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Tracing Non-conservative Mass Transfer Eras in Close Binaries from Observed Period Variations

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Abstract: The observed orbital evolution of eclipsing binary stars (centuries at most) by monitoring their eclipse timing variations is valuable for the study of many important physical mechanisms related to the stellar structure. As long as a binary system attains a semi-detached configuration, material begins to flow from the component that fills its Roche lobe toward its mate through the first Lagrangian (L1) point. Here, we examine two non-conservative mass transfer paths, impelling the system to lose mass and angular momentum (either through a hot spot emission from the gainer or via an outer Lagrangian point). Dealing with the less massive component as the donor in the latter path, it is shown that there is always a critical mass ratio over which the period is expected to decrease, contrary to what the fully conservative mass transfer predicts. The O–C diagram of two semi-detached systems, expecting to experience a liberal era, is individually examined aiming to estimate both the mass transfer and the mass loss rate.

1 Introduction

The analysis of O–C diagrams plays a vital role as a tool through which the orbital period variations of eclipsing pairs are disclosed in a direct way. These variations can be used in order to estimate crucial parameters connected to the physical mechanisms driving the orbital evolution of a binary system. Here, we are principally interested in studying the effects that different manifestations of mass transfer produce in the period monotony and the respective O–C diagram morphology of semi-detached systems. In the aforementioned framework, we distinguish our approach in the direct impact and the accretion disk mode, further accompanied by mass and angular momentum losses of a certain, arbitrary selected, level. Toward this direction, we make also a search for possible critical mass ratio values over which the orbital angular momentum loss (AML) dictates the secular period changes. Finally, we analyze the O–C diagram of two individual systems of particular interest, namely RR Dra and X Tri, expected to undergo a non-conservative mass transfer era and we estimate both the mass transfer (MT) and the mass loss (ML) rate for several degrees of liberalism.

2 Mass transfer modes

In the case of a fully synchronized semi-detached system, MT is realized by converging flow through the Lagrangian point L1 in the immediate neighborhood of the donor. The gaseous flow stream trajectories can either hit the gainer directly or completely miss it, forming as a result a rotating ring which is progressively transformed into a stationary accretion disk due to the effects of the gaseous material bulk viscosity. However, in the direct impact mode, the stream may be deflected by the Coriolis force before striking the gainer as long as the radius of the gainer lies within a narrow range which depends on the mass ratio of the system ([4]). In this way, the presence of a thin ring around the gainer seems unavoidable, gradually transformed into a quasi-stationary disk structure. This type of disk, generally

Table 1: Critical mass ratios $q_{\rm cr}$ as a function of the degree of liberalism β (see text for details).

β	ML through a hot spot $q_{\rm cr}$ (for $r_{\rm r}=0$)	ML through a hot spot $q_{\rm cr}$ (for $r_{\rm r}\neq 0$)	ML through the L3 point $q_{\rm cr}$ (for $r_{\rm r}=0$)	ML through the L3 point $q_{\rm cr}$ (for $r_{\rm r}\neq 0$)
0.0	—	—	—	—
0.1	—	—	0.047	0.011
0.2	—	—	0.104	0.041
0.3	—	—	0.168	0.078
0.4	—	—	0.240	0.121
0.5	—	0.954	0.322	0.172
0.6	—	0.876	0.417	0.231
0.7	—	0.801	0.527	0.300
0.8	—	0.728	0.657	0.381
0.9	—	0.659	0.813	0.477
1.0	1.000	0.591	1.000	0.591

called as *transient* (according to the notation of [1]), is characterized by small viscosity values which favor a weak tidal gainer-disk-orbit coupling regime, not efficient enough to return the proffered angular momentum back to the orbit. Hence, contrary to the classical stable accretion structure, a transient disk extracts orbital angular momentum with remarkable consequences to the orbital evolution of a binary system.

