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Published in:
Astronomy & Astrophysics

Link to publication

Citation for published version (APA):

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Wolf-Rayet stars and O-star runaways with HIPPARCOS

II. Photometry*


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Received 19 September 1997 / Accepted 2 December 1997

Abstract. Abundant HIPPARCOS photometry over 3 years of 141 O and Wolf-Rayet stars, including 8 massive X-ray binaries, provides a magnificent variety of light curves at the σ ∼ 1-5% level. Among the most interesting results, we mention: optical outbursts in HD 102567 (MXRB), coinciding with periastron passages; drastic changes in the light curve shape of HD 153919 (MXRB); previously unknown long-term variability of HD 39680 (O6V: [n] pe var) and WR 46 (WN3p); unusual flaring of HDE 308399 (O9V); ellipsoidal variations of HD 64315, HD 115071 and HD 160641; rotationally modulated variations in HD 66811=ζ Pup (O4Inf) and HD 210839=λ Cep (O6I(n)fp); dust formation episode in WR 121 (WC9). In a statistical sense, the incidence of variability is slightly higher among the WR stars, which might be explained by the higher percentage of known binary systems. Among the presumably single WR stars, the candidate runaways appear to be more variable then the rest.

Key words: stars: activity – stars: variables: other – stars: Wolf-Rayet

1. Introduction

In this paper we conclude the description of the results obtained in the framework of our HIPPARCOS programme. Our sample of 141 stars in total (see Moffat et al. 1997 - Paper I - for more details), comprises the bulk of the known Galactic Wolf-Rayet stars for v<12 mag, as well as a pre-selected (peculiar radial velocity component |v_r|pec > 30km/s) group of Galactic O stars, and 8 high-mass X-ray binaries (MXRB) known at the time of application (1982).

2. Data reduction and period search

All stars in our sample were observed by HIPPARCOS (ESA, 1997) between HJD 2447835 and HJD 2449063, from 40 to 270 times each. The observations are spread, often not uniformly, over the entire 3-3-yr period. The broad band photometric system (λ_c ∼ 5100Å, λ_max ∼ 4500Å, FWHM ∼ 2200Å: Hp magnitudes) was calibrated to provide Hp=V_J for B-V=0 (V_J stands for broad band Johnson magnitude).

We deleted problematic points (around 2-3 points per star on average) marked by warning flags (mainly ‘poor attitude reconstruction’, ‘perturbations’ and ‘Sun pointing’) from the original data; calculated the standard errors of the individual observation as s = [Σ(mi - ̄m)^2/(n - 1)]^0.5; converted s into peak-to-peak amplitude Am = 3.289 × s (Perryman 1996), and plotted Am vs. Hp in Fig. 1. Applying the 99.9% detectability limits recommended by the HIPPARCOS consortium, we found that all stars in our sample should be treated as variable, while many of them are actually known to be constant. As a more realistic, but tentative variability threshold we use twice the recommended level. Then exactly 50% of the stars fall in the ‘variable’ category. We then analyse this variable subsample in more detail. In general, analysis of the stars falling below our revised, tentative
detectability threshold provides no conclusive results, and we pay less attention to them.

We searched for periodic variations in the frequency range $f=0\text{.}{0-1.0}\text{ d}^{-1}$ (i.e. somewhat beyond the effective Nyquist frequency) for all stars with $H_p\text{>6.0 mag, and 0-3.0 d}^{-1}$ for $H_p\leq6.0\text{ mag (if the data were abundant enough, usually n\approx100 points). The reason for this split is the steep rise of the variability detection threshold starting from }H_p\text{=6 mag, which makes the search for high-frequency components practically hopeless. In performing the frequency analysis, we implement the approach that minimises the bias introduced by uneven data spacing: for the pre-selection of spurious periodicities we used the CLEANed frequency spectra (Roberts et al. 1987) along with the original Scargle (1982) periodograms - see also the detailed discussion in Antokhin et al. (1995). While CLEANing the data, we choose the gain parameter $g=0.2-0.4$ and the number of it-erations at 250-500. Once found, the periodic signal(s) is(are) further assessed via (a) calculation of the false alarm probability (FAP; Scargle 1982), usually neglecting those with $\text{FAP}>0.005$, and, finally, (b) by comparing the folded light curves with the known instrumental scatter. However, the calculated FAP should be regarded only as indicative, being seriously biased by many factors, with the uneveness of time series among the most influ-en-tial. Thus the temporal distribution of the data deserves an additional comment. All our program stars have one big time gap at HJD 2448750(\pm50) - ... 8950(\pm50). Among all stars listed as variable in Table 1, we mention some cases of particularly bad sampling: HD 34078 (Fig.3), HD 245770 (Fig. 2), HD 39680 (Fig. 3), HD 148937, 150136, 151804, 152408, 152667, 153919, 156212, 158186, 160641; WR 78, 79, 97, 103, 121 (Fig. 7). Under ‘bad sampling’ we specifically mean the cases when the data form 6-8 compact clusters, separated by big time gaps exceeding the cluster’s length (cf. HD 34078 or HD 39680: Fig. 3). Neglecting the influence of small variations in the total length of the observations (T) for a given star, we adopt a uniform accuracy of $\Delta f=0.001\text{ d}^{-1} (\sim 1/T)$ in all frequency estimations. Thus defined, $\Delta f$ overestimates the real error by a factor which depends on many parameters: temporal unevenness, signal-to-noise ratio, number and spectral distribution of the frequency components (Kovács 1981; Horne & Baliunas 1986). In each individual case this factor should be estimated via detailed extensive modeling, which is far beyond the scope of this paper. Hence, we retain a simplified, but uniform approach.

We summarize all results in Table 1, which includes only stars with detected variability. We list: HD/other names; HIP (HIPPARCOS catalog number); spectral type; mean observed $H_p$ magnitude; $s$ - standard deviation of one measurement; period(s) and full (peak-to-peak) fitted amplitudes (for a quasi-sinusoidal signal only) of the periodic signal(s). It is worth mentioning that among the 71 variable stars listed in Table 1, only 15 (HIP 24575, 26565, 27941, 35412, 38430, 44368, 57569, 58954, 64737, 82911, 83499, 85569, 100214, 102088 and 111633) were derived as variable in the ‘Hipparcos Vari-ability Annex’ (ESA, 1997, SP-1200).

3. Results

We discuss all preselected stars in the following order: (a) massive X-ray binaries (MXRB); (b) runaway O-type candidates; (c) WR stars. In each group the objects are reviewed in order of HIP number.

