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Betelgeuse – Towards Numerical Simulations of an Entire Supergiant

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Abstract

The brightness of the well-known red supergiant Betelgeuse varies on time-scales of weeks, months, and years. For a dedicated observer these fluctuations are even visible with the naked eye. In 1975 Martin Schwarzschild attributed them to huge convection cells, each of them covering a significant fraction of the stellar surface, so that the individual fluctuations result in an overall non-vanishing variation of the luminosity of the star.

Starting 10 years ago, interferometric observations in the visible wavelength regime revealed the existence of large-scale brightness inhomogeneities on the surface of Betelgeuse, described as 0 to 3 unresolved "hot spots" on a cooler circular stellar disk, varying in number, intensity, and position.

To improve the theoretical understanding of the surface phenomena of Betelgeuse, a new radiation hydrodynamics code has been written with the aim to include the entire star in the computational box. Starting with down-scaled toy models and approaching the parameter regime appropriate for Betelgeuse, some results about the dynamics of large convective cells on a spherical stellar surface will be presented.

Introduction: Some Facts about Betelgeuse

Parameters

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

Observations

Observations (for some examples see Figs. 1, 2, 3) reveal temporal brightness fluctuations ($\sim$ weeks, months, years), an extended hot atmosphere, and an irregular temporally variable surface structure.

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.

Observations

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 10 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 the following page); Klueckers et al., 1997, MNRAS 284, 711; Burns et al., 1997, MNRAS 290, L11; Young et al., 2000, MNRAS 315, 635.

In the most recent paper, the possibility of a fit with a circular disk and a single *dark* spot is discussed.

