The Origin of Outflows in Evolved Stars
Proceedings IAU Symposium No. 366, 2022
L. Decin, A. Zijlstra & C. Gielen, eds
doi:10.1017/S1743921322001065

The inner dust shell of Betelgeuse seen with polarimetry

Xavier Haubois

European Organisation for Astronomical Research in the Southern Hemisphere, Casilla 19001, Santiago 19, Chile
email: xhaubois@eso.org

Abstract. The origin of red supergiant mass loss still remains to be understood. Characterizing the formation zone and the dust distribution within a few stellar radii above the surface is key to understanding the mass loss phenomenon. With its angular diameter of about 42 mas in the optical, Betelgeuse makes an ideal target to resolve the inner structures that represent potential signatures of dust formation. Past polarimetric observations reveal a dust environment in the first stellar radii. Depending on their characteristics and composition, dust grains could interact with the stellar radiation, trigger mass loss by momentum transfer from photons to dust to gas. Using spatially-resolved polarimetric observations of Betelgeuse, we detect a quasi-symmetric inner dust shell centered at ∼0.5 stellar radii above the photosphere and attempt at constraining its dust population.

---

1. Introduction

The recent findings on the 2019-2020 Betelgeuse dimming highlighted further the importance of understanding dust formation to account for photometric variability that is observed in evolved stars (e.g., Dupree et al. 2020; Montargès et al. 2021). High angular-resolution polarimetric observations in these objects enable us to detect and characterize their dusty environments. In the case of stars belonging to the Asymptotic Giant Branch (AGBs), the combination of interferometry with polarimetry allows us to estimate the angular extent and flux ratio of dust environments with respect to the central photosphere (Ireland et al. 2005; Norris et al. 2012). Under assumptions of Mie scattering, dust grain sizes can be estimated. This technique was used for Betelgeuse where a polarizing structure was interpreted as a thin dust shell located only 0.5 stellar radius above the photosphere. With grain sizes of about 300 nm, the dust composition was found to be compatible with $MgSiO_3$ (enstatite) and Mg_2SiO_4 (forsterite) (Haubois et al. 2019). As these datasets didn't allow for reliable interferometric imaging, simple geometries made of spherical thin shells were assumed. However, depending on the scenario, mass loss mechanisms can leave characteristic signatures in the morphology of the dust environments. We here present preliminary results of an imaging campaign of Betelgeuse with the VLT/SPHERE instrument (Beuzit et al. 2019).

2. Observations with SPHERE

Observations in January 2019 were taken in 10 filters but we discarded the broad V-band filter as it showed evidence for instrumental polarization crosstalk. We present typical set of Stokes parameters and linear polarized intensity images in Fig. 1. The linear polarized intensity ($PI = \sqrt{Q^2 + U^2}$) and angle of linear polarization ($AoLP =$

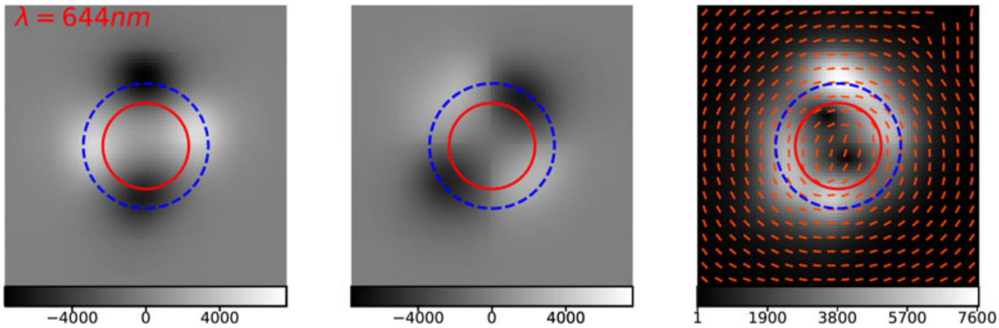

Figure 1. Stokes Q (left), U (middle) and polarized intensity (right) at 644nm. Solid red and dashed blue circles represent the photospheric radius (22 mas) and the position of the inner dust shell previously found in Haubois et al. (2019) (32 mas), respectively. On the polarized intensity map, angles of polarization are marked as orange segments. Units are W.m^{-2}.sr^{-1}.

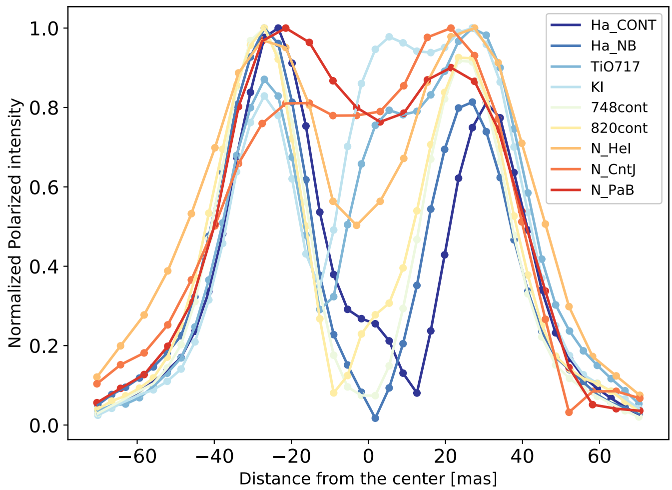

Figure 2. Normalized vertical cut of Polarized Intensities in each filter.

