Astronomy & Astrophysics manuscript no. main
May 15, 2024 ©ESO 2024

The variability of Betelgeuse explained by surface convection

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Received ...; accepted ...

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 (**?**). 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 **?**) while others have invoked a the magnetic field (**?**). The shorter periods of 400 and 200 days seem to have a different origin than the LSP. By studying a large sample of RSG, **?** attributed the 400 days period to radial pulsation modes, while the 200 days period was attributed to the first overtone (**?**), in agreement with the historical work of **?**.

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 ? and ? 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 (**?**) 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 (**?**).

At the end of 2019, Betelgeuse reached a historical minimum in its luminosity, called the Great Dimming (**?**). From interferometric and spectroscopic data, it has been proposed that this event was caused by the formation of a cloud of dust close to the line of sight (**?**). Interferometric images show a drop in luminosity in the southern hemisphere of Betelgeuse, which could be caused by a mass loss event and leading to this dimming (**?**). Other hypotheses have also been explored, such as a drop in temperature (**?**), or an increase in the molecular opacity (**?**). In this event, it turns out that a change in brightness may not be due to pulsation but to a change in the brightness distribution over the stellar disk. Since the end of the Great Dimming event, Betelgeuse has continue its random variation of brightness. But quite interestingly, it has been shown by **?** and **?** 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 d period, while after the great dimming, the main periods of Betelgeuse have shortened, oscillating between 97 d and 230 d (**?**), 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 of whether all changes in brightness can be due to similar changes in the brightness distribution over the disk and unrelated to any pulsation phenomenon. Our interest in an alternative explanation of the variability in terms of convective patterns arose. In order to address this question, we seek such typical periods of 400 and 200 d in observational proxies 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 **?**, 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 circular symmetry over the visible disk, which would cancel out the net linear polarization on a homogeneous disk. Thus, such mechanism of polarization must be combined with an inhomogeneous disk to produce the net linear polarization signal observed. This interpretation suggested the possibility of mapping those brightness inhomogeneities. This has been achieved by **?**, who produced even 3-dimensional images of the atmosphere of Betelgeuse (**?**) by taking advantage of the different heights of formation of different lines in the spectrum of Betelgeuse. The produced images compare very well with contemporaneous images made with interferometric techniques (**?**) and show clear convective patterns, akin to solar granulation.

Linear polarization observed in the atomic lines is therefore a proxy of convection, a priori 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.

«««< HEAD ======= In section **??**, we describe the dataset of linear polarization obtained with Narval and Neo-Narval at TBL, as well as the Lomb-Scargle periodograms used to derive periods. In section **??**, we seek periods in the LSD profiles of Betelgeuse using the Lomb-Scarlge periodogram. In section **??**, we associate the 200 d period with the convective timescale of the smallest granules and the 330 d periodicity with the largest granules. We speculate on an explanation in the change of variability of Betelgeuse before and after the great dimming. »»»> 234ba9bf04bfa56ec2de436422869ac280239091

2. The polarimetric data

«««< HEAD 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 (**?**). 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) (**?**) 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 **?**, **?** and **?**, which also give details on observing times and conditions as well as more detailed description on the data reduction[1]. ======= Betelgeuse has been observed for the last 10 years with Narval and Neo-Narval at the Telescope Bernard Lyot[1]. These two instruments measure the polarization over the visible and near infrared spectra of Betelgeuese (390-1000 nm) with high spectral resolution (R=65000) and high polarimetric sensitivity. The signal-to-noise ratios are not sufficient to measure the weak polarization signals in individual atomic lines of the spectrum. These amplitudes are known to be of the order of 10^{-4} times the continuum intensity, and they only exceptionally reach amplitudes of 10^{-3}. In those observations, enough photons can be accumulated per spectral bin to detect the linear polarization signal above noise in lines (**?**). Most commonly, the amplitudes of linear polarization are below noise levels. On those occasions, we have to add up the signals of thousands of lines to increase the signal-to-noise ratios. This addition is performed through a technique called Least-Squares Deconvolution (LSD) (**?**).This technique has been successfully used in the past to measure magnetic field distributions over stellar surfaces and is now employed to produce images of the brightness distributions in the photosphere of Betelgeuse and other RSGs, as cited in the Introduction.

