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MOST FINDS NO COHERENT OSCILLATIONS IN THE HOT CARBON-RICH WOLF-RAYET STAR HD 165763 (WR 111)[1]

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ABSTRACT

We have photometrically monitored the $V = 8$ mag Galactic Population I WC5 star WR 111 for 3 weeks nonstop using the *MOST* microsatellite. Each of the ~27,000 data points has a precision of ~3 mmag. We find no coherent Fourier components above the 50 part per million level over the whole interval for frequencies $f > 10$ cd^{-1} (periods $P < 2.4$ hr). This limit is nearly 2 orders of magnitude below recent predictions for early-type WR stars based on strange-mode pulsation simulations, with expected periods in the range 10–30 minutes. Simultaneous spectroscopic observations of WR 111 reveal a normal level of stochastic clumps propagating in the wind, which possibly manifest themselves in the slow $1/f$ rise in the *MOST* power spectrum below $f \sim 10$ cd^{-1}. Time-frequency analysis of the *MOST* data shows no obvious short-lived frequencies above the 1 mmag level, in stark contrast to the highly variable cool WR stars WR 123 (WN8) and WR 103 (WC9d), monitored previously by *MOST*. Radiation pressure therefore appears to be the main, if not sole, driver of WR 111's strong wind.

Subject headings: stars: early-type — stars: emission-line, Be — stars: individual (HD 165763) — stars: oscillations — stars: winds, outflows — stars: Wolf-Rayet

1. INTRODUCTION

Does radiation pressure alone drive the strong winds of Wolf-Rayet stars? With decreased estimates of mass-loss rates due to clumping and increased luminosities due to rotation, the problem of multiscattering has become somewhat alleviated, whereby the critical normalized momentum parameter $\eta \equiv \dot{M}v_\infty/(L/c)$ has fallen down to the more tractable level of $\lesssim 10$ (e.g., Hillier 2003).

Recent *MOST* photometry of the cool WR stars WR 123 (WN8) and WR 103 (WC9d) (Lefèvre et al. 2005; Moffat et al. 2008; S. V. Marchenko et al., in preparation) has revealed multimode oscillations mainly in continuum light that suggest stellar pulsations could be a significant contributing factor to the mass-loss rates, at least in these two stars. Both of these stars show variations on timescales of ~hours to a day at the ~10% level, with WR 123 also showing a variable subcomponent with a fairly stable period of 9.8 hr over the whole 5 week monitoring interval with *MOST*. This period was also present in the ground-based spectroscopic data obtained 1 year prior to the photometric run (Chené et al. 2008). From previous ground-based observations, all the ~10 relatively well-observed WN8 stars show a similar high degree of intrinsic variability (Antokhin et al. 1995; Marchenko et al. 1998), implying that all cool WR stars may show similar behavior.

The above results are in contrast to the claim by Blecha et al. (1992) that the brightest WN8 star in the sky, HD 96548 (WR 40), is pulsating at the ~2 mmag level with $P \sim 10$ minutes. However, subsequent work (Marchenko et al. 1994; Martinez et al. 1994; Schneider et al. 1994) failed to confirm this short period. Subsequent precision ground-based photometry has also failed to reveal any convincing periods above the 3 σ noise level of ~1 mmag in the range below ~30 minutes in several WR stars (e.g., Schneider et al. 1997).

In the case of WR 123, two quite different scenarios have been proposed to explain the *MOST* space observations. Townsend & MacDonald (2006) find that a deep, hot Fe opacity bump can lead to *g*-mode pulsations, while Dorfi et al. (2006) find that a cooler Fe opacity bump can produce strange-mode pulsations (SMPs). The latter is in contrast with previous work (e.g., Glatzel et al. 1993, 1999; succeeding the previous work of Noels & Scuflaire 1986), where SMP periods of order 10 minutes were predicted to prevail in WR stars. The longer timescales and period found in WR 123 are most likely a result of the puffed-up nature of WN8 stars ($R_\star \sim 15\ R_\odot$ according to Crowther et al. 1995), compared to their much more compact early-type WN brethren. In these two theoretical studies, the former group assumed a traditionally small stellar radius ($R_\star \sim 2\ R_\odot$), while the latter group assumed significant hydrogen ($X_{\rm H} = 0.35$, compared to the observed value of 0.00:

