Photospheric and dust structures of Betelgeuse during its Great Dimming

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Abstract

Betelgeuse is a red supergiant surrounded by a dust envelope characteristic to its evolutionary stage. From November 2019 to March 2020, it underwent the so-called "Great Dimming". Images in total intensity obtained with SPHERE/VLT (Montargès et al. 2021) show significant darkening of the southern half of the stellar disk. Meanwhile, our differential speckle polarimetry observations, carried out with 2.5-m telescope of Caucasian Mountain Observatory of SAI MSU (Safonov et al. 2020), indicate the presence of an envelope surrounding the star at a distance of about 1 $R_{\odot}$ from the photosphere, which was reported previously by Haubois et al. 2023.
Two main mechanisms have been discussed in literature to explain the dimming: the formation of a dust cloud along the line of sight or local cooling of the stellar photosphere. To investigate a scenario in which both mechanisms act simultaneously, we employ radiative transfer modeling. It is performed using the RADMC3D package (Dullemond et al. 2012), which we modified to account for an inhomogeneous photosphere. Our model includes a cold spot, a dust cloud on the line of sight and a dust envelope and allows us to reproduce resolved observations in both total and polarized intensity. The modeling demonstrates the possibility of using a single dust composition for both the cloud and the envelope, namely corundum with grain sizes from 0.005 to 0.13 μm, in agreement with Gail et al. 2020. We find that the cloud and the envelope had masses of 2.5×10^{-9} $M_{\odot}$ and 8×10^{-9} $M_{\odot}$, respectively. The cold spot had a temperature of 3150 K and covered 80% of the visible photosphere.

