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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, high spatial intensity fluctuations, and a surface pattern rather dissimilar to solar granulation. Some bright features over downdrafts might be interpreted as hot spots in low-resolution observations.

1. Introduction

Betelgeuse (α Ori) is a nearby ($d_{\mathrm{Hipparcos}}$=131$\pm$30 pc) M2 Iab Supergiant and the star with the largest apparent diameter (after the Sun). The basic parameters are not known with very high accuracy. "Reasonable average" values are M=6 $\mathrm{M}_\odot$, T_{eff}=3500 K, $\log g_{\mathrm{surf}}$=-0.5, R=22.1 mas $\Rightarrow$ R=620 $\mathrm{R}_\odot$. The surfaces abundances do not deviate much from a solar atmospheric composition.

2. Observations and Some Theory

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 (Goldberg 1984): The overall brightness of Betelgeuse varies on time-scales of weeks, months, and years.

Observations with optical interferometers started 12 years ago (see Buscher et al. 1990, Wilson et al. 1992, Tuthill et al. 1997, Wilson et al. 1997, Klueckers et al. 1997, Burns et al. 1997, Young et al. 2000). They still have a very 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). In the paper by Young et al. (2000), the possibility of a fit with a circular disk and a single *dark* spot is discussed.

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Ronald Gilliland and Andrea Dupree took a direct UV image with HST (1996) with obvious deviations from circular symmetry. The VLA radio-observations by Jermy Lim et al. (1998) 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 (see Alex Lobels contribution at this conference). But in general, spectroscopic observations of Betelgeuse are difficult to interpret due to the lack of a reliable (3D) model atmosphere (see David Gray 2000, and his contribution at this conference for an attempt).

Based on simple scaling arguments, Martin Schwarzschild suggested in 1975 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 (see e.g. Gilliland & Dupree 1996).

3. Numerical Simulations with COBOLD

The numerical simulations described here are performed with a new code "COBOLD" ("COnservative COde for the COmputation of COmpressible COnvection in a BOx of L Dimensions, l=2,3"). It uses a finite volume approach and relies on operator (directional) splitting to reduce the 2D or 3D problem to one dimension. In the 1D step an approximate 1D Riemann solver (Roe-type) is applied, modified to account for a realistic (tabulated) equation of state, a non-equidistant Cartesian grid, and the presence of source terms due to an external gravity field. In addition to the stabilizing mechanism inherent in an upwind-scheme with monotonic reconstruction method, a 2D or 3D tensor viscosity can be activated.

The radiation transport is solved in a separate sub time step. It uses a long characteristics method, in which the 1D-equation of radiative transfer is solved with a Feautrier method along a representative number of rays with various inclinations. Several sub-timesteps per global timestep are performed to account for the relatively short radiative time-scale.

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

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

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 (model st33gm06n03). 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 (Hauschildt et al. 1997) and OPAL tables (Iglesias et al. 1992), kindly provided by Hans-Günter Ludwig.

The model is characterized by the parameters $T_{\rm eff}\sim3200\,{\rm K}$, $\log g\sim$-0.5, $L_*\sim50000\,L_\odot$. It turns out to be slightly to cool for Betelgeuse and is lies at the lower end of the proposed surface gravity range but is sufficient to derive interesting preliminary conclusions.

4. Results

The initial model for the simulation 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 of surface intensity images from a later stage with completely irregular surface structures is given in Fig. 1. The temperature slices in Fig. 2 show the formation of shock waves in the atmosphere and deep-reaching downdrafts. Although envelope convection in a red supergiant is still driven by a network of surface cells, they significantly differ in properties and appearance from solar granulation:

First, convection in the supergiant is characterized by *significantly larger convective cells* (measured in atmospheric pressure scale heights).

The ratio of radiative to hydrodynamic time-scales is smaller than in the Sun. The more efficient radiation leads to a less efficient convective energy transport, a larger entropy jump between sub-surface layers and photosphere, and longer time-scales for the formation of new downdrafts (the splitting of granules).

