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Hot spots in numerical simulations of Betelgeuse

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Abstract

The spatial inhomogeneities on the surface of Betelgeuse revealed by modern interferometric observations are typically modelled as zero to three hot spots on a circular disk. While the surface structure appears to be generally consistent with an explanation as large-scale granular intensity fluctuations, the nature of the spots remains unclear.

The newly developed code COBOLD is now able to produce the first 3D radiation hydrodynamics simulations of a red supergiant, including realistic but simplified microphysics and non-local radiation transport.

The resulting models show giant convection cells and a surface pattern dissimilar to solar granulation. Some bright features over downdrafts might be interpreted as hot spots in low-resolution observations.

Introduction: Some Facts about Betelgeuse

Parameters

- α Orionis, HD39801, HIP27989
- M2 Iab Supergiant
- Star with largest apparent diameter (after the Sun)
- Distance $d_{\rm Hipparcos}$=131±30 pc
- Apparent radius R=22.1 mas ⇒ R=620 $R_\odot$
- M=6 $M_\odot$, $T_{\rm eff}$=3600 K, $\log g$=-0.5,
  (or M=15 $M_\odot$, $T_{\rm eff}$=3500 K, $\log g$=0.0)
- Solar atmospheric composition

Observations

Observations reveal temporal brightness fluctuations, an extended hot atmosphere, and an irregular temporally variable surface structure (for some examples see Fig. 1).

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 12 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). Fig. 1 shows a set of images I generated from the spot parameters from Buscher et al., 1990, MNRAS 245, 7p; Wilson et al., 1992, MNRAS 257, 369; Tuthill et al., 1997, MNRAS 285, 529; Wilson et al., 1997, MNRAS 291, 819 (their paper title became the headline of my Fig. 1); Klueckers et al., 1997, MNRAS 284, 711; Burns et al., 1997, MNRAS 290, L11; Young et al., 2000, MNRAS 315, 635.

In the last paper, 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 (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.

The Changing Face of Betelgeuse

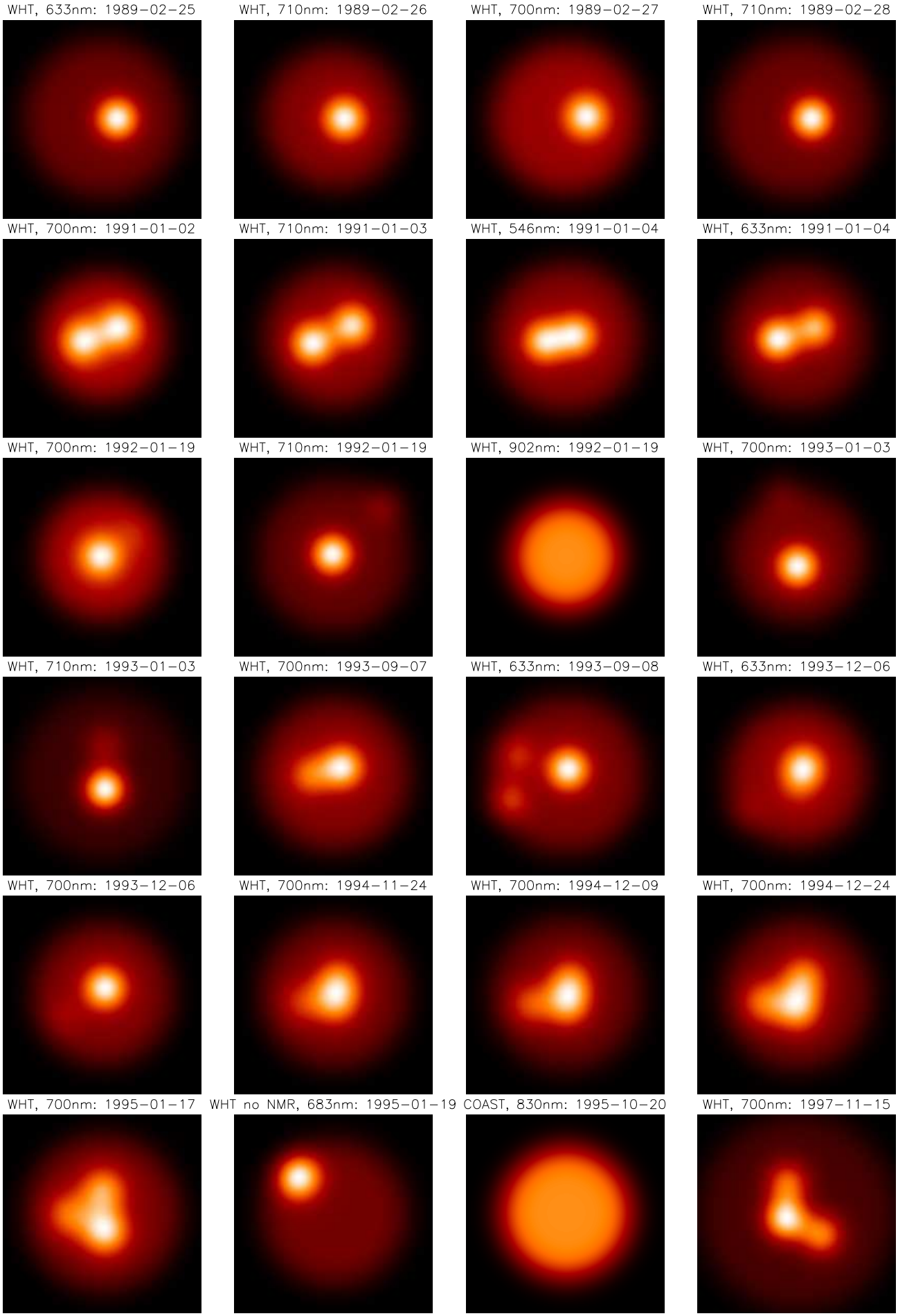

Figure 1: WHT and COAST observations in the visible and near IR. I compiled these images from the published data about spot positions and intensities.