In this work, we shall examine the signals produced through the LSD technique, which produce a pseudo-spectral line in intensity and linear polarization. This pseudo-spectral line does not correspond to any particular atomic species but rather represents an average of all species present and emitting in the photosphere of Betelgeuse. Following these procedures of line addition, the resulting profiles carry the coherent signals present in the photospheric lines, but the specific characteristics of individual spectral lines are erased. All of this data has been previously presented before by **?**, **?** and **?**, which also provide details on observing times and conditions as well as a more detailed description of the data reduction process[2].

Note that all the velocities mentioned in the text or in the figures are provided in the heliocentric frame. »»»> 234ba9bf04bfa56ec2de436422869ac280239091

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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 (**??**). 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. =======

3. Period search

Attempting to identify periods in an astrophysical context faces the challenge of unevenly spaced observed data. To overcome this hurdle, we used the Lomb-Scargle periodogram (**??**). This method involves fitting sinusoids to the data using least-squares with frequency sampled between the first and last observation. The quality of the fit determines 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 over a span of 10 years (2014-2024). However, the dataset available post-dimming is insufficient to produce meaningful periodograms. Therefore, our focus was on periodograns computed exclusively from data obtained before the great dimming, covering the period from 2014 to the end of 2019. »»»> 234ba9bf04bfa56ec2de436422869ac280239091

3.1. Variability of the Stokes parameters

«««< HEAD 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. **?**

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

[1] https://tbl.omp.eu/

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

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. ======= We first computed the Lomb-Scargle periodogram at each wavelength of the LSD profile, ranging from -25 km/s to +60 km/s to cover the entire signal present in the LSD profile. **?** identified the most blueshifted signal towards -20 km/s and interpreted it as the maximum velocity of the rising plasma. The most redshifted signal was often found at +40 km/s, interpreted as the rest velocity of the star. Sometimes, signals at velocities greater than +40 km/s can be found, which can be interpreted either as dark and cold plasma falling back to Betelgeuse or as rising plumes of plasma located on the hidden face of Betelgeuse, ascending so high that they appear above the limb (**?**, for the case of the RSG μCep). »»»> 234ba9bf04bfa56ec2de436422869ac280239091

«««< HEAD Figures **??**,**??**,**??** and **??** 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. ======= Figures **??**,**??**,**??** and **??** show the Lomb-Scargle periodogram of the LSD profile for Stokes I, Stokes Q, Stokes U and the total linear polarization, respectively. In each figure, the upper panel depicts the Lomb-Scargle periodogram of each velocity bin (black line) along with the total average (red line). The green line represents the window function. The lower panel shows the Lomb-Scargle periodogram for each velocity bin, with the white dotted lines marking the 400 and 200 d periods for reference. The right panel represents the mean profile of each Stokes parameter at each velocity bin. »»»> 234ba9bf04bfa56ec2de436422869ac280239091

«««< HEAD Looking into Fig. **??**, 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, **?** already found this 200 days periodicity in spectroscopic observations, in spite of a shorter observation period.

Figures **??** and **??** 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. **??** around 200 days. Concerning Stokes U, Fig. **??**, 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 **??** shows the Lomb-Scargle periodogram 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. ======= Examining Fig.**??**, which shows the Lomb-Scargle periodogram of the LSD of the intensity profile, we observe that the 400 and 200 d periods seem to be captured by the periodogram. However, the 400 d period is uncomfortably close to the peak of the window function. Furthermore, both periods are located at the same HRV and in the blue wing of the profile. Interestingly, **?** previously found this 200 d periodicity in spectroscopic observation, despite of a shorter observation period.

