Stars and their variability observed from space
C. Neiner, W. W. Weiss, D. Baade, R. E. Griffin, C. C. Lovekin, A. F. J. Moffat (eds)

BRITENESS VARIATIONS OF THE BRITEST HOT STARS

T. Ramiaramanantsoa[1] and A. F. J. Moffat[2]

Abstract. We and our collaborators have been using *BRITE-Constellation* since the beginning of the mission to observe some of the intrinsically and apparently brightest hot stars in the sky. This includes O stars, luminous blue variables (LBVs) and Wolf-Rayet (WR) stars, which share the feature of driving strong winds and ending in a supernova explosion yielding mainly a black hole, or a neutron star in some cases, or even no remnant at all. As such, O stars and their descendant LBVs and WR stars are tied to gamma-ray bursts and gravitational wave sources, as well as to the first stars to form in the Universe which were predominantly very massive. We present two key cases for O and WR stars observed by *BRITE*, with their implications for hot star winds and internal structure. In particular, contrary to expectations, hot luminous stars (especially the most extreme among them) tend to show hydrostatic-surface, semi-stable bright spots that betray the stellar rotation. Such bright spots are found to drive large-scale, spiral-shaped, wind features known as co-rotating interaction regions (CIRs), so far regarded as virtually present in all O-star and some WR-star winds. These bright spots are likely the direct result of a distinct layer of subsurface convection, as proposed by recent theoretical investigations. This layer may also be the ultimate source of shorter-lived stochastic perturbations in the photosphere, which are found to drive clumping in the inner part of O-star and very likely also WR winds.

Keywords: Stars: massive, Stars: rotation, (Stars:) starspots, Stars: Wolf-Rayet, Stars: winds, outflows, Turbulence, Techniques: photometric, Space vehicles

1 Introduction

BRIght Target Explorer (*BRITE-Constellation*; Weiss et al. 2014; Pablo et al. 2016) is a fleet of five independent nanosatellites each equipped with a 30-mm telescope and CCD detector to carry out precision, time-dependent optical photometry of bright stars down to $4-6$ visual apparent magnitude. *BRITE* is well adapted to observe massive stars in particular because (1) satellite pointing constraints favour the higher stellar density of apparently bright stars towards the Galactic plane, where massive stars also tend to lie, and (2) *BRITE* can observe for long, uninterrupted intervals of up to six months, well matched to the relatively long variability timescales encountered in massive stars.

Massive stars have initial masses $\mathrm{M_i} \gtrsim 8\mathrm{M_\odot}$ and explode as core-collapse or pair-instability supernovae at the end of their short lives. Very massive stars (VMS) are taken to be massive stars with strong stellar winds and $\mathrm{M_i} \gtrsim 20\mathrm{M_\odot}$, and include all O-type stars on the main sequence plus all of their descendants, mainly luminous blue variables (LBVs) and Wolf-Rayet (WR) stars. Compared to solar-like stars, VMS, while much rarer and shorter-lasting, dominate the luminosities and especially the mass-loss in star-forming regions like the spiral arms of spiral galaxies.

In the Hertzsprung-Russell diagram, O stars lie just above the β Cep instability strip, which includes mostly early-B stars. However, this instability strip spills over to higher luminosity and includes some of the latest-type, O9 stars. A good example of this is the O9.5V star ζ Oph, with clear β Cep-type pulsations as revealed most clearly by *BRITE*'s precursor, the *MOST (Microvariability and Oscillations of STars)* microsatellite mission (Walker et al. 2005), as well as other space-based observatories (Howarth et al. 2014).

On the other hand, early O-type stars show fewer pulsations, if any (section 1.1 in Ramiaramanantsoa et al. 2018a for a recent review). Instead, they are found to exhibit both stochastic and cyclic variability at their photosphere and in their wind, possibly ultimately connected to a subsurface convection zone caused by partial ionization of iron atoms with their prolific number of atomic transitions, despite their relatively low abundance (Cantiello et al. 2009; Cantiello & Braithwaite 2011). Massive He-burning WR stars have even

[1] School of Earth and Space Exploration, Arizona State University, 781 E. Terrace Mall, Tempe, AZ, USA 85287-6004
[2] Département de physique, Université de Montréal, CP 6128, Succursale Centre-Ville, Montréal, Québec, H3C 3J7

hotter hydrostatic surface temperatures than (H-burning) O stars (Hamann et al. 2019). Those WR stars with the coolest temperatures tend to be more variable (Michaux et al. 2014), because the subsurface iron convection zone is located deeper into the star and involves more driving mass. Here we concentrate on two prime examples, both single, one a well-known early-O supergiant, and the other a strongly variable WR star. Both serve as good proxies of other stars in their class.

