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## **Pulsations Beneath the Winds: Unique Precise Photometry from MOST**

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**Abstract.** It has now been three years since the first Canadian space telescope MOST (Microvariability and Oscillations of STars) continues to make its unique mark in stellar asteroseismology, exoplanetology and other studies of high-precision photometric variability. Among massive stars, three OB, three later-type B stars and two Wolf-Rayet stars have been studied so far with unprecedented precision and time coverage in samples with of order 100 000 data points collected without a break over several weeks. Of particular interest are: a first clear pulsation period of  $P = 9.8$ h has been found in a WR star (WR123, WN8); no short periods between a minute and an hour have been seen in either of the two WR stars observed (WR123; WR103, WC9d) to the 0.2 mmag level, although these stars both exhibit numerous short-lived oscillations mostly with periods longer than a day, which must be related to stellar pulsations; g-mode pulsations were detected in a blue supergiant; non-radial g-mode pulsations may be excited in all classical Be stars and thus may play a pivotal rôle in the Be-star mass-ejection process. A review of all the massive-star results to date from MOST and their implications are presented.

## 1. Background

Hot, luminous stars are distinguished by their strong fast winds, that are believed to be driven by radiation pressure. Their high flux in both photons and particles makes massive stars (together with the numerous intermediate-mass stars at the brief, luminous final stage of their lives in the AGB stage) major contributors to the ecology of the Universe. Nevertheless, for a subset of hot, luminous stars - the He-burning Wolf-Rayet stars - the “wind momentum problem” remains an outstanding challenge (Brown et al. 2004). The question then remains, even for the progenitors of WR stars, the OB stars: What is the rôle of pulsations, rotation and magnetic fields in accelerating the strong winds?

Asteroseismology is a unique window into the internal structure of stars. Once pulsations are detected, they can be used to constrain the density and rotation profiles of the star and shed light on the internal magnetic field. Previous attempts at detecting pulsations from the ground in hot, luminous stars have often been frustrated by the fact that the expected periods lie in the difficult range of hours to days, i.e. similar to nightly cycles. Clearly, means are needed to obtain intense, continuous and precise photometry over weeks. Asteroseismology has the potential to directly solve two of the fundamental outstanding problems still plaguing our understanding of massive stars, in particular, the size of the convective cores and the influence of rotation.

## 2. Enter MOST

MOST (Walker et al. 2003)<sup>1</sup> is a low-cost microsatellite designed to detect low-amplitude stellar oscillations with a precision of as low as a few micromagnitudes. With a relatively high pointing stability currently close to  $\pm 1''$  (compared with  $\pm \sim 2$ deg for previous microsatellites), and unprecedented high duty cycle ( $\sim 100\%$  for targets in the continuous viewing zone), MOST is ideally suited for the monitoring of targets with complex, rapidly changing (minutes to hours) light curves, although it has now proven itself capable of stretching this to days and even weeks. MOST was launched by a Rokot vehicle on 2003 June 30 from the Plesetsk Cosmodrome (Russia). It contains a 150 mm aperture Rumak-Maksutov telescope fed by a 45deg diagonal mirror, which focuses the light on science and tracking CCDs in a  $\approx 3000\text{\AA}$  bandpass centered at  $\lambda \simeq 5250\text{\AA}$  ( $\approx B$  plus  $V$ ). The focal-plane scale is  $\sim 3''\text{ pixel}^{-1}$ . There are two modes of observation possible: Fabry imaging (for stars of  $V \lesssim 6$  mag) and direct imaging (for fainter objects). Data are collected via three ground stations located in Vancouver, Toronto, and Vienna.

MOST’s main mission is to detect and analyze miniscule asteroseismic oscillations in solar-type stars, but also includes many other types of stars across the HRD as well as the monitoring of stars with planets. This paper reports on the results obtained for hot, luminous stars observed and analyzed so far with

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<sup>1</sup>MOST is a Canadian Space Agency mission, jointly operated by Dynacon, Inc., the University of Toronto Institute for Aerospace Studies Space Flight Laboratory, the University of British Columbia, and with the assistance of the University of Vienna, Austria

MOST, namely two WR stars, three OB stars, as well as three later-type B stars.