Numerical Simulations with COBOLD

To produce a model of the outer layers of Betelgeuse, a new 3D radiation hydrodynamics code (CO^{5}BOLD: "COnservative COde for the COmputation of COmpressible COnvection in a Box of L Dimensions, l=2,3") has been used:

Hydrodynamics Scheme

- Cartesian box: Operator (directional) splitting: 3D or 2D $\rightarrow$ 1D
- Approximate Riemann solver (Roe type)
- Including gravitation (external potential, non-split)
- Including ionization (tabulated EOS)
- Discrete conservation laws
- Reconstruction schemes of different order

Radiation Transport

- 1D equation of non-local radiative energy transfer along rays solved with Feautrier scheme
- 3 to 10 ray directions per sub-timestep
- Several sub-timesteps per global timestep possible
- Conservative energy transport
- Grey or frequency-dependent opacities (tabulated)
- No scattering, strict LTE

Setup for model st33gm06n03

To put the star in the box, a spherical potential for given stellar mass M_*=6 $M_\odot$, inner smoothing radius $r0_{\rm grav}$=166 $R_\odot$, and outer smoothing radius $r1_{\rm grav}$=1175 $R_\odot$ is prescribed by

$$\phi(r) = \frac{-G_{\rm grav} M_*}{\sqrt[4]{r0_{\rm grav}^4 + r^4 \sqrt{\frac{1}{1+\left(\frac{r^2}{r1_{\rm grav}^2}\right)^4}}}} \qquad (1)$$

with r as the distance to the center of the star. The computational volume is a cube with an edge length of $2\times 988 R_\odot$ and 127^3 grid points.

Within a sphere of radius $r0_{\rm grav}$ the internal energy is adjusted to keep the entropy close to a prescribed value (3.25 10^9 erg/K/g). This replaces the energy production by nuclear fusion in the real stellar core.

The outer boundaries are open, i.e. transmitting for waves.

The opacity tables rely on realistic data but are simple grey Rosseland means. They are a merger of the PHOENIX opacities (Hausschildt, P.H., Baron, E., Allard, F. 1997, ApJ 483, 390) and OPAL tables (Iglesias, C.A., Rogers, F.J., Wilson, B.G. 1992, ApJ 397, 717), kindly provided by Hans-Günter Ludwig.

The model is characterized by the parameters $T_{\rm eff}\sim$3200 K, $\log g\sim$-0.5, $L_*\sim$50000 $L_\odot$.

The model turns out to be slightly to cool for Betelgeuse and is lies at the lower end of the allowed surface gravity range but should be sufficient to draw some first conclusions and to demonstrate what the simulations can provide (and what they are not yet able to do).

The simulations were performed on a SGI at TAC in Copenhagen and a Cray at the computer center at the CAU in Kiel.

Results

Figure 2 shows a sequence of intensity snapshots from the very start of the simulation. The initial model is a sphere in hydrostatic equilibrium. Due to convective instability, a pattern of convective cells form, which is initially highly symmetric because of the initial conditions. After some time the symmetry is destroyed due to the influence of small non-isotropic numerical terms. A sequence from a later stage is given in Fig. 3.

A sequence of entropy slices is presented in Fig. 4 which nicely shows the deep-reaching downdrafts. The temperature slices in Fig. 5 demonstrate the formation of shock waves in the atmosphere.

The comparison with a sequence from a fake star with solar surface parameters ($T_{\rm eff}$=5770 K, $\log g$=4.44) but the diameter of the Moon (Fig. 6) illustrates that the surface patterns differ significantly. Convection in a red supergiant is characterized by

- smaller ratio of radiative to hydrodynamic time-scales
- larger convective cells (measured in atmospheric pressure scale heights)
- larger convective velocities (with particularly strong horizontal – or tangential – flows, see Fig. 8)
- larger pulsations
- stronger interactions between convection and pulsations
- more hidden granulation

While in the solar case (Fig. 6) small granules or the rims of some granules are the brightest structures, the surface images of the red supergiant (Fig. 3) shows its brightest features over intergranular lanes. This is due the temperature dependence of the opacities (see Fig. 7) and sensitively depends on the surface temperature of the star.

The variations of the surface intensities (Fig. 9) are due to irregular pulsations with a period of around 1.5 years plus some phenomena of convective origin on shorter time-scales.

Sequence I: Surface Intensity (Start)