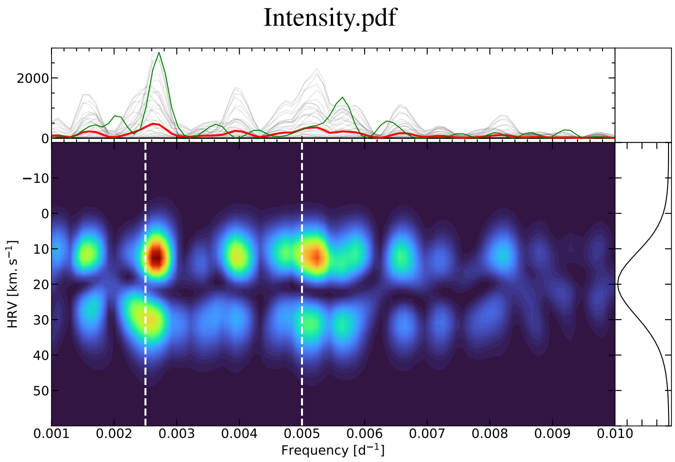

Fig. 1. Lomb-Scargle periodogram of the LSD profile of intensity. The upper panel is the Lomb-Scargle periodogram for each velocity bin (black line) and the average (red line). The green line is the window function. «««< HEAD In the lower pannel, the two white dashed lines mark respectively the 400 days and the 200 days periods. The right panel is the average intensity profile for each velocity bin. ======= In the lower panel, the two white dashed lines mark respectively the 400 d and the 200 d periods. The right panel is the average intensity profile for each velocity bin. »»»> 234ba9bf04bfa56ec2de436422869ac280239091

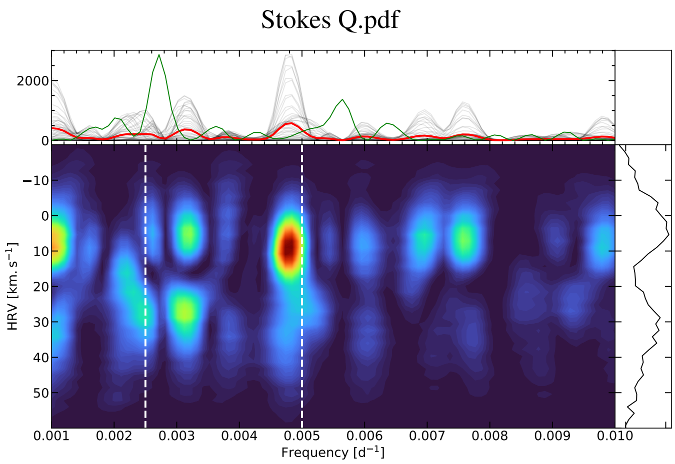

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Fig. 2. Same as figure **??** for Stokes Q.

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Fig. 3. Same as Fig. **??** for Stokes Q.

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Figures **??** and **??** display the Lomb-Scargle periodograms of Stokes Q and U. These periodograms exhibit significant differences compared to the intensity one. In Fig. **??**, a prominent signal is evident around 200 d. Regarding Stokes U in Fig. **??**, it appears that the primary period is approximately 0.003 d^{-1}

Stokes U.pdf

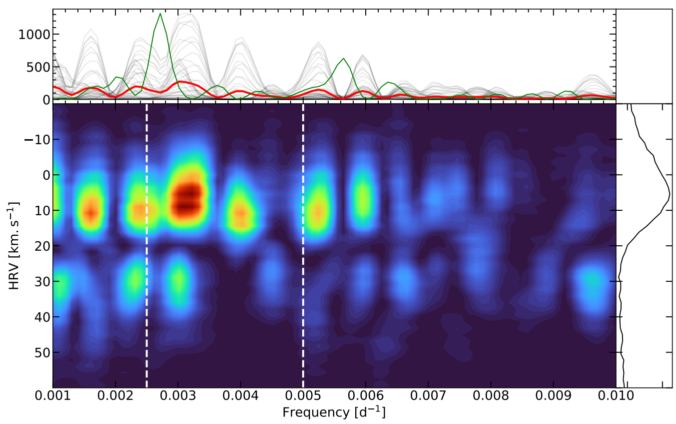

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Fig. 4. Same as figure **??** for Stokes U.
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Fig. 5. Same as Fig. **??** for Stokes U.
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linear polarization.pdf

