

THE GREAT DIMMING OF BETELGEUSE AS SEEN BY THE VLT/VLTI

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Abstract. Between November 2019 and April 2020, the second nearest red supergiant Betelgeuse experienced an historic drop in brightness, called the ‘Great Dimming’ of Betelgeuse. Here we summarize the findings of our spatially resolved observations with the European Southern Observatory’s VLT/VLTI. The VLTI/GRAVITY interferometric measurements indicate that between January 2019 and February 2020 the angular diameter of the star in the K-band continuum did not change significantly. The VLT/SPHERE images show an obscuration of the Southern hemisphere of the star. Using additional optical photometric observations from the AAVSO, we conclude that the ‘Great Dimming’ of Betelgeuse is best explained by both a cool photospheric patch, and a dusty cloud in the line of sight. The former may have triggered the latter.

Keywords: Stars: individual: Betelgeuse, supergiants, Stars: mass-loss, Stars: imaging, Techniques: high angular resolution

1 Introduction

Betelgeuse (α Ori) is the prototypical red supergiant (RSG) star. Located at 222^{+48}_{-34} pc (Harper et al. 2017; Joyce et al. 2020), it is the second closest RSG, and probably the most observed. Like most RSGs, it is

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a semi-regular variable with primary and secondary periods of $\sim 400 - 420$ and ~ 2100 days respectively (Stothers 2010). During the last months of 2019, as it was heading towards its February 2020 light minimum, the brightness of the star decreased rapidly (Guinan et al. 2019). It reached its historic minimum in the visible with $V = 1.614 \pm 0.008$ mag, on 7-13 February 2020 (Guinan et al. 2020 and Fig. 1).

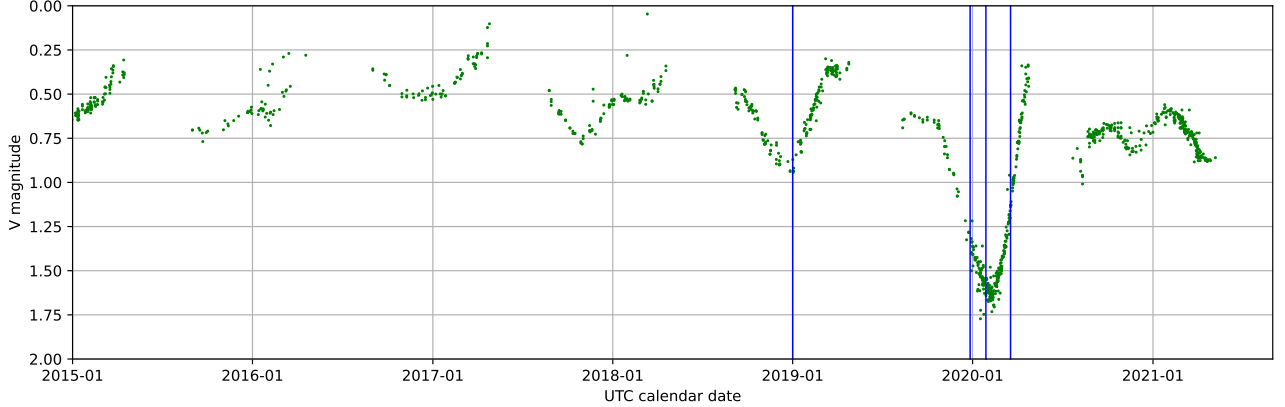


Fig. 1. V band light curve of Betelgeuse between 2015 and 2021 from the American Association of Variable Star Observers (AAVSO) measurements. The blue vertical lines correspond to the dates of the VLT/SPHERE-ZIMPOL images.