2 The O4I(n)fp star ζ Puppis

The very well-known hot massive O-type supergiant ζ Pup [O4I(n)fp] has been studied at many wavelengths as a standard for its type. This may be somewhat surprising, given its runaway nature and possibility of surface pollution. The most likely scenario explaining its current runaway status is that it might have been the secondary in a massive binary, in which the primary exploded as a supernova, likely leaving behind a black hole moving in the opposite direction to ζ Pup. Such a scenario explains its high projected rotational velocity (for a supergiant) of $v \sin i = 219 \pm 18$ km s^{-1} as a result of the spin-up expected in the Roche-lobe overflow (RLOF) stage of the pre-runaway process.

Several studies geared to exploring the variability of ζ Pup have led to periodicities ranging from 8.5 h to 5 d. Our recent investigation (Ramiaramanantsoa et al. 2018a) using *BRITE* is arguably the most far-reaching to date. We discovered for the very first time a direct link via variability between the surface of a massive, hot star and its strong wind. With 56M$_\odot$, ζ Pup is the most massive star observed so far by *BRITE*, although a recent revision of its distance decreases this mass somewhat (Howarth & van Leeuwen 2019). The *BRITE* light curve extends non-stop (except for odd gaps) over almost 6 months in both the blue and red *BRITE* optical filters. With orbit-binned cadence of $\sim$ 100 min, the blue and red light curves (varying at the 10 mmag level compared to the instrumental level of just over 1 mmag) are highly correlated, both supporting its reality and suggesting that the stellar surface source of continuum variability is either of similar temperature to (but brighter than) the rest of the stellar surface, or is much hotter than the surrounding photosphere (although the observations are not sensitive to a difference in temperature at the Rayleigh-Jeans tail far from the UV peak emission).

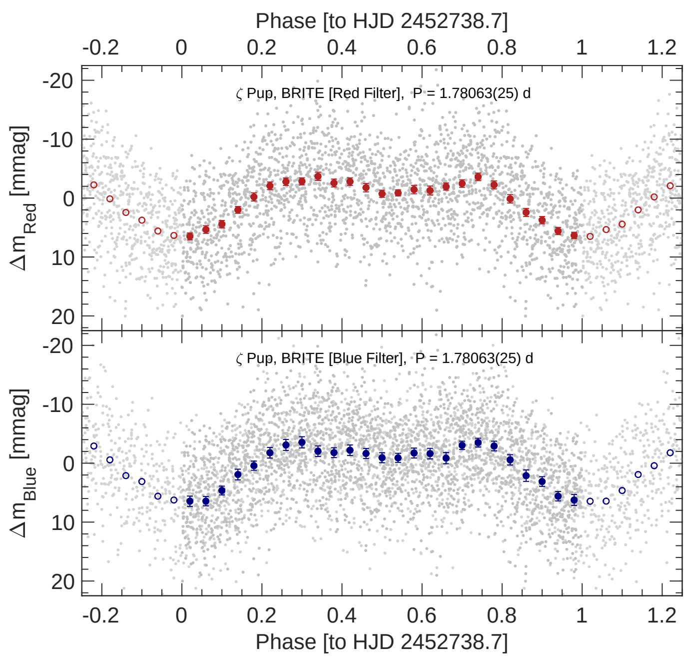

Fig. 1. *BRITE* light curves of ζ Pup phased with the 1.78-d period found to be the stellar rotation period. The scatter around the binned values is intrinsic, given the observed precision of $1 - 2$ mmag per datapoint.

2.1 Light variability arising from bright photospheric spots

The Fourier analysis of the whole *BRITE* light curves of ζ Pup reveals a period of 1.78 d, identical to that found from lower-precision but more voluminous, earlier *Coriolis/SMEI* satellite data (Howarth & Stevens

2014). Fig. 1 shows the orbit-binned light curve in each filter, phased with the 1.78 d period. While Howarth & Stevens (2014) found a single-peaked phased light curve, we now clearly see double (or even multiple) peaks. Also, in the frequency domain, while only the peak corresponding to the 1.78 d periodicity was present during the epoch of the *Coriolis/SMEI* observations, the first harmonic of that signal also appeared during the *BRITE* observing run.

