Astronomy & Astrophysics manuscript no. main
February 27, 2024

The variability of Betelgeuse explained by surface convection

Q. Pilate[1], A. López Ariste[1], A. Lavail[1], Ph. Mathias[1]

IRAP, Université de Toulouse, CNRS, CNES, UPS. 14, Av. E. Belin. 31400 Toulouse, France

Received ...; accepted ...

ABSTRACT

Key words.

1. Introduction

Betelgeuse is a prototypical red supergiant (RSG) known to be a semi-regular variable. Several periods can be found in the literature usually clustered around the so-called long secondary period (LSP) of 2000 days and other more or less well defined periods around 400 and 200 days. Such periods are often linked to radial pulsation modes, and have been used to model the characteristics of the resonant cavity, hence the size of the star and eventually its evolutionary stage **?**.

At the end of 2019, Betelgeuse reached a historical minimum in its luminosity, called the great dimming (Guinan et al. 2020). From interferometric data, we know that this event was caused by a cloud of dust close to the line of sight (Montargès et al. 2021). Interferometric images show a huge drop in luminosity in the southern hemisphere of Betelgeuse, leading to this dimming. In this event it was clear that a change in brightness was not due to any kind of pulsation but to a change on the brightness distribution over the stellar disk due to the presence of large quantities of dust. While this may be seen as a singular event, it brings up the question whether all changes in brightness cannot be due to similar changes in the brightness distribution over the disk, unrelated to any pulsation phenomenon.

Betelgeuse is known to present large convective cells with life times 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.

Since the end of the Great Dimming event, Betelgeuse has continue its random variation of brightness. Interestingly, it has been shown by Jadlovský et al. (2023) and Dupree et al. (2022) that the periodicity of Betelgeuse has changed after the dimming. Using the light curves from AAVSO, the authors showed that before the dimming, the dominant period of Betelgeuse was around 400 days. However, after the dimming, this period has changed and is now shorter, around 200 days. It means that, after the dimming, there was a change in the behaviour of the atmosphere of Betelgeuse: the period is now shorter than before the dimming. Our analysis is based on this change of periodicity. Faced with the dramatic change in stellar parameters and age that such change in a pulsation period would require, our interest in an alternative explanation of the variability in terms of convective patterns arose. In order to address this question we shall seek for such typical periods of 1000, 400 and 200 days in observational proxies related to the convective activite but unrelated to pulsations and which cannot be directly linked to brightness?

Linear polarization in the atomic lines of the spectra 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 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 it 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 height of formation of different lines in the spectrum of Betelgeuse. The images produced compare very well with cotemporaneous 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, unrelated to radial pulsations but linked to the brightness inhomogeneities due to the convective patterns in Betelgeuse. If one can find the aforementioned periods in linear polarization, we must conclude that these periods are related to the convective activity which originates those linear polarization signals and unrelated to any radial pulsation phenomena. 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 13 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 are not sufficient to measure the weak polarization signals in individual atomic lines of the spectrum.

These amplitudes are today known to be of the order of 10^{-4} times the continuum intensity, and only excepcionnaly 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). Most commonly, the amplitudes of linear polarization are below noise levels. In those occassions we have to add up the signals of thousands of lines to reduce the 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-spectral 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]

Trying to find periods in an astrophysical context carries the hurdle of unevenly spaced observed data. To overcome this issue, we used the Lomb-Scargle (hereafter LS) periodogram (Lomb 1976; Scargle 1982). For a given set of data, it fits sinusoid functions using least-squares at each frequency between the first and the last observation. The better the fit, the higher the power attributed to the frequency. We apply this technique to the LSD profiles of Stokes I, U and Q of Betelgeuse observed at the TBL during that span of 13 years.

We first computed the LS periodogram at each wavelength of the LSD profile, between -25 km/s and 80 km/s to span the entire signal present in the LSD profile. López Ariste et al. (2018) found the most blueshifted signal towards -20 km/s, and interpreted it as the maximum velocity of the rising plasma, seen from the Earth. The most redshifted signal was 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 can be 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 in normalised power of the LSD profile of respectively the intensity, stokes Q, stokes U and the linear polarization. For each figure, the upper panel is the LS periodogram with data taken before the great dimming of Betelgeuse, that is from 2013 to the beginning of 2019. The lower panel is the LS periodogram for the whole period before and after the dimming: from 2013 to 2023. The white dashed lines mark the different periods found in the literature: the LSP at 2000 days, the fundamental pressure mode at 400 days and its first overtone at 200 days.

