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# OSCILLATIONS IN THE MASSIVE WOLF-RAYET STAR WR 123 WITH THE *MOST* SATELLITE

L. Lefèvre,[1,2] S. V. Marchenko,[3] A. F. J. Moffat,[1] A. N. Chené,[1] S. R. Smith,[3] N. St-Louis,[1] J. M. Matthews,[4]
R. Kuschnig,[4] D. B. Guenther,[5] C. A. Poteet,[3] S. M. Rucinski,[6] D. Sasselov,[7]
G. A. H. Walker,[4] and W. W. Weiss[8]

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## ABSTRACT

We present the results of intensive visual-broadband photometric monitoring of the highly variable WN8 Wolf-Rayet star WR 123, obtained by the *MOST* (*Microvariability and Oscillations of STars*) satellite. This first Canadian astronomical space telescope observed WR 123 for 38 days nonstop during 2004 June and July. Fourier analysis shows that no periodic signal is stable for more than several days in the low-frequency domain ($f < 1$ day$^{-1}$), where most of the stochastic power is contained. Also, no significant variability is seen in the high-frequency domain (10 day$^{-1}$ $< f <$ 1400 day$^{-1}$) down to the level of 0.2 mmag, an order of magnitude lower than theoretical predictions for strange-mode pulsations. On the other hand, there seems to be a relatively stable 9.8 hr periodic signal present throughout the whole run. This period is probably too short to represent the axial rotation of the star, unless it is related to multiple substructures equidistantly spread along the stellar equator. It is also too short to be orbital in nature; it is more likely to be related to pulsational instablilities (although with a much longer period than expected), thus finally revealing a possible fundamental driver behind the highly variable wind of this object, and others of similar type.

*Subject headings:* stars: individual (HD 177230 = WR 123) — stars: oscillations — stars: Wolf-Rayet

## 1. INTRODUCTION

Most Population I Wolf-Rayet (W-R) stars are evolved He-burning descendents of massive O stars (Langer et al. 1994). W-R stars exhibit intense broad emission lines produced by highly ionized atoms (Conti 2000) that constitute a hot, fast, and dense stellar wind (Hamann & Koesterke 1998). Furthermore, the highly structured nature of the winds (Moffat et al. 1988; Lépine & Moffat 1999; Lépine et al. 2000) may be related to numerous, stochastic small-scale density enhancements embedded in the outflowing W-R wind. There are two broad classes of W-R stars: WN, where nitrogen lines dominate, and WC and WO, with dominance of carbon and oxygen, respectively.

WN8 stars are the descendents of moderately massive, luminous O stars (Maeder 1996; Crowther & Smith 1997). They can be distinguished from other W-R subtypes by several peculiar characteristics: they have the highest level of intrinsic variability, they have a low binary frequency, they tend to avoid stellar clusters and associations, and those in the Galaxy are usually found far from the plane, that is, many of them may be considered to be runaways. All these characteristics tend to link their formation to a supernova explosion scenario, most likely in a massive binary. Because of their peculiarities, WN8 stars, with WR 123 (HD 177230; van der Hucht 2001) among them, were the object of a photometric and spectroscopic survey between 1989 and 1995 by Marchenko & Moffat (1998, hereafter MM98) and Marchenko et al. (1998), following an earlier study by Antokhin et al. (1995). A detailed time-frequency analysis of the photometric data for WR 123 yielded a complicated multicomponent spectrum (MM98), with one frequency, $f_1 = 0.34$ day$^{-1}$, dominating over more than 10 other components at $f < 1$ day$^{-1}$.

However, the extreme complexity and dynamics of light-curve variations of W-R stars, in combination with inadequate time coverage, have resulted in a long string of ambiguous or unreproducible results (see Matthews & Beech 1987; Marchenko et al. 1994; references therein). With data from *MOST*, and its unprecedented time coverage, we are now able to address these deficiencies.

