A STARSPOT MODEL FOR THE RS CVn STARS

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We employ a simplified dynamo model to describe the long term photometric spectroscopic behavior of the RS CVn stars. The essential feature of the model is that the stars are in nearly synchronous rotation, with the differential rotation slower and the rotational velocity higher than for a single evolved 1 to 2 solar mass star. The spot groups are formed by eruption of enhanced toroidal fields, which have areas at the photosphere of several tenths of the surface area; the sizes of these regions are shear limited. Estimates of the lifetimes of active regions and of flare energetics are presented. The RS CVn phenomenon is then related to both the evolutionary status and the orbital parameters of the binary system.

In order to model the dark wave behaviour of the RS CVn stars, we shall assume a simplified kinematic dynamo, of the type described by Babcock (1961). Although this is only a crude approximation of the complex physical processes which lead to regeneration of magnetic fields and appearance of spots on the solar surface, we feel that the observational evidence for starspot activity is not sufficiently complete to warrant a more comprehensive treatment at the present time. We hope that results of "preserving the appearances" by the Babcock dynamo model will serve as guides to more complete developments.

With the rather short orbital periods, near unit mass ratios, and lack of large scale mass transfer between components, we expect synchronous rotation of the component stars in the RS CVn systems. Tidal locking might be sufficient to insure that the less evolved component (F or G, V or IV) is nearly rigidly rotating, but the more evolved component (G or K, IV or III) has a deep convective envelope and it seems some residual differential rotation is preserved despite the effects of tidal coupling. We assume this is described by a rotation law of the form

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$$\Delta\Omega = -\alpha \sin^2 \beta, \qquad (1)$$

where β is stellar latitude, Ω is the rotational frequency, and α is the differential rotation rate.

A toroidal field is produced by wrapping of frozen-in poloidal field lines due to the differential rotation of the stellar photosphere. This poloidal to toroidal conversion is give by $B_\lambda/B_\beta = \cos\beta\,(d\lambda/d\beta)$, where B_β and B_λ are the poloidal and toroidal field components, respectively, β is stellar latitude, and λ is stellar longitude.

The build-up time Δt_* at a given latitude is then given by

$$\alpha\ \Delta t_*\ \sin 2\beta\ \cos\beta = (B_\lambda/B_\beta)_c \qquad (2)$$

and $(B_\lambda/B_\beta)_c \approx 3$ (Babcock 1961).

The latitude at which starspots first appear is that for which Δt_* is a minimum. For a generalized rotation law $\Delta\Omega = -\alpha \sin^n \beta$, where $n \geq 1$, this latitude is given by

$$\beta_*^o = \sin^{-1} \left(\frac{n-1}{n+1}\right)^{1/2} . \qquad (3)$$

For the case $n = 2$, which we are assuming here for spotted stars in RS CVn systems, this yields $\beta_*^o = \pm 35\overset{\circ}{.}3$ for an equatorially symmetric dipolar initial field. (see e.g. Eaton and Hall 1979). This is the highest latitude at which spots will occur. The suggestion (Oskanyan et al. 1977) that spots appear at very high latitudes in some By Dra stars may be an indication that for those stars $n > 2$.

The value of α for an RS CVn star can be found from the observed migration curve. As the spot cycle progresses, the activity drifts towards the equator and the wave rotation frequency Ω increases. At the beginning of a spot cycle, the spots are at $\beta_*^o \approx 35^\circ$ and the wave's rotational frequency is minimal; at the end of a cycle the spots are very near the equator, and the wave's frequency is at its maximum. Since the wave's frequency Ω is given by $\Omega = 2\pi/P_{orb} + 2\pi/P_{migr}$, a direct application of the rotation law gives

$$\alpha = -\ (\Omega^o - \Omega^1)/(\sin^2 \beta_*^o - \sin^2 \beta_*^1) \approx 19/P_{mig}\ \mathrm{rad\ yr}^{-1}.$$

For the case of the prototype RS CVn, where $P^o_{migr} = 12$ yr and $P^1_{migr} =$ 8 yr (Hall 1972), $\alpha = 0\overset{\circ}{.}13\ \mathrm{day}^{-1}$, which is smaller than the solar case, as we anticipated above.

Once α is known, the build-up time Δt_*^o for the toroidal field at the latitude of first appearance, which corresponds to a dead time in the cycle of starspot activity, can be computed from eq. (2).

