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Exploring dynamo effects in DPV systems

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ABSTRACT

Context. Double Periodic Variables (hereafter DPVs) are a group of close interacting binaries of Algol type where the less massive star is more evolved and it is filling its Roche lobe transfering mass to its more massive accreting companion forming an optically thick accretion disc. These systems presents a characteristic long period that is an order of magnitude longer than the corresponding orbital period, many of them with a characteristic ratio of approximately 35.
Aims. In this work we study how the dynamo number and the ratio of long to orbital period changes throughout the evolution of our sample consisting on 17 DPV systems with well known stellar parameters, 11 of which also have known modulation periods.
Methods. We performed a multiparametric χ^2 minimization test to fit our systems to the binary evolution models proposed by van Rensbergen et al. (2008) in order to find a pontentially good description of the evolution of each system of our sample.
Results. We have found a relatively good fit for 11 out of 17 systems.

Key words. dynamo – stars: activity – binaries: close – stars: low-mass – stars: rotation

1. Introduction

The study of binary systems, specially the close interacting ones is specially important to probe stellar physics, to understand how close binaries evolve and how a binary component affects its companion due to their short distance to the centre of mass. There is an important class of close interacting binaries called the Algol-type variables which consist on semi-detached binaries with intermediate mass components. In such systems the less massive star (hereafter donor) is more evolved than the most massive one (hereafter gainer) this paradox can be understood if the donor star used to be the massive star in the system, it evolved first and started a fast exchange of mass through Roche lobe overflow onto the gainer star as first studied by Crawford (1955) and later confirmed by numerical calculations by Kippenhahn & Weigert (1967) and Eggleton & Kisseleva-Eggleton (2006).

This paper is focused in the double periodic variables (DPV) which are a sub-class of the Algol consisting in relatively massive stars with a gainer of $\sim 7M_\odot$ and the donor star is filling its Roche lobe transfering mass to its companion. This type of binary were found in the Magellanic Clouds showing roughly sinusoidal periodic light variations with periods from 140 to 960 days (Mennickent et al. 2003). They found a characteristic relation between long and short period given by $P_{long} = f \times P_{short}$ (Mennickent et al. 2003). Here f a correlation coefficient with an average value of ~ 33 but with single values for the period ratio tipically between 27 and 39 (Mennickent et al. 2016). An interesting feature of this relation is that it is not only true for galactic DPVs but also for non-galactic ones. Mennickent et al. (2003) found a $f = 32.4$ for the original sample of the LMC and SMC DPVs. Poleski et al. (2010) reported a value of $f = 33.1$ for 125 LMC DPVs. Mennickent et al. (2012) reported a value of $f = 32.7$ for thirteen galactic DPVs which were the only DPVs known at that time.

In this paper, our goal is to further assess whether magnetic activity is a feasible alternative to explain the origin of such long period present in the DPVs system. In particular, we note that in the context of isolated stars, characteristic relations have been inferred between the activity cycle and the rotation period (Saar & Brandenburg 1999; Böhm-Vitense 2007), which can be interpreted in terms of simple dynamo models, as already proposed by Soon et al. (1993) and Baliunas et al. (1996), they sugested a relation between rotation velocity, activity period and the dynamo number $D = \alpha\Delta\Omega d^3/\eta^2$. Here d is the characteristic legth scale of the convection, η is the turbulent magnetic diffusivity, $\Delta\Omega$ is the differential rotation and α is the magnetic helicity in the star.

2. Binary evolution and Dynamo model

In this section, we compare the systems parameters listed in table 1 with those predicted by binary evolution models which include epochs of non-conservative evolution. We inspected all the 561 conservative and non-conservative evolutionary tracks proposed by van Rensbergen et al. (2008, 2011) that are available at the Center Doneés Stellaires (CDS) in order to find the model that describes the best each system in our sample. We performed a multiparametric fit by doing a χ^2 minimization following the work by Mennickent et al. (2012), given by

$$\chi^2_{i,j} = \left(\frac{1}{N}\right) \sum_k w_k \left[\frac{(S_{i,j,k} - O_k)}{O_k}\right]^2, \quad (1)$$

here N is the number of observations (7), $S_{i,j,k}$ is the synthetic model where i indicates the model, j indicates the time t_j and k indicates the stellar or orbital parameter, O_k are the observed stellar parameters we are using to perform our fit, which are: mass, radii, luminosities and orbital period. The quantity w_k is