Larger convective velocities (in absolute values and in Mach-numbers, with particularly strong horizontal – or tangential – flows) tend to sweep small surface irregularities into existing downdrafts before they have time to grow and to develop new downdrafts because of the convective instability.

The deep reaching downdrafts let the convection "sense" deeper layers where the local pressure scale is much larger than at the surface. This favors (together with the short radiative time-scale and the increased horizontal velocities) larger convective cells and lets only a handful appear at one side at a given time.

Global irregular pulsations in the supergiant model have much larger amplitudes than solar 5-min oscillations. They manifest in surface intensity changes with a period of around 1.5 years which are superposed by some phenomena of convective origin on shorter time-scales. Strong interactions between convection and pulsations make a modulation of the convective flux near the surface and therefore the emitted energy possible.

Spatial intensity fluctuations are very pronounced. Sometimes, the intensity of a usually bright granule can drop well below the average value. While in the solar case small granules or the edges of some granules are the brightest structures, the surface images of the red supergiant shows its brightest features over intergranular lanes. This is due the temperature dependence of the opacities and sensitively depends on the surface temperature of the star.

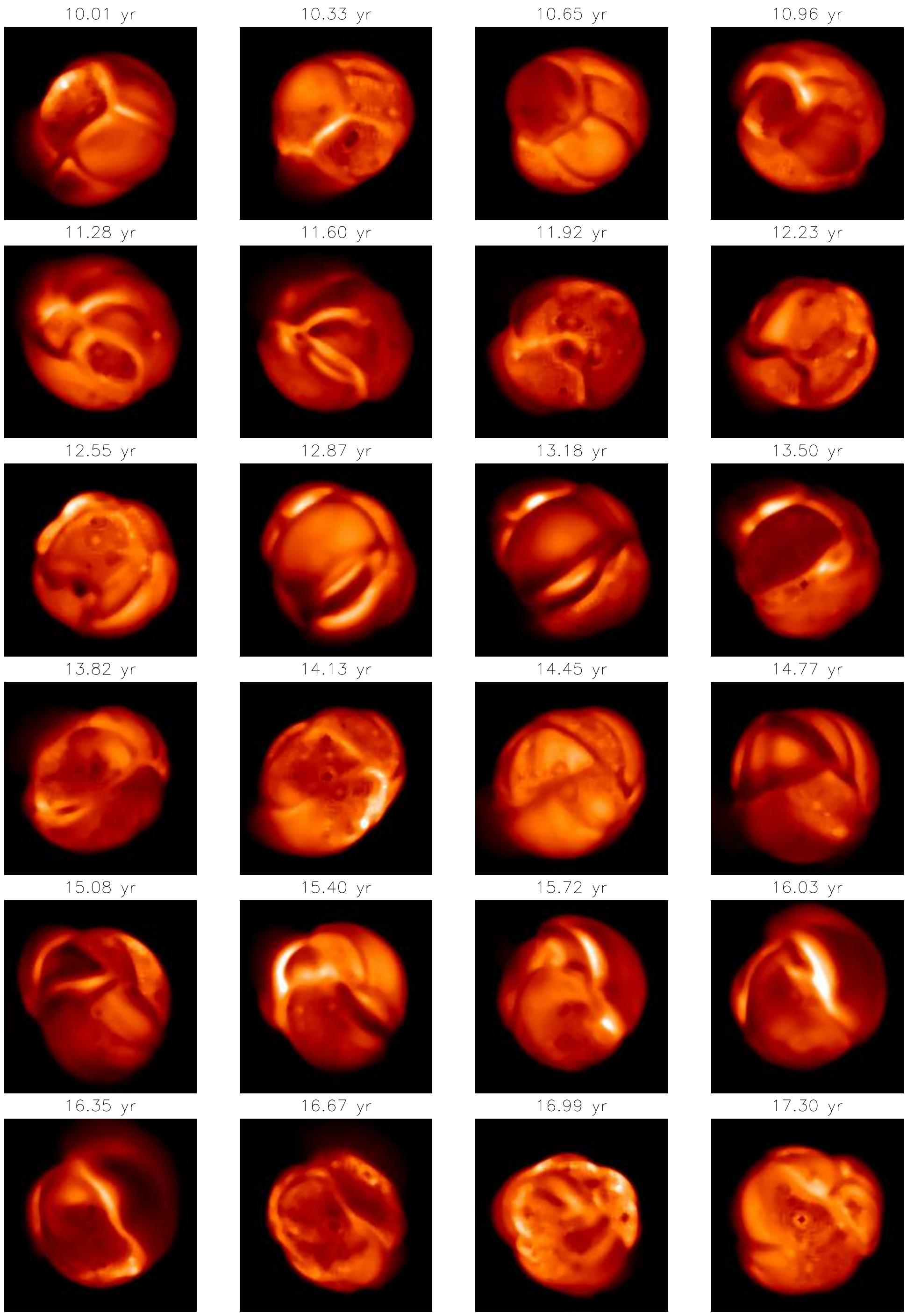

Figure 1. Sequence of surface intensity snapshots ($T_{\rm eff}$=3200 K, $\log g$=-0.5, 127^3 grid points). At the top the simulated stellar time is indicated in years. The surface cells are similar to solar granulation at 10.65 yrs. But occasionally, there are small bright features near the disk center (16.03 yrs) or the at the rim (15.40 yrs) above downdrafts.

