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Betelgeuse – Improved Numerical Simulations of an Entire Supergiant

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Abstract

In 1975 Martin Schwarzschild attributed the visual brightness fluctuations of the red supergiant Betelgeuse to huge convection cells: each of them covers a significant fraction of the stellar surface, so that the individual brightness changes result in a measurable variation of the total luminosity. Starting in 1989, interferometric observations in the visible wavelength regime revealed the existence of large-scale spatial inhomogeneities on the surface of Betelgeuse, typically described as 0 to 3 unresolved "hot spots" on a cooler circular stellar disk, varying with time in number, intensity, and position.

To improve the theoretical understanding of the surface phenomena of Betelgeuse, a new radiation hydrodynamics code ("CO^{5}BOLD") has been written with the aim to include the entire star in the computational box. Due to a relative small ratio of radiative to hydrodynamical time-scales, high Mach-number flows, stronger photospheric shocks with correspondingly larger opacity variations, and a stronger sub-photospheric jump in temperature these simulations turned out to be more demanding in terms of stability of the code and in CPU time than simulations of "ordinary" solar granulation.

Recent results from models with improved algorithms and increased numerical resolution will be presented.

Introduction: Some Facts about Betelgeuse

- Betelgeuse: α Orionis, HD39801, HIP27989
- M2 lab Red Supergiant
- Among the stars with largest apparent diameter
- Parameters not very well known:
  - Θ=42 – 65 mas, R=600 – 1000 $R_\odot$
  - Hipparcos-distance =131 $\pm$ 30 pc
  - M=5 – 20 $M_\odot$
  - $T_{\rm eff}$=3400 – 3600 K, $\log g$= -0.5 – 0.5

Observations of Betelgeuse

Observations reveal temporal brightness fluctuations, an extended hot atmosphere, and an irregular temporally variable surface structure.

By now, there are photometric data available covering a time span of almost 100 years. They come from various short-term photometric campaigns and from collected observations of amateur astronomers (Leo Goldberg 1984, PASP 96, 366). The overall brightness of Betelgeuse varies on time-scales of weeks, months, and years.

Observations with optical interferometers started 13 years ago. They still have an extremely low resolution but definitely show deviations of the image from circular symmetry. The measurements can be fitted by a model comprising a circular disc plus 0 to 3 bright spot(s) (see e.g. Buscher et al., 1990, MNRAS 245, 7p; Burns et al., 1997, MNRAS 290, L11). In Young et al. (2000, MNRAS 315, 635) the possibility of a fit with a circular disk and a single *dark* spot is discussed.

Ronald L. Gilliland and Andrea K. Dupree took a direct UV image with HST of the chromosphere of Betelgeuse. (1996, ApJ 463, L29). The deviations from circular symmetry are obvious.

The VLA radio-observations by Jeremy Lim, Chris L. Carilli, Stephen M. White, Anthony J. Beasley, Ralph G. Marson (1998, Nature 392, 575) cannot resolve the very surface of the star, but reveal an asymmetric extended outer atmosphere.

Spectra (even some spatial resolution is possible) indicate large atmospheric and chromospheric velocities. But in general, spectroscopic observations of Betelgeuse are difficult to interpret due to the lack of a reliable (3D) model atmosphere (see David F. Gray, 2000, ApJ 532, 487 for an attempt).

Some Theory

Based on simple scaling arguments Martin Schwarzschild suggested in 1975 (ApJ 195, 137) that a few giant granules on the surface of Betelgeuse are the cause for the observed temporal brightness variations: if the typical horizontal extent of a granule is a fixed multiple of some characteristic vertical scale length (e.g. the pressure scale height), granules on a supergiant will be much larger than on the Sun, not only in absolute but also in relative size.

In the meantime pulsations, shocks, rotation, and magnetic fields have been invoked besides convection to be responsible for some of the observed phenomena.