2 Observations and data reduction

Betelgeuse was observed a year before the ‘Great Dimming’ with VLTI/GRAVITY (Gravity Collaboration et al. 2017) in the compact configuration of the auxiliary telescopes (A0-B2-D0-C1), and with VLT/SPHERE (Beuzit et al. 2019), respectively on 20th January 2019, and 1st January 2019. The SPHERE observations were performed with two of its sub-units. The infra-red dual imaging and spectrograph (IRDIS, Dohlen et al. 2008) in its sparse aperture masking mode (SAM, Cheetham et al. 2016) was used to supplement the GRAVITY measurements with short baseline points sampling the inner part of the first lobe of the visibility function. The Zurich Imaging Polarimeter (ZIMPOL, Schmid et al. 2018) obtained spatially resolved images of the photosphere in the visible domain, using the P2 polarimetric mode. During the ‘Great Dimming’, the observations were obtained on 14th February 2020 with VLTI/GRAVITY, 27th December 2019 with VLT/SPHERE-IRDIS, and 27th December 2019 (before the light minimum), 28th January 2020 (at the light minimum), and 18th, 19th and 21st March 2020 (after the light minimum) with VLT/SPHERE-ZIMPOL.

The details on the data reduction, calibration and description is available in Montargès et al. (2021).

3 VLTI/GRAVITY and VLT/SPHERE-IRDIS: angular diameter measurements

We estimated the angular diameter of the star, as a change in size could be linked to the physical reason for the ‘Great Dimming’ event. This parameter is also a mandatory input of the models developed in Sect. 4.

We fitted the first lobe observations in the K band continuum ($2.22 - 2.28 \mu\text{m}$ for GRAVITY with the exclusion of several weak atomic and molecular lines, and Cnt_K2 filter for IRDIS) with a uniform disk (UD) model. We obtained the angular diameters values of $\theta_{\text{UD}} = 42.61 \pm 0.05$ mas (reduced $\chi^2 = 26.5$) before the Dimming, and $\theta_{\text{UD}} = 42.11 \pm 0.05$ mas (reduced $\chi^2 = 46.3$) during the Dimming. An attempt to fit the data with a power-law limb-darkened disk gave similar reduced χ^2 values without significant changes to the angular diameter.

The difference in angular diameter is within the variations observed over the previous decades (Ohnaka et al. 2009), and far from the 30% variation that would be required to explain the ‘Great Dimming’.

4 VLT/SPHERE-ZIMPOL: spatially resolving the photosphere

4.1 The VLT/SPHERE-ZIMPOL image series

The pre-dimming image (January 2019) shows an almost spherical photosphere with a slight elongation in the North-East to South-West direction. The three images acquired during the Dimming (December 2019, January 2020, and March 2020) are much different with a Southern hemisphere that appears obscured or hidden. In Sect. 4.3 and 4.4 we model these observations using a cool photospheric patch and a dusty clump, respectively.

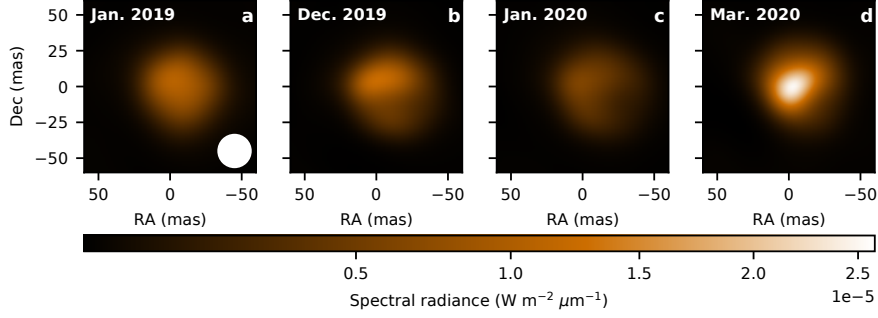


Fig. 2. VLT/SPHERE-ZIMPOL observations of Betelgeuse after deconvolution in the Cnt.H α filter. North is up; east is left. The beam size of ZIMPOL is indicated by the white disk in panel a. We used a power-law scale intensity with an index of 0.65 to enhance the contrast. a: January 2019. b: December 2019. c: January 2020. d: March 2020. The Cnt.H α filter (one of ZIMPOL’s filters) is centred at 644.9 nm.

