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The variability of Betelgeuse explained by surface convection

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ABSTRACT

Key words.

1. Introduction

Betelgeuse is a prototypical red supergiant (RSG) known to be a semi-regular variable. Several periods for this variability can be found in the literature, usually clustered around the so-called long secondary period (LSP) of 2000 days, plus shorter periods of 400 and 200 days (Kiss et al. 2006). The origin of the LSP remains poorly known: some have tried to find the explanation of the LSP in the lifetime of the large convective cells present at the surface of RSG (e.g Stothers (2010)) while others have invoked a the magnetic field (Wood et al. 2004). The shorter periods of 400 and 200 days seem to have a different origin than the LSP. By studying a large sample of RSG, Kiss et al. (2006) attributed the 400 days period to radial pulsation modes, while the 200 days period was attributed to the first overtone (Joyce et al. 2020), in agreement with the historical work of Stothers (1969).

Besides radial pulsation, surface activity leading to random brightness variation has also been mentioned to explain the variability of Betelgeuse. **Having been firstly theorised by Schwarzschild (1975) and Gray (2008) proposed that the 400 days period was a consequence of the convective activity**. Betelgeuse is known to present large convective cells with lifetimes in the order of one to two years (López Ariste et al. 2018) and measurable changes in the span of one week. Bright convection cells near disk center will increase the integrated brightness of the star when compared with other situations where such cells are found near the edges. So even without calling for the formation of dust or other changes in opacity, one may argue that the simple evolution of convective patterns of the star may create a variability. Such variability could be expected to be random, but will present quasi-periodicities related to the typical time scales of the convective patterns (Gray 2008).

At the end of 2019, Betelgeuse reached a historical minimum in its luminosity, called the Great Dimming (Guinan et al. 2020). From interferometric and spectroscopic data, it has been determined that this event was caused by a cloud of dust formed close to the line of sight (Montargès et al. 2021). Interferometric images show a drop in luminosity in the southern hemisphere of Betelgeuse, that might be caused by a mass loss event and leading to this dimming (Dupree et al. 2022). Other hypothesis have also been explored , such as a drop in temperature (Harper et al. 2020), or an increase in the molecular opacity (Kravchenko et al. 2021). This event is an extreme illustration of changes in brightness that were not due to any kind of pulsation but to a change on the brightness distribution over the stellar disk. Since the end of the Great Dimming event, Betelgeuse has continued its random variation of brightness. But quite interestingly, it has been shown by Jadlovský et al. (2023) and Dupree et al. (2022) that the periodicity of Betelgeuse has changed since the dimming. Using the light curves from AAVSO, the cited authors showed that before the dimming, the dominant period of Betelgeuse was the 400 days period, while after the great dimming the main periods of Betelgeuse have shortened, oscillating between 97 days and 230 days (Dupree et al. 2022), revealing a change in the behaviour of the atmosphere of Betelgeuse. While the great dimming may be seen as a singular event, such modifications of the variability periods bring up the question whether all changes in brightness cannot be due to similar changes in the brightness distribution over the disk, and unrelated to any pulsation phenomenon. In order to address this question we seek for the typical periods of 400 and 200 days in observational proxies which are related to the convective activity but not to any pulsation, such as the linear polarization spectra.

Linear polarization in the atomic lines of the spectrum of Betelgeuse, discovered by Aurière et al. (2016), has been interpreted as the joint action of two mechanisms. First the depolarization of the continuum by atoms which absorb linearly polarized light from the continuum and re-emit unpolarized light, the continuum photons being polarized by Rayleigh scattering. This depolarization produces signals with an azimuth symmetry over the disk that would cancel out the net linear polarization on a homogeneous disk. Thus, such mechanism of production of polarization must be combined with an inhomogenous disk to produce the net linear polarization signal observed. This interpretation suggested the possibility of mapping those brightness inhomogeneities. This has been done by López Ariste et al. (2018) even producing 3-dimensional images of the atmosphere of Betelgeuse (López Ariste et al. 2022) when taking advantage of the different heights of formation of different lines in the spectrum of Betelgeuse. The images produced compare very well with contemporaneous images made with interferometric techniques (Montargès et al. 2016) and show clear convective patterns, akin to solar granulation.