## 2. OBSERVATIONS AND REDUCTION

*MOST* (Walker et al. 2003)[9] is a low-cost microsatellite designed to detect low-amplitude stellar oscillations with a precision of a few micromagnitudes. With a relatively high pointing stability, typically better than $\pm 3''$ rms (compared with approximately $\pm 2^\circ$ for previous microsatellites), and unprecedented high duty cycle (~100% for targets in the continuous viewing zone, or CVZ), *MOST* is ideally suited for the monitoring of targets with complex, rapidly changing (minutes to hours) light curves. *MOST* was launched by a Rokot vehicle on 2003 June 30 from the Plesetsk Cosmodrome (Russia). It consists of a 150 mm aperture Rumak-Maksutov telescope fed by a 45° diagonal mirror, which focuses light on photometric and guiding CCDs in a $\approx$3000 Å bandpass centered at $\lambda \simeq 5250$ Å (approximately $B$ plus $V$). The focal-plane scale is $\sim 3''$ pixel$^{-1}$. There are two modes of observation possible, Fabry imaging (for targets with $V \lesssim 6$ mag) and direct imaging

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[1] Département de Physique, Université de Montréal, C.P. 6128, Succursale Centre-Ville, Montréal, QC H3C 3J7, Canada; lefevre@astro.umontreal.ca.

[2] Observatoire de Strasbourg, 11 rue de l'Université, F-67000 Strasbourg, France; lefevre@astro.u-strasbg.fr.

[3] Department of Physics and Astronomy, Western Kentucky University, 1906 College Heights Boulevard, Bowling Green, KY 42101-1077.

[4] Department of Physics and Astronomy, University of British Columbia, 6224 Agricultural Road, Vancouver, BC V6T 1Z1, Canada.

[5] Department of Astronomy and Physics, St. Mary's University, Halifax, NS B3H 3C3, Canada.

[6] David Dunlap Observatory, University of Toronto, P.O. Box 360, Station A, Richmond Hill, ON L4C 4Y6, Canada.

[7] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138.

[8] Institut für Astronomie, Universität Wien, Türkenschanzstrasse 17, A-1180 Vienna, Austria.

[9] *MOST* is a Canadian Space Agency mission, jointly operated by Dynacon, Inc., the University of Toronto Institute of Aerospace Studies, and the University of British Columbia, and with the assistance of the University of Vienna, Austria.

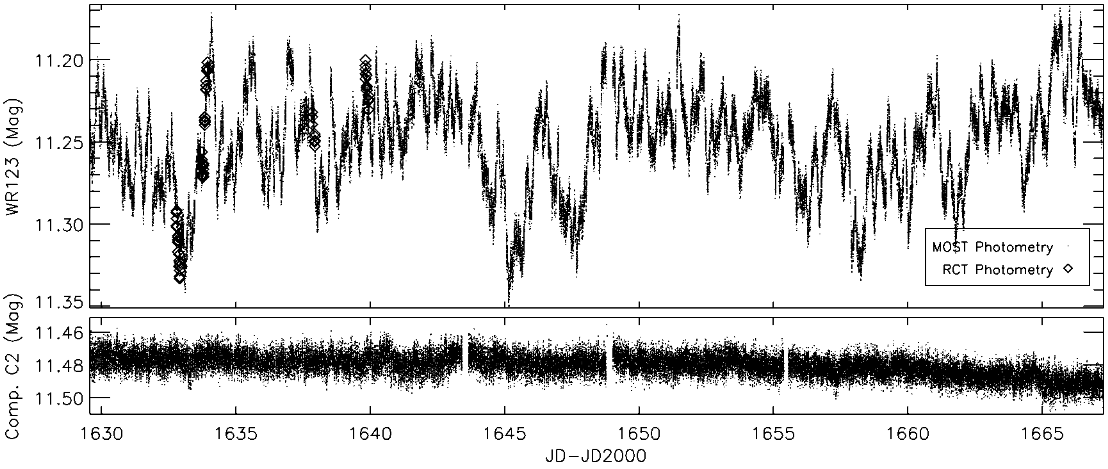

FIG. 1.—*Top*, 38 days of *MOST* photometry of WR 123 (*dots*), which includes the contribution from an unresolved neighboring star, compared with a subset of ground-based KPNO photometry whose angular resolution excluded the companion (*large diamonds*); *bottom*, comparison star C2 on the same scale.

(for fainter objects). Data are collected via three ground stations located in Vancouver, Toronto, and Vienna.

### 2.1. *Data*

The presumably single, relatively bright W-R star WR 123 ($V_{\rm GSC2} = 11.39 \pm 0.10$) is the only known WN8 star that falls in the normal *MOST* CVZ. It was observed by *MOST* in direct imaging mode in ~25 s exposures every 30 s for 38 days from 2004 June 19 to July 27. During this time of year, for such a faint target located in the southern part of the CVZ, the bright limb of Earth saturated the background during almost half the satellite's orbit, so that about half of the data had to be discarded. In addition, we chose three isolated external comparison stars on three different nearby subrasters (20 × 20 pixels: C2, C3, and C4) and a resolved comparison star closer to the target (18″; $V_{\rm GSC2} = 12.03 \pm 0.25$) on the same subraster (30 × 30 pixels: WR 123 + C1). There is also a much closer companion 5″ westward of WR 123 ($V_{\rm GSC2} = 15.11 \pm 0.26$), which remains unresolved by *MOST*.

