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Three-dimensional model of the atmosphere of an AGB star

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Abstract

Winds of tip-AGB (Asymptotic Giant Branch) stars are driven by radiation pressure on dust, leading to significant mass loss. This process has already been successfully modelled with time-dependent one-dimensional simulations.

In this poster we present preliminary results from first three-dimensional radiation hydrodynamic simulations of the atmosphere of an AGB star. Dust formation is already included. However, the description of the interaction of the dust with the gas and the radiation field needs further improvement, before a detailed comparison with 1D models is possible.

Introduction

Stars at the tip of the AGB show a significant mass loss. Their winds are driven by radiation pressure on dust. Efficient formation and growth of dust grains require low temperatures and high gas densities. Both conditions are not fulfilled simultaneously in hydrostatic models of stellar atmospheres. However, one-dimensional radiation hydrodynamic simulations can take into account the time-dependent generation and destructions of dust and its interaction with the gas and the radiation field. In these models, the inner boundary condition is a moving piston located below the stellar surface and mimicking observed stellar pulsations. The waves produced by the piston travel into the thinner outer layers and transform into shock waves with temperature and density fluctuations strong enough to trigger intermittent formation of dust. Large opacities allow the dust grains to capture the stellar radiation efficiently leading to an outward acceleration and finally a stellar wind.

In this contribution we discuss two of the assumptions inherent in these models: the spherical symmetry and the role of the piston at the lower boundary. We use three-dimensional radiation hydrodynamic simulations with CO^{5}BOLD of the outer convective envelope and the atmosphere of an AGB star to investigate the influence of spatial inhomogeneities induced by huge convection cells. As 3-D calculations are much more time-consuming than 1-D simulations they have to rely on simpler physics (only grey opacities so far, and no radiation pressure included yet) and comprise only the outer envelope and the immediate surroundings of the star. Nevertheless, these preliminary results give a first impression of the effects of non-spherical flows on the formation of dust grains.

Numerical Simulations with CO^5BOLD

To produce a model of the outer layers of an AGB star the 3D radiation hydrodynamics code CO^5BOLD has been used, which can be characterized by some keywords:

General

- Grid: Cartesian box
- Gravitation is included as external potential
- Ionization effects are accounted for by a tabulated EOS

Hydrodynamics Scheme

- Operator (directional) splitting reduces 3D or 2D problem to 1D
- 1D hydrodynamics equations are solved with an approximate Riemann solver of Roe type
- Additional 3D or 2D tensor viscosity improves stability

Radiation Transport

- Non-local radiative energy transfer for one direction solved with short-characteristics scheme
- Grey or frequency-dependent opacities (tabulated)
- No scattering, strict LTE

Dust source terms

- Time-dependent grain formation and growth (moment method)
- Classical nucleation rate
- Equilibrium carbon chemistry for molecules contributing to dust formation

Setup for models st28gm06n03/05

- Computational domain: cube, edge length 1674 $R_\odot$, 171^3 points
- Gravitation: spherical $1/r$ potential, smoothed in the center
- Energy source: within a sphere of radius r_0=78 $R_\odot$
- Outer boundaries: open, transmitting for waves
- Merged grey opacities: PHOENIX + OPAL tables (Hauschildt, P.H., Baron, E., Allard, F. 1997, ApJ 483, 390; Iglesias, C.A., Rogers, F.J., Wilson, B.G. 1992, ApJ 397, 717; kindly provided by Hans-Günter Ludwig)
- Stellar parameters:
  - solar composition (for EOS and opacity table)
  - $M_\star = 1 M_\odot$
  - $L_\star = 7\,000\, L_\odot$
  - $R_\star \sim 350\, R_\odot$
  - $T_{\rm eff} \sim 2800$ K
  - $\log g \sim$ -0.6 (cgs units)
- Dust parameters:
  - Grains consisting of amorphous carbon
  - Model st28gm06n03: no dust
  - Model st28gm06n05: dust with C/O=1.4

Results

- The sequence of frequency-integrated surface intensities in Fig. 1 shows a pulsating stellar atmosphere with complex structures. Even without detailed dust treatment in the opacity tables the optical thickness of the atmosphere is so large that the actual stellar surface becomes only occasionally visible (e.g. in snapshot at t=2.20 yrs in Fig. 1).