Numerical Simulations with CO^5BOLD

To produce a model of the outer layers of Betelgeuse the 3D radiation hydrodynamics code CO^5BOLD ("COnservative COde for the COmputation of COmpressible COnvection in a BOx of L Dimensions, L=2,3") has been used, which can be characterized by some keywords:

Hydrodynamics Scheme

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

Radiation Transport

- Non-local radiative energy transfer for one direction solved with short-characteristics scheme
- 3 to 10 ray directions per sub-timestep
- Several sub-timesteps per global timestep possible
- Grey or frequency-dependent opacities (tabulated)
- No scattering, strict LTE

Setup for model st35gm04n06

- Computational domain: cube, edge length 1626 $R_\odot$, 171^3 points
- Gravitation: spherical $1/r$ potential, smoothed in the center
- Energy source: within a sphere of radius r_0=135 $R_\odot$
- 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)
- Parameters:
  - solar composition
  - $M_\star = 5 M_\odot$
  - $T_{\rm eff} \sim 3330$ K
  - $\log g \sim$ -0.46 (cgs units)
  - $R_\star \sim 630\, R_\odot$
  - $L_\star \sim 44\,000\, L_\odot$

The simulations were performed on the Sun cluster at the Ångström laboratory in Uppsala and a Cray at the computer center at the CAU in Kiel.

Difficulties

Several details make simulations of the convective envelope of a red supergiant much more demanding in terms of code stability and CPU time than simulations of solar granulation:

- Small ratio of radiative to hydrodynamical time-step,
  $\approx$ 1/100th of solar value
- Violent convective flows, high Mach-numbers
- Temperature sensitivity of opacity:
  the resulting possible extreme variations in optical thickness from grid point to grid point tend to cause problems for the radiation transport scheme and require a very stable radiation transport operator.
- Non-local coupling by waves:
  importance of core and outer atmosphere

$\Rightarrow$ Simulations are CPU time consuming
and have relatively poor spatial resolution

Results

Figure 1 shows a sequence of snapshots of the frequency-integrated intensity seen from one side of the computational box (note: the simulations adopt only a grey opacity table so far). There are high-contrast features with large scales (see the blurred surface intensity in Fig 2) which can account for the observed brightness inhomogeneities on Betelgeuse. However, the structures differ significantly from the well-known pattern of bright solar granules surrounded by dark intergranular lanes.

The entropy (Fig. 3) is fairly constant within the envelope and has a sharp drop at the surface. Some downdrafts can reach very deep: the corresponding velocity field shows an extension down to the (artificial) stellar core. Other downdrafts correspond to cells which "live" only near the very surface.

The sequence of temperature slices in Fig. 4 shows similar finger-like downdrafts as Fig. 3 but additionally the shock waves travelling through the atmosphere. The waves start as small pressure fluctuations generated by the interaction of violent convective flows in the stellar interior and transform into pronounced shocks in the low-density material of the atmosphere.

The entropy isosurfaces for the standard high-resolution model (st35gm04n06, 171^3 points) in Fig. 5 and for the low-resolution comparison model (st35gm04n03, 127^3 points) in Fig. 6 indicate that in both cases there are only a few giant envelope convection cells outlined by lanes of downdraft "fingers". At the surface the high-resolution model has more and smaller cells. Nevertheless, both models show high-contrast large-scale variations of the surface intensity.

