Modelling the Entire Atmosphere of Betelgeuse with 3D Simulations

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Abstract

The large amount of observational data on Betelgeuse points to a highly dynamical atmosphere with phenomena that have not yet been described in detail by theory.

Efforts to improve theoretical understanding are being made with the help of the COBOLD computer code, which is now able to perform 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 with complex substructures, large velocities, and higher contrast than seen in solar granules. In this poster, we examine a recent time sequence and analyze the fluctuations in surface intensity and photospheric velocity fields.

Introduction

The overall brightness of the M2 supergiant Betelgeuse (α Orionis) varies on timescales of weeks, months and years (e.g., Goldberg, 1984). Interferometric observations reveal spatial inhomogeneities on the surface that are typically modelled as zero to three hot spots on a circular disk (e.g., Buscher et al. 1990). The very broad lines in the stellar spectrum indicate large atmospheric velocities, but recent spectroscopic observations by David Gray (2001) show no significant variations in the normalized line profiles.

Martin Schwarzschild (1975) suggested that the temporal brightness variations of Betelgeuse could be caused by a few giant granules on its surface. If the typical horizontal extent of a granule is a fixed multiple of some characteristic vertical scale length (e.g., the pressure scale height), then the granules on a supergiant will be much larger than on the Sun, not only in absolute but also in relative size.

Simulations with COBOLD

The 3D radiation hydrodynamics code COBOLD ("COnservative COde for the COmputation of COmpressible COnvection in a BOx of L Dimensions, L=2,3") has been used to produce a model of the outer layers of Betelgeuse.

Hydrodynamics

- Cartesian box
- Approximate Riemann solver (Roe scheme)
- Gravitation included (external potential, non-split)
- Ionization included (tabulated equation of state)
- Discrete conservation laws
- Reconstruction schemes of different order

Radiation Transport

- Equation of non-local radiative energy transfer solved with short-characteristic method for each direction
- 3 to 10 ray directions per radiative timestep
- Conservative energy transport
- Tabulated opacities
- No scattering; strict LTE

The Present Model

The simulations presented in this poster were performed on the local Sunfire cluster at the Uppsala Astronomical Observatory. The model (st35gm04n04) includes 162 timesteps of approximately 23 days each, yielding a time sequence that spans over 10 years (see Figure 1).