- The shock waves (see Fig. 2) associated with the giant convection cells (cf. Fig. 3) lead to a levitation of the upper atmospheric layers, similar to the effect of stellar pulsations as simulated by a piston in 1D models. The enhanced densities (see Fig. 4) are necessary for efficient dust formation.

- The time-scales for dust formation are comparable to the hydro- and thermodynamical time-scales in the atmosphere (cf. Fig. 5), leading to non-equilibrium effects. A time-dependent description of the dust component is necessary, as also indicated in 1D models with more detailed micro-physics.

- Non-spherical structures in the density and temperature of the atmosphere due to the convection cells are to a certain degree reflected in the dust distribution close to the star (see Fig. 6).

Surface Intensity (Model st28gm06n03)

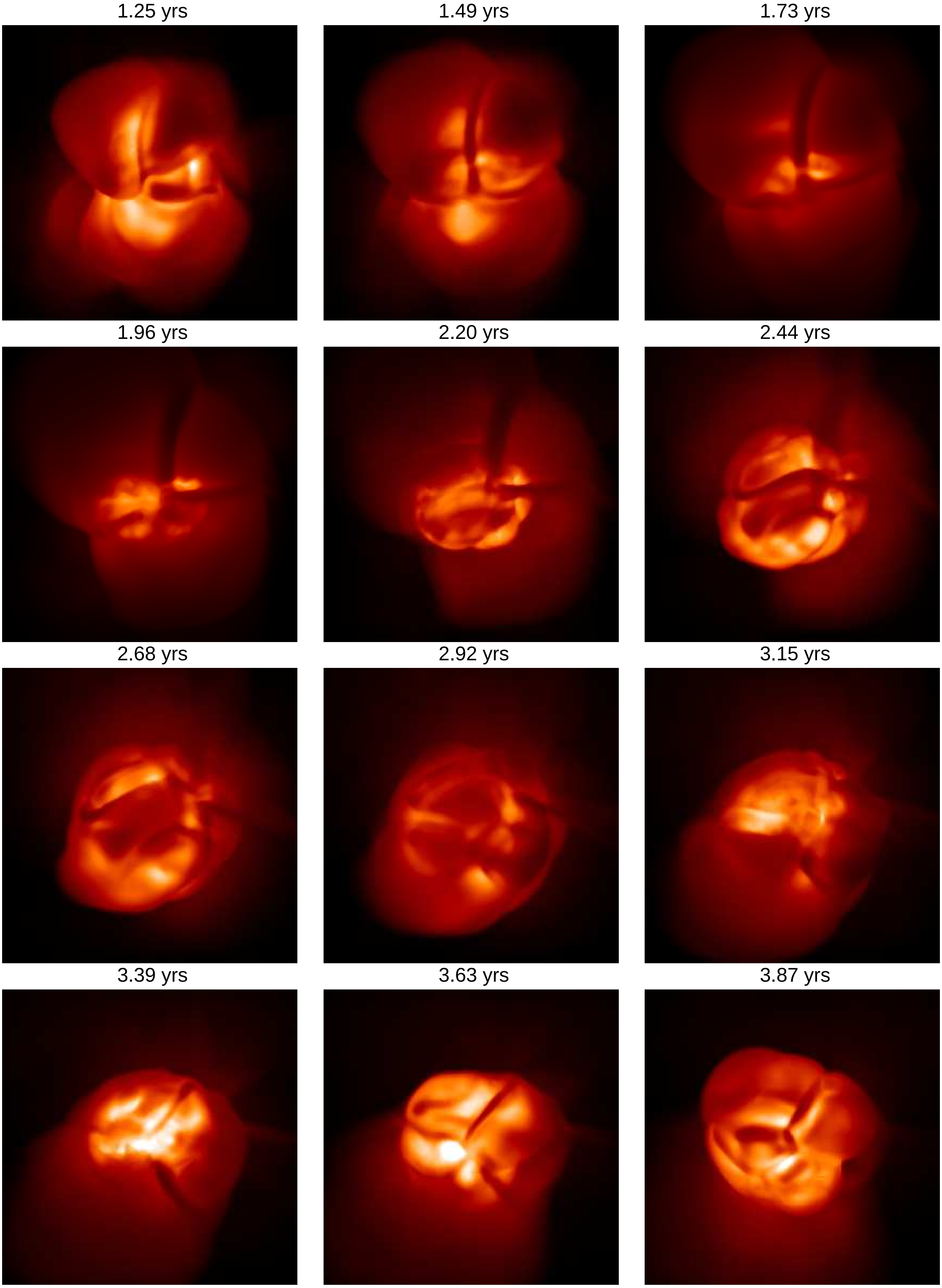

Figure 1: Sequence of surface intensity snapshots. The time step is indicated in years on top of each frame. Each image has an edge length of 1674 $R_{\odot}$. At most instances not granules at the top of the convection zone but shock fronts in the atmosphere cause the visible structures. The actual size of the star can better be inferred from Fig. 2 or Fig. 3.

Temperature Slices (Model st28gm06n03)