Optical: The Changing Face of Betelgeuse

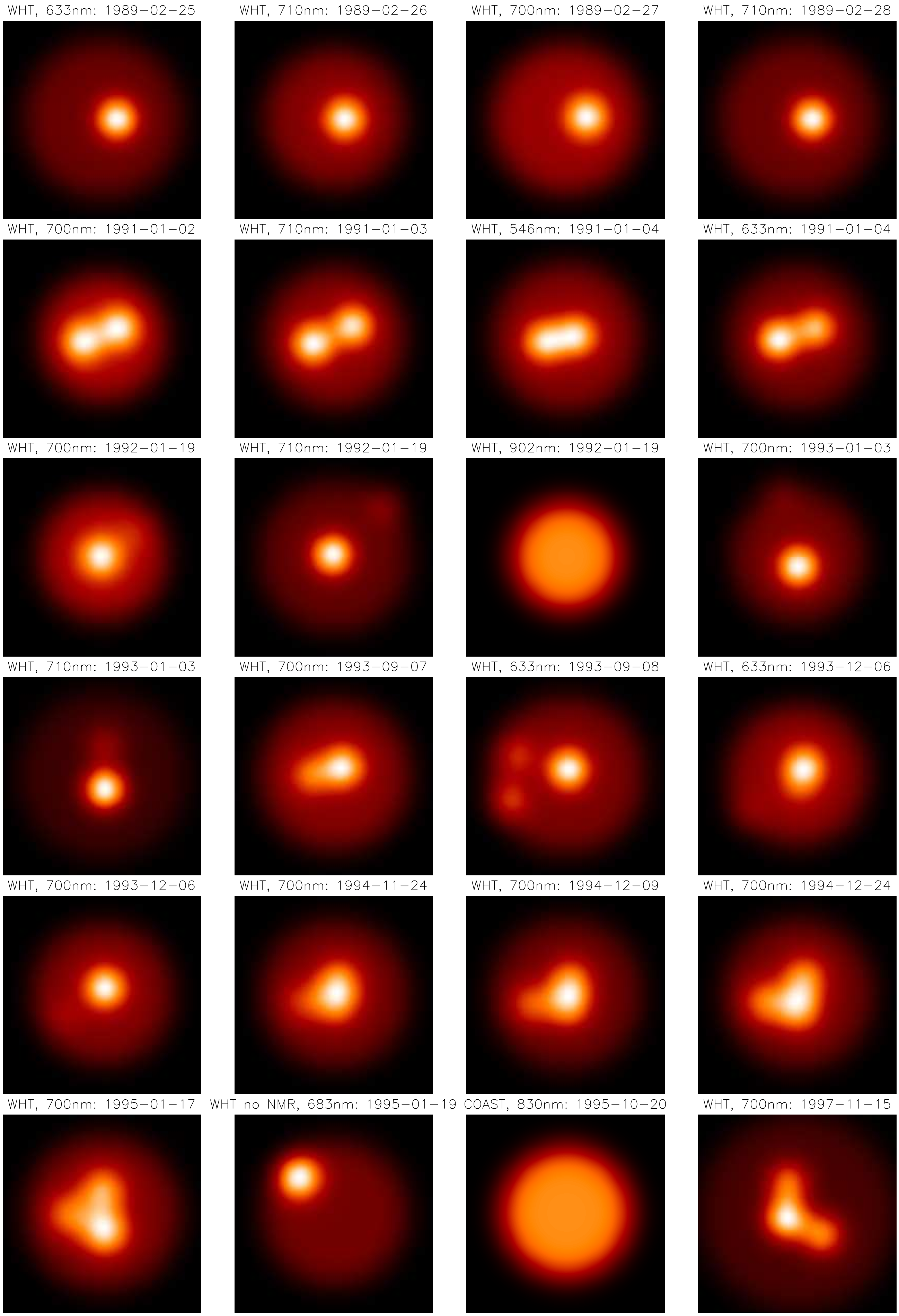

Figure 1: WHT and COAST observations in the visible and near IR. I compiled these images from the published data about spot positions and intensities.

Radio Observations with the VLA

The VLA radio-observations by Jeremy Lim, Chris L. Carilli, Stephen M. White, Anthony J. Beasley, Ralph G. Marson (1998, Nature 392, 575, see Fig. 2) cannot resolve the very surface of the star, but reveal an asymmetric extended outer atmosphere.

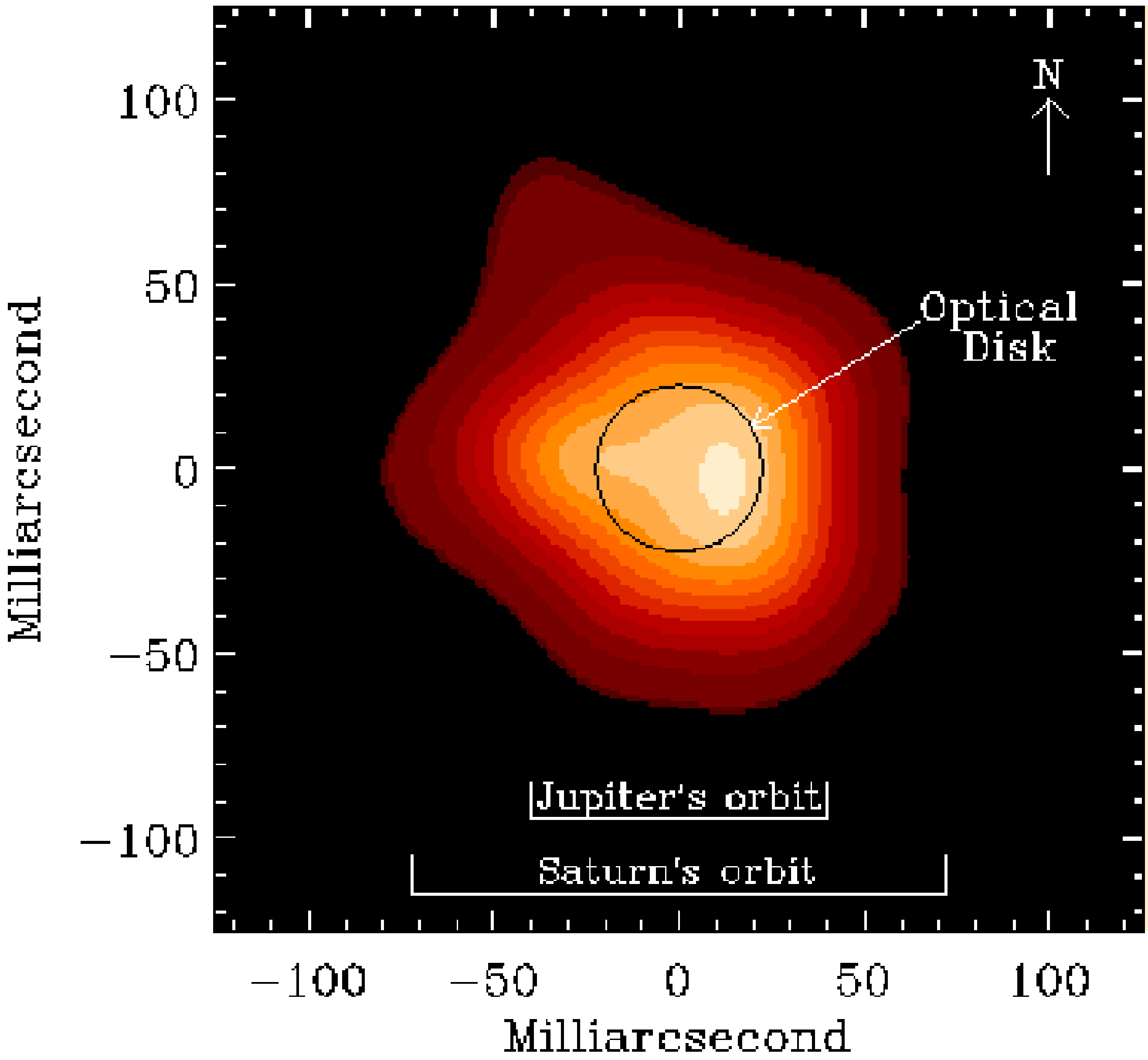

Figure 2: VLA image at 7 mm showing an asymmetric extended outer atmosphere.

