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THE PHOTOMETRIC VARIABILITY OF ζ ORI AA OBSERVED BY BRITE* **

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Abstract. Using BRITE photometry, we investigated the photometric variability of the magnetic O-type supergiant ζ Ori Aa. We found two independent frequencies, leading to several higher harmonics and simple linear combinations. One frequency is related to the rotation period, $f_{\rm rot} = 0.15 \pm 0.02\,{\rm d}^{-1}$. The derived rotation period from this frequency and its higher harmonics, $P_{\rm rot} = 6.65 \pm 0.28\,{\rm d}$, is compatible with the literature value ($P_{\rm rot} = 6.83 \pm 0.08\,{\rm d}$). Thanks to simultaneous CHIRON spectroscopy, we locate the origin of the second frequency, $f_{\rm env} = 0.10 \pm 0.02\,{\rm d}^{-1}$, at the circumstellar environment. We propose mass-loss events as the underlying origin.

Keywords: Stars: massive - Stars: mass loss - Stars: rotation - Stars: individual: ζ Orionis

1 Introduction

ζ Ori comprises several components organised in a hierarchical system. ζ Ori A and ζ Ori B orbit each other every 1509 years with an eccentricity of 0.07 (Mason et al. 2001; Turner et al. 2008), while the moderately eccentric Aa+Ab system, with $e = 0.338 \pm 0.004$, has an orbital period of 2687.3 ± 7.0 d (Hummel et al. 2013). We present the stellar parameters of these three components in Table 1.

In addition, ζ Ori Aa is currently the only known magnetic O-type supergiant. Its magnetic field was first detected by Bouret et al. (2008). Later, Blazère et al. (2015) confirmed and characterized its magnetic field, while accounting for the recently detected Ab component by means of spectral disentangling. The authors deduced ζ Ori Aa's magnetic field to be dipolar with a polar strength of about 140 G. Moreover, the star's rotation period was determined to 6.83 ± 0.08 d. No evidence for a (strong) magnetic field was found for the Ab component. Lastly, their calculations and Hα observations were compatible with a weak dynamical magnetosphere around ζ Ori Aa, indicating only weak interactions between the large scale magnetic field and the circumstellar environment.

2 Data analysis

ζ Ori was monitored during two observing campaigns by the BRIght Target Explorer (BRITE)-Constellation, which aims to observe the majority of stars brighter than $V \approx 5$ (Weiss et al. 2014). The constellation consists of five different nano-satellites, two Austrian, one Canadian, and two Polish, of which three satellites are equipped with a red bandpass filter and two have a blue filter. We have analysed these observations to unravel the photometric variability of ζ Ori Aa.

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** Based on CHIRON spectra collected under CNTAC proposal CN2015A-122.

Table 1. Stellar parameters of the three main components of ζ Ori, determined by Hummel et al. (2013) unless noted differently. Stellar masses and radii were determined from the photometric distance. (*a*: Sota et al. (2014); *b*: Simón-Díaz & Herrero (2014); *c*: Blazère et al. (2015); *d*: Bouret et al. (2008))

	Aa	Ab	B
m_V (mag)	2.08	4.28	4.01
SpT	O9.2Ib Nwk ^{a}	B1IV	B0III
M ($M_\odot$)	33 ± 10	14 ± 3	–
R ($R_\odot$)	20 ± 3.2	7.3 ± 1.0	–
$v \sin i$ (km/s)	127 ^{b}	< 100 ^{c}	350
$T_{\rm eff}$ (kK)	29.5 ± 1.0 ^{d}	29 ^{c}	–
$\log g$ (dex)	3.25 ± 0.10 ^{d}	4.0 ^{c}	–