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

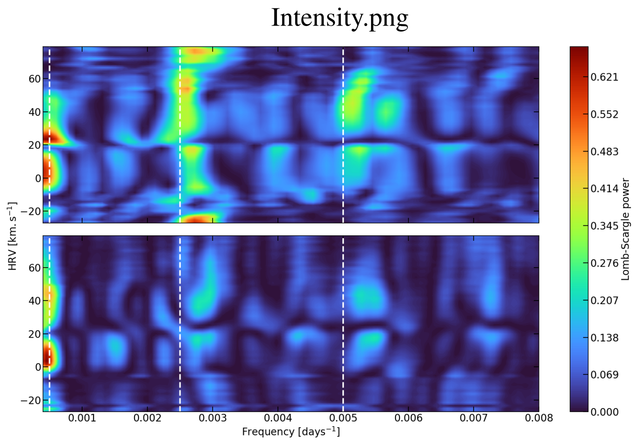

Fig. 1. Lomb-Scargle periodogram of the LSD profile of intensity. The upper pannel is the LS periodogram for data before the great dimming while the lower panel is the periodogram from the all dataset. The ordinate refers to the velocity in the heliocentric radial velocity in km/s. The abscissa is the period in days^{-1}. The three white dashed lines represent respectively (from left to right) the LSP at 2000 days, the 400 days period and its first overtone at 200 days. The Lomb-Scargle power refers to the quality of the fit from the LS periodogram.

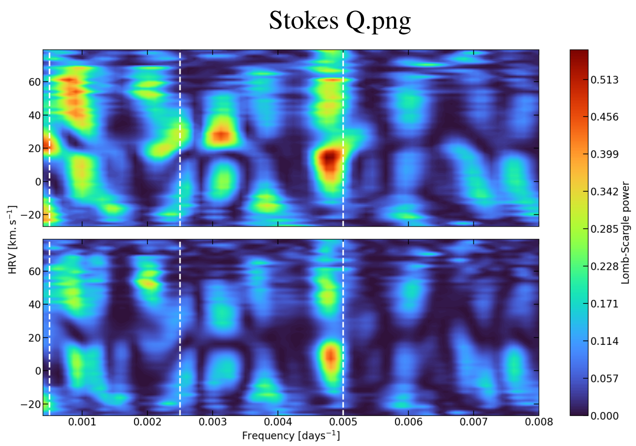

Fig. 2. Same as figure 1 for stokes Q.

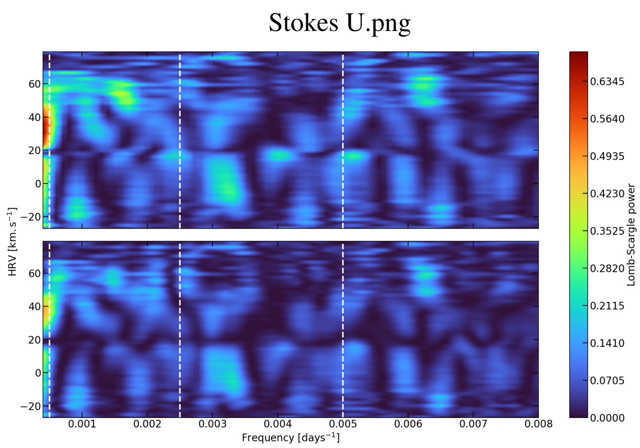

Fig. 3. Same as figure 1 for stokes U.