UV Observations with HST

Ronald L. Gilliland and Andrea K. Dupree took a direct UV image with HST (1996, ApJ 463, L29, see Fig. 3). The deviations from the circular symmetry are obvious.

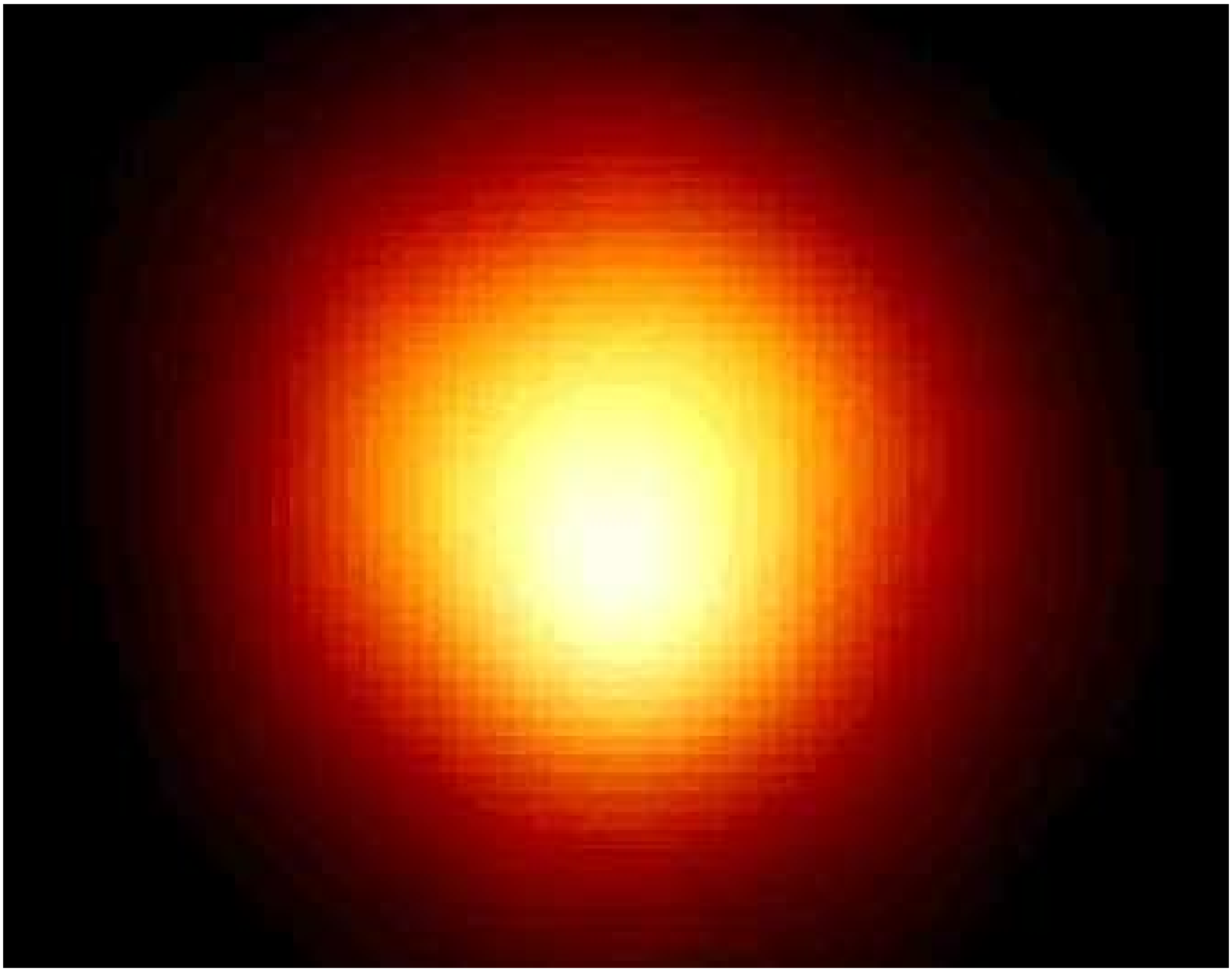

Figure 3: HST image (278 nm) by A. Dupree, R. Gilliland from 1995-03-03.

