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Twin Binaries as a Laboratory for Testing Wind-driven Mass Loss Theories

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Abstract: In the present work, we evaluate the efficiency of the wind-driven mass loss during the main sequence phase of rapid rotating, late spectral type binary stars by monitoring their eclipse timing variations (ETV). In this group of particular interest, strong magnetic fields and tidal forces can potentially elevate the stellar wind mass loss rates and thus affect the binary evolution. To estimate the contribution of these processes to the mass loss rate, we properly select a sample of short-period detached binaries with components of similar physical parameters. Provided that the knowledge of their observed orbital history is dense enough for a reliable inference, twin binaries serve as a direct probe for investigating this mechanism by eliminating the involvement of many free parameters. We show that the inferred mass loss rates are substantially enhanced up to several order of magnitudes, suggesting that the presence of a close companion can strongly affect the mass loss history of a late-type star and thus the evolution of the binary system itself.

1 Introduction

The analysis of eclipse timing variations (ETV) is a valuable tool through which the orbital history of eclipsing pairs can be thoroughly explored in order to estimate crucial parameters directly related to the underlying physical mechanisms. Here, we evaluate the efficiency of wind-driven mass loss (ML) theories of main-sequence late-type stars through proper parameterized semi-empirical laws, taking advantage of the long-term ETV modulation of several well monitored eclipsing binaries and the well defined physical properties of their components. Particularly, we examine the impact of the components rotation in the development of enhanced ML rates through X-ray activity indicators, as well as the Roche lobe filling factor by means of a unified mathematical approach. Aiming to set the ML rate as the only unknown parameter to be determined, five *twin binaries* were carefully selected as suitable cases for testing our methodology with respect to the values inferred from the ETV analysis. The magnetic braking (MB) process, as a strongly competitive mechanism, was also included in the overall analysis through an appropriate rotation-dependent parametrization adapting cool rapid rotating stars.

2 Modeling mass loss and magnetic braking

In late-type stars (F0 or later), stellar luminosity is a crucial factor that dictates the development of thermally driven winds. Several semi-empirical relations have been proposed in literature, allowing the estimation of the ML rate through the stellar absolute parameters and the evolutionary state that – either directly or indirectly – determine the luminosity contribution (e.g., [12]; [2]; [5]). In close binary systems, the wind-driven ML rate appears to be even more intense compared to the single-star counterparts since: (a) tidal interaction is strong enough to keep the spin locked with the high orbital angular velocities, leading as a result, to a significant enhancement of the stellar centrifugal potential, and (b) the components approach their Roche lobe radius (e.g., [13]). In the present work, we propose a ML scheme which takes into account both the impact of rotation in main sequence late-type stars and the effects of the tidal enhancement due to presence of a close companion, by means of the following equation:

$$\dot{M}_{\rm w} = -1.5 \times 10^{-8} \left(f \frac{L}{L_\odot} \right) \left(\frac{R}{R_\odot} \right) \left(\frac{M}{M_\odot} \right)^{-1} \left\{ 1 + 10^4 \left(\frac{R}{R_{\rm L}} \right)^6 \right\}, \tag{1}$$

where M, R, L is the stellar mass, radius and – bolometric – luminosity, respectively, f is the fraction of the stellar luminosity accounting for the total wind flux, $R_{\rm L}$ is the radius of the Roche lobe when the star belongs to a detached system, while $\dot{M}_{\rm w}$ is the ML rate in $M_\odot\,{\rm yr}^{-1}$. Assuming that the wind energy is totally modulated by the coronal thermal radiation, f can be safely expressed through the X-ray-to-bolometric luminosity ratio. This is a quantity strongly dependent on the rotation, ranging approximately from 10^{-6} to 10^{-3} for slow and fast rotators, respectively (e.g., [10]; [11]). Note that Eq. (1) is reduced to the associated formula given by [5] for single main sequence stars when $R << R_{\rm L}$, while it is further consistent with the relation given in [13] as far as the tidal enhancement is concerned. The Roche lobe radii $R_{\rm L}$ may be accurately estimated as a function of the mass ratio q of a binary system through appropriate empirical laws (e.g., [3]).