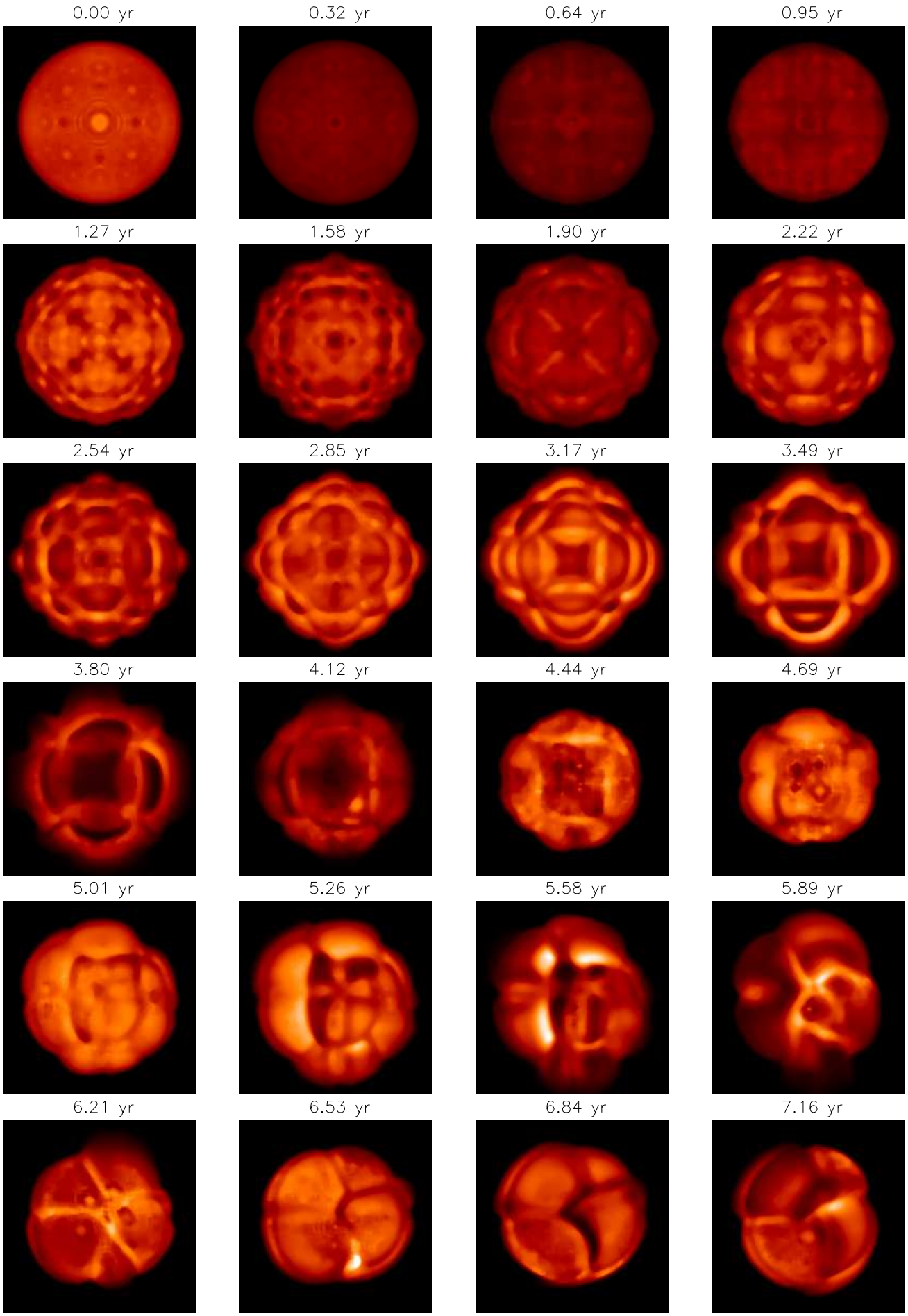

Figure 2: Sequence of surface intensity snapshots at start of simulation st33gm06n03. Surface parameters: $T_{\rm eff}$=3200 K, $\log g$=-0.5. Elapsed time is measured in years.