Spectra (even some spatial resolution is possible) reveal large 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).

Internal Structure of a Red Supergiant

Betelgeuse has an extended envelope convection zone. The pressure scale height at the surface is still a small fraction of the stellar radius (see lower panels in Fig. 4). It depends on the ratio of granule size to pressure scale height (and on the exact value of the pressure scale height and therefore the surface gravity) if there is a small or large number of granules on the surface.

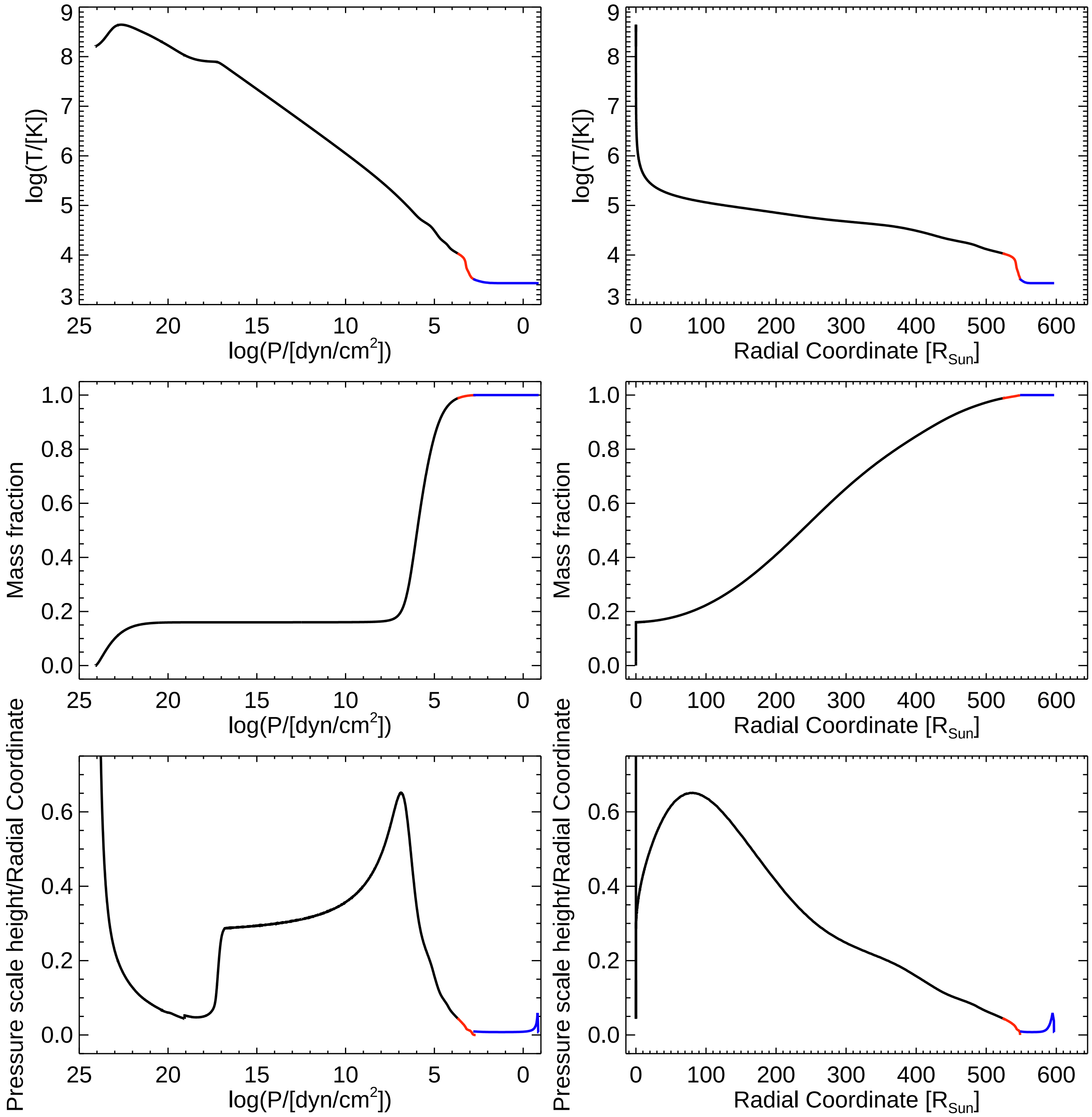

Figure 4: Internal structure of a red supergiant. Model data kindly provided by Thomas Blöcker (priv. comm. 2000). The stellar parameters are close to the case of Betelgeuse: mass M=5.76 $M_\odot$, radius R=550 $R_\odot$, luminosity L=29068 $L_\odot$, effective temperature $T_{\rm eff}$=3220 K, surface gravity $\log g$=-0.28.