Surface Intensity

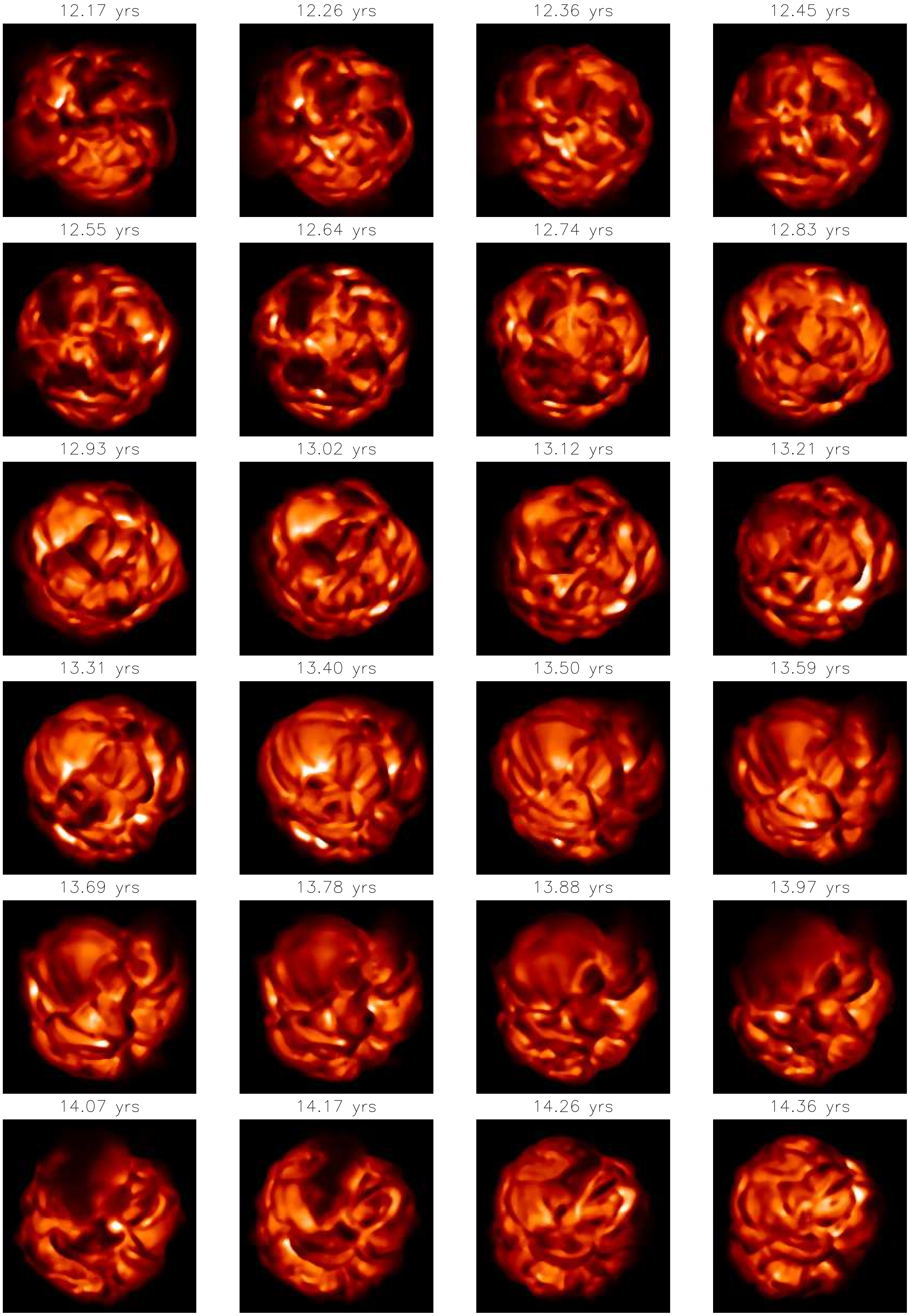

Figure 1: Sequence of surface intensity snapshots. The time step is indicated in years on top of each frame. Each image has an edge length of 1626 $R_{\odot}$. The convective surface pattern differs from that of solar granulation.

