The Art of Modelling Stars in the 21st Century
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Dust-driven Winds Beyond Spherical Symmetry

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Abstract. New 2D dynamical models for the winds of AGB stars are presented which include hydrodynamics with radiation pressure on dust, equilibrium chemistry, time-dependent dust formation theory, and coupled frequency-dependent Monte Carlo radiative transfer. The simulations reveal a much more complicated picture of the dust formation and wind acceleration as compared to 1D spherical wind models. Triggered by non-spherical pulsations or large-scale convective motions, dust forms event-like in the cooler regions above the stellar surface which are temporarily less illuminated, followed by the radial ejection of dust arcs and clumps. These simulations can possibly explain recent high angular resolution interferometric IR observations of red giants, which show an often non-symmetric and highly time-variable innermost dust formation and wind acceleration zone. The dependence of the mass-loss rates on stellar parameters is less threshold-like as used from 1D models, and therefore, it seems quite possible that the phenomenon of dust-driven winds may occur also in less evolved red giants.

Keywords. hydrodynamics,radiative transfer, stars: late-type, stars: winds, stars: mass loss

1. State of Art: 1D models

The massive winds of asymptotic giant branch (AGB) stars and red supergiants are of paramount importance for late stages of stellar evolution (see e.g. Siess and Willson, this volume) and undoubtably play an important role in the cycle of matter in galaxies.

But despite 40 years of active research, our theoretical understanding of these winds is still comparably poor. Shock waves created by the stellar pulsation have been identified to trigger the process of dust formation close to the star, and radiation pressure on newly formed dust grains can overcome local gravity. However, the details of the wind driving mechanism are still puzzling. The most advanced computational wind models nowadays include hydrodynamics, chemistry, time-dependent dust formation and radiative transfer with varying degree of sophistication (Winters *et al.* 2000, Höfner *et al.* 2003, Sandin & Höfner 2003, Schirrmacher *et al.* 2003, Jeong *et al.* 2003). Other 1D models rely on the assumption of stationarity (e. g. Ferrarotti & Gail 2006). These simulations can explain the general features of dust-driven winds for the coolest and most luminous AGB stars, in particular the carbon stars, but for slightly warmer or less luminous stars, the 1D models fail to predict the observed mass-loss rates. For example, Mattsson *et al.* (2007) concluded that the Höfner *et al.* models can only be applied to carbon stars with $T_{\rm eff} > 3200\,$K and $C/O > 1.2$. Otherwise, the dust forms too distant from the star or the resulting dust opacity is simply insufficient to drive the wind, respectively.

In contrast, observations tell us that massive dusty winds also exist for less extreme carbon stars (e. g. Hony & Bouwman 2004) as well as for red supergiants (Verhoelst *et al.* 2006), M-type giants and even S-stars (Ramstedt *et al.* 2007). The mass-loss rate rather seems to vanish smoothly as function of stellar parameter toward RGB stars and K giants without a clear cut-off, which would be expected if all these winds were actually dust-driven. The common winds of oxygen-rich AGB stars are particularly hard to understand, if frequency-dependent radiative transfer effects are taken into account, because the peak of the dust opacity around 10 μm differs strongly from the peak of the stellar radiation around 1 μm (Woitke 2006b, Höfner & Andersen 2007), in particular with regard to small grains which are supposed to drive the wind.

Regarding the current and future possibilities to monitor directly the dust formation and wind acceleration zones of red giants (AMBER on the VLTI, CHARA, ALMA, or MIRI on the JWST), spherical models actually appear as a non-starter. I have therefore developed the first 2D-models for dust driven-winds, both carbon-rich (Woitke 2006a) and oxygen-rich (Woitke 2006b) with frequency-dependent radiative transfer, which allow for a profound investigation of stability, symmetry breaking and pattern formation. The models can predict what types of spatial dust distributions and wind asymmetries form in red giant winds (shells, arcs, clumps, etc.), how they evolve in time, and how these stars would look alike (lightcurves, SEDs, visibilities, images).

Recently, Freytag & Höfner (2008) have published a combination of two radiation hydrodynamics models: an inner 3D model for the convection and pulsation of the AGB star, and an outer 1D model for the dust formation and wind acceleration. The inner grey 3D model shows large convection cells up to the scale of the star itself along with a strongly non-isotropic irradiation of the circumstellar environment where the dust forms. These simulations provide further motivations to drop the assumption of spherical symmetry and to study the complicated interplay between dynamics, dust formation and radiative transfer in more than one spatial dimension in the 21st century.

