Influence of the metal abundances on the dust-driven winds of LPVs

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Introduction

Combined investigations of IRAS and ISO observations have directed research's interest towards the dust forming circumstellar envelopes of AGB stars in the Large Magellanic Cloud (LMC), a gravitationally bound neighbor galaxy. Dust formation has been theoretically studied by various authors in the frame work of circumstellar envelopes (CSE) of late type stars for solar metallicity. Dust is a particular important dynamic component in such luminous objects due to its large opacity (at least $100 \times \kappa^{\rm gas}$). The dust formation process itself depends sensitively on the chemical composition of the gas as well as the thermodynamic conditions in the CSE which is similarly influenced by the dust via radiative transfer effects.
The metal abundance of the gas affects not only its composition but also its opacity as well as the dust formation process by the amount of available condensible material. About half an order of magnitude less carbon and oxygen are present in the LMC compared to our Galaxy which suggests a definite reduction of wind properties like the mean mass loss rate $\langle \dot{M} \rangle$ and mean outflow velocity $\langle v_\infty \rangle$ for dust driven outflows.
This presentation concerns time-dependent models of dust forming long-periodic variables (LPVs) which exhibit a non-solar metallicity designed to resemble that of the LMC. Models of different metallici-

ties (solar and LMC), where the gas opacity has been approximated by its Planck mean, are examined with regard to the effect on the mass loss of dust-driven winds. Implications for a mass loss formula and the appearance of molecular layers as general feature of time-dependent models are discussed.

Approach

Time-dependent models of carbon-rich dynamical atmospheres of LPVs have been calculated by means of the CHILD-code developed by Fleischer *et al.* (1992) in an updated version of Helling *et al.* (2000). The code solves the coupled differential equations describing time-dependent hydrodynamics, radiative transfer, chemistry, and dust formation. Dust nucleation, growth, and evaporation are treated by the moment method developed by Gail & Sedlmayr (1988) and Gauger *et al.* (1990). The composition of the gas is calculated by assuming chemical equilibrium and the interior pulsation of the star is simulated by a sinusoidal variation of the innermost grid point with prescribed period P and velocity amplitude Δu. The initial values are given by the hydrostatic, dust-free solution of the equations considered. The radiative transfer problem is solved in grey approximation by applying the Unno-Kondo method (Unno & Kondo 1976; Unno & Kondo 1977; Hashimoto 1995). The mean gas opacities are approximated by Planck means which have been explicitly tabulated for solar and LMC abundances (LMC abundances from Russel & Dopita 1992).

The time-dependent models are completely determined by four **stellar parameters**: $T_\star$, $L_\star$, $M_\star$, elemental abundances (C/O ratio), and the **pulsational parameters**: pulsation period P and velocity amplitude Δu.

Results

The effects of metallicity on dust and hydrodynamics

The local gas density and velocity are governed by the equation of motion and the equation of continuity. The metallicity enters the equation of motion via the dust and the gas opacity and determines the acceleration ratio $\alpha^{\rm tot} = a_{\rm rad}/g$ ($a_{\rm rad}$ radiative acceleration, g gravitational deceleration). As soon as dust forms efficiently, its opacity dominates $\alpha^{\rm tot} = \alpha^{\rm d} + \alpha^{\rm g}$ with $\alpha^{\rm d} \gg \alpha^{\rm g}$. The gas opacity can affect the radiative acceleration ($\alpha^{\rm g}$, dashed red line, Fig. 1) only in the innermost layers ($< 2R_0$, R_0 radius of the initial model) but it influences the global density level of the atmosphere due to its effect on the optical depth. This holds independent of metallicity although mainly the fraction of the dust contribution changes (compare l.h.s. and r.h.s. of Fig. 1).