Linear polarization observed in the atomic lines is therefore a proxy of convection, unrelated to radial pulsations but linked to the brightness inhomogeneities due to the convective patterns in Betelgeuse. If one can find the aforementioned variability periods in linear polarization, we must conclude that these periods are related to the convective activity which originates the linear polarization signals. This is the purpose of the present work.

2. Searching for periodicities in the polarization spectra of Betelgeuse

Betelgeuse has been observed for the last 10 years with Narval and Neo-Narval at the Telescope Bernard Lyot. These two instruments measure the polarization over the visible spectra of Betelgeuese (390-1000 nm) with high spectral resolution (R=65000) and high polarimetric sensitivity. Despite this high sensitivity, the signal-to-noise ratios per spectral bin are not sufficient to measure the weak polarization signals in individual atomic lines. These amplitudes are today known to be of the order of 10^{-4} times the continuum intensity, and only exceptionally do they reach amplitudes of 10^{-3} the continuum. In these exceptional observations, enough photons can be accumulated per spectral bin to see the linear polarization signal above noise (Aurière et al. 2016). But most commonly, the amplitudes of linear polarization are below noise levels and measuring them requires the addition of the signals of thousands of lines to reduce noise and increase the signal-to-noise ratios. This line addition is done through a technique called Least-Squares Deconvolution (LSD) (Donati et al. 1997) and assumes that the linear polarization signal is similar in all spectral lines up to scale factors in the sampling and amplitude. This technique has been successfully used in the past to measure magnetic field distributions over stellar surfaces and it is now used to produce images of the brightness distributions in the photosphere of Betelgeuse and other red supergiants as cited in the Introduction.

In this work we shall look into the signals produced through these line-addition techniques, and which produce a pseudo-line in intensity and linear polarization which does not belong to any atomic species in particular but to an average of all of them present and emitting in the photosphere of Betelgeuse. After such procedures of line addition, these signals carry the coherent signals present in the photospheric lines, but the particularities of this or that spectral line are erased. All these data has been presented before by Aurière et al. (2016), Mathias et al. (2018) and López Ariste et al. (2022), which also give details on observing times and conditions as well as more detailed description on the data reduction[1].

2.1. The variability in the Stokes profiles

Trying to find periods in an astrophysical context carries the hurdle of unevenly spaced observed data. To overcome this issue, we used Lomb-Scargle periodograms (Lomb 1976; Scargle 1982). For a given set of data, one fits sinusoids to the data using least-squares, with frequencies sampled between the first and the last observation. The better the fit, the higher the power attributed to a frequency. We applied this technique to the LSD profiles of Stokes I, U, Q and to the total linear polarization of Betelgeuse observed by the TBL during that span of 10 years.

[1] Beyond a 2-year proprietary embargo, and up to technical issues, all these data is available through PolarBase (http://polarbase.irap.omp.eu/).

We first computed the Lomb-Scargle periodogram at each wavelength of the LSD profile, between -25 km/s and +60 km/s to span the entire signal present in the LSD profile. López Ariste et al. (2018) found the most blueshifted signal in linear polarization towards -20 km/s, and interpreted it as the maximum velocity of the rising plasma, seen from Earth. The most redshifted signal was often found at +40 km/s. This velocity is interpreted as the rest velocity of the star in our reference frame. Seldom, signals at velocities larger than +40 km/s can be found and are interpreted as either dark and cold plasma falling back to Betelgeuse, or to rising plumes of plasma located in the hidden face of Betelgeuse, and rising so high that they appear above the limb.

Figures 1,2,3 and 4 show the Lomb-Scargle periodogram of the LSD profiles of respectively the intensity, Stokes Q, Stokes U and the total linear polarization. For each figure, the uper panel is the Lomb-Scargle periodogram of each velocity bin (black line) and the total average (red line). The green line corresponds to the window function. The lower panel is the Lomb-Scargle periodogram represented for each velocity bin, while the white dotted lines mark the 400 and 200 days periods for reference. The right panel shows the mean profile of each Stokes parameter at each velocity bin.

