Wolf-Rayet Stars with *BRITE*

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We briefly describe the four Wolf-Rayet (WR) stars that *BRITE-Constellation* has observed so far and how this array of nanosatellites can contribute to future work on WR stars. Some of the results are quite novel, even down to visual magnitude 7, the faintest star observed to date with *BRITE*.

1 Introduction

Classical WR stars (cWR) in the local Universe are to more common, less-evolved massive stars in general (initial mass $M_\mathrm{i} \sim 20 - 60\,\mathrm{M}_\odot$) as post-AGB stars are to more common, less-evolved medium-mass stars in general ($1 - 8\,\mathrm{M}_\odot$). cWR stars provide the He-burning (and subsequent very rapid burning without being noticed at the surface, up to the final nuclear product Fe) transition from the main sequence (MS) to the final state as a degenerate neutron star (NS) or, more likely, black hole (BH) after a type Ib/c supernova (SN). On the other hand a $1 - 8\,\mathrm{M}_\odot$ star will end up as a degenerate white dwarf (WD) after ejecting a planetary nebula (PN). In the intermediate range $M_\mathrm{i} \sim 8 - 20\,\mathrm{M}_\odot$ stars puff up as blue supergiants (BSGs) followed by red supergiants (RSGs) before they explode as type-II SNe.

Other types of WR stars include very massive hydrogen-containing Main Sequence stars of type WNh in the range $M_\mathrm{i} \sim 60 - 300\,\mathrm{M}_\odot$ and a lower–mass ∼15% subset of central stars of planetary nebulae (CSPN). A stellar photosphere is normally only seen in WNh stars (Moffat, 2015).

It turns out that these three types of WR star (cWR, WNh and 15% of CSPN) all have similar emission-line strengths that define them as WR. This can be understood in terms of their normalized line-emission measure, i.e. the volume integral of density-squared emission from wind material surrounding the star per unit stellar surface (Schmutz et al., 1989). A commonly asked question is: since the luminosities of cWR stars are indeed similar to those of their MS O-type progenitors, then why do cWR stars have mass-loss rates an order of magnitude higher, given that line radiation drives the wind in both cases? The answer lies in the fact that cWR stars are essentially the hot He-burning remnant cores of their progenitors. As such they emit more hard UV radiation, which delivers more radiative driving from the ambient-provided Fe-forest of spectral lines found in the UV. O stars are cooler and so provide a lower proportion of UV driving.

While mass-loss is highly important in the evolution of massive stars in general, it is most important during the WR stage (cWR or WNh). Yet we cannot see their hydrostatic cores, making them difficult yet fascinating as key elements in the chain of stellar evolution: we need to understand WR stars as much as any other phase in the evolution of massive stars. In the Galaxy 651 pop I WR stars are spectroscopically confirmed (Crowther's on-line web site[1]), while ∼700 are known outside our Galaxy (Massey et al., 2015).

2 Why observe WR stars with *BRITE*?

Taking advantage of long-term, high-precision, high-cadence photometry anywhere along the Milky Way from space, one can:

- Probe variable structures (stochastic clumps & co-rotating interaction regions) in the strong winds of WR stars leading to better understanding of hot-star winds in general
- Try to detect pulsations from the underlying star (if not filtered out by the wind) to probe internal stellar structure
- Constrain properties in binaries ($\sim 30-40\,\%$ of Galactic WR stars have OB companions: Vanbeveren et al., in prep.)
- Use two passbands that give temperature information
- Probe the dominating timescales ∼ hours-days, which are difficult from the ground

3 *BRITE* observations of WR stars

Details for the four WR stars observed so far with *BRITE* (Tab. 1) are as follows.

