Multiple Periodic Variable Stars
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THE RS CVn BINARIES AND BINARIES WITH SIMILAR PROPERTIES

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I. Introduction

This paper will review reasonably thoroughly and comprehensively the many observational properties of the remarkable RS CVn-type binaries. In addition this paper will show that many of these same properties are observed in other types of binary systems.

One difficulty in discussing the RS CVn binaries has been that the characteristics required for membership in the group have never been agreed upon. Therefore this matter is discussed in Section II and a working definition proposed: binaries with orbital periods between 1 day and 2 weeks, with the hotter component F-G V-IV, and with strong H and K emission seen in the spectrum outside eclipse. The remainder of Section II will review the many observed properties and physical characteristics of the RS CVn binaries. See Table 1. Periodicities and interrelationships among properties will be described. It is easy to see how much has been learned in the last seven years. The last time RS CVn was discussed in Budapest, the title of the Colloquium was "Non-Periodic Phenomena in Variable Stars". Now RS CVn is being discussed again in Budapest, but the title of the Colloquium is "Multiply Periodic Phenomena in Variable Stars".

Section III will treat related types of binaries. First are binaries with orbital periods longer than 2 weeks in which one component is of spectral class G-K IV-II and displays strong H and K emission. See Table 2. This group will be referred to as the long-period group. Second are the non-contact binaries with periods less than 1 day in which the hotter component is F-G V-IV and H and K emission is displayed in one or both components. See Table 3. This group will be referred to as the short-period group. Third are binaries consisting of dwarf K or dwarf M stars which display H and K emission. This group will be referred to as the flare star group. Fourth is the unique binary V471 Tau = BD +16°516. And fifth are W UMa binaries for which there is photometric evidence of uneven surface brightness on one component. This group will be referred to as the W UMa group.

I have tried to make my list of RS CVn binaries complete and the data in Table 1 up-to-date as of mid-1975. The same cannot be said for the other groups and the data in their respective tables. Locating the available information for the RS CVn binaries was difficult because much of it can be found only in observatory reports, unpublished theses, and private communications. Tables 1, 2, and 3 contain only one value for each quantity, but a reference to its source is given. The value chosen is the one I considered best, but the reference in most cases enables the reader to reconsider my decision.

In cases where more than one interpretation is possible, more time is spent discussing the one I consider most reasonable. In general, however, reference is made to alternate interpretations which merit consideration.

II. THE RS CVn BINARIES

A. Introduction

A complete, up-to-date list of proposed condidates for this group has not been published. The latest is that of Popper (1970). The unpublished thesis of Oliver (1974a), besides presenting many new results and important conclusions and a more up-to-date list of members, contains a good review of the older literature and provides the key to many unpublished results. Thus it was useful as a starting point for this review.

B. Historical Development of the Definition of the Group

From an historical point of view the definition of the group has proceeded as follows. Struve (1946) was probably the first to call attention to the existence of the group. He discussed 5 binaries with H and K (but not Balmer) emission lines which were visible outside eclipse, arose from a late G or early K component, seemed to reflect the orbital motion of that component, and were much stronger than would be expected in typical single stars of the same spectral class. Hiltner (1947) listed 13 binaries which he felt belonged to such a group. Gratton (1950) discussed a group of 19 late-type H and K emission binaries which included Hiltner's 13. The other 6 were generally longer in orbital period, more luminous, and not eclipsing variables. In a study of the absolute dimensions of eclipsing binaries Plavec and Grygar (1965) concluded that one group stood apart from the rest of the Algol-type binaries. Both components were late-type, the mass ratio was around unity, and the binary seemed to be detached. Included

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were RS CVn, WW Dra, Z Her, AR Lac, and SZ Psc. In his discussion of mass and radius determinations in eclipsing binaries Popper (1970, Table 2) presents a list of 22 eclipsing binaries which represents the most comprehensive list of possible candidates for the group published to date. Here he mentions the H and K emission, the curious fact that the component responsible for the emission usually is around K0 IV, the tendency for the mass ratio to be near unity, and the intrinsic variability in one or both components. Preliminary reports by Oliver (1971, 1973) drew further attention to the existence of this group and provided a more complete list of the remarkable properties. The unpublished thesis of Montle (1973) considered adding RT And, KO Aql, RZ Cnc, ER Vul, and the spectroscopic binaries HD 21242 = UX Ari and HD 209813 = HK Lac to the list of Popper. Oliver (1974a) bases his comprehensive study on the 22 binaries in Popper's list plus RT CrB and GK Hya.

C. A Proposed Working Definition for an RS CVn Binary

Oliver (1974a, p. 262) was the first to propose formally a set of observational characteristics to define the group. But this approach is not entirely satisfactory because, as he pointed out, some of his defining characteristics need not be present in all binaries. Therefore I want to consider this question of definition anew.

I think it is necessary to consider orbital period. One reason is the similarity between the long-period group (Herbst 1973) and the RS CVn group, which was first pointed out by Gratton (1950). Despite the obvious similarities, it is not yet known how the two groups are related to each other. Therefore, in case they are fundamentally different, it is safer to make a distinction; but, in case they are fun-

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damentally related, we should not forget the similarities. It turns out convenient (and perhaps significant) to take advantage of the absence of suspected candidates in either group with orbital periods in the range 11 to 17 days. In addition quite a few RS CVn-type properties occur in several short-period binaries (RT And, SV Cam, CG Cyg, and ER Vul) not generally considered members of the RS CVn group. This made me realize that the RS CVn group might need definition at the short-period end also. Since Oliver (1974a, p. 262) expressed the same concern for different reasons, I was encouraged to follow his tentative suggestion that systems with orbital periods less than 1 day be excluded from the RS CVn group. This takes advantage of the absence of suspected candidates in the range $0^d.9$ to $1^d.9$. Thus I propose that the RS CVn group contain binaries only in the orbital period range 1 day to 2 weeks.

The next step is to compile a list of RS CVn binaries, starting with the 24 systems considered by Oliver (1974a, Table 1). The orbital period criterion eliminates RZ Eri, WY Cnc, and UV Psc. Then there are 3 additional binaries which should be added: UX Com (Popper 1974), HD 21242 = UX Ari (Evans and Hall 1974), and HD 118216 (Conti 1967). The last two are not eclipsing variables. Now we have a list of 24 binaries which I propose as members of the RS CVn group. These are listed in Table 1 along with a summary of their various observational and physical properties.

