The variability of γ^2 Vel and other massive stars with strong stellar winds, as seen with BRITE and ground-based spectroscopy

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Massive stars lose a large portion of their mass prior to their supernova explosions. This has long been studied through spectroscopic and photometric techniques, but very few programs have offered a glimpse of the short-term variations through continuous coverage. We have arranged ground-based time-series spectroscopy for a number of massive stars that have strong stellar winds. This is leading to an understanding of the short-term variations in evolved, massive stars with programs that have been mostly inaccessible in the past. We describe the initial results on γ^2 Vel related to its colliding winds and orbit, and briefly outline future studies that we will have for both this system and other massive stars with large mass-loss rates.

1 Massive stars

Massive stars provide important feedback to their parent galaxies through both ionizing radiation, stellar winds, and their terminal supernova explosions. They are usually found in binary systems, and these binaries will often interact during their lives (Sana et al., 2012). During the course of binary evolution, a majority of interactions involve matter transferring from one star to the other. Sometimes, they merge into one rapidly rotating star, but the majority of the time, they involve Roche lobe overflow (RLOF) from the primary to spin up the companion star. Through either the RLOF process or strong stellar winds, the primary star can lose its envelope and become a classical Wolf-Rayet (WR) star.

There have been a few WR stars that were observed with precision time-series photometry with the *MOST* space telescope. These data are complicated in that they show variations which may be related to large-scale structures in the winds of these stars, but have not all been spectroscopically confirmed (Chené et al., 2011). In the case of WR 123, Lefèvre et al. (2005) found that the star may have pulsations with a period of 10 h, but this has not been proven for any other WR yet. Several WR stars show evidence of a photometric wind eclipses, where electron scattering causes symmetric dips in their light curves (Lamontagne et al., 1996). This was seen in the WR binary CV Serpentis with the *MOST* satellite by David-Uraz et al. (2012), but the eclipses changed with each cycle. The authors attributed the changing eclipse depths as evidence for sporadic dust formation within the wind of the WR star. The relative faintness of the WR stars observed with *MOST* has limited our understanding of the variability, as obtaining spectroscopic support for the photometry was not favorable to scheduling at telescopes in ideal locations. This study aims to fill these limitations to our understanding of the variability.

2 γ^2 Vel

γ^2 Vel is the brightest WR star in the sky due to its proximity to us at a distance of only 330^{+8}_{-7} pc (North et al., 2007). It is a double-lined spectroscopic binary, composed of a WC7 and an O7 star, with an orbital period of 78.53 d (Schmutz et al. 1997). The individual component stars were modeled with the non-LTE radiative transfer code CMFGEN by De Marco & Schmutz (1999) and De Marco et al. (2000). The spectroscopic orbit is fairly well-defined and was combined with an interferometric analysis of the orbit by North et al. (2007). The combination of these studies leads to very precise orbital parameters such as the inclination of $65.5{\pm}0.4°$ and stellar masses ($M_{\rm WR} = 9.0 \pm 0.6 M_\odot$; $M_{\rm O} = 28.5 \pm 1.1 M_\odot$), allowing us to study the binary in detail and constrain the physical processes in colliding-wind binaries.

The BRITE-Constellation nanosatellites observed γ^2 Vel photometrically for a continuous six months during 2014–2015. These measurements represent the best photometric time-series of any WR star to date. In parallel, we scheduled and executed a world-wide spectroscopic campaign on the system, collecting nearly 500 high-quality, high-resolution spectra of the system. These proceedings present the first analysis of these data, concentrating on the optical variability related to the orbit of the system. Future analyses will examine the orbit and colliding winds in detail, short-term variations, detailed modeling, and planned X-ray observations.