2.1 Data preparation

The individual BRITE nano-satellites monitored a large part of the Orion constellation from mid-September 2013 until mid-March 2014, and from late-September 2014 until mid-March 2015. These two campaigns lasted ~130 d and ~170 d, respectively, and are now known as Orion I and Orion II. During the Orion I run, the two Austrian BRITE nano-satellites (BAb and UBr) were used, while the Canadian (BTr), the Polish (BLb and BHr), and one Austrian (UBr) nano-satellites were employed for Orion II. Once the images are downlinked and the observing campaign has finished, lightcurves are extracted from the CCD frames, using circular apertures (Popowicz et al., submitted). The raw lightcurve files have been corrected for intrapixel sensitivity, and provide additional meta-data such as CCD centroid positions and CCD temperature. We continue to improve upon this extracted photometry by adjusting the timing to mid-exposure times, accounting for different cadences, and by cleaning the data for any flux and meta-data outliers. Lastly, we performed a decorrelation for instrumental effects, which are in part related to the changing on-board temperature, affecting both the CCD and the optical path. We show these temperature variations for all four satellites during the Orion II campaign in Fig. 1. The corrected and studied BRITE photometry for ζ Ori is shown in Fig. 2. Simultaneous blue and red observations agree well with each other.

2.2 Time-series analysis

Since we intended to perform a time-series analysis on the BRITE photometry, only data with the highest duty cycle and the best root-mean-square flux stability were considered for further analysis. As a consequence, we discarded the BTr and BAb observations obtained during the Orion II campaign. During the initial analysis, we also noted that the photometry of the two campaigns is variable on different timescales. Therefore, we continued to analyse Orion I and Orion II data separately.

To study the brightness variations in the selected BRITE photometry, we followed an iterative prewhitening approach (see e.g. Degroote et al. 2010). We determined the most significant frequency peak in the frequency diagram, fitted a sine model with that frequency to the data, calculated the residuals, and repeated this process on the residuals until no significant variability remained. Lomb-Scargle periodograms (Lomb 1976; Scargle 1982) were used for frequency diagrams, with ten times oversampling over the region of 0 - 10 d^{-1}. We used the signal-to-noise criterion (Breger et al. 1993) to deduce the significance of a peak in the periodogram, using a 4 d^{-1} frequency window and a threshold of four times the noise level. Lastly, the extracted frequency sets per BRITE lightcurve were compared with each others, and only frequencies appearing in at least two lightcurves were accepted.

3 Results

We extracted the main significant frequencies for ζ Ori, which are harmonics or linear combinations of two independent frequencies. These two frequencies are $f_{\rm rot} = 0.15 \pm 0.02\,\mathrm{d}^{-1}$ and $f_{\rm env} = 0.10 \pm 0.02\,\mathrm{d}^{-1}$, which we discuss in more detail below. We attributed these variabilities to ζ Ori Aa and its environment, because it produces about 80 % of the measured flux (Hummel et al. 2013).

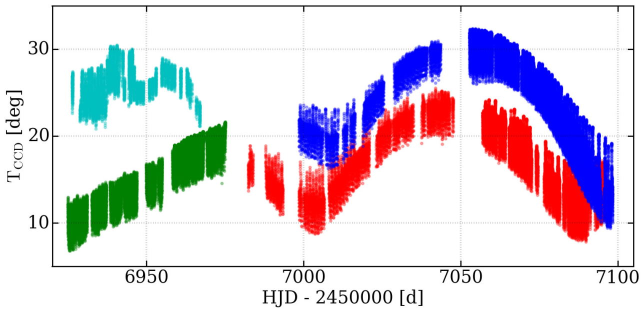

Fig. 1. On-board temperature variations for four nano-satellites during the Orion II campaign. The color represents the nano-satellite of the BRITE-Constellation: cyan for BAb, green for BTr, red for BHr, and blue for BLb.

