions of the emerging dust component (amorphous, crystalline, homogeneous, heterogeneous, ...) will result from the growth process. Since growth of the particles to macroscopic sizes requires of the order of $10^8 \ldots 10^9$ chemical reactions, the growth time usually exceeds the hydrodynamic time scale. Therefore, this process has to be treated by a time–dependent description (Gail & Sedlmayr 1988, Gauger et al. 1990).

A detailed overview of the different theoretical concepts currently applied to the problem of astrophysical grain formation is given in Sedlmayr (1994).

2.2. TEMPERATURE DEPENDENCE OF THE DUST COMPONENT

To demonstrate exemplary the temperature dependence of the dust formation process, Fig. 1 shows the behavior of the degree of condensation $f_{\rm c}$ and the number density of dust grains per H–atom $n_{\rm d}/n_{<{\rm H}>}$ in a gas element which undergoes a sinusoidal temperature variation with a period of 300d and a corresponding adiabatic density variation. In this simple example, nucleation, growth, and evaporation of pure carbon grains is considered for an element mixture with solar abundances, except that $\epsilon_{\rm C} = 3\epsilon_{\rm O}$. The nucleation process is treated in the framework of classical nucleation theory according to the formalism given in Gail et al. (1984), grain growth is described by the moment method developed by Gail & Sedlmayr (1988) which takes into account heteromolecular growth processes, and thermal evaporation is considered by the method described in Gauger et al. (1990).

The calculation starts at high temperature with a dust free gas element. After the *nucleation* process is terminated (i.e. the number of grains has reached the maximum value), the grains continue to *grow* until the remaining carbon not blocked by the CO molecule is completely contained in grains (i.e. $f_{\rm c} = 1$). With increasing temperature, first the outer layers of the grains evaporate (i.e. $f_{\rm c}$ decreases) once the supersaturation ratio in the gas element falls short of unity. Actual grain destruction only takes

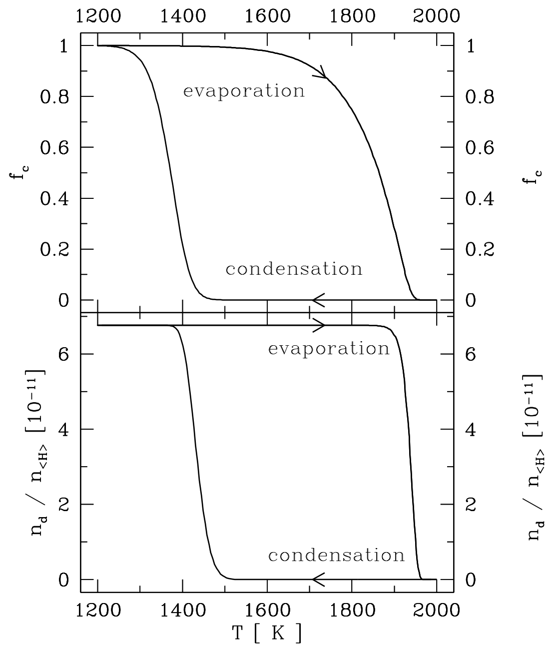

Figure 1. Temperature dependence of the degree of condensation (upper panel) and the number of dust grains per H–atom (lower panel)

place when the particles have reached the critical cluster size again, i.e. at still higher temperatures. The hysteresis resulting from this process demonstrates the large super-cooling of the gas necessary to allow the particles to nucleate. For the case of carbon grains considered here, the temperature difference between formation and destruction of grains amounts to $\approx$ 500K.

3. Dust formation in circumstellar dust shells of long–period variable stars

In a circumstellar environment, the dust component is strongly and non–linearly coupled to its surroundings, thereby changing the local hydrodynamic and thermodynamic conditions. This tight coupling of the dust to its surroundings mainly arises from its huge absorption cross–section with respect to the stellar radiation field:

– By absorbing and scattering the short wavelength photons of the stellar radiation field, the dust grains gain the photon momentum, which subsequently is effectively transferred to the ambient gas by collisional coupling of the grains to the molecules. Therefore, the dust component strongly couples to the hydrodynamic equations by causing a considerable radiative acceleration of the atmospheric material and thus strongly influences the density and velocity structure of the system.

- By thermalizing the energy of the absorbed short wavelength photons within their internal degrees of freedom, the dust grains transfer the photon energy to infrared radiation, which can escape from the circumstellar shell. This process causes the infrared excess which is characteristic for the spectra of these objects. Due to the blocking of the energetic short wavelength radiation, a steep temperature gradient develops inwards to the region where dust is present. By its coupling to the energy equation, the dust opacity gives rise to a pronounced backwarming effect, thereby changing the thermodynamic conditions in the system.