Observations for January 2020 epoch

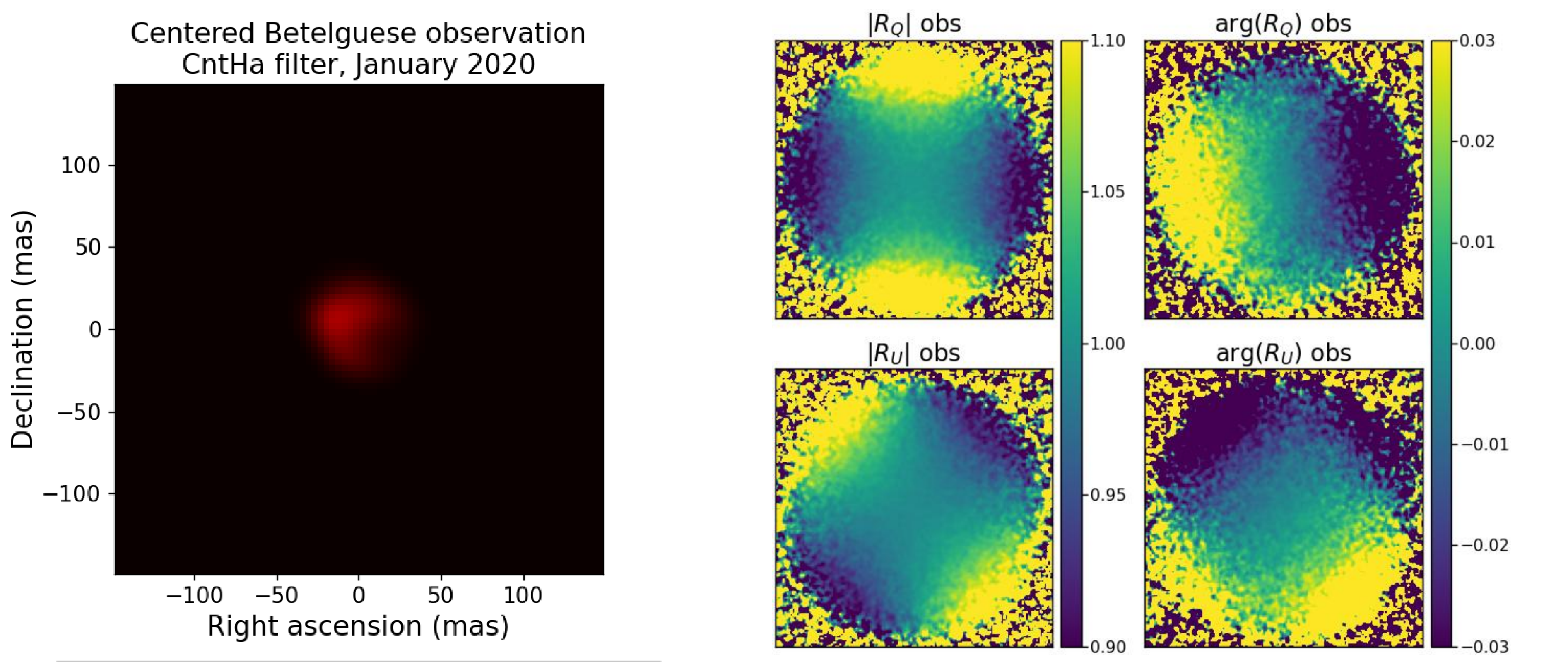


Fig.1. Left panel: image of Betelgeuse in total intensity, obtained on VLT. Right panel: differential polarimetric visibility data at 625 nm obtained on CMO.

We combine two complementary types of observations. The total intensity image was obtained with VLT/SPHERE-ZIMPOL on 28/01/2020, while the differential speckle polarimetry data were obtained with the 2.5-m CMO telescope on 07/02/2020. These data are treated as a single observational epoch. Total intensity images mainly constrain the cold spot and the line-of-sight dust cloud and the differential polarimetric visibility (DPV) is sensitive to scattered light from the extended circumstellar dust envelope.