### 3. Results and Discussion

#### 3.1. Wolf-Rayet Stars

In 2004 and 2005 (June-July) we obtained nearly-continuous photometry in direct mode of two WR stars with MOST. Our targets, WR123 = HD 177230 (WN8), and WR103 = HD 164270 (WC9d), respectively, were chosen from among presumably single WR stars, each belonging to one of the cool ends of the two evolutionary branches of the WR family. Both are extremely hydrogen-poor. Among all WN (WC) stars, WN8 (WC9) stars are known to be the intrinsically most variable (Marchenko et al. 1998). At  $z = -492$  pc from the Galactic plane, WR123 is considered to be a runaway, while at  $z = -188$  pc, WR103 can still be considered part of the extreme pop I disk population. Like many WC9 stars, WR103 exhibits a variable thermal IR excess as a result of warm dust formation.

After a first analysis of the MOST data for WR123 by Lefèvre et al. (2005) using conventional Fourier techniques, we have now calculated time-dependent wavelet power spectra of both stars, as depicted in Figs. 1 and 2. For these wavelet power spectra, we follow the approach of Torrence & Compo (1998). In these figures, we note the complete absence of oscillations in the  $f > 3$  d<sup>-1</sup> ( $P < 0.3$  d) domain, as well as the extremely unstable (both in frequency and amplitude) behaviour of the low-frequency components. Despite the different net amplitudes of photometric variability, both stars behave in a similar manner: (a) Their light curves can be represented by superpositions of short-lived (5-7 day coherency) pulsations, with typical amplitudes  $\sim 5$ -20 mmag and frequencies  $f \ll 10$  d<sup>-1</sup>. (b) Most of the power is concentrated in the  $f \leq 1$  d<sup>-1</sup> domain. (c) The traditional domain of WR pulsation theories,  $f \geq 10$  d<sup>-1</sup>, thought to be populated by a mixture of non-radial, radial and strange modes, is devoid of any periodic signals exceeding the *very strict detectability limit of amplitude*  $\approx 0.2$  mmag. Despite the complex and rapidly changing frequency spectrum, there might be relatively stable, long-living (over a month?) oscillatory components in WR123; e.g., at  $f = 2.45 \pm 0.03$  d<sup>-1</sup> ( $P \sim 0.4$  d in Fig. 1; see also Lefèvre et al. (2005)). However, WR103 shows no obvious stable oscillations in Fig.2.

Simultaneous time-dependent spectroscopy (Figs. 3 and 4), probing conditions in the respective stellar winds, shows that the observed photometric variability is unequivocally related to pulsations emanating from the stellar cores, since the magnitudes of the detected line profile variations fall short (by more than an order of magnitude) of accounting for the observed broadband B+V photometric fluctuations. Furthermore, the reaction of the winds to the pulsations is delayed (especially evident in Fig. 3, where the P Cygni absorption-edge changes lag behind the large variations in the continuum light level), probably triggered by a superposition of pulsation events.

If the observed photometric variations were completely stochastic and due to random clump formation and propagation in the winds, then one would expect continuum polarization fluctuations to be of similar amplitude compared to the photometric variations (Brown et al. 1995). However, based on previously published data, this is not seen in either star, i.e. the polarimetric variations of

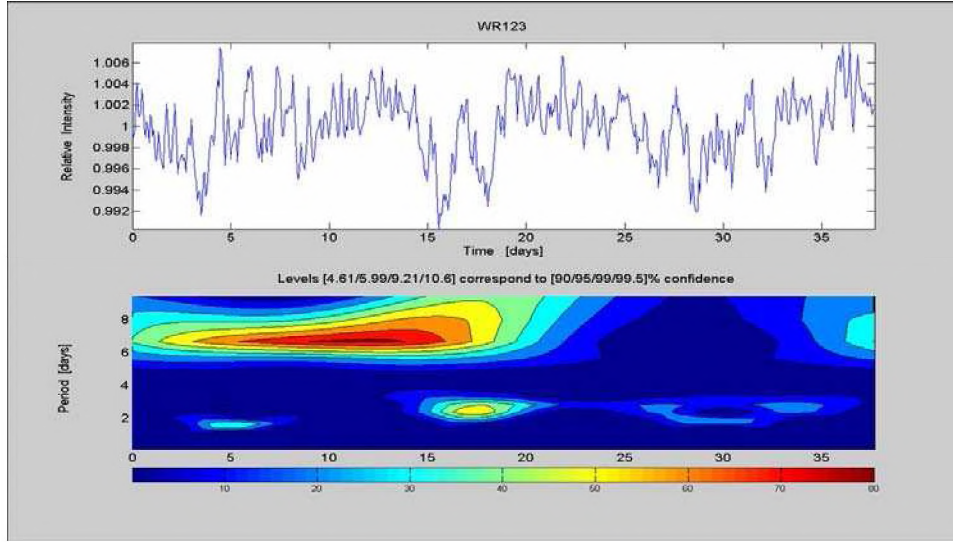


Figure 1. Upper panel: the light curve of WR 123, WN8. Lower panel: time-dependent wavelet power spectrum of WR123, WN8. Time is expressed in days. The horizontal bar shows the normalized spectral power, with the corresponding confidence levels listed above the panel.