2. New models

The 2D models are developed in the frame of the FLASH 2.4 hydrocode (Fryxell *et al.* 2000) which is an explicit, finite volume, high-order Godunov-type hydro-solver which uses Adaptive Mesh Refinement (AMR) and is fully parallel (MPI). The implementation of chemistry and dust formation into this hydro-solver is quite straightforward (operator splitting, see Woitke 2006a for details). In the C-rich case, the models use the standard theory for the formation of amorphous carbon grains (Gail & Sedlmayr 1988). Concerning the O-rich models, this kinetic description has been extended to model the nucleation, growth and evaporation of dirty dust particles, which consist of numerous small islands of different solid materials like Mg_2SiO_4, SiO_2, Al_2O_3, Fe and TiO_2, see Helling & Woitke (2006) and Helling, Woitke & Thi (2008) for details. A fast equation of state which includes ionization potential of H^+, dissociation potential of H_2, and vibrational and rotational excitation energies of H_2 is implemented (see Woitke 2008).

The coupling to an efficient radiative transfer tool has turned out to be rather difficult. The optical depths range from $\sim 10^4$ at the bottom of the atmosphere to truly zero at large distances from the star. The opaque, dusty regions can be confined into geometrically thin shells or clouds which move in an otherwise quite transparent medium, making long ray tracing unavoidable. The dusty regions scatter, re-emit and cast shadows, thereby illuminating the optically thin regions in between in complicated ways.

Moreover, the efficient absorption and thermal re-emission of radiation by the dust grains leads to a very fast relaxation of the internal dust temperature to the ambient radiation field with cooling timescales of the order of milliseconds to 10^{-1} seconds for small grains (Woitke *et al.* 1999). This fast relaxation introduces a stiff coupling between hydrodynamics and radiative transfer. All explicit schemes that are based on formal solutions of the radiative transfer problem (e. g. short and long characteristics methods)

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have the disadvantage to slow down the computational timestep (typically a few 10^4 sec) to this radiative cooling timescale, which is not acceptable in this application.

Therefore, I have used a Monte Carlo code (Niccolini, Woitke & Lopez 2003) to calculate the radiation field *under the auxiliary condition that the dust is in radiative equilibrium*, which de-stiffens the physical problem at hand by the elimination of the shortest characteristic timescale in the system. In contrast to the dust temperature which is hence a direct result of the radiative transfer, the gas temperature is calculated time-dependently via the energy equation with radiative heating and cooling. To my knowledge, this coupling to Monte Carlo radiative transfer is an innovative approach in computational hydrodynamics.

The basis for the radiative transfer treatment are monochromatic molecular gas opacities from the Marcs stellar atmosphere code (Jørgensen *et al.* 1992), extracted by Helling *et al.* (2000), and dust opacities calculated in the Rayleigh limit of Mie theory according to the Jena Optical Data Base (for amorphous carbon, I use the 1000 K sample from pyrolysis experiments (Jäger *et al.* 1998). The frequency space is subdivided into five spectral bands with two opacity distribution points in each band, resulting in altogether 5×2 effective wavelengths sampling points. High and low opacity values are pre-tabulated for each spectral band in such a way that the band-mean Planck and Rosseland opacities are properly represented. The details will be explained in Woitke (2008).

3. Results

As an illustrative example, a carbon star with stellar mass $M_\star = 1M_\odot$, stellar luminosity $L_\star = 5000L_\odot$, effective temperature $T_\star = 2500$K, solar metallicities ($\epsilon_{\rm He} = 10.99$, $\epsilon_{\rm O} = 8.87$) except carbon (C/O$\,=\,$1.4), pulsational period $P = 1$yr and piston amplitude $\Delta u = 3$km/s is simulated. In order to focus on the effects of multi-dimensionality, a sub-sonic *p-mode-like* non-radial stellar pulsation is considered as inner boundary condition by means of the following modified piston approach

$$u(r_{\rm in}, \theta, t) = \Delta u \sin\left(\frac{2\pi t}{P}\right)\cos(2\theta), \tag{3.1}$$

where u is the velocity at the inner boundary $r_{\rm in}$ and θ is the latitude angle. Although the calculated mean wind properties are quite similar to a 1D spherical model with equal parameters (mass loss rate $\langle\dot{M}\rangle = 7\cdot 10^{-7}\,M_\odot$/yr, final outflow velocity $\langle v_\infty\rangle = 20\,$km/s, dust-to-gas mass ratio $\langle\rho_{\rm d}/\rho_{\rm g}\rangle = 3\cdot 10^{-4}$, the model yields quite a different picture of the dust and wind formation close to the star (see Fig. 2).

