Understanding the photometric variability of ζ Ori Aa* **

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We studied the variability of the magnetic O-type supergiant ζ Ori Aa using multi-colour BRITE photometry. We confirmed the known rotation frequency $f_{\rm rot} = 0.15 \pm 0.02$ c/d, and detected some of its higher harmonics, of which $4f_{\rm rot}$ is compatible with the known DAC recurrence timescale. Thanks to simultaneous high-resolution CHIRON spectroscopy, we could identify another frequency $f_{\rm env} = 0.10 \pm 0.02$ c/d, caused by the circumstellar environment. Variations in the circumstellar environment are believed to cause the observed difference between the BRITE lightcurves.

Massive stars show various types of time-dependent variability. This variability can originate at the stellar surface, e.g. non-radial stellar pulsations or surface brightness inhomogeneities, or it can be related to the circumstellar environment, e.g. Discrete Absorption Components (DACs) — related to Corotating Interaction Regions (CIRs) — or magnetospheres. In this work, we studied ζ Ori Aa, which is the only known magnetic O-type supergiant as of today.

1 ζ Orionis

ζ Ori is a hierarchical multiple system, comprising ζ Ori A and ζ Ori B in a visual binary system. The *Washington Double Star Catalog* indicated an orbital period of about 1509 y with an eccentricity of 0.07 using the common proper motion (Mason et al., 2001). More recently, Hummel et al. (2013) characterized the orbit of the Aa+Ab subsystem. This system is slightly eccentric ($e = 0.338 \pm 0.004$) with an orbital period of approximately 7.4 y. ζ Ori Aa has an O9.2 Ib N-weak spectral type, while ζ Ori B and ζ Ori Ab are classified as B0 III and B1 V, respectively (Hummel et al., 2013; Sota et al., 2014).

A weak magnetic field was detected for the massive supergiant ζ Ori A (Bouret et al., 2008) using high-resolution spectropolarimetry. Blazère et al. (2015) refined the study of the magnetic field of the supergiant by accounting for ζ Ori Ab and additional observations. They determined the rotation period of ζ Ori Aa ($P_{\rm rot} = 6.83 \pm 0.08$ d) and confirmed the presence of a weak dipolar magnetic field ($B_d \approx 140$ G). Using spectral disentangling, ζ Ori Ab was isolated in the observations, leading to the non-detection of a magnetic field for the secondary, with a detection threshold of 300 G. The authors also found additional variability in their 2011–12 magnetic measurements compared to those of the 2007–8 campaign.

Finally, Kaper et al. (1996, 1999) detected weak DACs for ζ Ori A using UV spectroscopy. The analysis was hampered by a short time base and a poor cadence, yet they were able to determine the recurrence timescale of the DACs to be $t_{\rm rec} = 1.6 \pm 0.2$ d, about 1/4 of the rotation period.

2 BRITE photometric study

2.1 Observations

The BRIght Target Explorer (BRITE) (Weiss et al., 2014; Pablo et al., 2016) monitored ζ Ori during two separate observing campaigns, each time using both red and blue nanosatellites. All observations were taken in 'classical' mode with a typical exposure of 1 s. However, on-board stacking was applied for some of the measurements. Lightcurves were extracted from the downlinked pixel rasters using circular apertures (Popowicz et al., 2017) and additional meta-data (CCD centroid positions and CCD temperature) were provided. We developed specific routines to further correct the extracted BRITE photometry (Buysschaert et al. 2016, these proceedings; Buysschaert et al. 2017). We corrected the timings of the observations, cleaned the data by performing outlier rejection, reduced the noise by accounting for the variable PSF shape, and corrected for instrumental effects. Lastly, we calculated the duty cycles and root-mean-square (RMS) of the flux to assess the quality of the BRITE photometry. Only the best data were considered for further analysis. We show the data characteristics in Table 1 and present the individual lightcurves in Fig. 1. Simultaneous red and blue photometry agree well. Since ζ Ori Aa is the brightest component in the system, we assume in the following analysis that all BRITE variability is caused by ζ Ori Aa or its circumstellar environment.

2.2 Time-series analysis

Since the frequency diagrams of ζ Ori's BRITE lightcurves indicate that the character of their variability differs, we subdivided this data into three distinct epochs, namely Orion I, Orion IIa, and Orion IIb.