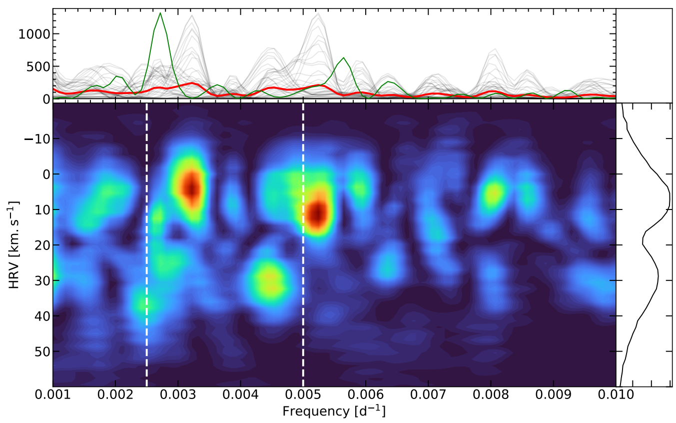

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Fig. 6. Same as figure **??** for total linear polarization: $\sqrt{Q^2 + U^2}$.
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Fig. 7. Same as Fig. **??** for the total linear polarization: $\sqrt{Q^2 + U^2}$.
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(equivalent to 330 d). Although other periods, such as those at 200 d or 250 d (0.004 d^{-1}) are present, but are difficult to trust. From both periodograms of Stokes Q and U, we recover the 200 d period, and also the 330 d period is notable, which aligns closely with the 400 d period reported in the literature and is in agreement with the timescale of the hysteresis loop reported by **?**. Figure **??** shows the Lomb-Scargle periodogram of $\sqrt{Q^2 + U^2}$, representing the total linear polarization of Betelgeuse. This periodogram confirms the significant powers at both 330 d and 200 d, consistent with the periodograms of Stokes Q and U. »»»> 234ba9bf04bfa56ec2de436422869ac280239091

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3.2. The variability in polarimetric imaging

Using linear polarization, **?** were able to reconstruct images of Betelgeuse that have been successfully compared to inteferometric images of **?**. 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 (**?**). 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?** (**?**). =======

3.3. Variability of the polarimetric imaging

Using linear polarization, **?** successfully reconstructed images of Betelgeuse, which have been compared favourably to inteferometric images obtained by **?**. The images are produced by finding the brightness distribution that better fits the observed linear polarization LSD profile using a Marquardt-Levenberg minimisation.

Betelgeuse is observed, on average, every month by the TBL, enabling the tracking of its surface activity through this technique of polarimetric imaging. This technique has previously allowed for the estimation of the size and the lifetime of convective cells on the surface (**?**). From these images, we computed a photo-center, a quantity sensitive to the size and number of convective cells. A 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 exhibit a more siginificant photo-center displacement, up to a few percent of the stellar radius in the case of RSGs (**?**). »»»> 234ba9bf04bfa56ec2de436422869ac280239091

Since the photo-center is linked to surface convection, it is worth checking for periods in its dynamics over the 5 years of observations of Betelgeuse before the dimming. While these periods may overlap with those presented in the previous section, they are likely to capture additional 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 **?**. 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 **??** shows the Lomb-Scargle periodogram of the photo-center displacement for each of the 100 series (blue lines)