Best-fit model

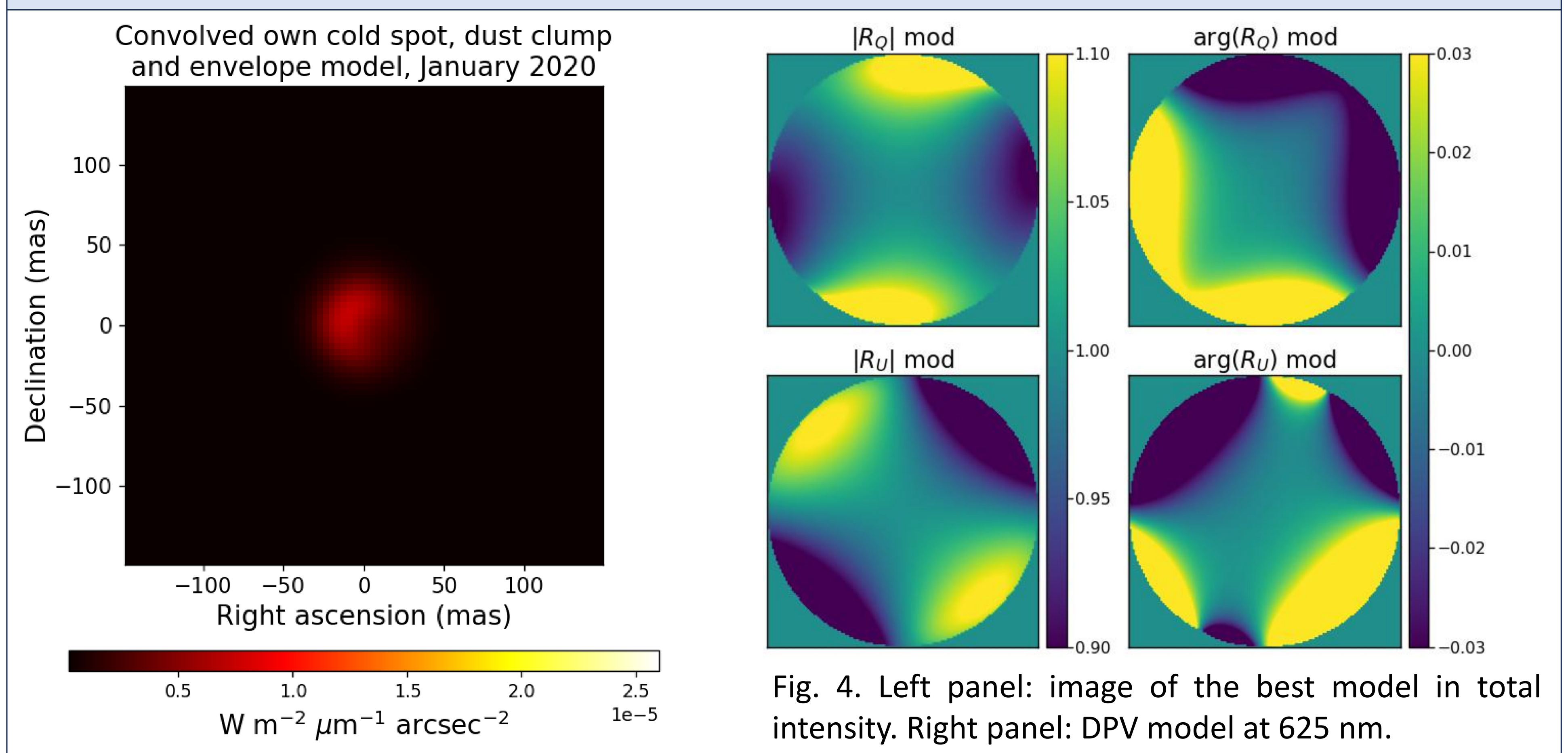
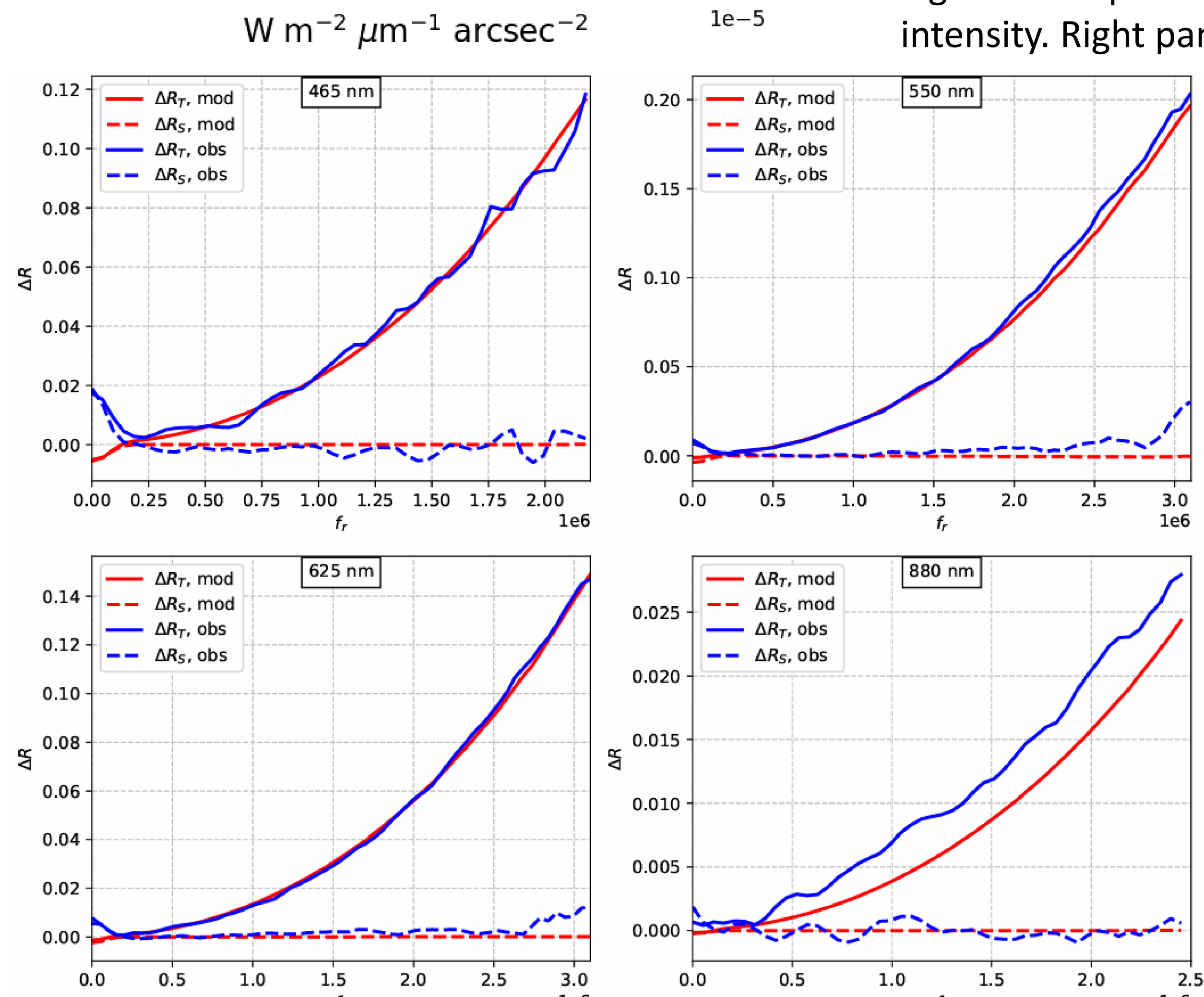