At this point I think the best strategy is to examine these 24 binaries and note which characteristics are exhibited by all 24. This should give us a reasonably restrictive working definition for an RS CVn binary which should be useful in the search for additional members. Thus the proposed definition is as follows: The orbital period is in the range 1 day to 2 weeks, the hotter component is of spectral type F or G and luminosity class V or IV, and strong H and K emission is seen outside eclipse. The term "strong" here means stronger than the normal Wilson-Bappu emission observed in the H and K reversal in single stars. It is interesting to note that this definition automatically excludes the three other related groups: the flare star group, V471 Tau, and the W UMa group. Needless to say this definition can, step by step, be made more restrictive if accumulation of better and more complete data shows us that other properties are shared by all or virtually all systems.

Somewhat confusing is the fact that not everyone agrees what the name of this group should be. Most people name the group after RS CVn as the prototype, but some refer to AR Lac as the prototype. A few are careful to stress the fact that, until now, the group has not officially been defined. Consequently they have hesitated to name a prototype and instead have referred to the group with a sentence or a phrase which summarizes the characteristics. Let me propose RS CVn as the prototype of the group defined in this paper, since it is at present generally considered as such and is an appropriate choice.

D. Observed Characteristics and Physical Properties

This subsection discusses the large collection of fascinating observational characteristics and physical properties exhibited by the 24 RS CVn binaries in Table 1.

1. Light Curve Variations

To me the multiply periodic variations in the light curve are

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the most fascinating aspect of the RS CVn binaries. Before the middle of the 1960's it appeared that the light curves just varied irregularly with a variety of time scales. A breakthrough was made by the astronomers at Catania (Chisari and Lacona 1965; Catalano and Rodono 1967, 1969) when they observed a persistent nearly-sinusoidal wave-like distortion in the light curve of RS CVn outside eclipse ($\approx 0\overset{m}{.}2$ from maximum to minimum) which migrated slowly (one cycle every $\approx$ 10 years) towards decreasing orbital phase. They also showed that this wave migration was correlated with a variable depth of primary minimum and a variable displacement of secondary minimum.

One consequence of the wave is to render the two maxima unequal in brightness. This particular phenomenon in eclipsing binaries was first investigated systematically by Mergentaler (1950) and by O'Connell (1951). The migration of the wave causes the sense of the inequality to change with time. This also was observed in the past.

Oliver (1971, 1973, 1974a) made the important finding that these persistent waves and their migration towards decreasing orbital phase seem to be a common property of the RS CVn binaries in general. A look at Table 1 shows that 15 are now known or suspected to have waves, of which 8 are known or suspected of migrating. The migration periods range from about 5 years to about 75 years.

Hall (1972) analyzed in some detail the available photometry of RS CVn and showed that a simple model could account for a large number of observed properties, periodicities, and interrelationships. He considered the H and K emission as indication of chromospheric activity and made use of analogies with sunspot activity in our sun. In his model a region of large-scale spot activity darkens one side of the cooler star within 30° of its equator. This darkening produces the wave, explains its red color, and accounts for the anomalously shallow depth of secondary minimum. A compromise between differential rotation (like that observed in our sun) and synchronous rotation (like that observed in most binaries with rather small separations) produces the migration of the wave towards decreasing orbital phase. The migrating wave naturally explains the variable depth of primary minimum and the variable displacement of secondary eclipse. A 23.5-year "sunspot cycle" operating in the cooler star accounts for the variable amplitude of the wave, which ranges between $0\overset{m}{.}2$ and $0\overset{m}{.}05$. This cycle also causes the spots to drift periodically in latitude, as is seen in the so-called butterfly diagram of sunspot activity, and thereby can account for the non-uniformity of the migration rate, the period of which varies between 8 and 12 years every 23.5 years.

Table 1 shows that there are other examples of variable amplitudes and other examples where the migration rate is not constant. Variable depth of primary minimum and displacement of secondary eclipse are not considered in Table 1 among the observable properties because they can be considered consequences of the migrating wave.

Table 1 lists binaries with irregular light curve changes. These are changes not accounted for by a migrating wave, a variable wave amplitude, a variable migration period, and associated changes in the depth of primary minimum and displacement of secondary eclipse. Examples would be changes in the overall level of brightness from one season to the next, a disruption in the shape or phase of the wave, or short-time-scale flaring. Such irregular changes have been suspected in certain binaries but until recently there was some reason to doubt their validity. To date the only published work illustrating such a change is the UBV photometry of UX Ari (Evans and Hall 1974), which indicates that the overall light level decreased by over $0^{m}.1$ sometime between late 1972 and late 1974. Irregular changes in AR Lac have been reported by both Wood (1946) and Kron (1947) but unfortunately they both used HD 209813 = HK Lac as a comparison star, which Blanco and Catalano (1970) showed to be a variable. It is cruel irony that HK Lac appears in Table 2 of this same review paper as a member of the long-period group, the first one in which a migrating wave was observed. The HK in the variable star designation provides additional irony. And the final irony is that more recent photoelectric photometry based on different comparison stars (Babaev 1971, Chambliss 1975) shows that AR Lac does exhibit irregular fluctuations in brightness afterall.

2. Spectroscopic Characteristics

It follows from the definition proposed in this paper that all 24 binaries in Table 1 display strong H and K emission lines outside eclipse. In virtually every one the emission can be attributed to the cooler component. For the newly added member UX Com I do not have enough information to decide; Andersen and Popper (1975) say that the two components in TY Pyx have the same spectral type; RV Lib appears to be the one exception to the rule. The earlier component also displays H and K emission in 4 of the binaries; Popper (1970) thinks this tends to happen when the hotter component is cool enough.

In addition to H and K emission, several of the binaries show Hα in emission. RS CVn also shows Hβ emission (Naftilan 1975). There is some tendency for this emission to arise from the cooler component. Weiler (1975a) observed 6 RS CVn binaries, selected only on the basis of apparent brightness, and detected Hα emission in all 6.

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An important point which has been stressed most recently by Popper (1970) and Oliver (1974a) is that the H and K emission lines give velocities which always agree well with the absorption line velocities arising from the same component. Another important point (Popper 1970, p. 53) is that the width of the emission line corresponds approximately to that of a photosphere rotating synchronously with the orbit. A third point is that the radial velocity curves from both components are remarkably well-defined, free of distortion and scatter, and usually indicative of circular orbits. From these three points one can safely conclude that the H and K emission is fundamentally different in its origin from the Balmer emission in Algol-type binaries, which arises from faster-than-synchronously rotating circumstellar rings around the hotter star or from gas streams connecting the two stars.