3.1. MXRB

HD 5394 = $\gamma$ Cas is claimed to harbour a white dwarf (Murakami et al. 1986; Haberl 1995) or a neutron star companion (Frontera et al. 1987; see also Parmar et al. 1993). However, there is no indication of binary motion. The star is notorious for its spectacular long-term photometric and spectral variations. Our data show no signs of secular variability, despite persistent long-term brightening of the star during the last 20 years (Telting et al. 1993). A period search in the range $f=0\text{-}3.0\text{ d}^{-1}$ yields rather marginal results. Two possible peri-ods emerge: $P=1.634\text{ d (f=} 0.612 \pm 0.001\text{ d}^{-1}\text{), peak-to-peak amplitude A=} 0.010\text{ mag, and P=} 1.045\text{ d (f=} 0.956\text{ d}^{-1}\text{), A=} 0.011\text{ mag, both with FAP} \sim 10^{-6}$ (Fig. 2). These periodic light variations are probably induced by the axial rotation of the star rather than by any phenomena related to the binary revo-lution. For the latter, the expected period falls in the range of months to years. Note that Smith (1997) reports X-ray variations with tentative period $P=1.12499\pm0.00001\text{ d}$, which is compatible with the expected axial rotation rate.

HD 24534 = X Per is a well studied MXRB with a slowly rotating pulsar ($P_p=385\text{ s}$; Leahy 1990) in a $P=580.5\text{ d}$ orbit (Hutchings 1977, but see also Penrod & Vogt 1985). The system is known to be photometrically variable on timescales from

![Fig. 1. Dependence of the peak-to-valley amplitude of the variability $A_{\text{mv}} = 3.289 \times \sigma_{H_p}$ on $H_p$. The $\sim 99.9\%$ detectability threshold is marked by a dashed line. Circles are O stars, triangles WR. The brightest and the most variable stars are identified.](image-url)
seconds to years. The correlation between optical and X-ray activity is rather feeble (Roche et al. 1993). The HIPPARCOS observations were secured during a low state of the system (both in activity and mean flux level - cf. Roche et al. 1993, 1997), i.e. during the presumable loss of a circumstellar shell with subsequent build-up of a new envelope. We note the gradual brightening of the system (Fig. 2) along with the absence of any trace of the P~580 d orbital modulation. Also, there are no hints of the P~ 0.94 d variability (stellar rotation?) suggested by Hutchings (1977).

\textbf{HD 245770 = 4U 05335 + 26.} The long quest for any coherent manifestations of orbital motion in this outbursting, transient X-ray binary have not led to any consensus (cf. the dedicated review by Giovannelli & Graziati 1992), with efforts to find a universal orbital ‘clock’ ongoing (Hao et al. 1996). We supplement the HIPPARCOS data by the time-overlapping photometry of Hao et al. and use the ephemeris of Janot-Pacheco et al. (1987): the orbital period P=111.5 d, and the time of periastron passage at T0=2442724.5 were derived by re-analysing the data from Hutchings (1984), supplemented by additional observations. With these data, and this ephemeris, we can claim some overlap between the times of periastron passage and optical outbursts (Fig. 2). We also note the following: (a) not every periastron passage is accompanied by an optical/X-ray outburst; (b) as with the X-ray flaring (Giovannelli & Graziati 1992), the optical bursts are distributed practically over an entire orbit, with some clustering around periastron passage. This directly points to the intrinsic variability of the Be companion. Its variable circumstellar shell along with the phase-related orbital separation might control the rate of accretion onto the neutron star, introducing some randomness into the optical/X-ray flaring.

\textbf{HD 77581 = Vela X−1.} We use the orbital period P=8.96442 d from Nagase (1989) and the time of the X-ray eclipse at T0=2441446.533 (φ = 0: Nagase et al. 1983; Sadakane et al. 1985) to fold the HIPPARCOS data (Fig. 2). The general shape of the light curve matches well the combined data of van Genderen (1981), allowing for the significant spread caused by the epoch-related variability. To illustrate the latter, we subdi-
vide our dataset into two equal parts. Note the difference between these subsets around \( \phi = 0.5 \) (neutron star in front), probably caused by reconfiguration of the stellar surface (cf. the discussion of microvariations by van Genderen 1981).

HD 102567 = 4U 1145\,−\,61 undergoes periodic X-ray outbursting caused by a steep increase of accretion during periastron passage. We use the ephemeris of Watson et al. (1981) and find that the X-ray outbursts are accompanied by significant growth of the optical flux (Fig. 2). The amplitude of the optical flares depends on the current mean flux of the system, with a clear saturation effect, up to complete disappearance of the optical outbursts during the stage of maximum mean light level.

HD 152667 = V861 Sco exhibits \( \beta \) Lyr-like variations with two clear minima of unequal depth (ellipsoidal variations) for \( P = 7.84825 \) d. The shape of the light curve has been stable for 20 years (Bunk & Haefner 1991), and remains so in our data (Fig. 2).

HD 153919 = 4U 1700\,−\,37. The extreme characteristics of the Of companion (O 6.5 Iaf+; cf. Stickland & Lloyd 1993) result in an unstable light curve with changes occurring on timescales from a few hours to months (van Paradijs et al. 1984; Balona 1992). The minima are caused by tidal distortion of the primary star without significant heating by the X-ray source. We use the ephemeris from Sazonov et al. (1995) to produce the folded light curve in Fig. 2. Overplotting the mean light curve from van Paradijs et al. (1984), we immediately note outstanding changes in the light curve shape.

HD 226868 = Cyg X\,−\,1 has a well established orbital period of \( P = 5.59985 \) d (Kemp et al. 1987; Nadzhip et al. 1996) with an additional long periodicity of \( P = 294 \) d suggested by the X-ray observations (Ninkov et al. 1987). We find no trace of the latter in the HIPPARCOS data. Folding the light curve with the orbital period and arbitrarily subdividing the data into two equal parts, we immediately note (Fig. 2): (a) growth (\( \sim 1.5 \times \)) of the total amplitude of the optical light curve compared to previous epochs (Khaliliullin & Khaliliulla 1981); (b) long-term distortions of the light curve, with frequent filling-in of the secondary (\( \phi = 0.5 \)) minimum (cf. Walker & Rolland Quintanilla 1978; Voloshina et al. 1997); and (c) possible flaring around the \( \phi = 0.75 \) light curve maximum (cf. Walker & Rolland Quintanilla 1978).