Sequence II: Surface Intensity

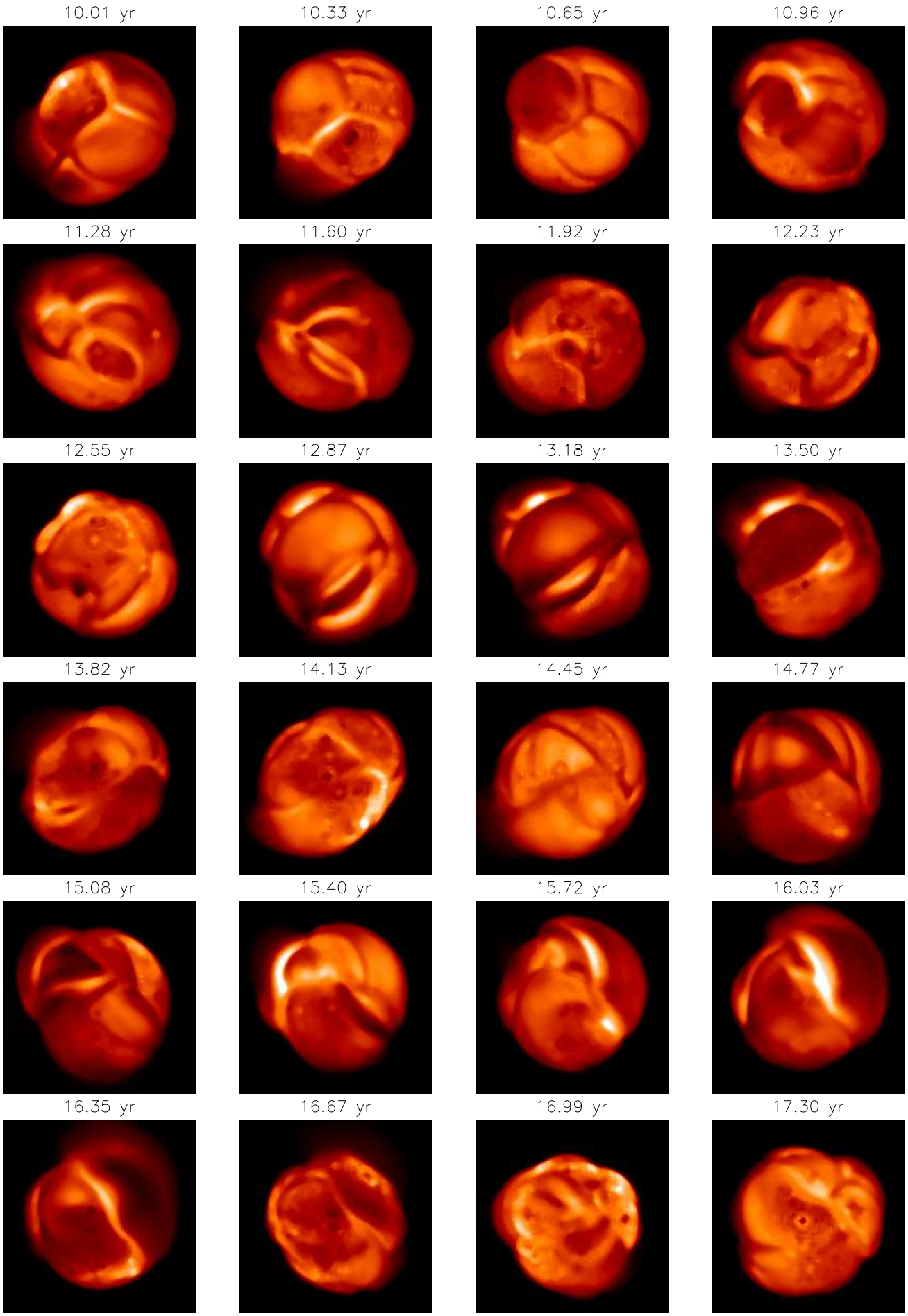

Figure 3: Sequence of surface intensity snapshots of model st33gm06n03. Surface parameters: $T_{\rm eff}$=3200 K, $\log g$=-0.5.

Sequence II: Entropy

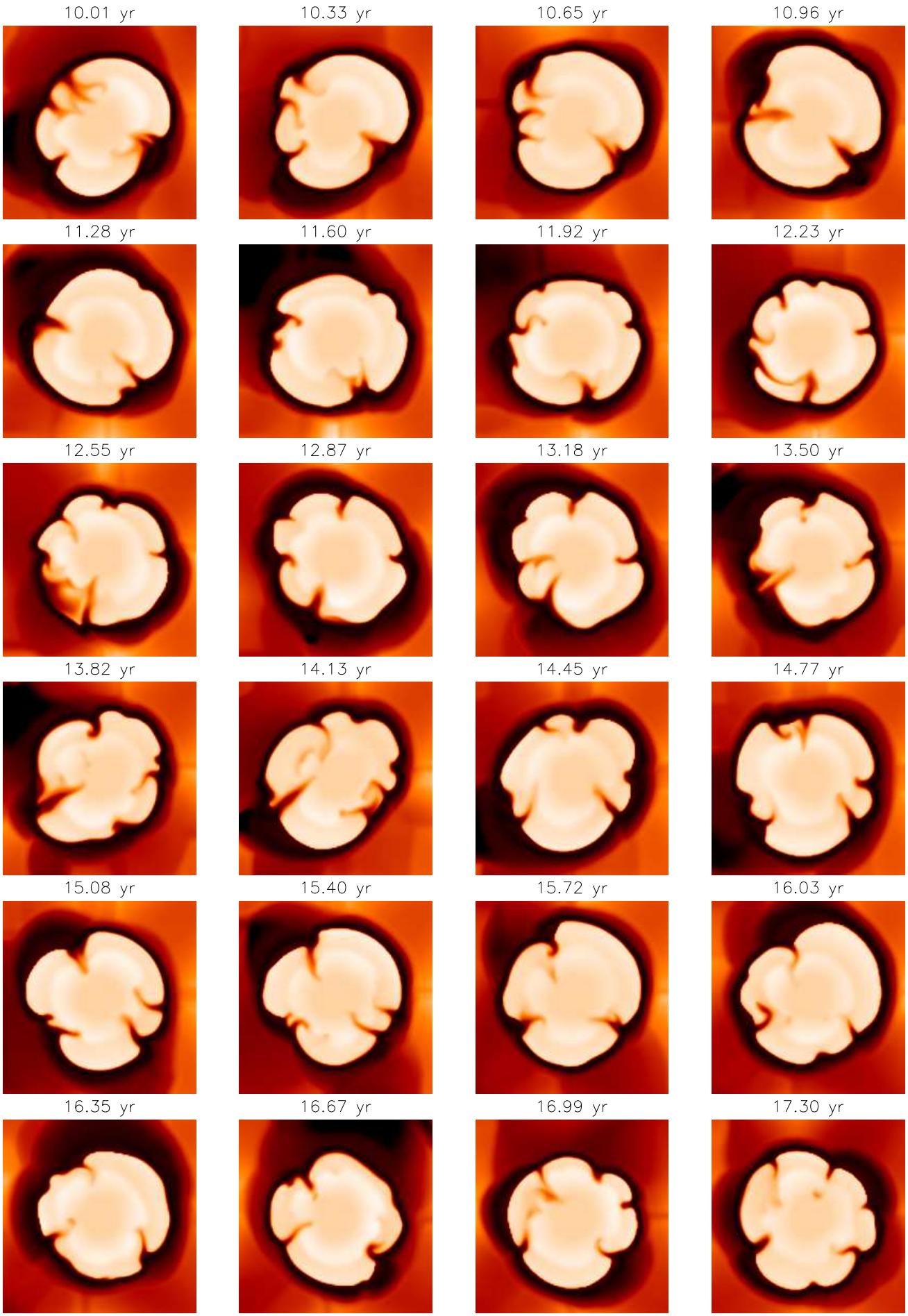

Figure 4: Sequence of entropy slices of model st33gm06n03. Surface parameters: $T_{\rm eff}$=3200 K, $\log g$=-0.5. The star is not really spherical anymore.