Intensity.pdf

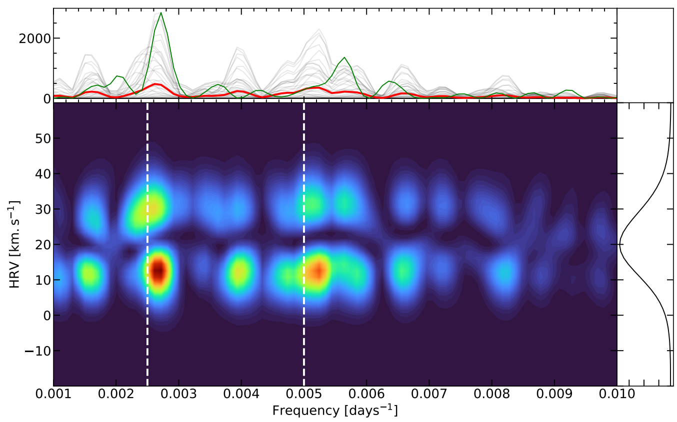

Fig. 1. Lomb-Scargle periodogram of the LSD profile of intensity. The upper panel is the Lomb-Scargle periodogram for each velocity bin (black line) and the average (red line). The green line is the window function. In the lower pannel, the two white dashed lines mark respectively the 400 days and the 200 days periods. The right panel is the average intensity profile for each velocity bin.

Looking into Fig. 1, which shows the Lomb-Scargle periodogram of the LSD of the intensity profile, we notice that the 400 and 200 days periods seem to be recovered by the periodogram. However, the 400 days period is uncomfortably close to the peak of the window function. We also notice that the two periods are present at the same HRV. Interestingly, Mathias et al. (2018) already found this 200 days periodicity in spectroscopic observations, in spite of a shorter observation period.

Figures 2 and 3 show the Lomb-Scargle periodograms of Stokes Q and U. These periodograms are completely different from the intensity one. A strong signal is present in fig. 2 around 200 days. Concerning Stokes U, Fig. 3, it appears on the other hand that the main period is around 0.003 days^{-1} (330 days). Other periods such as those at 200 days or 250 days (0.004 days^{-1}) are present but difficult to trust. From both Stokes Q and U, we recover the 200 days period, and also a 330 days period which is more or less close to the 400 days period found in the literature. Figure 4 shows the Lomb-Scargle periodogram

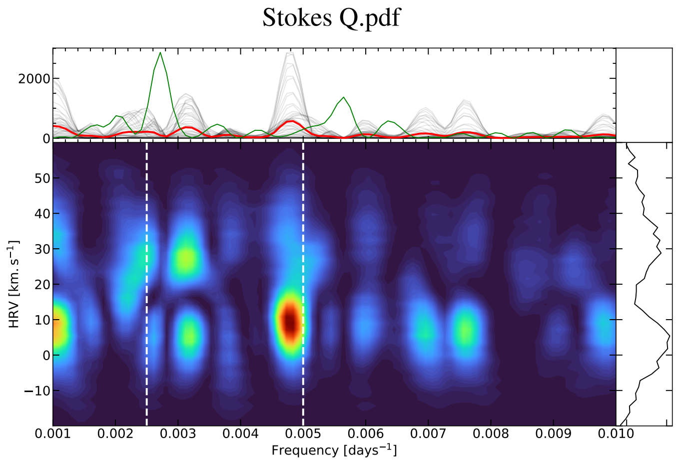

Fig. 2. Same as figure 1 for Stokes Q.

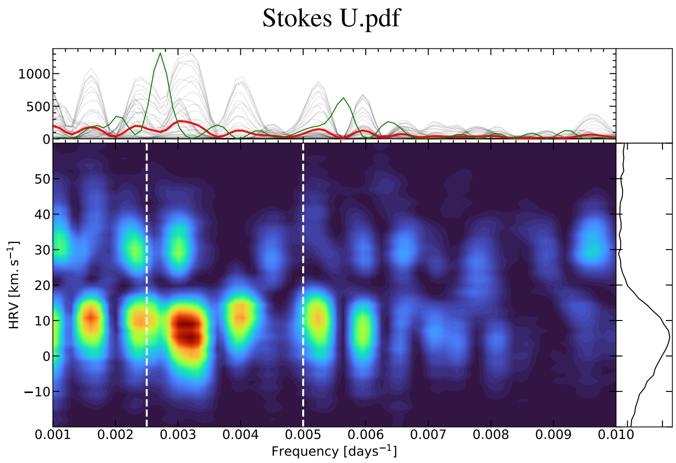

Fig. 3. Same as figure 1 for Stokes U.