Photo-center.pdf

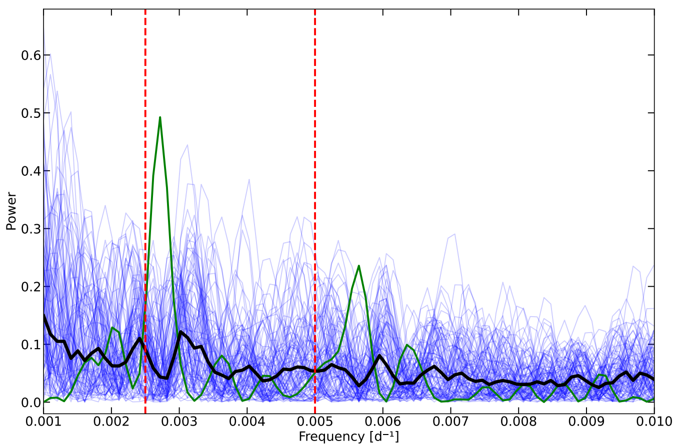

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Fig. 8. Lomb-Scargle periodogram of the 100 series of photo-center displacements of Betelgeuse. Each blue line correspond to a Lomb-Scargle periodogram of one series of photo-center displacement. The black line is the average of the 100 periodograms. 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.

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Fig. 9. Lomb-Scargle periodogram of the 100 photo-center displacement of Betelgeuse. Each blue lines correspond to a Lomb-Scargle periodogram of one photo-center displacement. The black line is the average of the 100 periodogram. The red dashed lines represent the 400 and 200 d period respectively (from left to right). The green line is the window function.

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and the average Lomb-Scargle periodogram (black line). «««< HEAD 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.

4. 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 compared 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 **?** found a period 388 ± 30 days). It has been found by **?** 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 (**?**). 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 **?**, 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. ======= The red dashed lines indicate the 400 and 200 d periods, respectively. Similar to previous figures, the window function is represented by the green line. Interestingly, we find two peaks around the 400 d period in the periodogram, although they are not individually significant to confirm the presence of such period. However, these peaks are consistent with the findings of the previous section. Since polarimetry imaging involves only surface convection, this provides further support for a variability being explained by surface convection alone.

4.1. Variability of the light curve

After examining the periods identified by the Lomb-Scargle technique in the polarization data obtained by the TBL over the last years before the dimming, it is worth contextualizing them alongside the periods traditionally identified in light curves over the same period of time. Two aspects are of our interest in this comparison: the behaviour of the light curve before and after the great dimming.

We have retrieved the light curve of Betelgeuse in the visible from the AAVSO database for the past 10 years, as shown in Fig. **??**. Before the great dimming, Betelgeuse's magnitude exhibited variations on a yearly timescale, whereas after the dimming, its variability has shortened. Figure. **??** clearly illustrates that the variability of Betelgeuse now occurs on a timescale shorter than one year. This qualitative change has been pointed out before, before the great dimming, the primary period of Betelgeuse was approximately 400 d (**?**), often associated with the fundamental pressure mode. However, after the dimming, this period seems to have vanished, and only timescales shorter than 230 d are visible since (**?**). No explanations have been put forth regarding this change of variability after, or perhaps because of the dimming. Consequently, we can afford proposing alternative scenarios for the observed periodicities in the light curve (see

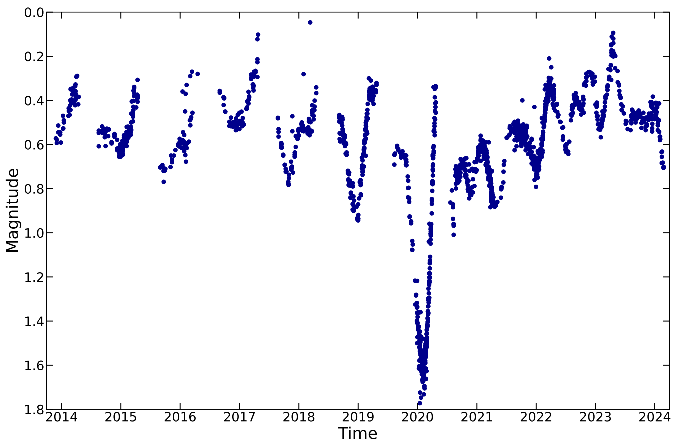

Fig. 10. Light curve of Betelgeuse from AAVSO in the V-band.

Section **??**).