The photospheric and outer atmospheric regions ($\lesssim 2R_0$) of late type stars are too hot to allow for a gas - solid phase transition. Only the radial pulsation

increases the scale height of the atmosphere to such an extent that the density is high enough at a distance where the gas temperature is sufficiently low for dust formation. The range of efficient nucleation spans $1.5 \ldots 2.5R_0$ stellar radii but the nucleation rate J_* is considerably smaller in the low metallicity case (Fig. 2). Efficient dust growth sets in almost independent of metallicity at $\approx 2 \ldots 3R_0$ (compare degree of condensation f_c, Figs. 1, 2) causing $\alpha^{\rm d}$ to increase (dotted red line, Fig. 1). Since less material is available, $\alpha^{\rm d} \lesssim 1$ barely exceeds the gravitational deceleration in the LMC case, in contrast to the solar metallicity models where $\alpha^{\rm d} \lesssim 3$ in regions of efficient dust formation. Only a very few large particles of $\approx 0.1\mu$m form (see the mean particle radius $\langle r\rangle$ in Fig. 2).

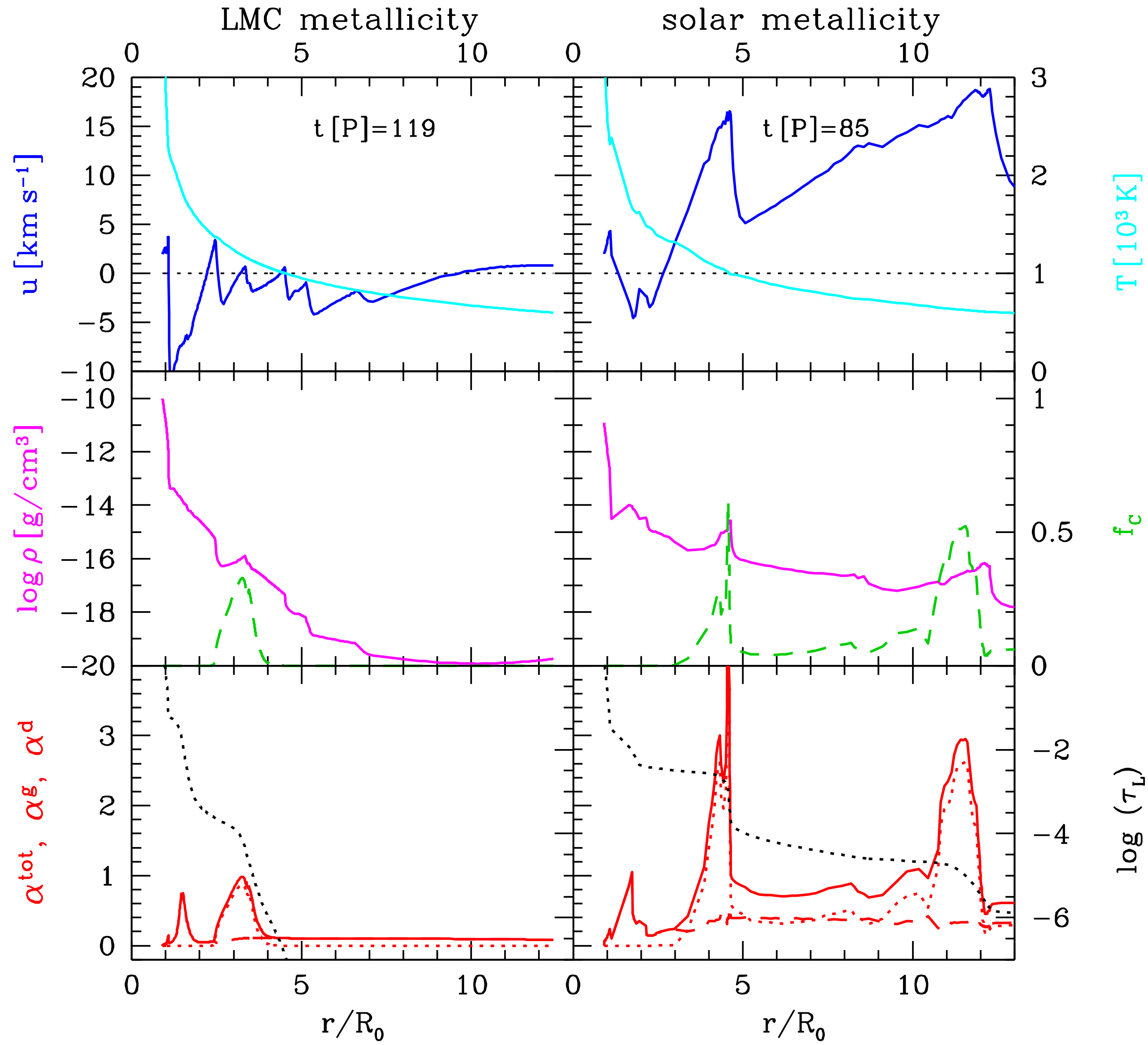

Figure 1: Hydrodynamic model structures for one instant of time for low-metallicity (LMC, left) and solar (right) metallicity. **Model parameter**: $T_\star = 3000$K, $L_\star = 10^4 L_\odot$, $M_\star = 1 M_\odot$, C/O=1.8, $\Delta u = 2$km s^{-1}, $P = 650$d.

Upper Panels: blue - velocity u [km s^{-1}], cyan - temperature T [10^3K] **Middle Panels**: magenta - gas density $\log \rho$ [g cm^{-3}], green - degree of condensation f_c **Lower Panels**: red solid - total acceleration ratio $\alpha^{\rm tot}$ (dotted - $\alpha^{\rm d}$, dashed - $\alpha^{\rm g}$), black - grey optical depth $\log \tau_{\rm L}$