A toroidal field trapped at the base of the stellar convection zone will become unstable to buoyant eruption should it come into pressure equilibrium with the surrounding medium. The maximum field which the dynamo may produce by simple field wrapping is $B_\phi^2 \approx 16\pi\Omega v_c \ell$ where v_c is the convective velocity, Ω is the rotational frequency and ℓ is the length scale. This may be compared with the equilibrium field $B_\phi^2 \approx 8\pi P_{G,BCZ}$ where $P_{G,BCZ}$ is the pressure at the base of the convective zone. For the typical parameter of an RS CVn star, we expect that the field will be strong. We can now crudely estimate the appearance of the starspot region which these flux tubes will generate at the photosphere as follows. Assuming that the tube has a characteristic cross section size of a pressure scale height, H_p, at the base of the convection zone we take the depth of the spot region to be also H_p at the photosphere. If the tube conserves flux and adiabatically expands during its ascent, its area should increase in order to maintain local pressure equilibrium giving for the area of the photospheric active region,

$$A_{RS} \approx \left(\frac{P_{G,1}}{P_{G,\odot}}\right)^{-1/2} \left(\frac{P_{G,BCZ}}{P_{G,BCZ\odot}}\right)^{1/2} \left(\frac{H_{p,BCZ}}{H_{p,\odot}}\right)^{2} A_\odot \approx \left(\frac{P_{G,1}}{P_{G,\odot}}\right)^{-1/2}$$

$$\left(\frac{T_{BC}}{T_\odot}\right)^{2} \left(\frac{g}{g_\odot}\right)^{-2} A_\odot$$

scaled to the solar values. This is typically $\approx 10^4 A_\odot$, of the order of magnitude required for the standard models of RS CVn systems (e.g. Hall 1976). In the solar case, the sizes of active regions are limited by internal processes, such as the decay of a given large spot or flaring. Shearing will be, however, the mechanism of destruction in the RS CVn systems, due to the enormous size of the active region. If we compare the area, we find that

$$A_{shear} \approx \left(\frac{\Omega}{\alpha}\right)^2 \lesssim A_{RS}$$

so that the stability of a region is on the timescale of the differential rotation. If there is one major region on the surface, then the depth of the dark wave should decrease with time, as the activity site is sheared and diffuses more uniformly over the photosphere, so that we expect that the magnitude of the dark wave should vary as A^{-1}, with the decay time being $\tau_S \propto \frac{2\pi}{\alpha \sin\beta}$.

We have used these values to fit an extremely simple starspot cycle to the observations of Haslag (1977 MSc Thesis, Vanderbilt) for RT Lac, shown in figure 1. The agreement for the rise time and decay time is reasonable, but it is clear that more than one active region is responsible for the dark wave.

The ratio of rise to decay time for a typical RS CVn spot cycle should be smaller than the solar case, $\Delta t_*^o/\tau_s \lesssim 0.3$, while for the sun, it is of order 1. Since the fraction of inactive stars is $\lesssim \Delta t_*^o/\tau_s$, we expect 1 or 2 non x-ray stars in the current sample. Z Her may be one star like this.

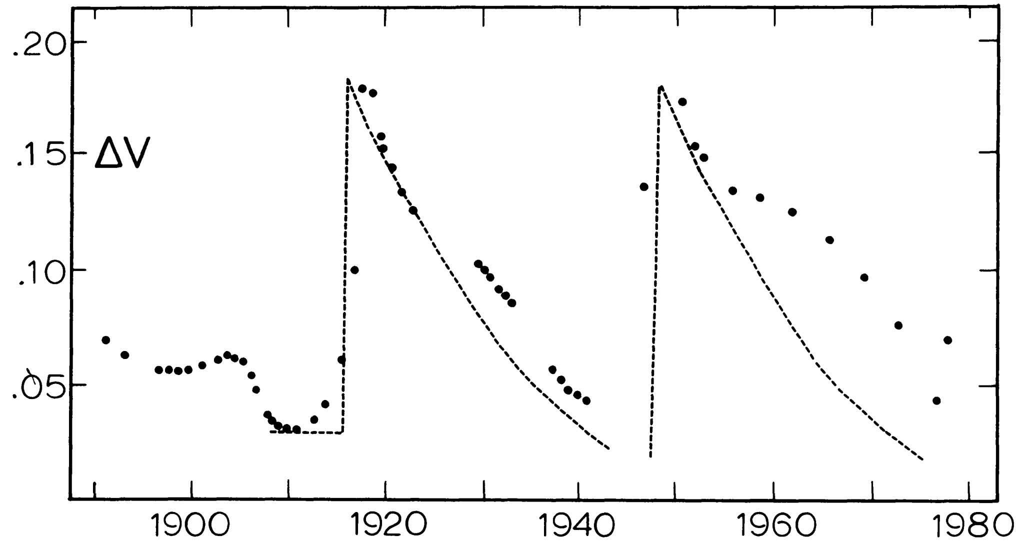

Figure 1. The wave amplitude in RT Lac (Haslag 1977). The dashed line is the theoretical light curve, in magnitudes, for a single active region $A^o_{RS} = 0.21$ being sheared out by differential rotation. Dilution by the secondary is assumed from light curve synthesis.