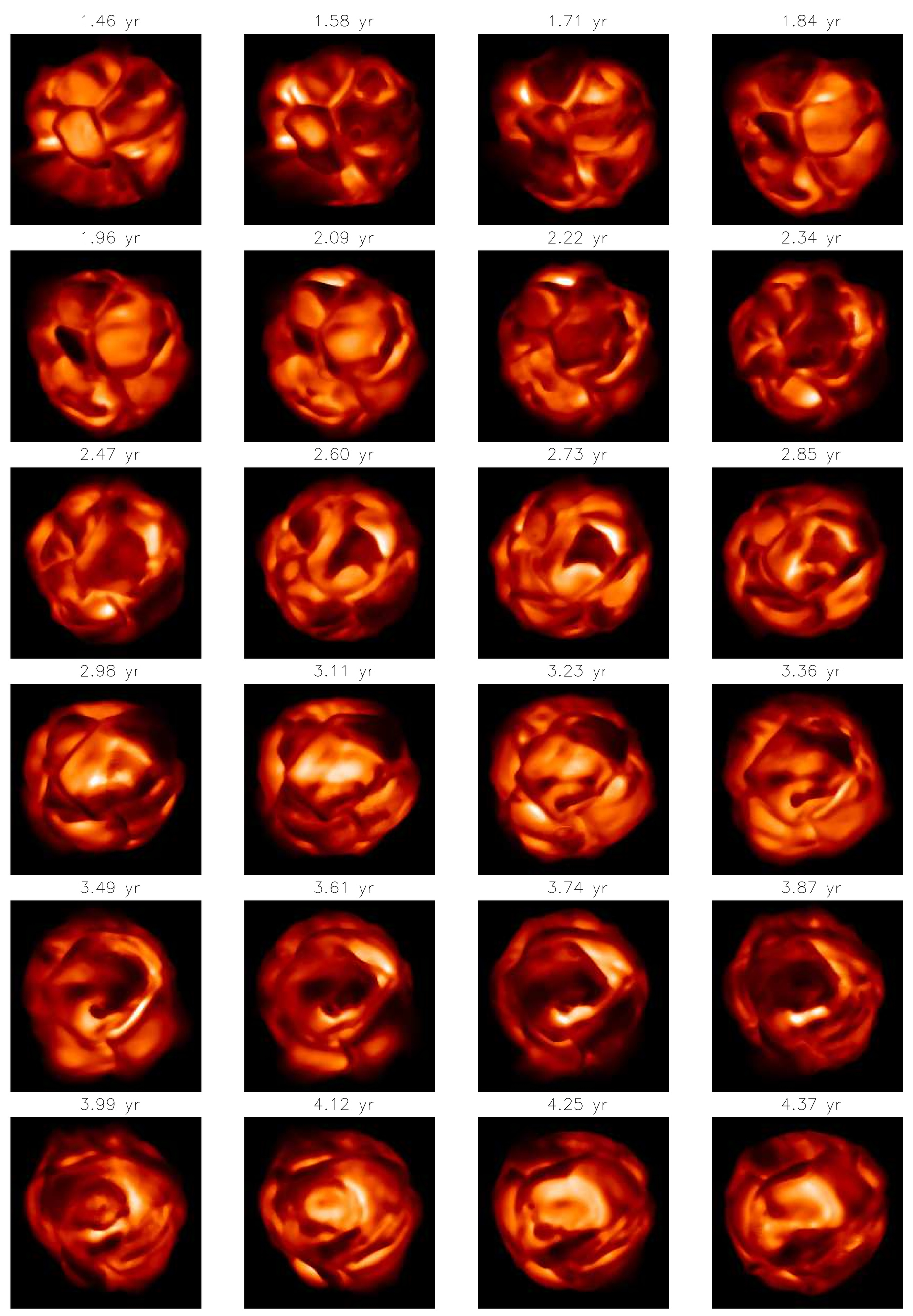

Fig. 1. Surface intensity (slightly smoothed) for some of the timesteps in the current model.

The computational volume is a cube with an edge length of $2 \times 813\,R_\odot$. The grid contains $171^3 = 5\,000\,211$ points.

Gravitation is described by a $1/r$ potential for a mass of $M_\star = 5M_\odot$, where the central singularity is avoided by smoothing within a radius of $r_\mathrm{i} = 135\,R_\odot$.

The boundary conditions are set by adjusting the internal energy within a sphere of radius r_i to keep the entropy close to a fixed value (3.25×10^9 erg $\mathrm{K}^{-1}\,\mathrm{g}^{-1}$). This replaces the energy production by nuclear fusion in a real stellar core. The outer boundaries are open, i.e., transmitting for waves.

The opacity tables are grey Rosseland means, provided by Hans-Günter Ludwig and based on PHOENIX (Hauschildt et al. 1997) and OPAL opacity tables (Iglesias et al. 1992).

The model is characterized by the parameters $T_\mathrm{eff} \sim 3340\,\mathrm{K}$, $\log g \sim -0.47$ (cgs) and $L_\star \sim 46\,000\,L_\odot$. The model turns out to be slightly too cool for Betelgeuse and lies at the lower end of the allowed range in surface gravity.

Analysis

We have begun a closer investigation of the properties of the model. The first (not very obvious!) choice is how to define the extent of the star.