Numerical Simulations

To produce a model atmosphere of Betelgeuse, a new 3D radiation hydrodynamics code has been employed, based on standard ingredients:

Hydrodynamics Scheme

- 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

Non-local Radiation Transport

- 1D equation of non-local radiative energy transfer along rays
- 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, LTE)

Boundary conditions

- Inner: smoothed gravitational potential to circumvent the difficulties with modelling the complicated internal structure (see Fig. 4)
- Outer: open for outgoing radiation, waves (and possibly wind)

THE Big Problem: Steep Temperature Gradient

While the typical horizontal extent of a granule scales well with the pressure scale height, the temperature incline below the photosphere becomes steeper with decreasing surface gravity due to the variation of the temperature dependence of the opacity with density. Figure 5 shows an example of the problem.

A steeper temperature jump puts higher demands on the numerical resolution and/or the stability of the radiation hydrodynamics code. During the development of the code, this property has been significantly improved. However, currently the code still cannot handle surface parameters appropriate for Betelgeuse.

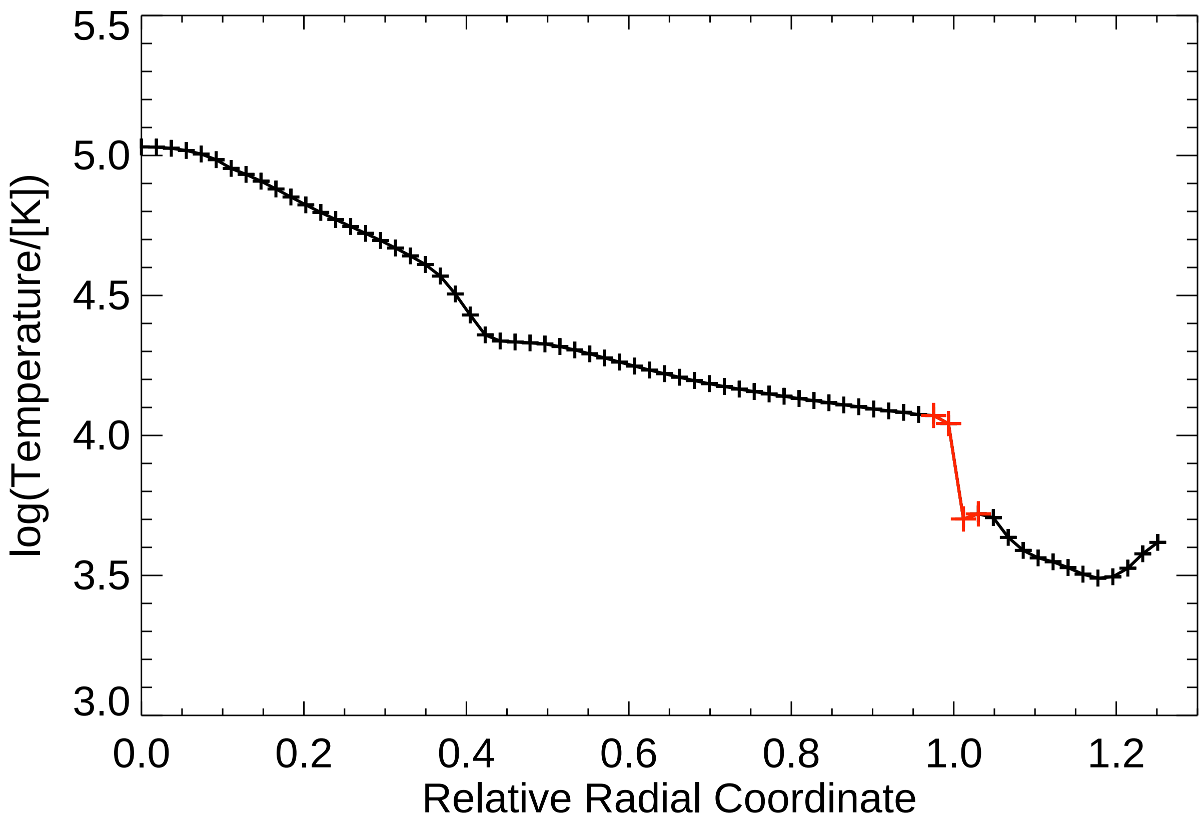

Figure 5: Temperature over radial coordinate for a selected grid column of model st47g20n05-01. The special inner boundary treatment keeps the central temperature in a practicable regime (far away from realistic values).

The Trick: Scaling of Density and Opacity

To produce at least some preliminary models, the density and thus the surface opacities were shifted to “easier” values by the following scaling: The surface gravity (and equally the effective temperature) was artificially increased and the radius of the star was reduced in a way to keep the ratio of the granular diameter to the stellar radius close to values expected for Betelgeuse.

