Observing the Massive Binary η Carinae with BRITE

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η Carinae was observed both during 2016 and 2017 with the *BRITE* nanosatellites. We found two coherent photometric variations that we interpret as possible tidally excited oscillations. We briefly review the system and present our essential findings here.

1 The enigmatic η Carinae

η Car is one of the most studied objects in the sky. Photometric observations can be traced back to before the Great Eruption that occurred around 1843 (e.g., Humphreys & Davidson, 1994; Smith & Frew, 2011), when the binary system expelled many solar masses of material to create the bipolar Homunculus nebula that surrounds the system today. After dust began to form and this eruption ended, the system faded to below naked eye visibility. Since then, the system has been slowly growing in brightness, and is currently at a V-band magnitude near 4.2. There are excursions in the brightness observed near periastron, as seen by Whitelock et al. (2004) and Fernández-Lajús et al. (2010). The primary star is often considered to be a prototypical luminous blue variable (LBV).

The binary nature of the system was first proposed by Damineli et al. (1997). The binary has an orbital period of 5.54 years, and is highly eccentric. The companion provides a large ionizing flux that keeps at least part of the pstellar wind and circumbinary gases in a higher ionization state (Mehner et al., 2010). During periastron passages, the companion gets extremely close to the primary star, and penetrates deep into the primary stellar wind. This causes the ionization to change rapidly, which can be tracked through X-ray variability (Corcoran et al., 2017) as well as through optical emission line variability (e.g., Teodoro et al., 2016; Richardson et al., 2016).

Modeling of the system has been accomplished through smoothed particle hydrodynamical simulations and has been able to reproduce many observed properties of the system. Some of the best modeling was described by Madura et al. (2013). These models were verified with spatially resolved spectroscopy from the *Hubble*

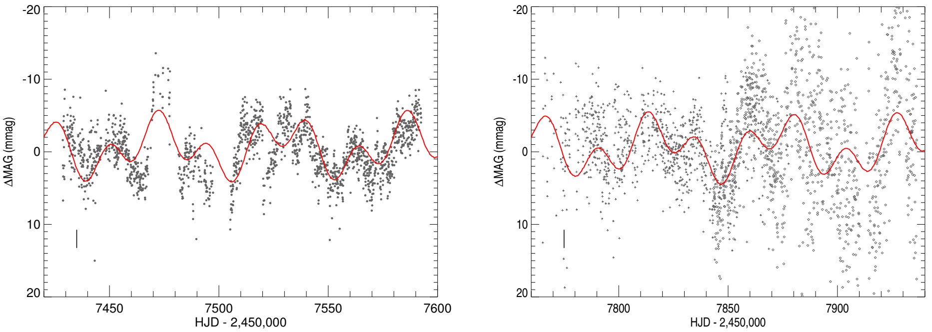

Fig. 1: The light curves observed by *BRITE* in 2016 (left) and 2017 (right). The data points are solid circles (●; BTr), plus signs (+; UBr), and open diamonds (◇; BHr) with the two-frequency fit shown in red. Each panel shows 180 d of time on the abscissa, with nearly 180 d between the two panels. A typical 2σ error bar for the data is shown in each panel.

Table 1: Observed Frequencies and possible Orbital Harmonics for η Car

	Frequency ($\mathrm{c\ d^{-1}}$)	Period (d)	Amplitude (mmag)	Phase	S/N	Potential Harmonics
f_1	0.0174(5)	58.8	2.64	0.551	4.05	30–40
f_2	0.0440(5)	22.7	2.47	0.042	4.00	85–94

Space Telescope and the Space Telescope Imaging Spectrograph. They were able to reproduce the X-ray variability observed by Corcoran et al. (2017), the variability of the He II λ4686 emission line in the wind shocks (Teodoro et al., 2016), and the characteristics of the He I P Cygni absorptions observed by Richardson et al. (2016).

2 BRITE observations

LBVs have not been well-studied with high-precision, high-cadence, time-series photometry, showing the importance of the *BRITE* network. η Car was observed as part of the CruCar field in 2016 with BRITE-Toronto (BTr), and again as part of the Car-I field in 2017 with both UniBRITE (UBr) and BRITE-Heweliusz (BHr). LBVs tend to have longer timescales present in their variability, so we concentrated on using binned data from each satellite orbit. The combined light curve has a precision of 1–2 mmag per point, with 1631 points from BTr, 884 points from UBr, and 1056 points from BHr. The light curves are shown in Fig. 1.

The *BRITE* light curves are plotted in Fig. 1. The variability is clearly at a higher amplitude than the errors of the individual points, so we began our analysis by using the `Period04` software (Lenz & Breger, 2005) to calculate the amplitude of the Fourier transform of the data, shown in Fig. 2.

Also shown in Fig. 2 is the noise floor for the Fourier transform amplitude, similar to that described by Pablo et al. (2017). The noise floor represents the level at which no reliable signal is fit. It includes any contribution from the actual periods that are

