**Wolf-Rayet Stars**
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# WR Time Series Photometry: A Forest of Possibilities

**H. Pablo[1], A. F. J. Moffat[1] & the *MOST* team**
[1] *Université de Montréal, Canada*

We take a comprehensive look at Wolf Rayet photometric variability using the *MOST* satellite. This sample, consisting of 6 WR stars and 6 WC stars defies all typical photometric analysis. We do, however, confirm the presence of unusual periodic signals resembling sawtooth waves which are present in 11 out of 12 stars in this sample.

## 1 Introduction

The Wolf-Rayet (WR) phenomenon, or evolutionary phase, is by its very nature most easily identifiable spectroscopically. The intense winds result in large emission line features that are quite unique. Therefore it is not hard to understand why the many of the breakthroughs in our understanding of these stars has been a result of spectroscopic analysis. While this is important, one look at the abstracts listed in this proceedings will show a very obvious gap in observations and study: photometry.

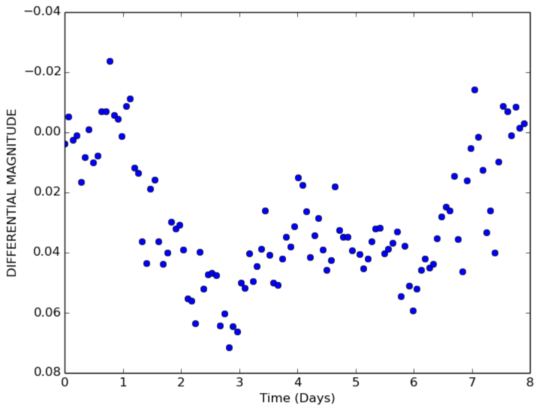


**Fig. 1:** False eclipse from WR 71. This eclipse has the longest duration lasting ≈ 8 days.

This is mainly because large scale photometric studies of multiple WR stars over long time periods just simply hasn't been done until the onset of the Canadian space telescope *MOST*. From its observations we have been able to say rather definitively that WR stars are all variable at some level. Unfortunately though, the photometry is not as insightful as hoped. The variations in the data have been attributed to a variety of things including spots, pulsations, and atmospheric eclipses (David-Uraz et al. 2012; Lefèvre et al. 2005; Chené et al. 2011). One thing that hasn't been found though is any sense of uniformity. There are as many causes of photometric variation as there are published papers. This is not to say that these explanations are incorrect, but rather that they lack cohesion.

In this proceedings our aim is to find similarities and/or links between the photometric variability of all 12 WR stars in the *MOST* archive, including those which have already been published. First we apply a full frequency analysis looking for evidence of pulsational modes. Next we search for similarities in the 1/f noise associated with these stars. Finally, as a last resort we apply phenomenological classification to the photometric variability observed and discuss the results.

## 2 Data & Observations

We obtained optical photometry with the *MOST* microsatellite that houses a 15-cm Maksutov telescope through a custom broad-band filter covering 3500–7500 Å. The sun-synchronous polar orbit has a period of 101.4 minutes ($f = 14.20\ \mathrm{d}^{-1}$), which enables uninterrupted observations for up to eight weeks for targets in the continuous viewing zone. A pre-launch summary of the mission is given by Walker et al. (2003).

The sample consisted of 12 targets, 6 of WC type and 6 of WN type all chosen because they are in the limited window of MOST observability, are relatively bright, and in most cases were already known to be highly variable. These data were then extracted using the technique of Reegen et al. (2006). Specific information for each target is given in Table 1. The instrumental scatter according to what we know about *MOST* is close to 1 mmag per *MOST*-orbit bin for the WR stars of the magnitude that were observed. This is much lower than what is given in Table 1, which is a measure of the raw, un-binned light curve.

