VII. THE RS CANUM VENATICORUM STARS

PERIOD CHANGES AND MASS LOSS RATES IN 34 RS CVn-TYPE BINARIES

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We have collected all available times of minimum, over 1650, for 23 regular, 7 short-period, and 4 long-period eclipsing RS CVn binaries using the card catalogues at the Sternberg Astronomical Institute and the Krakow Astronomical Observatory, as well as unpublished data. We examined them critically, discarded those grossly in error, and assigned weights. For AD Cap, RV Lib, and ϵ UMi there are virtually no data. For the remaining 31 we determined quadratic ephemerides by weighted least squares. Values of dlnP/dt are given in the Table with their errors. Roughly 2/3 are variable at greater than the 2σ level. Significant decreases outnumber significant increases by almost 2:1. We show that light curve asymmetry produced by the distortion wave probably accounts for the relatively small, rapid fluctuations in the O-C curve but not the long-term period changes.

In our model one star, usually the cooler and more evolved one, has a convectively driven wind which corotates with the star (and with the system, since rotation is synchronous) out to the Alfven radius R_A. Because the well-defined long-lived photometric wave in most RS CVn systems indicates strong longitudinally asymmetric spot activity, we allow for possible anisotropy in the wind, stronger from the unspotted hemisphere, which should be a large coronal hole. The equation is

$$\frac{d\ln P}{dt} = 3\left[\frac{U}{V} f \sin\theta(\mathrm{min}) - 2\frac{M_c}{M} + 3\frac{M}{M_h}\left(\frac{R_A}{a}\right)^2\right]\frac{d\ln M_c}{dt}, \qquad (1)$$

where M is mass, subscript c refers to the cooler mass-losing star, U is wind velocity, f is a geometrical factor about $4/\pi^2$, θ(min) is phase of wave minimum, V is relative orbital velocity, and a is orbi-

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Table. Derived Rates of Mass Loss From the Active Star.

Name	dlnP/dt (yr^{-1})	minimum B (Gauss) n=3	minimum B (Gauss) n=2	$\dot{M}$ ($M_\odot$ yr^{-1}) minimum	$\dot{M}$ ($M_\odot$ yr^{-1}) maximum	$\dot{M}_{th}$ ($M_\odot$ yr^{-1})
RT And	-1.17±0.06(-7)	526	243	2.1(-9)	2.6(-9)	3.1(-8)
CQ Aur	+2.45±0.42(-6)					
SS Boo	+2.16±1.38(-7)	0	0	8.2(-8)	3.7(-7)	5.5(-8)
SS Cam	+2.07±1.72(-7)	0	0	4.1(-7)	4.5(-6)	2.1(-6)
SV Cam	+1.58±0.64(-8)	0	0	1.3(-8)	3.1(-8)	1.0(-8)
RU Cnc	-2.09±0.80(-7)	111	40	4.8(-11)	2.4(-10)	2.1(-8)
RZ Cnc	-2.39±2.06(-7)	8	5	3.2(-13)	6.0(-11)	9.2(-6)
WY Cnc	-1.74±2.50(-8)	0	0	0	1.7(-8)	4.5(-8)
RS CVn	-3.17±0.48(-7)	156	68	4.3(-10)	7.8(-10)	3.4(-7)
UX Com	-2.06±0.96(-6)	579	220	1.4(-8)	1.1(-7)	1.1(-7)
RT CrB	+5.61±3.85(-7)					
CG Cyg	-6.53±1.49(-8)	1118	325	1.4(-9)	3.7(-9)	1.9(-8)
WW Dra	-1.70±0.55(-7)	106	48	9.2(-11)	3.6(-10)	3.2(-7)
RZ Eri	+4.48±4.01(-7)	0	0	1.1(-7)	2.0(-6)	3.4(-7)
Z Her	-2.84±1.59(-8)	71	25	2.3(-12)	3.0(-11)	1.1(-7)
AW Her	-0.70±1.27(-6)					
MM Her	-1.40±2.03(-7)	0	0	0	5.9(-9)	1.6(-7)
PW Her	-4.92±6.70(-7)					
GK Hya	-2.28±1.27(-7)					
RT Lac	+2.89±0.32(-7)	0	0	5.9(-7)	7.3(-7)	4.4(-7)
AR Lac	-2.58±0.22(-7)	165	93	7.0(-10)	9.9(-10)	2.1(-7)
VV Mon	-2.23±0.54(-6)	156	91	4.8(-9)	1.3(-8)	5.2(-7)
AR Mon	-1.98±1.49(-6)	44	22	1.0(-10)	5.2(-9)	5.9(-6)
LX Per	+1.13±1.05(-6)	0	0	1.1(-7)	3.0(-6)	2.0(-7)
SZ Psc	-5.25±0.33(-6)	252	173	6.1(-8)	7.8(-8)	1.1(-6)
UV Psc	+1.46±0.42(-7)					
TY Pyx	+1.71±3.00(-7)	0	0	0	3.2(-7)	9.0(-8)
RW UMa	-2.65±0.75(-7)	245	79	4.4(-10)	1.4(-9)	3.5(-7)
XY UMa	+8.82±3.09(-8)	0	0	1.3(-7)	2.6(-7)	2.7(-8)
RS UMi	+1.46±2.96(-6)					
ER Vul	-2.47±0.92(-7)	723	295	3.6(-9)	1.8(-8)	2.7(-8)