We utilized the AAVSO database to search for periodicities in the light curve of Betelgeuse using the Lomb-Scargle periodogram, aiming to identify periods previously reported in the litterature. In Fig.**??**, we computed the periodogram from the light curve of Betelgeuse spanning from 1990 to 2024 (blue line), alongside the periodogram computed using AAVSO observations corresponding to the observation dates of the TBL (orange line) within a range of 5 days. For the periodogram since 1990, we binned the observations with an interval of 10 days, as Betelgeuse has been more observed in the 21st century (**?**). Our analysis reveals the recovery of the 400 d period and also a period close to 200 d, while the other peaks are due to the windowing effect. Thus, the Lomb-Scargle periodogram succssfully identifies periods mentioned in the literature. However, when focusing on the periodogram derived from the light curve corresponding to the TBL observation dates, we fail to retrieve the periods mentioned in the literature. Hence, the small peaks present in Fig. **??** are attributed to the limited number of TBL observations.

AAVSO.pdf

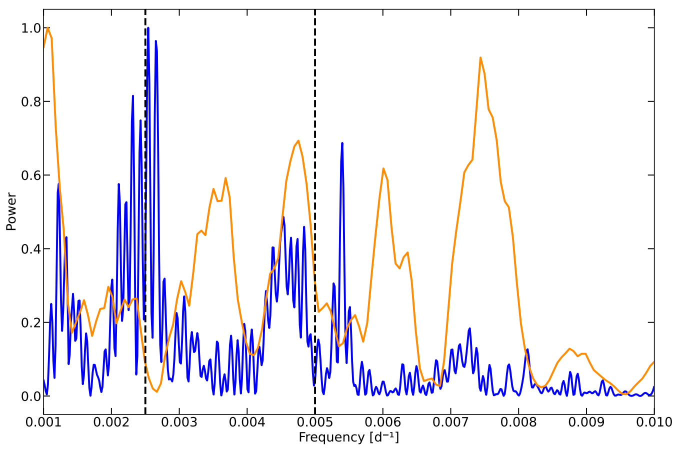

Fig. 11. Lomb-Scargle periodogram of the light curve of Betelgeuse since 1990 (blue line) and from the light curve where the dates correspond to the observation of the TBL. The two black dashed lines are respectively the 400 and 200 d periods.

5. Discussion

The presence of the same periods and, considering the time span and sparsity of the TBL data series, the larger amplitude of the peaks found in polarization data compared to those in the light curve point to a common origin, one that is rather based upon convective dynamics. Since we associate Stokes Q and U to proxies of convection, we associate the 200 d period to the typical timescales on which the Stokes parameters evolve. The LSD profiles of Stokes Q or U undergo slight changes when observing Betelgeuse monthly, but are completely overhauled on time scales of several months. The Lomb-Scargle periodograms seem to capture this spectral dynamic at periods of aproximately 200 d. Such changes in the profiles are directly linked to the dynamics of the surface, to the evolution, and movements of convective cells across the visible hemisphere. Therefore, the 200 d period appears to be related to the evolution of the convective patterns on the surface of Betelgeuse. The stronger presence of this peak in Stokes Q compared to U could be interpreted as a temporal situation of how convective patterns have been distributed in the last years.

The other period found in the total linear polarization and Stokes U, the 330 d periods, is not so far from the 400 days period often mentioned in the literature (e.g **?** found a period of 388 ± 30 d). It has been shown by **?** that large convective cells can persist for one to two years. Thus, the 330 d period could be associated to the timescale on which the largest granules evolve. This characteristic timescale has also been observed in the numerical simulations and might play an important role in determining stellar distances through the displacement of the photo-center (**?**). Once again, we observe the 330 d periodicity to be more prominent in Stokes U than in Q, what may unravel a random situation due to convective motions in the last years. This interpretation aligns with the work of **?**, who attributed the 400 d period to large convective cells.

