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A. Siebert, K. Baillié, M. Béthermin, F. Cantalloube, E. Josselin, N. Lagarde, J. Malzac, J. Richard, L. Selliez, O. Venot (eds)

THE ORIGIN OF MASS LOSS IN RED SUPERGIANTS

Q. Pilate[1], A. López Ariste[1], P. Mathias[2] and A. Lavail[1]

Abstract.

Red supergiants (RSGs) are able to enrich the interstellar medium with heavy elements through stellar winds. However, the mechanisms that trigger those winds are not yet known. In 2020, the RSG Betelgeuse underwent a historical dimming that was associated with a strong mass-loss event, which offered a unique opportunity to study mass-loss mechanisms. The study of the linear polarisation signal using the tomographic method allowed us to probe the dynamics of the different layers of Betelgeuse's photosphere several months before the dimming event. Usually, the amplitude of the linear polarisation signal increases monotonically with height. However, in March 2019, the linear polarisation signal of the different layers collapsed. We associate this phenomenon with an increase in opacity that enhanced the radiation pressure and counterbalanced gravity. Also, in early 2019, the sign of the bisectors of the intensity profiles reversed from a classical C-shape to a reverse C-shape, revealing the presence of low velocity gradients in the atmosphere. The low velocity gradients indicated by the bisectors, combined with the increase in opacity revealed by linear polarisation, suggest that Betelgeuse's mass-loss event was caused by the increase in radiation pressure that counterbalanced gravity, ultimately leading to the dimming event several months later.

Keywords: Red supergiants, Betelgeuse, Mass-loss, Spectropolarimetry

1 Introduction

Red supergiants (RSGs) are among the brightest objects in the universe. Their study is essential to understand how heavy chemical elements are formed and how they are able to enrich the interstellar medium through their winds. However, the mechanisms that trigger mass loss in RSGs are still under debate. One of the most famous RSGs is Betelgeuse. Its high luminosity and close distance to Earth make it an interesting target for ground-based observations. Aurière et al. (2016) measured a strong linear polarisation signal in the atomic lines of Betelgeuse. This signal was attributed to the depolarisation of the continuum by the atomic lines and to the presence of large convective cells. Later on, López Ariste et al. (2018) produced images of the photosphere of Betelgeuse, and by exploiting the line-forming regions, López Ariste et al. (2022) produced three-dimensional images of the photosphere. The authors identified plumes of plasma with constant velocity throughout the atmosphere, revealing a force able to counterbalance gravity at photospheric levels and likely to trigger stellar winds. Thus, the study of linear polarisation is a powerful tool for investigating the mechanisms that can trigger stellar winds.

At the end of 2019, Betelgeuse underwent a historical dimming event, known as the Great Dimming, which was associated with a mass-loss event that had occurred several months earlier (Montargès et al. 2021). Using the tomographic method, Kravchenko et al. (2021) identified the propagation of two shock waves, one in February 2018 and another one in January 2019; the later was amplified by the former, resulting in a strong outflow that cooled the outer layers of Betelgeuse, thereby increasing molecular opacity and leading to the dimming event. Hence, the Great Dimming event offers a unique context for studying mass-loss phenomena.

[1] IRAP, Université de Toulouse, CNRS, CNES, UPS. 14, Av E. Belin, 31400 Toulouse, France
[2] IRAP, Université de Toulouse, CNRS, CNES, UPS. 57, AV. d'Azereix, 65000 Tarbes, France

2 Linear polarisation in early 2019

The spectropolarimeter Narval, at Pic du Midi, France, has monitored Betelgeuse since 2013. It measures the polarisation over the visible spectrum up to 1050 nm and with a high spectral resolution (R=65 000). The study of linear polarisation in the individual lines is difficult since the amplitude of the signal is close to noise level. To increase the signal-to-noise ratio, we used the Least-Squares Deconvolution (LSD) method (Donati et al. 1997), which consists of summing spectral lines using a synthetic mask. We used a line mask from VALD (Ryabchikova et al. 2015), computed with the fundamental parameters of Betelgeuse and including lines with central depressions deeper than 40% of the continuum. Further details about the line mask are provided in Aurière et al. (2016).

