THE SIZE DISTRIBUTION OF STARDUST INJECTED INTO THE ISM

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ABSTRACT. A multi-component method for the description of the evolution of the grain size distribution in consideration of a size dependent grain drift and growth rate is applied in order to model dust driven winds around cool C-stars.

Grain drift introduces several modifications concerning dust growth: On the one hand the residence time in the region of efficient growth is reduced, on the other hand the growth efficiency is higher due to an increased collisional rate. For carbon grains the surface density of radical sites is increased, but on the other hand there is a reduction of the sticking efficiency of the growth species for drift velocities larger than a few $\mathrm{km\,s^{-1}}$.

It is found that the consideration of drift results in a considerable distortion of the size distribution as compared to the case of zero drift velocity. Generally, there are less, but larger grains if drift is included.

1. INTRODUCTION

The extended atmospheres of cool red giants are places of considerable dust formation accompanied by substantial mass loss. Radiation pressure on the dust grains with subsequent momentum transfer to the gas via grain-gas collisions is often discussed as a mechanism to drive these massive stellar winds (e. g.Gail & Sedlmayr, 1987).

Although the photon momentum absorbed by the dust is completely transfered to the bulk of the gas, i. e.complete momentum coupling may be assumed (e. g.Krüger *et al.*, 1994), the grains are not position coupled to the gas but move with a size-dependent drift velocity instead. This introduces several modifications concerning dust formation and growth: Since the grain drifts out of the gas element where it has been created, the time of residence in a region of efficient growth is reduced. On the other hand, the growth rate of grains is increased due to a larger collisional rate, and for carbonaceous grains the surface density of reactive radical sites increases with the drift velocity. However, for drift velocities larger than $\sim 5\ \mathrm{km\,s^{-1}}$there is a reduction of the sticking efficiency of the growth species. Last not least: Since the flux of grains is conserved the dust component becomes increasingly dynamically diluted for high drift velocities.

To study the effects of grain drift on dust formation and growth in circumstellar dust shells we have applied a new multi-component method for the description of the evolution of the grain size distribution (Krüger *et al.*, 1995) and calculated self-consistent models of stationary dust driven winds around cool C-stars.

2. METHOD

The stellar wind model is characterized by a combined eigen- and boundary value problem for a system of ordinary differential equations with an internal singularity (this is the critical or sonic point). The resulting wind solution is completely determined by the stellar mass M_*, the stellar luminosity L_*, the effective temperature T_* and the elemental abundances ϵ_i. The mass loss rate $\dot{M}$ follows as an eigenvalue.

By means of the multi-component method of Krüger *et al.*(1995) the grain size distribution can be determined on a non-uniform grid which is moving in grain size space. This grid is constructed by following the size evolution of a large, successively incremented number of grains (typically $N_{\rm max} \sim 300$) originating from appropriately chosen radii in the stellar envelope. A detailed description of carbonaceous grain growth according to a hydrogen–abstraction/acetylene–addition surface reaction scheme (Krüger *et al.*, 1996) was also included.

Further details on the self-consistent treatment of a multi-component dust driven wind and the method of solution can be found in Krüger & Sedlmayr (1996).

3. RESULTS AND DISCUSSION

For the construction of an exemplary model of a cool C-star envelope we adopted parameter values of $M_* = 1\,{\rm M}_\odot$, $L_* = 4\,10^4\,{\rm L}_\odot$, and $T_* = 2100$ K. The elemental abundances have been taken to be solar except for $\epsilon_{\rm C} = 1.7\epsilon_{\rm O}$. The corresponding mass loss rate is $\dot{M} = 3.6\,10^{-5}{\rm M}_\odot/{\rm yr}$. For comparison, the model was recalculated with the drift velocity of the grains artificially set equal to zero.

Figure 1a shows the radial course of the relevant velocities in the resulting wind model. Although the mean drift velocity $v_{\rm dr,0}$ is rather small and comparable to the isothermal sound velocity c_T, the center of mass of the dust component drifts with a velocity $v_{\rm dr,3}$ that is clearly supersonic. In the inner region of the wind the drift velocity may even be much higher than the gas velocity $v_{\rm g}$. Remarkably, the general hydro- and thermodynamical structure of the envelope is quite similar, regardless of whether drift is considered or neglected. This is also true for the values of the mass loss rate and the terminal outflow velocity $v_{{\rm g},\infty}$ of the gas.