Figure 1 shows the LS periodogram of the LSD of the intensity profile. Interestingly, we recover the LSP at 2000 days, but located at a HRV of ∼ 20 km/s rather than over the whole profile. This periodicity is still present after the dimming, but it is located at a HRV between 0 and 10 km/s. There is also a weaker signal at

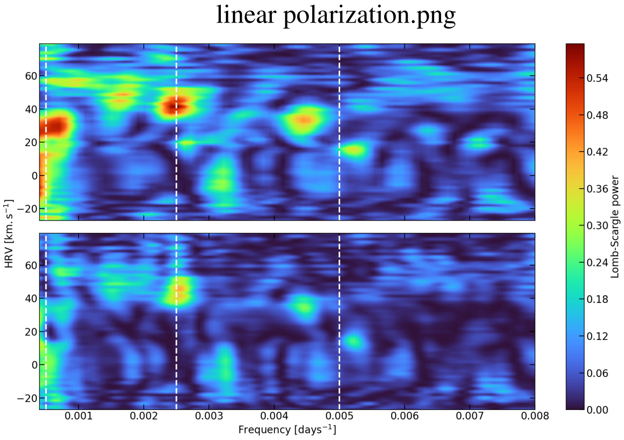

Fig. 4. Same as figure 1 for the linear polarization: $\sqrt{Q^2 + U^2}$.

the fundamental mode, around 400 days before the dimming. But this signal completely disappears after the dimming. From these observations we find hard to attribute the observed LS power to a global period of Betelgeuse. Our results in the intensity profile are consistent with the one from Mathias et al. (2018) who used 2D fourier analysis and found that the dominant period was the LSP.

2.1. Stokes Q and U

Figure 2 and 3 show the LS periodogram of both stokes Q and U. It is clear that the LS periodogram is completely different from the intensity one. A strong signal is present in fig. 2 around 200 days. Once again, this signal is weaker after the dimming. Concerning stokes U in fig. 3, it appears that we only recover the LSP, which once again, is weaker after the great dimming. Those periodograms rise a lot of questions: why is the 200 days period only present in stokes Q? Why not in stokes U or intensity? We will discuss about those questions in the next section. It also appears that stokes Q is not sensitive to the LSP, or to be more precise, it is much more sensitive to the 200 days period. From this, we can conclude that stokes Q evolves on a time scale much more closer to the first overtone mode than the LSP or even the fundamental mode. Since Stokes Q is sensitive to different periods, we must conclude that it is due to other mechanisms than the one behind the periodicitys observed in intensity. Linear polarization in Betelgeuse is interpreted to be a proxy of convective cells, so we can speculate that the signal present in the periodogram may be related to the lifetime of convective cells. Such hypothesis is comforted by what we see in the LSD profiles of Betelgeuse whose shape is overhauled in typical time scales of a few months, Such time scales observed in the Stokes profiles and attributed to the convective time scales appear to explain the strong signal present at 200 days in the LS periodogram of Stokes Q.

2.2. The linear polarization

Figure 4 shows the LS periodogram of the total linear polarization of Betelgeuse: $\sqrt{Q^2 + U^2}$. Interestingly, the LS periodogram shows a strong power at 400 days and 2000 days. This signal is much more weaker after the dimming. While the LSP is already present in the LS of intensity, here we recover the 400 days periodicity, often invoked in the literature. Nonetheless, the power of this period peaks at a HRV of around 40 km/s. We recall that this velocity is the rest velocity of the star. Every signal beyond this velocity is either due to plasma sinking in Betelgeuse, or to plumes of plasma rising beyond and above the limb of the star. Such plumes from the back hemisphere haven been often seen in other red supergiants like μ Cep (López Ariste et al. 2023). This suggests that both signals at these period of 400 days found in intensity and total linear polarisation could well be due to the periodic appearance of plumes in the back himisphere rising high enough to appear above the visible limb and generating a supplementary source of brightness. Once again we find a plausible explanation of these periods unrelated to pulsations, but rather to the convective dynamics of the star.

2.3. The variability of Betelgeuse inferred from polarimetry imaging

Using linear polarization, López Ariste et al. (2018) have been able to reconstruct images of Betelgeuse that have been sucessfully 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 profile using a Marquardt-Levemberg minimisation.

Betelgeuse is observed in average every other weeks by the TBL, and hence we are able to follow its surface activity through polarimetry imaging. This has allowed in the past the estimatation of the size and the life time of the convective cells at the surface. From these images, we can compute a photo-center, which is sensitive to the size and the number of convective cells. An homogeneous star will have a photo-center coinciding with barycenter of the star, whereas a star with one or two huge convective cells will have a photo-center displacement more important, up to a few percent of the stellar radius in the case of RSG (Chiavassa et al. 2022).

