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Wolf–Rayet stars mass-loss rates determined from spectroscopic measurements of the orbital evolution for close WR + OB binary systems

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Abstract. The most reliable method for estimating the rate of mass-loss by the Wolf–Rayet stars wind is based on the assessment of secular variations in the orbital periods for close binary systems containing such stars, most often WR + OB systems. Previously, almost only photometric observations of well-studied eclipsing close WR + OB binaries were used for these purposes. This report describes the results of the work on the search for mass-loss-induced evolutionary variations in the orbital period for close WR + OB binaries and the mass-loss rates measurements for WR stars in these systems. Orbital period variations were detected in five systems studied: V444 Cyg, CQ Cep, CX Cep, WR 127 (Hen 3-1772), and WR 141 (V2183 Cyg). In addition, phase deviations between the radial velocity curves obtained at different epochs are suspected for the A pair of the GP Cep quadruple system. For eclipsing systems, estimates of the rate of change of the orbital period from the radial velocity curves are in good agreement with the corresponding estimates obtained from the light curves. A secular shortening of the orbital period has been confirmed for the CQ Cep system, which can be explained by the high degree of closeness of this system and the associated mass transfer processes. For the WR 127 and WR 141 systems, dynamic estimates of the change of the orbital period and the rate of mass loss have been obtained for the first time. Estimates of the rate of mass-loss by Wolf–Rayet stars show a power-law dependence on the mass of the star with an exponent of about 2. The effect of the finite size of stars, which turns out to be significant for estimates of the rate of mass loss to the wind in the closest systems, is discussed.

Keywords: stars: Wolf–Rayet, mass-loss, winds, outflows, binaries: spectroscopic

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1 Introduction

The significant rate of mass loss by Wolf–Rayet (WR) stars when such a star is part of a close binary system leads to an effective loss of mass and angular momentum, and, as a consequence, to a slow evolution of the orbit. Most often, WR are found in a pair with a massive star of a spectral type O or early B (WR + OB type systems). If a series of photometric (for eclipsing systems) or spectroscopic observations covering a sufficient number of orbital cycles is available, the change in the orbital period can be estimated by superimposing the phase curves corresponding to different epochs (the $O-C$ method). The pioneering work in this direction was performed by Khaliullin et al. (1974) for the V444 Cyg system. Unfortunately, the number of known WR + OB systems with sufficiently pronounced eclipses is limited to a few, so the $O–C$ spectroscopic method based on a comparison of radial velocity curves seems to be more widespread. This opens a way to a model-independent estimate of the mass loss rate of Wolf–Rayet stars and to a study of the empirical relationship between the WR mass loss rates and their masses.

In a recent series of our papers, we studied a number of WR + OB close binary systems: first, we showed that comparisons of radial velocity curves for eclipsing systems yield orbital period variation rates consistent with the results of the $O-C$ photometric method (Shaposhnikov et al. 2023a,b), and then we obtained a result for a system with weak photometric variability (Shaposhnikov et al. 2024). Additionally, we obtained preliminary results for three more systems: WR 141 (V2183 Cyg), WR 145 (AS 422), and the pair A of the GP Cep quadruple system. In this paper we analyze the obtained result. Our estimates of the WR mass-loss rates show a power-law dependence on the mass of the star with an exponent slightly less than 2. We consider the nuances of determining the mass-loss rate from the $\dot{P}$ measurement, such as taking into account the finite sizes of stars and interpreting the $\dot{P} < 0$ cases. We also compare the mass loss rates we determined for systems with observed orbital period increases with the mass loss rates measured by other methods.

2 Observational data

All observations of WR + OB close binaries are carried out using telescopes of the SAI Caucasian Mountain Observatory (CMO). Spectroscopic observations are carried out using a 2.5-m telescope with a low-resolution dual-beam spectrograph TDS (Potanin et al. 2020). In addition, multicolor photometric observations of eclipsing systems were additionally carried out using the 60-cm robotic telescope RC600 (Berdnikov et al. 2020). The constructed light curves and radial velocities for CQ Cep, CX Cep, V444 Cyg and WR 127 are given in the corresponding papers (Shaposhnikov et al. 2023a,b, 2024). The radial velocity curves for WR 141, WR 145 and GP Cep are shown in Fig. 1. Fig. 2 shows the $O-C$ curves for all systems studied so far. For eclipsing systems, the $O-C$ curves for photometric data are plotted on the same graph as the spectral data.

