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Dynamical Evolution of the RS CVn-type Binaries

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Abstract

The orbital angular momentum (orbital AM) of a sample of forty RS CVn-type binaries with the orbital periods P≤10 days were estimated and the orbital AM distribution with respect to P was critically interpreted as the orbital AM evolution of these systems caused by the magnetic breaking process with the existence of spin-orbit coupling. The empirical relations (between the orbital AM loss, mass loss and period variation) derived from the diagram of the orbital AM distribution were used in deriving a semi-empirical formula for the dynamical evolution of the RS CVn-type binaries.

The magnetic breaking induced dynamical evolution of the RS CVn-type binaries maybe at different rates but is always towards the shorter periods in the existence of spin-orbit coupling and before the Roche lobe filling of a component star.

1. Introduction

The RS CVn-type binaries are known to be detached active binaries with late type (mostly G or K) evolved components [1, 2, 3]. The high level of magnetic activity in these stars originate from the interaction of deep convection and the rapid, near synchronous rotation of these tidally-locked binaries. The absolute dimensions of the component stars are mostly in the following intervals [4]: $0.90<M/M_\odot<2.3$, $1.0<R/R_\odot<6.3$, $0.8<L/L_\odot<32$, $4500°K<T_{eff}<7100°K$, $3.0<\log g(cgs)<4.4$. With the exception of Algol-type systems (e.g. RZ Cnc, AR Mon, RT Lac) and the systems with WD components (e.g. AY Cet, V471 Tau), the average mass ratio of the RS CVn systems are $q=m_h/m_c=0.92\pm0.10$.

The dynamical evolution of binary systems are controlled by the mass loss from the system and the mass transfer from one component to the other. The angular momentum

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loss (AML) from the components of RS CVn systems through the stellar wind mass loss should be greatly enhanced by the large scale magnetic loops which enforce the wind to corotation out to a critical distance (the Alfvén radius R_A). The enhanced AML from the component stars is fed by the orbital angular momentum of the system by the process of tidal friction so that a strong braking torque on the individual components causes the binary orbit to shrink, and eventually spiriling into forming a contact binary system [5, 6, 7]. The time scale for reaching contact depends on the initial orbital separation, the magnetic activity of the stars, the nature of the breaking mechanism, and the extent of the stellar wind. For such magnetic breaking to be effective, the main sequence components of the detached binary systems would have masses smaller than about 1.6 $M_\odot$ which corresponds to spectral types of ∼F0 and later [8]. In addition, tidal effects on the components would have to be large enough so that the spin angular momentum would be coupled with the orbital angular momentum. It is well known that the relatively longer period RS CVn systems (P≥10 days) contain relatively larger mass components [9, 10]. Such systems should lose less angular momentum during their main sequence lifetimes because dynamo generated activity should be negligible due to absence of convective envelopes. These longer period higher mass systems could evolve into Algol-type binaries as the more massive component fills its Roche lobe and undergoes mass transfering to its companion.

In this paper, I will use a new observational constraint in the magnetic breaking mechanism at work in the relatively short period (P≤10 days) RS CVn-type binaries, and use the results in exploring the dynamical evolution of these systems.

2. Angular Momentum Distribution

Altogether 40 RS CVn-type binaries with $P_{orb} < 10^d$ and known masses and radii for the component stars were selected from the Catalog of Chromospherically Active Binary Stars [11]. For the 29 systems $P < 5^d$ and $5^d < P < 10^d$ for the remaining 11 systems. The orbital AM of this sample of 40 RS CVn systems were estimated by using the well known relation

$$J = \left(\frac{G^2}{2\pi}\right)^{\frac{1}{3}} \frac{m_1 m_2}{(m_1+m_2)^{\frac{1}{3}}} P^{\frac{1}{3}} \tag{1}$$

in terms of the masses $m_{1,2}$ of the component stars and the orbital period P of the system. Where G is the universal gravity constant. The estimated orbital AM of the sample stars were listed in Table 1 together with their known parameters, and the estimated orbital AM values which were plotted in Fig.1 against the orbital periods of the systems. The constant total mass lines (m_1+m_2=2 and 4) for the mass ratio q=1 were also drawn in Fig.1.

According to the magnetic breaking theory, Fig.1 represent, in fact, the orbital AM evolution of the RS CVn-type binaries, just like the HR diagram of a star cluster, representing the nuclear evolution of the cluster members. The orbital AM evolution in Fig.