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Marchenko et al. 1998 and references therein; Marchenko et al. 1998 also discuss the strong influence of hydrogen on the variability of WN7–8 stars). Both of these assumptions contradict what we know about this star, thus casting some doubt on their applicability. Nevertheless, it does appear at least from an empirical point of view that pulsations are at work here in both WR 123 and WR 103. Most pulsation modes do not last for more than a few days, but they are seen mainly in continuum light, since the wind lines do not vary enough to account for the broadband *MOST* photometric variations.

Additional support for some other factor besides radiation pressure to drive the strong winds in WN8 stars comes from the spectroscopic analysis of Gräfener & Hamann (2008). They show that among all WN stars, only the WN8 star spectra have spectral emission lines that are too strong to be simulated with the observed mass-loss rates and radiation pressure alone. Another wind driver is needed. That driver may well be pulsations.

What about hotter WN and WC stars? While no WC stars appear to contain hydrogen, most hot WN stars (i.e., WNE) in the Galaxy contain little if any H, in contrast to cooler WN stars (i.e., WNL), which often show H ranging up to nearly solar values. This presumably more advanced evolutionary stage of hot WR stars leads (at a given ambient metallicity) to their being generally more compact, with high ratios of L/M. These are exactly the conditions that favor SMPs, with simulations revealing expected continuum amplitudes of several mmag (Glatzel et al. 1993, 1999). Such amplitudes are difficult to verify from ground-based observations, although some attempts have been made (see above) leading to a lack of coherent ≈10 minute pulsations above the mmag level. Thus, we decided to use the advantage of the *MOST* satellite in space to probe another WR star, this time of the hot carbon sequence. For this purpose, we chose the bright, single isolated WC5 star WR 111.

The advantage of choosing WR 111, besides its convenient brightness, is that (1) it is a single WR star with detailed modeling available (Hillier & Miller 1999; Gräfener & Hamann 2005); (2) its wind is essentially spherically symmetric (Kurosowa et al. 1999) (this is important, because an asymmetric stellar wind can reduce the observable amplitude of the SMP; Dorfi et al. 2006); (3) it shows a relatively large number of small stochastically variable spectral subpeaks (see below); and (4) it is extremely quiet in broadband optical linear polarization (Drissen et al. 1987). As a hot, compact WR star with relatively high L/M, WR 111 is ideal to search for SMPs in the minutes–hours range with *MOST*, with minimal perturbation by systematic, stochastic wind fluctuations.

2. OBSERVATIONS

2.1. *MOST Photometry*

The *MOST* satellite, launched 2003 June, is fully described by Walker et al. (2003). A 15/17.3 cm Rumak-Maksutov telescope feeds two CCDs, one for tracking (now dysfunctional) and the other for science (now also used simultaneously for tracking), through a single, custom, broadband filter (350–700 nm). Starlight from bright science targets ($V < 6$) is projected onto the science CCD as a fixed (Fabry) image of the telescope entrance pupil covering some 1500 pixels. For targets fainter than this, direct imaging is available. The experiment was designed to detect photometric variations with periods of minutes at several micromagnitude precision and does not use comparison stars or flat-fielding for calibration. There is no direct connection to any photometric system. Tracking jitter was dramatically reduced early in 2004 to $\sim 1''$, which subsequently led to significantly improved photometric precision. In fact, *MOST* has also proved useful in search of longer periods in the range of days.

MOST observed WR 111 along with five comparison stars in its vicinity during 3 weeks without major interruptions from 2006 June 15 to July 7 using the direct imaging mode. Individual exposures were 1.5 s in length (necessary for tracking) and 10 consecutive images were stacked on board the satellite. The analyzed CCD images have an effective exposure time of 15 s sampled every 20 s. Photometry was extracted from the stacked CCD images by using an aperture with a radius of 4 pixels. Pointing jitter between each 1.5 s exposure caused the PSF (point-spread function) shape of each stacked image to vary considerably. Direct comparison between PSF and aperture photometry revealed that aperture photometry gave more reliable results.