All of the following example results rely on this scaling, which can hopefully be dropped in the near future.

Results

Figure 6 shows a sequence of intensity snapshots from the very start of a simulation. The initial model is a sphere in hydrostatic equilibrium with some tiny random velocity fluctuations. Due to convective instability, small cells form, which quickly merge to larger granules. In the longer run, when the velocities grow also in the deeper layers, the surface pattern becomes more and more irregular.

A sequence of entropy slices of the same model is presented in Figure 7.

The above model employs solar values for effective temperature and gravity, which is comparatively “easy” for the code. Figure 8 shows intensity images of a model with values for effective temperature and gravity between the Sun and Betelgeuse: the “intermediate” case.

Sequence I: Surface Intensity

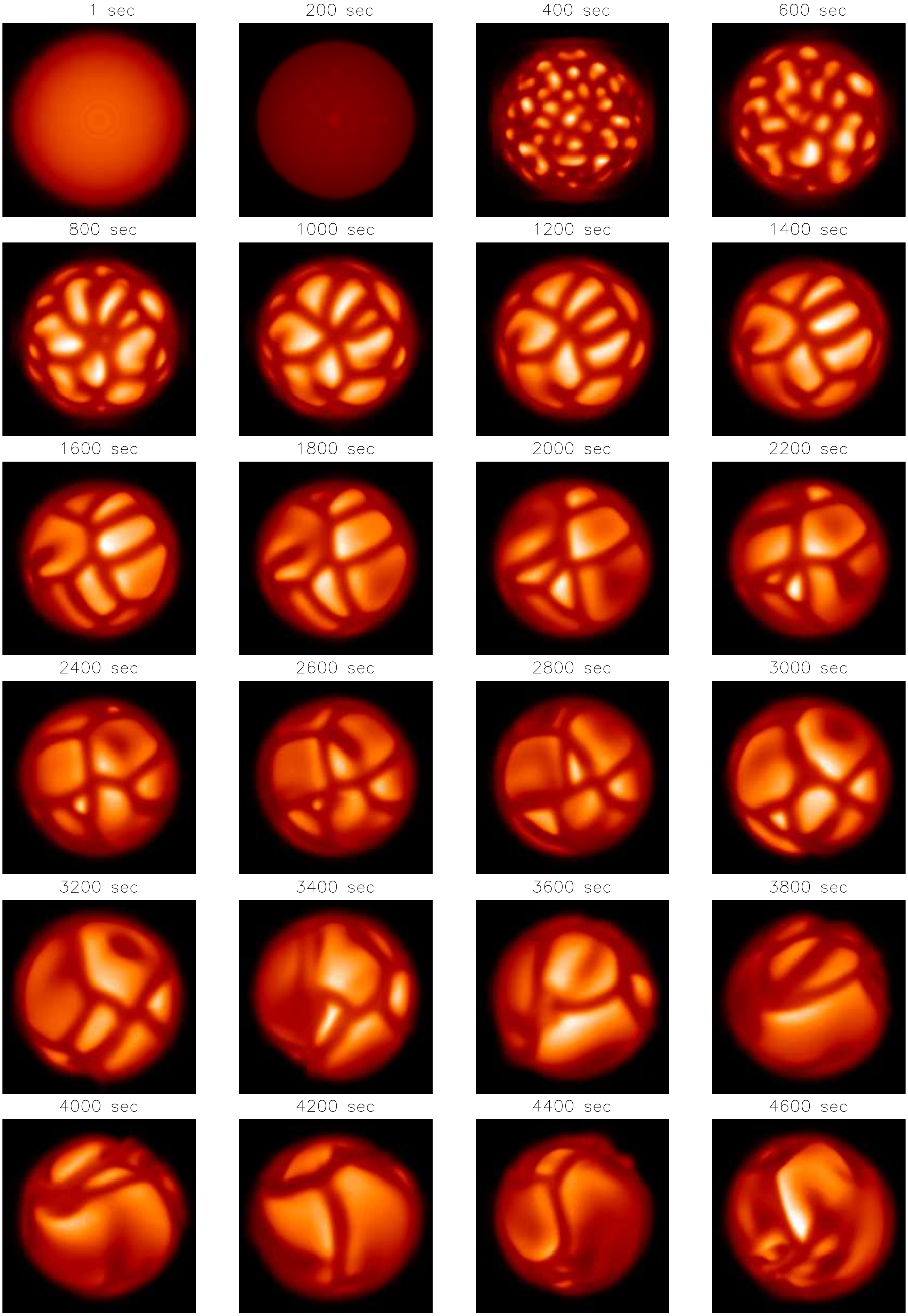

Figure 6: Sequence of surface intensity snapshots of model st57g44n01-06. Surface parameters: $T_{\rm eff}$=5770 K, $\log g$=4.44, 127^3 grid points (the "easy" case).