As a first step, we performed an iterative prewhitening approach to determine the significant periodic variability present in each lightcurve. We used ten times oversampled Lomb-Scargle periodograms in the frequency domain up to 10 c/d. These frequency diagrams are presented in Fig. 1. During the detailed frequency analysis, we considered a frequency peak significant if it reached a SNR greater than four

Sat.	Run	Setup Set	Stack-ed obs.	Epoch	T_{start} [HJD − 2450000]	Length [d]	RMS corr. [ppt]	D_{sat} [%]
BAb	I	3	1	Orion I	6628.43	74.01	0.86	32.2
BAb	I	4	1	Orion I	6702.51	29.99	0.72	66.5
UBr	I	7	1	Orion I	6603.61	129.28	0.64	40.6
BLb	II	3	5	Orion IIa	6998.52	45.04	1.19	75.8
BLb	II	6	1	Orion IIb	7052.75	45.53	0.55	89.2
BHr	II	5	5	Orion IIa	6998.56	49.06	0.85	78.1
BHr	II	7	1	Orion IIb	7056.99	38.53	0.52	67.7

Table 1: Diagnostics related to studied BRITE observations of ζ Ori. We mark the satellite name, the visit and setup number, the number of on-board stacked observations, the BRITE epoch as defined in this work, the start and length of the observations, the RMS of the corrected flux, and the satellite duty cycle (D_{sat}).

within a frequency window of 4 c/d. Each of the extracted frequencies was then compared between the various studied BRITE lightcurves and only considered for further inspection if it was obtained in at least two lightcurves.

Second, we determined the short-time Fourier transform (STFT) to investigate the variability of the periodic fluctuations with respect to time. Since most of the variability happens in the low-frequency regime, a sufficiently high frequency resolution was needed. Therefore, a time window of 20 d (leading to $\delta f = 0.05$ c/d) was chosen, together with a time step of 4 d. We again employed ten times oversampled Lomb-Scargle periodograms. No periodograms were calculated when the duty cycle was below 50 %. An example of such STFT is shown in Fig. 2.

2.3 Results

Performing an iterative prewhitening approach on all BRITE lightcurves of ζ Ori and comparing the extracted frequencies leads to 17 significant frequencies. These are understood to be simple linear combinations and higher harmonics of three individual frequencies, namely $f_{\rm rot} = 0.15 \pm 0.02$ c/d; $f_{\rm env} = 0.10 \pm 0.02$ c/d; and $f_{\rm x} = 0.03 \pm 0.02$ c/d. We discuss these further in Sect. 4. The STFT analysis confirmed the differences between the various BRITE epochs for ζ Ori. In addition, the amplitudes of variability changes with time within a given data set and between the various epochs, and sharp features are observed, indicating that non-periodic events could also be present in the observations.

3 CHIRON spectroscopic study

3.1 Observations

ζ Ori was observed 65 times, typically twice per night, between 06/02/2015 and 16/03/2015, simultaneously with BRITE and the CHIRON échelle spectrograph mounted on the 1.5m-CTIO telescope (Tokovinin et al., 2013). The spectroscopic observations include the 459 nm – 760 nm range, with a wavelength resolution of 80,000, and is the combination of two consecutive 8-s sub-exposures. These observations were

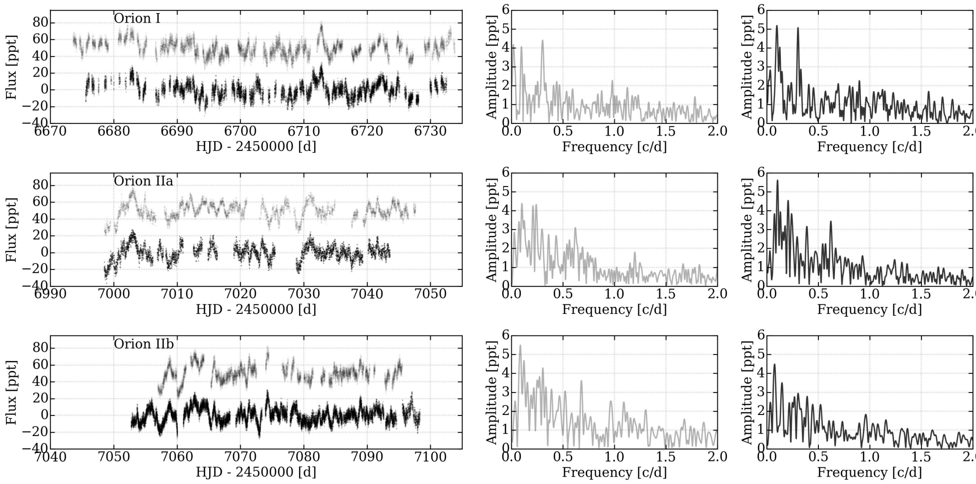

Fig. 1: Studied BRITE lightcurves for ζ Ori separated per epoch (left panels) with their corresponding Lomb-Scargle periodograms (middle and right panels). The blue flux photometry is given in black, while the red lightcurves are marked in gray and have an offset of 50 parts-per-thousand (ppt) for enhanced visibility. No significant variability was found above 1 c/d.