### 3.2. Candidate O-star runaways

HD 16429 = V482 Cas is a suspected \( \beta \) Cep-like variable with two clear minima of unequal depth (ellipsoidal variations) for \( P = 7.84825 \) d. The shape of the light curve has been stable for 20 years (Bunk & Haefner 1991), and remains so in our data (Fig. 2).

HD 24912 = \( \xi \) Per. Gies & Bolton (1986) find periodic variations in RV with \( P = 7.3876 \) d and very low amplitude, \( K = 5.9 \) km s\(^{-1}\), suggesting binary motion as a cause. We found a slightly better solution, folding their data with \( P = 11.1841 \) d, yielding \( K = 6.4 \) km s\(^{-1}\). On the other hand, Bohannan & Garmany (1978) detected no periodic variations, placing a less restrictive upper limit of \( K < 30 \) km s\(^{-1}\); and Stone (1982) claimed long-term RV changes, suggestive of an orbital period of \( P > 185 \) d. \( \xi \) Per has been found to be an ideal object for study of the phenomenon of discrete absorption components (Henrichs et al. 1994). The star...
Fig. 4. Photometry of 9 O stars: all folded light curves. HD 158186 and HD 219286: the bottom curves are shifted by +0.25 mag for clarity.

is photometrically variable, being just above the detectability threshold (Fig. 1). Searching in the range 0-3.0 d$^{-1}$, we find no conclusive periodicities. With the present data, we are able to place a stringent upper limit of $A=0.011$ mag on the presence of any coherent periodic variations.

HD 34078 = AE Aur has confirmed runaway status (Blauw 1993), and was suspected as a photometric variable. Neverthe-
less, there are no hints of binary motion down to the limit $K<2.5$ km s$^{-1}$ (Gies & Bolton 1986). We find the star clearly variable (Fig. 3). After a period search in the CLEANed data we find the best period $P=213.7$ d (Fig. 3). In a quite preliminary fashion, we suspect this star to belong to the MXRB group. However, search for radio pulsations from a neutron star has yielded negative results (Philp et al. 1996; Sayer et al. 1996).

HD 37737 cannot be regarded as a variable in accordance with our selection criteria. We find only weak and inconclusive traces of the $P=2.490$ d period mentioned by Gies & Bolton (1986).

HD 38666 = $\mu$ Col is a ‘bona fide’ runaway star (Blauw 1993), extensively observed by Balona et al. (1992), who made no further comments. We searched for periods in the range 0-3.0 d$^{-1}$ with negative results. We place an upper limit of $A=0.008$ mag on any periodic component.

HD 39680 is an extreme emission-line object with the entire Balmer sequence exhibiting double-peaked emissions (Gies & Bolton 1986). Suspected long-term changes (decades) of the emission spectrum are not accompanied by significant RV variations. The star is listed as micro-variable with $\sigma=0.023$ mag (Ruefener & Bartholdi 1982). We find spectacular long-term variations, recalling the trends frequently seen in Be stars (Fig. 3).

HD 52533 falls in the category of variable stars, but the current data cannot be treated as reliable - all points are marked with warning flags in the original HIPPARCOS file.

HD 57060 = 29 CMa: for this well known binary system, we simply fold the data with the ephemeris provided by Stickland (1989; see also Wiggs & Gies 1993). This demonstrates the reliability and robustness of the HIPPARCOS photometry (Fig. 4), along with the long-term stability of the light variations in this close binary system.

HD 60369. Despite the abundant data (173 measurements) and promising location of the star above the detectability threshold, we find no significant periodic variations.

HD 64315. RV variability was suspected by Crampton (1972) and confirmed by Solivella & Niemela (1986), with the announcement of a SB2 (O6+O6) orbit, $P_{orb}=1.34$ d. Only one period completely dominates the CLEANed power spectrum,
Table 1. Summary of pertinent data for the variable O and WR stars