Several spectroscopic investigators have studied the behavior of H and K emission with orbital phase. Oliver (1974a, p. 251) summarizes these by saying that the H and K emission from the cooler component seems sometimes to be concentrated on the stellar disk so as to be partially or totally obscured during secondary minimum. Hiltner (1947) claimed that there was a tendency for the H and K emission to originate from the opposite ends of the star in question, the ends elongated by tidal distortion. This interpretation has been repeated by others since then, even though the polarimetric observations of AR Lac by Struve (1948) failed to find the degree of polarization which would be expected in such an interpretation.

Most recently Weiler (1975b) made an important finding. In the three binaries UX Ari, RS CVn, and Z Her he finds that the intensity of both H and K emission and Hα emission appeared to be correlated

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with orbital phase, which is equivalent to correlation with wave orientation since his observations were made within an interval of about one year. In the case of UX Ari and RS CVn there were sufficient photometric data available to fix the orientation of the migrating wave in 1974, the year of his observing program. In both cases he found that maximum H and K emission and maximum Hα emission coincided very closely with phases when the fainter hemisphere faced the earth. Since Weiler finds emission strength correlated with wave orientation and not phase of conjunction or quadrature, his observations argue against the Hiltner interpretation and provide support for the model of a migrating spotted region.

Oliver (1974a, p. 251) concluded also that there were variations in the absorption line strengths but that they were not well correlated with light curve variations.

Abundance anomalies have been reported for some of the RS CVn binaries by Miner (1966), Hall (1967), and Naftilan (1975). Somewhat surprisingly these three find heavy elements apparently underabundant, but the significance of this finding is not clear. I think this underabundance should not be regarded as real until the effect of possible veiling in the ultraviolet and violet has been allowed for. To my knowledge lithium has been searched for in only one RS CVn binary. Conti (1967) looked for lithium in his spectra of HD 118216 and was unable to detect it in the F5 component.

3. Physical Parameters

Reliable masses are relatively easy to determine for the RS CVn binaries (Popper 1967) because their spectra tend to be two-lined and because, as mentioned above, radial velocities derived from the absorption <u>and</u> the emission lines are not distorted by the influence of gas streams and other masses of circumstellar material as they are in the Algol-type binaries. The most recent and complete list of reliable masses is given by Oliver (1974a, Table 47). These are given in Table 1 along with a few from other sources. I have included none which were not derived from two-lined spectrograms.

The data in Table 1 show that for all but two binaries the mass ratio tends to be very close to unity. With AD Cap and RT Lac excluded, the average mass ratio is 1.03 ± 0.03 (rms). The rms deviation of a single value from this mean is only ± 0.1, part of which must be observational uncertainty. It is perhaps significant (but puzzling) that the only two binaries known to have mass ratios markedly different from unity (AD Cap and RT Lac) are among the 4 (out of 24) systems in which <u>both</u> components display H and K emission.

Of the RS CVn binaries in Table 1 for which both masses and radii are known, all are detached. This important characteristic was first noticed by Plavec and Grygar (1965) and most recently demonstrated by Oliver (1974a, Figure 64). The ratio of the radius of each star to that of its respective Roche lobe averages about 60% for the cooler star and about 35% for the hotter, so these RS CVn binaries are detached by no small margin.

The total mass of the RS CVn systems in Table 1 ranges between 1.75 $M_\odot$ and 2.98 $M_\odot$ if we consider only those near unit mass ratio. The lower limit becomes a bit smaller, around 1.6 $M_\odot$, if we include AD Cap.

In cases where both components have been classified, the spectral type of the hotter star ranges between F4 and G9 and the luminosity class ranges between V and IV. The tendency for the hotter star to lie slightly above the main sequence appears to be significant. As pointed out by Popper (1967, 1970), Oliver (1974a), and Andersen and Popper (1975), there is a marked tendency for the cooler component to be very near spectral class KO IV, the only exception known to date being TY Pyx.

Distances for most of these systems were determined by Montle (1973). These are included in Table 1 because distances are not generally available from other sources.

4. Period Variations

One of the most remarkable properties is the tendency for the orbital periods to be variable. These involve both increases and decreases, are around $\Delta P/P \approx 10^{-4}$ or 10^{-5}, and occur on time scales of years or tens of years. O-C deviations from the best linear ephemeris can amount to as much as $\pm\, 0^{d}.25$ (Arnold, Hall, and Montle 1973). In some cases a linear ephemeris taken arbitrarily from a catalogue can, after only ~ 10 years elapsed time, lead to phases which are in error by one fourth of the orbital cycle. Adequate data are not available to tell us how many systems have variable periods, but about a third are known to so far. I suspect virtually all do.

It should be clear that quite different mechanisms are likely to be responsible for period changes in RS CVn binaries and those in Algol-type binaries even though both experience alternate period changes of comparable size and on comparable time scales. For Algol-type binaries the most likely mechanism seems to be loss of mass on a dynamical time scale from a convective star which fills its Roche lobe (Hall 1975a). In RS CVn binaries both components are smaller than their Roche lobes by $\sim 1\ R_{\odot}$ or more, so this Algol mechanism definitely

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cannot work.

It should also be very clear by now that these period changes cannot be explained via apsidal motion or orbital motion around a third body, simply because the observed changes are not strictly periodic, let alone sinusoidal.

In my opinion the most useful clue to understanding these period changes is the interesting correlation observed between period changes and wave migration (Hall 1975b). In the 4 RS CVn binaries RS CVn, SS Cam, AR Lac, and RT Lac and the 2 related binaries CG Cyg and V471 Tau, attempts have been made to demonstrate that period decreases occur when the minimum of the wave is around orbital phase $0\overset{p}{.}25$ and period increases occur when the minimum of the wave is around $0\overset{p}{.}75$. Catalano and Rodono (1974) pointed out that the migrating wave can distort the shape of primary minimum in a way which will generate spurious O-C variations which are in the sense of the above correlation. Hall (1975b) showed that this influence is not large enough to account for the observed O-C variation in RS CVn, CG Cyg, or SS Cam. In fact in SS Cam the observed O-C variation is $\sim$25 times larger than the maximum possible shift due to the distortion of primary eclipse. Nevertheless, Catalano and Rodono were right to emphasize that period changes in RS CVn binaries should be investigated only after effects of light curve distortion have been carefully discussed.