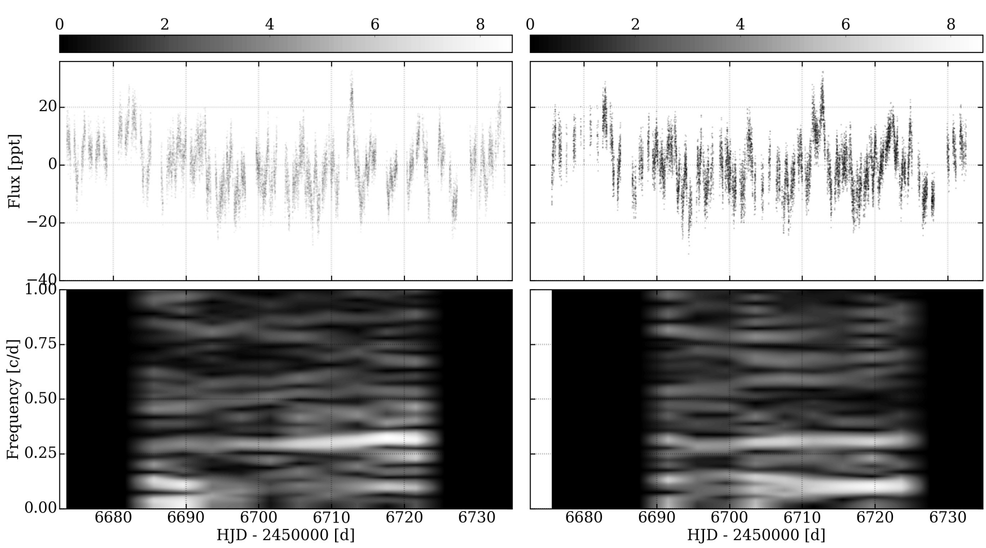

Fig. 2: STFTs of the Orion I data (bottom panels), compared to their respective lightcurves (top panels). The amplitude of the variations within the STFT are indicated by the grayscale. Red photometry is shown on the left, and blue photometry on the right.

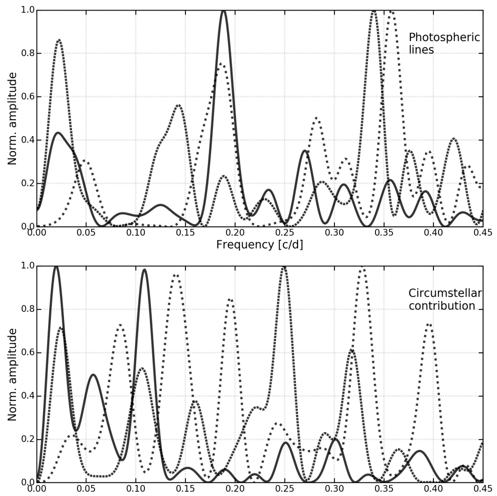

Fig. 3: Normalized CLEAN periodograms showing the variations of selected spectroscopic lines. *Top*: solid – He II $\lambda\lambda$5411.5; dashed – O III $\lambda\lambda$5592.3; dotted – C IV $\lambda\lambda$5801.3. *Bottom*: solid – Hα; dashed – He I $\lambda\lambda$6678.2; dotted – He I $\lambda\lambda$4921.9.

corrected with the CHIRON pipeline for bias and flat-field effects and wavelength calibrated. Lastly, they were blaze-corrected and normalized to the continuum level.

3.2 Time-series analysis

We selected several spectroscopic lines known either to be influenced by the circumstellar environment (Hα, He I $\lambda\lambda$6678.2, and He I $\lambda\lambda$4921.9) or either to be purely photospheric (He II $\lambda\lambda$5411.5, O III $\lambda\lambda$5592.3, and C IV $\lambda\lambda$5801.3). To study the time-dependent variability of these lines, we measured their respective equivalent width (EW). For Hα, we performed this EW integration over both the emission and absorption feature of the P Cygni profile. Next, we calculated CLEAN periodograms of the EW variations (Roberts et al., 1987), using a gain of 0.5 and 10 iterations, because this type of periodograms is less influenced by the moderate sampling. We limited the investigated frequency domain to 0.5 c/d, again to be less influenced by aliasing effects. We show these periodograms in Fig. 3.