For convenience, we chose a line of sight along the z-axis of the grid's spatial coordinates, tracing the paths of rays in the z direction through each of the 171^2 grid points on the near face of the cube. For each timestep, we selected those (x, y) points for which the optical depth $\tau \geq 100$ was obtained at the place where the line of sight intersects the back face of the cube. The number of such points correspond to an area that can be taken as a measure for the extent of the model stellar disk.

The surface intensities at each timestep and (x, y) pair were read off directly from the model data and smoothed to minimize artifacts resulting from the limited numerical resolution (see Figure 2). The z component of the velocity at a particular optical depth was calculated for each (x, y) pair by taking the grid points along the line of sight and linearly interpolating the velocity along the optical-depth scale (see Figure 3).

More quantitative information on the variations in effective surface area, surface intensity, and velocities as a function of time is shown in Figures 4 and 5.

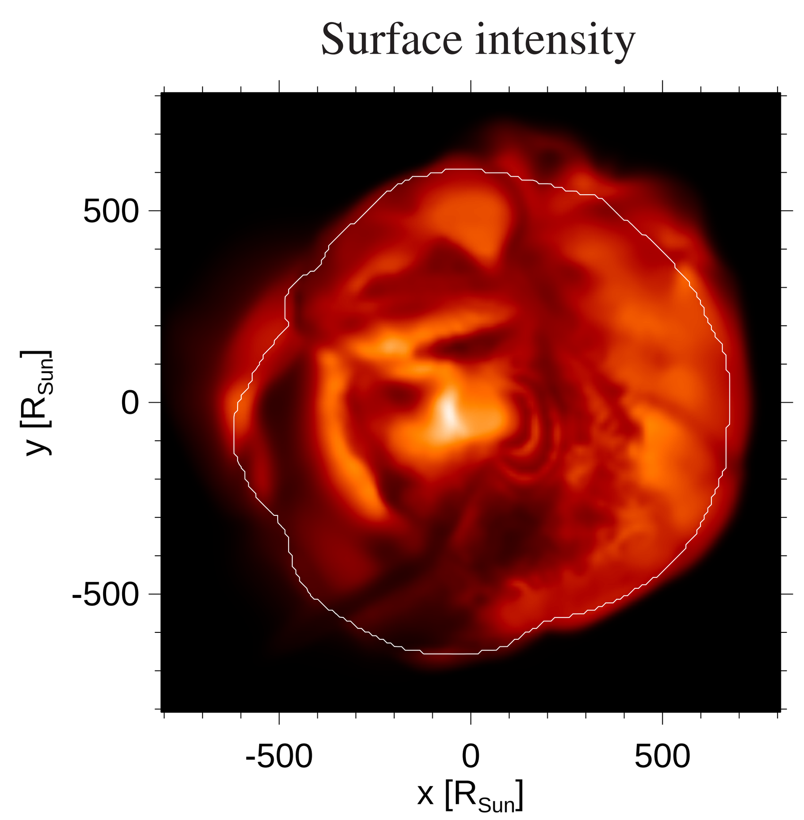

Fig. 2. Surface intensity for a sample timestep in the current model. The contour line encloses grid points with $\tau \geq 100$.

As can be seen from Figure 4, changes in the surface area of the model "disk" (dotted green line) are no greater than 12% and can account for only a part of the relatively strong temporal intensity fluctuations (black line). The spatial intensity contrast (red line) as well as the range of values (black dots) is much larger than on the Sun.