<table>
<thead>
<tr>
<th>HD/DM</th>
<th>Other</th>
<th>HIP</th>
<th>Sp</th>
<th>Hp (mag)</th>
<th>σ(Hp) (mag)</th>
<th>P (day)</th>
<th>A (mag)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>4004</td>
<td>WR 1</td>
<td>3415</td>
<td>WN5</td>
<td>10.20</td>
<td>0.040</td>
<td>11.6?</td>
<td></td>
<td>SB1?</td>
</tr>
<tr>
<td>5394</td>
<td>γ Cas</td>
<td>4427</td>
<td>B0Iab</td>
<td>2.14</td>
<td>0.009</td>
<td>1.045</td>
<td></td>
<td>MXRB(+WD? or +c?)</td>
</tr>
<tr>
<td>6327</td>
<td>WR 2</td>
<td>5100</td>
<td>WN2</td>
<td>11.24</td>
<td>0.064</td>
<td>long-term</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16429</td>
<td>V428 Cas</td>
<td>12495</td>
<td>O9.5II((n))</td>
<td>7.82</td>
<td>0.018</td>
<td>long-term</td>
<td>P=0.38 d and 0.28 d</td>
<td></td>
</tr>
<tr>
<td>24534</td>
<td>X Per</td>
<td>18350</td>
<td>O9.5pe</td>
<td>6.82</td>
<td>0.014</td>
<td>long-term</td>
<td>MXRB, P=580 d</td>
<td></td>
</tr>
<tr>
<td>24912</td>
<td>ξ Per</td>
<td>18641</td>
<td>O7.5III(n)((f))</td>
<td>4.03</td>
<td>0.006</td>
<td>variable?</td>
<td>P orb = 7.4 d or 11.2 d</td>
<td></td>
</tr>
<tr>
<td>34078</td>
<td>AE Aur</td>
<td>24575</td>
<td>O9.5V</td>
<td>6.05</td>
<td>0.019</td>
<td>213.7 d</td>
<td>0.040</td>
<td>runaway</td>
</tr>
<tr>
<td>E245770</td>
<td>4U05335+26</td>
<td>26566</td>
<td>Bpe</td>
<td>9.27</td>
<td>0.078</td>
<td>outbursts?</td>
<td>MXRB, P orb = 111.5 d(?)</td>
<td></td>
</tr>
<tr>
<td>50896</td>
<td>WR 6</td>
<td>33165</td>
<td>WN5</td>
<td>6.63</td>
<td>0.028</td>
<td>3.77</td>
<td>periodic and secular var.</td>
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</tr>
<tr>
<td>52533</td>
<td></td>
<td>33836</td>
<td>O9V</td>
<td>7.68</td>
<td>0.030</td>
<td>variable?</td>
<td>see text</td>
<td></td>
</tr>
<tr>
<td>56925</td>
<td>WR 7</td>
<td>35378</td>
<td>WN4</td>
<td>11.44</td>
<td>0.052</td>
<td>long-term</td>
<td></td>
<td></td>
</tr>
<tr>
<td>57060</td>
<td>29 CMa</td>
<td>35412</td>
<td>O7.5III(n)((f))</td>
<td>4.03</td>
<td>0.006</td>
<td>variable?</td>
<td>P orb = 7.4 d or 11.2 d</td>
<td></td>
</tr>
<tr>
<td>60369</td>
<td></td>
<td>36706</td>
<td>O9III</td>
<td>8.14</td>
<td>0.019</td>
<td>no periods</td>
<td>variable</td>
<td></td>
</tr>
<tr>
<td>62910</td>
<td>WR 8</td>
<td>37791</td>
<td>WN6+WC4</td>
<td>10.21</td>
<td>0.048</td>
<td>114.6</td>
<td></td>
<td>SB2?</td>
</tr>
<tr>
<td>63099</td>
<td>WR 9</td>
<td>37876</td>
<td>WC5+O7</td>
<td>10.63</td>
<td>0.036</td>
<td>atmosph. ecl.</td>
<td>SB2, P orb = 14.3 d</td>
<td></td>
</tr>
<tr>
<td>64315</td>
<td></td>
<td>38430</td>
<td>O6ne</td>
<td>9.25</td>
<td>0.039</td>
<td>2×0.51</td>
<td>0.084</td>
<td>ellipsoidal var.?</td>
</tr>
<tr>
<td>66811</td>
<td>ζ Pup</td>
<td>39429</td>
<td>O4Inf</td>
<td>2.14</td>
<td>0.009</td>
<td>2.56</td>
<td>0.012</td>
<td>rotat. modulation?</td>
</tr>
<tr>
<td>68273</td>
<td>WR 11</td>
<td>39953</td>
<td>WC8+O9I</td>
<td>1.70</td>
<td>0.012</td>
<td>78.5</td>
<td>SB2, P orb = 78.5 d</td>
<td></td>
</tr>
<tr>
<td>69106</td>
<td></td>
<td>40328</td>
<td>O5e</td>
<td>7.11</td>
<td>0.010</td>
<td>1.484</td>
<td>0.009</td>
<td></td>
</tr>
<tr>
<td>77581</td>
<td></td>
<td>44368</td>
<td>B0.5Ib</td>
<td>7.00</td>
<td>0.031</td>
<td>ellipsoidal var.</td>
<td>MXRB, P orb = 9.0 d</td>
<td></td>
</tr>
<tr>
<td>86161</td>
<td>WR 16</td>
<td>48617</td>
<td>WN8</td>
<td>8.30</td>
<td>0.022</td>
<td>11.7?</td>
<td>20.9?</td>
<td>75.2?</td>
</tr>
<tr>
<td>89358</td>
<td>WR 18</td>
<td>50368</td>
<td>WN5</td>
<td>10.73</td>
<td>0.058</td>
<td>long-term</td>
<td></td>
<td></td>
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<tr>
<td>90657</td>
<td>WR 21</td>
<td>51109</td>
<td>WN4+O4-6</td>
<td>9.76</td>
<td>0.031</td>
<td>atmosph. ecl.</td>
<td>SB2, P orb = 8.2 d</td>
<td></td>
</tr>
<tr>
<td>92740</td>
<td>WR 22</td>
<td>52308</td>
<td>WN7+O6.5-8.5</td>
<td>6.38</td>
<td>0.013</td>
<td>0.67 or 5.20?</td>
<td>SB2, P orb = 80.3 d</td>
<td></td>
</tr>
<tr>
<td>96264</td>
<td></td>
<td>54175</td>
<td>O9.5IV</td>
<td>7.57</td>
<td>0.017</td>
<td>variable?</td>
<td>see text</td>
<td></td>
</tr>
<tr>
<td>96548</td>
<td>WR 40</td>
<td>54283</td>
<td>WN8</td>
<td>7.67</td>
<td>0.036</td>
<td>2.39?</td>
<td>+irregular(?) var.</td>
<td></td>
</tr>
<tr>
<td>E308399</td>
<td>CP-61 2163</td>
<td>55078</td>
<td>O9V</td>
<td>10.95</td>
<td>0.136</td>
<td>flares!</td>
<td></td>
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Table 1. (continued)

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| 210839|          | 109556 | O6I(n)fp | 5.13   | 0.011     | 0.63     | 0.016 | rotational modulat.?
| 211853| WR 153   | 110154 | WN6+O   | 9.09   | 0.034     | eclipsing | SB2, P_ orb = 6.7 d |
| 214419| WR 155   | 111633 | WN7+B(c?)| 8.90   | 0.137     | eclipsing | SB2, P_ orb = 1.6 d |
| AC+60 38562| WR 156 | 113569 | WN8     | 10.92  | 0.037     | 10.05    | ~0.1  | 'transient' periodicity |
| 219286|          | 114868 | O9      | 8.82   | 0.023     | 1.16     | 0.031 |                    |
| 219460| WR 157   | 114791 | WN4.5   | 9.72   | 0.059     | 1.79 ?   | 2.03 ? |                    |
| 193928| WR 141   | 120155 | WN6+O4-5| 9.87   | 0.033     | 21.03    | SB2, P_ orb = 21.7 d |

Notes: HIP = HIPPARCOS Catalogue #.
Hp: ~B+V magnitude
A refers to the peak-to-valley amplitude of a sine-wave fit to the data; relevant for some stars only.

P=0.5095 d with A=0.084 mag. Interpreting this as probable ellipsoidal variations, we plot the data folded with P_ orb = 2×P in Fig. 4.

HD 66811 = ζ Pup is traditionally used as a prototype in hot star wind modeling (Pauldrach et al. 1994; Schaerer & Schmutz 1994). Balona (1992) has found P=5.21 d (with ~1 d alias at 3.21 d) from his 1986-1989 photometry. This period (usually interpreted as due to axial rotation: Moffat & Michaud 1981) was not present in the entire dataset of Balona. However, we find P=2.563 ± 0.005 d (A=0.012 mag) in the HIPPARCOS data (Fig. 4), which is exactly half (within the quoted errors) of the period cited by Balona. This points to large-scale inhomogeneity of the stellar surface modulating the structure and kinematics of the stellar wind in this rapidly rotating (for a supergiant) star (Howarth et al. 1995; Reid & Howarth 1996).