The raw instrumental light curves were decorrelated against the sky background as shown in Rowe et al. (2006) and also for location of the PSF centroid on the CCD. The positional correlation in the photometry was removed by computing the average magnitude at a 0.25 pixel scale. This subpixel map was then used to interpolate to the PSF position and estimate the magnitude correction. Observations obtained during passage through the SAA were cut from the data set because of large numbers of cosmic-ray hits on the detector that made the estimate of the flux near the photometric aperture unreliable.

In the final stage of processing we evaluated and removed from the data all the instrumental trends, such as the slight sensitivity dependence on the CCD temperature, the flux sensitivity to positional shifts across the CCD field of view, and the slight flux bias introduced at high levels of background light. This iterative procedure provided 27,047 flux measurements for WR 111, each of $\sigma = 2.5$ mmag rms accuracy. The selected comparison star, HD 165856 (K5 III), yielded 26,607 measurements with $\sigma = 2.9$ mmag. This particular comparison star is the brightest in the sample and shows the least intrinsic variability, thus providing an estimate of point-to-point instrumental scatter in the measured fluxes that is similar to that for WR 111.

The complete *MOST* light curves of WR 111 and the comparison star are shown in Figure 1. The orientation of the satellite orbit resulted in a limited visibility of the target, thus creating regular ∼1 hr long gaps (Fig. 1, *inset*) and providing an overall duty cycle of ∼25%.

2.2. *Ground-based Spectroscopy*

WR 111 was observed spectroscopically in parallel with the *MOST* photometry during 4 nights in 2007 June using a CCD detector in the optical spectrograph at the Observatoire du mont Mégantic. The individual spectra covered ∼2000 Å in the visual band with 3 pixel resolution of ∼2 Å and S/N of ∼150. The mean spectrum is shown in Figure 2, along with a zoom of the line most sensitive to density fluctuations, C III λ5696, and a montage of individual differences from the mean for this line. The variations on the top of this line statistically match those obtained over a decade ago (see Lépine & Moffat 1999), with peak-to-peak amplitude of ∼7% ($\sigma \sim 2\%$). This is significantly above the instrumental level of variability, as can be judged by looking at the adjacent (stellar continuum) parts of the spectrum. There is therefore no reason to believe that WR 111

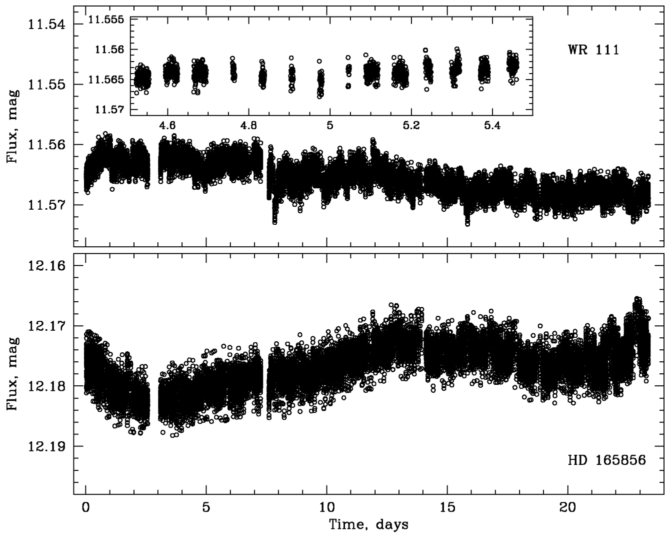

FIG. 1.—*MOST* light curves of WR 111 (with a zoom on a 1 day long segment) and the comparison star HD 165856.

behaved any differently during the *MOST* run than at any time previously. This implies that our present results are likely to be typical for WR 111. The stellar line-profile variations are the result of clumping in the wind.