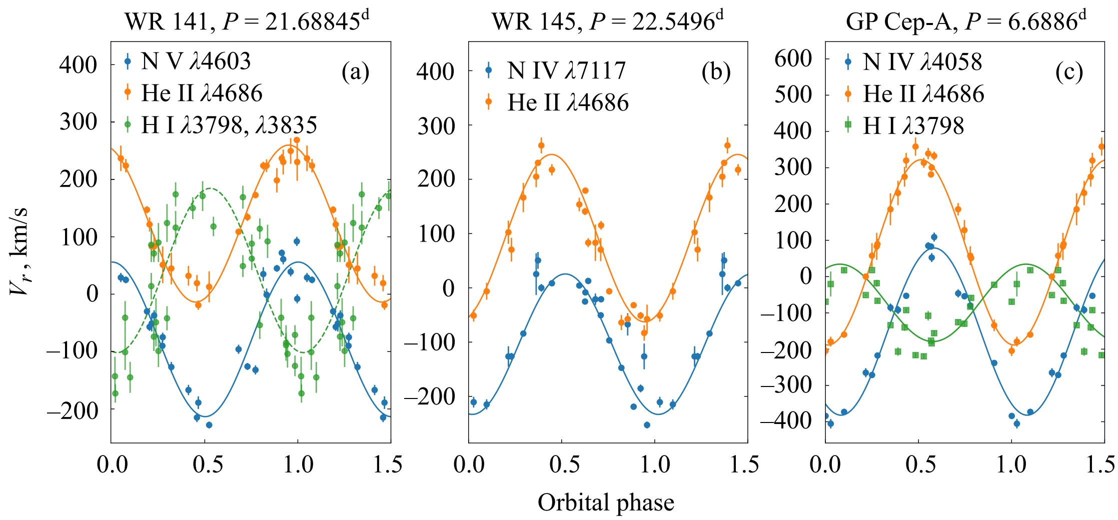

Fig. 1. WR 141 (a), WR 145 (b) and GP Cep-A (c) radial velocity curves from CMO observations.

3 WR + OB obrital evolution interpretation

Table 1 provides a summary of all systems studied to date. Five of the seven systems studied showed an increase in orbital period $\dot{P} > 0$. According to the well-known Jeans mode formula, the rate of mass loss from the system can be expressed as $\dot{M}/M = -1/2 \times \dot{P}/P$. However, this formula may give incorrect results for the closest systems, where it is necessary to take into account the sizes of the stars and possible mass transfer between the stars. The formula linking the orbital evolution of a close binary system of outflowing spherical (with radii $R_{1,2}$) tidally synchronized stars was derived in Shaposhnikov et al. (2023a) and has the form:

$$\frac{\dot{P}}{P} = -\frac{\dot{M}_1}{M_1}\left\{3 + 3\frac{x-\beta}{q} - \frac{\alpha + x}{1+q} - 3\frac{1+q}{q}\left(\alpha\left[\left(\frac{q}{1+q}\right)^2 + \frac{2}{3}\left(\frac{R_1}{a}\right)^2\right] + x\left[\left(\frac{1}{1+q}\right)^2 + \frac{2}{3}\left(\frac{R_2}{a}\right)^2\right]\right)\right\}, \quad (1)$$

where index "1" means a more massive star, $q = M_1/M_2$, and α, β and x describe relationships between wind and transfer parts of mass-loss as $\dot{M}_1 = \dot{M}_{1,w} + \dot{M}_{1,t} = \alpha\dot{M}_1 + \beta\dot{M}_1$ $(\alpha + \beta = 1)$, $\dot{M}_2 = \dot{M}_{2,w} - \dot{M}_{1,t} = x\dot{M}_1 - \beta\dot{M}_1$.