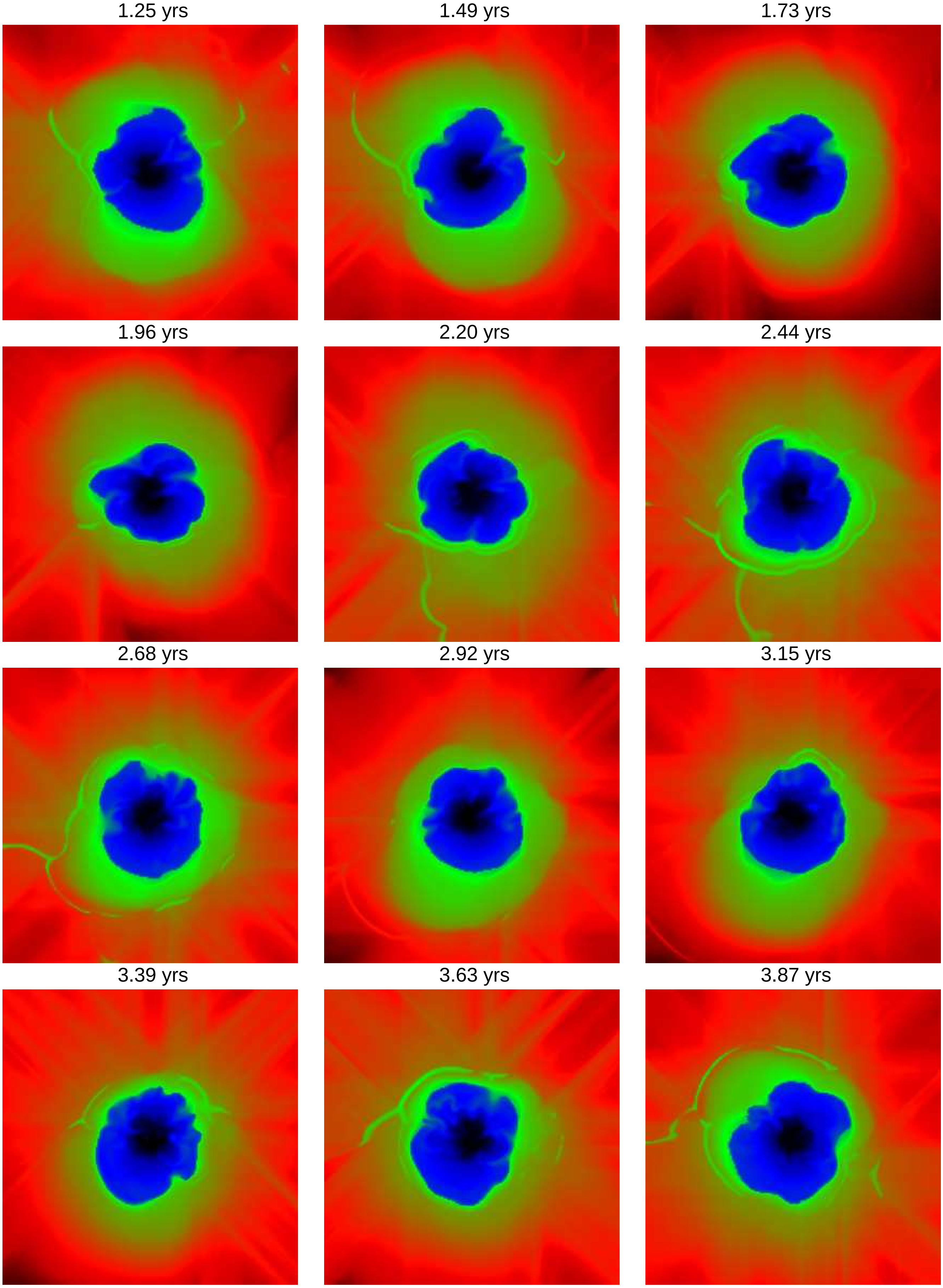

Figure 2: Sequence of temperature slices through the center for the same sequence as shown in Fig. 1. The temperature ranges from 800 K to 51 000 K. Shock waves run into the outer atmosphere. Some radial structures are artefacts from the simplified (speed-optimized) radiation transport scheme chosen for this model.

Entropy Slices (Model st28gm06n03)