HD 69106 can be classified as marginally variable, being slightly below the detectability limit. We find the most probable period P=1.584 d with A=0.009 mag, with unacceptably high FAP=0.038.

HD 96264 lies just over the variability threshold, but any conclusions should be drawn with extreme caution, owing to the numerous warning flags in the HIPPARCOS file. We tentatively give P=1.367 d and/or P=1.159 d.

HDE 308399 = CP − 61° 2163 has the most unusual light curve among all the stars under consideration. Big flares (Fig. 3) occur at irregular intervals. The star was not detected as an X-ray source during the EINSTEIN mission (Chlebowski et al. 1989) and is not known to be a binary. Its spectrum (O9V) fails to show anything extraordinary.

HD 122879 is listed as having constant RV (Gies 1987). We find that the star is variable with P=1.580±0.002 d, A=0.023 mag and FAP~ 10^{-6} (Fig. 4).
Fig. 5. Photometry of 7 WR stars: all time-plotted data, with folded light curve also shown for WR 55.

HD 123008 has constant RV (Levato et al. 1988). We find \( P = 4.502 \pm 0.020 \) d, \( A = 0.027 \) mag, FAP \( \sim 10^{-5} \) in the HIPPARCOS data, but flag this result as uncertain (large scatter in the folded light curve).

HD 148937 is surrounded by the spectacular bipolar nebula NGC 6144/45 (Scowen et al. 1995, and references therein). There is no compelling evidence for large-amplitude (\( K \geq 20 \) km s\(^{-1}\)) radial velocity variations (Conti et al. 1977; Andersen 1985). Reports on photometric variability are somewhat controversial: Balona (1992) finds variability on timescales from months to years, but van Genderen et al. (1989) conclude that the star is constant. Our data are too sparse (only 44 points) to draw any meaningful conclusions about coherent variations. We mention as very tentative some possibilities: \( P = 3.995 \) d; \( 3.488 \) d; \( 2.542 \) d; \( 1.236 \) d, all with \( A = 0.02-0.03 \) mag.

HD 150136. Arnal et al. (1988) classify this star as SB1 with \( P = 2.676147 \) d. We report no trace of this period, keeping in mind that all HIPPARCOS data are marked by warning flags.

HD 151804 = V973 Sco is listed as single by Conti et al. (1977), but exhibits pronounced spectral (Prinja et al. 1996) and photometric (van Genderen et al. 1985, 1989; Balona 1992) variations on timescales vaguely determined as ‘days-to-weeks’. We cannot improve the situation with our relatively sparse data (57 points), beyond confirming the week-to-week variability.

HD 152408. As in HD 151804, there are no indications of binary motion (Conti et al. 1977), despite well documented, smooth day-to-day photometric variations (Balona 1992), roughly matching the order of a day recurrence time of the discrete absorption components (DACs: Prinja & Fullerton 1994). We note variations of 0.02-0.03 mag on a timescale \( \sim 20-50 \) d in the HIPPARCOS data, without a recognizable periodic component.

HD 156212 is a definitive runaway star (Gies 1987) surrounded by a bow shock or shell (Noriega-Crespo et al. 1997). Levato et al. (1988) have detected RV variations, being unable to assign any distinct period. The star is variable in accordance with our criterion. We mention, without insistence, one possible period: \( P = 5.8 \) d, \( A = 0.035 \) mag - the data are too sparse for a detailed period search.

HD 158186 is suspected to be a SB1 system (Crampton 1972; Gies 1987). We find clear indication of variability, with an eclipse-like light curve. However, the data are not complete enough to choose between three possibilities: \( P = 8.7700 \) d (ESA, 1997, SPP-1200), and our solutions at \( P = 3.478 \) d and \( P = 2.515 \) d, each showing a single minimum (Fig. 4).

HD 160641 = V2076 Oph is an extreme He-rich blue star, believed to be undergoing the post-asymptotic giant branch evolutionary phase. The star is known as a non-radial pulsator.
with epoch-dependent, dominating harmonics at $f=0.497, 0.894, 1.416 \text{ d}^{-1}$, etc. - cf. Lysa-Gray et al. (1987). Having only 52 points spread over 3 years, we are not able to follow any of these frequently changing (to complete disappearance) oscillations. To our surprise, we find a clear periodic signal with $f=2.236 \text{ d}^{-1}$ ($P=0.4472 \text{ d}$, $A=0.091 \text{ mag}$ (Fig. 4) in the CLEANed data, which escapes any straightforward interpretation.

HD 173820 falls in the category of variable stars, slightly exceeding the threshold. We select $P=10.87 \pm 0.12 \text{ d}$, $A=0.056 \text{ mag}$, FAP $\sim 10^{-7}$ as the best candidate to fit the apparently variable flux.

HD 210839 = \lambda Cep, Gies & Bolton (1986) put a firm upper limit, $K < 14.5 \text{ km \ s}^{-1}$, on any hypothetical binary motion with $P=4.0-890 \text{ d}$. However, the star is known for strong spectral variations (Underhill 1995; Fullerton et al. 1996) and a $\sim 1.4 \text{ d}$ reappearance time scale of the DACs (Kaper et al. 1996). An extensive period search on the CLEANed data in the $f=0-3.0 \text{ d}^{-1}$ interval leads to $P=0.6326 \pm 0.0004 \text{ d}$, $A=0.016 \text{ mag}$ (Fig. 4), corresponding to $\sim 0.5$ of the DAC recurrence time scale as well as $\sim 0.5$ of the minimal rotation period (Kaper et al. 1996). The modulation might be related to large-scale surface inhomogeneities.

HD 219286. Searching for short-term $\beta$ Cep-like variability, Percy & Madore (1972) found no variations exceeding 0.01-0.015 mag during 7-8 hours of observation. On the other hand, we find two possible periods: $P=1.341 \pm 0.002 \text{ d}$, $A=0.034 \text{ mag}$, and $P=1.155 \pm 0.001 \text{ d}$, $A=0.031 \text{ mag}$, both with FAP $\sim 10^{-6}$ (Fig. 4), with some preference for the former.