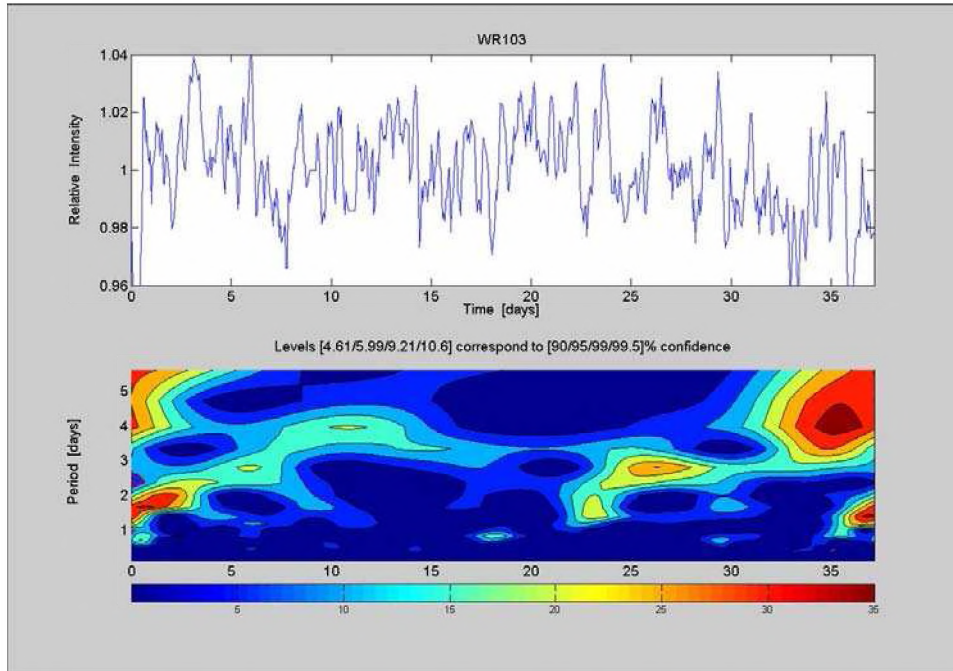


Figure 2. Time-dependent wavelet power spectrum of WR103 (WC9d) as in Fig.1 for WR123.

St-Louis et al. (1987) and Drissen et al. (1987) ( $< 1\%$ ) are an order of magnitude lower than the photometric variations ( $< 10\%$ ). This indeed supports the idea

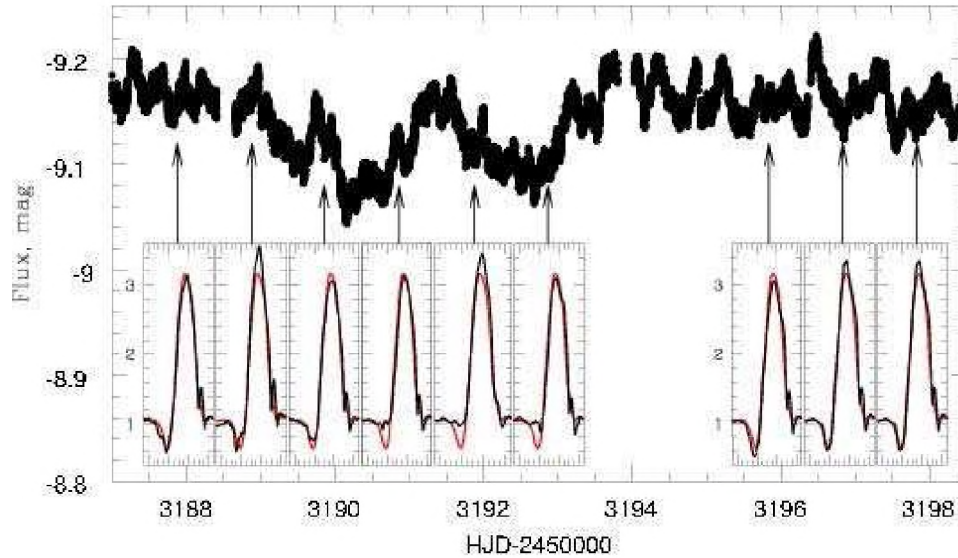


Figure 3. Simultaneous spectroscopy of WR123. Both average and individual profiles of the line He I 5876Å are shown.