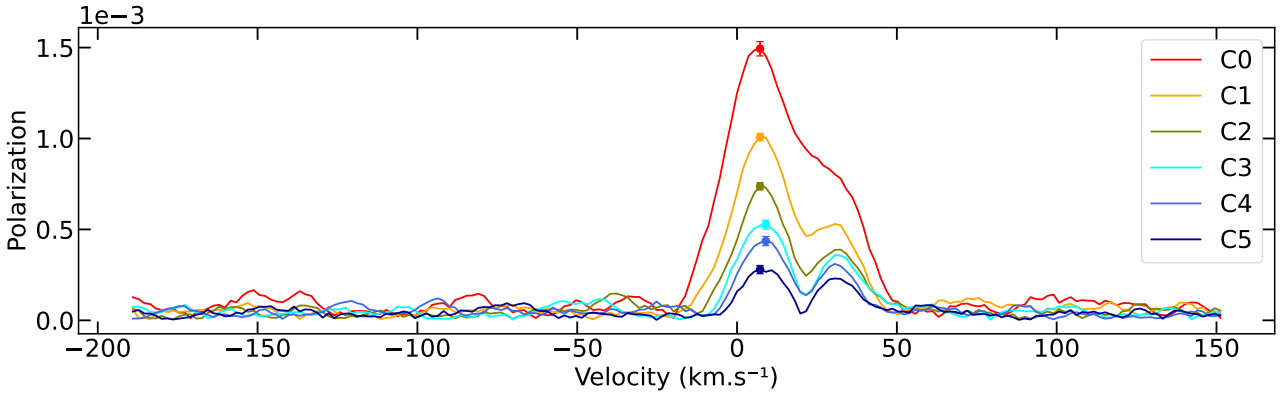

Fig. 1. LSD profiles of the total linear polarisation of Betelgeuse on 26 January 2019. The colour code corresponds to the different masks used to produce the profiles. Mask $C0$ includes only lines with central depths between 90% and 100%, mask $C1$ includes only lines with central depths between 80% and 90%, and so on.

Figure 1 shows the LSD profiles of the total linear polarisation $\sqrt{Q^2+U^2}$ of Betelgeuse on 26 January 2019. As in López Ariste et al. (2022), the different LSD profiles were produced by selecting lines with different central depths. The deepest lines are expected to probe the highest photospheric regions, while the weakest ones probe the innermost layers. In Figure 1, the LSD profiles obtained from lines forming in the outermost layers clearly exhibit a larger amplitude than those obtained from lines forming in the innermost layers. López Ariste et al. (2022) showed that the amplitude of the linear polarisation signal follows the law of a single scattering in a grey atmosphere. In other words, for most observations, the maximum amplitude of the linear polarisation signal is well ordered with height, except for some cases where two different layers exhibit the same linear polarisation amplitude. Those rare cases remain unexplained.

Figure 2 depicts the evolution of the amplitude of the linear polarisation signal in early 2019. The colour code is the same as in Figure 1. In March, the amplitude of the layer $C4$ collapses, and layers $C4$ and $C3$ reach the same amplitude. To explain how two different layers can exhibit the same amplitude, we follow the heuristic argument of López Ariste et al. (2012). If a gas cloud with opacity τ is illuminated by a light cone of intensity I_0, the fraction of photons that traverse the cloud is $I_0 e^{-\tau}$. Assuming isotropic scattering, the photons leaving the cloud in other directions are proportional to $(1-e^{-\tau})I_0 = pI_0$. The same argument applies to the amount of linear polarisation; thus, pQ_0 will leave the cloud in any other direction. After a single scattering, the amount of polarisation observed from Earth is Q_0/I_0, independent of p. After a second scattering, the amount of photons scattered is $(p+p^2)I_0$. For the amount of polarisation, after the first scattering, the distribution of the photons is isotropic, thus no additional linear polarisation is generated. Hence, after two scatterings, the amount of polarisation observed is

$$\frac{1}{1+p}\frac{Q_0}{I_0}. \tag{2.1}$$

After two scatterings, the amplitude of the linear polarisation signal can collapse as a result of an increase in opacity in a given layer. In the case of a single scattering, we have $p = 0$. Our objective is to identify the day when the amplitude of the linear polarisation signal is consistent with a single scattering event, and then

compute the variation in opacity for the other days. The collapse of the linear polarisation amplitude implies an increase in p and, consequently, in τ.