Figure 1 shows the Fourier transforms of the red and blue light curves of γ^2 Vel. We have marked the orbital period in frequency space, and it is readily seen to be the strongest frequency in the Fourier transform. In order to best explain the effect of the orbital modulation on the light curves, we phase-binned them (which originally covered just over two orbital cycles) as shown in Fig. 2. The result was that there was a $\sim$1% increase in flux at periastron as opposed to apastron, which demonstrates that the light curve follows a trend inversely proportional to the separation of the two stars. There could be two reasons for this: The continuum changes as the shocks increase at periastron, or the excess line emission causes an observed change in the precise photometry observed with BRITE.

We investigated the C III λ5696 transition through an analysis of its equivalent width. We found that it also had a $1/d$ relationship. This prompted us to investigate the integrated, normalized spectra as a function of phase. We find that the differences recorded by BRITE and the differences recorded from excess line emission are virtually identical, so that the excess flux comes from line emission formed in the colliding winds. Further efforts are underway to understand all of the spectroscopic effects

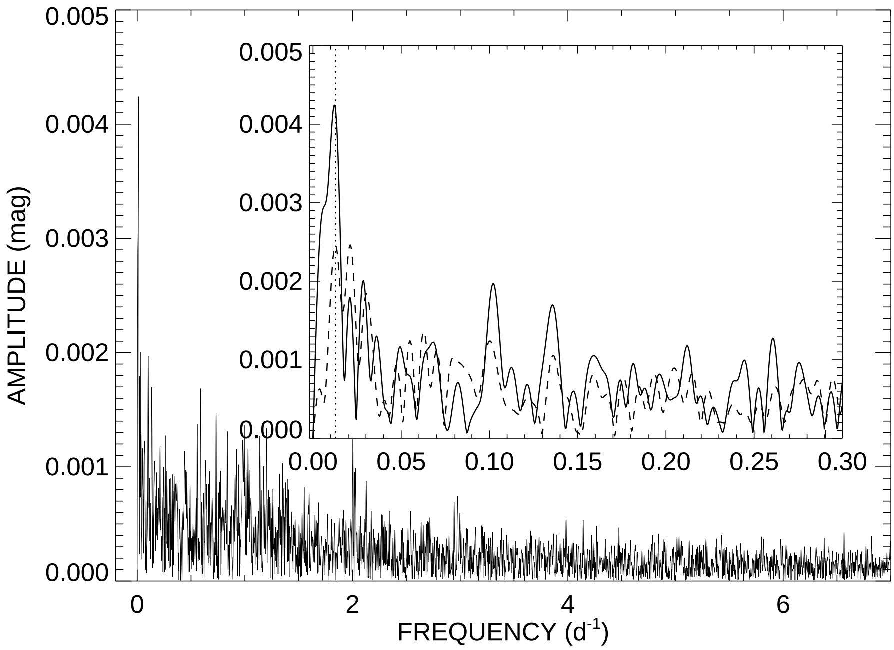

Fig. 1: Fourier Transform of the γ^2 Vel light-curve from BRITE-Austria (blue filter; large window). The inset shows both the BRITE-Austria and the BRITE-Toronto (red filter, dashed line) data for longer periods. The vertical dashed line denotes the orbital frequency ($P = 78.53$ d).