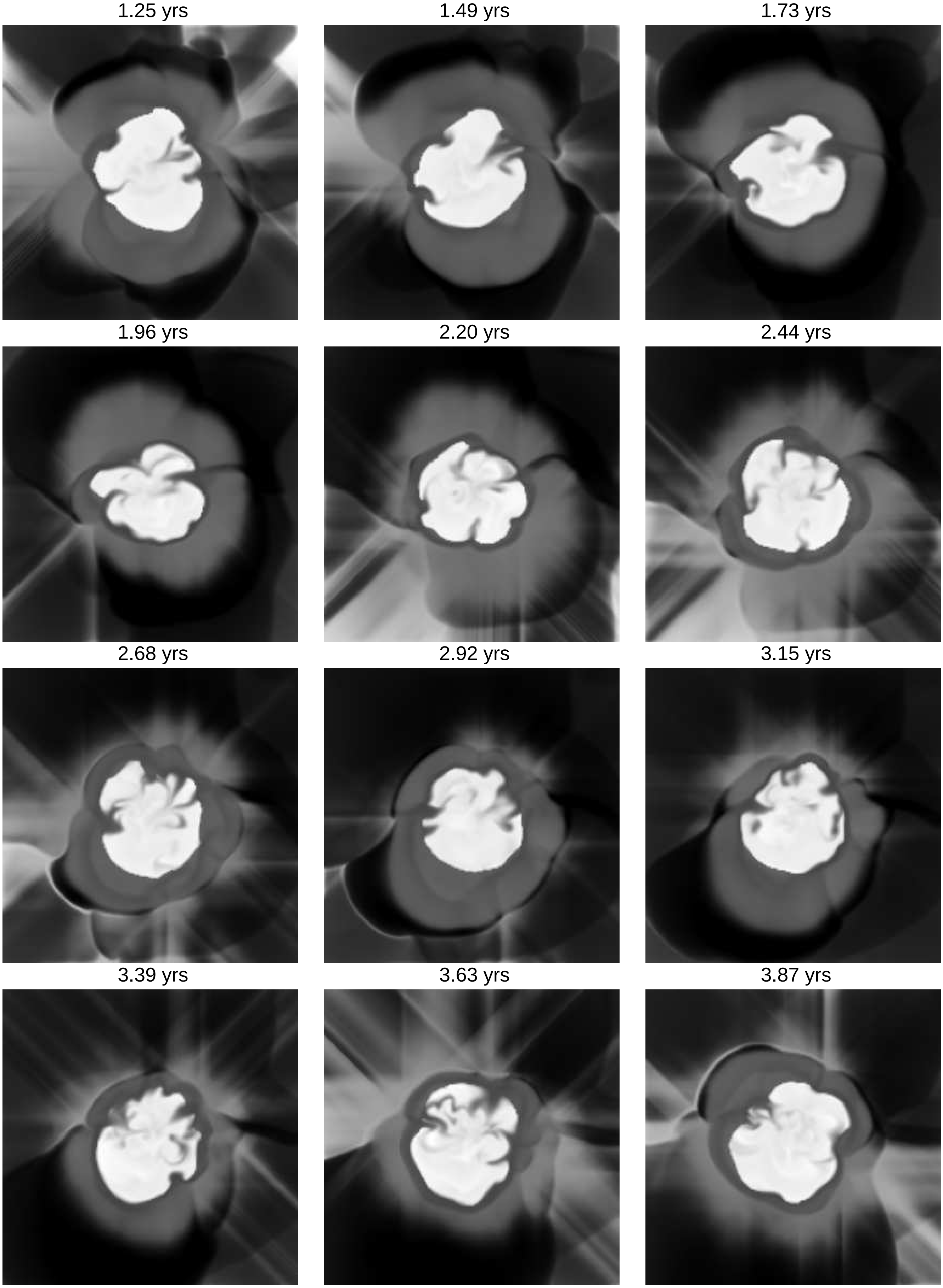

Figure 3: Sequence of entropy slices for same model and time steps as in Fig. 1. The star has huge convective structures. The "entropy rays" in the atmosphere are artefacts.

Density Slices (Model st28gm06n03)