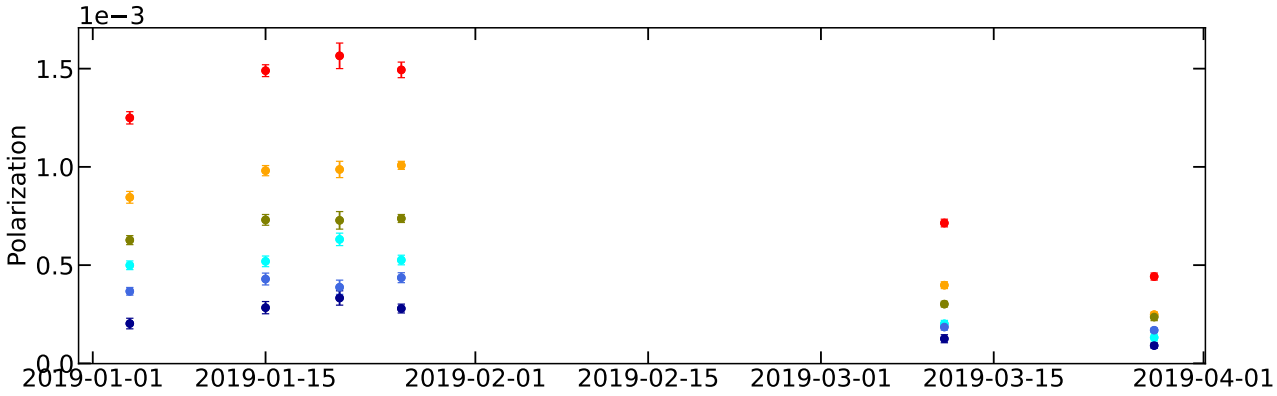

Fig. 2. Evolution of the amplitude of the total linear polarisation for the different layers. The colour code is the same as in Figure. 1.

Using this approach to understand the linear polarisation signal in Figure 2, it is clear that in January 2019, the amplitudes of the linear polarisation signals of the different layers were well separated. However, in March, the amplitudes of the different layers began to collapse, starting with the layers $C3$ and $C4$ exhibiting the same amplitude. Later, at the end of March, the layers $C1$ and $C2$ reached the same amplitude. We interpret this collapse of the linear polarisation signal as an increase in opacity in the different layers. The exact value of τ in Eq. 2.1 is difficult to estimate, but a rough approximation involving multiple scattering leads to $\tau \sim 0.5$.

This increase in opacity resulted in an increase of the radiative acceleration that counterbalanced gravity. A rough estimate of the radiative acceleration can be obtained by assuming the relevant physical quantities to be constant along the line-forming region, ignoring their obvious variation with height. Using a density $\rho = 10^{-9}$ kg.m^{-3}, $T = 3650$ K, $R = 1000$ $R_\odot$ and a line-forming region of 10 $R_\odot$ (Kravchenko et al. 2018), we find that the radiative acceleration is roughly equal to the gravitational acceleration. Using the same physical quantities, we also estimate the mass loss by Betelgeuse during the Great Dimming event, assuming that a convective cell with a radius of 30% of the stellar radius was ejected. This leads to $M_{loss} \sim 5.9 \times 10^{-7}$ $M_\odot$, in good agreement with the estimation of Montargès et al. (2021).

3 Intensity profile

Contrary to the linear polarisation profile, the behaviour of the intensity profile before the Great Dimming has been widely studied. Using the tomographic method, Kravchenko et al. (2021) identified line doubling in the innermost regions of Betelgeuse's photosphere at the beginning of January 2019, which the authors attributed to the propagation of a shock wave that led to the dimming several months later. Using the Ca II K-line, Dupree et al. (2022) found hints of outflowing plasma in the lower chromosphere in March 2019.

Recent work by López Ariste et al. (2025) showed that the intensity profile of Betelgeuse was the consequence of velocity gradients along the line-forming region. Our focus therefore shifted to the bisectors of the intensity profile, which are known to probe the photospheric velocity gradients. In a medium where the plasma follows a ballistic motion, the bisectors exhibit their typical C-shape, whereas when the plasma accelerates with height, the bisectors adopt a reverse C-shape. Figure 3 shows the line bisectors in January and March 2019. The colour code is the same as in Figure 1. On 4 January, the bisectors from the innermost layers display a typical C-shape, while those from the outermost layers exhibit a reverse C-shape. By 15 January, the innermost bisector changes sign, adopting a reverse C-shape, and a week later, the second innermost bisector also exhibits a reverse C-shape. The sign reversal of the bisectors continues until the end of January. This behaviour can be interpreted as the presence of low velocity gradients in a large convective cell. Those low gradients may come from radiation pressure counterbalancing gravity.