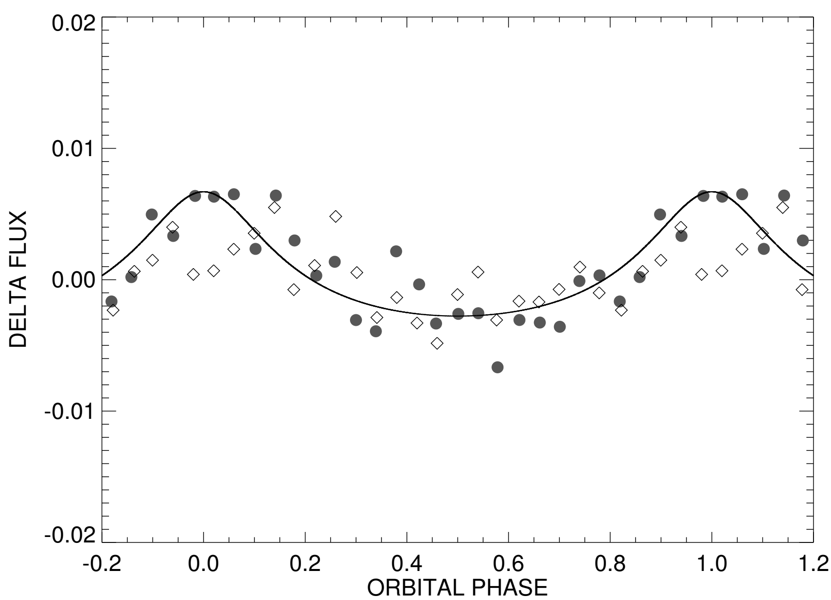

Fig. 2: Evidence of a $1/d$ trend in the BRITE-Austria (blue filter; solid circles) and BRITE-Toronto (red filter, open diamonds) light curves.

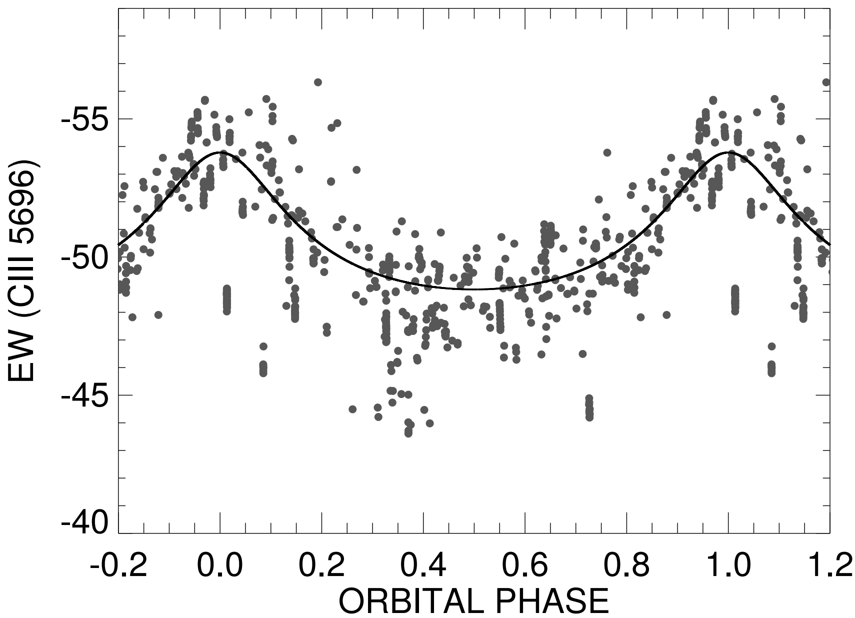

Fig. 3: Measurements of the equivalent width of the C III $\lambda 5696$ line are easily explained with a $1/d$ trend formed in the shock from the colliding winds.

of the colliding winds, both with the collected data, and with future *XMM-Newton* spectra.

3 Other windy stars to examine in the future

γ^2 Vel is one of many massive stars being observed with BRITE-Constellation, and as such we can look to the future studies of many systems to understand wind variations. While γ^2 Vel is the brightest Wolf-Rayet, it will not be the only one observed by BRITE. Recently, we made a concentrated effort to observe WR 6 (EZ CMa; HD 50896) with BRITE-Toronto, and simultaneously collected more than 100 optical spectra. Unlike γ^2 Vel, WR 6 has a well-established non-binary period of 3.77 d (Morel et al., 1997). This period has been shown to most likely be caused by co-rotating interaction regions (CIRs), such as those inferred on ζ Pup. This WR star has some of the strongest CIRs observed in a WR star, and with the spectroscopy will lead to interesting discussions of the lifetime of CIRs in massive stars. This is important as we know that they often change from one epoch to the next, and only two WR stars have measurements of their CIR lifetimes (Aldoretta et al., 2016; Chené & St-Louis, 2010).