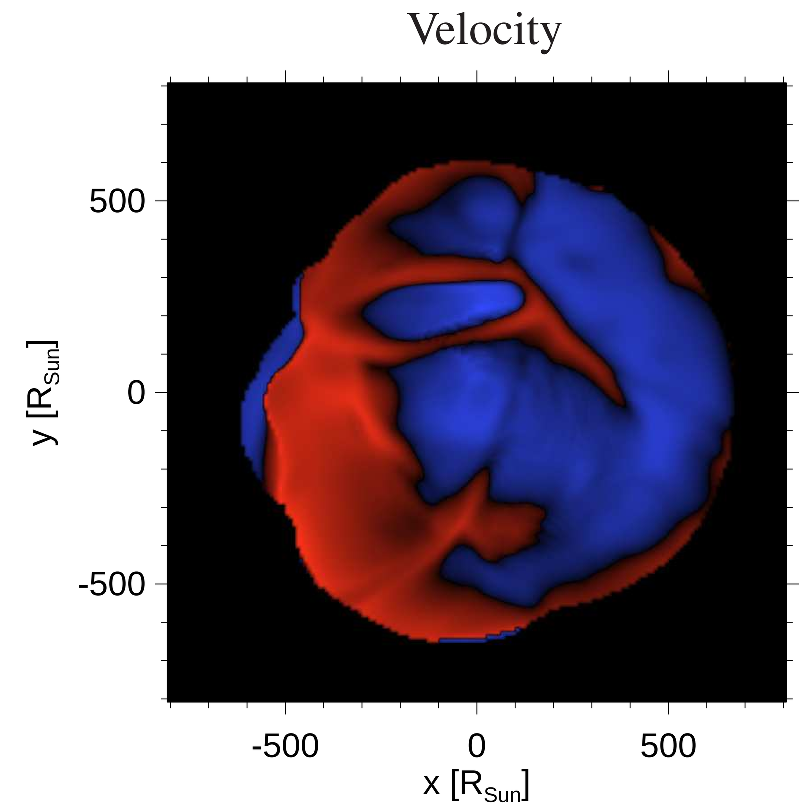

Fig. 3. Redshifted and blueshifted velocities at $\tau = 1$ for the selected points in Figure 2.

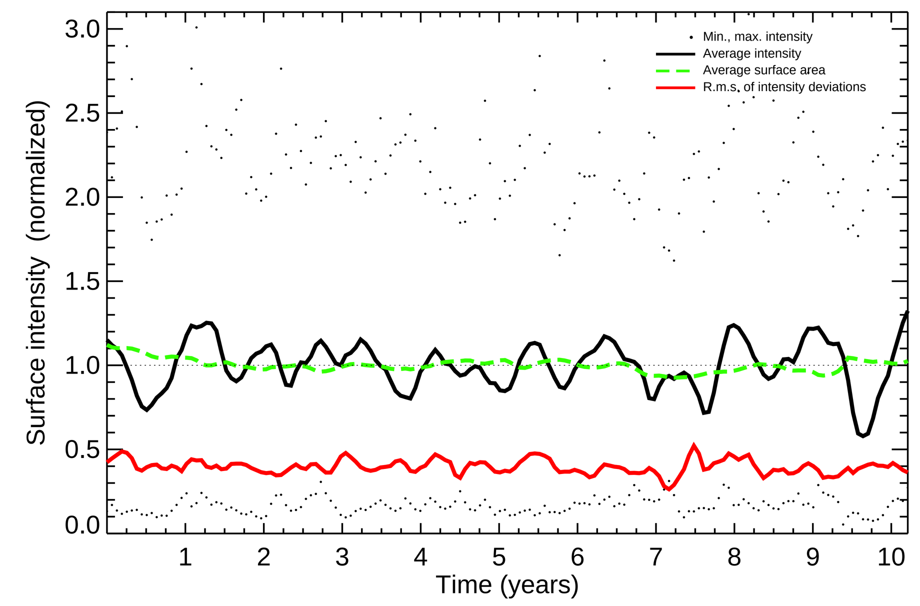

Fig. 4. Surface intensity vs. time. Minimum and maximum intensity (dots), mean intensity (black line), and relative intensity variation or root-mean-square deviation (red line) for all points on the "disk" at each timestep, along with the corresponding surface area (dotted green line). All quantities have been normalized to their respective averages over time.