The individual active regions may consist of numerous aglomerated pores, as discussed in Meyer, et al. (1974) with characteristic sizes H_p. To attain the requisite areas, some 10^4 to 10^5 separate pores are needed. This implies stable dark waves and continuous flaring, in addition to strong and steady x-ray emission. Perhaps coincidentally, this is the order of magnitude of coronal loops required by Walter et al. (this volume) to explain the observed x-ray emission.

The longevity of an individual spot within an active region is limited by turbulent dissipation processes, and consequently the lifetime is approximately $\tau \sim \ell^2 \eta_T^{-1}$ where η is the turbulent diffusion coefficient and ℓ is the characteristic length within the spot. Taking $\ell^2 \sim A$, and scaling the convective velocities, we obtain a timescale of several years for an individual spot, which should be the shortest timescale for the variation of the shape of the dark wave in these systems. Observations of UX Ari (Hall, et al. 1977), λ and (Bopp 1978; Guinan 1979, private communication) and RS CVn (Luddington 1978, private communication) agree with this expectation. The overall amplitude of the wave is variable on the shearing timescale, while the shape of the wave, which is generally a saw-tooth, changes on the turbulent timescale.

Scharlemann (1979) has suggested a model in which the spots appear like floating, highly opaque but geometrically thin disks which are mobile in the presence of photosperic circulation currents. These floaters are assumed to cool the ambient photosphere setting up thermal convection currents which drag the spots together. If the wavelength of the disturbance tends to infinite length (vanishing wavenumber), then agglomeration occurs. The velocity of these floaters as estimated from the rise time for the spot cycle (typically of order $\sim$ 3 to 5 years) is $v_{floater} \approx 0.1$ km s^{-1}. This is the same order of magnitude expected for thermally driven currents for a spot group with temperature deficit ΔT, $\upsilon_{Th} \sim 0.1\ (\Delta T)^{1/3}$ km s^{-1}, evaluated using the atmospheric parameters in Kurucz (1979) for a (5500,3.0) star. The group will not be stable since meridional circulation driven by rotation should disperse its members. In addition, there are problems with the shape of the wave, which should be a sawtooth with a sharp leading edge, due to these currents, while the observed waves tend to be mirror images of this. It is an attractive model, with the analog of ice cubes in a very large martini glass being an inducement for experimentation.

The magnetic energy available for the generation of relativistic particles, assuming complete annihilation of the fields and direct conversion, is approximately the total magnetic energy contained within the active region, which is

$$\varepsilon_{RS}/\varepsilon_{\odot} = (B_{RS}/B_{\odot})^2\ (A_{RS}/A_{\odot})\ (g_{RS}/g_{\odot})^{-1} \approx 10^4 .$$

Here we have taken the characteristic depth of the active region to be the pressure scale height, which is about ten times that in the sun. The total number of particles accelerated in reconnection by complete, efficient conversion scales as:

$$N_{rel} \sim B_s^2\ A\ \ell_a^{-2}\ \sigma^{-1},$$

where σ is the conductivity and ℓ_a is a scale length for field annihilation. This is assumed to be a function of the area of the active region only.

We have assumed a complex structure for the active region, not a <u>single</u> spot. While this is a difficult point to test observationally in these systems, the largest spot regions observed on the sun are usually highly complex, being composed of many smaller activity centers which vary in size and number on timescales shorter than the lifetime of the region as a whole. We use this analog to provide some estimate of the annihilation length ℓ_a. If we assume that the spot region is densely populated and that the scale height is larger than in the solar case, it is possible that ℓ_a is smaller for RS CVn stars than the sun. Close packing of spots creates flux tubes in the active regions so that assuming $\ell_a \sim A^{-1/2}$, we obtain $N_{rel} \sim A^2$.

The total energy emitted in flares, which is related to N_{rel}, may be as high as 10^7 times the solar case. Hence flaring activity in the RS CVn stars should be much more pronounced than in the sun. The use of the flux tube picture appears to be supported by the high coherence and circular polarization of the observed radio events.

Alternatively, the solar data is consistent with the view that the number of spots increases with the total area of the spot group. If N_{rel} is proportional to the number of annihilations, and the RS CVn flares are composed, in fact, of many subflares (as appears to be the case e.g. HR 1009) then $N_{rel} \sim A^2$ even if $\ell_a \sim \ell_{a,\odot}$.