3. RESULTS AND DISCUSSION

We present the results of a period search in Figure 3. The upper first and third panels show a Fourier transform of the whole *MOST* data set for WR 111. In order to see the uncontaminated high-frequency part in these data, we reduced the influence of low-frequency signal (likely of instrumental origin) by de-trending the original data (as in Fig. 1). One can see that there are no significant frequencies above $f = 10$ cd^{-1} ($P <$ 2.4 hr) with amplitudes $A > 50$ ppm. (The features which slightly exceed the 50 ppm limit in the WR amplitude Fourier spectrum are related to the orbital harmonics and their sidelobes; i.e., they are of artificial origin.) This is nearly 2 orders of magnitude below the level expected for SMPs and implies

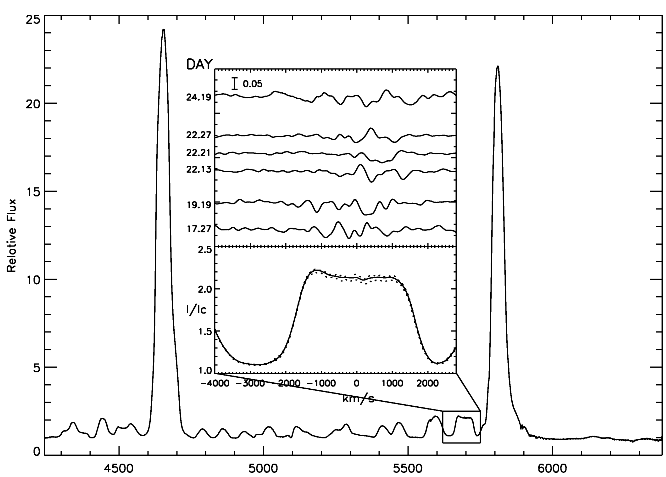

FIG. 2.—Mean optical spectrum of WR 111 with inset showing a zoom of the strongly variable C III λ5696 line and the six individual difference spectra for 2006 June. The scale for the spectral montage is expanded by a factor of 2.7 (cf. the lower part of the insert). The dashed lines show the limits of variability.

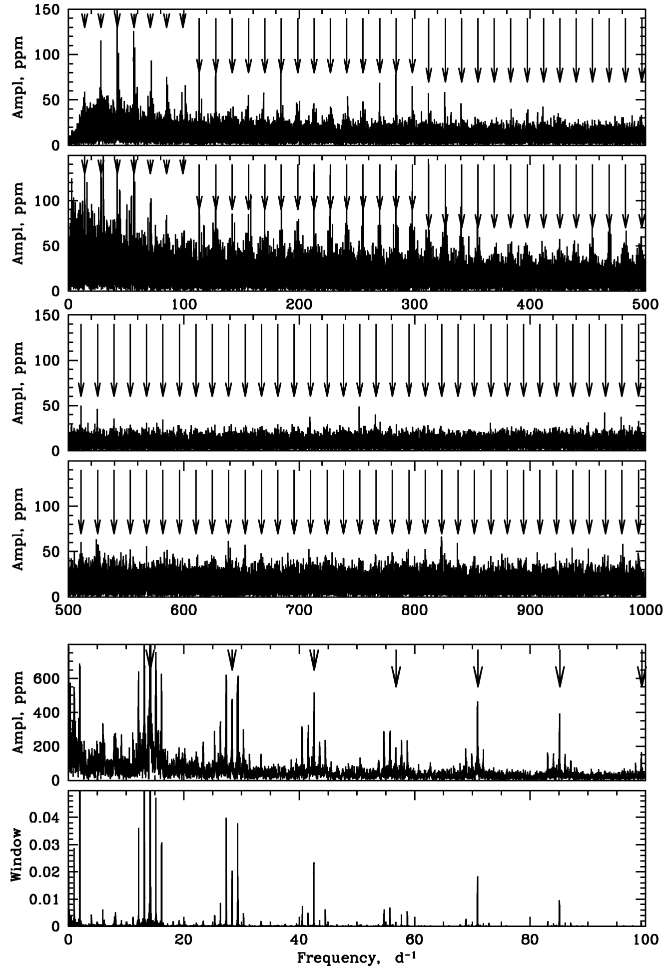

FIG. 3.—Fourier amplitude spectrum of the whole light curve of WR 111 (*top and third panels*) and the comparison star (*second and fourth panels*). The original WR 111 data (as in Fig. 1) were de-trended in order to produce a relatively uncontaminated high-frequency spectrum. The fifth panel shows the low-frequency part of the Fourier spectrum of the original light curve, and the last panel shows the related window function. In all panels, vertical arrows, if present, mark the spectral components related to the orbital period of the *MOST* satellite and its higher harmonics.