The MT process may be accompanied by mass losses either from the gainer or via the outer Lagrangian points L2 and L3. The impact of a non-conservative era is highly important since the orbital angular momentum is forced to further reduce. Concerning the first scenario (losses from the gainer), a hot spot seems to play a crucial role. When a semi-detached binary undergoes a MT phase, a hot spot is expected to be created in the area that the inflowing material impacts the mass gaining component (whether an accretion disk is present or not). As long as the radiative energy of such a hot spot exceeds the gravitational binding energy, the system is subject to a short liberal era, generally expected soon after the onset of the Roche lobe overflow phase ([7]). Regarding the second scenario (losses through the L2/L3 point), the outer Lagrangian points are paths that material, surviving the transferred process, can escape most easily from the gravitational field of the binary (lowest potential barriers), usually as a result of the small accumulating efficiency of the accretion disk surrounding the gainer. As distant points, with respect to the common center of mass of the system, they support a very efficient mechanism of orbital AML.

3 Mathematical procedure

To examine the combined effects of MT, ML and AML processes might have in the period and the subsequent O–C modulations, the generalized $\dot{J}-\dot{P}$ relation of [2] is first adopted in order to associate the variations of the main physical parameters describing a binary system with its orbital period. The present approach is developed assuming circular orbits with small only departures from synchronism. The spin contribution of the components to the total angular momentum is also considered negligible. Although the mathematical procedure can be designed whether the donor is the more or the less massive star (see the analytical description in [5]), here we focus on the latter case only, for reasons of simplicity. According to the aforementioned assumptions and simplifications, the generalized $\dot{J}-\dot{P}$ relation of [2] is reduced to:

$$\frac{\dot{P}}{P}=\left[-3(q-1)-3\sqrt{(q+1)r_{\rm r}}-\frac{1-\beta}{\beta}\cdot\frac{3q^2-2q-3}{q+1}\right]\frac{\dot{M}_1}{M_2}, \qquad (1)$$

when the ML and AML is realized from the gainer (due to the presence of a hot spot), and

$$\frac{\dot{P}}{P}=\left[-3(q-1)-3\sqrt{(q+1)r_{\rm r}}-\frac{1-\beta}{\beta}\cdot\frac{3j_{\rm L3}(q+1)^2-2q-3}{q+1}\right]\frac{\dot{M}_1}{M_2}, \qquad (2)$$

when the ML and AML is realized through the L3 point (non-captured mass from the gainer).

Table 2: Mass accretion and ML rates (only when $r_r \neq 0$) for the RR Dra system as a function of the degree of liberalism β.

β	ML through a hot spot $\dot{M}_1$ $[M_\odot\,\mathrm{yr}^{-1}]$	ML through a hot spot $\dot{m}$ $[M_\odot\,\mathrm{yr}^{-1}]$	ML through the L3 point $\dot{M}_1$ $[M_\odot\,\mathrm{yr}^{-1}]$	ML through the L3 point $\dot{m}$ $[M_\odot\,\mathrm{yr}^{-1}]$
0.0	0.000	-2.64×10^{-7}	—	—
0.1	2.84×10^{-8}	-2.56×10^{-7}	—	—
0.2	6.12×10^{-8}	-2.45×10^{-7}	—	—
0.3	9.95×10^{-8}	-2.32×10^{-7}	—	—
0.4	1.45×10^{-7}	-2.17×10^{-7}	—	—
0.5	1.99×10^{-7}	-1.99×10^{-7}	—	—
0.6	2.66×10^{-7}	-1.77×10^{-7}	—	—
0.7	3.49×10^{-7}	-1.50×10^{-7}	6.49×10^{-6}	-2.78×10^{-6}
0.8	4.56×10^{-7}	-1.14×10^{-7}	1.64×10^{-6}	-4.09×10^{-7}
0.9	5.99×10^{-7}	-6.66×10^{-8}	1.04×10^{-6}	-1.15×10^{-7}
1.0	8.00×10^{-7}	0.000	8.00×10^{-7}	0.000