Given such a correlation, it is most obvious to explore mechanisms involving mass loss from either the fainter or the brighter hemisphere of the cooler star, which produces the wave. Arnold and Hall (1973) considered high-velocity impulse-type mass ejection from the brighter hemisphere. Catalano and Rodono (1974) objected to the idea of having mass lost from the brighter hemisphere, whereas one would

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expect flare-type mass ejection from the darker hemisphere, which is supposed to be experiencing the spot activity. Another objection is to the large amount of mass loss required: 10^{-6} $M_{\odot}$/year. But there are many other possible mechanisms to explore besides the simple impulse-type mass ejection mechanism. For example the mass might corotate with the system out to some Alfven radius. This could counter the two objections. First, using the Alfven radius as the effective moment arm instead of the orbital axis of the mass-losing star lets the observed period changes be produced with less mass loss per year. Second, since trajectories of particles ejected from flares are curved as they go from the photospheric limb to the Alfven radius, it is possible that particles leaving the binary system in the vicinity of that part of the Alfven radius lying above the brighter hemisphere of the cooler star actually were ejected from the darker hemisphere, as one would expect. In any case, this interesting problem of period changes demands more attention by observers and theoreticians alike.

Ulrich (1976) argues that an enhanced solar-wind-type mass loss of around 10^{-9} $M_{\odot}$/year is reasonable to expect from the KO IV component. One should explore the possibility that mass loss of this size is capable somehow of producing the observed period changes.

In two of the binaries, AR Lac and RT Lac, there is photometric evidence of an envelope of material surrounding one of the two components. Catalano (1973) reported observations which showed a $\approx 0\overset{m}{.}05$ depression in the light curve of AR Lac just before first contact of primary eclipse and just after fourth contact. I would interpret this as a result of occultation of the hotter star by an envelope or shell of material surrounding the cooler star, perhaps filling its Roche lobe. Hall and Haslag (1976) found the same effect in the light curve of RT Lac. It seems that an increase in the density of this shell around the beginning of World War I was responsible for the remarkable fact that the light curve of RT Lac changed from Algol-type ($A_2 \approx$ -0.03) to β Lyrae-type ($A_2 \approx$ - 0.09) at that time. Such envelopes could be an additional observable consequence of the mass outflow hypothesized to explain the period changes observed in RS CVn binaries.

5. Ultraviolet, Infrared, and Radio Observations

The most recent and complete discussion of ultraviolet excess in RS CVn binaries is that of Oliver (1974a). He says that frequently there is an indication of ultraviolet excess in the U-B color of the cooler star and that sometimes an excess is seen also in the hotter star. Photometry on a standardized system such as UBV is not available for most of the RS CVn binaries, so it is quite possible and even likely that ultraviolet excess occurs in virtually all. Using chromospheric activity as the point of comparison, Hall (1972) suggested that this excess might be analagous to that found in the T Tau variables.

Infrared excess also seems to be characteristic of most RS CVn binaries. Atkins and Hall (1972) found an infrared excess in 5 of 6 RS CVn systems for which they obtained sufficient JHKL photometry to make the decision. These 6 systems were selected only on the basis of apparent magnitude and availability in the sky, so it seems that a large fraction of the RS CVn binaries have infrared excesses. In all cases they found the excess is about $0^{m}.5$ in J, H, K, and L if it is attributed entirely to the cooler star. Since then Milone (1976) has detected an infrared excess in 2 of these 5 (RS CVn and AR Lac) and in another (RT Lac). Needless to say, infrared excess is an expectation of the model in which an appreciable area of the cooler star is affected by large-scale spot activity. Atkins and Hall pointed out that the effective temperature derived from the energy distribution between ultraviolet and infrared is appreciably cooler than that derived from the $(B-V)_o$ or the observed spectral type alone; in fact their lower effective temperature places a KO IV star on the Hayashi track for a star of $\approx 1\ M_\odot$. Milone (1976) considers circumstellar material as a possible source of the infrared excess. This interpretation should not be ignored since, as mentioned above, there are photometrically detectable envelopes in at least two systems (RT Lac and AR Lac).

One of the most remarkable recent discoveries pertaining to the RS CVn binaries is the detection of strong radio emission from several members: AR Lac, UX Ari, and RT Lac. It is remarkable that a star as faint as RT Lac ($V = 10^m_.2$ at maximum) and relatively distant (205 parsecs) emits detectable radio emission. Gibson and Hjellming (1974) are thinking that the ultimate energy source for the radio emission in these and in the Algol-type binaries is gravitational infall of matter transferred from one component to the other. One should, however, explore the possibility that some other mechanism is responsible in the RS CVn binaries; we know that radio emission in the same frequency range is associated with sunspots in our sun and that radio emission coincident with optical flares is observed even in single stars. A crucial test would be to see if radio emission, like Hα emission and H and K emission, is correlated with phases when the fainter hemisphere of the cooler star is facing the earth.

6. Space Density, Galactic Distribution, and Kinematical Properties

The space density of the RS CVn binaries is very large. Using

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the distances of Montle (1973) I find a space density of 1.0×10^{-6} systems/pc^3. Dworak (1973) has listed 40 eclipsing binaries probably within 100 pc of the sun, of which 7 are among those listed in Table 1 of this review. This implies a space density of 1.7×10^{-6} systems/pc^3. The smallness of the sample in each case produces some statistical uncertainty, but not much: ± 20% for Montle and ± 35 % for Dworak. Both of these estimates are lower limits since the non-eclipsing RS CVn binaries, of which there should be many, are not being counted. Such a space density is remarkably high; the W UMa binaries, at one time thought to be the most plentiful type of binary system, have a space density of only about 10^{-6} systems/pc^3 (Kraft 1967) even when non-eclipsing systems <u>are</u> counted.

Montle determined the mean height above and below the galactic plane to be $\langle z \rangle$ = 109 ± 20 pc for his entire sample of 29 systems or $\langle z \rangle$ = 112 ± 20 pc for a restricted sample which excluded the three doubtful cases RT And, KO Aql, and HK Lac. These determinations involved careful allowance for incompleteness effects. He constructed a calibration of $\langle z \rangle$ versus age by using data on several different types of galactic objects available from a variety of published sources. The accidental uncertainty in this calibration was about ± 5 pc at the part of the curve he used. Entering the observed $\langle z \rangle$ into the calibration yielded an age of 2×10^8 years, and considering the uncertainties of both indicated an age in the range $1 - 4 \times 10^8$ years.

Montle also determined the dispersion of their velocity component perpendicular to the galactic plane to be $\langle Z^2 \rangle^{1/2}$ = 10.0 ± 2.5 km/sec. This value is the intrinsic dispersion in the sense that Montle did remove the influence of observational error in each individual determination of Z. He constructed a calibration of $\langle Z^2 \rangle^{1/2}$ versus age, as he did with $\langle z \rangle$, but from different sources, primarily from the data compiled by Delhaye (1965). The accidental uncertainty in this calibration was only about ± 1 km/sec. Entering the observed $\langle Z^2 \rangle^{1/2}$ into the calibration again yielded an age of 2 X 10^8 years, and considering the uncertainties of both indicated an age in the range 0.5 - 3 x 10^8 years.