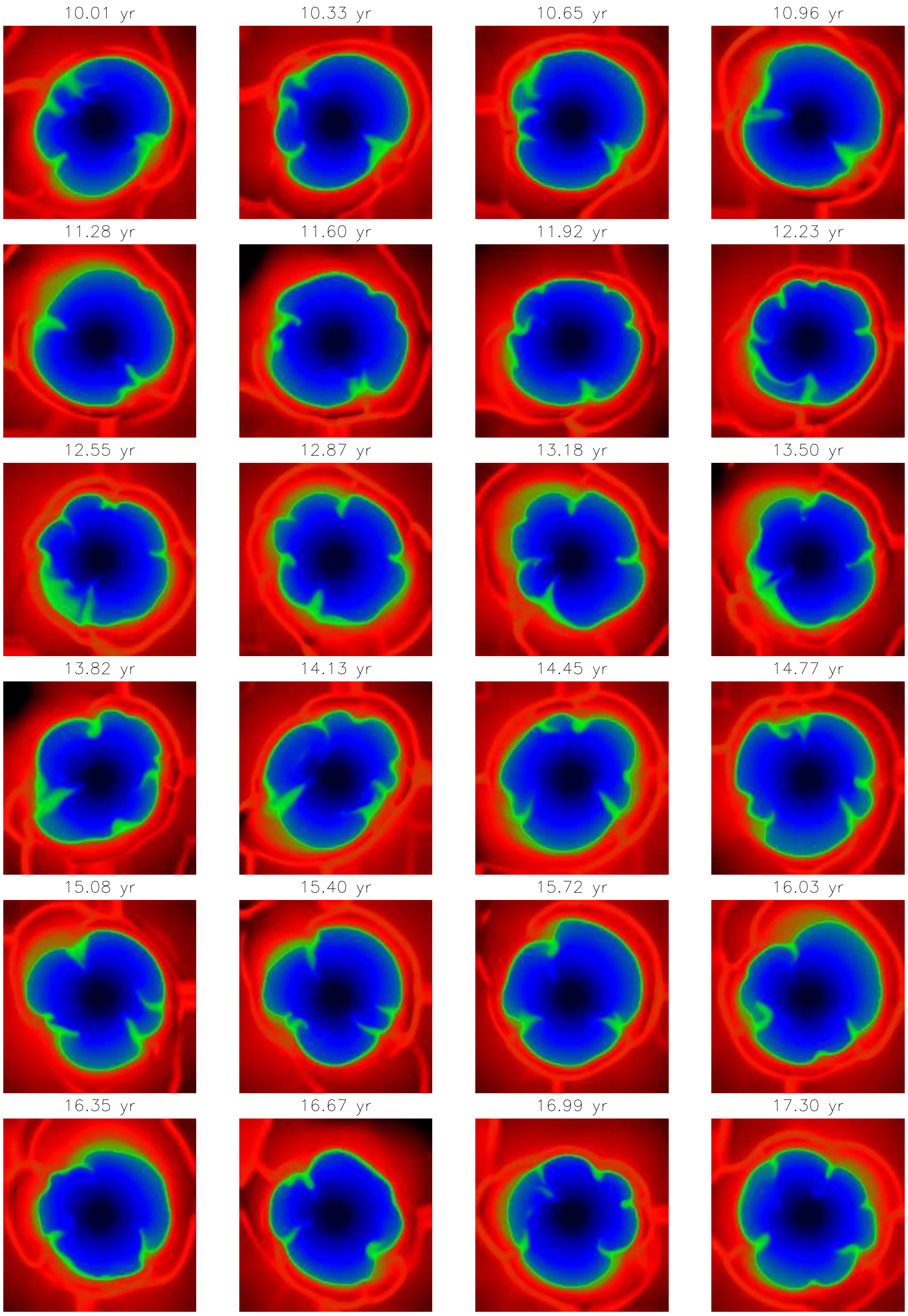

Figure 2. Sequence of temperature (ranging from 1500 K to 150 000 K) slices ($T_{\rm eff}$=3200 K, $\log g$=-0.5, 127^3 grid points). In a slice there are 3 to 6 downdrafts, some of them reaching deep into the star. Shock waves run into the outer atmosphere, moving mainly radially.

5. Conclusions

The first realistic simulations of a red supergiant "star-in-a-box" including non-local radiative transfer are now feasible, although many simplifications are still necessary. 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 indeed (as suggested by Schwarzschild 1975) covered by a few *giant convection cells*. The stars shows significant deviations from spherical symmetry. Atmospheric *velocities are large* (with peak values up to 20 – 30 km/s). *Shock waves* are ubiquitous. The granulation appears in general 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. The surface intensity contrast is higher than on the Sun.