Blurred Surface Intensity

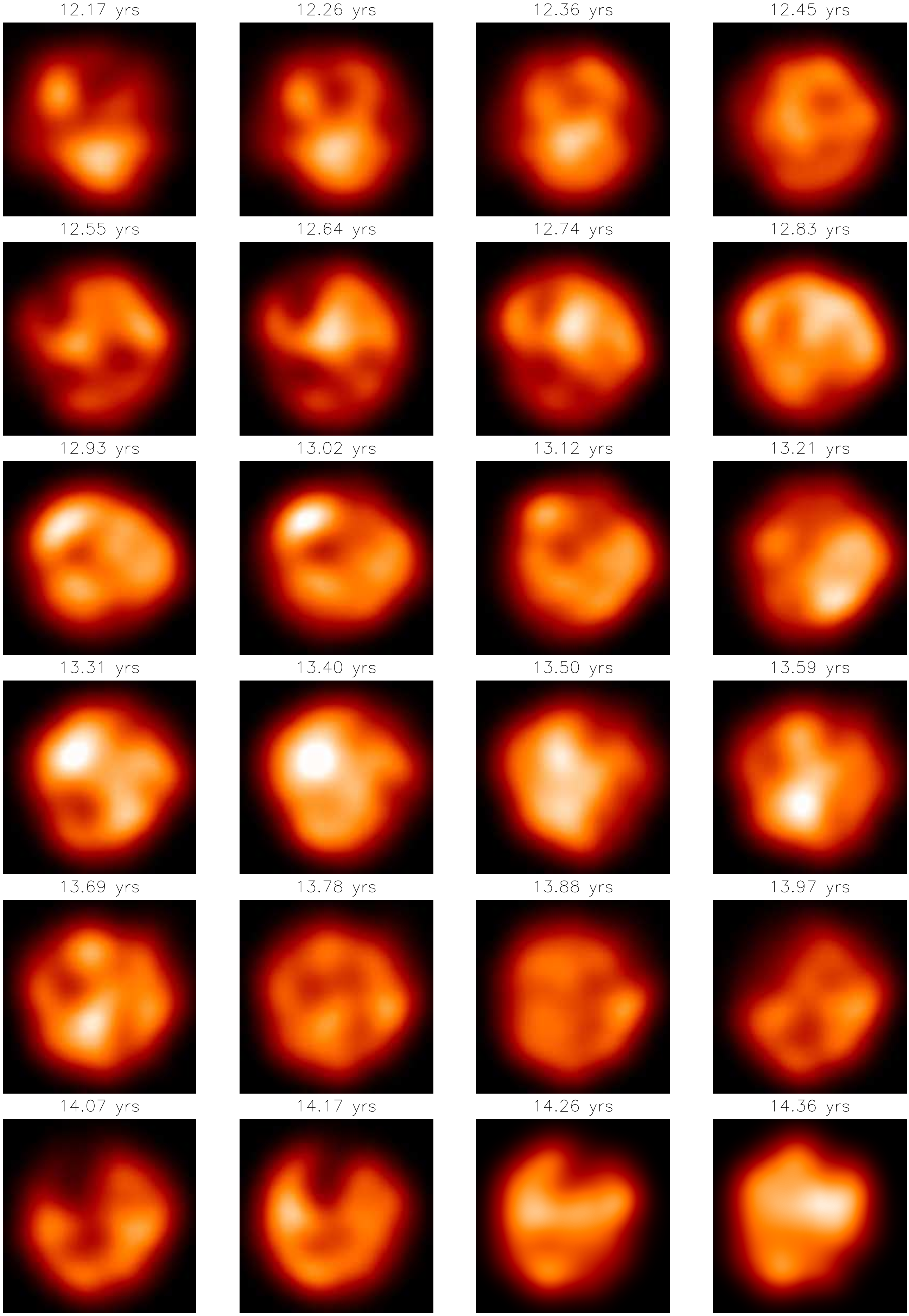

Figure 2: Same intensity sequence as in Fig. 1, smoothed with a Gaussian. Sometimes a description with a hot spot seems OK (e.g. at t=13.40 yrs), sometimes a dark feature is more adequate (e.g. at t=14.17 yrs).