tal semi major axis. R_A is given by

$$R_A/R_c = (B/\Omega)^{1/n}(U/\dot{M}_c)^{1/2n} , \quad (2)$$

where B is the surface magnetic field, Ω is rotational (= orbital) frequency, n = 2 for a monopole field, and n = 3 for a dipole field. The first term in Equation (1) can produce a rocket effect, period changes in either direction depending on the value of θ(min). The last two give the long-term period change, which can be positive or negative depending on the size of R_A.

For a given value of B, dlnP/dt in Equation (1) has an absolute minimum at a certain value of $\dot{M}_c$. Therefore we derive minimum values of B required to produce the observed long-term period decreases and give them in the Table. Stars with blanks had no available absolute dimensions.

Also in the Table are $\dot{M}_c$ values derived with Equation (1) from the long-term period decreases by assuming n = 2, B = 1000 Gauss, U equal to the escape velocity from the cooler star, and from the long-term period increases by assuming $R_A = R_c$. They are from 10(-6) to 10(-11) $M_\odot$/yr, with individual values uncertain by typically an order of magnitude. The 10(-9) $M_\odot$/yr which we expect from evolutionary considerations is in good accord. Actually, since mass loss occurs over a fraction α of the cooler star's surface, R_A in Equation (1) should be replaced by $R_A \alpha \exp(1/2n)$, a change which would increase the values of $\dot{M}_c$ in the Table by a factor of $\sim$ 2. Also $\dot{M}_c$ would be larger if n = 3 but would be smaller if U is greater than the escape velocity or if B > 1000 Gauss. The cooler star's thermal mass loss rate $\dot{M}_{th}$ is given in the last column of the Table. In most cases, if we consider the errors $\dot{M}_c$ is less than 1% of $\dot{M}_{th}$. Only in SZ Psc and the four short-period systems RT And, SV Cam, CG Cyg, and XY UMa is it comparable. The long-term increase for RT Lac might be produced by Algol-type mass transfer from the other (less massive) star, which fills its Roche lobe.