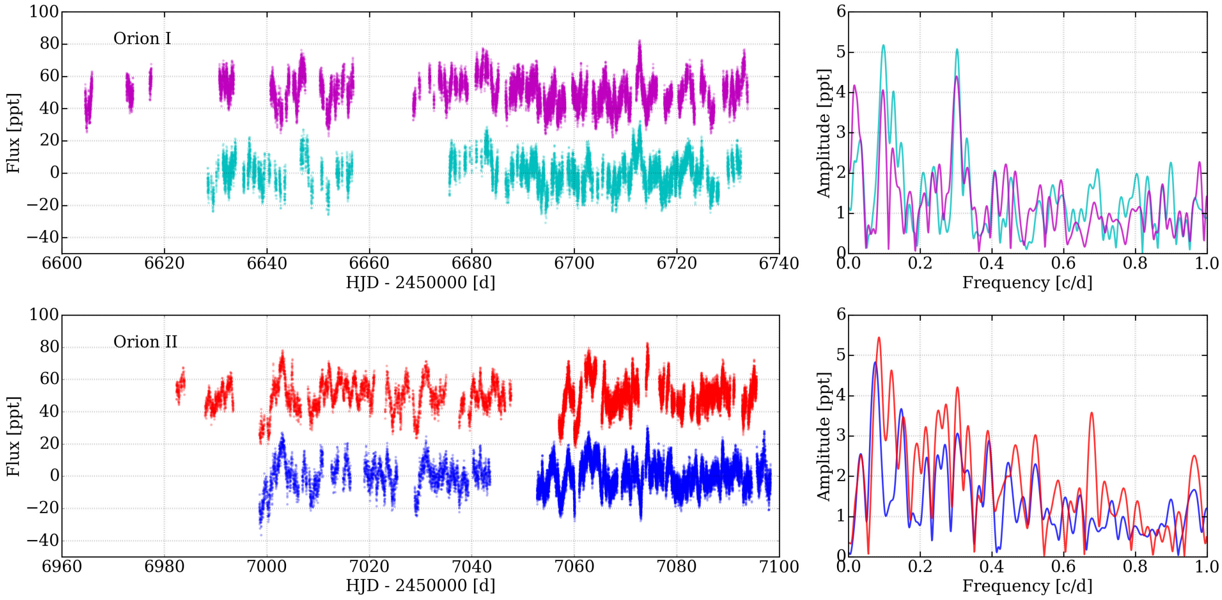

Fig. 2. *Left*: Studied BRITE photometry for ζ Ori, fully detrended and corrected for instrumental effects for the Orion I (*top*) and Orion II (*bottom*) observing campaigns. The color represents which nano-satellite of the BRITE-Constellation monitored ζ Ori: cyan for BAb, red for BHr, blue for BLb, and magenta for UBr. The flux variations are given in parts-per-thousand (ppt). Observations taken by a red nano-satellite (UBr, BHr) have an offset of 50 ppt for increased visibility. *Right*: Corresponding Lomb-Scargle periodograms of the photometry. The amplitude of the variability is marked in ppt. No significant variability was found outside the region of 0 to 1 d^{-1}.

3.1 Rotation

Both the Orion I and Orion II photometry of ζ Ori Aa show variations with f_{rot} and its higher harmonics, irrespectively of the color. Of these harmonics, $2f_{rot}$ is the most pronounced, and is most likely related to the magnetic poles coming twice into view per rotation cycle. This is often observed for magnetic massive stars (e.g. σ Ori E Oksala et al. 2015). The amplitudes of the variations related to the rotation and its harmonics differ per observing campaign. $2f_{rot}$ is the strongest of the rotational variation for Orion I data, while it is f_{rot} itself for Orion II. Combining the measurements of f_{rot} and its higher harmonics to increase the precision, we obtain $P_{rot} = 6.65 \pm 0.28$ d. This value is consistent within the error bars with the rotation period of Blazère et al. (2015, i.e. 6.83 ± 0.08 d).