Entropy Slices

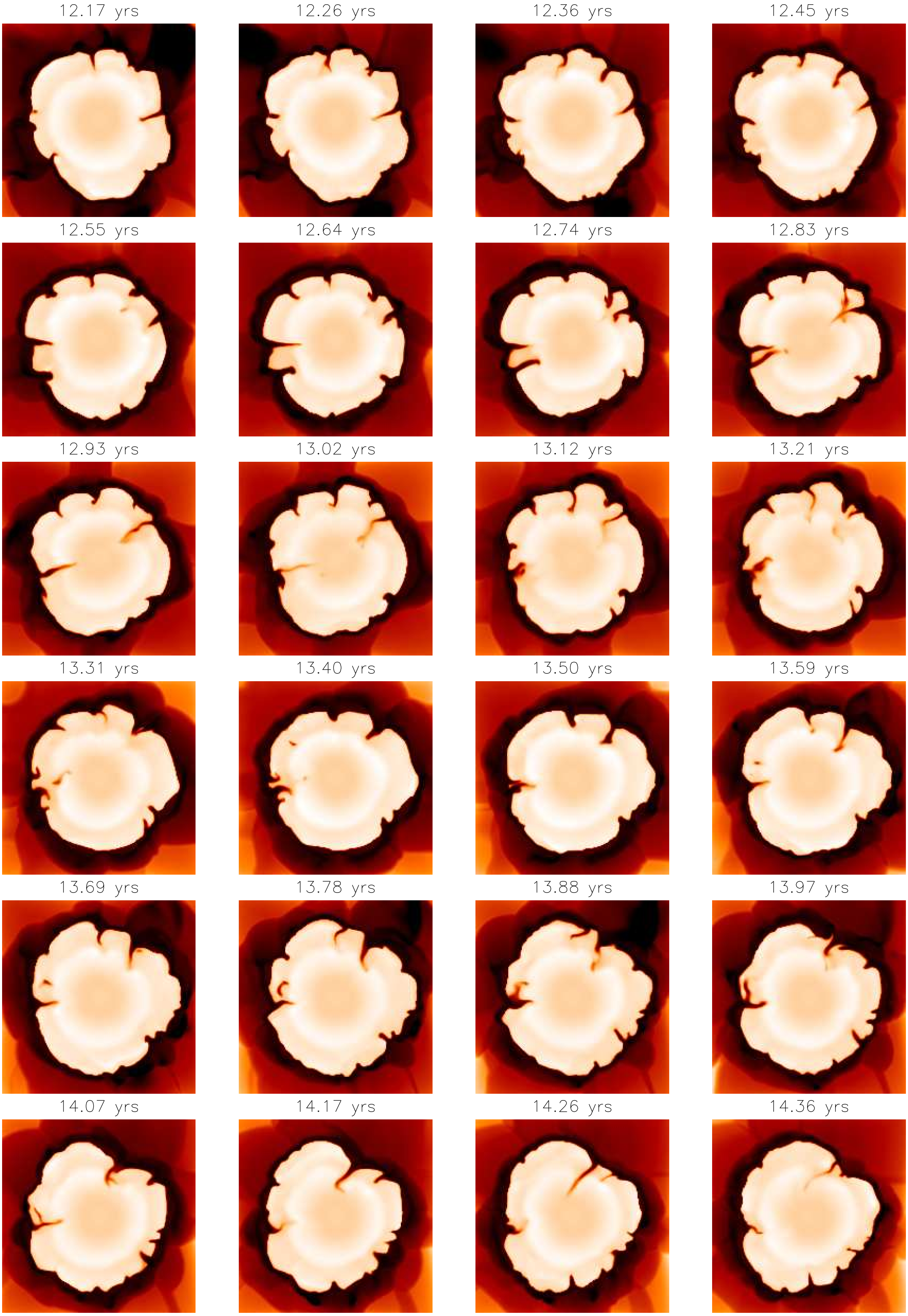

Figure 3: Sequence of entropy slices for same model and time steps as in Fig. 1. The entropy is fairly constant within the envelope and has a sharp drop at the surface. Some downdrafts can reach very deep. Others correspond to cells near the surface.