Montle's $\langle z \rangle$ and $\langle Z^2 \rangle^{1/2}$ values were determined from different combinations of several different observed quantities (distance, galactic latitude and longitude, systemic radial velocity, and proper motion), though admittedly they both made use of the distance. Moreover, their calibrations versus age were based on different bodies of published data. Therefore, since the two different approaches indicated the same age (2 X 10^8 years) within small ranges, the agreement would seem to indicate that Montle's result is reliable. There is, however, a newer calibration of velocity dispersion versus age by Wielen (1974) which, with Montle's value of 10.0 km/sec, would indicate a considerably older age: around 2 X 10^9 years.

To my knowledge no RS CVn binary is known or suspected of being a member of a star cluster. Fortunately at least one RS CVn binary is known to have a visual companion. Hall (1975c) has shown that the less massive F8 V visual companion to the eclipsing system WW Dra is evidence that WW Dra cannot be pre-main-sequence. The nearest associations are about 1 kpc away whereas the known RS CVn binaries have distances between 50 and 315 pc. Thus, although in principle there could be RS CVn binaries connected with associations, the presently known sample cannot possibly be.

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Explanation of Tables 1, 2, 3.

Numbers in parentheses refer to the bibliography, which is numbered correspondingly.

Letters in parentheses refer to notes, which are given at the end of these three tables.

A check mark (√) or a question mark (?) means that the characteristic is present or is possibly present.

h = hotter component

c = cooler component

b = both components

δ_{uv} = ultraviolet excess

δ_{ir} = infrared excess

Corr. = the alternate period variations are correlated with the wave migration

The amplitude of the wave is measured from maximum to minimum, usually in the visual. A range indicates that the amplitude is variable.

P(migr.), used in Tables 1 and 3, is the amount of time required for the wave to complete one retrograde migration and return to the same orbital phase. A range indicates that the migration rate is not uniform.

P(wave), used in Table 2, is the period of the wave-like variation itself.

The distances are taken from Hontle (1973).

Table 1. The RS CVn Group

Name	P(orb) days	Spectral Class hot + cool	H & K em.	Hα em.
UX Ari	6.438	G5V + K0IV (28)	c (28)	√ (128)
CQ Aur	10.621	G0 (112, C)	c (112)	
SS Boo	7.606	dG5 + dG8 (11)	c (11)	
SS Cam	4.824	dF5 + gG1 (67)	c (102)	
RU Cnc	10.173	dF9 + dG9 (11)	c (11)	
RS CVn	4.798	F4V-IV + K0IV (109)	c (109)	√ (109, 128)
AD Cap	6.118 (H)	G5 (112, C)	b (112)	
UX Com	3.642	G5-9 (53, F)	√ (114)	
RT CrB	5.117	G0 (B)	c (102)	
WW Dra	4.630	sgG2 + sgK0 (11)	c (11)	√ (110)
Z Her	3.993	F4V-IV + K0IV (106)	c (11)	√ (128)
AW Her	8.801	G2IV + sgK2 (107)	c (11)	
MM Her	7.960	G8IV (70, C)	c (70)	
PW Her	2.881	G0 (112, C)	c (112)	
GK Hya	3.587	G4 (B)	c (102)	
RT Lac	5.074	sgG9 + sgK1 (11)	b (11)	√ (110)
AR Lac	1.983	G2IV + K0IV (34)	b (11)	√ (128)
RV Lib	10.722	G5 + K5 (11, 47)	h (102)	
VV Mon	6.051	G0 (108, C)	c (102)	
LX Per	8.038	G0V + K0IV (127)	c (127)	√ (128)
SZ Psc	3.966	F8V + K1V-IV (9)	c (9)	√ (128)
TY Pyx	3.199 (2)	G5 + G5 (2)	b (2)	
RW UMa	7.328	dF9 + K1IV (95)	c (11)	
HD 118216	2.613 (38)	F2IV + K IV (38)	c (38)	√ (38)

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Table 1 continued. The RS CVn Group

Name	Wave magnitudes	P(migr.) years	Irreg. Lt. C. Var.
UX Ari	0.03 - 0.10 (43)		√ (43)
CQ Aur			
SS Boo	0.05 - 0.19 (62,102)	7.5 (102, J)	
SS Cam	0.11 (102)	78 (5 , K)	√ (6)
RU Cnc			
RS CVn	0.05 - 0.20 (57)	8 - 12 (57)	
AD Cap			
UX Com	√ (114)		
RT CrB			
WW Dra	0.06 (102)	√ (102,77)	
Z Her	0.03 (102)	5.1 (102, I)	
AW Her			
MM Her			
PW Her	√ (114)		? (63)
GK Hya	√ (114)		
RT Lac	0.01 - 0.17 (61)	5 - 40 (61)	√ (61)
AR Lac	0.04 (35)	15 - 45 (36)	√ (35)
RV Lib	√ (114)		
VV Mon			
LX Per			
SZ Psc	√ (102)		? (9)
TY Pyx	√ (103)		√ (2)
RW UMa	0.11 (102)	√ (102)	
HD 118216			

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Table 1 continued. The RS CVn Group

Name	δ_{uv}	δ_{ir}	Radio em.	Var. P(orb.)	Corr.	dist. pc
UX Ari		√ (64)	√ (50)			50
CQ Aur						220
SS Boo	√ (102)					220
SS Cam	? (102)			√ (5)	√ (5)	255
RU Cnc						190
RS CVn	√ (102)	√ (7)		√ (57)	√ (57)	145
AD Cap						250
UX Com						
RT CrB				? (74)		
WW Dra	√ (102)					180
Z Her	√ (102)	√ (7)		? (74)		85
AW Her						315
MM Her						190
PW Her						285
GK Hya						
RT Lac	√ (102)	√ (90)	√ (51)	√ (61)	? (61)	205
AR Lac		√ (7)	√ (49)	√ (55)	√ (36)	50
RV Lib						270
VV Mon				? (74)		260
LX Per						145
SZ Psc		√ (7)		√ (65)		100
TY Pyx						85
RW UMa						150
HD 118216						

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Table 1 concluded. The RS CVn Group