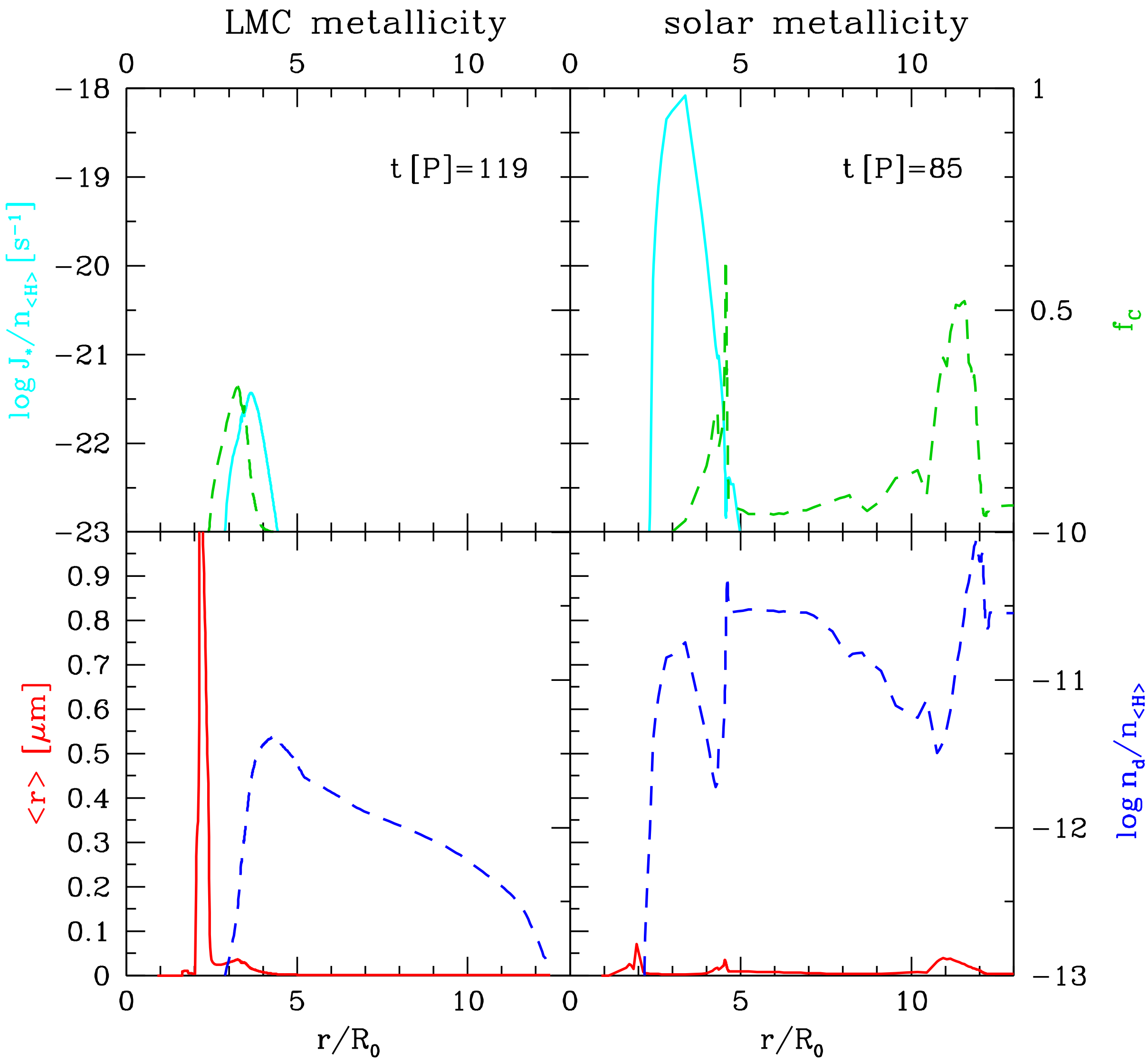

Figure 2: Characteristic dust properties for one instant of time of low-metallicity (LMC, left) and solar (right) metallicity hydrodynamic models. **Model parameter**: $T_\star = 3000$K, $L_\star = 10^4 L_\odot$, $M_\star = 1 M_\odot$, C/O=1.8, $\Delta u = 2$km s^{-1}, $P = 650$d.

Upper Panels: cyan - nucleation rate per H atom $\log J_*/n_{<\mathrm{H}>}$ [s^{-1}], green - degree of condensation f_c **Lower Panels**: red - mean particle radius $\langle r \rangle$ [μm], blue - number of dust grains per H atom $n_\mathrm{d}/n_{<\mathrm{H}>}$

The radiative acceleration by dust has only little influence on the velocity field in the low-metallicity model (l.h.s., Fig. 1), whereas it can even lead to the generation of new shock waves for solar metallicity (r.h.s., Fig. 1). The backwarming of the layers inside of the dust forming region is also much smaller than in the case of a solar composition and therefore, no onion-like shell structure develops as it is observed in the solar metallicity case (dashed green lines, Fig. 1). On the contrary, a quasi-static situation develops where the dust is almost at rest in one shell without significant movement at $2.5 \ldots 4R_0$ (depending on the chosen stellar parameter). Furthermore, the circumstellar dust shell is much less extended than in the solar metallicity case since a comparable mechanism for momentum transfer is missing.

Since less momentum is transfered to the gas, the star looses smaller amounts of matter at low metallicities. Table 1 shows that the mean mass loss rate $\langle \dot{M} \rangle$ decreases by four orders of magnitude when the metallicity is half a magnitude smaller ($T_\star = 3000$K models). Similarly large changes appear for the mean outflow velocity $\langle v_\infty \rangle$ but not for the mean dust-to-gas ratio $\langle \rho_{\rm dust}/\rho_{\rm gas} \rangle$. However, the change in $\langle \rho_{\rm dust}/\rho_{\rm gas} \rangle$ with metallicity is considerably larger than in the model grid used by Arndt *et al.* (1997) (see also Winters *et al.* 2000) where the stellar parameters have been varied assuming solar metallicity. Therefore, a comprehensive mass loss formula for any metallicity, as derived by Arndt *et al.* (1997) based on statistical methods, has also to consider the dependence on the metallicity of the gas.

