Dynamo effect in the double periodic variable DQ Velorum

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Resumen / DQ Velorum es una variable de doble período galáctica que consiste de un sistema binario semi-separado con una estrella acretora de tipo espectral B y una estrella donadora de tipo espectral A, además de un disco de acreción en la estrella acretora. El sistema presenta un período orbital de 6.08337 días y un período largo de 189 días cuyo origen sigue en debate. En este trabajo estudiamos la posibilidad de que este período sea producto de una dínamo magnético, estudiando la evolución completa del sistema. Nuestro modelo ajusta de muy buena manera el estado actual del sistema y puede ser usado para describir la evolucion de DQ Velorum. Además, el modelo predice un incremento en el número de dínamo en la estrella donor en épocas de alta transferencia de masa y una razón de los períodos largo y orbital muy cercana a la que se observa en el sistema.

Abstract / DQ Velorum is a galactic double periodic variable (DPV), this system is a semi-detached binary comprised of a B-type gainer and an A-type donor star plus an extended accretion disc around the gainer. The system presents an orbital period of 6.08337 days and a long period of 189 days whose origin is still under debate. Here we studied the possibility that this period may be driven by a magnetic dynamo while investigating the entire evolution of the system. Our model matches in a very good way the current state of the system and it can potentially be used to describe the evolution of DQ Velorum. It also predicts an increase of the dynamo number of the donor during epochs of high mass transfer in this system, and a theoretical long to orbital period ratio that is very close to the observed one at the present system age.

Keywords / stars: activity — low-mass — rotation — binaries: close — dynamo

1. Introduction

An important class of close interacting binaries are the so-called Algol-type variables. Such systems consist of semi-detached binaries with intermediate mass components. In these systems the less massive star (donor) is more evolved than the most massive star (gainer) and the mass ratio indicates that some processes may have occurred in order to explain the high mass of the main sequence companion star. In particular mass transfer, as originally explained by Crawford (1955) and confirmed by Kippenhahn & Weigert (1967); van Rensbergen et al. (2011) and de Mink et al. (2014) through numerical calculations. The apparent mass paradox between binary components can be well understood if the donor star was once the most massive star in the system, it evolved faster than its companion starting a fast process of mass exchange through Roche lobe overflows (RLOF) onto its companion (Eggleton & Kisseleva-Eggleton, 2006).

One of the most important features in the Algol-type binaries is the presence of long cycles. The presence of these cycles is known since a long time (e.g. Lorenzi (1980a,b); Guinan (1989)). Nevertheless, the interpretation and origin of such a cycles are still under debate.

We aim to give an explanation on the origin of this cycle. We focused our study on a sub-class of the Algol classification which are the double periodic variable (DPV) binary systems, which consist of semi-detached interacting binary systems with intermediate mass components that were found by Mennickent et al. (2003), presenting the main characteristics of the Algol systems.

This report is based on the DPV system DQ Velorum, a binary system that was fully studied by Barría et al. (2013a,b, 2014) which presents the following stellar parameters: $M_d = 2.2 \pm 0.2\ M_\odot$, $M_g = 7.3 \pm 0.3\ M_\odot$, $R_d = 8.4 \pm 0.2\ R_\odot$, $R_g = 3.6 \pm 0.2\ R_\odot$, $L_d = 2.66 \pm 0.036\ L_\odot$, $L_g = 3.14 \pm 0.16\ L_\odot$, $P_{orb} = 6.08337 \pm 0.00013$ days and a long period of $P_{long} = 189$ days. Here we explored the magnetic dynamo cycle as a potential origin of the long period. For this purpose we studied the entire evolution of this systems using the binary evolution models proposed by van Rensbergen et al. (2008, 2011). For the dynamo we used the relation proposed by Soon et al. (1993) and Baliunas et al. (1996) that relates the rotational velocity, activity period and the dynamo number via $D = \alpha \Delta\Omega d^3/\eta^2$. Here α is a measure of helicity, $\Delta\Omega$ is the large-scale differential rotation, d is the characteristic length scale of convection and η the turbulent magnetic diffusivity in the star.