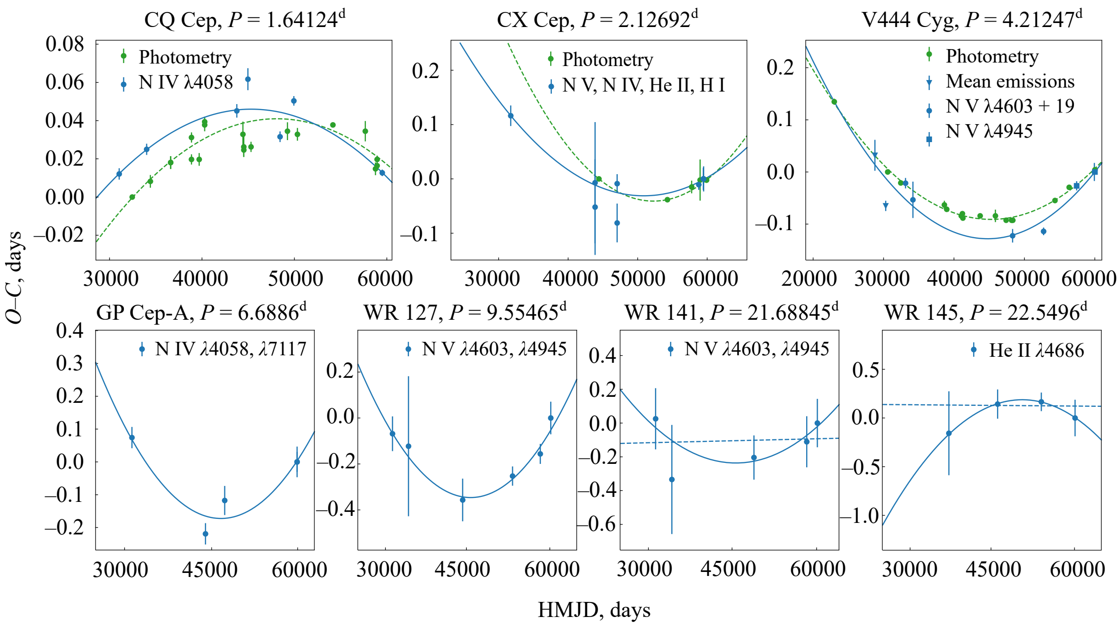

Fig. 2. $O-C$ curves for studied WR + OB systems.

For the CX Cep system, taking into account the sizes of the stars and the presence of a wind from the O-star under realistic assumptions the estimate of $\dot{M}_{\rm WR}$ changes by approximately 30% (Shaposhnikov et al. 2023a), while for the case of V444 Cyg the correction is only about 3% (Shaposhnikov et al. 2023b). Thus, these corrections turn out to be significant for the closest systems.

As the data in Table 1 show, there is a correlation between the WR mass and $\dot{M}_{\rm WR}$. Fig. 3 shows a graph of $\dot{M}_{\rm WR}$ versus $M_{\rm WR}$, with the obtained points for systems with $\dot{P} > 0$ plotted on it. The point corresponding to the GP Cep system is also plotted on the graph, but the $\dot{P}$ observed in this case may be partially due to the motion along a wide orbit in a quadruple system and is not reliable. The lower error limit for CX Cep corresponds to the estimate of $\dot{M}_{\rm WR}$ determined without taking into account the radii. The main coefficient of the straight line in Fig. 3 is drawn through our points (except for GP Cep) is 1.61 ± 0.29.

In addition, we also decided to compare our results with measurements of $\dot{M}_{\rm WR}$ made by other methods. In Fig. 3 the results for polarization (St.-Louis et al. 1988),

Table 1. Close binary systems WR + OB type with measured orbital evolution by spectroscopic $O-C$ method and $\dot{M}_{\rm WR}$ estimations.