3.2 Circumstellar environment

The origin of the photometric variations with f_{env} can be understood by performing a comparison with high-resolution CHIRON spectroscopy (Tokovinin et al. 2013), simultaneously taken with the second part of the

Orion II campaign (Fig. 3). In particular, we investigated the variability of the P Cygni profile of the Hα line and changes of its equivalent width with respect to time. Both analyses confirmed the presence of the variability with $f_{\rm env}$ in the Hα emission line, indicating that the circumstellar environment of ζ Ori Aa is causing the brightness changes seen in the BRITE photometry. Since the timescale is not related to the rotation period of the star, we consider it unlikely that the magnetosphere is causing the variations. Instead, we propose that periodic mass loss produces these variations, although the exact mechanism remains unknown at present. Discrepancies in the circumstellar behaviour could also explain why the BRITE lightcurves of the Orion I and Orion II campaigns display significant differences, with stronger activity in Orion II.

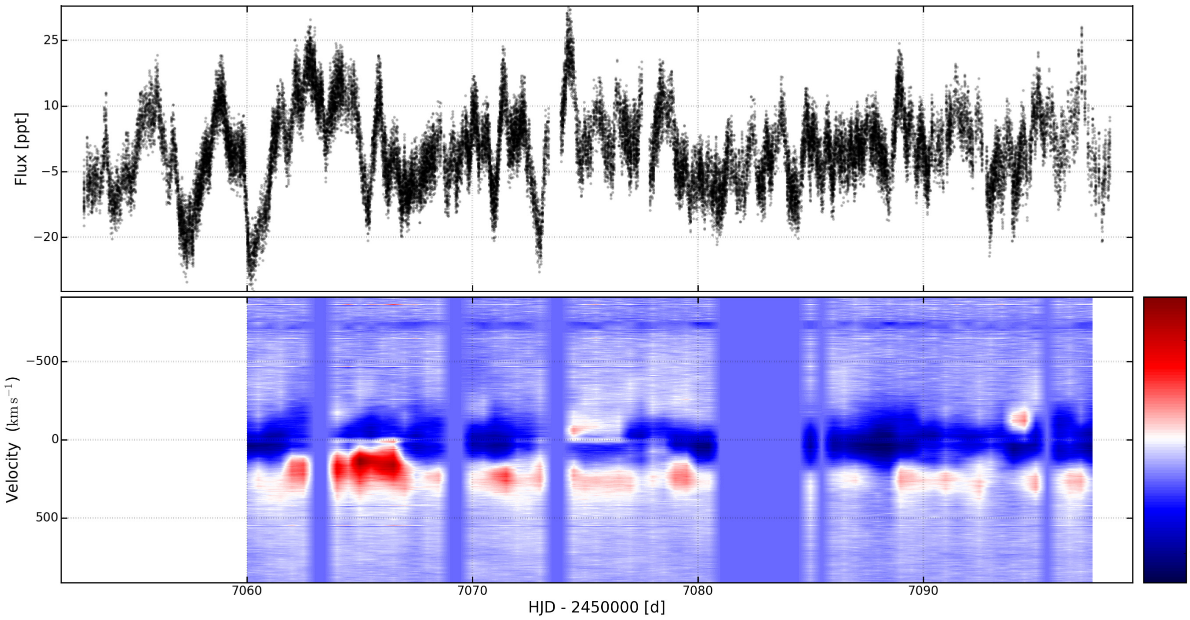

Fig. 3. *Top*: BRITE photometry during the second half of the Orion II campaign, with merged blue and red color information. *Bottom*: Dynamical plot of the Hα line observed in the simultaneous CHIRON spectroscopy.

4 Conclusions

We analysed two-color BRITE photometry of ζ Ori, taken during two observing campaigns. The data indicates the star is photometrically variable. Thanks to an iterative prewhitening approach, we recover several significant frequencies, which can be explained as higher harmonics and simple linear combinations of two fundamental frequencies. The first frequency is $f_{\rm rot} = 0.15 \pm 0.02\,{\rm d}^{-1}$, the rotation period of ζ Ori Aa, and agrees well with the literature value. The second frequency is $f_{\rm env} = 0.10 \pm 0.02\,{\rm d}^{-1}$. Thanks to simultaneous spectroscopy of the Hα line, we show that it has its origin in the circumstellar environment of ζ Ori Aa. Period mass loss is the proposed driving mechanism for these variations. Additional variability remains present in the residuals.

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