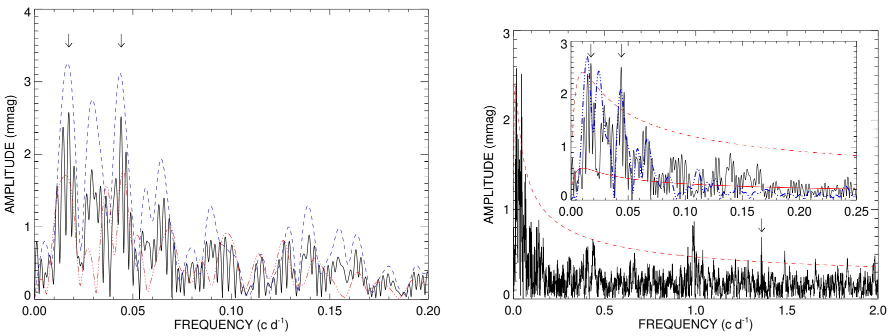

Fig. 2: Fourier amplitude spectrum of the photometric data. On the left, we show the Fourier spectrum of the 2016 data (blue dashed line), the 2017 data (red dot-dashed line), and the combined dataset (black solid line). The combined dataset provides similar peaks to the peaks from the individual seasons. In the right panel, we show the Fourier amplitude spectrum of the combined data set, highlighting the frequency that represents a harmonic of the orbital period of CPD $-59°2628$. In the inset plot, we show the noise floor in red, along with a 4σ detection threshold in a dashed red line. The two periods from Table 1 are highlighted. The blue dot-dashed line shows a Fourier amplitude spectrum of the TIDES model discussed in the text.

present in the data, so may be over-estimated at low frequencies. The two observed significant frequencies are listed in Table 1, along with their corresponding periods and amplitudes. The signal-to-noise ratio of the peaks is about 4× the noise floor. We note that these values of significance may actually be higher as the noise floor could be over-estimated for these low frequencies. With additional data taken by *BRITE* in the future, the significance of these peaks should increase. Further, these peaks are diluted by contamination from the Homunculus nebula and the strong Hα emission from the central star.

We note that there is contamination of the light curve by other sources, as η Car is in a very crowded region of the sky. One example is the eclipsing binary CPD $-59°2628$ (Freyhammer et al., 2001). We performed a strong de-trending of the *BRITE* data through binning on the orbital period of CPD $-59°2628$, and were able to recover the eclipsing nature of its light curve. The star shows 0.5 magnitude eclipses when observed alone, but the depth of the eclipse is only ~ 2 mmag in this case. Given that the main contaminants of the light curve of η Car are the Homunculus nebula, and 6 other O stars, we suspect that the larger variability seen in the Fourier amplitude (amplitudes of ~ 2.5 mmag) must come from the η Car system as no O star has been observed to have coherent oscillations at these timescales.

3 Possible interpretations

Pulsations or pulsation-like behavior have been observed in LBVs before. The oscillations detected by *BRITE* could represent strange mode pulsations that are expected to be the primary pulsations for stars that have gone through a red supergiant phase (Saio et al., 2013). LBVs have been observed to have non-periodic variations in their photometry lasting decades (Humphreys & Davidson, 1994) and these are thought to be driven by either an enhanced κ-mechanism or strange mode oscillation which can account for many of the observed time-scales in LBVs and in normal supergiants (Saio et al., 2013). However, η Car is not expected to have passed through the RSG phase. Lamers et al. (1998) examined the variability of several LBVs and found that the microvariability may be able to be explained by g-modes. They found periods ranging from 18–195 d, but all periods showed large changes over time scales of a few hundred days. Given the results of the *BRITE* photometry, f_1 may have been stable for many decades when compared with past ground-based measurements (van Genderen et al., 1995; Sterken et al., 1996).

The strange modes and g-modes are not necessarily good interpretations of these data as the coherence is much better than in other LBVs. Thus, we suspect that the probable source of these pulsations appears to be tidally excited oscillations (TEOs) and this seems plausible given our derived periods. While there has never been a system with such a long orbital period observed to exhibit TEOs, η Car also has an unusually high eccentricity, and unusually high masses ($90+30 M_{\odot}$; Madura et al., 2013). It is reasonable to suspect that these pulsations are TEOs as seen in several "heartbeat" systems (e.g., Guo et al., 2017), even though these pulsations are observed far from the periastron event.

We tested our hypothesis of the TEOs using the TIDES code (Moreno & Koenigsberger, 1999; Moreno et al., 2011). The calculations assumed masses similar to those most modern simulations of the system (Madura et al., 2013), namely the primary star having a mass of $100\,\mathrm{M}_{\odot}$ and a radius of $90\,\mathrm{R}_{\odot}$, with the secondary star having a mass of $30\,\mathrm{M}_{\odot}$. One parameter used in these simulations is the synchronicity between the rotation of the primary star and that of the orbit at periastron. For these first calculations, we use a ratio of the two of 0.464, i.e., the star is rotating at 46% of the angular rate of the orbit at periastron. The results of the calculations are the radius as a function of orbital phase. We used this with the Stefan-Boltzmann law with $T_{\mathrm{eff}} = 27,500\,\mathrm{K}$ to derive a light curve for the same phase region as our *BRITE* observations. Our effective temperature is from the models of Hillier et al. (2001).

From this simulated light curve, we extracted the portion from the same orbital phase range as these *BRITE* measurements. We de-trended the light curve in a similar manner as the data reduction from the observations, and then calculated the Fourier transform amplitude of the simulated light curve. We scaled the Fourier amplitude to match the intensity of the strongest peaks in Fig. 2, shown as a blue line. The resulting Fourier analysis shows similar peaks to our derived f_1 and f_2 from *BRITE.* We note that while the parameters of this specific simulation were not fine-tuned to our derived photometric frequencies, they nevertheless show that TEOs are a reasonable interpretation of the data, and that further observations with the nanosatellites will provide a better precision on the pulsational frequencies. This provides a natural explanation for the long-lived nature of f_1 that was first reported from data collected more than two decades ago (van Genderen et al., 1995; Sterken et al., 1996). Since our times of maxima seem to coincide with those of the previous studies, we suspect these modes to be tidally excited.

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