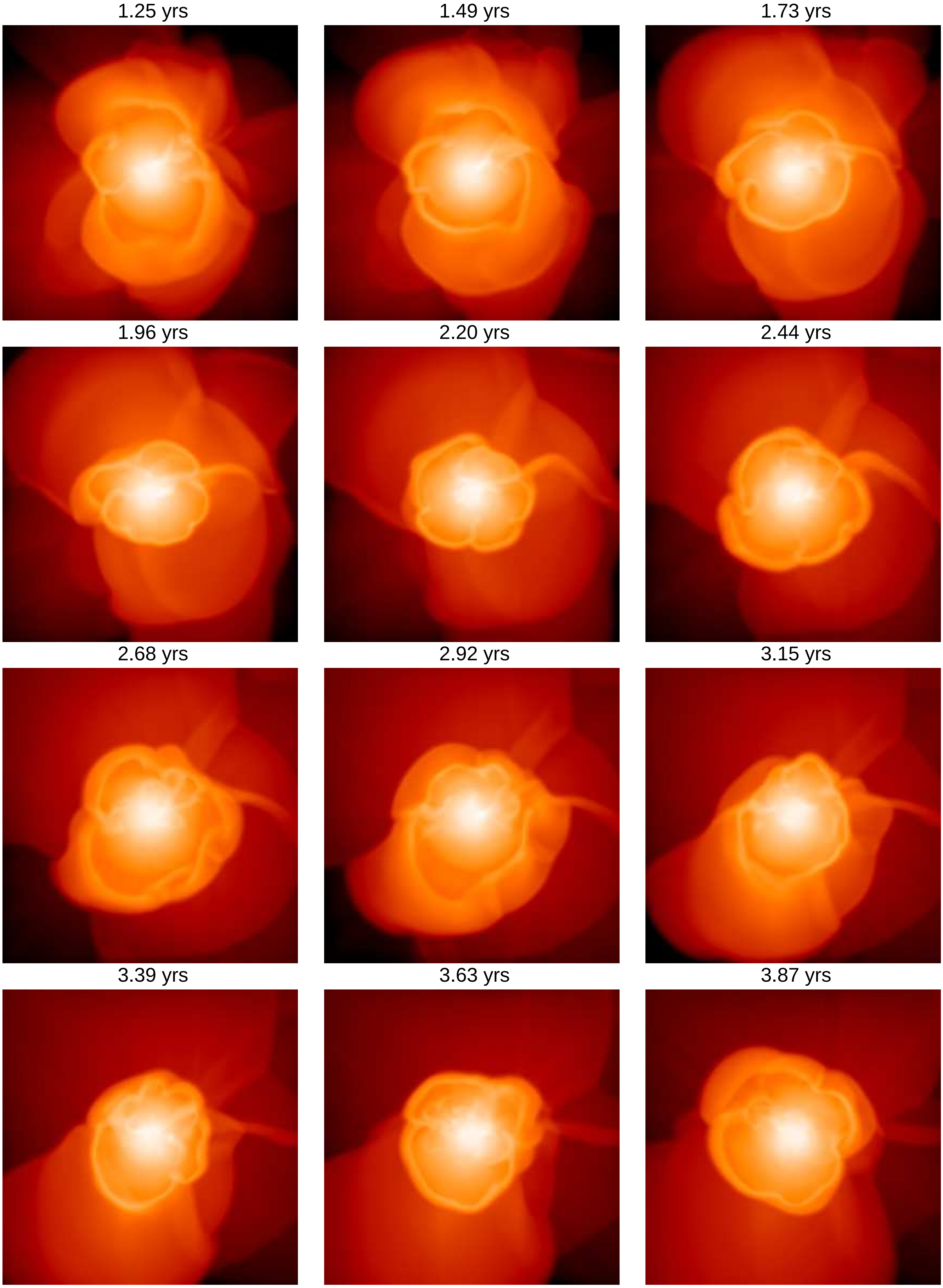

Figure 4: Sequence of (logarithmic) density slices through the center for the same sequence as shown in Fig. 1. The density in this sequence lies between 10^{-18} and $2{\cdot}10^{-7}\,\mathrm{g/cm^3}$. The density inversion at the distorted stellar surface is clearly visible. Shock waves in the atmosphere are even more prominent than in the temperature plot in Fig. 2.

Dust Formation (Model st28gm06n05)