Sequence I: Entropy

Figure 7: Sequence of entropy slices of model st57g44n01-06. Surface parameters: $T_{\rm eff}$=5770 K, $\log g$=4.44, 127^3 grid points (the “easy” case).

Sequence II: Surface Intensity

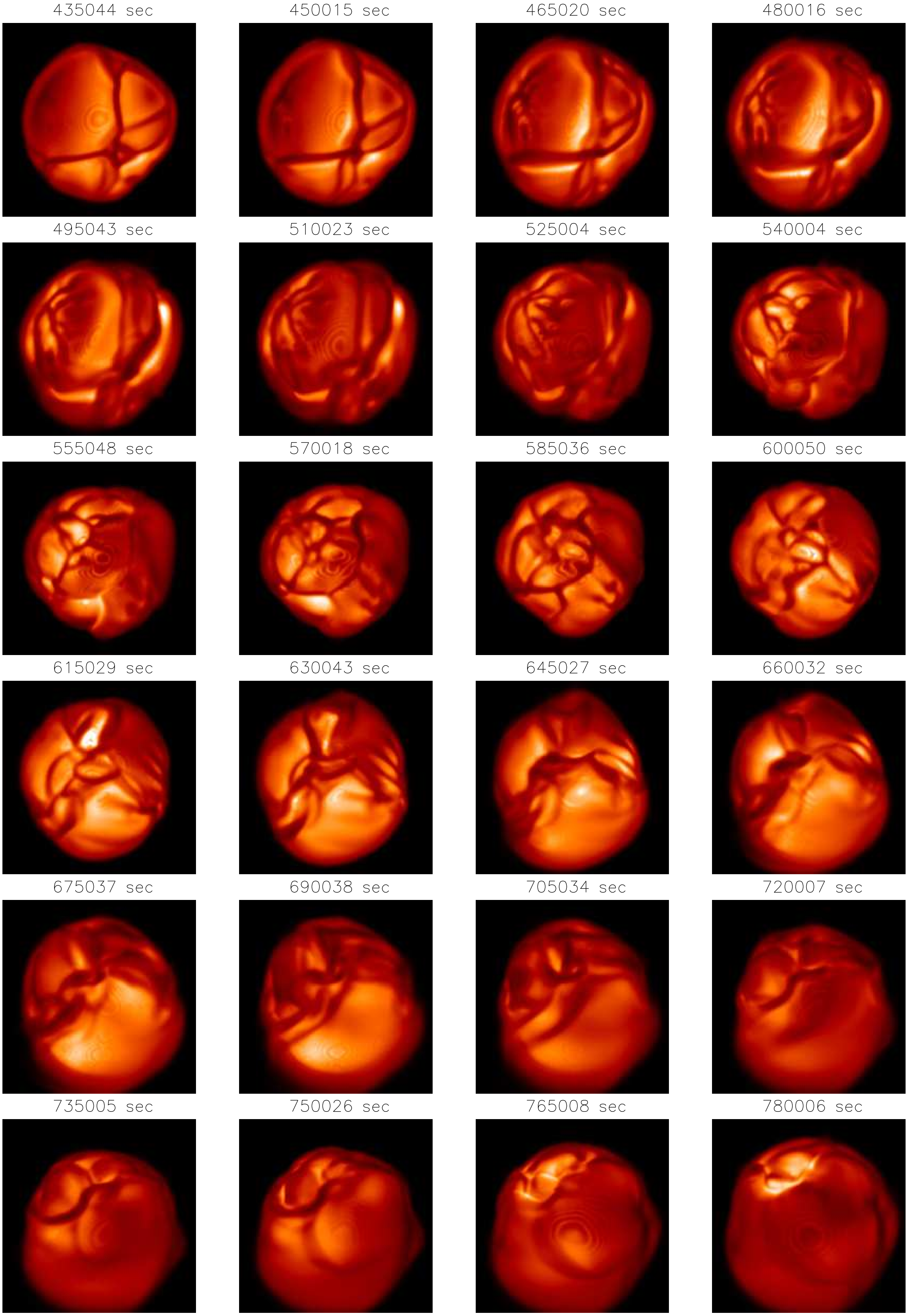

Figure 8: Sequence of surface intensity snapshots of model st47g20n05. Surface parameters: $T_{\rm eff}$=4700 K, $\log g$=2.00, 137^3 grid points (the "intermediate" case).

Velocities

Figure 9 gives an indication of the size of the typical velocities in the atmosphere. Mach numbers of one are easily reached and even exceeded in some regions. Values much beyond these value rarely occur so far.