Apart from the pure ML case, in late-type stars, the magnetic nature of the stellar winds causes significant angular momentum losses via the MB mechanism. The stellar material, kept by strong magnetic fields, corotates with the star up to a distance determined by the Alfvén radius (dead zone); it escapes out of this region in a steep way producing the well-known stellar wind (wind zone) by further exerting a strong magnetic torque which spins down the star. This braking mechanism depends principally on the strength and the geometry of the stellar magnetic field (e.g., [6]). Here, we adopt the parametrization described in [4], properly modified to address an intermediate field topology as widely suggested in literature (e.g., [4]; [1]):

$$\dot{J}_{\rm w} = -K_{\rm kaw} \Omega^a \left(\frac{R}{R_\odot} \right)^{1/2} \left(\frac{M}{M_\odot} \right)^{-1/2}, \tag{2}$$

where $\dot{J}_{\rm w}$ is the MB-induced angular momentum loss, a is an exponent which denotes the strength of the spin-down law, typically taking values from 1 to 3 for fast and slow rotators, respectively, Ω is the stellar angular velocity, while $K_{\rm kaw}$ is a positive parameter strongly dependent on a that can be calibrated through the rotational evolutionary state of solar-like stars that belong to young open clusters of similar ages (see, e.g., [8] and references therein). Note that the strength of the magnetic field does not depend constantly on the angular velocity; a saturation regime is expected when the rotational period drops below a threshold which is estimated in the range of 0.8-2.2 d ([1]; [11]) for solar-type stars. Although the saturation regime seems to be mass-dependent, the values $f = 10^{-3}$ for the X-ray-to-bolometric luminosity ratio in Eq. (1), and $a = 1$ for the MB law in Eq. (2), are representative.

3 Selection criteria

To eliminate both the number of the driving mechanisms and the involved parameters, we adopted a sampling sequence which facilitates the evaluation of the examined wind-driven ML model.

First, we restricted our sample in detached only systems in order to secure that mass transfer is absent. Any mass transfer mode (i.e., either direct impact or disk formation mode accompanied by various types of mass and angular momentum losses) might produce ETV strong enough to dominate the observed modulations (see, [9]). Secondly, to exclude the effects of an asynchronous rotation, we further focused on short-period systems, so that tidal locking of the components to be feasible and the orbits to be circular. In a third phase, main sequence late-type components searched as candidates. To minimize the number of the entangled free parameters, nearly twin binaries were chosen as in such systems the incorporated physical parameters are halved. Furthermore, as the critical value of MB saturation angular velocity seems to be mass dependent, the selection of the proper spin-down law becomes less complicated. Finally, binaries with a long observed orbital history were preferred for a reliable inference.

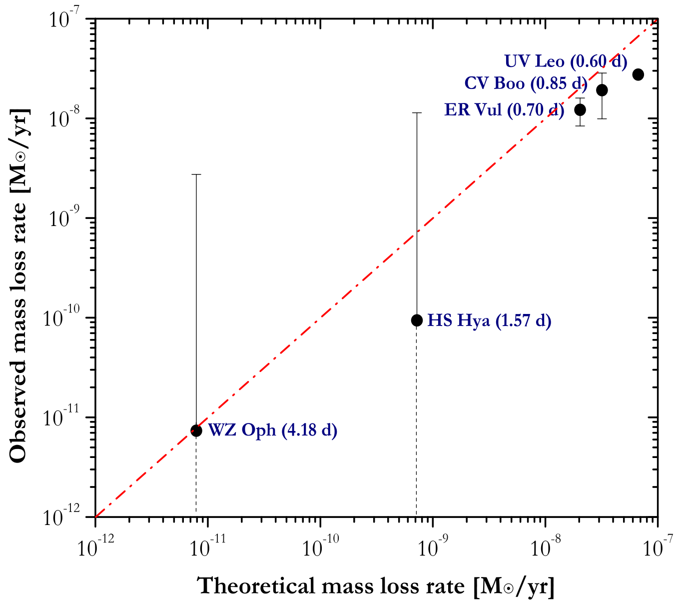

Figure 1: Comparison of the theoretical and the observed mass loss rates of the examined systems.