Sequence II: Temperature

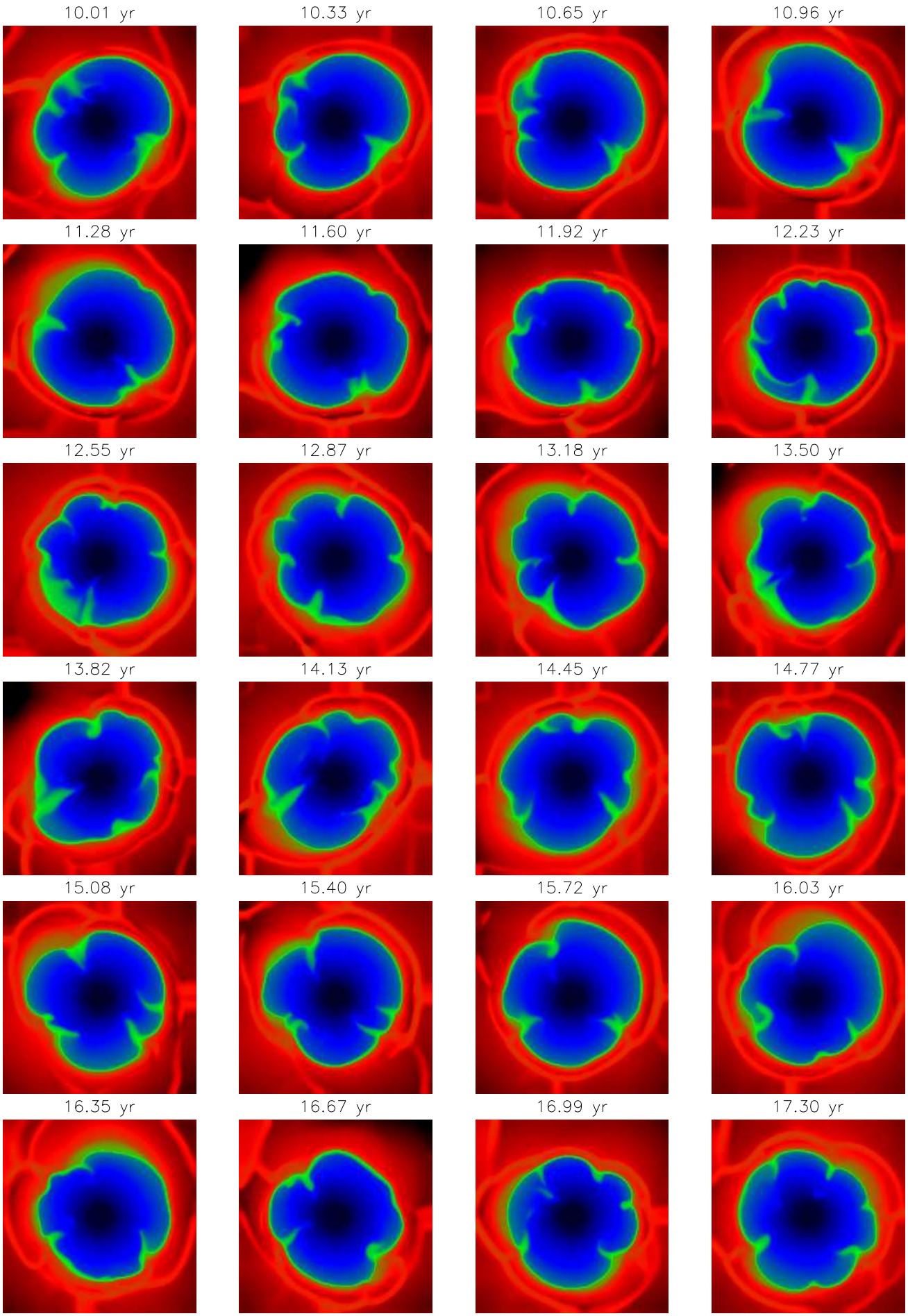

Figure 5: Sequence of temperature (ranging from 1500 K to 150 000 K) slices of model st33gm06n03. Surface parameters: $T_{\rm eff}$=3200 K, $\log g$=-0.5.

Sequence III: Surface Intensity (fake giant)