A non-spherical stellar atmosphere (let it be caused by non-radial pulsations or convective motions) illuminates its environment in a likewise non-uniform way. For example, an oblate-shaped star releases its luminosity preferentially along the poles, because the additional gas above the stellar equator blocks the straight escape path of the photons (see Fig. 1, lower plot). Therefore, the gas just above the stellar atmosphere changes its temperature as the star changes its shape from prolate to spherical to oblate to spherical, and so on, in this model. Consequently, there are always thermodynamical conditions present in spatially limited regions above the stellar surface that are just favorable for new dust formation (high densities & low temperatures). This leads to a non-uniform dust production, sometimes astonishingly close to the star, followed by radial ejections of dust arcs or smaller cap-like clumps due to radiation pressure which expand tangentially like mushroom clouds (see Fig. 1, upper plot).

Figure 2 shows a comparison between a high-resolution (20 milli-arc-sec) speckle interferometry image of IRC+10216 in the K-band from the KECK telescope (Monnier 2002) and a Monte-Carlo simulated monochromatic image for $\lambda = 2.2\,\mu$m based on a calculated

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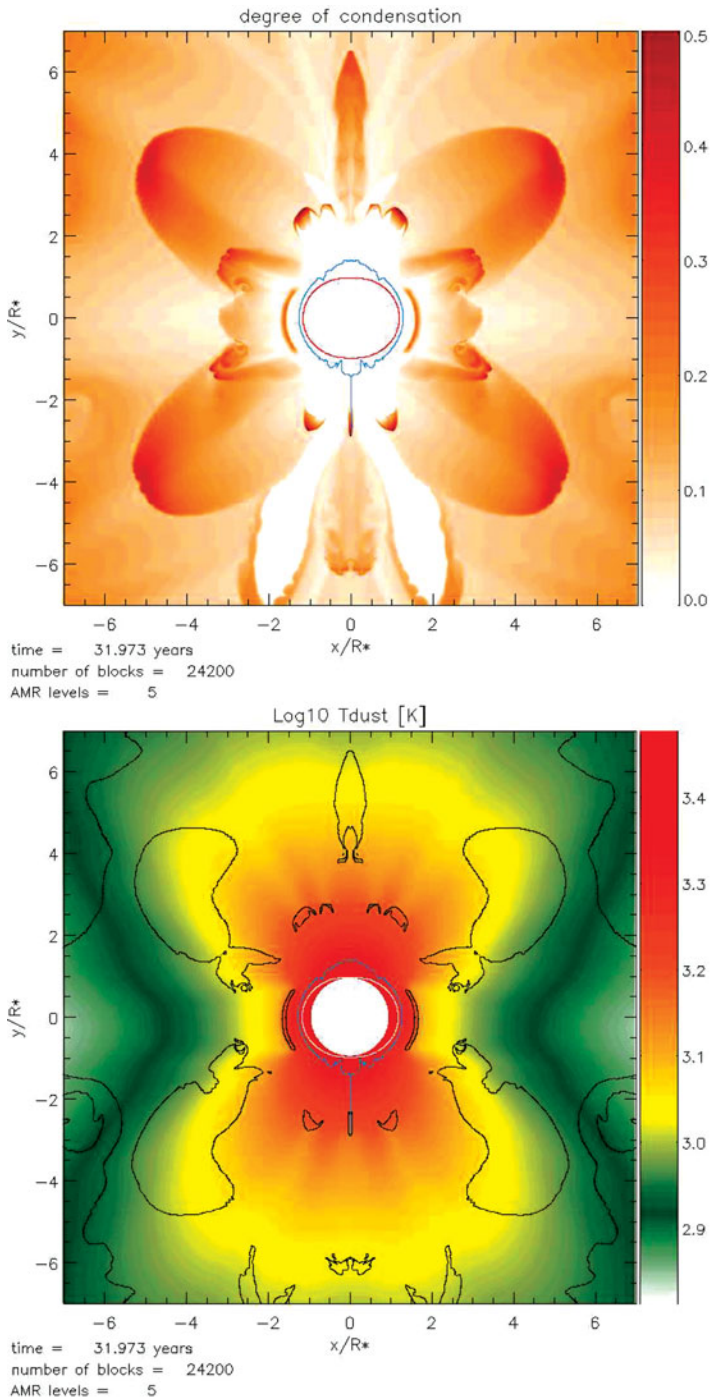