Since tidal evolution suggests that orbital circularization is feasible in systems consisting of stars with convective envelopes (i.e., late-type stars) when their period is of the order of 8 d or below (e.g., [14]), the following set of selection criteria were adopted: (a) orbital periods less than 8 d and eccentricities less than 0.05, (b) main sequence components possessing a convective envelope, (c) detached, and nearly twin binaries (with mass and radius deviations less than 10% from equality), and (d) systems with a long record of photoelectric and photographic times of minima, spanning over at least half a century. To satisfy these selection criteria, we performed a thorough investigation among several well-known catalogues of eclipsing binary stars by filtering all the possible candidates. Five systems were finally selected, namely UV Leo, ER Vul, CV Boo, HS Hya, and WZ Oph (see [7] for their detailed documentation); apart from the first two systems, patrol plate and visual times of minima were also included in order to exceed the minimum required 50 yr interval.

4 Analysis and results

Both the wind-driven ML and the MB processes are able to drive the orbital evolution of short-period detached binaries in amounts traced on typical human life timescales ([8]). Hence, adopting the angular momentum loss description of Eq. (2), and neglecting the weak impact of gravitational radiation and the spin contribution of the components, it is implied ([7]) that the common ML rate of the components can be estimated through the following formula:

$$\dot{M}_{\rm w} = -\frac{M_1 + M_2}{5}\left[\frac{2c_2}{P^2} + bP^{\left(-a+\frac{1}{3}\right)}\right], \tag{3}$$

where P is the orbital period, M_1 and M_2 are the masses of the more and the less massive component, respectively, while b is a quantity which depends both on the braking law (i.e., on the $K_{\rm kaw}$ constant and the exponent a) and the absolute parameters of the components (see [8] for details). Assuming that the observed secular variations are adequately described by a quadratic polynomial, c_2 represents the coefficient of its second order term, inferred by means of a weighted least-squares regression approach.

Throughout the computational procedure the spin-down law was chosen according to the criteria given by [1] among the values 1, 2, and 3 for the exponent a, relying on the rotational period. The values 0.82 d and 4.67 d were used as the critical periods for the transition to the fast ($a = 1$; UV Leo and ER Vul cases) and intermediate ($a = 2$; CV Boo, HS Hya, and WZ Oph cases) rotators regime, respectively, while the $K_{\rm kaw}$ values were selected to be consistent with the choice of the exponent a for solar-type stars. To compare the inferred rates with our theoretical ML scheme, the X-ray-to-bolometric luminosity ratios were estimated for each component according to the stellar activity-rotation data given in [11]. The results are depicted in Fig. 1, where the errors stem from the coefficient c_2 as the main source of uncertainty for the observed ML values. All five examined systems lie along or close to the identity line within errors, suggesting that our proposed ML semi-empirical model reproduces successfully the observed rates.

5 Concluding remarks

To evaluate the efficiency of wind-driven ML theories for cool dwarf stars, we have explored five detached binaries with nearly twin components, whose orbital evolution is dominated by ML and MB. In the case of UV Leo, ER Vul, and CV Boo, which are the systems of the shorter period in our sample, the ML dominates the observed period variations; strong ML rates of the order of $10^{-8}\,M_\odot\,\mathrm{yr}^{-1}$ are estimated in these systems. The MB process seems to resist in the case of HS Hya and WZ Oph where the estimated ML rates found to be three orders of magnitude weaker; unlike the UV Leo, ER Vul, and CV Boo cases, the orbital period appears to be either constant or slightly decreasing over a century in HS Hya and WZ Oph, indicating the possible existence of a critical transition period between the ML and MB prevalence regime (see also [8]). Regardless of the ETV diagram morphology, the observed ML rates were found well consistent with our combined ML scheme, implying that both rotation and tidal enhancement are crucial factors that should not be considered negligible in the period analysis of close binaries. In a forthcoming paper, various wind-driven ML models, addressing a wide range of spectral types and luminosity classes, will be assessed by means of the present methodology.

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