3.3 Results

The periodograms of the EW variations for lines with a circumstellar contribution and those purely photospheric look fairly different. However, the data did not permit a detailed frequency analysis. Therefore, we compared these periodograms to those of the simultaneous BRITE photometry (Orion IIb). For circumstellar environment polluted lines, the dominant variability occurs in the region of $f_{\rm env} = 0.10 \pm 0.03$ c/d, with the He I lines showing some additional variability with $f_{\rm rot} = 0.15 \pm 0.003$ c/d and $2f_{\rm rot}$. The purely photospheric lines, however, exhibit their strongest variability with a frequency of 0.19 ± 0.03 c/d, as well as with $2f_{\rm rot}$.

4 Discussion

4.1 Rotation

For each studied BRITE lightcurve, we determined variability related to the rotation frequency and its higher harmonics. Our photometric study of the BRITE data indicates $f_{\rm rot} = 0.15 \pm 0.02\,{\rm c/d}$, compatible with the literature value for ζ Ori Aa of $0.146 \pm 0.002\,{\rm c/d}$ (Blazère et al., 2015). The strongest variability occurs with $2f_{\rm rot}$, as often observed for hot magnetic stars because of their dipole field.

4.2 DACs

Another harmonic of the rotation frequency, $4f_{\rm rot}$, was often retrieved. This variability coincides with the literature DAC recurrence timescale with $f_{\rm rec} = 0.625 \pm 0.075\,{\rm c/d}$ (Kaper et al., 1999). DACs are understood to be related to surface inhomogeneities connected to CIRs. Yet the exact mechanism to produce and sustain four (enhanced) brightness regions on ζ Ori Aa remains uncertain. Both the STFT and the individual lightcurves indicate that the amplitude varies with time.

4.3 Circumstellar environment

It is thanks to the CHIRON spectroscopy that we were able to comprehend the photometric variability of $f_{\rm env} = 0.10 \pm 0.02\,{\rm c/d}$, as this variation is only present in spectroscopic lines with a circumstellar contribution, while being strikingly absent in purely photospheric lines. Therefore, we conclude that this variability originates in the circumstellar environment of ζ Ori Aa. This variability is not related to the stellar rotation, hence it is not produced by the weak magnetosphere of ζ Ori Aa. Instead, we propose periodic mass loss as the driving mechanism for this variability, possibly produced by beating between undetected non-radial pulsations, similar to the Be-phenomenon (e.g. Rivinius et al., 1998, 2003). As the circumstellar environment influences the BRITE photometric measurements, it could naturally explain the differences observed between the studied BRITE epochs.

4.4 Low-frequency variability

To explain all the observed frequency combinations, we need one additional independent frequency (besides $f_{\rm rot}$ and $f_{\rm env}$). We chose $f_{\rm x} = 0.03 \pm 0.02\,{\rm c/d}$, as it produces the combinations in the easiest way. Yet, no easy physical interpretation is available for this variability. We note that it is close to the frequency precision. In addition, the power of this frequency was significantly altered during the correction of the extracted BRITE lightcurves. Therefore, we conclude that this frequency might not be physical.

5 Conclusions

For the magnetic massive supergiant ζ Ori Aa, we performed a detailed time-series analysis of the individual red and blue BRITE photometry, as well as of the simultaneous high-resolution CHIRON spectroscopy. This study identified three independent frequencies, two of stellar origin and one likely non-physical, leading to several higher harmonics and simple linear frequency combinations.

Our value for the rotation frequency is compatible with the literature value. We have also detected variability with $2f_{\rm rot}$, corresponding to the magnetic dipole, and $4f_{\rm rot}$, agreeing with the known DAC recurrence timescale. We propose that the source of the DACs is located at the stellar surface and lay at the origin of the CIRs. With simultaneous CHIRON spectroscopy, we determined the circumstellar environment to be variable with a frequency of 0.10 ± 0.02 c/d.

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Fig. 4: Jörg Weingrill, Bram Buysschaert, Coralie Neiner, Andrew Tkachenko, Ela Zoclonska, Cyril Georgy, Ewa Niemczura and Monika Rybicka.