The shape-changing behaviour of the observed phased light curve and the behaviour of its periodogram are indicative of rotational modulation due to localized brightness enhancements in the stellar photosphere from where $\gtrsim 99\%$ of the optical continuum light is arising. We then carried out a light-curve inversion to locate the bright spots on the stellar surface using the algorithm developed by Harmon & Crews (2000). We found that, depending on the epoch of observation, two to three bright spots are required along with slow variability in relative strength to reproduce the observed light curve. We also found that the spots grow and fade on timescales of weeks.

Such spots may be the footprint seeds of the well-observed CIRs (or their projected UV resonant-line P Cygni absorption manifestations called discrete absorption components) in the wind of ζ Pup (e.g. Howarth et al. 1995), with two dominating and spaced typically about 20 h (about half a 1.78 d rotation period) apart. Our ground-based high S/N contemporaneous optical spectra bear this out, showing that we see the same 1.78 d periodicity in the strongest optical He II λ4686 emission line from the inner wind (see Fig. 2). Further modeling of this spectral recombination line with CIRs at three distinct intervals of the *BRITE* observations corroborate this idea for the origin of the 1.78 d period as due to rotation of slowly varying bright spots fixed in the rotating frame of the stellar surface. We also detected rotation-phase delays for different wind lines formed at different distances from the central star.

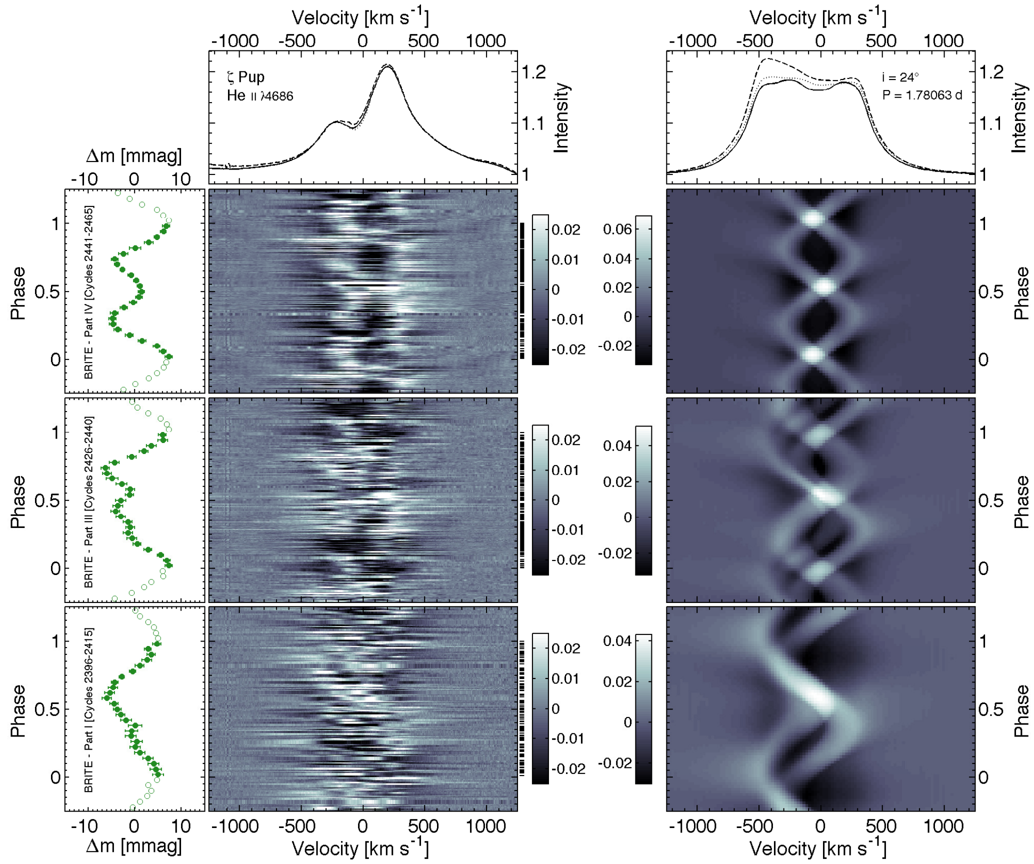

Fig. 2. *BRITE* light curve of ζ Pup and variations in its He II λ4686 emission line phased with the 1.78-d period (left), along with models of wind emission line-profile variations due to arms of CIRs.