Temperature Slices

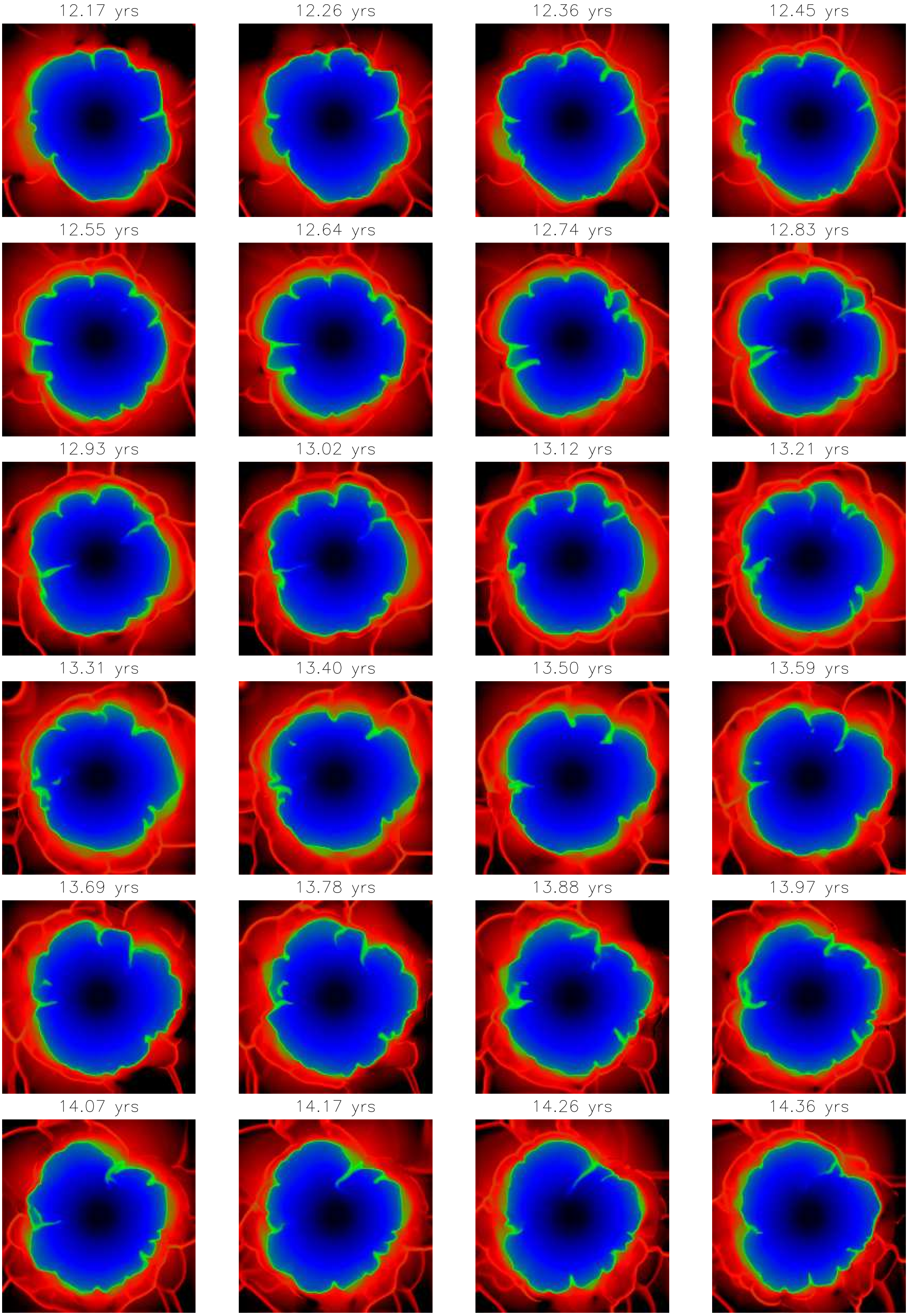

Figure 4: Sequence of temperature slices through the center for the same sequence as shown in Fig. 1. The temperature ranges from 1500 K to 150 000 K. Shock waves run into the outer atmosphere.