Since the photo-center is linked to surface convection, it is worth checking for periods in its dynamics over the 13 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.

We computed the LS periodogram of the displacement of the photo-center. But, before going any further, 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° degree, 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 ambigous solutions possible. To obtain a continuity between the series images, for a given day we use the brightness distribution of the previous day as initial point of the fitting iteration; and for the first image, we start with a random brightness distribution as the beginning of the fit. 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 the choice of the first image. To overcome this issue, we decided to compute the photo-center displacement from 100 different initial parameters and their subsequent series of images in an effort to recover from the ensemble properties that are independent of the choice of the first image.

Figure 5 shows the LS periodogram of the photo-center displacement of each one of those 100 series (blue lines) and the average LS periodogram (black line). As before, the upper panel shows the LS from images before the great dimming of Betelgeuse only, whereas the lower panel is the LS for the whole set of

Photo-center.png

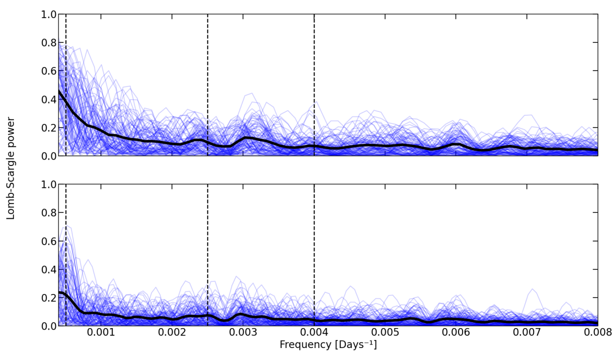

Fig. 5. Lomb-Scargle periodogram of the 100 photo-center displacement of Betelgeuse. Each blue curve corresponds to a LS periodogram of one photo-center displacement. The black line is the average of the 100 LS periodogram. The black dashed lines represent the 2000, 400 and 200 days period respectively (from left to right). The upper panel is the LS from data before the dimming. The lower panel is the LS from the all dataset, including data after the great dimming.

data, including images after the dimming. The black dashed lines mark the 2000, 400 and 200 days periods respectively. First, we find the the LS power is high around the LSP, though uncomfortably close to the auto-correlation peak. We also notice a decrease in the Lomb-Scargle power from before to after the dimming, in concurrence to what was seen in the LS periodograms of the LSD profiles. Before it, there are two smalls bumps around the 400 days period. But those bumps almost completely disappear after the dimming. Even though it is hard to identify the 400 days period from those bumps alone, we still find that there is a difference before and after the dimming. And this is concluded from images that exclusively involve surface convection. The LS of the photo-center displacement points towards a variability explained by convection only. And this is consistent with what we obtained from linear polarization.

2.4. The variability of the light curve of Betelgeuse

After examining the periods found by the Lomb-Scargle technique on the polarization data, and its derivatives, obtained by the TBL over the last 13 years, it is worth putting them in the context of the periods found traditionally on 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, and the amplitudes of the peaks at the main cited periods.

We have recovered the light curve of Betelgeuse in the visible from the AAVSO database for the last 13 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 changed. 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. In the literature, it is reported that 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 the period at 200 days, associated to the first overtone of the fundamental mode, is visible since (**?**). No explanations based upon pulsations have been ofered concerning this change of variability after or perhaps because of the dimming. But this is a behaviour that fully concurs with what we find in the polarization data, and which cannot be related to any stellar pulsation but rather convective dynamics. Beyond the actual values of the periods found in a Lomb-Scargle periodogram, we also see a correspondence between polarization and the light curve in these changes in the observed periods before and after the great dimming. Such concurrence points to an explanation in terms of convective dynamics also for the variability of the light curve.