If indeed the 1.78 d periodicity is identified as the rotation period, this leads to a rather low rotation-axis inclination of 24^{+10}_{-6} degrees. In this case, the true equatorial rotation speed would be just over 500 km/s, making ζ Pup an extreme rotator, likely spun up in a pre-separation RLOF process.

2.2 Stochastic photospheric light variability

Of equal interest as the cyclic light variations due to localized bright surface spots is the fact that the *BRITE* scatter around the 1.78 d binned light curve depicted in Fig. 1 is quite real, with variation amplitude comparable to that of the periodic signal. This appears to be the first time such apparently random variability has been unequivocally seen in ζ Pup, facilitated by the contemporaneous observations by three independent *BRITE* satellites in two distinct optical filters, allowing one to better assess the potential contribution of instrumental errors.

After removing the slowly varying 1.78 d signal from the observed light curve, we see no significant periodicity in either filter, rather just stochastic variations at the ±10 mmag level (same as for the 1.78 d modulation) coherent over several hours (Fig. 3). These are likely relatively short-lived randomly-triggered photospheric perturbations whose origin may lead back to stochastically-triggered oscillations in the iron subsurface convection zone and/or gravito-inertial waves generated at the interface between any convection and radiative zones (see also e.g. Aerts & Rogers 2015; Ramiaramanantsoa et al. 2018b). Given the correlation between these random surface variations seen by *BRITE* and variations in the wind-line of He II λ4686, we propose that the random photospheric perturbations act as drivers to form the (largest visible) clumps in ζ Pup's wind.

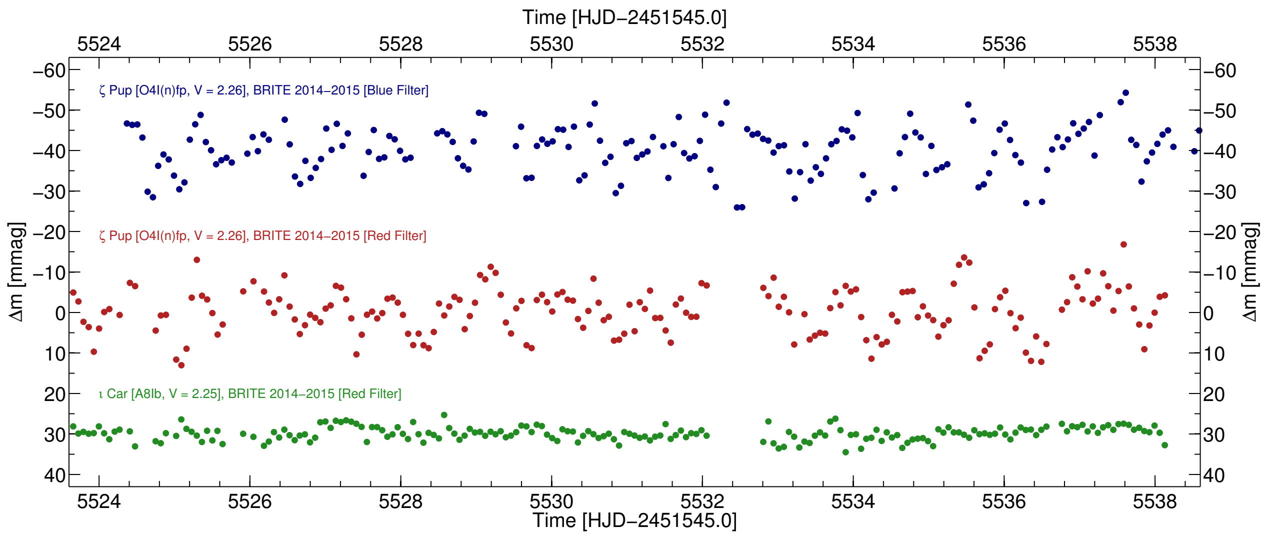

Fig. 3. Residual *BRITE* light curves of ζ Pup after removal of the 1.78 d variability.