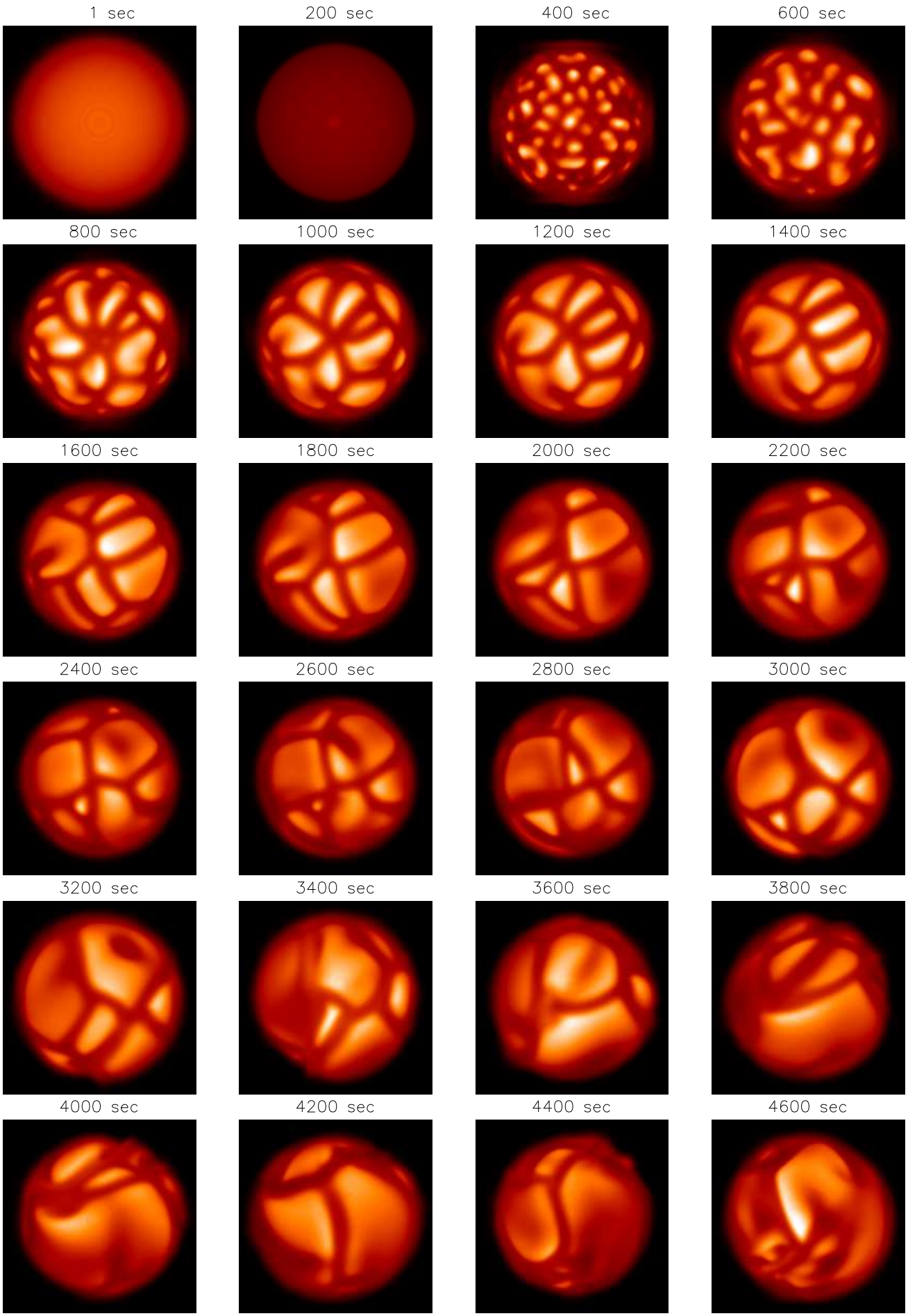

Figure 6: Sequence of surface intensity snapshots of comparison model st57g44n01-06. Surface parameters: $T_{\rm eff}$=5770 K, $\log g$=4.44, 127^3 grid points (the "solar" case).