However, grain drift decisively influences the growth efficiency of the dust. In the subsonic regime close to the star the growth efficiency is depressed by a factor of up to 10, since the grains quickly drift away from their point of creation outwards to less efficient growth regions. The majority of the grains is created around the sonic point. Here, the two drift effects of "sweeping up" the condensable material and "drifting away" approximately cancel for these small grains ($a \sim 20$ nm). However, further growth of the larger grains is quite suppressed: Although the large drift velocity of these grains somewhat increases their surface radical density, the sticking efficiency is reduced. In the outer region ($r \gtrsim 3\,R_*$) growth is enhanced by a factor of up to 3 for the small and medium sized grains mainly due to the "sweeping up" of condensable material. No further growth of large particles takes place in the supersonic region.

Eventually the stardust will be injected into the interstellar medium (ISM). As has been shown by Woitke *et al.*(1993) dust destruction in the transition region of the red giant wind into the ISM is negligible. However, after the grains have come to rest in the ISM grain densities are increased by a size dependent factor $(v_{{\rm g},\infty} + v_{\rm drift}(a))/v_{{\rm g},\infty}$.

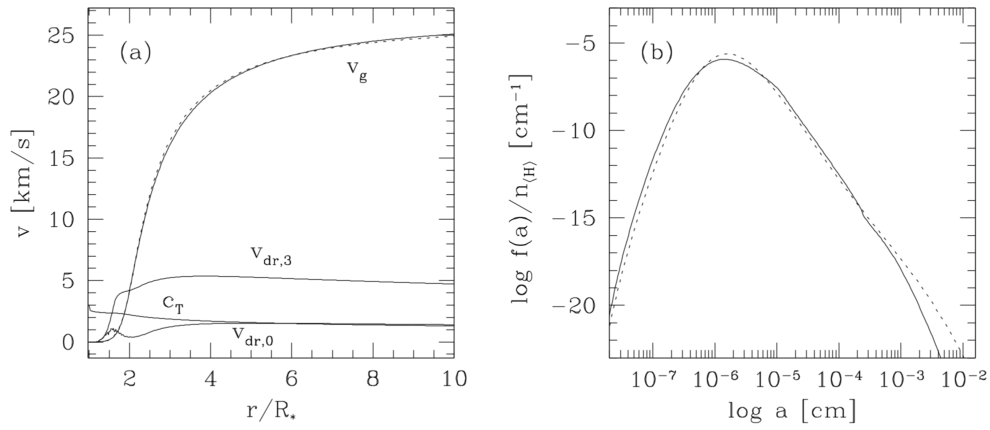

Figure 1. **a** Dynamical structure of the exemplary windmodel. **b** Grain size distribution after injection into the ISM. Dashed lines indicate the results neglecting drift.

The resulting size distribution after injection into the ISM is shown in Fig. 1b. Compared to the model neglecting drift (dashed line), the size distribution appears somewhat flattened. There is a pronounced decrease of the distribution at medium grain sizes (10 nm $< a <$ 50 nm). Furthermore, the amount of ultrasmall particles ($a \lesssim 10$ Å) is increased by almost an an order of magnitude. The existence of such an ultrasmall grain component in the ISM has been suggested on the ground of observations of 1–25 μm infrared emission from interstellar clouds (Sellgren *et al.*, 1983).

To first order, the distribution function can be fitted piece-wise by power laws of the form a^γ. The relevant part of the size distribution of the exemplary model including drift can be fitted by power laws with spectral indices $\gamma_1 \approx -2.5$ (20 nm $< a < 0.1\mu$m) and $\gamma_2 \approx -5.1$ ($a > 0.1\mu$m), respectively. Though tempting in this context, we think it is not apt to compare the obtained spectral indices with the one deduced for the size spectrum of the carbonaceous grain component in the interstellar medium (Mathis *et al.*, 1977) which is $\gamma \sim -3.5$. The latter is bound to result from the superposition of many size distributions originating from distinct dust forming objects, and is furthermore subject to repeated processing by interstellar shock waves.