Figure 1. Snapshot of the innermost 13 × 13 stellar radii after 32 years of simulation. The upper plot shows the degree of condensation $f_{\rm cond}$ (0 = dust-free, 1 = complete condensation) and the lower plot the calculated dust temperature $T_{\rm d}$. The blank circle in the center is not modelled. The inner red/white contour line shows a density of $\rho = 10^{-10}\,{\rm g/cm^3}$ inside the star, the outer blue contour line marks $\tau_{\rm std} = 1$. The black contour lines in the lower plot encircle the dusty regions with $f_{\rm cond} = 0.15$. Note the asymmetric illumination by the deformed star, the shadows of the dust clouds and the new dust formation event just above the equator.

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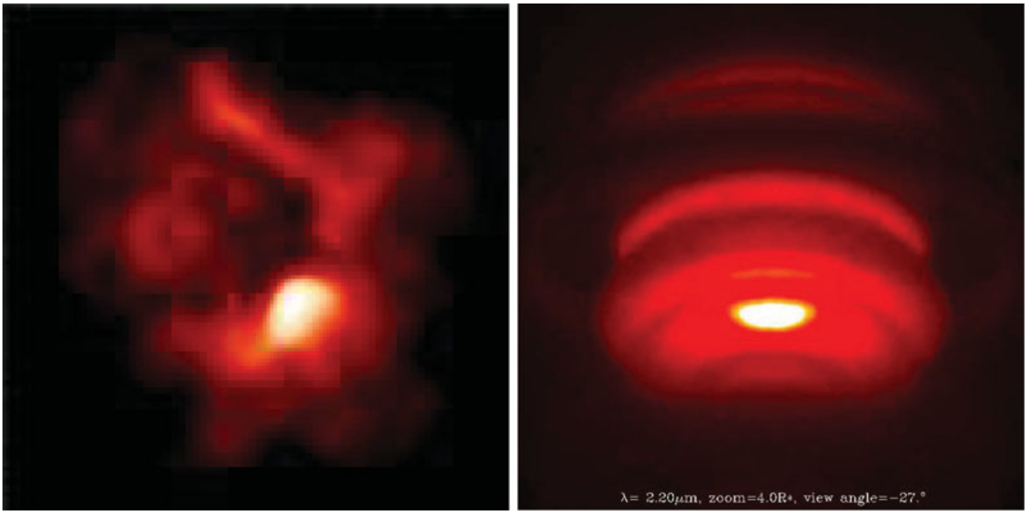

Figure 2. Comparison of observation and theory. IRC+10216 in the K-band from the KECK telescope with speckle interferometry (angular resolution 20 milli-arc-sec, J. Monnier, 2002, priv. comm.) and a simulated image from a 2D wind model at $\lambda = 2.2\,\mu$m. The bright spot in the simulated image originates from a hole in the dust shell. Although the star is situated in the center of this image, it is mostly obscured by dust at $2.2\,\mu$m. The stellar disk would be clearly visible at $10\,\mu$m in the model.

model structure. The images of the 2D model show a strong dependency on time and inclination angle. Sometimes, the calculated dust distribution around the star possesses a hole which, if viewed from a particular direction, produces a bright spot in the image, because the hot material close to the star becomes visible.

4. Summary and Conclusions

The wind driving mechanism of red giants and supergiants is still a matter of debate. For radiation pressure on dust, two conditions must be fulfilled:

(1) The gas close to the star must provide, at least temporarily, the necessary thermodynamical conditions for the gas-to-dust phase transition to occur: sufficiently low dust *and* gas temperatures (about 1000 K to 1600 K, depending on the dust grain material) and sufficiently high densities ($\gtrsim 10^9\,\mathrm{cm}^{-3}$).

(2) The opacity of the formed dust integrated over the incident radiation flux must be sufficiently high to cause a radiative acceleration that locally overcomes gravity.

In 1D spherically symmetric models, condition 1 translates into rather robust threshold values for stellar parameters. For too high T_{eff}, the temperature window shifts to too large distances from the star where the density is already too low (in absence of another driving mechanism). Stellar pulsations help to fulfil condition 1. Condition 2 puts similar constraints on the $L_\star/M_\star$ ratio, and on $\epsilon_{\mathrm{C}} - \epsilon_{\mathrm{O}}$ in case of C-stars or on the metallicity in case of O-rich AGB stars. Condition 2 makes it hard to understand why M-type, S-type and C-type AGB stars actually appear so similar in observed mass-loss rates and outflow velocities, although the amount and type of dust should be quite different.