It may be argued that the periodograms presented in the previous sections and, in particular, those of the photo-center displacements, present low amplitude peaks at the referred main periods. One may wonder whether we are over-interpreting mere fluctuations of the periodograms, while the peaks seen in the literature from analysis of the light curve are unmistakable. It is therefore worth to take advantage of the availability of the AAVSO data to perform a Lomb-Scargle periodogram of the light curve in the same period covered by our polarization data and, furthermore, taking into consideration data around the dates for which TBL data is available. Periodograms with such constraints are shown in Fig.**??**. Even when the full dataset for the period is taken into account, the periods present small amplitudes, and are fully and favourably comparable with the periodograms presented above. This is even more dramatic when the periodogram is made from data at the exclusive dates at which TBL data is available. It stands out that the low amplitude peaks are rather due to both the sparse cadence and short span of time of the TBL data series rather than to a physical absence. Actually, the present tests puts more emphasis on the importance of the strong peaks seen at selected wavelengths in the LSD profiles, strong when compared to the peaks at similar periods arising from the light curve.

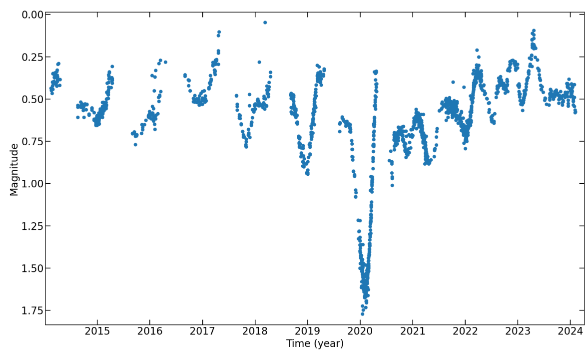

Fig. 6. Light curve of Betelgeuse from AAVSO in the V-band.

3. Surface convection suffices to explain the observed variability

Before summing up the conclusions of this work, we can afford proposing alternative scenarios for the observed periodicities in the light curve, the LSD profiles and the displacement of the photo-center of the inferred photospheric image reconstructions. 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 in polarization data than in the light curve point to a common origin, one that is rather based upon convective dynamics and not to radial or other global pulsations.

The 400-day period appears prominently in both the intensity and the total polarization profiles. And in both cases, it is mostly present at wavelengths in the red wing, often beyond the 40 km/s value. We recall that in the present scenario for the formation of the polarization signal, this signal is supposed to remain between -20 and 40km/s. Signals above 40km/s are uncommon and can be associated to plasma rising behind the limb of Betelgeuse. Such scenario has been observed in the RSG μ Cep and was introduced by López Ariste et al. (2023) to explain the excess of linear polarization beyond the rest velocity of the star, which for Betelgeuse is fixed at +40km/s. In μ Cep, such linear polarization signal beyond the limit of the rest velocity of the star is very strong and particularly common, two features that prompted a dedicated explanation. In Betelgeuse, such signals, when present, are weaker. However, they are visible from time to time, with regularities that are captured by the LS periodogram at 400 days. Without further justification, we may propose that convective plumes in the hidden hemisphere of the star and rising above the limb from time to time are responsible for the 400 days period in the light curve. When such plumes rise high enough to be geometrically visible above the limb they show signals in intensity and polarization at redshifted wavelengths. They also increase the emitting surface of the star and the number of photons that we receive, leading to an increase of the brightness visible in the light curve. After a few weeks or months, the plume falls back to Betelgeuse, disappearing from our point of view, leading to a decrease of the brightness.

The appearance of such high-rising plumes is not necessarily periodic. And the star can easily shift from active periods when such plumes are a common feature to calmer periods when no plume is visible for months. μ Cep may be in one such active period presently, while Betelgeuse may have experienced recently one great such event in the direction of the Earth that, after dust formed, became the great dimming, but since then no other high-rising plume has appeared, explaining the absence of the 400-day period since the great dimming. From the point of view of convective dynamics we can offer an explanation of the 400-day period which not only explains the observation of this period both in the light curve and in the polarization profiles, but also its presence at redshifted wavelengths and its present (and probably temporary) disappearance since the great dimming.

Concerning the 200 days period, we notice that it coincides with 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 two weeks. But they are completely overhauled on time scales of several months. The Lomb-Scargle perioograms appear to capture this spectral dynamic around periods of 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. As showed by López Ariste et al. (2018), some of those convective cells can live up for years. We may speculate that the LSP may be related to those long living structures. However the present span of data from the TBL is insufficient to do more than just speculate. It should be noticed that the peak is not present in stokes U, and this may point to a more stochastic event than just long-living structures.