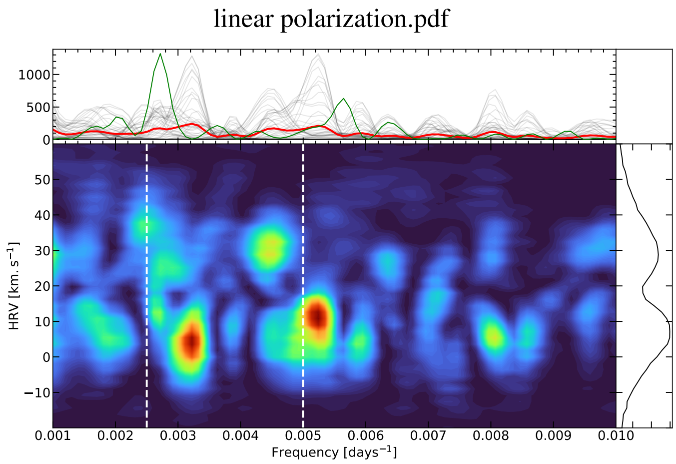

Fig. 4. Same as figure 1 for total linear polarization: $\sqrt{Q^2 + U^2}$.

of $\sqrt{Q^2 + U^2}$, the total linear polarization of Betelgeuse. The periodogram recovers the strong powers at both 330 days and 200 days, already found in either Stokes Q and U.

2.2. The variability in polarimetric imaging

Using linear polarization, López Ariste et al. (2018) were able to reconstruct images of Betelgeuse that have been successfully compared to inteferometric images of Montargès et al. (2016). The images are produced by finding the brightness distribution that better fits the observed linear polarization LSD profiles, using a Marquardt-Levenberg minimisation.

Betelgeuse is observed in average every month by the TBL, and hence we are able to follow its surface activity through this technique of polarimetric imaging. This has allowed in the past the estimation of the size and the lifetime of the convective cells at the surface (López Ariste et al. 2018). From these images, we can also compute a photo-center, which is sensitive to the size and the number of convective cells. An homogeneous star will have a photo-center displacement coinciding with the barycenter of the star, whereas a star with one or two large convective cells will have a photo-center displacement more important, up to a few percent of the stellar radius in the case of **red giants?** (Chiavassa et al. 2022).

Since the photo-center is linked to surface convection, it is worth checking for periods in its dynamics over the 10 years of observations of Betelgeuse at the TBL. Such periods will not be completely unrelated to the ones presented in the previous section, but will capture other aspects of the phenomena at work.

But, before proceeding to search for periods in the movements of the photo-center, we have to warn about the interpretation of such images. Linear polarization suffers from a 180° degree ambiguity already mentioned in Aurière et al. (2016). For that reason, our images can be rotated by 180° degrees, and the brightness distribution will still fit the observed LSD polarization profiles. If a particular observation were to be treated independently of previous observations, the solution found by the algorithm could be any of the ambiguous solutions possible. To obtain a continuity between the time series of images, for a given day we use the brightness distribution of the previous day as initial point of the fitting iteration. The first image of the series starts its minimization iteration with random brightness distribution. Even though we are able to produce a series of images consistent with each other, it is important to keep in mind that the photo-center displacement computed from the series will be affected by that first image of the series. To overcome this issue, we decided to compute the photo-center displacement from 100 different time serieas, each one starting from a different initial image, in an effort to recover from such ensemble properties that are independent of the choice of the first image.

Figure 5 shows the Lomb-Scargle periodogram of the photo-center displacement of each one of those 100 series (blue lines) and the average Lomb-Scargle periodogram (black line), while the red dashed lines mark the 400 and 200 days periods respectively. As before, the window function is represented by the green line. We find two bumps around the 400 days period, which are not sufficiently significant to confirm the presence of such period on their own. However, they concur with the results of the previous section, and since polarimetry imaging involves only surface convection, this is a further argument towards a variability explained by surface convection alone.