Prior to the WR phase, massive stars can pass through a luminous blue variable stage. There are two LBVs that can be studied with BRITE. The best example is P Cygni, which has now been observed for three consecutive observing seasons with BRITE-Constellation along with support spectroscopy from both professional and amateur facilities. P Cygni was previously studied by Richardson et al. (2011) who found that the Hα profiles and V-band variability are related, although also quite complicated. Aside from a well-documented variability history, P Cygni has a

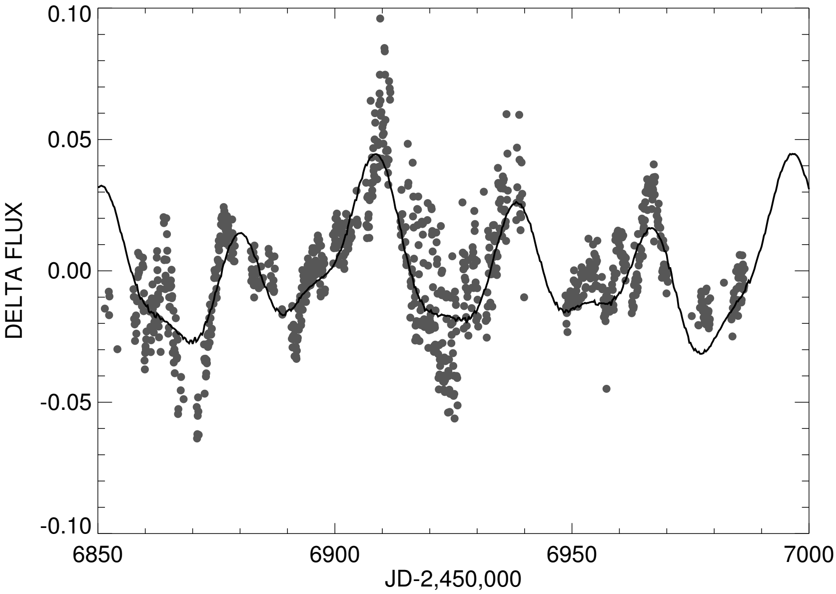

Fig. 4: The light curve of P Cyg from BRITE-Lem with four frequencies fit from the Fourier transform. The fit suggests a more stochastic origin to the variability and doesn't significantly improve with the addition of more frequencies.

full spectroscopic model as reported by Najarro et al. (1997). The properties of the models indicate a mass loss rate of $3.0 \times 10^{-5} M_{\odot}\mathrm{yr}^{-1}$ and a luminosity of $5.6 \times 10^{5} L_{\odot}$, making this an ideal target for probing our understanding of the LBV phenomenon.

Figure 4 shows the light curve of P Cyg from the first season of BRITE observations. We have begun an analysis using Fourier decomposition of the light curve, for which we show a four-frequency fit in Fig. 4. We will be further analyzing the relationship between the measured flux and wind properties from spectroscopic features such as Hα in the near future.

The second LBV that will be studied with BRITE-Constellation is η Car, which was observed this year and will be again in the following year. This star is an extreme, massive binary with a primary star having a mass-loss rate near $10^{-3} M_{\odot}\mathrm{yr}^{-1}$, and a secondary also having a large mass-loss rate. The system properties were recently reviewed by Madura et al. (2013) and Richardson et al. (2016). The stars orbit in a highly eccentric, long-period system ($P_{\mathrm{orb}} = 5.54$ yr), and the initial BRITE-Constellation observations are taken near apastron. We anticipate being able to compare between the optical variations and the X-ray behavior. Future studies with BRITE-Constellation, targeted near the 2020 periastron could provide strong constraints on the properties of the colliding winds and orbital changes. Past photometric studies of η Car (Fernández-Lajús et al., 2010) have not seen many short-term changes, so the BRITE-Constellation observations will probe new timescales with a precision never-before reached with this unique laboratory for understanding mass-loss, massive star evolution, and binary-related physics.

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