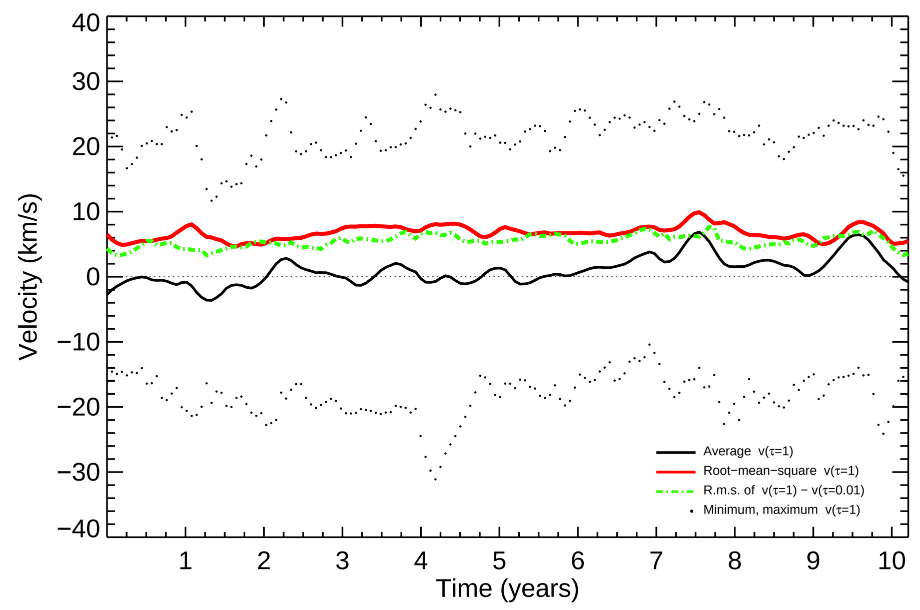

Fig. 5. Line-of-sight velocities vs. time. At each timestep and for all points on the "disk": minimum and maximum (dots), straight arithmetic mean (black line), and root-mean-square (red line) of the velocities at $\tau = 1$, as well as the r.m.s. of the difference between the velocities at $\tau = 1$ and $\tau = 0.01$ (dotted green line).

The range of velocities along the line of sight is of the same order of magnitude as the wing-to-wing span of line profiles in the spectrum of Betelgeuse as reported by David Gray (2001). Typical model velocities (Figure 5) agree reasonably well with velocities derived from line widths. The short time span covered by Gray's observations (17 months) may not be long enough to provide reliable results for variations of the line profile. Nevertheless, if such measurements can be considered representative of longer timescales as well, then the relatively small variations he found might indicate some shortcomings of the numerical models.

In either case, a few words of caution are in order.

- Physical quantities in the models are not direct observables.
- The velocity fields in the models lead to complicated Doppler shift distributions within the convection cells, and so predictions regarding resulting line profiles are difficult.
- Increased numerical resolution (see poster by Freytag & Finnsson) is expected to increase the velocities somewhat and decrease the surface cell size, which will result in smaller fluctuations of the r.m.s. velocity with time.
- Higher surface gravity will lead to smaller convective cells and a further decrease of the r.m.s. velocity fluctuations.
- The model shows phases with rather stationary overall flows, as well as phases with significant variations in the r.m.s. velocity. Observations should be long enough to cover both situations…

Conclusions

- Intensity fluctuations—both temporal and spatial—are strong, while the relative surface area does not change very much.
- Atmospheric velocities are large, with peak values up to 20 or 30 km/s. The r.m.s. speed of typically 7 km/s lies somewhat above the sound speed, which is around 5.5 km/s.
- The temporal fluctuations in the r.m.s. velocity should give rise to variations in the line widths. Measurements of line profiles over a sufficiently long time span could be used to determine the number of surface cells, provided that a proper model for the surface convection is used as a basis for spectrum synthesis.

In addition to continued improvement of the code (increases efficiency to allow a finer grid, more detailed opacities), a project is underway to develop the tools needed to translate information from the models into photometric and spectroscopic quantities that are accessible to observers.

References

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