Entropy Isosurface

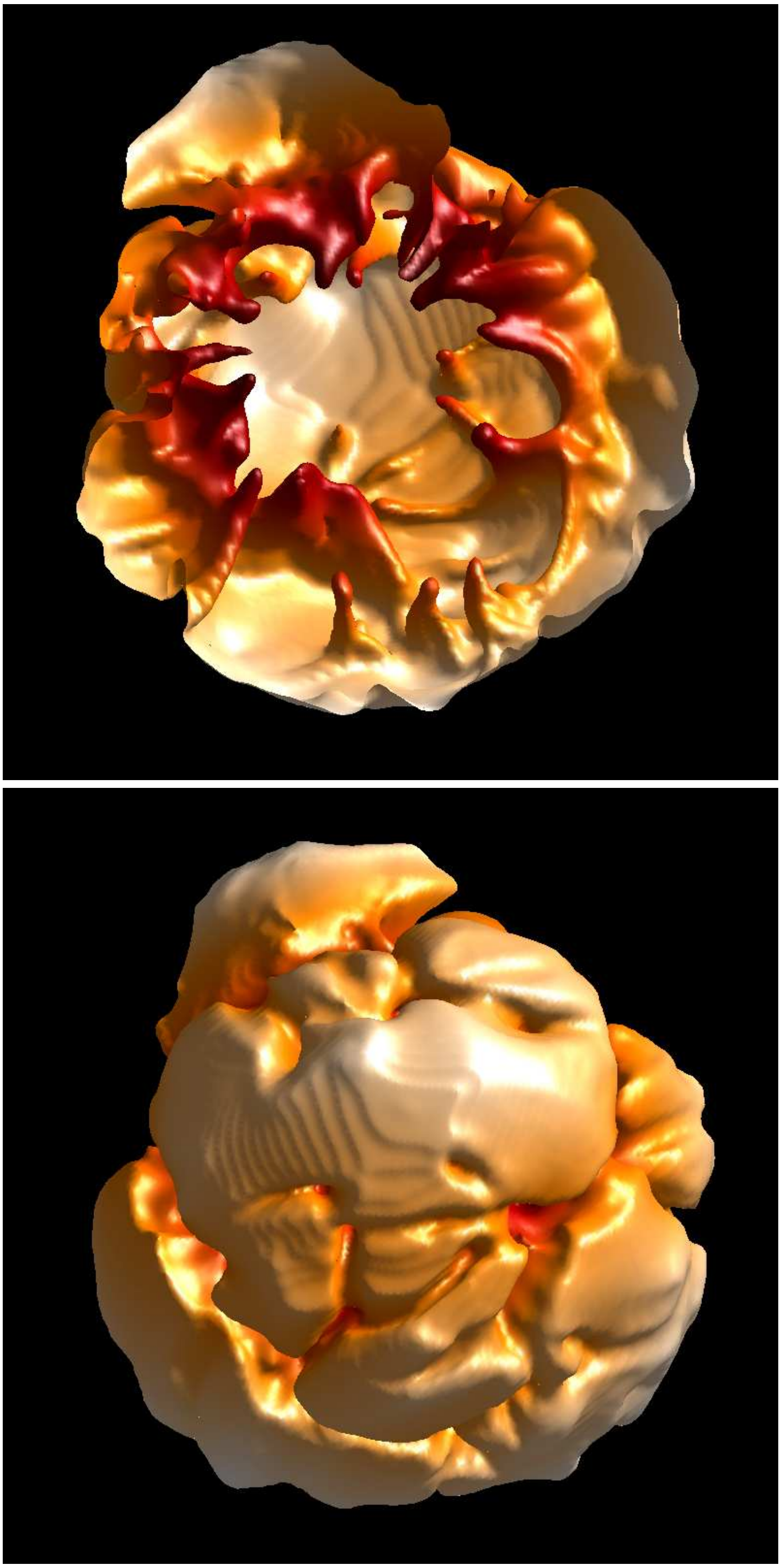

Figure 5: The top image shows an isosurface of the entropy seen "from the inside" for the standard high-resolution model (st35gm04n06). The radius is used for shading ("darker" means "further in") and the star is cut in half. The bottom image shows the same data seen properly from the outside. The steps at the center of both images are due to the finite numerical resolution. These images were produced by Sigurður Finnsson.