Summarizing these constraints from the 1D models, the dust-driving hypothesis seems to work only for rather low-mass, cool and luminous AGB stars, preferentially carbon stars which can produce the necessary dust opacity in the near IR to efficiently absorb the stellar radiation. Taking into account frequency-dependent radiative transfer effects,

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the hypothesis already seems to fail for O-rich AGB stars which simply cannot provide the necessary dust opacity in the near IR (Woitke 2006b).

However, deviations from spherical symmetry may help! Stars which undergo violent convection or non-radial pulsation motions on their surfaces provide a rich variety of thermodynamical conditions in the gas just above the photosphere. The radiation leaves the star non-isotropically (see Fig. 1 in Freytag & Höfner (2008), right column) preferentially via the hot surface areas, leaving "cool spots" in between that provide the perfect conditions for dust formation. Once formed, the dust just has to wait until the region of interest is again strongly illuminated, which then produces the necessary combination of high opacity and high luminosity.

In this way, it seems quite possible that even warmer AGB stars may possess dust-driven winds, because extended parts of their surfaces are actually cooler. Thus, the dependency of the mass-loss rate on stellar parameter should be less threshold-like and the range of applicability of dust-driven winds more extended toward less evolved stars as compared to the results of 1D models. In that respect, I disagree with the conclusions of Freytag & Höfner (2008) that the overall spherical expansion of shock waves justifies the application of 1D models, since the inclusion of multi-D radiative transfer effects is crucial for the above line of argumentation.

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References

Ferrarotti, A. S. & Gail, H.-P., 2006, A&A 447, 553
Fryxell, B., Olson, K., Ricker, P., Timmes, F. X., & Zingale, M., *et al.*, 2000, ApJ 131, 273
Freytag, B. & Höfner S., 2008, A&A 483, 571
Helling, Ch., Winters, J. M., & Sedlmayr, E, 2000, A&A 358, 651
Helling, Ch. & Woitke, P., 2006, A&A 455, 325
Helling, Ch., Woitke, P., & Thi, W.-F., 2008, A&A accepted, astro-ph 0803.4315v1
Höfner, S., Gautschy-Loidl, R., Aringer, B., & J/orgensen, U. G., 2003, A&A 399, 589
Höfner, S. & Andersen, A. C., 2007, A&A 465, L39
Hony, S. & Bouwman, J., 2004, A&A 413, 981
Jäger, C., Mutschke, H., Dorschner, J., & Henning, Th., 1998, A&A 332, 291
Jørgensen, U. G., Johnson, H. R., & Nordlund, Å, 1992, A&A 261, 263
Jeong, K. S., Winters, J. M., Le Bertre, T., & Sedlmayr, E., 2003, A&A 407, 191
Mattsson, L., Höfner, S., Wahlin, R., & Herwig, F., 2007 astro-ph 0705.2315v2
Monnier, J. D., Millan-Gabet, R., & Tuthill, P. G., *et al.*, 2004, ApJ 605, 436
Niccolini G., Woitke P., & Lopez B., 2003, A&A 399, 703
Ramstedt, S., Schoeier, F. L., & Olofsson, H., 2007, astro-ph 0706.2559v1
Sandin, C., & Höfner, S., 2003, A&A 404, 789
Schirrmacher, V., Woitke, P., & Sedlmayr, E., 2003, A&A 404, 267
Gail, H.-P., & Sedlmayr, E., 1988, A&A 206, 153
Verhoelst, T., Decin, L., van Malderen, R., Hony, S., Cami, J., Eriksson, K., Perrin, G., Deroo, P., Vandenbussche, B., & Waters, L. B. F. M., 2006, A&A 447, 311
Winters, J. M., Le Bertre, T., Jeong, K. S., Helling,. Ch., & Sedlmayr, E., 2000, A&A 361, 641
Woitke, P., 1999, in Astronomy with Radioactivities, ed. R. Diehl & D. Hartmann (Schloß Ringberg, Germany: MPE Report 274), 163–174
Woitke, P., 2006a, A&A 452, 537
Woitke, P., 2006b, A&A 460, L9
Woitke, P., 2008, "Monte Carlo Radiative Transfer from $\tau = 0$ to $\tau = \infty$", MNRAS, in preparation