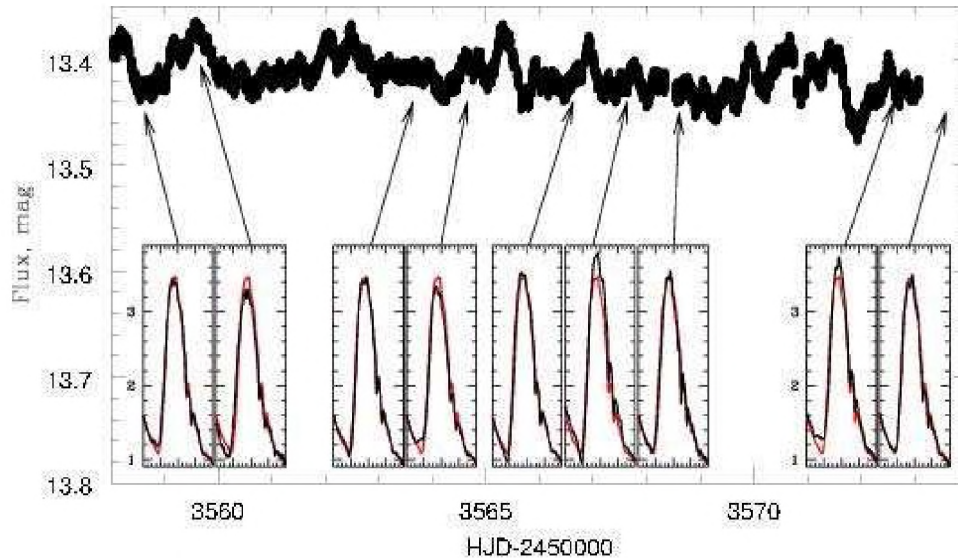


Figure 4. Simultaneous spectroscopy of WR103. Both average and individual profiles of the line He I 5876Å are shown.

put forward here that we are actually seeing stellar pulsations, which may have been somewhat filtered or distorted by the inner dense winds and emitted at  $\tau = 1$ , i.e. at the base of the observable wind. Furthermore, G. Gräfener and W.-R. Hamann (these proceedings) are not able to reproduce the observed spectra of some WN subtypes, especially WN8, with their spectral models based solely on radiation-pressure wind-driving. We therefore strongly suspect that pulsations

could be the main wind-driver in the strongly variable, enigmatic WN8 (and possible also WC9) stars.

Immediately after we published the MOST results for WR123 (Lefèvre et al. 2005), two groups independently came out with different models that proclaimed to have successfully reproduced the 10-hour periodicity. Both models neglect stellar winds. Dorfi et al. (2006) claim strange-mode pulsations (SMP) after all, with the internal stellar driver being the iron-opacity bump. But, whereas Glatzel et al. (1999) claimed SMP periods for WR stars of  $\approx 10$  minutes based on stellar radii of  $\approx 1 R_\odot$ , Dorfi et al. (2006) used a more realistic  $R_\star \simeq 15 R_\odot$  from Crowther (1997) for WR123, which after scaling with  $R^{3/2}$  for fundamental pulsation periods, leads to a period of  $\approx 10$  hours! However, Dorfi et al. (2006) took a relatively high hydrogen abundance  $X_H = 0.35$ , compared to the observed low value close to 0.00, which leaves some doubt about the applicability of the model.

On the other hand, Townsend & MacDonald (2006) claim that low-order g-modes *can* reproduce the observed period in WR123. Such modes have considerably longer periods than the fundamental one and are driven by a deep (mainly Fe) opacity bump at  $\log T \approx 6.25$ . However, although they correctly used  $X_H = 0$ , Townsend & MacDonald (2006) used a small radius ( $R_\star \sim 2 R_\odot$ ), which they thought was more compatible with the low hydrogen abundance. Such a radius is still incompatible with the spectroscopic analysis (Crowther, priv. comm.); in particular, the relatively low wind terminal-speed of  $\sim 1000 \text{ km s}^{-1}$  requires a larger radius. Again, we are left with some doubt as to the applicability of the model.