3.1 WR6 = EZ CMa

This is strongly believed to be a single WN4b ('b' means broad-line with no H) star with the clearest large-scale structures (Morel et al., 1997) known as co-rotating interaction regions (CIRs: see Dessart & Chesneau, 2002) known in any WR star. It is the faintest of any star observed so far by *BRITE*, with a respectable 3.5 mmag rms error per 100-minute orbit in one filter (red). Our *BRITE* light curve (Fig. 1) is by far the most intense and comprehensive ever obtained for this star and shows its typical variability on its well-known period of 3.76 d (confirmed by its Fourier power spectrum – not shown here for lack of space – with power peaks of the fundamental frequency due to rotation, $P_{\rm rot} = 3.76$ d, and its harmonics, along with Lorentz-broadened profiles caused by slowly evolving CIRs), for which the most important finding is a dynamic plot (Fig. 2) showing how its CIRs come and go over timescales of ∼10 rotation cycles, probably driven by rotating bright spots at the

[1] http://pacrowther.staff.shef.ac.uk/WRcat/

Star	V (mag)	Sp	Binarity
WR11 = γ^2 Vel	1.8	WC8+O7.5III	SB2, $P = 78.5$ d
WR48 = θ Mus	5.7	WC6(+O9.7Iab)	SB1, $P = 19.1$ d
WR79a	5.8	WN9ha	single?
WR22	6.4	WN7h+O9IV	SB2, $P = 80.35$ d
WR24	6.5	WN6ha	single
WR78	6.5	WN6ha	single
WR79	6.6	WC7+O6.5	SB2, $P = 8.89$ d, crowded cluster
WR133	6.8	WN5o+O9I	SB2, $P = 112.8$ d, crowded cluster
WR6 = EZ CMa	6.9	WN4b	single, prominent CIRs, $P_{\rm rot} = 3.76$ d
WR140	6.9	WC7pd+O5.5fc	SB2, $P = 2900$ d, prototype colliding winds
WR90	7.0	WC7	single

Table 1: The 11 WR stars brighter than $V = 7$ mag with the four already observed by *BRITE* indicated in bold font.

hydrostatic stellar "surface" that create the CIRs, as in O-stars (Cranmer & Owocki, 1996). We interpret the *BRITE* variability as due to bright CIRs poking out of the optically thick wind below, where they scatter continuum light into the line-of-sight and possibly radiate themselves. Finally we have a potential way to probe the inner thick wind! A paper will appear soon that includes ground-based simultaneous spectroscopy (St-Louis et al., in prep.).

3.2 WR11 = γ^2 Vel

This well-known WC8+O7.5III 78.5 d binary is the brightest WR star in the sky and has been resolved as a visual system (North et al., 2007). Our *BRITE* light curve shows a binary-period modulation with the same amplitude in each filter along with significant intrinsic scatter likely due to wind clumping in the WR component. The phased light-curve can be fit by a $1/D$ (D = orbital separation) curve, as expected, with amplitude ~ 0.01 mag. Parallel spectroscopy shows that this light modulation is due entirely to variations in spectral lines as a result of colliding winds (CWs). A first journal paper has been published (Richardson et al., 2017), which will be followed by others.

3.3 WR24

This single WNh star is the only WR star known to have exhibited discrete absorption components (DACs), normally semi-periodic, in its unsaturated He II λ1640 UV line as monitored by the *International Ultraviolet Explorer (IUE)* in 1985 (Prinja & Smith, 1992). Our *BRITE* light-curve shows stochastic variability with no significant periods, unlike what might be expected from the DACs. A paper will follow soon (St-Louis et al., in prep.).