## 3 Photometric Analysis

### 3.1 Looking for Pulsations

In order to search for pulsational signals we first did a full frequency analysis of every target in our sample. The method we used is called prewhitening. In this method we took the fourier transform of our target, identified and fit the largest peak, and then removed a sinusoid matching the peak's fit parameters from the data. This process was then repeated until the peaks fall below our significance threshold

**Tab. 1:** *MOST* Observations. The point to point scatter is a measure of the raw observation precision, but can be biased by real variations in the data.

| Target | Sp. Type | V Mag | Start Date (JD-2450000) | Length (Days) | Scatter (Mag) |
|---|---|---|---|---|---|
| WR 71 | WN6 | 10.1 | 6806 | 27 | 0.00911 |
| WR 92 | WC9 | 10.2 | 6092 | 26 | 0.00792 |
| WR 103 | WC9d | 8.7 | 3535 | 37 | 0.00688 |
| WR 110 | WN5 | 9.9 | 5812 | 30 | 0.00266 |
| WR 111 | WC5 | 7.8 | 3892 | 23 | 0.00100 |
| WR 113 | WC8+O8-9IV | 9.1 | 5009 | 45 | 0.00350 |
| WR 113 | WC8+O8-9IV | 9.1 | 5361 | 28 | 0.00311 |
| WR 115 | WN6 | 11.84 | 5720 | 38 | 0.00811 |
| WR 119 | WC9d | 12.43 | 6454 | 48 | 0.00978 |
| WR 120 | WN7 | 12.28 | 5720 | 38 | 0.01428 |
| WR 121 | WC9d | 11.9 | 6455 | 47 | 0.00908 |
| WR 123 | WN8 | 11.12 | 3174 | 38 | 0.01281 |
| WR 124 | WN8h | 11.5 | 4651 | 32 | 0.01066 |

of 4 sigma. This was done using Period04 (Lenz & Breger 2005).

Using the lists of frequencies that were found, we looked for the most typical sign of pulsations: spacings. Regular pulsations often show common spacings either in frequency (p-modes) or period (g-modes). As it was not clear what type of pulsations would be expected we searched for both. At first glance the results seemed to be promising as we found 5 stars with strong evidence of period spacing and 3 stars with evidence for frequency spacing. However, it was difficult to explain the presence of both p-modes and g-modes in this dataset. In addition, there were no apparent correlations between spectral type, radius, or any other fundamental parameter and the frequency or period spacings we found. It is important to note that this does not rule out pulsations entirely for each individual star, but it makes it unlikely to be a common source of variation for all WR stars.

## 3.2 Signal in the Noise

While the peaks in the Fourier transform were hard to quantify, they were not the only source of variability present. Something that occurs often in the Fourier regime is the presence of the so called 1/f noise which is where the mean level of the transform increases as you got to lower and lower frequencies. Although it is often referred to as noise it can be evidence for specific astronomical signals such as flickering on the surface of the star (Stanishev et al. 2002). It's form is given by

$$P(f) = \frac{C}{1 + (2\pi f)^{\gamma}} \tag{1}$$

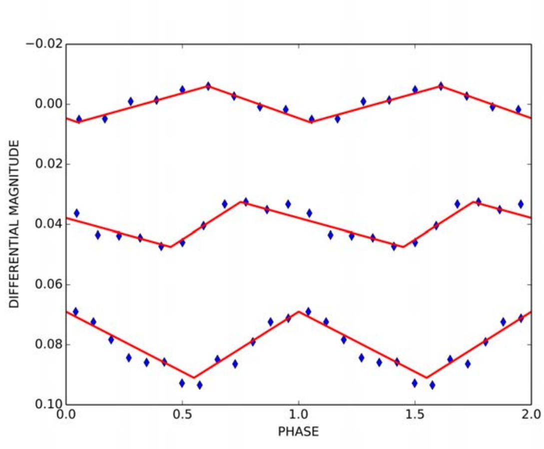


**Fig. 2:** Phased and binned data from WR 71 (top and middle) and WR 103 (bottom) in blue with periods of 0.73 d, 1.63 d, 0.59 d respectively. In red is an overlay of a sawtooth wave with different slopes for each wave. It is important to note that the red line is not a fit to the data, and is only present to show how well this form matches the observed data.

We fit the Fourier Transform for each star and compared the results of the fit to fundamental parameters found in Hamann et al. (2006) & Sander et al. (2012). The only significant result was a confirmation of Michaux et al. (2014) that the size of the variation is inversely dependent on temperature.