4. Conclusion

The main observation presented in this work is that the very same periods identified in the light curve of Betelgeuse are also seen in the intensity and polarization spectra measured with the TBL. Periods in the light curve have often been traditionally associated to pulsation due to pressure modes. But such pulsation would in no case affect the polarisation signals nor would explain the fact that the periods can be observed with stronger amplitude at selected wavelengths but no others. Pulsation appears to offer no coherent explanation to these observations, are hardly to the observed changes in the variability since the great dimming. The concurrence of observational facts, actual period values, evolution before and after the dimming, the larger amplitude of the period peaks in polarizarion data, points towards a common origin for those variabilities. And such origin cannot be pulsations.

The interpretaion 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: the observed periods are related to convective dynamics and not to radial pulsations of the star.

Although of secondary importance, we may suggest with more or less ease what phenomena are at the origin of the main periods. The 400-day period appears to be strongly related to the appearence of plumes in the back hemisphere of the star rising high enough to be seen above the limb. Such plumes have been described in another RSG, μ Cep, and while less common or prominent, they are also present in Betelgeuse. The irregularity of their presence justifies the 400-day period, which is captured by the Lomb-Scargle periodogram in the polarization signals attributed to this phenomenon. The redshifted wavelengths at which this periodicity is found are justified by the plume moving away of the star and of the Earth while raising in the back hemisphere, while the brightness increase is justified by the extra surface of emitting plasma visible. The 200-day period is less prominent but appears to be correlated to the typical time scales of the evolution of the convective structures themselves on the visible hemisphere. The LSP origin is harder to pinpoint given the insufficient time length of our time series. One can speculate if it may be related to the longest living photospheric structures, but this explanation does not adequately explain all the features associated to this period. Longer time series of spectropolarimetric observations of Betelgeuse will be required to shed light on this.

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) An acknowledgement to the AAVSO may be required?????????????????

References

Aurière, M., López Ariste, A., Mathias, P., et al. 2016, Astronomy and Astrophysics, 591, A119

Chiavassa, A., Kudritzki, R., Davies, B., Freytag, B., & De Mink, S. E. 2022, Astronomy & Astrophysics, 661, L1

Donati, J.-F., Semel, M., Carter, B. D., Rees, D. E., & Collier Cameron, A. 1997, Monthly Notices of the Royal Astronomical Society, 291, 658

Dupree, A. K., Strassmeier, K. G., Calderwood, T., et al. 2022, The Astrophysical Journal, 936, 18

Guinan, E., Wasatonic, R., Calderwood, T., & Carona, D. 2020, The Astronomer's Telegram, 13512, 1, aDS Bibcode: 2020ATel13512....1G

Jadlovský, D., Krtička, J., Paunzen, E., & Štefl, V. 2023, New Astronomy, 99, 101962

Lomb, N. R. 1976, Astrophysics and Space Science, 39, 447, aDS Bibcode: 1976Ap&SS..39..447L

López Ariste, A., Georgiev, S., Mathias, P., et al. 2022, Three-dimensional imaging of convective cells in the photosphere of Betelgeuse, Tech. rep., publication Title: arXiv e-prints ADS Bibcode: 2022arXiv220212011L Type: article
López Ariste, A., Mathias, P., Tessore, B., et al. 2018, Astronomy and Astrophysics, 620, A199
López Ariste, A., Wavasseur, M., Mathias, P., et al. 2023, Astronomy and Astrophysics, 670, A62, aDS Bibcode: 2023A&A...670A..62L
Mathias, P., Aurière, M., López Ariste, A., et al. 2018, ArXiv e-prints, arXiv:1804.01831
Montargès, M., Cannon, E., Lagadec, E., et al. 2021, Nature, 594, 365, number: 7863 Publisher: Nature Publishing Group
Montargès, M., Kervella, P., Perrin, G., et al. 2016, Astronomy & Astrophysics, 588, A130
Scargle, J. D. 1982, The Astrophysical Journal, 263, 835