Entropy Isosurface: Low-Resolution Model

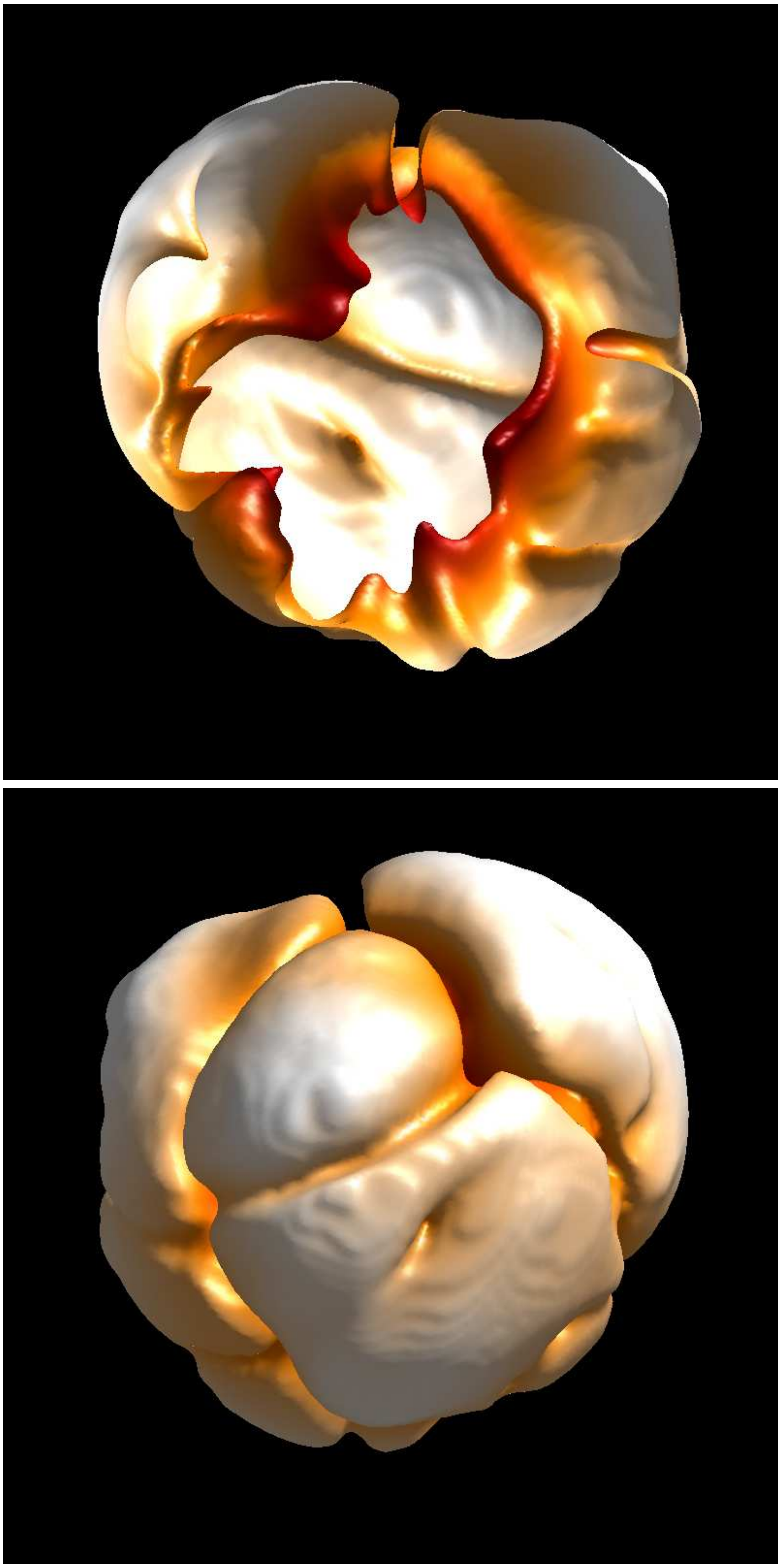

Figure 6: Similar data (entropy isosurface) as in Fig. 5 for a model (st35gm04n03) with lower numerical resolution (127^3 compared to 171^3) and higher numerical viscosity. The fine-scale features are missing.

Conclusions

- Simplified but realistic simulations of a red supergiant "star-in-a-box" including non-local radiative transfer are now becoming feasible.
- The models display a complex surface pattern which is created by the interaction of
    - A handful of giant envelope convection cells
    - More and smaller surface cells
    - Waves/pressure fluctuations

⇒ Large-scale high-contrast brightness fluctuations

⇒ Qualitative agreement between existing observations and models

Main Problems

- The short radiative time-scales make the computation of the radiation field very time-consuming.
- A high number of grid points is needed to resolve all features, particularly the steep temperature jump just below the photosphere. The size of the surface cells (still) depends on the numerical resolution.
- High Mach numbers and the extreme temperature sensitivity pose high demands on the stability of the code.

Current Development

- Much effort has been put into the improvement of the speed and stability of the code. The next model generation will have $>200^3$ grid points. While the stability is now satisfying, an even faster version of the code would allow a further increase of the number of grid points or the introduction of several frequency-bins for the radiation transport.
- Together with Michelle Mizuno-Wiedner and Bengt Gustafsson work is going on to write a code to compute synthetic spectra based on the numerical models. This program will allow the detailed comparison with observational data.

Future Development

- A small set of models with different stellar masses and luminosities will allow to pin down the basic parameters most appropriate for Betelgeuse.
- Improved input physics (frequency-dependent opacities, radiation pressure, self-consistent gravity, dust, ...) will lead to more realistic models. It is planned to implement a scheme for the description of dust formation and destruction processes in collaboration with Susanne Höfner. Such an extended code could be applied to model the inner atmospheric layers of AGB stars.