Name	Masses in solar units hot + cool	Relative Radii hot + cool	Detached
UX Ari	0.63 + 0.71 (28, L)		
CQ Aur			
SS Boo	0.91 + 0.84 (102)		
SS Cam		0.140 + 0.412 (73)	
RU Cnc		0.064 + 0.173 (73)	
RS CVn	1.35 + 1.40 (102)	0.11 + 0.24 (102)	√
AD Cap	0.5: + 1.1: (102)		
UX Com			
RT CrB			
WW Dra	1.4 + 1.4 (102)	0.14 + 0.24 (102)	√
Z Her	1.22 + 1.10 (102)	0.11 + 0.19 (102)	√
AW Her	1.31 + 1.31 (102)		
MM Her	1.22 + 1.19 (70)	0.12 + 0.065 (70)	√
PW Her	1.35 + 1.58 (102)		
GK Hya			
RT Lac	0.8: + 1.7: (102)		
AR Lac	1.31 + 1.32 (102)	0.19 + 0.32 (102)	√
RV Lib			
VV Mon			
LX Per	1.33 + 1.39 (127, M)		
SZ Psc	1.33 + 1.65 (102)	0.10 + 0.26 (102)	√
TY Pyx	1.20 + 1.22 (2)	0.135 + 0.135 (2)	√
RW UMa	1.1: + 1.1: (102)	0.07 + 0.20 (102)	√
HD 118216			

Table 2. The Long-Period Group

Name	P(orb.) days	Spectral Class hot + cool	H and K emission
ζ And	17.769	K1II (11, D)	c (11, E)
λ And	20.521	G8IV-III (11, D)	c (11, E)
α Aur	104.023	G0III + G5III (18)	c (11)
12 Cam	80.174	K0III (1, D)	c (1, E)
RZ Cnc	21.643	K1III + K4III (26)	h (26)
RZ Eri	39.283	A5-F5V + sgG8 (110)	c (11)
σ Gem	19.605	K1III (11, D)	c (11, E)
HK Lac	24.428 (52)	FIV + K0III (18)	c (52)
AR Mon	21.207	F-G + K0II (117)	c (117)
ϵ UMi	39.481	dA8-dF0 + G5III (11, 69)	c (11)
BS 7275	28.59	K1IV (A, D)	c (11, E)
BS 7428	108.58	A + K2III-II (11)	c (11)
BS 8703	24.65	K1IV-IIIp (66, D)	c (66, E)
HD 158393	30.9 (83)	G8III (83, D)	c (83, E)
HD 213389	17.755	K2IV-IIIp (66, D)	c (66, E)

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Table 2 continued. The Long-Period Group

Name	Wave magn.	P(wave) days	Distance parsecs
ζ And	0.02 (118)	= P(orb.) (66)	
λ And	0.3 (66)	55.82 (66)	
α Aur	√ (18)	366 (18)	
12 Cam			
RZ Cnc	0.01 (26)		310
RZ Eri			105
σ Gem	? (66)		
HK Lac	0.10 (18)	25.3 (18)	150
AR Mon			495
ε UMi	? (69)		
BS 7275	? (66)		
BS 7428			
BS 8703	0.16 (66)	~100 (66)	
HD 158393			
HD 213389	0.13 (66)	= P(orb.) (66)	

Table 2 concluded. The Long-Period Group

Name	Masses in solar units hot + cool	Radii in solar units hot + cool
ζ And		
λ And		
α Aur	3.03 + 2.91 (135)	
12 Cam		
RZ Cnc	3.1 + 0.55 (26)	11 + 13 (26)
RZ Eri	2.23 + 1.72 (102)	
σ Gem		
HK Lac		
AR Mon	2.6 + 0.8 (113)	6 + 15 (113)
ε UMi		
BS 7275		
BS 7428		
BS 8703		
HD 158393		
HD 213389		

Table 3. The Short-Period Group

Name	P(orb.) days	Spectral Class hot + cool	H and K emission
RT And	0.629	F8V + G5V (40)	√ (79, G)
SV Cam	0.593	G3V-IV + K3V (46)	√ (68, G)
WY Cnc	0.829	G± (B, F)	h (102)
CG Cyg	0.631	G9V-IV (89, F)	√ (89, G)
UV Psc	0.861	G2 (112, C)	b (112)
ER Vul	0.698	G0V + G5V (98)	√ (20, G)

Table 3 continued. The Short-Period Group

Name	Wave magn.	P(migr.) years	Irregular Lt.C.Var.	Distance parsecs
RT And			√ (40)	95
SV Cam			√ (125)	
WY Cnc	0.02 (33)	5.5: (102)	√ (102)	160
CG Cyg	0.07 (88)	10 (59)		
UV Psc	0.04 (102)			125
ER Vul			√ (98)	45

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Table 3 continued. The Short-Period Group

Name	δ_{uv}	δ_{ir}	Var. P(orb.)	Corr.
RT And			√ (131)	
SV Cam			√ (46)	
WY Cnc				
CG Cyg		√ (90)	√ (59)	√ (59)
UV Psc	? (102)	•		
ER Vul				

Table 3 concluded, The Short-Period Group

Name	Masses in solar units hot + cool	Relative Radii hot + cool
RT And	1.50 + 0.99 (40)	0.322 + 0.239 (40)
SV Cam		0.40 + 0.25 (46)
WY Cnc		0.090 + 0.303 (73)
CG Cyg		
UV Psc		
ER Vul	1.07 + 0.98 (98)	0.297 + 0.282 (73)

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Notes to Tables 1, 2, 3.

a. the 1964 Yale Bright Star Catalogue

b. the 1969 General Catalogue of Variable Stars

c. spectral type of the hotter component

d. only this component seen in the spectrum

e. assuming the one component seen in the spectrum is the cooler

f. refers to the composite spectrum

g. not known which component(s) responsible for the emission

h. Oliver (1974a) says the period is around 3 days

i. 3.8 years is also possible

j. 9.3 years and 6.4 years are also possible

k. based on 39 years for half a migration cycle

l. $M \sin^3 i$ values

m. $M \sin^3 i$ values, but $i \approx 90^{\circ}$

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7. Summary of Properties

In this final subsection I want to recapitulate by listing in Table 4 the observed properties and physical characteristics of the RS CVn binaries and indicating what fraction of the known sample exhibits (or is known to exhibit) each. The first three are exhibited by all 24 because they make up my proposed working definition. The denominator in some of the fractions is less than 24 because sufficient data are not available for all. In evaluating the numerator I have counted question-mark entries in Table 1 as one half. Percentages are given as lower limits if the accumulation of additional data is likely to increase the value.