Fig. 4. Left panel: image of the best model in total intensity. Right panel: DPV model at 625 nm.



Unlike previous models, our model implements both the cold spot and the cloud, and also includes a dust shell around the star. Both dust structures are composed of the same corundum grains.

The cloud is located at 20 au with a radius of 4 au and has a mass of 2.5×10^{-9} $M_{\odot}$, while the shell extends from 6 to 8 au with a mass of 8×10^{-9} $M_{\odot}$ The cold spot has a temperature of 3150 K and covers about 80% of the visible photosphere.

Fig. 5. Modeled and observed radial DPV parameters for 4 wavelengths. Discrepancy at 880 nm can be related to an unaccounted population of larger particles.

RADMC3D modifications

In the standard RADMC3D framework, stellar emission is assumed to be isotropic: photon packets are generated uniformly over the stellar surface and propagate through the grid, where they may be absorbed, scattered, or pass without interaction. The resulting image includes attenuated stellar radiation, scattered light, and thermal emission from dust.

To account for an inhomogeneous photosphere, we introduce temperature maps of the stellar surface. The star is modeled as a sphere divided into M×N surface elements, each assigned a temperature. For each sector, a cumulative spectrum is constructed from the Planck function and used to sample photon wavelengths.

- In dust heating calculations, the contribution of each element is weighted by T^4 following the Stefan-Boltzmann law.
- For scattered radiation, the emissivity is determined by the local intensity from Planck's law.
- Direct images are computed via ray tracing: rays intersect the stellar surface, and the final intensity is calculated from the local temperature of the sector and dust distribution along the line of sight.