The star was also observed with the 1.3 m Robotically Controlled Telescope (RCT) at KPNO[10] (Gelderman et al. 2004). The robotic facility obtained three to five groups of CCD images in Johnson *V* per night, with five short exposures (6–8 s) in each. The full RCT data set will be discussed elsewhere.

Figure 1 shows the light curves of WR 123 (*MOST* plus RCT) and comparison star C2 (*MOST*), which was chosen because of both its stability and comparable magnitude. Note that there is a slow drift of C2 to fainter magnitudes (also seen in the three other comparison stars). This drift is definitively instrumental, and although this tendency was not subtracted from WR 123, its impact was thoroughly checked in both the time and Fourier domains and found to be negligible in the frequency ranges considered. Comparing the RCT and *MOST* data, we found a good match, with both telescopes showing the same trends in the overlapping sections. However, RCT returns a light curve with identical shape but slightly (~10%) higher amplitude, which can be explained by the presence of the faint, nonvariable (and thus diluting) companion in the *MOST* data. A second source of reduced *MOST* amplitude may be related to the broader photometric response: the roughly *B* plus *V MOST* band versus the RCT standard *V* band. The presence of intense emission lines, especially in the *B* band, may reduce the observed *MOST* photometric amplitude, since these emissions do not follow the variability patterns detected in the adjacent continuum.

### 2.2. *Reduction*

The reduction of the *MOST* data basically consists of finding the best estimate of the local background around the star (if this exceeded an empirically determined threshold level, the image was discarded), subtracting it from each usable frame, and carrying out aperture or point-spread function (PSF) fitting photometry on each target star. The high levels of stray light have shortened the duty cycle to 52%. A preliminary analysis was first carried out by one of the authors (L. L.) using PSF fitting and by another (S. V. M.) using variable-aperture photometry on a 7 day subset of the data. Later, the entire data set was reduced with custom software developed by L. L. using fixed-aperture photometry. These three methods yield basically the same results (with occasional discrepancies of a few millimagnitudes), but the first two were discarded for being either too approximate (L. L.) or too time-consuming (S. V. M.). The final rms error is roughly 5 mmag per point for WR 123. Note that the *MOST* reduction pipeline (Rowe et al. 2005) also gave similar, although somewhat noisier, results.

The image processing for RCT data was performed under IRAF.[11] Using multiple comparison stars from the field for differential photometry, we achieved 3–6 mmag accuracy per individual observation. During aperture photometry of the images, we carefully eliminated any contamination from the close 5″ companion.

## 3. RESULTS

Since the final duty cycle of the data was reduced to about 50%, we searched for periodic variations with CLEAN (Scargle 1982; Roberts et al. 1987). No stable periods were found in the low-frequency domain ($f < 1$ day$^{-1}$), including $f = 0.34$ day$^{-1}$ from MM98, although most of the fluctuating power is located there (see Fig. 2, *left*). However, the frequency spec-

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[10] Kitt Peak National Observatory is operated by the Association of Universities for Research in Astronomy (AURA), Inc., under cooperative agreement with the National Science Foundation.

[11] IRAF is distributed by the National Optical Astronomy Observatory.