Should we add additional membership requirements to make the sample of RS CVn binaries more pure and homogeneous? I think this is premature. In most cases the absence of a given property in a certain binary is not firmly established; there is inadequate observation to decide. In cases where apparently adequate observations are available but a certain property such as a wave-like distortion or infrared excess is not present, it might be that the binary is near the minimum of its "sunspot cycle" and only temporarily not displaying those properties. Based on more permanent features like spectral type and mass ratio one might be tempted to purge certain members. Mentioned earlier was TY Pyx, the only binary not having a cooler star near KO IV; and the unit mass ratio criterion would eliminate RT Lac and RV Lib. Probably one should consider the conservative use of sub-groups rather than exclude certain binaries outright. For the near future, however, I think the first three properties are sufficient to define an "RS CVn binary", to allow us to make use of existing data in theoretical investigations, and to guide the search for additional members.

Table 4. Summary of Properties for the RS CVn Group

	Property	Fraction	
1.	Orbital period between 1 day and 2 weeks	24/24	100 %
2.	Strong H & K emission seen outside eclipse	24/24	100 %
3.	Hotter star is F or G, V or IV	24/24	100 %
4.	H & K emission is from cooler star (or both)	22/23	96 %
5.	Cooler star is around KO IV	23/24	96 %
6.	$H\alpha$ emission seen outside eclipse	6/6	100 %
7.	Wave-like distortion outside eclipse	> 15/24	> 62 %
8.	Wave migrates towards decreasing phase	> 7/15	> 47 %
9.	Variable depth of primary minimum		
10.	Variable displacement of secondary eclipse		
11.	Irregular light curve variations	> 6/24	> 25 %
12.	UV excess in one or both components	5.5/12	46 %
13.	IR excess in one or both components	5/6	83 %
14.	Radio emission	> 3/24	> 12 %
15.	Variable orbital period	> 6.5/24	> 27 %
16.	Period variations correlated with migration	> 3.5/6.5	> 54 %
17.	Mass ratio near unity	13/15	87 %
18.	Binary is detached	8/8	100 %

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III. THE RELATED BINARIES

A. The Long-Period Group

As explained earlier, I am defining this group as binaries with periods greater than 2 weeks in which one component is of spectral class G-K IV-II and displays strong H and K emission. Table 2 lists all 15 candidates for this group which I am aware of, but there may be more.

Only 3 of these 15 have two-lined spectra, and only 4 are known to be eclipsing. In the 4 cases where something is known about the hotter component, we find its spectral type ranging between A-F and early K.

The mass ratio has been measured only in 4 systems, but in 3 it is far from unity, with the cooler component always the less massive. This would seem to set them apart from the RS CVn group, where the mass ratio is almost always very near unity and, in the two exceptions, the cooler component is the more massive.

An important question to answer is whether binaries of this group are detached or semi-detached. Broglia and Conconi (1973) found RZ Cnc semi-detached. The data in Table 2 indicate that AR Mon is also semi-detached. According to Lloyd Evans (1973) the primary component in HD 158393 and other one-spectrum members of this group is "probably close to filling its Roche lobe". This indication that binaries of the long-period group are semi-detached is another property which seems to set them apart from the RS CVn binaries.

Binaries of the long-period group do display wave-like distortions in their light curves. The amplitudes of these waves are comparable

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to those displayed by the RS CVn binaries. But we do not as a rule see them migrating slowly towards decreasing orbital phase as we do in the RS CVn binaries. According to the model of Hall (1972), the key to the migration phenomenon is the binary's attempt to reconcile synchronous rotation and differential rotation. Thus it seems the cooler star in binaries of the long-period group is not as a rule rotating synchronously, whereas the cooler star in the RS CVn binaries always is. According to Herbst (1973) the period of the wave in ζ And and HD 213389 equals the orbital period, whereas in λ And, α Aur, and BS 8703 the period of the wave is longer by a factor of several. The wave period in HK Lac is also longer than the orbital period, but only by about 5%. This would correspond to a migration period of only about 2 years, but in the direction of <u>increasing</u> orbital phase. Lloyd Evans (1973) finds the cooler star in HD 158393 rotating rapidly. Thus we see 2 rotating synchronously, 3 rotating much more slowly, 1 rotating a little more slowly, and 1 rotating more rapidly. The reason for this general lack of synchronism is not entirely obvious. Although their orbital periods are longer, the star in question is also larger and the tidal forces felt by it might be comparable to those felt by the KO IV star in the RS CVn group.

Masses have been determined only for α Aur, RZ Eri, and AR Mon. These indicate total masses in the range 3.2 $M_{\odot}$ to 5.94 $M_{\odot}$, which is entirely above the upper end of the RS CVn mass range. This fact is, indirectly, consistent with the Period-Luminosity relation noted by Gratton (1950).

B. The Short-Period Group

As mentioned earlier, I am defining this group as non-contact binaries with periods less than 1 day in which the hotter component is of spectral class F-G V-IV and H and K emission is displayed in one or both components. Table 3 lists 6 candidates for this group which I am aware of. XY UMa, discussed recently by Geyer (1976), appears to be another. The requirement that they not be contact is necessary to separate this group from the W UMa binaries.

Oliver (1974a) says that the H and K emission arises from the hotter star in WY Cnc and from both in UV Psc; in the other 4 it is not known which star is responsible. Thus no clear pattern can be seen here.

There is a wave in WY Cnc, CG Cyg, UV Psc, and XY UMa; the waves in the first two have been found to migrate towards decreasing orbital phase. Irregular light curve variations, of the sort described with the RS CVn binaries, are observed dramatically in RT And, SV Cam, WY Cnc, and ER Vul.

Large alternate period variations, $\Delta P/P \sim 10^{-5}$, are observed in RT And, SV Cam, and CG Cyg. In CG Cyg, the one of these with a well-defined wave, the period variations seem to be correlated with the wave migration (Hall 1975b).

This group seems to be closely related to the RS CVn group if we judge by similarity of observed properties. For those binaries like RT And, SV Cam, and ER Vul which show only irregular light curve changes instead of a persistent wave, it might be that large spotted regions are appearing and disappearing without, as far as we can tell, remembering to have a preferential longitude.

The general shape of the light curve outside eclipse indicates that binaries in this group are neither contact nor supercontact. With reliable absolute dimensions available for only a few, it is difficult to be sure whether these binaries are detached or semi-detached. It seems clear that ER Vul is detached (Northcott and Bakos 1967) and it is possible that RT And is detached also (Dean 1974) even though Kopal (1959, Table 7-5) considered it semi-detached. Frieboes-Conde and Herczeg (1973) think SV Cam is probably semi-detached, with the <u>hotter</u> component filling its Roche lobe.