### 3.3. Wolf-Rayet stars

HD 4004 = WR 1 is an apparently single star with variable spectrum (Niedzielski 1995, 1996) and continuum flux (Moffat & Shara 1986; Morel 1997), and ‘quiet’ X-ray flux (Wessolowski 1996). Period searches have led to controversial results: $P=8 \text{ d}, 6.1 \text{ d}, 2.667 \text{ d}, 0.775 \text{ d}$ (cf. references above). Despite the indication of variability, there is no conclusive periodicity in the HIPPARCOS data. The ‘best’ possibility (with high uncertainty) is: $P=11.68 \pm 0.14 \text{ d}$, $A=0.044$, FAP $= 0.006$.

HD 6327 = WR 2 lies just above the detectability threshold with possible long-term trends (Fig. 5). As for coherent periodic variations, we isolate two: $P=18.59 \pm 0.034 \text{ d}$, $A=0.074 \text{ mag}$, FAP $\sim 10^{-6}$; $P=2.171 \pm 0.005 \text{ d}$, $A=0.064$, FAP $\sim 10^{-4}$.

HD 50896 = WR 6 = EZ CMa demonstrates spectacualr spectral (Morel et al. 1997), photometric (Duijssens et al. 1996) and polarimetric (Driessen et al. 1989) variations, on a unique period $P=3.77 \text{ d}$ (Antokhin et al. 1994), along with secular (years to decades) trends (Robert et al. 1992; Duijssens et al. 1996). A formal period search on the HIPPARCOS photometry gives $P=3.771 \pm 0.011 \text{ d}$. To stress the importance of the secular light curve changes, we arbitrary subdivide the entire set into 4 equal parts (50 points each) and plot them folded with the ‘traditional’ $P=3.766 \text{ d}$ (Fig. 6).

HD 56925 = WR 7. Despite the presence of a long-term trend (Fig. 5), we find no evidence of periodic variations.

HD 62910 = WR 8. Periodic RV variations were detected by Niemela (1991) and attributed to binary motion with 3 equally probable periods: $P=38.4 \text{ d}$, $55 \text{ d}$ and $64 \text{ d}$. We find a tentative, but tempting (twice the suggested period of $55 \text{ d}$ $P=115 \pm 13 \text{ d}$, $A=0.068 \text{ mag}$, FAP $\sim 10^{-6}$.

HD 63009 = WR 9 is known to be a SB2 binary (Niemela 1995) with orbital period $P=14.305 \text{ d}$, and undergoing shallow atmospheric eclipses (i.e. light variations due to the phase dependency in scattering of the O star light by the extended WR envelope - cf. Lamontagne et al. 1996). Relative faintness of the star, as well as shallowness of the eclipses, makes this phenomenon barely recognizable in the HIPPARCOS data (folded and binned to $\Delta \phi = 0.1$ phase bins: Fig. 6).

HD 68273 = WR 11. There are some slightly different estimates of the orbital period: $P=78.519 \text{ d}$ (Pike et al. 1983), $P=78.5002 \text{ d}$ (Moffat et al. 1986) and $P=78.53 \text{ d}$ (Schmutz et al. 1997). Their ephemeris produce very similar light curves. We retain the orbital elements from Moffat et al. (1986: phase zero at periastron passage) and find that the system undergoes broad light maxima during periastron passage (Fig. 6), which is rather unique for a typical WR+OB binary. This might be related to an increase of the O-star light scattered off the extended WR wind, as the orbital separation decreases.

HD 86161 = WR 16. Balona et al. (1989 a,b) describe the photometric variations as quasi-periodic with $P=17.5 \text{ d}$, while extensive 3-month continuous photometric monitoring by Antokhin et al. (1995a; see also Gosset et al. 1990) yields two ‘primary’ frequencies with $P_1 = 26.3 \text{ d}$ and $P_2 = 10.7 \text{ d}$, the latter being equal to the period in RV variations found by Moffat & Niemela (1982). The star is obviously variable (Fig. 5). We find 3 possible periods: $P=75.2 \pm 5.6 \text{ d}$, $A=0.026 \text{ mag}$, FAP $\sim 10^{-4}$; $P=20.88 \pm 0.44 \text{ d}$, $A=0.028 \text{ mag}$, FAP $\sim 10^{-5}$; $P=11.74 \pm 0.14 \text{ d}$, $A=0.032 \text{ mag}$, FAP $\sim 10^{-7}$.

HD 89358 = WR 18. Beyond pronounced long-term variations (Fig. 5), we find no conclusive periodicities.

HD 90657 = WR 21. We use the ephemeris from Lamontagne et al. (1994) to produce a binned ($\Delta \phi = 0.1$) light curve with $P=8.255 \text{ d}$, unveiling a weak atmospheric eclipse (Fig. 6).

HD 92740 = WR 22. We find no coherent relations related to the orbital period of $P=80.325 \text{ d}$ (Rauw et al. 1996b). Unfortunately, all the times of the sharp ($\sim 1 \text{ d}$) eclipse dip occurring when the WR star is in front (Balona et al. 1989 a,b; Gosset et al. 1991) were not covered by our data. Among other possibilities we find: $P=5.200 \pm 0.027 \text{ d}$, $A=0.028 \text{ mag}$, FAP $= 0$ (probably spurious, due to grouping of the data); $P=0.6719 \pm 0.0004 \text{ d}$, $A=0.018 \text{ mag}$, FAP $\sim 10^{-3}$.

HD 94546 = WR 31. There are no manifestations of the announced $P=4.831 \text{ d}$ orbital period (Niemela et al. 1985; Lamontagne et al. 1996), possibly below the detection limit.

HD 96548 = WR 40. We refer to the extensive discussion in Antokhin et al. (1995a) of the long history of period searches in this star. WR 40 is evidently variable (Fig. 5), but without dominating period(s). We find a rather elusive $P=2.39 \text{ d}$ which is left without further comment.
Fig. 6. Photometry of 8 WR stars: all folded light curves. WR 6: we split the data into 4 ∼ equal subsets and plot them in two subpanels, where the open circles mark the second and fourth subsets. WR 9, WR 21 and WR 47: the HIPPARCOS data are presented in φ = 0.1 bins and plotted as filled dots with error bars; the open circles refer to previously published data of higher quality. WR 48: the zero epoch is from Moffat & Seggewiss (1977). WR 78: we shift the bottom light curve by +0.15 mag for clarity.

HD 97152 = WR 42. The shallowness of the atmospheric eclipse (∼ 0.01 mag in the binary with P=7.886 d; Lamontagne et al. 1996) makes it undetectable by HIPPARCOS.