3. Explanations for the variability of the light curve of Betelgeuse

The presence of the same periods and, after taking into consideration the time span and sparsity of the TBL data series, the larger amplitude of the peaks found in polarization data com-

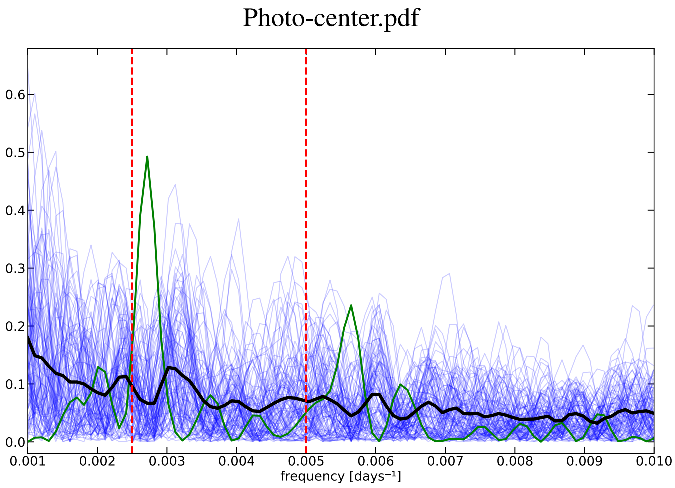

Fig. 5. Lomb-Scargle periodogram of the 100 series of photo-center displacements of Betelgeuse. Each blue line correspond to a Lomb-Scargle periodogram of one series of photo-center displacement. The black line is the average of the 100 periodograms. The red dashed lines mark the 400 and 200 days periods respectively (from left to right). As before, the green line is the window function.

pared to those in the light curve point to a common origin, one that is rather based upon convective dynamics.

The 200-days period appears prominently in the Stokes Q and U profiles. We can associate the 200-days period to the typical timescales on which the Stokes parameters evolve. The LSD profiles of Stokes Q or U will slightly change when we observe Betelgeuse every month, but are completely overhauled on time scales of several months. The Lomb-Scargle periodograms appear to capture these dynamics at periods of about 200 days. Such changes in the profiles are directly linked to the dynamics of the surface, to the evolution and movements of convective cells over the visible hemisphere. So the 200-day period appears to be related to the evolution of the convective patterns on the surface of Betelgeuse. The fact that this peak is strongly present in Stokes Q but less in U can be interpreted as a temporal situation of how the convective patterns have been distributed in the last 10 years.

The other period found in the total linear polarization and Stokes U, the 330-days period, is more or less close to the 400 days period often present in the literature (e.g Kiss et al. (2006) found a period 388 ± 30 days). It has been found by López Ariste et al. (2018) that large convective cells can live one to two years, and this period could be associated to the timescales on which the largest granules evolve. This typical timescale has also been observed in the numerical simulations and might play an important role in the determination of stellar distances through the displacement of the photo-center (Chiavassa et al. 2022). Once again we observe this 330-days periodicity to be more present in Stokes U than in Q, what may unravel a random situation due to convective motions in the last 10 years. This interpretation appears to be consistent with the work of Gray (2008), who attributed the 400 days period to the large convective cells.

Finally, the intensity profiles do seem to vary in 400 days periods, but the measured peak is uncomfortably close to a peak of the window function of the time series observed with the TBL. This 400-days period, it could be a mix of the typical convective timescales of large granules associated with stochastic pulsations exited by convective cavities. Up to this point, the model developed to interpret linear polarization does not involve pulsations, that is why we interpret the 200 days period as the convective turnover timescale. The 400 days period involve the intensity profile, thus the 400 days period is probably caused by both convective timescales and stochastic pulsations.

3.1. The light curve of Betelgeuse from the point of view of convection

We have recovered the light curve of Betelgeuse in the visible from the AAVSO database for the last 10 years (Figure 6). Before the great dimming, the magnitude of Betelgeuse evolves on a timescale of a year, whereas after the dimming, the variability of Betelgeuse has shortened. It is clear from fig. 6 that the variability of Betelgeuse is evolving on a timescale shorter than one year. This qualitative change has been pointed out before, before the great dimming the main period of Betelgeuse was of 400 days (Kiss et al. 2006). This period is often associated to the fundamental pressure mode. After the dimming however, this period appears to have disappeared and only timescales shorter than 230 days are visible since (Dupree et al. 2022). No explanations have been offered concerning this change of variability after or perhaps because of the dimming, thus we can afford proposing alternative scenarios for the observed periodicities in the light curve.