Binary	$Md[M_\odot]$	$Rd[R_\odot]$	$Mg[M_\odot]$	q	$P_{orb}[d]$	$P_{long}[d]$	P_{long}/P_{orb}
U Cep	3.22 ± 0.143	7.045 ± 0.279	4.938 ± 0.532	0.652	$3.38 \pm (0.05)$	$515 - 26663$	152-7889
UX Mon	3.9 ± 0.29	9.8 ± 0.003	3.38 ± 0.4	1.15	5.90 ± 0.005	$\text{no}^{(1)}$	-
DQ Vel	2.2 ± 0.2	8.4 ± 0.2	7.3 ± 0.3	0.31	6.08337 ± 0.00013	189	31.1
V448 Cyg	13.7 ± 0.7	16.3 ± 0.3	24.7 ± 0.7	0.55	$6.52 \pm (0.05)$	*no*	-
CX Dra	$1.7 \pm (0.5)$	$13.25 \pm (0.05)$	$7.3 \pm (0.5)$	0.23	6.95957 ± 0.000043	yes	-
TT Hya	$0.63 \pm (0.05)$	$4.3 \pm (0.5)$	$2.77 \pm (0.05)$	0.23	$6.95 \pm (0.05)$	?	-
iDPV	1.9 ± 0.2	8.9 ± 0.3	9.1 ± 0.5	0.21	$7.241 \pm (0.005)$	172	23.8
V393 Sco	2.0 ± 0.2	9.4 ± 0.50	7.8 ± 0.30	0.25	$7.71259 \pm (0.00005)$	253	32.8
LP Ara	$3.0 \pm (0.5)$	$11.6 \pm (0.5)$	$9.8 \pm (0.5)$	0.30	$8.53295 \pm (0.000005)$	273	32
V360 Lac	1.2 ± 0.05	$8.8 \pm (0.5)$	7.45 ± 0.3	0.16	10.085449 ± 0.000078	322.2	31.9
AU Mon	1.20 ± 0.2	10.1 ± 0.5	7.0 ± 0.3	0.17	11.1130374 ± 0.0000001	421	37.9
BR CMi	$0.137^{+0.0017}_{-0.0026}$	$5.49^{+0.22}_{-0.37}$	$2.31^{+0.29}_{-0.43}$	0.06	12.919 ± 0.000015	*no*	-
β Lyr	2.97 ± 0.2	15.2 ± 0.2	13.16 ± 0.3	0.23	12.941 ± 0.002	282.4	21.8
HD170582	1.9 ± 0.1	15.6 ± 0.2	9.0 ± 0.2	0.21	16.87177 ± 0.002084	537	31.8
RX Cas	1.8 ± 0.4	23.5 ± 1.2	5.8 ± 0.5	0.32	$32.31211 \pm (0.00005)$	516.1	16
V495 Cen	0.91 ± 0.2	19.3 ± 0.5	5.76 ± 0.3	0.17	33.492 ± 0.002	1283	38.3
SX Cas	1.5 ± 0.4	23.5 ± 1.3	5.1 ± 0.4	0.29	$36.56 \pm (0.05)$	?	-

Table 1. The table includes both donor and gainer masses, donor radius, ratio $q = M_d/M_g$, orbital period, the available information on the presence of a long period and the ratio P_{long}/P_{orb} as well as the error for each parameter where the number in () means that we are estimating the error affecting only the last digit.

the statistical wight of the parameter O_k which is calculated as

$$w_k = \sqrt{\frac{O_k}{\epsilon O_k}}, \tag{2}$$

where ϵO_k is the error associated to the parameter O_k. The model with the minimum χ^2 will correspond to the model with the best evolutionary system for the corresponding system and the absolute minimum χ^2 will identifies the theoretical stellar parameters as well as the age of the system.