HD 104994 = WR 46. To our big surprise, we discovered spectacular long-term variations in the HIPPARCOS photometry (Fig. 5). The star is suspected to be a binary with P=0.28-0.31 d (!): van Genderen et al. (1991); Niemela et al. (1995); Veen et al. (1995).

HDE 311884 = WR 47. Plotting the binned (Δφ = 0.1) HIPPARCOS data folded with the ephemeris from Lamontagne et al. (1996), we match their light curve modulated by a deep and clear atmospheric eclipse (Fig. 6).

HD 113904 = WR 48 = θ Mus is a SB2 system (P = 18.341 ± 0.008 d was assigned as tentative by Moffat & Seggewiss 1977) with particularly strong wind-wind collision effects (St-Louis et al. 1996). We find a small maximum in the light curve occurring exactly at φ=0, when using T=2440663.193 for φ=0 (WR in front) and folding the HIPPARCOS data with P=18.05±0.32 d (Fig. 6). Phase-dependent variability of the ∼ continuum like this was noted by Moffat & Seggewiss (1977). A light curve of slightly lower quality may be obtained for P=1.748 d. If we insist on the orbit-related periodicity, then this maximum light might be interpreted the same way as variability of WR 11, i.e. occurring around periastron passage. However, the currently available orbital parameters are not precise enough to confirm this in θ Mus.

HD 115473 = WR 52 and HD 117297 = WR 53. Both these stars lie just above the detectability threshold, thus being classified as probably variable. We find nothing conclusive from a period search in the range f=0-1.0 d −1.

HD 117688 = WR 55 is apparently a single star with large-amplitude (∼ 0.1 mag) fluctuations (Lamontagne & Moffat 1987). Indeed, the star is clearly variable (Fig. 5). We find P=8.84±0.08 d, resulting in a light curve of unusual form (Fig. 5).

WR 61 = LSS 3208 is close to the sensitivity limit of HIPPARCOS. There are no evident intrinsic light variations in the presence of the large instrumental noise.

HD 134877 = WR 66 brings another surprise, exhibiting a long-lasting maximum (Fig. 7). Note that like WR 46, WR 66 has a well-established, extremely short period, with P=0.146 d (Antokhin et al. 1995a; Rauw et al. 1996a).

HD 136488 = WR 69 is known to be variable (Balona et al. 1989 a,b). CLEANing the HIPPARCOS data, we find a possi-
Fig. 7. Photometry of 4 WR stars: all time-plotted data. WR 134: the dashed line denotes the P=614 d periodicity derived from an independent data set.

**HD 143414 = WR 71.** The star is evidently variable (Fig. 7; cf. Balona et al. 1989 a,b), but without a distinct periodic component.

HD 151932 = WR 78 is described as ‘eclipsing’, with P=22.7 d, by Balona et al. (1989). Small-amplitude (A≤0.01 mag) coherent variations with P=24 min (!) were reported by Bratschi (1995). We find two probable periods (Fig. 6) in the sparse HIPPARCOS data (only 51 points): P=13.28±0.18 d, A=0.029 mag; P=2.243±0.005 d, A=0.030 mag, both with FAP∼10⁻⁷.

**HD 152270 = WR 79.** We use the ephemeris of Lamontagne et al. (1996) to confirm the presence of a very wide and shallow atmospheric eclipse (Fig. 8). However, the minimum is apparently shifted by Δφ∼0.1 from the expected position at φ=0, which could be a consequence of an inaccurate ephemeris. Our data are not abundant enough to perform any meaningful revision of the period.

**HD 164270 = WR 103.** Neither Lamontagne et al. (1996), nor we find any phase-locked variations in this SB2 binary (Niemela 1995: P=12.595 d), despite assigning this star to the ‘variable’ group.

**HD 168206 = WR 113.** We found no traces of the shallow atmospheric eclipse discussed by Lamontagne et al. (1996).

**WR 121 = AS 320** is an efficient dust maker. We detect an extremely deep and narrow R CrB-like light minimum (Fig. 7) in addition to a previously reported dust formation episode (Veen et al. 1997).

**HD 177230 = WR 123** has the well established status of a variable WN8 star (cf. Marchenko et al. 1997 and references therein). Searching for periodic variations, we find P=2.349±0.005 d (Fig. 8), which is practically equal to the 1-day alias of the previously reported P=1.751 d (P=2.331 d as 1-d alias: Moffat & Shara 1986) and P=1.730 d (P=2.370 d as 1-d alias: Marchenko et al. 1997). Note the large scatter in the folded light curve, which may be caused by additional unresolved (quasi-)periodic variations - this star has a multicomponent frequency spectrum (cf. Marchenko et al. 1997).

**HD 186943 = WR 127.** We bin our data to Δφ=0.1 bins and plot them in Fig. 8. They confirm the shallow atmospheric eclipse reported by Lamontagne et al. (1996).

**HD 187282 = WR 128** is variable, but without any definitive period (Moffat & Shara 1986). We share this conclusion.

**HD 190918 = WR 133** is a SB2 system with P=112.4 d (Underhill & Hill 1994). We find no light variations coherent with the binary revolution. Surprisingly, another possible period emerges from the data: P=1.244±0.002 d, A=0.024 mag, FAP∼10⁻⁷ (Fig. 8).

**HD 191765 = WR 134.** The main part of the variations in the HIPPARCOS data (Fig. 7) arises as a long-term trend, with P~614 d established in an independent data set (Marchenko et al. 1996a). These rather unique long-term variations lack a plausible explanation.
Fig. 8. Photometry of 9 WR stars: all folded light curves. WR 127: the HIPPARCOS data are binned to $\phi = 0.1$ bins and plotted as filled dots as for WR 9 in Fig. 6. WR 141: the zero epoch is from Lamontagne et al. (1996).

HD 193077 = WR 138. This long period SB1 binary (P=1538 d: Annuk 1991) can be considered as variable. However, we failed to find any periodic component in the seemingly stochastic fluctuations.

HD 193576 = WR 139 = V444 Cyg is a 'bona fide' WR+O eclipsing binary. We fold the HIPPARCOS data with the ephemeris provided by Khaliullin et al. (1984) and immediately note the significant scatter at $\phi = 0.2-0.3$ and $\sim 0.7$ (Fig. 8; see also Antokhin et al. 1995b).