3 The WN8h star WR 40

Among WR stars, those of the cooler nitrogen-sequence of type WN8 generally show the strongest light variability, normally completely stochastic in nature. The apparently brightest WN8 star in the sky is the V=7.7 mag WN8h ("h" means with some hydrogen left in its wind) star WR 40 = HD 96548. On the other hand, WR 40 is by far the faintest star observed intentionally by *BRITE* so far (Ramiaramanantsoa et al. 2019). However, its faintness is made up for by its relative isolation as a runaway in the sky (as are most, if not all, WN8 stars) and its high level of variability as known from previous ground-based observations (e.g. Marchenko et al. 1998). Such ground-based observations are always severely limited by day-night rhythms and weather, making space photometry a welcome tool.

Fig. 4 shows the complete *BRITE* light curve of WR 40, obtained only in the red filter. The peak-to-valley amplitude exceeds 100 mmag compared to the typical *BRITE* orbital mean bins with 5 mmag rms instrumental noise. Fig. 5 shows the overall and time-dependent Fourier transform of the *BRITE* data, revealing no outstanding Fourier peaks among a "forest" of peaks at low frequency. While short observing runs from the ground generally do show a small number of dominating power peaks, with a very long data-string such a forest would degenerate into a very broad Fourier power excess centered at around 0.2 d^{-1} in frequency (∼ 5 d in period), presumably the dominant timescale of the variations.

The time-dependent Fourier transform bears this out, with stochastically triggered signals that are present for typically 4 − 10 days (Fig. 5). We simulated this light curve using stochastic clumps that define the wind