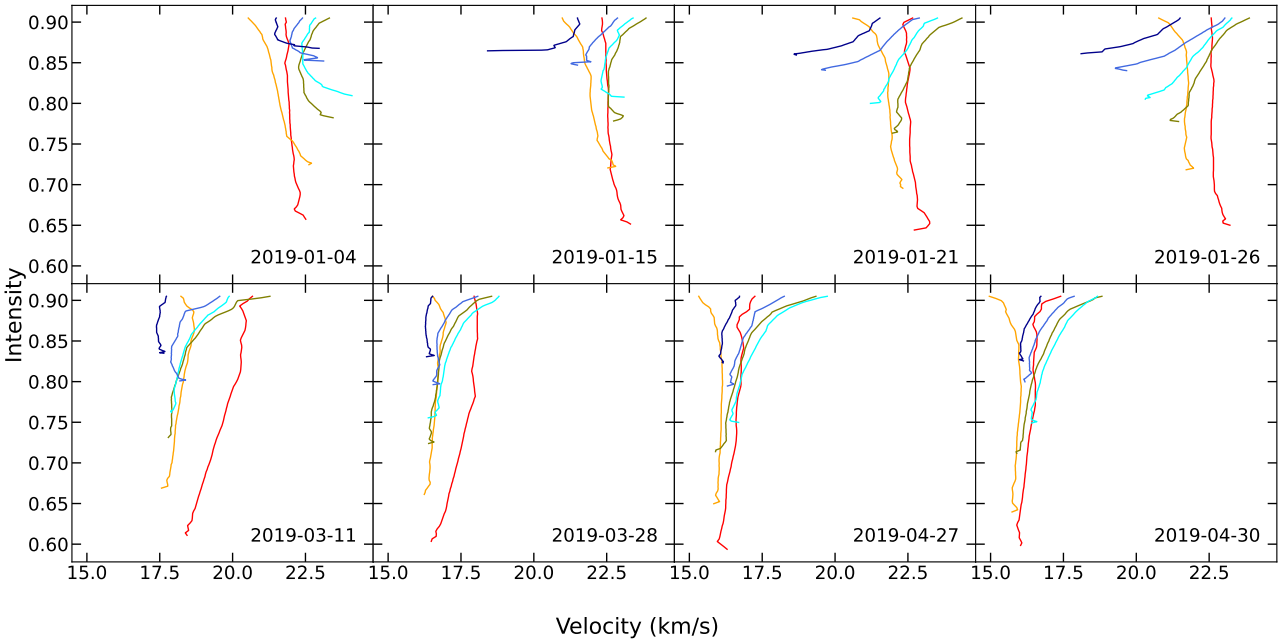

Fig. 3. Bisectors of Betelgeuse of the different layers. The colour code is the same as in Figure 1.

4 Conclusion

The RSG Betelgeuse underwent a historical dimming at the end of 2019 that was associated with a mass-loss event. The study of the linear polarisation signal with the tomographic method allowed us to probe different layers of the star's photosphere at the beginning of 2019, several months before the Great Dimming. We found that the linear polarisation signal of the different layers of Betelgeuse collapsed, and we linked this collapse to an increase in opacity at photospheric levels. We then associated the increase in opacity with an increase in radiation pressure, and we propose that this mechanism was able to counterbalance gravity and eject a large portion of plasma, which condensed several months later and caused the Great Dimming. Those results are consistent with the work of Kravchenko et al. (2021) and Dupree et al. (2022), who proposed that plasma was ejected by Betelgeuse in early 2019. In addition, by analysing the bisectors of the intensity profile, we found hints of low velocity gradients through their sign reversal. The Great Dimming offered an unprecedented opportunity to explore the mechanisms that can trigger mass-loss events. In this context, we propose that radiation pressure on atoms and molecules is able to trigger mass-loss episodes. Once the plasma is sufficiently far from the star, it can condense into dust, making radiation pressure even more efficient.

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