4.2 Estimation of the pre-dimming circumstellar extinction

Previous observations of Betelgeuse have revealed that it is surrounded by a dusty circumstellar envelope (eg. Verhoelst et al. 2009; Kervella et al. 2011). Before looking at the ‘Great Dimming’, we estimated the extinction caused by this circumstellar dust. We estimated the parameters of a Cardelli extinction law (Cardelli et al. 1989) that would be required to reproduce our VLT/SPHERE-ZIMPOL photometry and the contemporary American Association of Variable Stars Observers (AAVSO) measurements in January 2019 (pre-dimming). Further details on this modeling are available in Montargès et al. (2021). In the following results, the Cardelli extinction law with $R_V = 4.2$ and $A_V = 0.65$ is always implemented in order to focus on the effect of the Dimming.

4.3 Modeling: a photospheric cool patch

To reproduce the ZIMPOL images (Fig. 2), we first constructed a stellar disk with a cool patch, using PHOENIX spectral energy distributions (SEDs, Lançon et al. 2007). The cool patch was defined by three parameters: its center position on the stellar disk (x_p, y_p), and its size r_p . The modeling details are available in Montargès et al. (2021). The best-match parameters are summarized in Table 1. The images are shown in Fig. 3. We wish to emphasize that the goal was not to estimate precisely the effective temperature of the photosphere and of the patch, but to rather assess the compatibility of the model with the ‘Great Dimming’.

4.4 Modeling: radiative transfer with a dusty clump in the line of sight

To test the dust clump hypothesis we used 3D radiative transfer simulations produced with the code RADMC3D (Dullemond 2012). In the following the x axis is oriented West to East, the y axis is South to North and z axis points towards the observer. In front of the star, we put a spherical dust density centred at (x_c, y_c, z_c) , with r_c as its radius, and constant dust density ρ_0 . We adopted a canonical silicate composition for the dust (MgFeSiO₄, Jaeger et al. 1994; Dorschner et al. 1995). We set the grain size to have maximum absorption of the dust clump in the visible; ranging from 0.18 to 0.24 μm . The modeling details are available in Montargès et al. (2021). Unfortunately, the procedure did not converge towards simulations reproducing the images for

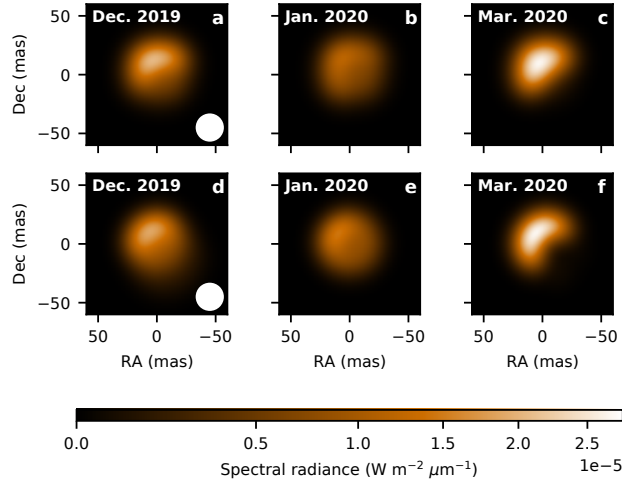


Fig. 3. Best matching models for the ZIMPOL images in the Cnt_H α filter (644.9 nm). The upper images correspond to the cool spot PHOENIX model, the lower images to the dusty clump RADMC3D simulations.

Table 1. Result of the match between the synthetic cool patch PHOENIX models and the ZIMPOL observations

Parameter	December 2019	January 2020	March 2020
x_p (mas)	-7.1	-2.4	-28.4
y_p (mas)	-14.2	-2.4	-35.6
r_p (mas)	23.7	19.0	45.0
T_{hot} (K)	3,700	3,700	3,700
T_{cool} (K)	3,400	3,400	3,200
$\log \mathcal{L}$	-8.8×10^6	-5.5×10^7	-4.0×10^7

January and March 2020. Instead, we tuned the parameters manually to obtain best guesses. The results are summarized in Table 2, and the images are shown in Fig. 3.

5 Discussion

Both the cool photospheric patch model and the dusty clump simulations are able to reproduce the morphology of the ZIMPOL images. However, the SED of both type of models fail to properly reproduce the near infrared AAVSO measurements (Fig. 4). The cool patch models reproduce better these measurements. However, it should be noted that while the parameter space exploration is complete for the cool photospheric patch models, it is not the case for the dusty clump simulations. Indeed, we did not consider other grain size distributions, nor did we explore alternative dust compositions, since we were mostly interested in reproducing the visible obscuration. Therefore, we considered both type of models being equally able to match the observations, since with more time and more computation resources, we could have likely found a more favorable dust model.