Table 1. The RS CVn-type binaries (with P$\leq 10^d$) studied in this work. The data (which were extracted from the Catalog of Chromospherically Active Binary Stars [11]) were used in the calculation of the orbital AM J which is given in the last column. In the table, the orbital period P_{orb} is in days, the masses and radii are in solar units, and the AM J is in cgs units.

Name	Sp type	P_{orb}	m_h	m_c	r_h	r_c	logJ
FF And	dM1e/dM1e	2.170	0.55	0.54	0.60	0.60	51.67
CF Tuc	G0V/K4IV	2.798	1.06	1.21	1.67	3.32	52.23
UV Psc	G4-6V/K0-2V	0.861	1.22	0.87	1.21	0.91	51.99
LX Per	G0IV/K0IV	8.038	1.24	1.32	1.64	3.05	52.47
UX Ari	G5V/K0IV	6.438	0.97	1.10	0.93	4.70	52.29
V711 Tau	G5IV/K1IV	2.838	1.10	1.40	1.30	3.90	52.30
V837 Tau	G2V/K5V	1.930	1.00	0.67	1.05	0.74	51.94
V818 Tau	G6V/K6V	5.609	1.09	0.78	0.95	0.70	52.18
SV Cam	G2-3V/K4V	0.593	0.93	0.67	1.11	0.74	51.75
VV Mon	G2IV/K0IV	6.051	1.42	1.50	1.75	6.00	52.53
YY Gem	dM1e/dM1e	0.814	0.62	0.57	0.62	0.62	51.59
GK Hya	F8/G8IV	3.587	1.25	1.34	1.51	3.39	52.37
TY Pyx	G5IV/G5IV	3.199	1.22	1.20	1.59	1.68	52.30
XY UMa	G3V/(K4-5V)	0.479	0.95	0.70	0.98	0.73	51.74
BF Lyn	K2V/(dK)	3.804	0.76	0.74	0.78	0.78	51.98
DH Leo	(K0V/K7V)K5V	1.070	0.83	0.58	0.97	0.67	51.74
XY Leo B	M1V/M3V	0.805	0.50	0.35	0.60	0.40	51.33
RW UMa	F8IV/K0IV	7.328	1.56	1.49	2.31	4.24	52.59
IL Com	F8V/F8V	0.962	0.85	0.82	1.20	1.20	51.86
UX Com	G2V/K1(IV)	3.642	1.02	1.20	1.00	2.50	52.25
RS CVn	F4IV/G9IV	4.798	1.41	1.44	1.99	4.00	52.48
SS Boo	G0V/K0IV	7.606	0.97	0.97	1.31	3.28	52.27
RT CrB	G2/G5-8IV	5.117	1.40	1.42	2.60	3.00	52.48
σ^2 CrB	F6V/G0V	1.140	1.12	1.14	1.22	1.21	52.10
WW Dra	G2IV/K0IV	4.630	1.36	1.34	2.12	3.90	52.43
Z Her	F4V-IV/K0IV	3.993	1.61	1.31	1.85	2.73	52.46
MM Her	G2/K0IV	7.960	1.22	1.28	1.58	2.83	52.46
V772 Her	(G0V/M1V)G5V	0.880	1.04	0.59	1.00	0.55	51.79
PW Her	F8-G2/K0IV	2.881	1.17	1.50	1.40	3.80	52.35
AW Her	G2/G8IV	8.801	1.25	1.33	2.40	3.20	52.49
CG Cyg	G9.5V/K3V	0.631	0.52	0.52	0.88	0.87	51.45
V1396 Cyg	M2V/M4Ve	3.276	0.42	0.27	0.40	0.25	51.37
ER Vul	G0V/G5V	0.698	1.10	1.05	1.07	1.07	51.99
HR 8170	F8V/wK5V	3.243	1.17	0.66	1.11	0.74	52.07
BD -00° 4234	K3Ve/K7Ve	3.757	0.69	0.55	0.55	0.45	51.83
RT Lac	G5:/G9IV	5.074	0.78	1.66	4.20	3.40	52.31
AR Lac	G2IV/K0IV	1.983	1.30	1.30	1.80	3.10	52.28
RT And	F8V/K0V	0.629	1.50	0.99	1.17	0.84	52.07
SZ Psc	F8IV/K1IV	3.966	1.28	1.62	1.50	5.10	52.46
KT Peg	G5V/K6V	6.202	0.93	0.62	0.93	0.72	52.06