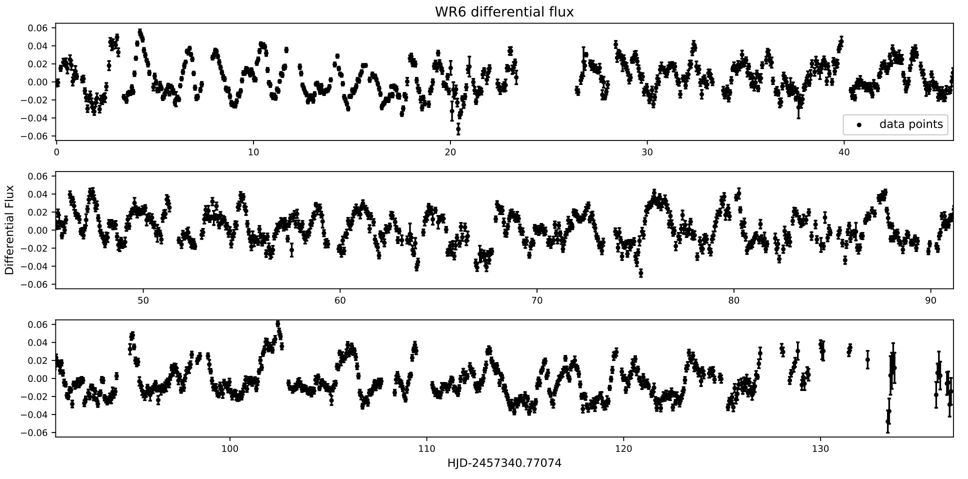

Fig. 1: *BRITE* light-curve of EZ CMa obtained by BTr in 2016.

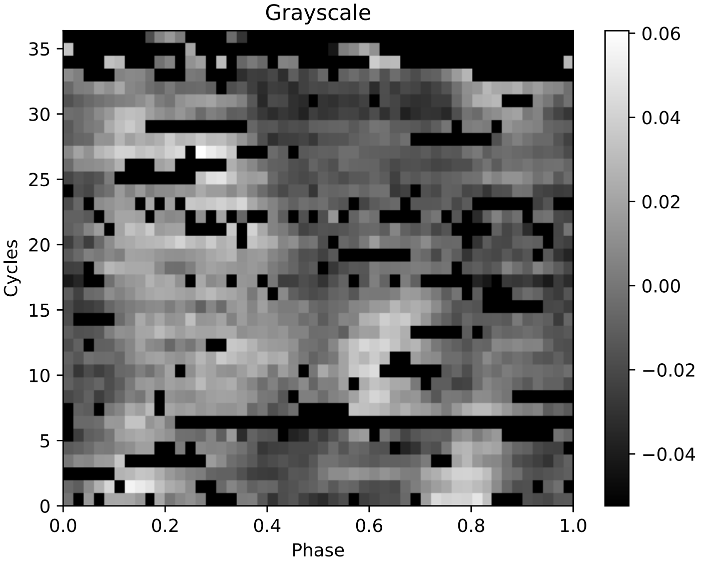

Fig. 2: Dynamic plot of the *BRITE* light-curve for EZ CMa with $P = 3.76\,\mathrm{d}$ and arbitrary time zero-point. Intensity is grayscale coded (right). Discrete events stand out at various phases, with some confusion (several CIRs piling up at phases $0.1 - 0.4$ over cycles $10 - 30$).

3.4 WR48 = θ Mus

This second-brightest WR star in the sky is a known triple system involving a 19.1 d WC6+O binary subsystem in a much longer orbit with a late-O supergiant, which dominates the light and spectrum. The *BRITE* light-curve shows lots of variability at different timescales, although without any significant period beyond the possible Fourier peak at the orbital period. Such orbital modulations are often seen in short-period WR+O binaries and are due to atmospheric eclipses of the O-star as it orbits in the wind of the WR star (Lamontagne et al., 1996). In such cases, analysis of the light-curve shape reveals useful information on the orbital inclination and WR mass-loss rate not enhanced by density-squared radiative processes. In the original binary discovery paper, Moffat & Seggewiss (1977) failed to reveal such an orbit-modulated light-curve, probably due to the shorter and less-precise ground-based observing run. This work will be the subject of a pending publication (Pablo et al., in prep.).

4 Conclusions

- *BRITE* works well even at $V \sim 7$ mag (BTr): $\sigma = 3.5$ mmag per *BRITE* orbit
- At least six more WR stars are well observable to $V = 7$ mag
- Unique results can be obtained for WR stars with *BRITE*

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