# 4 Morphological Classification

The conclusions from the previous sections have shown us that the intrinsic variability was either too transient or non-sinusoidal for Fourier methods to be of much use. Therefore, we turned to looking for inherent similarities between the light curves themselves. While this method does not a priori provide any physical insight, our first priority was to find commonalities in the data.

### 4.1 False Eclipses

One of the most obvious variations that was apparent in 4 out of 12 light curves is the presence of eclipse like structures. They never happened more than once per dataset and were typically the largest variations present. However, while they looked fairly similar to an eclipse (see Fig. 1) the length was abnormally long, on the order of several days.

Even if these dips were periodic they were much too long to belong to the presence of a companion star. We also considered the presence of large clumps as they could block a significant amount of light as they pass into the line of sight. However, while the depth of the eclipse is relatively consistent with this phenomenon, the wind speed is far too great for such an eclipse to last for several days. One thing that did seem apparent though, was that these eclipses were uncorrelated with the other variations seen in the light curves.

### 4.2 Unusual Waves

In addition to these false eclipses, we had a large amount of semi-periodic transient variability which appeared in every single light curve. Under close examination of a small section of one of these light curves we noticed something strange; the presence of a unique repeatable triangular or sawtooth shape (see Fig. 2).

While we originally ignored this as a consequence of a poorly sampled sine wave, closer examination of all light curves revealed that this simply could not be the case. Further investigation of several other unrelated *MOST* light curves did not reveal this unique shape making it unlikely to be of instrumental origin. In addition, this same shape was present once or multiple times in 11 of 12 targets at a variety of different periods. The only noticeable difference between these waves was the slope of the waves' rise and fall.

In addition, we see the presence of two other unique wave forms referred to as the w-wave and the reverse w-wave due to their w-like shapes. The w-wave and reverse w-wave, though not pictured due to lack of space, occur with slightly less regularity appearing in 3 out of 12 and 2 out of 12 light curves respectively. However, their singular appearance makes it likely that they are real phenomena.

## 5 Discussion & Future Work

We have used the largest space-based photometric dataset of WR stars which exists to determine similarities between these stars in a search for underlying physics. It is abundantly clear that the normal mechanisms attributed to most stars such as pulsations are not sufficient to adequately describe their variability. However, though our current understanding does not predict what the variability in these objects is, it is most certainly correlated. The fact that their are consistent, unique, repeatable shapes indicates that their is a common source which responsible this triangular and w shaped variability.

The only issue is that this variability is so unusual that the underlying cause is unclear. While it is quite easy to speculate that these odd shapes are related to light propagation through a wind, what the original cause could be or what interactions cause these unique but repeatable shapes is currently nearly impossible to say. There are simply too many possibilities and a lack of viable theories to test them against. Therefore, we choose not to make wild or unfounded claims as to the possible nature of these variations and instead present simply what we see.

While models are likely far in the future, we do hope to characterize these data more rigorously. This includes fitting the slopes of the triangular waves and seeing if there are any correlations with parameters such as radius or spectral type. We also eagerly await the presence of the Gamma Velorum, a WR recently observed photometrically with the BRITE-constellation project for 6 months in two filters. This data set will be unprecedented and hopefully help our understanding of WRs stars in our sample.

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**Norbert Langer:** What timescales can you probe with your data?

**Herbert Pablo:** This depends largely on whether or not the target can be viewed continuously or for only part of each *MOST* orbit (which is more common). In the latter case we will always bin on the orbital period (0.0704 d). Therefore, in all cases we are sensitive to periods which are greater than 0.14 d.

**Peredur Williams:** How much of the scatter in your light curves is intrinsic to the star and how much is instrumental?

**Herbert Pablo:** If we bin on the *MOST* orbital period then the precision of each point is typically less than 1 mmag for all the stars sampled. The point to point scatter can be quite a bit higher, but as we are talking about long periods (greater than 0.5 d) binning is quite appropriate. Therefore we can believe variations that are at least a mmag in amplitude.