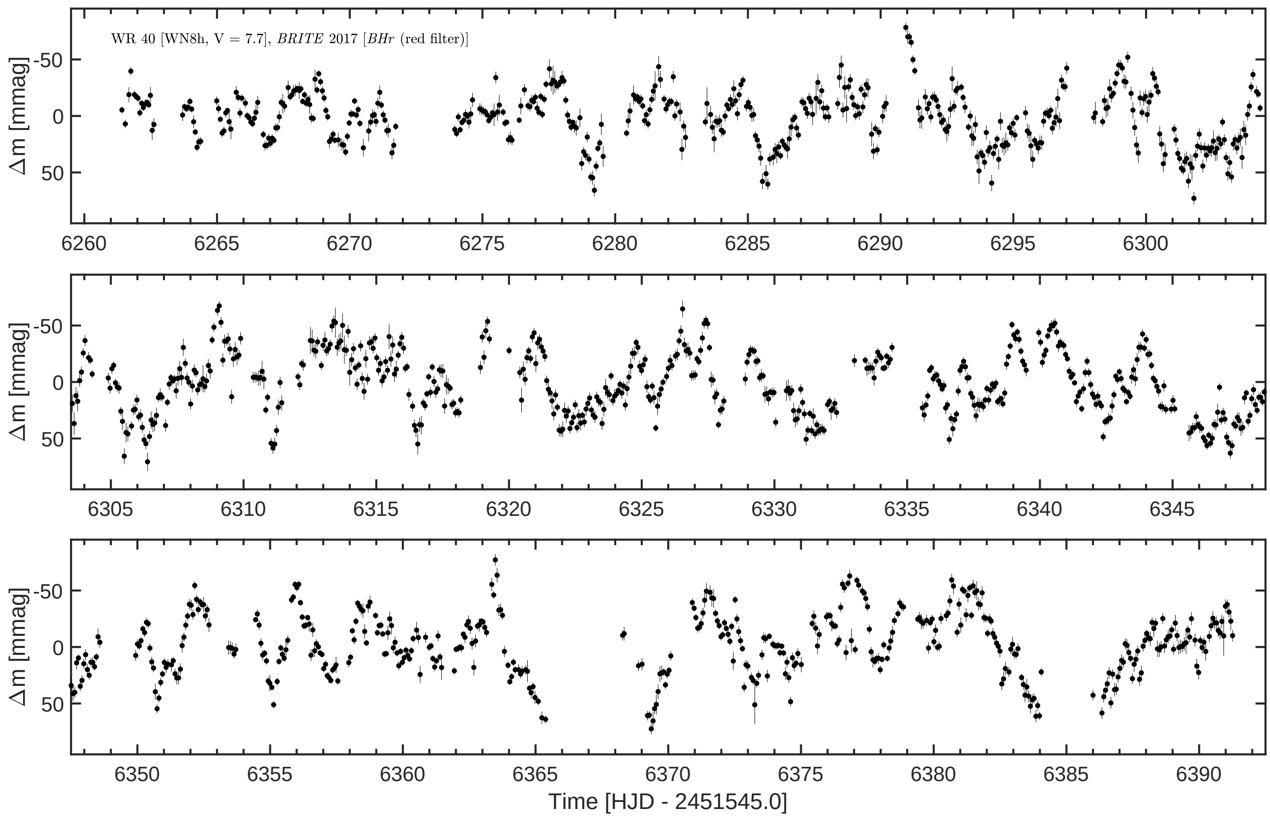

Fig. 4. Four-month long *BRITE* light curve of WR 40.

and electron-scattered light into the observer's direction. Somewhat surprisingly, both a turbulent power-law and a constant clump-size distribution yield qualitatively similar model light curves, compared to both each other and to the data. This may be a fundamental limitation of one-dimensional light curves. However, the effective higher dimension of analysis of WR 40's (and other WR stars') spectroscopic variations does favour the power law generated by the plausible presence of compressible turbulence (Moffat 1994). In any case, it seems likely that the light and spectral variations of WR 40 in particular and WN8 stars in general are dominated by random clumps being created and fading away as they propagate outward in the wind. By analogy with their progenitor O-stars, it also seems likely that the clumps are created at their hydrostatic surfaces, with enhancement possibly occurring in the wind via line-driving instability (Sundqvist & Owocki 2013).

4 Conclusions

The two highlighted massive stars illustrate:

1. how the variability of hot O-stars, with ζ Pup as a proxy, is dominated by surface features:
   (a) stochastic short-lived photospheric perturbations leading to the creation of wind clumps;
   (b) longer-living bright spots driving corotating interaction regions (CIRs) in the wind.
2. how the intrinsic variability of WR stars, with WR 40 as a proxy, is dominated by short-lived stochastic clumps.

Another WR star (WR6; St-Louis, these proceedings) is dominated by longer-living CIRs (uncertain if universal in WR stars), with clumps playing a secondary role. Both WR wind structures are likely associated with photospheric features similar to those seen in O-type stars, but unfortunately the hydrostatic stellar surfaces of WR stars are hidden by their opaque inner wind.

Although these *BRITE* observations illustrate new variability effects in just one O and one WR star, we believe that there is no reason not to expect to see similar behaviour in virtually all other early-type O stars