HD 193928 = WR 141 is a SB2 binary with P=21.64 d (Ganesh & Bappu 1968), slightly revised to P=21.722 d (Marchenko et al. 1998). A substantial aperiodic component ('flickering': Khalack 1996a,b) masks any regular orbit-related light variations (Lamontagne et al. 1996). We fold the data with our newly obtained P=21.03 $\pm$ 0.44 d (Fig. 8), which is significantly different from the spectroscopic period. The origin of this divergence needs further clarification.

HD 197406 = WR 148. As in WR 141, the intrinsic ‘noise’ dominates over the regular variations in this binary. We find no significant trace of the well established orbital period P=4.31 d, which emerges quite clearly from our ground-based data set secured 3 years after the HIPPARCOS observations (Marchenko et al. 1996b; Marchenko et al. 1997).

HD 211853 = WR 153 = GP Cep is immediately recognized as variable. We take P=6.6884 d from Lamontagne et al. (1996) and plot the folded data in Fig. 8.

HD 214419 = WR 155 = CQ Cep can be used as an additional test of the stability and reliability of the HIPPARCOS data acquisition system (Fig. 8: ephemeris from Walker et al. 1983).

WR 156 = AC + 60$^\circ$38562. We find P=10.05 d dominating in the HIPPARCOS data (Fig. 8). This periodicity must be treated as transient; the onset of long-term fluctuations with P $\sim$ 15 d was detected in 1995 (Marchenko et al. 1997).

HD 219460 = WR 157 is located well above the detectability threshold. We find two possible periodic signals: P=1.786$\pm$0.003 d, A=0.088 mag (!); P=2.032$\pm$0.004 d, A=0.100 mag (!), both with practically zero FAP (owing to unusually high amplitude), which should be treated with caution - the field of view is fairly crowded for HIPPARCOS, thus probable leading to some confusion during the data extraction.

4. Conclusions

Besides detection of variability for individual stars, the homogeneous HIPPARCOS photometric data base provides some room for general statistical conclusions. Despite the presence of a
magnitude-dependent threshold for detection of significant variability, we can conclude that:

(a) All 8 MXRB are variable at varying degrees. This is not surprising, as these stars were pre-selected on the base of their strong, variable X-ray flux. The optical variability is caused by (1) a phase-dependent accretion rate with subsequent X-ray and optical outbursting (the long-period binaries with highly eccentric orbits), (2) ellipsoidal distortions (binaries with \( P \lesssim 10 \) d), (3) short-term wind instabilities (close binaries), or (4) long-term, global wind (or shell) restructuring (long-period binaries), significantly altering the accretion rate and causing large variations, unrelated to the orbital phase.

(b) Approximately half of the O-star sample shows intrinsic variability. The only bias for selection (besides apparent magnitude) is a suspected RV runaway nature, which may or may not favor variability, depending on the origin of the runaway mechanism (SN binary acceleration or cluster ejection - cf. Paper I). For example, since binarity is less common among runaways (Gies & Bolton 1986), one expects to see less variability. On the other hand, an increase in variability might occur if spin-up takes place in the SN runaway scenario (Blaauw 1993). However, even the present runaway selection is not entirely reliable (cf. Paper I). Therefore, to look at the problem in a general way, we separate the OB sample into two groups: \( |v_{\text{tan}, \text{pec}}| < 40 \) km s\(^{-1}\) - 'low-velocity' stars, and \( |v_{\text{tan}, \text{pec}}| \geq 40 \) km s\(^{-1}\) - 'high-velocity' stars (cf. Paper I for the peculiar tangential velocities). It appears that incidence of variability is practically the same: 47 \pm 16\% for the former vs. 32 \pm 19\% for the latter. The former value can be additionally reduced to 42\% by excluding from the 'low-velocity' group two eclipsing binaries, since this form of variability is unrelated to any intrinsic stellar activity. Taking into account that some among the remaining 'low-velocity' variables are suspected (cf. Table 1) short-period binaries, we treat these two groups as indistinguishable from the point of view of variability.

Variability in the O-star group is caused by many (often interrelated) mechanisms. Periodic variations are usually attributed to: binarity (eclipses, ellipsoidal variations), or/and axial rotation (sometimes combined with non-radial pulsations - NRP). Relatively low photometric accuracy (per data point) limits the ability to detect any short-term stochastic variability (with flaring as an extreme case) in OB stars: the expected amplitudes rarely exceed \( \sim 0.05 \) mag limit. However, long-term aperiodic variations can be more easily detected even at a low S/N ratio, owing to the same-sign deviations of the data groups, rather than individual points. Three OB stars out of 66 observed in our program exhibit long-term variations of unknown origin (Fig. 3: Be-like phenomena extended to higher effective temperatures?).

(c) The incidence of variability among the WR group is slightly higher than among the OB sample. The only known bias here is apparent magnitude, which may slightly favor intrinsically brighter stars. Again, we can ask if the WR runaways tend to be more or less variable than non-runaways. Dividing the WR sample into two parts: \( |v_{\text{tan}, \text{pec}}| < 40 \) km s\(^{-1}\) and \( |v_{\text{tan}, \text{pec}}| \geq 40 \) km s\(^{-1}\), we find that 62 \pm 16\% and 61 \pm 19\% of them are variable, respectively. Eliminating all cases related to geometric or atmospheric eclipses, we reduce those numbers to: 33 \pm 16\% for the 'low-velocity' group, and 46 \pm 19\% for the 'high-velocity' stars. It is worth mentioning that the vast majority of known massive WR+O binaries falls into the 'low-velocity' category. Some additional mechanism might rise the incidence of variability among the 'high-velocity' WR stars. Here we could turn back to the WR+c (compact companion: a neutron star or a black hole) hypothesis, referring to WR 148 (Marchenko et al. 1996 b) as a possible prototype.

Variability in WR stars is due to any of: binarity (geometric and wind eclipses, proximity effects), rotational modulation (again, sometimes with NRP), seemingly aperiodic phenomena (as the dust formation episodes in WR 121), and long-term effects of unknown origin (binarity? - WR 46 and WR 66).

Acknowledgements. This research made extensive use of the SIMBAD database, operated at Centre de Données de Strasbourg (CDS), Strasbourg, France. AFJM is grateful for financial assistance from NSERC (Canada) and FCAR (Québec). WSeg acknowledges gratefully financial support by the German Bundesminister für Forschung und Technologie (FKZ 50009101). JPDC contributed in the framework of the project IUAP P4/05 financed by the Belgian State (DWT/SSTC).

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