Main problems for the simulations are the *short radiative time-scales*, which make the computation of the radiation field very time-consuming, and the *high number of grid points* needed to resolve all features properly, particularly the steep temperature jump just below the photosphere.

Future development will concentrate on an *adjustment of the basic parameters* 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.

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References

Burns, D. et al. 1997, MNRAS, 290, L11

Buscher, D.F., Haniff, C.A., Baldwin, J.E., Warner, P.J. 1990, MNRAS, 245, 7p

Gilliland, R.L, Dupree, A.K. 1996, ApJ, 463, L29

Goldberg, L. 1984, PASP, 96, 366

Hauschildt, P.H., Baron, E., Allard, F. 1997, ApJ, 483, 390

Iglesias, C.A., Rogers, F.J., Wilson, B.G. 1992, ApJ, 397, 717

Klueckers, V.A. et al. 1997, MNRAS, 284, 711

Lim, J. et al. 1998, Nature 392, 575

Schwarzschild, M. 1975, ApJ, 195, 137

Tuthill, P.G., Haniff, C.A., Baldwin, J.E. 1997, MNRAS, 285, 529

Wilson, R.W. et al. 1992, MNRAS, 257, 369

Wilson, R.W., Dhillon, V.S., Haniff, C.A. 1997, MNRAS, 291, 819

Young, J.S. et al. 2000, MNRAS, 315, 635