By this intimate coupling, the dust grains determine the conditions of their own formation: In a real astrophysical system, dust formation is a self–regulating process.

The reliable description of a dust forming circumstellar shell therefore requires the simultaneous treatment of the complete problem, consisting of hydrodynamics, thermodynamics, chemistry, dust formation, and radiative transfer. Applying this kind of consistent description, the radial and temporal structure of the resulting dust shell model is completely determined by the four stellar parameters: mass, luminosity, stellar temperature and the element abundances. In the case of a long-period variable, the pulsation of the star usually is simulated by a *piston approximation*, i.e. a sinusoidally moving inner boundary (cf. Wood 1979, Bowen 1988, Fleischer et al. 1992, Feuchtinger et al. 1993), which introduces two additional parameters, the pulsation period P and the pulsation amplitude Δu_P.

In Fig. 2 the radial structure of a dynamical model for a dust forming circumstellar shell around a pulsating AGB star is shown at a fixed instant of time. A detailed description of the modeling approach is given in Fleischer et al. (1992). The parameters of the model shown in Fig. 2 are: $M_* = 1M_\odot$, $L_* = 1.3 10^4 L_\odot$, $T_* = 2200\mathrm{K}$, ϵ_i = solar, except $\epsilon_\mathrm{C} = 1.38\epsilon_\mathrm{O}$, $P = 696\mathrm{d}$, $\Delta u_P = 8\mathrm{kms}^{-1}$.

Several distinctive features characterize the appearance of the shell:

- the circumstellar dust shell exhibits a discrete or onion–like structure, i.e. the dust is not distributed homogeneously across the shell but is concentrated in discrete layers. This can be seen, for instance, in the radial course of the degree of condensation f_c in the 2nd row of Fig. 2 (dashed line)

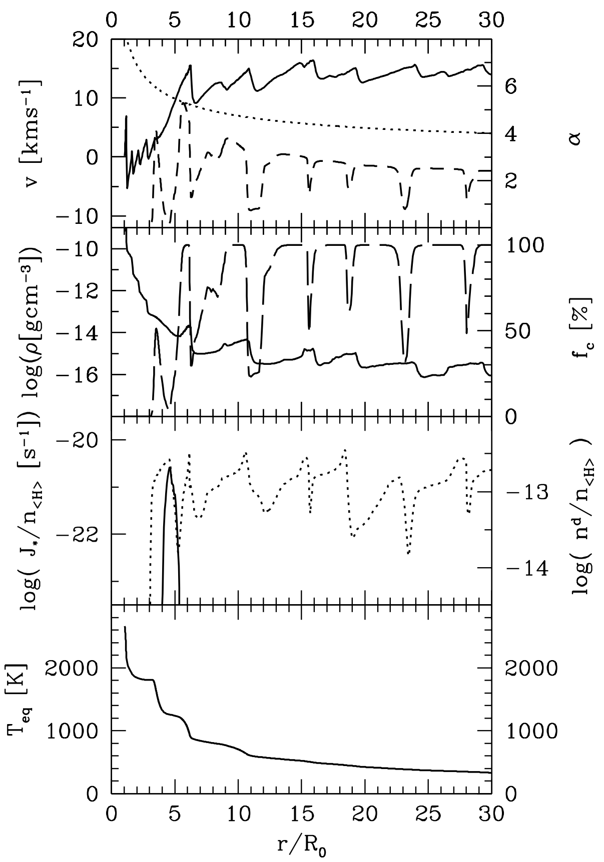

Figure 2. Radial structure of a consistent dust shell model (adopted from Winters et al. (1997a))

- these dust layers are spatially correlated with the hydrodynamic structure, e.g. the radiative acceleration α and the velocity v (upper diagram, dashed and solid line, respectively), which suggests that the strong shocks propagating through the shell are accelerated by radiation pressure on dust
- the temperature stratification is characterized by a pronounced *back–warming effect*, i.e. the material located inwards of the dust layers is heated due to the blocking of the short wavelength radiation by the dust opacity.

The consequence of this backwarming effect for the nucleation process can be seen from the sharp inner edge of the nucleation rate J_* (3rd. row of Fig. 2, solid line). The sharp onset of dust nucleation is caused by the steep temperature gradient between 3.5 and 4 R_0. However, as can be seen from the distribution of the number of dust particles $n_\mathrm{d}/n_{<H>}$ (3rd row, dotted curve) and from the degree of condensation, a considerable amount of dust is in fact present at high temperatures, i.e. inside the region where dust nucleation actually takes place. These particles have been formed during a previous time interval when the temperature in this region has been lower. The presence of particles at these high temperatures is possible by the fact, that the dust grains, once they have formed, are quite stable against thermal evaporation (see Sect. 2.2).