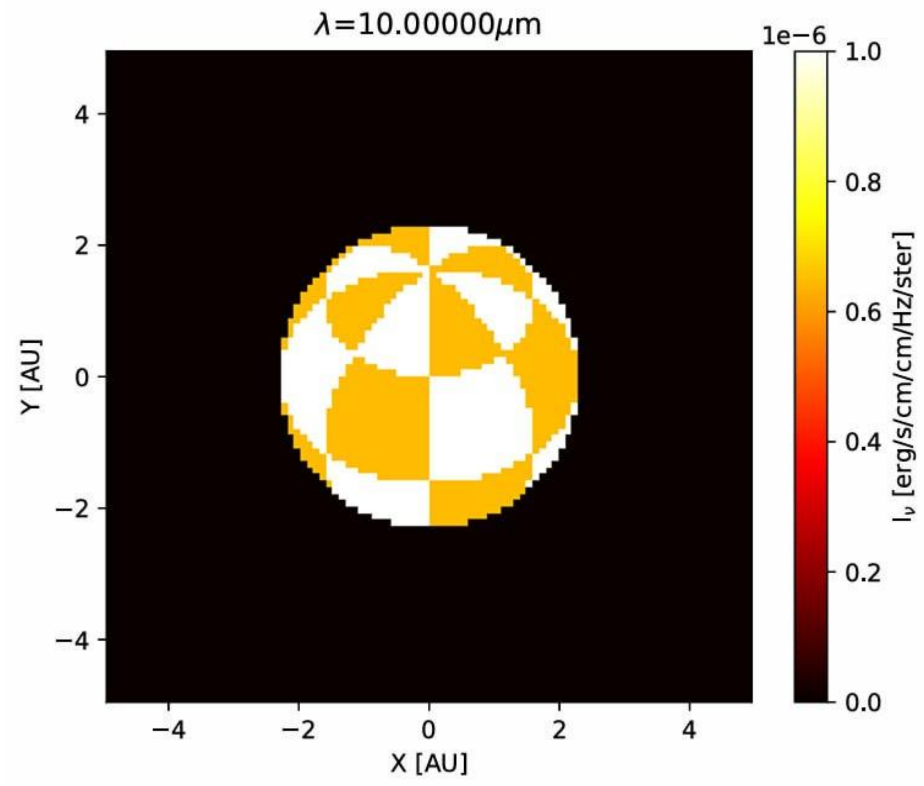


Fig. 2. Exaggerated example of a temperature map used when building a radiation source in RADMC-3D. Colder sectors are set to 3000 K, hotter sectors to 5000 K.

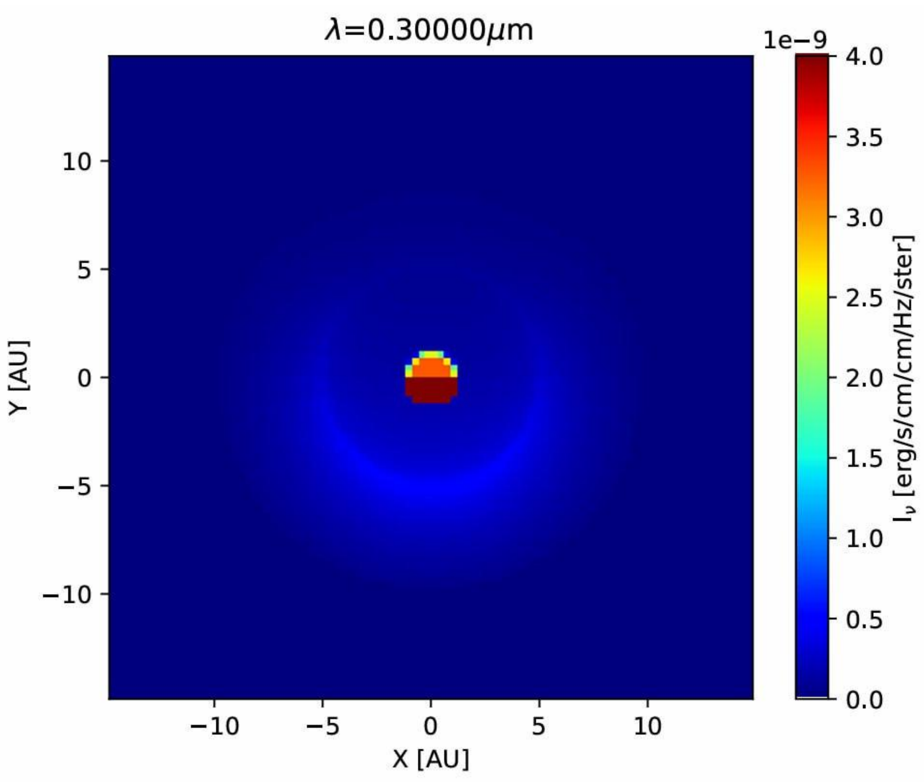


Fig.3. Example of the effect of an inhomogeneous photosphere on the dust envelope. A hotter southern hemisphere results in higher brightness of the envelope in the corresponding region.

Future implications

As the resolving power of modern telescopes increases, observations provide more detailed constraints on red supergiants, their dust envelopes, and photospheric inhomogeneities. To interpret these constraints, models must be able to reproduce different types of observational data within a single framework. We will therefore continue to develop radiative transfer modeling tools to include inhomogeneous photospheres more accurately in context of dusty stellar environments.

References

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Direct link to the best-fit model in webMCRT — collaborative environment for radiative transfer modeling in dust envelopes around stars developed at SAI MSU.