For SS Cam, SV Cam, RS CVn, CG Cyg, RT Lac, and AR Lac, which apparently show period changes in both directions, we consider nine possible explanations. Three which proved quantitatively unreasonable were supposing (1) that B varies between $\sim$0 and $\sim$1000 Gauss, perhaps during the course of a magnetic spot cycle, (2) that the limb of the star is deformed by its spot group, and (3) that Algol-type mass transfer is occurring. All six systems cannot be explained by any single mechanism. In some we cannot rule out or confirm apsidal motion (SS Cam) or a third body (SV Cam). Deciding between the rocket effect and light curve asymmetry is difficult because of the ironic and unfortunate coincidence that both lead to effects in the O-C curve which are identical in phasing and the maximum expected size is often comparable for both and comparable to the observed effect. Nevertheless we can conclude that not one of the six shows convincing evidence that the rocket effect is making the dominant contribution to the alternating excursions seen in their O-C curves.

The full version of this study, including tabulation of the times of minimum and plots of the O-C curves, will be published in Acta Astronomica.

DISCUSSION FOLLOWING HALL, KREINER AND SHORE

Naftilan: In your model for the period changes, how does the mass ratio affect the rate of change; and in particular would we expect RT Lac, which has a mass ratio considerably different from the other systems listed to have a greater period change rate?

Hall: The equation describing period change for conservative mass transfer would be very sensitive to mass ratio , specifically, near unit mass ratio (typical of inert RS CVns) would produce no period change. An equation for mass loss, however, is not sensitive to mass ratio. The size of the corotating Alfven radius is the controlling factor.

Stencel: In the interest of expanding the data base on RS CVn's, I am pleased to announce that on the basis of moderate and high dispersion spectra obtained at CTIO, the stars HD 39937, 101379, 155555 and 174459 are probable southern RS CVn systems. HD 155555 is also an X-ray source. Southern observers should be advised that these and fifty other southern candidates deserving observations will soon be available in a published list (Weiler and Stencel, 1979 Astron. J., in press).

van 't Veet: For the same system the sign of the period change may change on a short time scale. Do you explain this by a rapid change of the Alfven radius?

Hall: A variable Alfven radius was one mechanism we explored to explain the supposed period changes of alternating algebraic sign. It proved not to be a satisfactory explanation basically because, for very small values of R_A, the coefficient connecting dlnP/dt with dlnMc/dt always remains very small and the $\dot{M}$ required must be very large . Other mechanisms must be responsible, one of which is light curve distortion.

Walter: You stated that your computations of mass loss rate were consistent with that required to explain the X-ray emission. Our estimate of $\dot{M}$ was for a simple model assuming supersonic outflow with the X-ray emission arising in the flow. This is probably not the case. The X-rays most likely arise from solar-like magnetic flux tubes, which confine the hot gas. We do not require any mass loss. The mass would be lost from regions with open field lines, i.e., coronal holes. It may be possible to constrain $\dot{M}$ from measurements of the soft X-ray absorption, but this has yet to be done.

Dupree: Is there any spectroscopic evidence for mass loss in RS CVn systems?

Hall: The observations of asymmetries in Hα and velocity variations in MgII h and k indicate mass flows, albeit at lower than the escape velocity. The lines, however, are not formed that far out and one has no progressions to use for $v_{rad}(r)$.

COMMENT BY POPPER (Chairman of the Session) PRECEDING THE NEXT PAPER BY SHORE AND HALL

Popper: The next talk is a general topic concerning RS CVn systems. I wish to take advantage of this opportunity to make a general comment about them. A few months ago I received a call from a scientist at the Jet Propulsion Laboratory working in X-ray astronomy. For 30 minutes, we discussed whether σ CrB is a RS CVn system or not.

Why not a simple "yes" or "no"? The star is a double-lined spectroscopic binary with H and K emission in both components, late F or early G, period between one and two days. Furthermore it is an X-ray and radio source. What more does it take for a system to be clearly an RS CVn? σ CrB has a pretty good parallax showing that the two components are main-sequence stars, close to the zero-age main sequence. Most of us tend to consider that bona fide RS CVn are evolved, with at least one component a G or early K subgiant. Systems now being referred to as "RS CVn" include a wide variety in which a number of interrelated phenomena occur in various combinations. A class of systems should probably have common evolutionary status. Perhaps we should be referring to RS CVn phenomena rather than RS CVn systems.

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