The expansion velocity exceeds the local escape velocity (dotted curve in the upper diagram of Fig. 2) at $\approx 5R_0$, i.e. in a region of comparably high densities. The final outflow velocity results to be $\approx 15\,\mathrm{kms}^{-1}$ and the wind carries a mass loss rate of about $10^{-4}M_\odot\mathrm{yr}^{-1}$. From the course of the velocity it can be seen, that the hydrodynamic structure of the wind region, which is dominated by dust induced shocks, decouples from the hydrodynamic behavior in the inner part of the shell, which is dominated by shocks produced by the pulsation of the star. Concerning the mass loss mechanism this means, that the interior pulsation of the star essentially provides the favorable conditions required for the onset of dust formation. Once grains are present, the dust component takes over the leading part in determining the shell structure, the final outflow velocity of the wind, and the mass loss rate, which is fixed by the density in the dust formation region.

A further property of this model is the formation of new dust layers on a time scale longer than the pulsation period. This effect of *multiperiodicity* is connected to the fact, that the circumstellar dust shell possesses an eigenperiod controlled by the dynamics of the dust formation process (see Fleischer et al. 1995, Höfner et al. 1995).

3.1. GLOBAL QUANTITIES OF C-RICH LONG-PERIOD VARIABLES

Applying a maximum–likelihood method to a grid of models, Arndt et al. (1997) derived fit formulae, which express the mass loss rate, the final outflow velocity and the dust–to–gas ratio in terms of the parameters of these models, i.e. the stellar parameters. In particular, they find that the mass loss rate strongly increases with decreasing stellar temperature, decreasing stellar mass, and increasing stellar luminosity, but is almost independent on the carbon abundance, the pulsation period and the pulsation amplitude. Since the evolution along the AGB leads to increasing luminosity, slightly decreasing temperature and, due to mass loss, to decreasing stellar mass, the mass loss rate driven by radiation pressure on dust is expected to strongly increase along the AGB evolution.

In contrast, the outflow velocity (and of course the dust–to–gas ratio) mainly depend on the amount of dust actually formed in the shell. In a carbon–rich situation, these quantities are therefore proportional to the carbon abundance.

4. Observable consequences

The spatial structure and the time variation of these dust shell models manifest itself in the calculated infrared appearance. The synthetic light curves, brightness profiles and spatial spectra show intrinsic features, which are caused by the structure and dynamics of the circumstellar shell, and resemble similar ones, which are present in the observations, e.g. intermediate maxima in the light curves, multiperiodic light curves (Winters et al. 1994), or step–like structures in the brightness profiles and the spatial spectra (Winters et al. 1995).

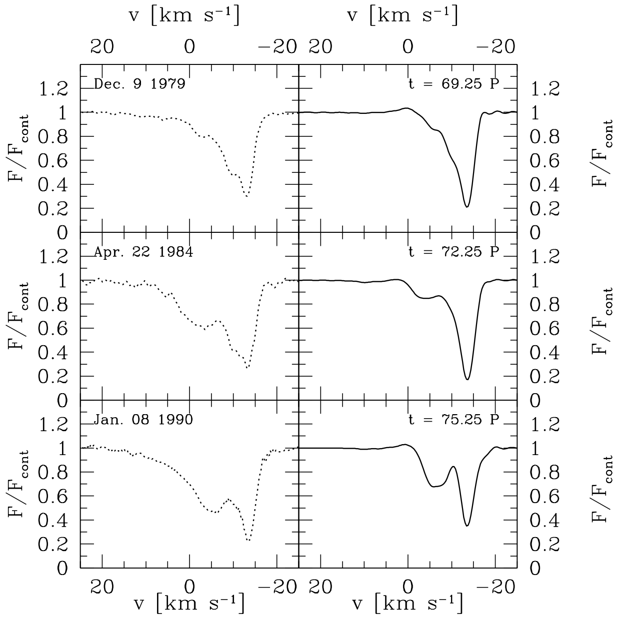

Figure 3. Temporal evolution of the CO (2-0) first overtone line profile (Winters et al. (1997b)). l.h.s.: profile observed in IRC +10216 (Sada 1993), r.h.s.: calculated line profile. The pulsation period is $P = 650$d

A further observable consequence of the formation of dust layers on a time scale longer than the pulsation period of the star is the occurrence of an additional low–velocity absorption feature e.g. in the first overtone CO line profiles (cf. Fig. 3). This feature increases in strength on a time scale of several pulsation periods, corresponding to the time scale, on which a new dust layer forms. This result is in excellent agreement with respective observations obtained for the carbon-rich object IRC +10216. The increasing strength of this additional absorption feature is caused by a density enhancement in the inner shell region initiated by radiation pressure on the newly forming dust layer (cf. the density stratification displayed in Fig. 2).

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