2.1. Fitting observed systems to evolutionary tracks

We have found a good model match for 11 out of 17 systems in our sample. All the parameters predicted by the van Rensbergen et al. (2008, 2011) binary evolution models are listed in table 2. We can note that the models predicts in a good way the eleven well fitted systems. For the donor components of each system the deviation between model and observations is between $\sim 2\% - 56\%$ for the mass, for the radius this differece is between $\sim 1\% - 12\%$. On the other hand, for the gainer component of the systems there is a difference between prediction and observations of about $\sim 0.95\% - 21.1\%$ for the mass and $\sim 0.61\% - 28.43\%$ for the radius. For the orbital period P_{orb} the deviation between model prediction and observations is between $0\% - 5\%$..

2.2. The dynamo model

We focused this work in the model proposed by Schleicher & Mennickent (2017), using the relation between long period and orbital period (Soon et al. 1993; Baliunas et al. 1996)

$$P_{long} = D^\alpha P_{rot}, \tag{3}$$

with D the dynamo number, P_{long} the activity cycle of the star and P_{rot} the rotational period of the star. As DPVs are close binaries, we are able to assume that the system is tidally locked (Zahn 1989; Zahn & Bouchet 1989), making P_{rot} equal to the binary period. α is a power law index that depends on the activity level of the star (Dubé & Charbonneau 2013) and it is normally

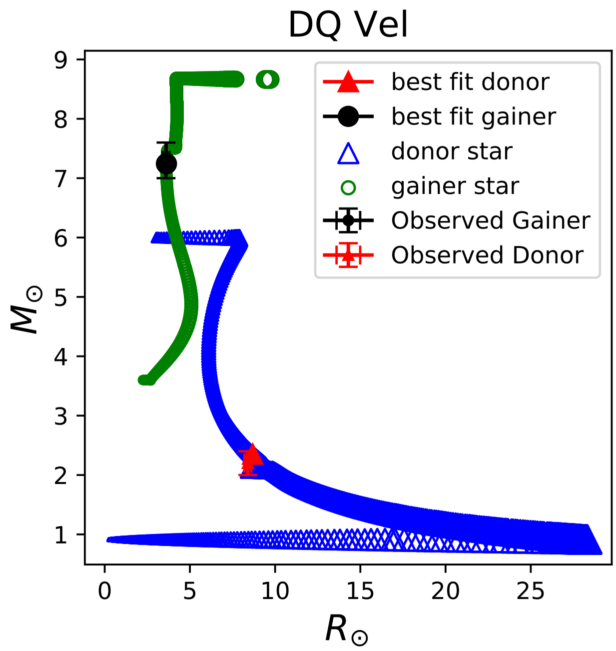

Fig. 1. Best fit of van Rensbergen binary evolution model for the system DQ Velorum with a $\chi^2 \sim 0.021$. The figure shows the evolutionary track of the mass as a function of radius for both donor (blue) and gainer (green) star of the as well as the predicted current state of each component and the observed state of the system. Also the figure shows the predicted state of both components of the system with non-error bars black dot (gainer) and red triangle (donor) as well as the observed state of the each component marked with error bars black dot (gainer) and red dot (donor). The fit has the following ratios between observed and predicted parameters: $M_{d,obs}/M_{d,model} = 0.94$, $M_{g,obs}/M_{g,model} = 1.007$, $R_{d,obs}/R_{d,model} = 0.97$, $R_{d,obs}/R_{d,model} = 0.99$, $P_{orb,obs}/P_{orb,model} = 0.99$.

between $\sim \frac{1}{3}$ and $\sim \frac{5}{6}$. Schleicher & Mennickent (2017) found a value of $\alpha = 0.31$ which yields to a good agreement of the observational data with the average population. D can be related to the rossby number by the relation $D = Ro^{-2}$, where $Ro = P_{rot}/\tau_c$