Regarding the Stokes I profile, it seems to correspond to the 400 d period, but is uncomfortably close to a peak of the window function of the TBL, making this peak difficult to trust. A secondary peak close to 200 d is also present in the Stokes I profile. Since we are able to recover the 200 d period in the Stokes parameters, we attribute this period to convective timescales. Up to this point, the model developed to interpret linear polarization involves only surface convection, which is why we interpret the 200 d period as the convective timescale of the smallest structures, while the 400 d period corresponds to the timescale of the largest structures.
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We have recovered the light curve of Betelgeuse in the visible from the AAVSO database for the last 10 years (Figure **??**). 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. **??** 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 (**?**). 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 (**?**). 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 **?** 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 **?** 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. =======

Before summing up the results of our work, we can afford to explain the variability of Betelgeuse after the great dimming with surface convection. RSGs experience mass loss event, where plasma is ejected into the interstellar medium (**?**). These events have been inferred in RSG such as μCep, where **?** found an excess of linear polarization beyond the limb of the star, attributing it to rising plumes of plasma in the back hemisphere of the star. In the case of Betelgeuse, the excess of linear polarization beyond the limb is rare and not as pronounced as those observed in μCep. Also, they do not change the variability of the star. However, since the great dimming, the variability of Betelgeuse has changed. This suggests that the great dimming differed significantly from the usual mass loss event, that it hustled the dynamics of the photosphere.

In a scenario where the variability of Betelgeuse is primarily governed by convection, before the great dimming, the variability of the star was associated to the typical timescale at which convection occurs: approximately 200 d for the small structures and roughly 350 d for the large structures. The great dimming affected the behaviour of the photosphere in such a way that the largest structures no longer evolved on a timescale around 350 d, but rather on the timescale of the smallest convective structures, around 200 d. We hypothesise that since the great dimming event, the photosphere has not returned to equilibrium, and the largest convective structures have been disrupted by the turbulent motion of the photosphere. Consequently, identifying periods after the great dimming is hard, which **?** noticed. We expect that the 400 d variability will gradually reappear in the coming years as the photosphere returns to equilibrium. However, it is essential to note that this scenario is speculative but provides a rough explanation of how convective activity could lead to a change in variability since the great dimming. A more detailed explanation of this variability change falls beyond the scope of this paper and is left for future research. »»»> 234ba9bf04bfa56ec2de436422869ac280239091

6. Conclusion

«««< HEAD 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. ======= The main result presented in this work is that the same periods identified in the light curve of Betelgeuse are also observed in the intensity and polarization spectra measured with the TBL. Traditionally, periods in the light curve have been associated to pulsations due to pressure modes. »»»> 234ba9bf04bfa56ec2de436422869ac280239091 «««< HEAD 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 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 **?**, 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. ======= However, the interpretation of the linear polarization profiles is made in terms of convective structures in the atmosphere of Betelgeuse. We propose that the true reason for the observed periodicities in both the light curve and spectropolarimetric observations lies within these convective structures and their temporal evolution. This is the main conclusion of our work: since we are able to recover the different periods in the linear polarization profiles, we associate the 200 d periodicity to convective dynamics, while the 400 d periodicity is linked to convective timescales of the largest granules. This conclusion concurs with the scenario proposed by **?**, attributing the variability of Betelgeuse to surface convection.

Although of secondary importance, we can speculate on the phenomena underlying the change in variability before and after the great dimming event. We hypothesize that the great dimming event disrupted the dynamics of the photosphere, leading to the destruction of the largest granules 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 timescale of smaller convective cells, around 200 d. If this scenario is correct, we shall expect in the coming future, the re-emergence of the 400 d variability as the dominant period once the photosphere returns to some form of equilibrium. Longer time series of spectropolarimetric observations of Betelgeuse will be necessary to provide further insights into this phenomenon. »»»> 234ba9bf04bfa56ec2de436422869ac280239091

Acknowledgements. This work was supported by the "Programme National de Physique Stellaire" (PNPS) of CNRS/INSU co-funded by CEA and CNES. We acknowledge support from the French National Research Agency (ANR) funded project PEPPER (ANR-20-CE31-0002). We acknowledge the observers of the AAVSO International Database who provided more data than enough to produce this work.

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