that if SMPs are active, which appears unlikely, they must be at an exceedingly low level. In order to investigate the behavior of the Fourier amplitude spectrum at lower frequencies, we use the original signal (as in Fig. 1) and plot the spectrum of WR 111 and the related spectral window in Figure 3 (*two bottom panels*). It is obvious that in the 0–100 day^{-1} range the amplitude spectrum closely follows the structure of the window; i.e., there are no intrinsic periodic components in the light curve of WR 111. This would appear to lend little support for the presence of *g*-mode pulsations in WR 111, assuming the model of Townsend & MacDonald (2006) applies more appropriately to this smaller star.

Could larger SMPs or *g*-mode amplitudes be filtered or damped by the surrounding dense wind? An empirical answer to this important question comes from the *MOST* results for WR 123 and WR 103. Both these stars have dense winds, yet we do appear to be seeing pulsations, albeit at low frequencies because these stars are much larger and less dense than WR 111. The case of WR 123 is rather exemplary. Indeed, the persistent $P = 9.8$ hr is seen both in the *MOST* photometry (dominated by the deep layers of the stellar wind which are relatively close to the hydrostatic core) and in the profiles of optical lines (the remote parts of the wind). Theoretical work is in progress (S. P. Owocki et al. 2008, private communication) to check for this using perturbed hydrodynamical wind simulations.

The optical spectra show that WR 111 was still as active as usual during the *MOST* run, as far as clump-driven wind variability is concerned. However, this variability involves tens of thousands of discrete wind fluctuations varying stochastically (Lépine & Moffat 1999), so that no discrete frequencies show up. On the other hand, the continuous rise in power seen in Figure 3 at low frequencies (de-trended for WR 111 at the lowest frequencies) may be a result of this activity, although it does occur in both stars.

In order to detect any short-lived pulsations in the *MOST* data for WR 111, such as those dominating the variability patterns of WR 123 and WR 103, we apply the well-reputed technique of wavelet analysis. Following the approach of Torrence & Compo (1998), we use the Morlet wavelet on evenly spaced time series. The latter is produced from the original data by time-binning and optimal interpolation. Before the analysis, the long-term trends (cf. Fig. 1) were removed from the data. In both cases, WR 111 and the comparison star, we do not find any periodic short-lived signals, with the sole exception of the highly nonstationary 1 day trend and its harmonics. This spurious signal (seen in all simultaneously observed stars) arises due to modulation of imperfectly eliminated stray light on a ∼daily basis, when *MOST* orbits above the same geographic latitude.

We also search for any short-term (flarelike?) variability in the original data. The regular, ∼1 hr long time gaps (see Fig. 1) severely limit our ability to relate any isolated events to a proper background level and, thus, to evaluate their statistical significance. Nevertheless, we find no convincing cases of microvariability in WR 111 above the 1 mmag level. On the other hand, the comparison star does show more convincing levels of microvariability; this is not surprising, considering its K5 III spectral class. We must caution, however, that in all detected cases, the characteristic amplitudes of the events in HD 165856 only marginally surpass the instrumental noise.