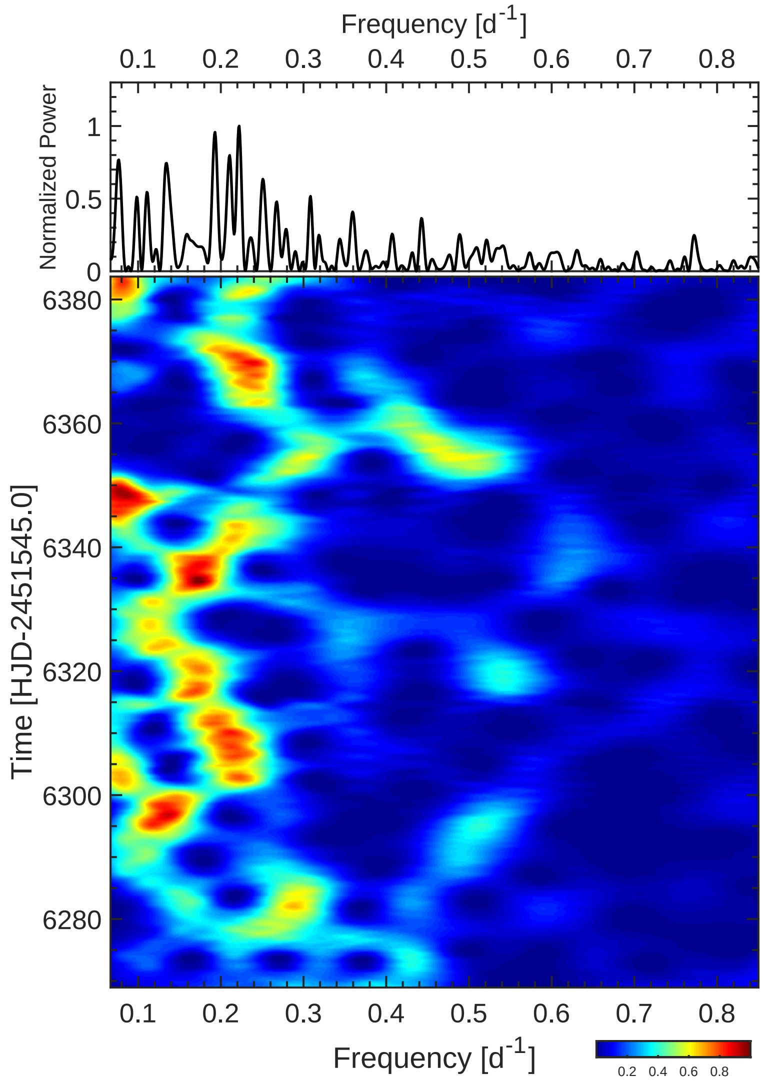

Fig. 5. Sliding windowed (15 d) Fourier transform of the *BRITE* light curve of WR 40.

and wind-dominated single WR stars. In the case of ζ Pup, we see a direct link both between bright (probably magnetic) spots in the photosphere and semi-periodic CIRs, and between randomly-triggered photospheric perturbations and stochastic clumps in the wind. In the case of WR 40 where we are limited to seeing only the wind, we do not see any indication of a periodicity, rather random variability that must be linked to the strong stochastic variability of clumps, as seen in virtually all hot-star winds.

This may be the long-sought answer for the origin of both semi-periodic (CIR-related) variations in O-star and some WR winds, and stochastic clumping variations in the winds of all massive hot stars.

Based on data collected by the BRITE-Constellation satellite mission, designed, built, launched, operated and supported by the Austrian Research Promotion Agency (FFG), the University of Vienna, the Technical University of Graz, the University of Innsbruck, the Canadian Space Agency (CSA), the University of Toronto Institute for Aerospace Studies (UTIAS), the Foundation for Polish Science & Technology (FNiTP MNiSW), and National Science Centre (NCN). AFJM is grateful to NSERC (Canada) for financial aid.

References

Aerts, C. & Rogers, T. M. 2015, ApJ, 806, L33

Cantiello, M. & Braithwaite, J. 2011, A&A, 534, A140

Cantiello, M., Langer, N., Brott, I., et al. 2009, A&A, 499, 279

Hamann, W. R., Gräfener, G., Liermann, A., et al. 2019, A&A, 625, A57

Harmon, R. O. & Crews, L. J. 2000, AJ, 120, 3274
Howarth, I. D., Goss, K. J. F., Stevens, I. R., Chaplin, W. J., & Elsworth, Y. 2014, MNRAS, 440, 1674
Howarth, I. D., Prinja, R. K., & Massa, D. 1995, ApJ, 452, L65
Howarth, I. D. & Stevens, I. R. 2014, MNRAS, 445, 2878
Howarth, I. D. & van Leeuwen, F. 2019, MNRAS, 484, 5350
Marchenko, S. V., Moffat, A. F. J., van der Hucht, K. A., et al. 1998, A&A, 331, 1022
Michaux, Y. J. L., Moffat, A. F. J., Chené, A.-N., & St-Louis, N. 2014, MNRAS, 440, 2
Moffat, A. F. J. 1994, Reviews in Modern Astronomy, 7, 51
Pablo, H., Whittaker, G. N., Popowicz, A., et al. 2016, PASP, 128, 125001
Ramiaramanantsoa, T., Ignace, R., Moffat, A. F. J., et al. 2019, MNRAS, 490, 5921
Ramiaramanantsoa, T., Moffat, A. F. J., Harmon, R., et al. 2018a, MNRAS, 473, 5532
Ramiaramanantsoa, T., Ratnasingam, R., Shenar, T., et al. 2018b, MNRAS, 480, 972
Sundqvist, J. O. & Owocki, S. P. 2013, MNRAS, 428, 1837
Walker, G. A. H., Kuschnig, R., Matthews, J. M., et al. 2005, ApJ, 623, L145
Weiss, W. W., Rucinski, S. M., Moffat, A. F. J., et al. 2014, PASP, 126, 573