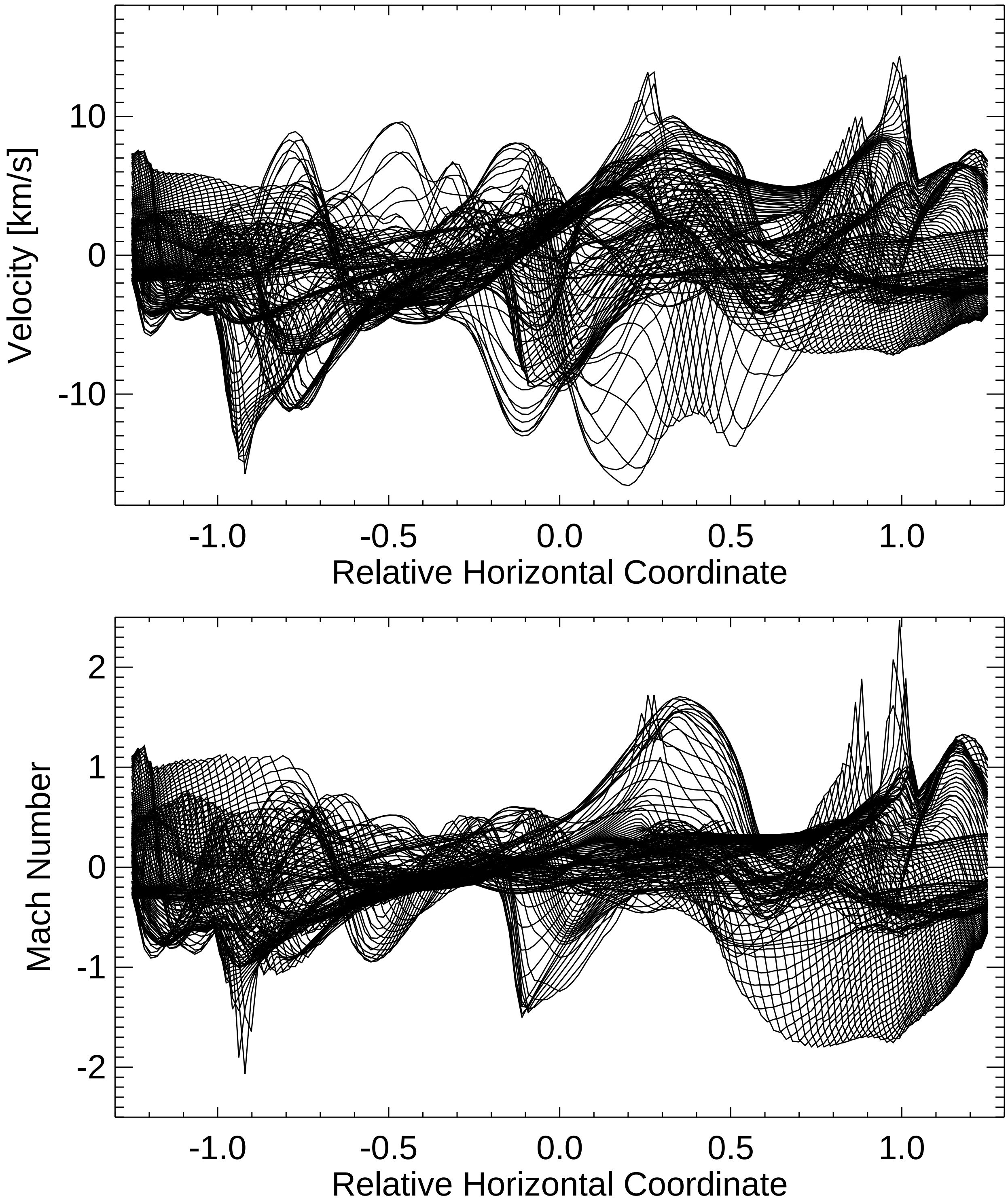

Figure 9: Velocity in one direction (top) and corresponding Mach number (bottom) over horizontal coordinate for a selected slice through the model st47g20n05-01.

Conclusions

- A newly developed code is already able to handle an idealized (scaled) hydrodynamics model of a "Star in a Box", including non-local radiative transfer. Some first results have been presented.

- The proper numerical treatment of the stellar surface, which is crucial for the detailed modelling of surface convection and the stellar atmosphere, poses a major problem.

- The stability of the code near the sub-photospheric temperature jump has been considerably improved during the development and the scaled models have become feasible. Further advances are necessary (and possible) to simulate a "real" supergiant.

- In the near future, radiation magneto-hydrodynamics models of the entire outer envelopes and atmospheres of at least some stars will become widely accessible and help to understand large-scale surface features, as eg. global surface convection, magnetic phenomena, or rotationally induced flows.