Hot spots

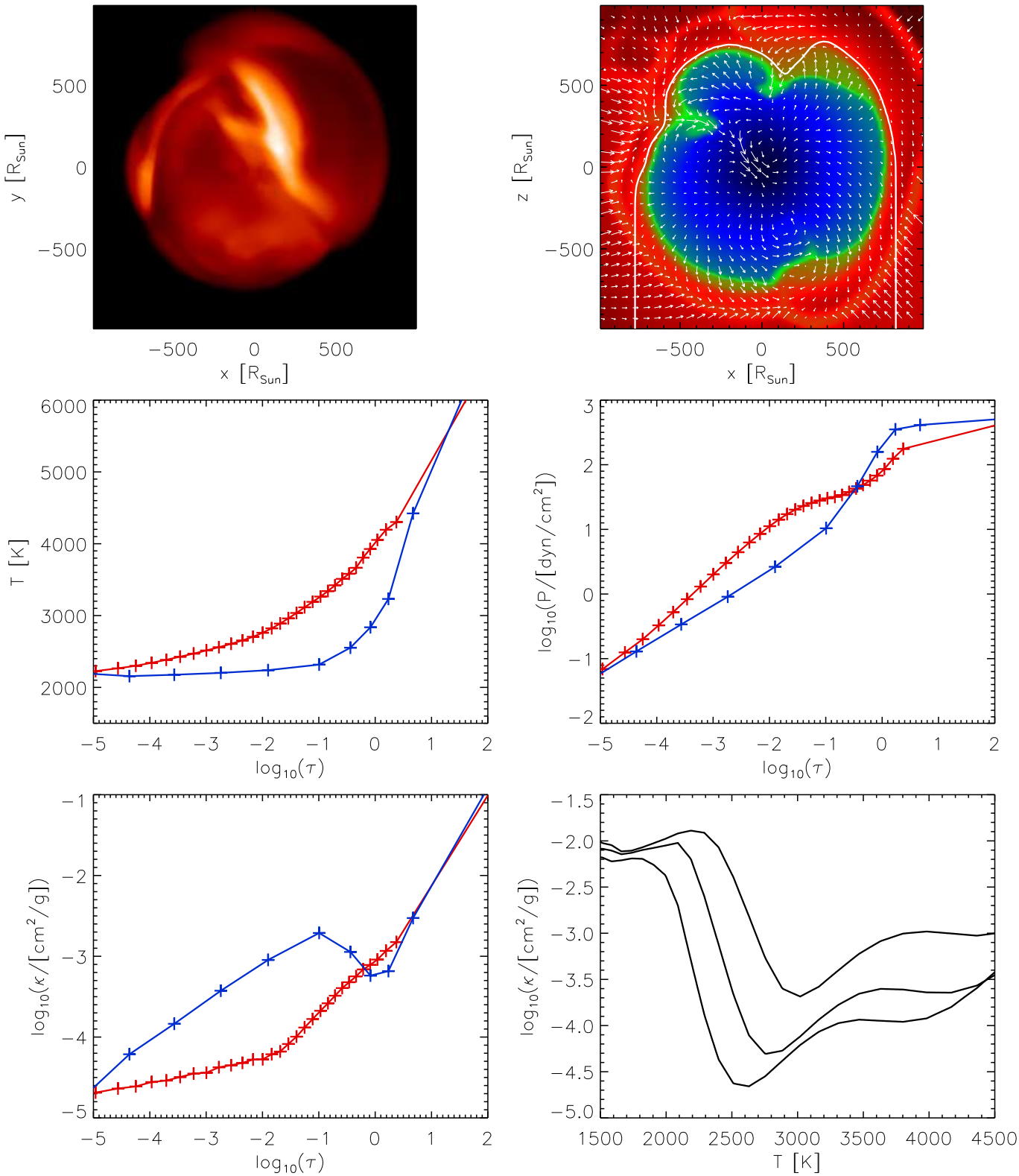

Figure 7: Upper left: selected intensity snapshot from Fig.3 (16.03 yr) with bright feature over downdraft, upper right: Temperature slice trough hotspot with contour line of optical depth unity as seen from the top; both center and lower left: temperature, pressure, and opacity over optical depth along ray through hot spot (red) and neighboring cool surface region (blue); lower right: opacity over temperature for three pressure values (1, 10, 100 dyn/cm^2). At the bright feature the atmospheric material has the right temperature to allow a view "further in" due to the lower opacities.

Velocities

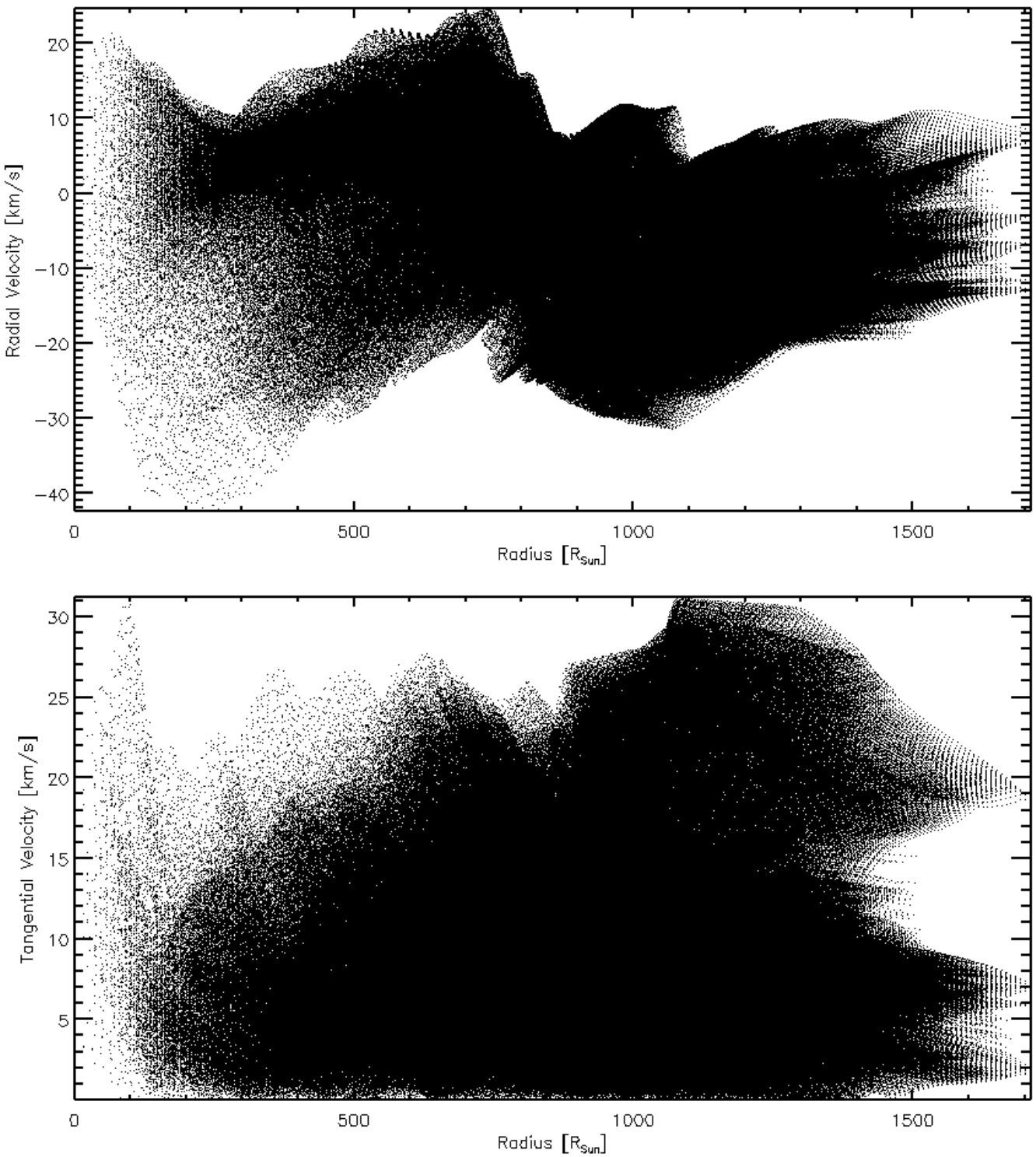

Figure 8: Radial (upper panel) and tangential velocities (lower panel) for same snapshot as in Fig. 7. It gives an indication of the size of the typical velocities in the atmosphere. Mach numbers of one are easily exceeded in the atmosphere. The peak radial velocities occur in shock waves. Typically, the tangential component of the velocity is larger than the radial one.