We also present plots of $f(a)$ multiplied by a and a^4. In the left panel of Fig. 2 the area below the curve is proportional to the *number* of grains in a corresponding size interval. Obviously, in the negligible drift case the total number of grains is much higher than in the case where drift is included, although the position of the maximum, i. e.the most probable grain radius, does not vary much.

This reduction of the grain density due to drift by a factor of almost 2 can be explained by the nucleation rate peaking at a lower value. This is due to the fact that comparatively many large grains are formed in the inner region consuming a significant portion of condensable material (and therefore suppressing further efficient nucleation) without efficiently driving the wind (since these grains are dynamically diluted). This effect of drift should be quite independent of the the specific nucleation mechanism adopted here, since every realistic expression for the nucleation rate will to *some* degree be dependent on the amount of condensable material.

In the right panel of Fig. 2 the area below the curve corresponds to the *mass*

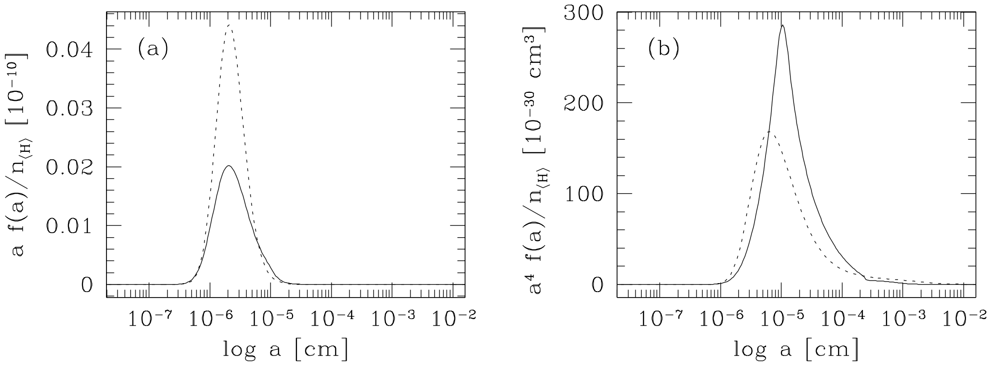

Figure 2. Grain size distribution after injection into the ISM. **a** Weighted by a. **b** Weighted by a^4. Dashed lines indicate the results neglecting drift.

contained in the grains. The consideration of drift leads to a significant shift of the distribution of condensed matter towards larger grain radii. The average grain mass is more than twice as large, and the dust-to-gas mass ratio $\dot{M}_{\rm d}/\dot{M}_{\rm g}$ injected into the ISM is increased by about 30% compared to the case of neglected drift.

4. CONCLUSIONS

To summarize, it can be said that although the consideration of grain drift does not greatly affect the resulting general hydro- and thermodynamical structure of the circumstellar envelope it has an decisive influence on the resulting grain size spectrum. Generally, less but more massive grains are being formed when drift is included. Concerning microscopic processes, drift mainly reduces the sticking efficiency of the growth species acetylene on large grains with significant drift velocities, although for carbon grains the surface density of radical sites is somewhat increased.

In conclusio, it seems that grain drift directly affects the modelling of observational quantities like the mass density ratio $\rho_{\rm d}/\rho_{\rm g}$ of dust and gas, the prediction of the amount $\dot{M}_{\rm d}$ of dust injected into the ISM, as well as the modelling of the optical appearence of circumstellar dust shells.

References

Gail, H.-P., and Sedlmayr, E. 1987, *Astr. Ap.***171**, 197.

Krüger, D., Gauger, A., and Sedlmayr, E. 1994, *Astr. Ap.*, **290**, 573.

Krüger, D., Woitke, P., and Sedlmayr, E. 1995, *Astr. Ap. Suppl. Ser.*, **113**, 593.

Krüger, D., Patzer, A. B. C., and Sedlmayr, E. 1996, *Astr. Ap.*, **in press**.

Krüger, D., and Sedlmayr, E. 1996, *Astr. Ap.*, **submitted**.

Mathis, J. S., Rumpl, W., and Nordsieck, K. H., 1977, *Ap. J.*, **217**, 425.

Sellgren, K., Werner, M., and Dinerstein, H. L., 1983, *Ap. J. (Letters)*, **271**, L13.

Woitke, P., Dominik, C., and Sedlmayr, E. 1993, *Astr. Ap.*, **274**, 451.