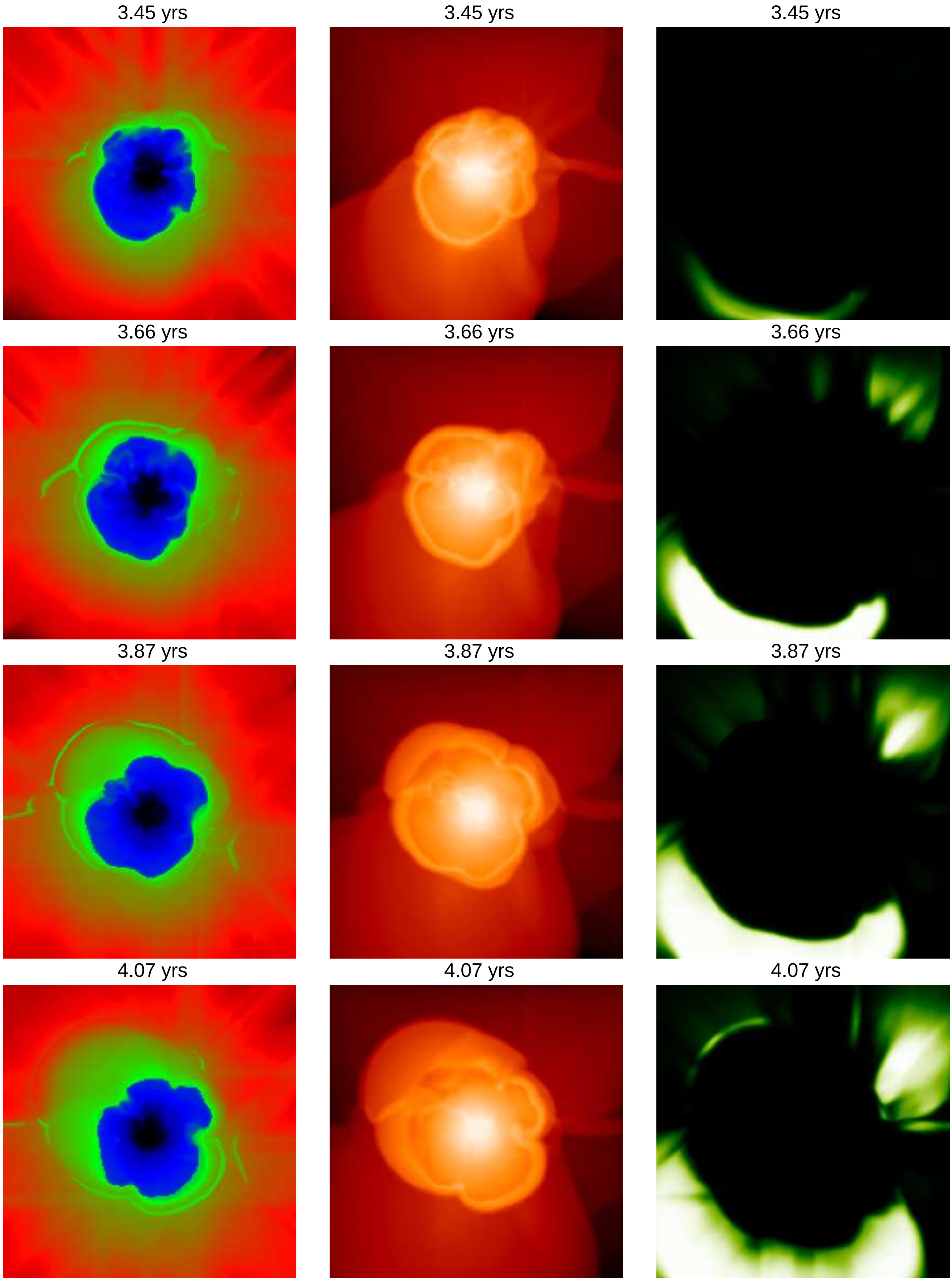

Figure 5: Time sequence: left: temperature slices through the center of model st28gm06n05; middle: gas density slices; right: degree of condensation into dust. The temperature has to be low enough to allow dust to form at all. And only if the density is high enough dust can form on a time-scale comparable to the dynamical time-scale of the atmosphere.

Tomography (Model st28gm06n05)

