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Modelling light curves of binary systems: accounting for extended winds

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We propose a simple synthesis model of an eclipsing binary system, which includes one component with strong stellar wind. Numerical simulations show that the shape of the light curve (and in particular the width of the minima) strongly depends on the wind parameters. Wind effects are crucial in modelling light curves of binaries including, e.g., WR stars.

Keywords: Binaries: eclipsing; Stars: Wolf–Rayet, mass-loss

1 Introduction

Several very massive Wolf–Rayet (WR) stars have been recently discovered in eclipsing binaries, e.g., WR20a with WR mass $M_{\rm WR} \approx 80\,M_\odot$ (Bonanas et al., 2004), NGC 3601-A1 with $M_{\rm WR1} \approx 116\,M_\odot$, $M_{\rm WR2} \approx 89\,M_\odot$ (Schnurr et al., 2008), etc. The radii of the WR stars in those systems turned out to be surprisingly large ($\sim$20 $R_\odot$) (Bonanas et al., 2004; Moffat et al., 2004), similar to the radii of main-sequence (MS) stars of comparable masses. According to common evolutionary scenarios, a WR star is formed through a massive loss of its hydrogen-rich outer layers. One could expect that the resulting stellar radii should be smaller than the radii of MS stars of comparable masses.

The radii of the WR stars in the above binaries were obtained by analysing eclipses. Absorption in extended winds of WR stars was not accounted for; instead, a standard Roche model (Wilson, 1979) of stars with thin atmospheres was used for both components of a binary. Including extended wind in a model is expected to reduce the radii and hopefully make them compatible with predictions of theory. Earlier attempts to account for wind absorption were made in Pustyl'nik & Einasto (1984), Antokhina & Cherepashchuk (1988), Kallrath & Milone (1999). In those papers, wind was assumed to expand with constant velocity. The only advantage of this assumption is the simplicity of calculations. At the same time it is clearly inadequate to an actual situation in hot star winds expanding with acceleration. In this paper, we present

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a simple wind model, which allows the use of any parametric form of the velocity law for the wind.

2 Model

The Roche model (Antokhina, 1988; Antokhina et al., 2000) is used for both components. One component is surrounded by homogeneous, spherically symmetric wind. While computing the model light curve, emission from every elementary area of each Roche surface is summed up, accounting for eclipses by stellar bodies and for absorption in the wind. The velocity law is set by a parametric expression, e.g., the β-law: $v(r) = v_\infty \left(1 - \frac{r_*}{r}\right)^\beta$. The main absorption agent in optical continuum is electron scattering, the optical depth from the point (p, z_0) in the wind (see Fig. 1) is

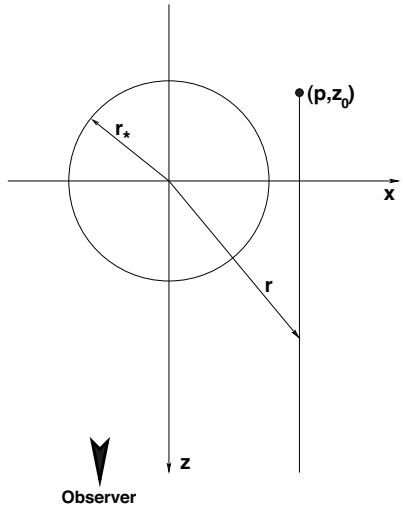


Figure 1 The coordinate system for the wind model.

$$\tau(p, z_0) = \int_{z_0}^{\infty} \epsilon(z) \mathrm{d}z, \tag{1}$$

where the absorption coefficient

$$\epsilon(r) = \sigma_T n_e(r) = \frac{k\sigma_T \dot{M}}{4\pi m_p v(r) r^2}; \tag{2}$$

k is the ionization parameter. If the chemical abundance of the wind is solar, hydrogen being the most abundant element, $k = 1$ (in hot star winds, hydrogen is ionized). In WR winds the most abundant element is helium, so $k \simeq 0.5$ if helium is fully ionized, $k \simeq 0.25$ in the He II zone.

The model parameters along with their description are listed in Table 1.

Table 1 Input parameters of the model.

Parameters	Description
	Binary parameters
M_1, M_2 ($M_\odot$)	Stellar masses
P (d)	Period
e	Eccentricity
ω	Longitude of periastron, star No. 1
i (deg)	Orbital inclination
μ_1, μ_2	Roche lobe filling coefficients ($\mu = 1$ for star filling its inner critical Roche lobe at periastron position)
T_1,T_2 (K)	Average effective temperatures of the components
β_1,β_2	Gravity darkening coefficients
A_1,A_2	Bolometric albedos
F_1, F_2	Ratio of surface rotation rate to synchronous rate
x_1, x_2	Limb darkening coefficients
l_3	Third light
	Wind parameters
$\dot{M}$ ($M_\odot$/year)	Mass-loss rate
V_∞ (km/sec)	Terminal velocity of the wind
β	Parameter of the velocity β-law
k	Ionization parameter in (2)

3 Results

To illustrate the influence of wind absorption on model light curves, we computed two models, a detached binary (Model 1) and a contact binary (Model 2) (see Fig. 2). In each model the stellar parameters of both components are identical but the secondary component is surrounded by a wind. This configuration helps us to isolate the effects of wind absorption on the light curve. When the wind is absent, the two minima of the light curve are identical. When the wind is "turned on", the depth of the secondary minimum is dramatically increased, while the depth of the primary minimum