Time Variations

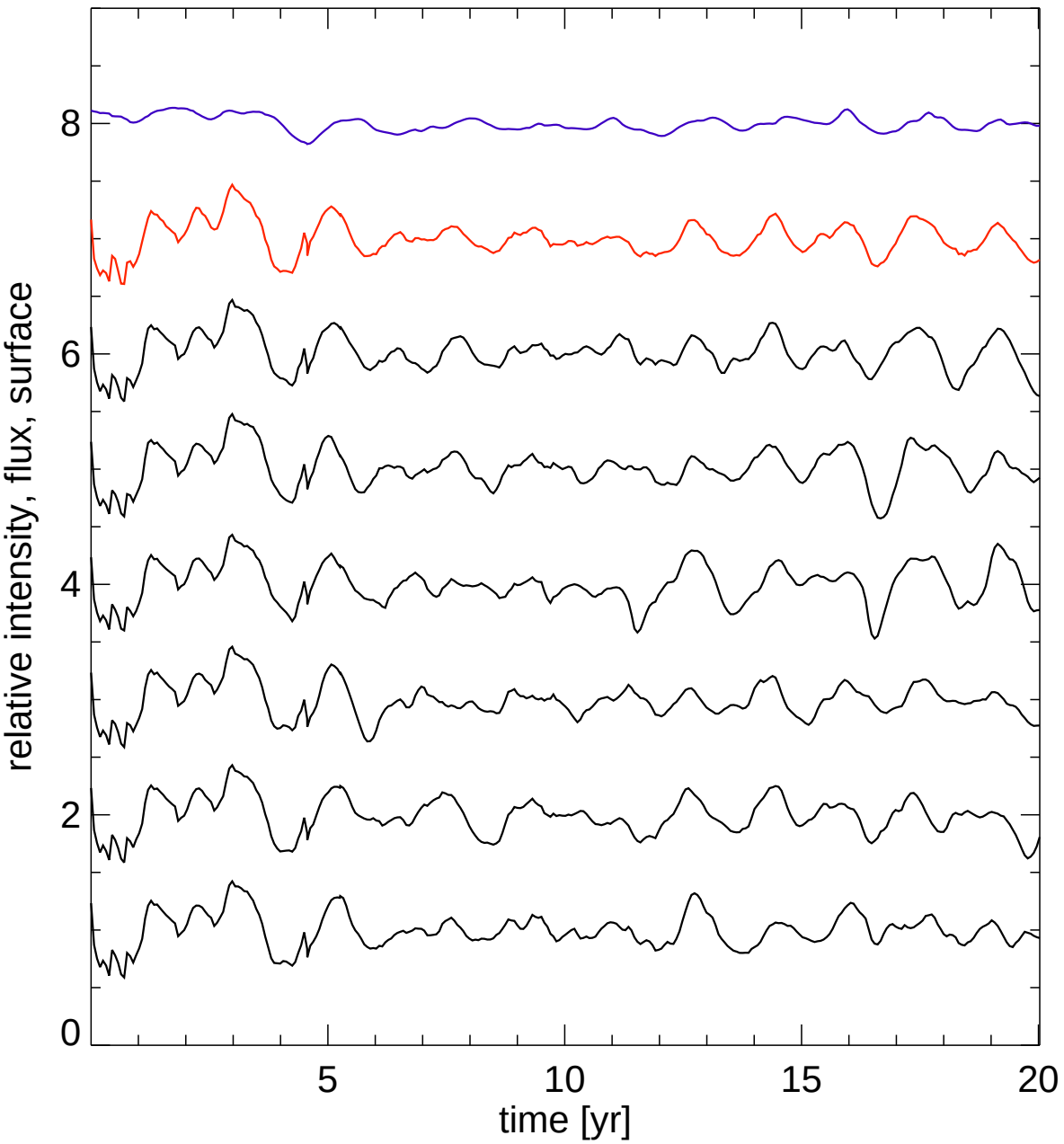

Figure 9: The relative (and shifted by 0,1,2,...) surface intensities viewed from six different directions (lower black curves), the normalized and shifted total flux (red curve), and an estimate for the relative (and shifted) surface area (blue curve) are plotted for model st33gm06n03 with surface parameters: $T_{\rm eff}$=3200 K, $\log g$=-0.5. The glitch at t=4.6 yr is due to major changes in the radiation transport module. After 6 years the initially symmetric configuration is forgotten. The pulsations appear to develop from a relatively quiet phase.

Conclusions

- Simplified but realistic simulations of a red supergiant "star-in-a-box" including non-local radiative transfer are now feasible. While the current model is slightly to cool to be appropriate for Betelgeuse, it nevertheless shows interesting results...
- The surface of a red supergiant is covered by giant convection cells.
- The deviations from spherical symmetry are significant.
- Atmospheric velocities are large (20 – 30 km/s). Shock waves are ubiquitous.
- The granulation appears not to be solar-like. The surface pattern is not simply composed of "bright granules and dark intergranular lanes".
- Occasionally, there are bright features (hot spots?) over downdrafts.
- Pulsations and their interaction with convection play an important role.

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.

Future development

- An adjustment of the basic parameters is necessary to find values most appropriate for Betelgeuse.
- A faster version of the code is needed to allow an increase of the number of grid points, frequency-bins,...
- Improved input physics (frequency-dependent opacities, radiation pressure, self-consistent gravity, dust, ...) will lead to more realistic models.