Binary	$Md[M_{\odot}]_{model}$	$Rd[R_{\odot}]_{model}$	$Mg[M_{\odot}]_{model}$	$R_g[R_{\odot}]_{model}$	$P_{orb}[d]_{model}$	χ^2_{min}
DQ Vel	2.36	8.64	7.23	3.62	6.05	0.0058
iDPV	1.95	9.09	9.25	4.82	7.24	0.0215
V393 Sco	2.11	9.55	7.49	3.79	7.71	0.0163
LP Ara	2.36	10.79	8.83	4.79	8.51	0.0465
V360 Lac	1.16	9.45	7.24	6.74	10.14	0.0130
AU Mon	1.48	11.11	5.52	4.74	11.13	0.1077
β Lyr	2.25	14.36	13.31	6.02	12.95	0.0297
HD170582	2.01	16.28	9.24	6.15	16.78	0.0226
RX Cas	1.72	24.04	6.69	3.21	32.48	0.0585
V495 Cen	1.42	21.64	6.49	3.49	31.98	0.179
SX Cas	1.34	23.05	6.57	3.26	36.35	0.0679

Table 2. The table shows each parameter predicted by van Rensbergen binary evolution models of each binary component for every system. Also is shown the minimum χ^2 obtained for every system.

is defined as the ratio between the stellar rotational period P_{rot} and the convective turnover time, $\tau_c = 2H_p/v_c$. Following Soker (2000), Rossby number Ro can be written as

$$Ro = 9\left(\frac{v_c}{10\text{km/s}}\right)\left(\frac{H_p}{40R_{\odot}}\right)^{-1}\left(\frac{\omega}{0.1\omega_{Kep}}\right)^{-1}\left(\frac{P_{Kep}}{yr}\right), \tag{4}$$

where v_c and H_p are the convective velocity and pressure scale height of the star, repectively. ω is the angular velocity, ω_{Kep} and P_{Kep} are the Keplerian angular velocity and orbital period, respectively. In order to perform our analysis we follow the derivation proposed by Schleicher & Mennickent (2017) where they studied the dependance of the dynamo number on the stellar parameters by using mixing length theory, finding the following expresion

$$P_{long} = P_{rot}\left(11.5\left(\frac{2\sqrt{2}}{15}\right)^{1/3}\frac{R_{\odot}}{km\,s^{-1}yr}\right)^{-2\alpha} \times\left(\frac{L_2^{2/3}R_2^{2/3}}{M_2^{2/3}}\left(\frac{l_m}{H_p}\right)^{-4/3}\left(\frac{P_{kep}}{\epsilon_H R_2}\right)^2\right)^{-\alpha}. \tag{5}$$

with l_m the mixing length.

2.3. Typical evolution of a representative system.

2.4. Evolution of the dynamo number and long-to-short period over the age of the systems

Acknowledgements.

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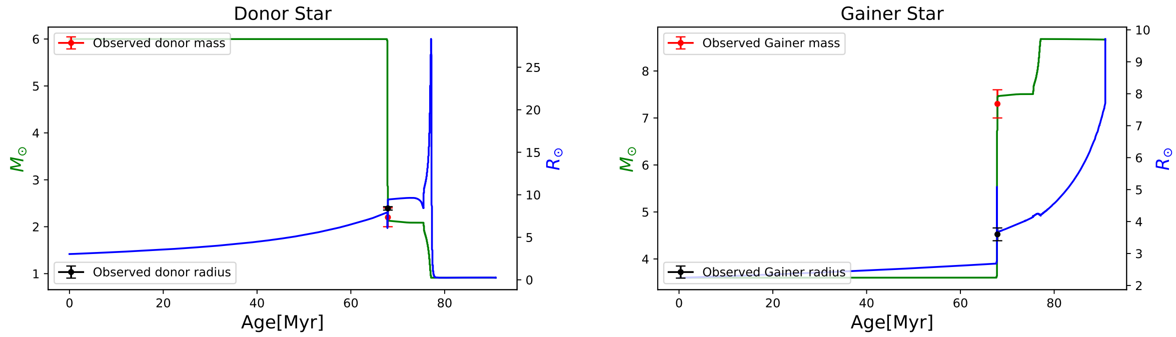

Fig. 2. Evolution of mass and radius of both binary components. On the left the figure shows the evolution of mass (green path) and radius (blue path) of the donor star also is plotted the current state of the donor component in red and black dots for mass and radius respectively. On the right the figure shows the evolution of mass (green path) and radius (blue path) of the gainer star also is plotted the current state of the gainer component in red and black dots for mass and radius respectively. Both stars are the components of DQ Velorum system.