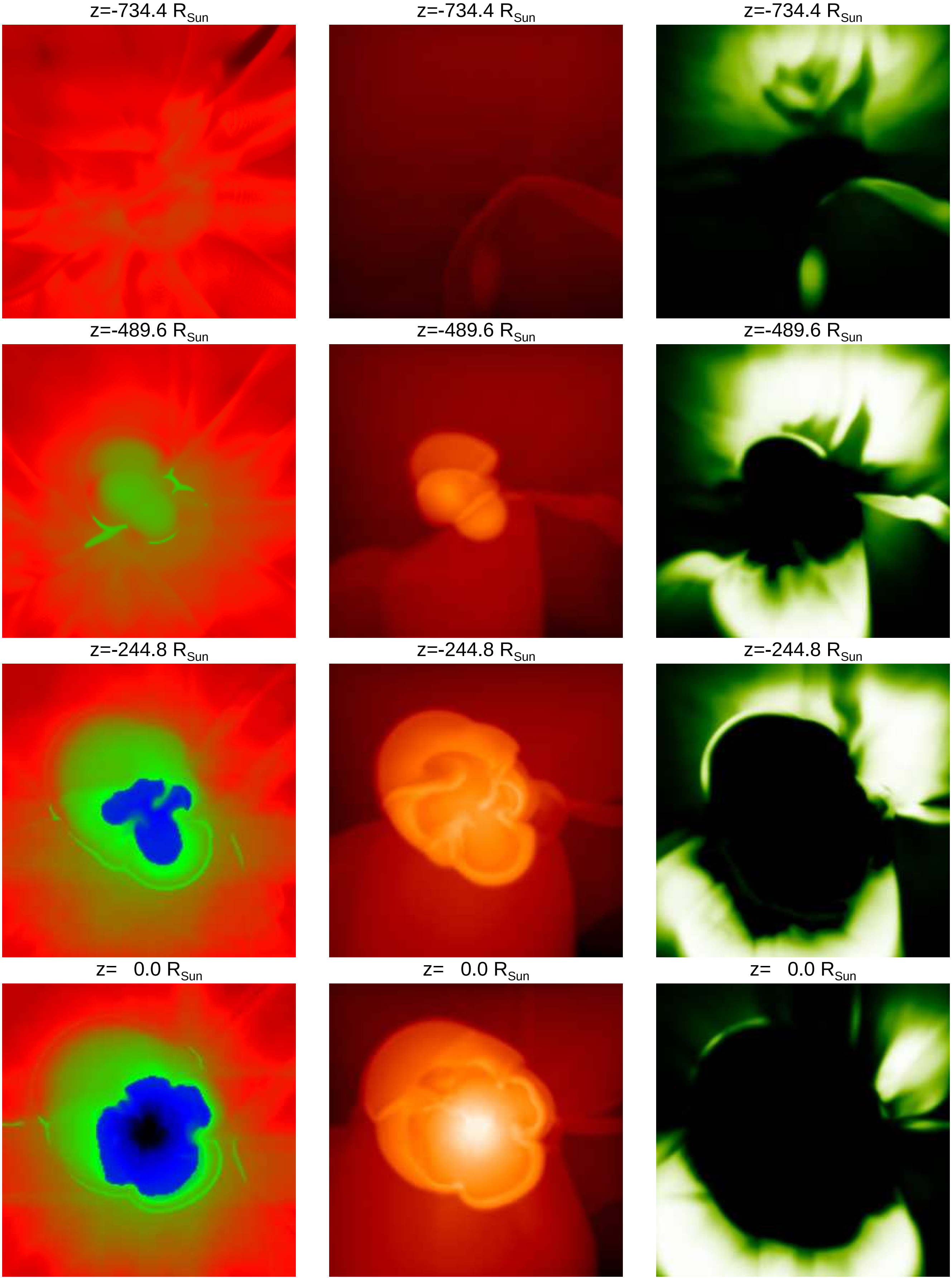

Figure 6: Spatial sequence: Left: temperature slices at four different z values; middle: gas density slices; right: degree of condensation into dust. Dust formation occurs predominantly in a certain radius interval. The actual dust distribution depends on the history (i.e. $T(t)$ and $\rho(t)$) of each gas element.

Conclusions

- Simplified but reasonably realistic simulations of a tip-AGB "star-in-a-box" including non-local radiative transfer are getting within reach.
- Irregular stellar pulsations and strong shock waves are generated by convective motions. No artificial piston is needed to create a dynamical levitation of the outer atmosphere and to make efficient dust formation possible.
- Time-dependent three-dimensional simulations require an enormous amount of computer resources and therefore have to adopt simplifications that are not necessary in one-dimensional calculations.

Topics of Further Development

- Radiation pressure
- Dust opacities
- Strong thermal coupling of dust to radiation field