WR#	Alias	SpT	P days	$M_{\rm WR}$ $M_\odot$	$\dot{P}$ s/yr	$\dot{M}_{\rm WR}$ $10^{-5}\,M_\odot$/yr
127	Hen 3-1772	WN3+O9.5V	9.55465	21.0±2.5	0.83±0.14	2.6±0.5
139	V444 Cyg	WN5+O6II-V	4.21247	10.7±1.1	0.119±0.003	0.60±0.04
141	V2183 Cyg	WN5-w+O5V-III	21.68845	39±10	1.6±0.9	3.1±1.9
145	AS 422	WN7o/CE+O7V(f)	22.5496	17.7±2.8	<= 0?	?
151	CX Cep	WN4+O5V	2.12692	13.9±0.7	0.062±0.005	$0.91^{+0.10}_{-0.31}$
153	GP Cep	WN6o+O6I (A)	6.6886	6.6±1.5	0.43±0.11	1.1±0.3
155	CQ Cep	WN6o+O9.5V	1.64124	∼ 11	-0.0151±0.0013	∼ 1

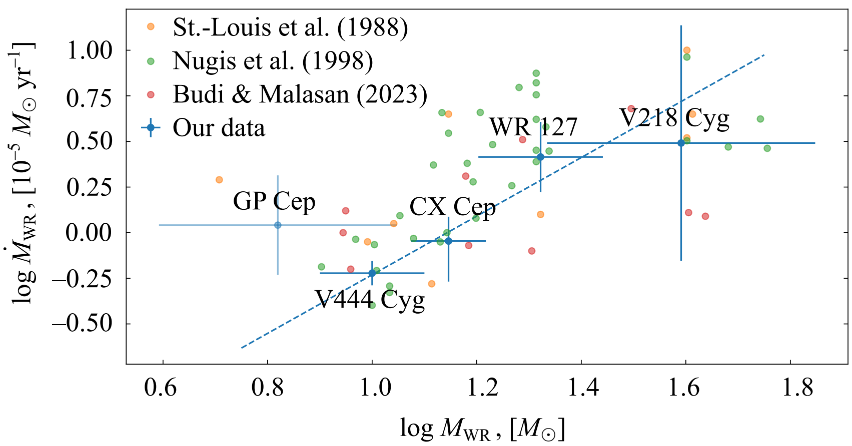

Fig. 3. Relationship between $M_{\rm WR}$ and $\dot{M}_{\rm WR}$. Blue dots with error bars—our estimations. Orange—polarimetric measurements (St. -Louis et al. 1988), green—from IR/radio fluxes (Nugis et al. 1998), red—from spectral lines profiles (Budi & Malasan 2023).

IR/radio fluxes (Nugis et al. 1998) and recent results of spectral line profile measurements (Budi & Malasan 2023) are plotted. In general, the results of measurements by all methods are in good agreement with each other.

As for the two cases out of seven in which $\dot{P} < 0$ were detected, there can be found a physical interpretation for CQ Cep. This system is the closest among all known systems of the type under consideration; the O star is close to filling the Roche lobe and realizes the flow of matter onto the WR star. Since $M_O > M_{\rm WR}$ in the case of CQ Cep, this flow tends to equalize the masses of the stars and shorten the orbit. In turn, the winds from WR and O carry away mass and angular momentum from the system and partially resist the convergence of the stars. Unfortunately, based on the observed $\dot{P}$ value alone, it is impossible to give specific estimates of

$\dot{M}_{WR}$; only order estimates and wide ranges of accessible parameters (Shaposhnikov et al. 2023a) are available. The CQ Cep case is truly nontrivial and requires further study, including in the field of gas-dynamic modeling and the development of orbital evolution models for close binary systems. For the WR 45 = AS 422 system the result does not seem reliable, unlike the WR 141 = V2183 Cyg system with a similar period, but with a huge mass and the strength of the WR stellar wind. Thus, we are forced to conclude that systems with periods $P \geq 20^{\mathrm{d}}$ are no longer available for studying the mass loss rate by the dynamic method, except for the cases of the most massive stars.

4 Summary

The change in the orbital period of a close binary system is an observable characteristic of its evolution, and in the case of WR + OB systems it can provide a way to determine one of the key parameters of the evolution of massive stars—the rate of mass loss to the stellar wind. The results obtained from the comparison of radial velocity curves for the studied systems are in good agreement with both the available estimates from the light curves and those obtained by other model-dependent methods. We plan to expand the sample of studied WR + OB systems, covering all systems in the northern sky with orbital periods up to 20–30 days, and, if possible, supplementing it with systems in the southern sky with a sufficient number of archival epochs of spectroscopic observations.

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