Can one reconcile the above low upper limit (<1 mmag) for any stochastic photometric variability of WR 111 in the light of the otherwise normal amplitude of variability on timescales of hours in the optical spectral lines? While the latter is ∼2% for the C III λ5696 line, most lines vary at much lower levels (Lépine & Moffat 1999; Lépine et al. 2000). Thus, taking a typical upper limit of line variability of ∼1% with ∼10 large variable spectral subpeaks dominating the lines at any given time, one expects an average line variability of ∼0.3%. Further assuming only partial coherence of variability in different lines (with a reduction by a factor $2^{1/2}$ for half the lines behaving independently of the other half) and no significant clump-caused continuum variability, with lines contributing ∼50% of the total light in the *MOST* bandpass, we estimate an *upper limit* of stochastic variability due to clump activity in the *MOST* data of ∼1 mmag, consistent with the above estimate.

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REFERENCES

Antokhin, I. I., Bertrand, J.-F., Lamontagne, R., Moffat, A. F. J., & Matthews, J. 1995, AJ, 109, 817
Blecha, A., Schaller, G., & Maeder, A. 1992, Nature, 360, 320
Chené, A.-N., et al. 2008, ApJ, submitted
Crowther, P. A. C., Hillier, D. J., & Smith, L. J. 1995, A&A, 293, 403
Dorfi, E. A., Gautschy, A., & Saio, H. 2006, A&A, 453, L35
Drissen, L., St.-Louis, N., Moffat, A. F. J., & Bastien, P. 1987, ApJ, 322, 888
Glatzel, W., Kiriakidis, M., Chernigovskij, S., & Fricke, K. J. 1999, MNRAS, 303, 116
Glatzel, W., Kiriakidis, M., & Fricke, K. J. 1993, MNRAS, 262, L7
Gräfener, G., & Hamann, W.-R. 2005, A&A, 432, 633
———. 2008, in ASP Conf. Ser. 388, Mass-Loss from Stars and the Evolution of Stellar Clusters, ed. A. de Koter, L. J. Smith, & L. B. F. M. Waters (San Francisco: ASP), in press
Hillier, D. J. 2003, in IAU Symp. 212, Massive Star Odyssey, ed. K. van der Hucht, A. Herrero, & C. Esteban (San Francisco: ASP), 70
Hillier, D. J., & Miller, D. L. 1999, ApJ, 519, 354
Kurosawa, R., Hillier, D. J., & Schulte-Ladbeck, R. E. 1999, AJ, 118, 539
Lefévre, L., et al. 2005, ApJ, 634, L109
Lépine, S., & Moffat, A. F. J. 1999, ApJ, 514, 909
Lépine, S., et al. 2000, AJ, 120, 3201
Marchenko, S. V., Antokhin, I. I., Bertrand, J.-F., Lamontagne, R., Moffat, A. F. J., Piceno, A., & Matthews, J. M. 1994, AJ, 108, 678
Marchenko, S. V., Moffat, A. F. J., Eversberg, T., Morel, T., Hill, G. M., Tovmassian, G. H., & Seggewiss, W. 1998, MNRAS, 294, 642
Martinez, P., Kurtz, D., Ashley, R., & Tripe, P. 1994, Nature, 367, 601
Moffat, A. F. J., et al. 2008, in ASP Conf. Ser. 388, Mass-Loss from Stars and the Evolution of Stellar Clusters, ed. A. de Koter, L. J. Smith, & L. B. F. M. Waters (San Francisco: ASP), in press
Noels, A., & Scuflaire, R. 1986, A&A, 161, 125
Rowe, J. F., et al. 2006, Mem. Soc. Astron. Italiana, 77, 282
Schneider, H., Glatzel, W., & Fricke, K. J. 1997, in ASP Conf. Ser. 120, Luminous Blue Variables, ed. A. Nota & H. Lamers (San Francisco: ASP), 206
Schneider, H., Kiriakidis, M., Weiss, W. W., Glatzel, W., & Fricke, K. J. 1994, in IAU Symp. 162, Pulsation, Rotation, and Mass Loss in Early-Type Stars, ed. L. A. Balona, H. F. Henrichs, & J. M. Contel (Dordrecht: Kluwer), 53
Torrence, C., & Compo, G. P. 1998, Bull. Am. Meteorol. Soc., 79, 61
Townsend, R. H. D., & MacDonald, J. 2006, MNRAS, 368, L57
Walker, G. A. H., et al. 2003, PASP, 115, 1023