As an additional astrophysically interesting point concerning the RS CVn and related stars, we note that if these stars contribute substantially to the background diffuse x-ray emission literature, they may also contribute to the background of low energy cosmic rays. The implication of this suggestion for the synthesis of the light elements, is that since the RS CVn stage in a close binary system happens only in low mass, close binaries, the contribution to the cosmic ray background is not prompt . That is, there is a delay of $\gtrsim 10^9$ years for this stage to occur after star formation, so that the rise in the low energy cosmic ray flux will not be immediate upon the formation of these stars, but will only have occurred "recently" in the evolution of the galaxy. The low energy flux might show a steep rise after $\sim 10^9$ years, remaining roughly constant thereafter, so that the abundances of Li, Be and B might have been frozen in relatively recently, and might differ substantially from the primordial values.

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REFERENCES

Babcock, H. W. (1961), Astrophys. J., 133, 572.
Bopp, B. (1978), IAU Comm. 42 Working Group Meeting, Socorro.
Eaton, J. and Hall, D. (1979), Astrophys. J. 227, 907
Hall, D.S. (1976), in Multiply Periodic Phenomena in Variable Stars. IAU Colloq. 29, Pt. 1 (ed. W.S. Fitch) Reidel, Dordrecht.
Hall, D.S., Montle, R. and Atkins, H. (1975), Acta Astron. 25, 125.
Hall, D.S. (1972), Publ. Astr. Soc. Pac., 84, 323.
Kurucz, R. (1979), Astrophys. J. Suppl, 40, 1.
Meyer, F., Schmidt, H., Weiss, N. and Wilson, P. (1974), MNRAS. 169, 35.
Oskanyan, V., Evans, D., Lacy, C. and McMillan, R. (1977), Astrophys. J. 214, 430.

DISCUSSION FOLLOWING SHORE AND HALL

Webbink: The evolutionary state of the RS CVn stars seems now well-defined as corresponding to binaries with nearly equal mass components in which the primary is now creeping up to the onset of rapid mass transfer. In the context of a dynamo model for the many peculiarities of these systems, it is not immediately obvious why their descendant binaries, namely those of Algol type, should not also show the same phenomena. Given that the Algol systems are much more dominated by the unevolved component, what evidence can be brought to bear concerning the existence or extent of the RS CVn phenomenon among them?

Shore: Yes, the progeny of the RS CVn stars will and probably do show evidence for surface activity. Gibson has made the point that the Algol radio events bear a striking resemblence to RS CVn flares. These stars are X-ray sources (at least β Per itself). However, you would not be able to observe the surface activity optically except perhaps H and K emission, which may be due to the stream. In the high energy phenomena, of course, we remove this obscuration and see the activity aright. A good analog is probably RT Lac.

Feldman: Rather than produce weak, infrequent radio flaring as you suggest it might, SZ Psc is perhaps the most radioactive RS CVn. (It is certainly in the same class as HR 1099, UX Ari, and RT Lac in this respect.) Moreover, Bopp (Univ. of Toledo) has found that it is similarly very active in Hα; he knows of no other RS CVn system that is more active.

Shore: It is true that pressure arguments give weak magnetic fields for this star. There is another possibility here. The fields which can be built up by equilibrium of Lorentz and Coriolis forces are quite large and almost certainly exceed the local pressure in the nearly semidetached systems. Therefore bouyancy will bring flux tubes quickly to the surface even as the dynamo operates at the base of the convection zone. What causes the problem I suggested is the straightforward interpretation of the pressure condition.

Fraquelli: I agree with Feldman's comment. I have several plates of SZ Psc obtained at DDO, which show highly variable H-alpha profiles. During Jakate's observations in October 1978, I obtained several spectra. At the same phase, one orbital cycle apart, there are drastic changes in the Hα profile. Not only is the emission variable, but whatever is going on in the system can happen on short time scales as well.

Shore: This system also shows one of the largest period changes of a secular nature, and my reply to Feldman should be added here as well. It would be very interesting, considering your comments, to check systems like SS Cam to see whether it too is as haywire a binary as SZ Psc.

Walter: As Walter et al. have pointed out in a paper submitted to Ap. J. Lett., the coronal surface fluxes in single stars with active chromospheres and in the weaker RS CVn systems are nearly identical. However, the most active RS CVn's show an order of magnitude more coronal activity. This shows that there may be something fundamentally different with these more active systems, although the basic mechanisms appear solar in nature.

Shore: I completely agree, and it is that these stars are in binaries, where a helper exists to keep the stellar photosphere well behaved. The energy sources for producing a hot corona are enhanced by the number of stable loops existing in the active regions of these stars compared with field differential rotators. However, I also agree that physical laws are covariant from solar physics to binary star papers.

Budding: Could you point out any special significance to be attached to the correlation of activity of the cool component to its passage across the Herzsprung Gap?

Shore: It is at this stage that the stellar envelope structure builds up sufficiently active convection at great enough depth to form flux ropes of the type required. In addition, field stars must be different from these binaries, which are nearly synchronous at this stage. The stage is of importance, but so is the fact that these stars are easily found.