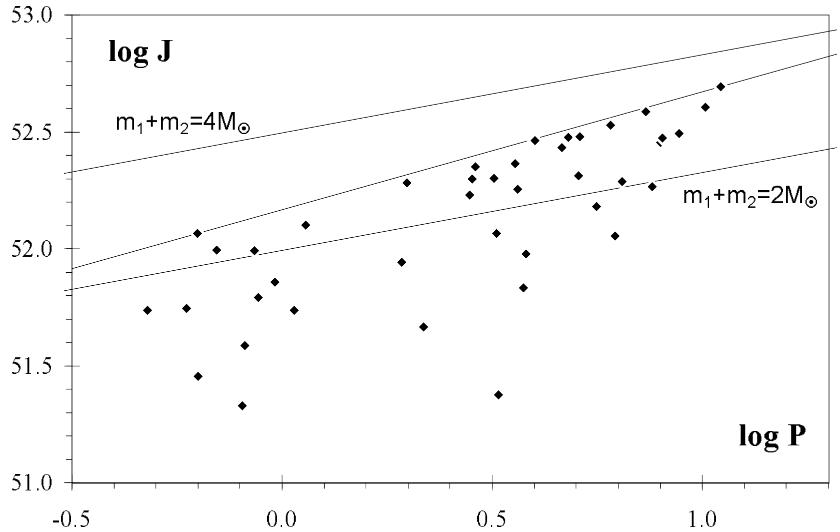

Figure 1. The orbital AM distribution of the RS CVn-type binaries listed in Table 1.

1 is expected towards lower left corner of the diagram where the contact binaries are located. An important finding is that the upper boundary of the distribution in Fig. 1 is not parallel to the constant mass lines but inclined towards lower J values for shorter orbital periods. This is clearly the indication of wind driven mass loss and decreasing angular momentum through tidal coupling of the rotational angular momentum causing eventually the binary orbit to shrink until the contact configuration is formed.

The upper boundary of the angular momentum distribution diagram in Fig. 1 can be estimated by the straight line given as

$$logJ(cgs) = (0.489 \pm 0.003)logP(d) + (52.17 \pm 0.03) \tag{2}$$

which is valid in 0.16≤logP(d)≤1.0, for the relatively short period (P≤10^d) RS CVn systems. Below the lower limit logP(d)≅0.16, the mass loss rate is much higher which drive the system shortly to form a contact binary. Beyond the upper limit logP(d)≅1.0 the systems may contain higher mass components which loss little angular momentum because dynamo generated activity should be negligible due to the absence of convective envelopes.

Consideration of the upper boundary line of the angular momentum distribution together with the constant total mass lines in Fig. 1 allows us to determine the following empirical relations

$$\frac{dP}{dt} \cong (1.51 \pm 0.91) \times 10^{-27} \frac{dM}{dt} \tag{3}$$

$$\frac{dJ}{dt} \cong (1.99 \pm 0.51) \times 10^{46} \frac{dP}{dt} \tag{4}$$

$$\frac{dJ}{dt} \cong (3.03 \pm 0.57) \times 10^{19} \frac{dM}{dt} \tag{5}$$

between the mass loss, the rate of orbital period and angular momentum changes where m, P, J and t are all expressed in cgs units.

3. Dynamical Evolution

Decreasing orbital AM through tidal coupling of the rotational AM, i.e. spin-orbit coupling, can be expressed, by taking the derivative of the orbital angular momentum J_{orb} with respect to time, as

$$\frac{dJ}{dt} = \frac{1}{3}\left(\frac{G^2}{2\pi}\right)^{\frac{1}{3}} \frac{m_1 m_2}{(m_1+m_2)^{\frac{1}{3}}} P^{-\frac{2}{3}} \frac{dP}{dt} \tag{6}$$

in terms of the orbital period decrease. The terms formed by the partial derivatives with respect to masses m_1 (and m_2) were ignored in Eq. 6 because of smallness. Substituting Eq. 5 into Eq. 6 yields a semi-empirical relation between the mass loss from the system and the orbital period decrease

$$\dot{M} = \frac{dM}{dt} \cong 0.068 \frac{m_1 m_2}{(m_1+m_2)^{\frac{1}{3}}} P^{-\frac{2}{3}} \frac{dP}{dt} \tag{7}$$

where the masses and the orbital period are expressed in solar unit and days, respectively. It is interesting to note that the combination of Eq. 3 and Eq. 7 require (within the error of empirical relations 3-5)

$$\chi = \frac{m_1 m_2}{(m_1+m_2)^{\frac{1}{3}}} P^{-\frac{2}{3}} \cong 0.41 \tag{8}$$

for each system of our sample in Table 1. Indeed, the average value of χ for the whole sample is found to be (0.40±0.23). Let us now consider the semi-empirical relation given by Eq. 7. It allows us to estimates the time needed for the period to change from an initial long period to a shorter value through AML