On the l.h.s. of Eqs. (1) and (2), $P = P(t)$ is the orbital period and $\dot{P} = \dot{P}(t)$ its rate of change, while on the r.h.s. M_2 is the mass of the donor (secondary component), $q = M_2/M_1 \leq 1$ is the mass ratio of the system and $\dot{M}_1 > 0$ declares the rate at which mass is accreted by the gainer (primary component). The first term within the brackets refers to the MT through the L1 point, the second represents the orbital angular momentum which is lost due to the presence of a transient disk with radius r_r (in units of the orbital radius) and the third term expresses the impact of the ML/AML non-conservative mechanism (j_{L3} is the specific angular momentum carried away from the L3 point) with a degree of conservatism β. Hence, if $\dot{M}_2$ is the MT rate from the donor, $\dot{M}_1 = -\beta\dot{M}_2$ expresses the amount captured by the gainer, while $\dot{m} = (1-\beta)\dot{M}_2$ represents the remaining part which eventually is lost from the system. Note that $\beta = 1$ accounts for the conservative case (where all the transferred mass is captured from the gainer) and $\beta = 0$ accounts for the fully liberal case (where all the transferred mass is rejected from the gainer).

The numerical expression within the brackets on the r.h.s. of Eqs. (1) and (2) depends exclusively on the mass ratio q of the system, given that $r_r = r_r(q)$ and $j_{L3} = j_{L3}(q)$, which is valid for small initial flow stream velocities. Hence, critical mass ratio values q_{cr} can emerge by determining the roots of this expression, assuming different degrees of liberalism, i.e. different β values. Values for the r_r and j_{L3} parameters can be found in [4] and [6], respectively, for several mass ratios, inferred from semi-analytical ballistic models. Empirical relations may be also sufficiently employed (see, e.g., [8] and [5]). The procedure was also implemented in absence of a transient disk by posing $r_r = 0$. Results for q_{cr} values are given in Table 1. *Systems with mass ratio q greater than the listed q_{cr} values are expected to show a decreasing orbital period (and a concave O–C diagram).*

4 Applications

The foregoing procedure can be applied individually, i.e. for a specific binary system. We selected from the literature two semi-detached systems of particular interest, namely RR Dra (2.83 d) and X Tri (0.97 d), with the contact component to be the less massive star. The available times of minima show a clear long-term O–C modulation which is convex for the case of RR Dra and concave for the case of X Tri, representing a secular period increase and a secular period decrease, respectively. RR Dra consists of a $M_1 = 2.15\,M_\odot$ and $M_2 = 0.6\,M_\odot$ components corresponding to a $q = 0.28$ mass ratio (see, e.g., [9] and references therein), while X Tri consists of a $M_1 = 2.30\,M_\odot$ and $M_2 = 1.20\,M_\odot$ components with a $q = 0.52$ mass ratio (see, e.g., [3] and references therein). Assuming that the observed secular variations are adequately described by a second order polynomial, the temporal period change for each system was estimated equal to $\dot{P} = +8.9079 \times 10^{-9}\,\mathrm{yr\,yr^{-1}}$ and $\dot{P} = -1.5269 \times 10^{-10}\,\mathrm{yr\,yr^{-1}}$ for the case of RR Dra ([9]) and X Tri ([3]), respectively. Hence, the mass accretion rate $\dot{M}_1$ may be easily calculated by means of Eqs. (1) and (2), while the rate at which mass escapes from the system is derived by $\dot{m} = -(1-\beta)\dot{M}_1/\beta$. The inferred values for several degrees of liberalism are tabulated in Tables 2 and 3 for the RR Dra and the X Tri system, respectively.

Table 3: Mass accretion and ML rates for the X Tri system as a function of the degree of liberalism β.