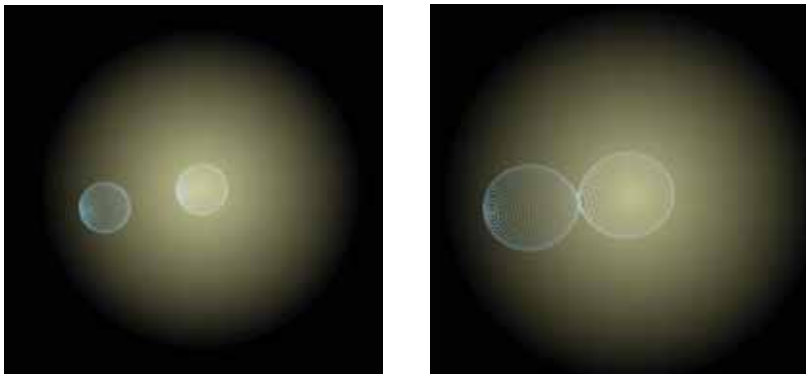


Figure 2 Sky-plane view of Model 1 (left) and Model 2 (right).

is decreased (in the secondary minimum the component surrounded by the wind is in front). The stellar parameters in both models were fixed while the wind parameters varied. The values of model parameters are listed in Table 2. The wind parameters were varied one by one. While varying one parameter, the other two were fixed. The fixed values are $\dot{M} = 2 \cdot 10^{-5}\, M_\odot$/year, $V_\infty = 2000$ km/s, $\beta = 0.5$. We assumed that wind consists of fully ionized helium ($k = 0.5$).

Table 2 Parameters of simulated models.

Parameter	Model 1 (detached configuration)	Model 2 (contact configuration)
	Binary parameters	
M_1 ($M_\odot$)	10	10
M_2 ($M_\odot$)	10	10
P (d)	5	5
i (deg)	80	70
μ_1	0.5	1.0
μ_2	0.5	1.0
$T_1(K)$	30000	30000
$T_2(K)$	30000	30000
F_1, F_2	1.0	1.0
β_1, β_2	0.25	0.25
A_1, A_2	1.0	1.0
x_1, x_2	1.0	1.0
e	0.	0.
ω	0.	0.
l_3	0.	0.
λ (Å)	4400	4400
	Wind parameters	
$\dot{M}$ ($M_\odot$/year)	$10^{-5} - 4 \cdot 10^{-5}$	$10^{-5} - 4 \cdot 10^{-5}$
V_∞ (km/sec)	1000 − 2000	1000 − 2000
β	0.5 − 1.5	0.5 − 1.5
k	0.5	0.5

Simulations show that the shape of the light curves strongly depends on the wind parameters (see Figs. 3–5). Clearly there is some degeneracy between the parameters. It is unlikely that the three most essential wind parameters can be obtained independently from the light curve analysis alone. Luckily, when solving light curves, most of them can be fixed at values obtained from independent sources (e.g., V_∞ from UV spectra, $\dot{M}$ from radio data etc.). In light curve analysis, the increase in the width of the minima most importantly influences the radii and temperatures of stars. Our simulations show that it is absolutely crucial to take into account extended winds while modelling light curves of binary systems including WR stars.

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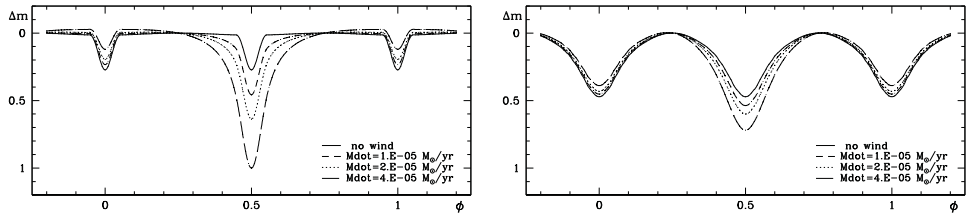


Figure 3 Influence of mass-loss rate $\dot{M}$ on the shape of a light curve. Model 1 (left), Model 2 (right).

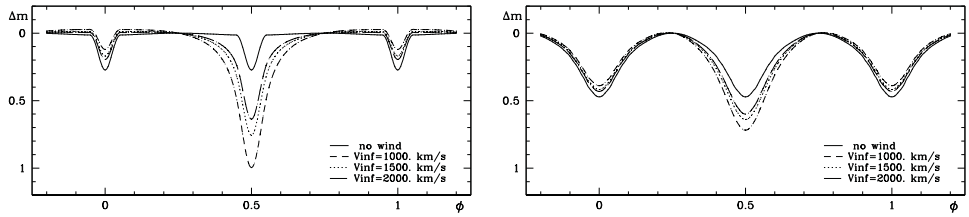


Figure 4 Same as in Fig. 3, for terminal wind velocity V_∞.

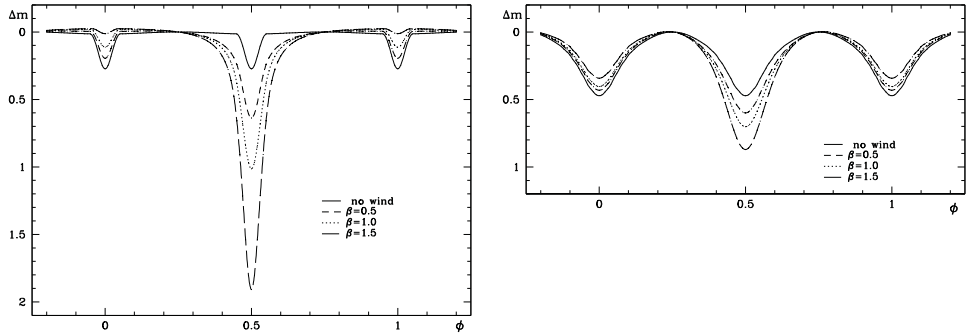


Figure 5 Same as in Fig. 3, for parameter β of the velocity law.

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