$$\begin{aligned} t(yr) &\cong \frac{0.068}{\dot{M}} \frac{m_1 m_2}{(m_1+m_2)^{\frac{1}{3}}} \int_{P_o}^{P_t} P^{-\frac{2}{3}} dP \\ &\cong \frac{0.204}{\dot{M}} \frac{m_1 m_2}{(m_1+m_2)^{\frac{1}{3}}} (P_o - P_t)^{\frac{1}{3}} \end{aligned} \tag{9}$$

where P_t is the instantaneous orbital period at a given age t, after to corresponding to the initial orbital period P_o. The P_t is always smaller than the P_o, i.e. $P_t \leq P_o$ for $t \geq t_o$.

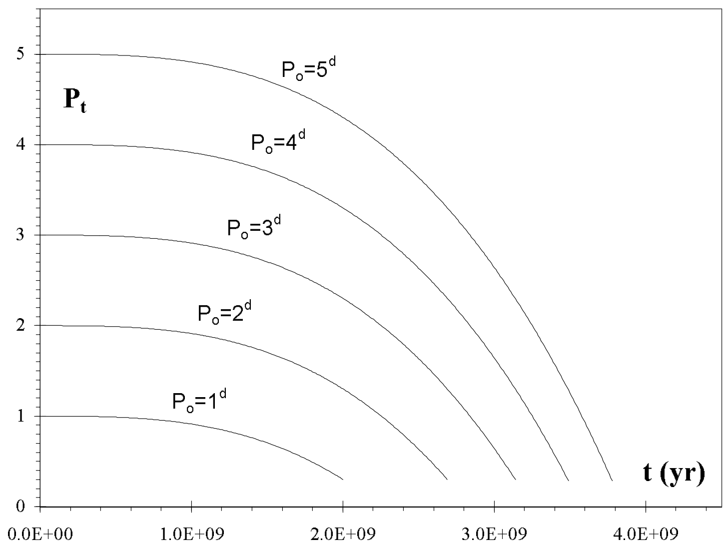

Figure 2. Dynamical evolution of the system RT And for five different assumed initial orbital periods from 1 to 5 days. The orbital period decrease is due to angular momentum loss from magnetic breaking under spin-orbit coupling

The quantity $\dot{M}$ in Eq. 9 is the mass loss (in $M_\odot$/yr unit) from the system. It is inversly proportional with time t, i.e. increased mass loss shortens the evolution time, just as expected from the theory. It is seen that by using the above expression given by Eq. 9 we can calculate the time needed for a short period ($P \leq 10^d$) RS CVn-type binary of a certain mass and initial period to reach a certain shrinked orbit. The orbital size a, at any time t after t_o can also be estimated by using the relation between P and a through the Kepler's law.

As an example, we have estimated the orbital period evolution of the system RT And for five different assumed initial periods P_o from 1^d to 5^d. We assumed the components of RT And system have masses of m_1=1.5 $M_\odot$ and m_2=1.0 $M_\odot$, and the wind driven mass loss from the system $\dot{M} \simeq 1\times10^{-10}$ $M_\odot$/yr. The resulting period evolution of the system is shown in Fig. 2 for five different assumed initial periods. As seen in the figure, the dynamical evolution of a short period RS CVn-type binary depends strongly on $\dot{M}$ and P_o.

4. Conclusion

From this study it appears that the orbital AM distribution of the relatively short period ($P \leq 10^d$) RS CVn-type binaries with respect to their orbital period can be interpreted as the AM evolution of these systems. The empirical relations derived from the diagram of AM distribution serve as important tools in exploring the dynamical evolution of the RS CVn-type systems resulting from the AML with the existence of spin-orbit coupling. The RS CVn-type systems having initial periods $P_o \geq 10^d$ may not experience spin-orbit coupling since the tidal effects become small due to their relatively large seperation. Moreover, it is well established that the longer period systems accomodate larger more massive stars [9, 10] which are expected to lose little AM if the dynamo gererated activity is negligible as a result of shellow convective envelopes. Thus, the dynamical evolution of these systems would be very slow untill the more massive star evolves off the main sequence and ultimately fill its Roche lobe. The more massive star of a short period system may also fill its Roche lobe while the system evolving towards shorter period under the wind deriven mass loss and spin-orbit coupling mechanism. When the Roche lobe overflow and the transfer of this mass to the other component starts then the control in dynamical evolution is dominated by the mass transfer process. This is evident in the complicated period variations of the Algol-type binaries [12].

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