	Stellar Parameter					**Pulsation Parameter**	
#	$T_\star$ [K]	$L_\star$ [$L_\odot$]	$M_\star$ [$M_\odot$]	$\epsilon_{\rm el}$	C/O	P [d]	Δu [$\rm km\,s^{-1}$]
1	2600	10^4	1	LMC	1.8	650	2
2	3000	10^4	1	LMC	1.8	650	2
3	3000	10^4	1	solar	1.8	650	2

	Resulting Quantities		
#	$\langle\dot{M}\rangle$ [$M_\odot$/yr]	$\langle v_\infty\rangle$ [km/s]	$\langle\rho_{\rm dust}/\rho_{\rm gas}\rangle$
1	$2.1\,10^{-10}$	0.1	$0.7\,10^{-3}$
2	$6.2\,10^{-11}$	-0.3*	$0.2\,10^{-3}$
3	$5.9\,10^{-7}$	17.1	$1.4\,10^{-3}$

Table 1: Hydrodynamic models for LMC and solar metallicity. Results for $\langle\dot{M}\rangle$, $\langle v_\infty\rangle$, and $\langle\rho_{\rm dust}/\rho_{\rm gas}\rangle$ are mean values in time and space as described by Winters *et al.* (2000).

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* $\langle v_\infty\rangle < 0$ and $\langle\dot{M}\rangle > 0$ is possible because $\langle\dot{M}\rangle = 4\pi\langle\rho v r^2\rangle_{r,t}$ is a mass-weighted mean, whereas $\langle v_\infty\rangle$ is not. The model in fact exhibits periods of massive dust and gas outflow but also periods when thin material falls inward.

Molecular layers

Time-dependent model atmospheres provide a possible explanation for regions of enhanced molecular abundances as detected by ISO (e.g. Tsuji et al., de Jong et al.). Hydrostatic models are not capable to explain these observations since the treatment of shock waves is beyond their scope. Investigations by Woitke *et al.* (1999) and Helling & Winters (2000) have shown that pulsation *and* radiation pressure on dust and gas produce such extended atmospheres consisting of several molecular layers. Since these layers are an *inherent feature* of the time-dependent models, metal-deficient stars are also expected to be surrounded by them (Fig. 3).

Three distinct layers (I, II, III) of various molecules can be identified in the model atmosphere. They form in the inner shell region below $4\,R_0$ and are the result of several physical mechanisms:

Layer I, the first maximum and located in the photosphere at about $1R_0$, is mainly influenced by periodic shock waves and affects all molecules. **Layer II**, the second maximum, forms an extended atmosphere and is characterized by the levitation by shock wave dissipation or radiation pressure on molecules. The latter is only of significance in the solar metallicity case. **Layer III** is dominated by radiation pressure on dust.

Though all mechanisms are less active in the low metallicity case, a layered structure of the molecular abundances can also be observed in this case, indicating the universality of the phenomenon know as *warm molecular layers*.

Since we assume chemical equilibrium, the properties of the molecular layers are determined solely by the local gas temperature and pressure, which in turn depend closely on the hydrodynamic structure of the model. By applying the law of mass action for calculating the molecular composition of the gas, in particular the polyatomic molecules are affected by the varying local density in the wind-driving zone.