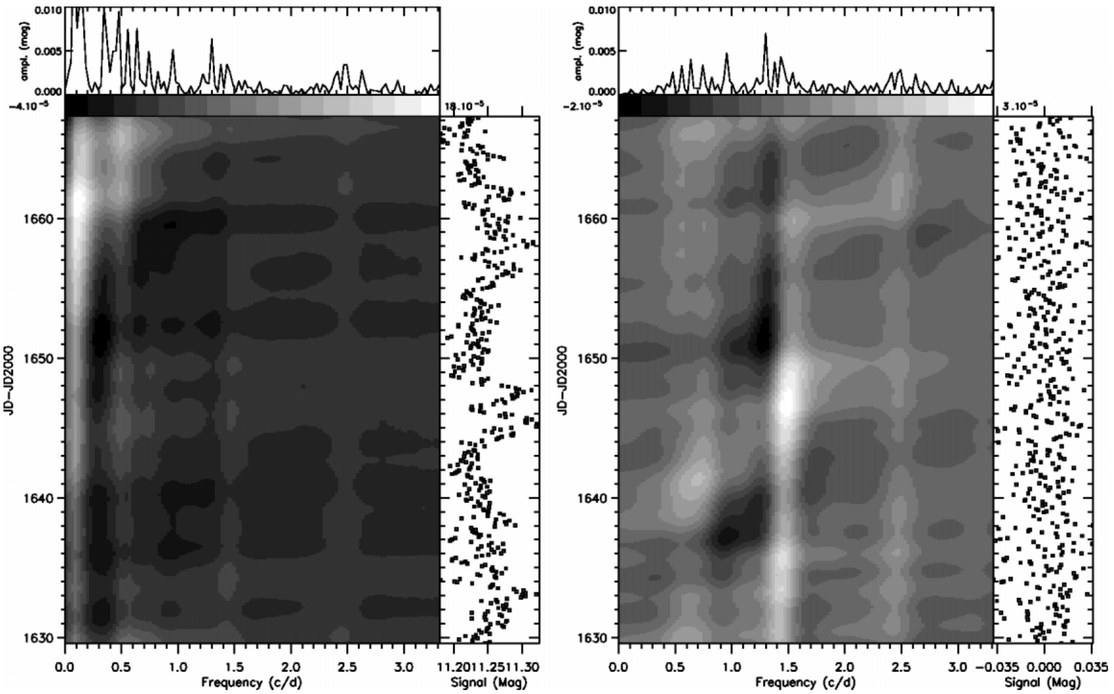

FIG. 2.—Time-frequency analysis of the WR 123 data for the whole set. *Left*: Data set binned every 2 hr. The upper panel represents the CLEANed spectrum of the whole set and the panel at right is the binned light curve. *Right*: Data binned every 2 hr and prewhitened, where all signals with $P > 1$ day have been removed with a high-pass filter. The upper panel is the CLEANed spectrum, and the panel at right is the binned and detrended light curve. The gray-scale calibration is given with lower and upper limits above each gray-scale plot.

tra are greatly affected by large-amplitude fluctuations in the star, as can be seen in Figure 1, for example, around days 1633–1634 or 1644–1648.

To compare the frequency content of this better sampled data set with the MM98 photometry, we applied the same time-frequency technique they used. The frequency domain 1 day$^{-1}$ $< f <$ 10 day$^{-1}$ revealed evidence for more-coherent variations than may have been detectable by MM98. Figure 2 (*left and right panels*; we only show up to 3 day$^{-1}$ for clarity) shows a 2.45 day$^{-1}$ peak that seems to be present and stable throughout the whole data set. Note that the aliases introduced by the satellite orbital frequency should occur at multiples of about 14.199 day$^{-1}$, and so even the alias peaks at lower frequencies should introduce most of their leaked power well beyond the frequency range discussed here. Moreover, the frequency peaks considered significant in this frequency range are not present in the CLEANed Fourier spectra of the comparison stars.

This 9.8 hr period (2.45 day$^{-1}$) can in fact be followed by eye over the majority of the data set (e.g., over days 1638–1641.5 in Fig. 1), surviving for at least 38 days, although slowly changing between 2.4 and 2.5 day$^{-1}$. Even if the amplitude of the 9.8 hr component seems to be relatively stable (compared with other frequencies), Figure 2 shows that there are some epochs when the 9.8 hr period is less well defined. This slow drift may explain the double-peaked appearance of the signal in the CLEANed spectra (Fig. 2, *upper panels*). On the other hand, for some peaks the significance is not as clear; that is, the 1.3–1.5 day$^{-1}$ family might seem important at first glance, but a closer look reveals that it is in fact unstable.

To reveal any signals in the high-frequency domain, $f >$ 10 day$^{-1}$, we detrended the light curve from any low-frequency signals ($f <$ 0.1 day$^{-1}$), reasonably expecting them to "leak" significant power across the spectrum. Then we created subsamples (days or hours long) and calculated corresponding frequency spectra. No significant peaks were found in the range from 10 to 1400 day$^{-1}$ (the Nyquist frequency for the complete set), down to a detection limit of 0.2 mmag. Only about 0.8% of two *MOST*-orbit–long sets exhibit one peak over the ∼3 mmag individual threshold, which is likely instrumental in nature.