Comparison with other observations of this event obtained with various techniques are performed in Mon-

Table 2. Result of the match between the RADMC3D clump simulations and the ZIMPOL observations

Parameter	December 2019	January 2020	March 2020
x_c (au)	-1.9	-0.8	-1.9
y_c (au)	-3.0	-0.6	-1.8
z_c (au)	12.5	20.0	20.0
r_c^{in} (au)	6.5	5.0	4.5
ρ_0^{in} (g cm^{-3})	3.2×10^{-19}	4.0×10^{-19}	2.0×10^{-18}

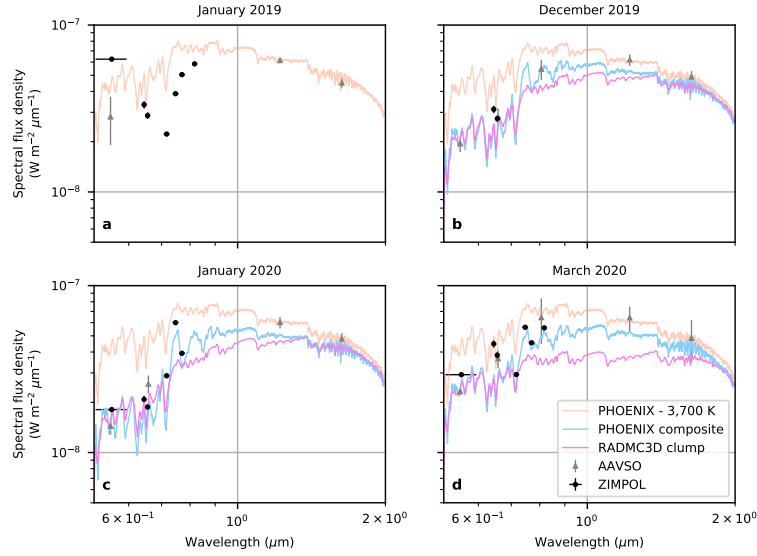


Fig. 4. Observed photometry and modeled SEDs for Betelgeuse before (a), and during the ‘Great Dimming’ (b, c, and d). The black dots correspond to the ZIMPOL photometry, the gray triangles to the AAVSO measurements. The orange curve represents the SED of a PHOENIX $15 M_{\odot}$ RSG with $T_{\text{eff}} = 3700$ K. The blue curve corresponds to the best matching PHOENIX cool patch model, and the purple curve to the best dusty clump RADMC3D simulation.

targès et al. (2021).

6 Conclusion

We presented observations of Betelgeuse obtained before and during its ‘Great Dimming’ in 2019–2020. The VLTI/GRAVITY interferometric observations and VLT/SPHERE-IRDIS sparse aperture masking measurements showed that the angular diameter of the star did not change. The VLT/SPHERE-ZIMPOL spatially resolved imaging of the photosphere revealed that the Southern hemisphere of the star was obscured.

Using PHOENIX model atmospheres to build a composite synthetic image of the stellar surface, we tested the hypothesis of a cool photospheric patch as the cause of the Dimming. We also build a dusty clump simulation using the radiative transfer code RADMC3D. Both scenarios are able to reproduce the morphology and the photometry of the event. In agreement with observations by other teams, with other techniques, and to fit the ‘Great Dimming’ within the general pulsation pattern of Betelgeuse, we conclude that both events happened consecutively. A cool patch formed on the photosphere perhaps consistently with the primary light curve period and the periodic outflow velocity, that caused dust to form from plasma ejected months before in the line of sight. This caused an unusual light minimum for the red supergiant.

This ‘Great Dimming’ calls for a more frequent monitoring of the photosphere and close circumstellar environment of nearby RSGs that can be spatially resolved.

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‡ Available at <http://www.astropy.org/>

§ Available at <http://pythonhosted.org/uncertainties/>