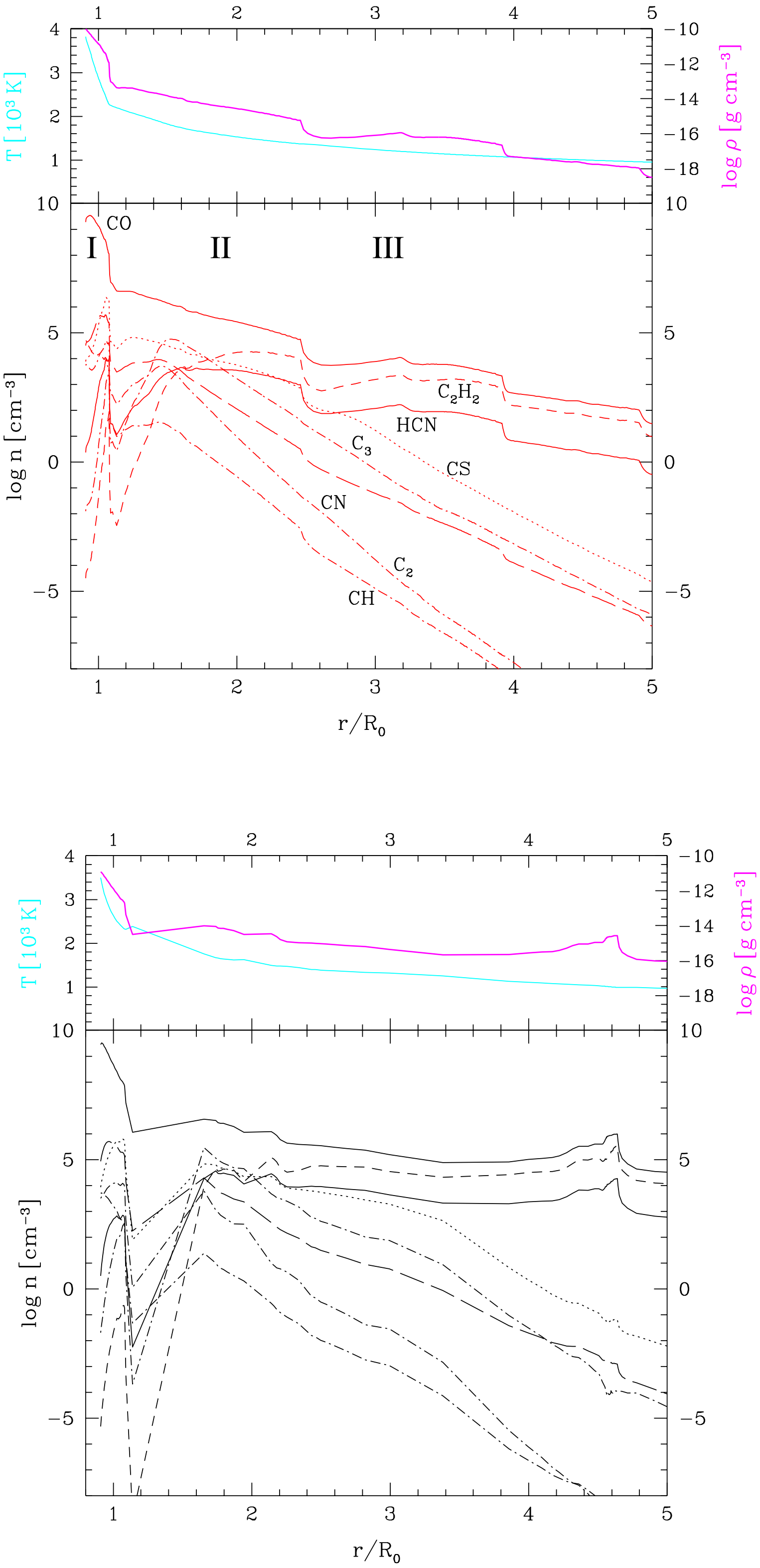

Figure 3: Molecular abundances depending on the metallicity of the gas at one instant of time for the innermost $5R_0$: red - LMC (upper panel), black - solar (lower panel). Independent of metallicity, three distinct layers may be identified. **Model parameters**: $T_\star = 3000$K, $L_\star = 10^4 L_\odot$, $M_\star = 1 M_\odot$, C/O=1.8, $\Delta u = 2$km s^{-1}, $P = 650$d.

Conclusions

- The decrease of the metal abundance significantly lowers the amount of dust formed and thereby causes a considerably smaller mean mass loss rate, mean outflow velocity, and mean dust-to-gas ratio. LMC models rather develop a quasi-static structure where the dust appears solely in one layer without any significant movement outwards because of the small radiative acceleration.
- The quasi-static appearance with almost negligible outflow velocities for the LMC-metallicity models presented here raises the question whether pulsation and dust alone can drive the wind of metal-poor stars, as it has be shown for solar abundances. The radiation pressure on molecules, as a possible candidate, seems to be negligible since we have already considered its upper limit by applying Planck means. It might, however, be just this upper limit which prevents the dust to take a more active role in the models presented here due to the resulting overall lower density.
- Molecular layers are a characteristic feature of time-dependent models and are closely linked to levitating processes like shock wave dissipation and radiation pressure on gas and/or dust. Therefore these layers are also expected to be present in low metallicity stars.

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Acknowledgment
This work has been partly supported by the DFG (grant Se 420/19-1).