### 3.2. OB Stars

Among the OB stars observed so far by MOST in order of decreasing luminosity, are  $\zeta$  Oph, O9.5V (Walker et al. 2005a), HD 163899, B2Ib/II (Saio et al. 2006a) and  $\delta$  Ceti, B2IV (Aerts et al. 2006a).

With  $v \sin i \sim 400 \text{ km s}^{-1}$ ,  $\zeta$  Oph is one of the fastest rotating Oe/Be stars known. It is also a runaway star paired with a fast-moving pulsar and is believed to lie at the blue edge of the  $\beta$  Cep variability strip. The detection by MOST in the Fabry mode of at least a dozen radial and non-radial mode oscillations, with periods in the range  $\sim 2$ -20 d, clinches the case for  $\beta$  Cep type pulsations in this star, driven by an iron opacity bump. Unfortunately, the rotation period still remains ambiguous.

HD 163899 is a mild blue supergiant, observed as one of the 20 guide stars for the photometry of the prime target WR103. MOST detected 48 frequencies below 2.8 c/d, with amplitudes of a few mmag or less. Groups of both p-mode and g-mode oscillations are seen at high and low frequencies, respectively. Although previous results indicated a lack of g-modes in such less-luminous B supergiants, the new theoretical models do reveal non-radial g-mode pulsations that are consistent with the new MOST data for stars of mass 15-20  $M_\odot$ . This is the first time that so many g-modes have been seen in such a star, although some indication of single g-modes in similar, less-luminous supergiants was claimed by Waelkens et al. (1998). This opens up a great potential for asteroseismology to probe the inner structure of mild blue supergiants.

The B2 subgiant  $\delta$  Ceti was MOST's very first target star, observed in the Fabry mode. Despite the slightly less precise data obtained then, MOST revealed this star to have multi-periods, compared to its previously-assumed monoperiodic nature. Comparison with models gives a best fit for a star of mass  $10.2 M_{\odot}$  and age 18 Myr.

### 3.3. Cooler B-Type Stars

MOST has also observed several later-type B stars, of which three have now been fully analyzed so far: HD 163830, B5II/III (Aerts et al. 2006b), HD 163868, B5Ve (Walker et al. 2005b), and  $\beta$  CMi, B8Ve (Saio et al. 2006b). As for HD 163899 above, both HD 163830 and HD 163868 were observed among the guide stars for WR103. In the case of HD 163830, MOST has revealed it to be a new slowly-pulsating B-star (SPB) with by far the largest number (20) of detected, g-mode frequencies to date in any B star. Most of these frequencies are consistent with low-degree, high-order nonradial g-modes of seismic models for an evolved star of mass  $4.5 M_{\odot}$ . In the case of HD 163868, MOST has detected 60 modes, some of which represent the first detection in a Be star of r-modes of very-low frequency and g-modes, driven by the iron opacity bump. This shows that indeed nonradial pulsations may be important in the Be-star phenomenon. Finally, MOST detected several low-amplitude multi-oscillations in  $\beta$  CMi. The dominant periods in the range 0.3 d are consistent with prograde, high-order g-modes excited by Fe-bump opacity in a  $3.5 M_{\odot}$  star rotating nearly critically in a period of 0.38 d. This is the first detection of non-radial g-mode pulsations in a Be star later than B6. This leads to the possibility that pulsations are excited in all classical Be stars and thus may play an important rôle in the Be-star mass-ejection process.

## 4. Conclusions

MOST has now succeeded in starting a new frontier for exploring the structure of massive stars. The potential could be enormous, providing for the first time real constraints on the internal structure and solving problems that have persisted for several decades (convective cores and rotation). In the case of WR stars, secure evidence is now at hand that the strong variations seen in two cooler-type WN and WC stars actually are due to pulsations, with timescales that can now be matched with models, although the two current modeling attempts seem to have potentially serious shortcomings. Whether the source of the pulsations is due to these stars being closer to their Eddington limits than other WR stars, as suggested by Gräfener and Hamann (these proceedings), remains to be seen. In the case of O and B stars, considerable progress has been made with MOST to reveal g-mode pulsations, which may be the key to probing the deepest layers of the star, once one has a large enough bank of reliable, precise frequencies to constrain the models better.

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