2. Methods

In order to study how the dynamo number D and the ratio of the long to orbital period changes as the system is evolving, we are fitting our system to the van Rensbergen binary evolution models (van Rensbergen et al., 2008, 2011). These models were developed in order to study the evolution of close binaries, including both conservative and non-conservative scenarios, by solving the stellar structure equations using the *Brussels* binary evolutionary code (for a detailed description of the code see De Loore & Doom (1992)). The code was modified in order to include convective mixing, radius corrections and nuclear physics, following Prantzos et al. (1986). Also, following De Loore & De Greve (1992) a moderate convective core overshooting is applied. Mass loss by stellar winds and period changes due to angular momentum loss are also included in this model. Initial conditions were established by using an unevolved system with a B-type primary at birth from the 9th catalog of spectroscopic binaries (Pourbaix et al., 2004), distinguishing between late B-type $[2.5, 7]$ M$_\odot$ and early B-type $[7, 16.7]$ M$_\odot$ primaries. We inspected all the 561 conservative and non-conservative evolutionary tracks that are available at the Center Doneés Stellaires (CDS) looking for the model that describes the best our system. A multi-parametric χ^2 minimization was performed in order to find the best match, this test is given by (Mennickent et al., 2012):

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

where N is the number of observations (7), $S_{i,j,k}$ is the synthetic model where i indicates the model, j the time t_j and k the stellar or orbital parameter, O_k are the observed stellar parameters. To perform our test, we are fitting the mass, radii and luminosities of both stars in the system and also the orbital period of the binary. $w_k = \sqrt{O_k/\epsilon O_k}$ is the statistical weight of the parameter O_k and ϵO_k is the error associated to the parameter O_k. The model with the minimum χ^2 corresponds to the model that describes best the evolution of the system. After we found the best model for our system, we are following the relation between the long period P_{long} and the orbital period P_{orb} given by (Soon et al., 1993; Baliunas et al., 1996)

$$P_{long} = D^\gamma P_{rot}, \quad (2)$$

where D is the dynamo number and γ is a power law index, with values usually between 1/3 and 5/6 (Saar & Brandenburg, 1999; Dubé & Charbonneau, 2013). In order to calculate the dynamo number D we follow the dynamo model by Schleicher & Mennickent (2017), they proposed that the long period is related to the orbital period following the relation

$$P_{long} = P_{orb} \left(11.5 \left(\frac{2\sqrt{2}}{15}\right)^{1/3} \frac{\mathrm{R}_\odot}{\mathrm{km\,s^{-1}\,yr}}\right)^{-2\gamma} \times \left(\frac{L_2^{2/3} R_2^{2/3}}{M_2^{2/3}} \left(\frac{l_m}{H_p}\right)^{-4/3} \left(\frac{P_{kep}}{\epsilon_H R_2}\right)^2\right)^{-\gamma} , \quad (3)$$

where l_m is the mixing length, H_p is the pressure scale height and P_{kep} is the Keplerian orbital period of a test particle on the surface of the donor star. They found a good fit with $\gamma \sim 0.31 \pm 0.05$. More recently, Navarrete et al. (2018) and Völschow et al. (2018) showed that a magnetic dynamo can explain the modulation periods which are produced by changes in the quadrupole moment of the star in post common envelope (PCE) binaries. The latter shows that the model is potentially feasible in systems where the evolutionary process is different in comparison with the DPV systems.

2.1. Model fitting

We applied the χ^2 minimization test to the parameters listed in Table 1. We found that, the model that describes best the system corresponds to the same non-conservative and with slow mass transfer rate under synchronous rotation model reported by Barría et al. (2014). The latter also presents the following ratios between observations and model predictions: $M_{d,obs}/M_{d,model} = 0.94$, $M_{g,obs}/M_{g,model} = 1.007$, $R_{d,obs}/R_{d,model} = 0.97$, $R_{g,obs}/R_{g,model} = 0.99$, $L_{d,obs}/L_{d,model} = 1.11$, $L_{g,obs}/L_{g,model} = 0.93$ and $P_{orb,obs}/P_{orb,model} = 0.99$ at a stellar age of $\sim 68 \pm 0.5$ Myr. This means that the model can describe in a very good way the evolution of the system. The top panel in Fig. 1 presents the evolutionary track of both components of the system, there, the path with circles denotes the evolution of the gainer star. We also indicate the observational and predicted state of the gainer (black dot with and without error bars, respectively). The path with triangles corresponds the evolution of the donor star, also it is plotted the observational state of the donor (red triangle with error bars) and the prediction of the model for the donor (red triangle without error bars). The prediction of the current state of each component of the system, almost overlaps with the current observational state of the binary.

2.2. Evolution of the dynamo number and long-to-orbital period ratio

Once the fit is done both dynamo number D and ratio of long to orbital period were calculated using Eq. 3. As seen in Fig. 1 middle, the dynamo number D follows an almost constant evolution during the first 55 Myr, after this, the dynamo number grows dramatically fast, which will possibly produce a strong magnetic activity and the stars begins an active mass transfer phase. This situation lasts for a very short time (~ 1 to ~ 2 kyr) and right after the dynamo peak, it starts to decrease until the star becomes magnetically inactive at a stellar age of ~ 77 Myr. The ratio of long to orbital period also grows as fast as the dynamo number, this means that both periods (long and orbital) are almost constant during the first 55 Myr. After this interval of constant evolution both periods grow very rapidly, producing a star with a longer magnetic cycle and with a longer orbital period as seen in the bottom panel of Fig. 1.