$\frac{1}{2}\arctan\left(\frac{U}{Q}\right)$) are consistent with a quasi-azimuthal polarizing structure centered around 30 mas of distance (see vertical cuts as a function of the filters in Fig. 2). The variation of mean polarized intensity along a ring of 30-mas radius is about 50%.

As a first modelling step, such ring-like structures can be reproduced with spherical dust shells. In order to fit the images, their external radius should be of about 9.5 AU (about 2 stellar radii). The spectral variation of the polarized intensity varies depending on the azimuthal sector but can be relatively well approximated using a silicate composition for the dust shell (Fig. 3). More details of the modeling will be presented in a forthcoming publication. The nature of the dark central features seen on the right part of Fig. 1 is ambiguous. In principle, they could be the results of a lesser scattering efficiency, e.g. zones of multi-scattering , under-densities, or effects of the radiation field illuminating this inner dust shell, like large surface convective cells. It is then useful to make use of complementary techniques such as spectro-polarimetry where brillance maps can be reconstructed from linear polarization spectral profiles (López Ariste et al. 2018). Comparison of the two datasets are on-going.

Finally, the temporal variation of polarized intensities can give us precious hints on the origin and mechanisms affecting the inner dust shell of Betelgeuse. Fig. 4 shows three epochs in two filters. Over a few years, we can see that the external radius doesn't change

https://doi.org/10.1017/S1743921322001065 Published online by Cambridge University Press

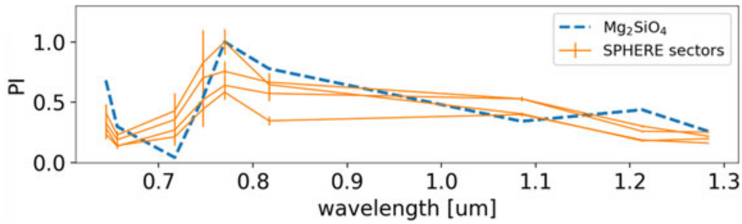

Figure 3. Spectral variation of the normalized polarized intensities for 4 azimuthal sectors (sectors are defined by large departure to the average value). A dust shell model made of enstatite dust grains is represented in dashed line.

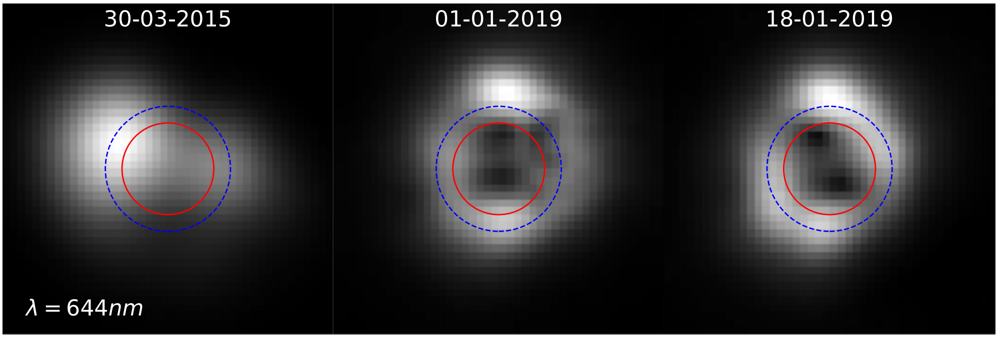

Figure 4. Evolution of Betelgeuse polarized intensities at 644 nm. The meaning of circles is the same as in Fig. 1.

dramatically but that the morphology does with a timescale that is probably beyond 1–2 months. This is consistent with Safonov et al. (2020) who shows a particularly well time-sampled variation of images obtained with speckle polarimetry during Betelgeuse's dimming. It is not surprising that so close to the photosphere, timescales are similar to those of surface convection in red supergiants. However, the way a convective surface would shape the inner dust shell remains to be established.

3. Conclusion

High angular-resolution polarimetry reveals that the inner dust shell of Betelgeuse is encircled in the first 2 stellar radii and its morphology and density distribution vary with a timescale of about 1–2 months. A characterization of the dust population can be attempted using radiative transfer methods. To connect this dusty structure to other mass loss components, it appears critical to perform a polarimetric monitoring at a sufficient cadence and combine it with other techniques such as spectro-polarimetry.

References

Beuzit, J. L., Vigan, A., Mouillet, D., et al.,2019,*A&A*, 631, A155
Dupree, A. K., Strassmeier, K. G., Matthews, L. D., et al. 2020, *ApJ*, 899, 68
Haubois, X., Norris, B., Tuthill, P. G., et al. 2019, *A&A*, 628, A101
Ireland, M. J., Tuthill, P. G., Davis, J., et al. 2005, *MNRAS*, 361, 337
Kervella, P., Perrin, G., Chiavassa, A., et al. 2011, *A&A*, 531, A117
López Ariste, A., Mathias, P., Tessore, B., et al. 2018,*A&A*, 620, A199
Montargès, M., Cannon, E., Lagadec, E., et al. 2021, *Nature*, 594, 365
Norris, B. R. M., Tuthill, P. G., Ireland, M. J., et al. 2012, *Nature*, 484, 220
Safonov, B., Dodin, A., Burlak, M., et al., 2020, arXiv e-prints, arXiv:2005.05215

https://doi.org/10.1017/S1743921322001065 Published online by Cambridge University Press