RSGs encounter mass loss event, where due to stellar winds, plasma is ejected in the interstellar medium. Those events have already been inferred in RSG like μCep, where López Ariste et al. (2023) found an excess of linear polarization beyond the limb of the star and associated it to rising plumes of plasma in the back hemisphere of the star. In the case of Betelgeuse, this kind of event happened only once or twice during the last 10 years, with no change in the variability of the star. However, since the great dimming, the variability of Betelgeuse has changed, meaning that this event was such different from the usual mass loss event, that it hustled the dynamics of the photosphere.

Considering a scenario where the variability of Betelgeuse is mostly governed by convection, before the great dimming, the variability of the star was linked to the typical timescale on which convection occurs, that is 200 days for the small structures and roughly 350 days for the large structures. The great dimming impacted the behaviour of the photosphere, such that the largest structures do not evolve on timescale of the order of 350 days but rather 200 days, that is the smallest convective structures. We hypothesise that since the dimming, the photosphere is not in equilibrium and the largest convective structures are destroyed by the turbulent motion of the photosphere. Therefore, it is hard to identify periods after the great dimming, which Dupree et al. (2022) noticed. We expect to recover the 400 days variability within the next years, which corresponds to the time for the photosphere to go back to equilibrium.

4. Conclusion

The main result presented in this work is that the same periods identified in the light curve of Betelgeuse are also seen in the intensity and polarization spectra, as measured with the TBL. Periods in the light curve have often been traditionally associated to pulsation due to pressure modes. But the interpretation of the linear polarization profiles is made in terms of convective structures in the atmosphere of Betelgeuse. We suggest that it is in these convective structures and their temporal evolution that we will find the true reason for the observed periodicities both in the light curve and in the spectropolarimetric observations. This

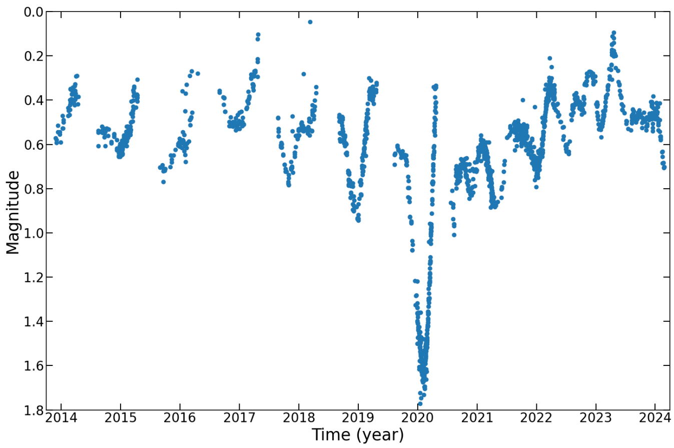

Fig. 6. Light curve of Betelgeuse from AAVSO in the V-band.

is the main conclusion of this work: since we are able to recover the different periods in the linear polarization profiles, we associate the 200-days periodicity to convective dynamics while the 400-days periodicity may be related **to both stochastic pulsations and convective timescales of the largest granules.** This conclusion concurs with the scenario proposed by Gray (2008), who attributed the variability of Betelgeuse to surface convection.

Although of secondary importance, we may suggest with more or less ease what phenomena are at the origin of the change of variability before and after the great dimming. We speculate that the great dimming event hustled the dynamics of the photosphere, and the largest granules were destroyed by the turbulent motions caused by the non equilibrium of the photosphere. Since this event, the variability of Betelgeuse has quickened in adequacy with the timescales of smaller convective cells, about 200-days. Were this be true, we shall expect in the coming future to see the 400-days variability re-appear as the dominant period, whenever the photosphere returns to some equilibrium. Longer time series of spectropolarimetric observations of Betelgeuse will be required to shed light on this.

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