We note that the only effect of the faint 5″ companion is to diminish the Fourier amplitude by ∼10%. This has no impact on our interpretation of the *MOST* Fourier spectrum of WR 123.

Simultaneously with the *MOST* monitoring, we obtained optical spectra using the 1.5 m telescope and Ritchey-Chrétien spectrograph at CTIO.[12] Figure 3 shows the He II 5412 Å line

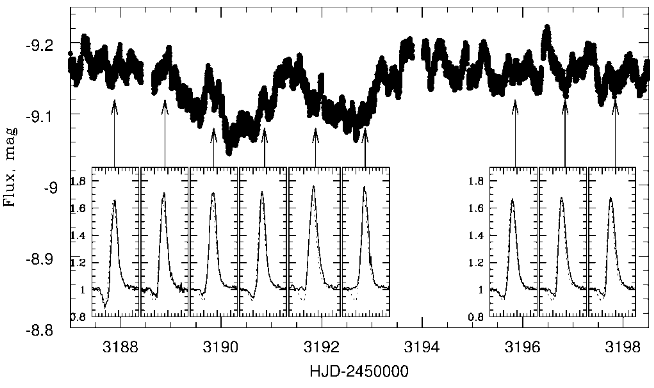

FIG. 3.—Simultaneous spectroscopy from CTIO: the He II 5412 Å line. Dotted lines show an average line profile of the spectra obtained 1 yr before the *MOST* run.

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[12] Cerro Tololo Inter-American Observatory is operated by AURA, Inc., under cooperative agreement with the National Science Foundation.

profiles that were observed simultaneously with the *MOST* photometry. Other, more blended lines behave similarly. One can see that the P Cygni absorption trough deepens with brightening of the star. The emission part remains unaffected. The origin of this behavior will be examined and modeled in a subsequent paper. Spectroscopy carried out a year before the *MOST* observations also indicates a period of ∼5 hr (A. N. Chené et al. 2005, in preparation), close to half the 9.8 hr period seen in the *MOST* photometry.

## 4. DISCUSSION

Could the relatively stable 9.8 hour period be related to a close-orbiting companion, such as a neutron star or stellar black hole, resulting from a supernova explosion that propelled the system to its present high Galactic distance from the plane ($-492$ pc; van der Hucht 2001) without separating the two stars? If so, then such a companion must be orbiting at $a \sim 7\ R_\odot$, that is, deep inside the stellar hydrostatic core, with $R_\star \sim 15\ R_\odot$ (Crowther et al. 1995). The equatorial rotation speed for $P = 9.8$ hr goes far above the breakup speed for such a star, unless the accepted parameters for WR 123 in particular and WN8 stars in general are considerably in error, or if the "$\zeta$ Puppis scenario" from Howarth et al. (1995) is also applicable to WR 123. In this case, the 9.8 hr period would represent only a fraction of the real rotation period, depending on the exact number of substructures more or less uniformly distributed in longitude around the star's equator.

No stable component was found in the low-frequency domain, although $f \simeq 0.5$ day$^{-1}$ from Moffat & Shara (1986) appears from time to time in the time-frequency plot in Figure 2. We suspect that most of the variability of WR 123 comes out below $f = 1$ day$^{-1}$ as a result of stochastic formation of wind inhomogeneities on timescales of about a day, as one sees in another (relatively slow wind) WN8 star, WR 40 (Lépine & Moffat 1999).

A period of 9.8 hours also seems improbable in the context of radial and nonradial pulsations, since they are not expected to exceed $P \sim 1$ hr in W-R stars (Scuflaire & Noels 1986; Glatzel & Mehren 1996). We can reject oscillations with amplitudes above 0.2 mmag and periods shorter than an hour. This appears to eliminate the hypothesis of strange-mode pulsations, predicted by Glatzel et al. (1999) to have periods of a few minutes and amplitudes of at least several millimagnitudes. Perhaps these high-frequency pulsations, if they exist at all, have been severely filtered out by the wind, with its drastically different density profile as compared with the hydrostatic layers of the star. It is probable that the lower density of the wind could transform the pulsations, substantially lowering the characteristic frequencies. The dynamic, ever changing frequency spectrum of WR 123 prompts us to suspect a strong imprint from a stochastically structured wind. To our knowledge, there are no models that consider the propagation of pulsations into an expanding wind. We plan to address this issue in a forthcoming paper.

If indeed the observed variability is related to pulsations, then one might be able to claim an additional source of acceleration for massive W-R winds, thus alleviating the acute wind-momentum problem (Hillier 2003).

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