	ML through the L3 point for $r_r = 0$		ML through the L3 point for $r_r \neq 0$	
β	$\dot{M}_1$ $[M_\odot\,\mathrm{yr}^{-1}]$	$\dot{m}$ $[M_\odot\,\mathrm{yr}^{-1}]$	$\dot{M}_1$ $[M_\odot\,\mathrm{yr}^{-1}]$	$\dot{m}$ $[M_\odot\,\mathrm{yr}^{-1}]$
0.0	0.000	-2.15×10^{-8}	0.000	-2.10×10^{-8}
0.1	2.45×10^{-9}	-2.21×10^{-8}	2.35×10^{-9}	-2.11×10^{-8}
0.2	5.89×10^{-9}	-2.36×10^{-8}	5.33×10^{-9}	-2.13×10^{-8}
0.3	1.11×10^{-8}	-2.58×10^{-8}	9.24×10^{-9}	-2.16×10^{-8}
0.4	1.98×10^{-8}	-2.96×10^{-8}	1.46×10^{-8}	-2.19×10^{-8}
0.5	3.73×10^{-8}	-3.73×10^{-8}	2.24×10^{-8}	-2.24×10^{-8}
0.6	9.14×10^{-8}	-6.10×10^{-8}	3.47×10^{-8}	-2.31×10^{-8}
0.7	—	—	5.72×10^{-8}	-2.45×10^{-8}
0.8	—	—	1.12×10^{-7}	-2.79×10^{-8}
0.9	—	—	4.25×10^{-7}	-4.72×10^{-8}
1.0	—	—	—	—

5 Concluding remarks

Considering the hot spot case, it is shown that in absence of a transient disk the period is expected to increase continuously without any further restriction ($r_r = 0$), otherwise, the monotony clearly depends on the extent at which liberalism occurs since a transient disk appears to be a powerful source of orbital AML ($r_r \neq 0$). Thereby, period turns to be decreasing over a critical mass ratio q_{cr} which can be specified for any given level of liberalism. Obviously, *the critical mass ratio q_{cr} is displaced toward smaller values as long as the degree of liberalism is abridged.* This still happens when mass is lost from the L3 point with a wider, however, mass ratio range.

As far as the two individual systems are concerned, RR Dra was examined considering that a transient disk surrounds the more massive component, a finding reported in the spectroscopic investigation of [1]. We point out that there is a small deviation between the conservative mass transfer rate of $3.2 \times 10^{-7}\,M_\odot\,\mathrm{yr}^{-1}$, as given in [9], and the one of $8.0 \times 10^{-7}\,M_\odot\,\mathrm{yr}^{-1}$, as found in the present study, due to the orbital AML contribution from the disk. Despite the convex O–C diagram morphology, mass losses through the L3 point are still supported for a narrow mass ratio range. Inversely, the concave O–C modulation of X Tri can be ascribed to a non-conservative mass transfer process accompanied by ML and AML through the L3 point only. The procedure was performed either in presence or in absence of a transient disk, since no prior information was found in the literature. *Apparently, the present study predicts reasonable mass transfer rates from the less massive to the more massive component, contrary to the expectations of the fully conservative approach, even when a semi-detached system shows a secular period reduction.*

References

[1] Kaitchuck, R. H., Honeycutt, R. K., and Schlegel, E. M.: 1985, PASP, 97, 1178.

[2] Kalimeris, A., and Rovithis-Livaniou, H.: 2006, Ap&SS, 304, 113.

[3] Liakos, A., Zasche, P., and Niarchos, P., 2010: in Binaries – Key to Comprehension of the Universe, ed. A. Prša, and M. Zejda (San Francisco: ASP), ASP Conf. Ser., 435, 101.

[4] Lubow, S. H., and Shu, F. H.: 1975, ApJ, 198, 383.

[5] Nanouris, N., Kalimeris, A., Antonopoulou E., and Rovithis-Livaniou H.: 2013, to be submitted in A&A.

[6] Shu, F. H., Anderson, L., and Lubow, S. H.: 1979, ApJ, 229, 223.

[7] van Rensbergen, W., de Greve, J. P., de Loore, C., and Mennekens, N.: 2008, A&A, 487, 1129.

[8] Verbunt, F., and Rappaport, S.: 1988, ApJ, 332, 193.

[9] Zasche, P., Liakos, A., Wolf, M., and Niarchos, P.: 2008, NewA, 13, 405.