3. Conclusions

We have found that DQ Velorum is an old system with a small mass transfer rate as reported by Barría et al. (2014). The system is well described by the models proposed by van Rensbergen et al. (2008, 2011), so it seems

Table 1: Observational stellar parameters for DQ Velorum. Taken from Barría et al. (2013b); Mennickent et al. (2016)

Parameter	Value
M_d [$M_\odot$]	2.2 ± 0.2
M_g [$M_\odot$]	7.3 ± 0.3
R_d [$R_\odot$]	8.4 ± 0.2
R_g [$R_\odot$]	3.6 ± 0.2
L_d [$L_\odot$]	2.66 ± 0.036
L_g [$L_\odot$]	3.14 ± 0.16
P_{orb} [days]	6.08337 ± 0.00013

feasible to use them as a potential description for the system evolution. We studied the evolution of the dynamo number D, finding that after an almost constant evolution of this parameter the star becomes strongly active in a short period due to the short orbital period of the system starting a rapid mass transfer phase. The latter also applies to other stellar parameters like radius, mass and luminosity. This strongly active phase of the star lasts for a very short time (~ 1 to ~ 2 kyr) and is followed by a magnetic activity decrease until the star becomes magnetically inactive, with no mass exchange between both stars.

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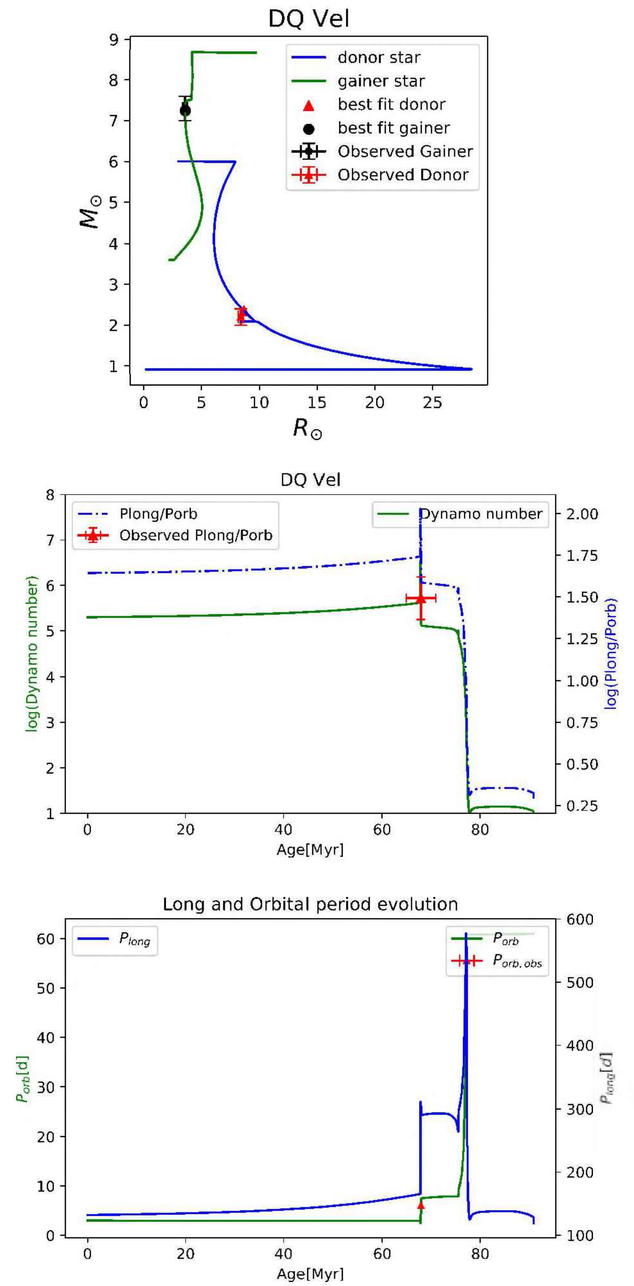

Figure 1: Top: The best model for DQ Velorum. We show the evolution of the gainer (circles), its observed (black dots with errors) and predicted (red triangles) parameters. The path with triangles shows the evolution of the donor, the observed (red triangle with error bars) and predicted parameters (red triangle without error bars). Middle: The dynamo number (solid line) and the ratio of long to orbital period (dashed line). We also plot the observed ratio of long to orbital period (triangle with error bars) with a value of $\log(P_{long}/P_{orb}) = 1.492$, the same value reported by Schleicher & Mennickent (2017). Bottom: Evolution of the orbital (path with asterisks) and long (path with triangles) periods, along with the observed value of the orbital period (marked with an error-bar triangle in log scale).