The range of total mass, judging by just RT And and ER Vul, is included within the RS CVn mass range. The mass ratio for ER Vul is near unity (Northcott and Bakos 1967); the mass ratio for RT And is not reliably determined but might be around 1.5 (Dean 1974). I think it is premature to decide now whether or not the short-period group and the RS CVn group are similar with respect to mass ratio.

This short-period group seems to be a subset of the short-period eclipsing binaries with β Lyrae-type light curves,discussed recently by Lucy (1975). Lucy explains that, although detached binaries shortly before they undergo mass exchange have primaries nearly filling their Roche lobes and hence will have β Lyrae-type light curves (e.g. MR Cyg) and although some semi-detached binaries actually undergoing post-main-sequence mass exchange have β Lyrae-type light curves (e.g. β Lyr itself), most eclipsing binaries with β Lyrae-type light curves have periods less than 1 day. Lucy further notes a sharp drop in frequency of these binaries with orbital periods below $0\overset{d}{.}45$ which coincides with a sharp rise in the frequency of the W UMa systems.

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This group is defined as binaries in which the hotter component is a dKe or a dMe star. Here the emission refers to strong H and K emission. Three well-known examples of such a group would be BY Dra, CC Eri, and YY Gem, but there are certainly others which would fit such a definition. See, for example, Krzeminski (1969, Table I).

In all three of these binaries, both components are known to exhibit the H and K emission. YY Gem is similar to the RS CVn binaries in that the radial velocity curve amplitude and shape are virtually the same for both the absorption lines and the emission lines (although there is a systematic difference in γ velocity) and the doppler width of the emission lines corresponds to synchronous rotation (Bopp 1974a). All three are also known to exhibit Hα emission (Anderson and Bopp 1975, Evans 1971, Moffett and Bopp 1971).

All three are known to exhibit wave-like distortions in their light curves. In BY Dra and CC Eri the wave is remarkably well-defined (Bopp and Evans 1973) and in YY Gem a wave seems definitely to be present (Budding 1976). In the first two the wave is known to have changed phase with respect to the orbital period, and in the one case of BY Dra the period of this wave has been determined and found to be $3\overset{d}{.}838$. Since the orbital period of BY Dra is $5\overset{d}{.}976$, its wave would migrate towards decreasing orbital phase, as is observed in the RS CVn binaries, but very rapidly. It is clear that, unlike the RS CVn binaries, BY Dra is far from synchronous rotation. The amplitude of the wave in CC Eri and BY Dra is known to be variable, another similarity between this group and the RS CVn group. In fact one could say that the amplitude can dwindle to zero, because at times observations of both CC Eri (Evans 1971) and BY Dra (Martins 1975) have failed to re-veal any measurable light variation. Bopp (1974a) summarizes by saying that spots and active regions on these stars apparently can develop and disappear on time scales of one month (YY Gem) or a few months (CC Eri and BY Dra).

All three undergo rapid flare activity (Cristaldi and Rodono 1971, Nather and Harwood 1972, Moffett and Bopp 1971). In other words, all three are flare stars. It is quite possible that flares of the same intrinsic brightness occur in the RS CVn binaries also, but that these flares go unnoticed because the RS CVn binaries are intrinsically more luminous than the dMe or dKe binaries.

It has been suspected that the orbital period of YY Gem is variable. The other two are not eclipsing variables and a variation in the orbital period will be much more difficult to detect and substantiate. The detection of circumstellar material in YY Gem (Bopp 1974 a) suggests that matter is actually being ejected from one or both components. Such mass ejection would make YY Gem similar to the RS CVn binaries if mass ejection is indeed the cause of their period changes.

Although radio emission has not yet been detected from any of these three flare star binaries, it is well known that many flare stars do emit radio waves coincident in time with optical flares. Thus radio emission might be another property which the flare star group and the RS CVn group have in common. Bopp, Gehrz, and Hackwell (1974), how-ever, observed BY Dra and YY Gem and found no measurable infrared excess.

The mass ratio in YY Gem is exactly unity within the observational uncertainty. That of BY Dra is rather close to unity. Very few masses are known for binaries of this group, but the total mass of each binary system is no doubt considerably less than that for each RS CVn binary. Their orbital periods range from $0\overset{d}{.}8$ to $6\overset{d}{.}0$, overlapping somewhat the range for the RS CVn group but tending to be somewhat shorter.

It is generally agreed that there are important differences between the dwarf M and dwarf K stars which have H and K emission and those which do not. As Krzeminski (1969) points out, periodic or quasi-periodic light variations are found in some dMe stars, but never in dM stars.

D. V471 Tau = BD +16°516

V471 Tau is a detached binary consisting of a K0 dwarf and a white dwarf and having an orbital period of 12.5 hours. No similar binary is yet known. The work of Flesch, Oliver, and Smak (1974) first made me aware of the many properties it shares with the RS CVn binaries.

The cooler component displays strong H and K emission. There is a well-defined wave, attributable to the cooler star, which migrates towards decreasing orbital phase with a migration period of around one year. The orbital period is variable (Lohsen 1975) in a way which might possibly be correlated with the wave migration in the sense found in the RS CVn binaries (Oliver 1975). The difficulty in establishing such a correlation is that the migration period is nearly a year and the orbital period is nearly a half day.

The mass ratio is very nearly unity according to Young and Nelson (1972), yet another point of similarity with the RS CVn binaries.

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E. The W UMa Group

In this group I am considering W UMa binaries in which there is photometric evidence of uneven surface brightness distribution on one or both components. Among these are U Peg (Binnendijk 1960a), AH Vir, (Binnendijk 1960b), RZ Com (Binnendijk 1964), SW Lac (Bookmeyer 1965), AM Leo (Binnendijk 1969), VW Cep (Leung and Jurkevich 1969), W UMa (Rigterink 1972), and 44 ι Boo (Bergeat et al. 1972). There may be others which would fit into this group.

Binnendijk analyzed light curves of AH Vir, U Peg, RZ Com, and AM Leo, paying particular attention to asymmetries and changes in the light curve as a function of time. Bookmeyer did the same for SW Lac, and Rigterink did for W UMa. In every case they arrived at a model in which there was a subluminous region on the surface of the larger = more massive star. This subluminous region caused the affected hemisphere to be fainter than the other hemisphere by as much as $0\overset{m}{.}05$. In the case of AH Vir and SW Lac there was a significant displacement of the phase of secondary minimum with respect to primary minimum. In both cases this could be explained as a direct consequence of the subluminous region; this is, of course, the same way Hall (1972) accounted for the displaced secondary minimum in RS CVn.

In the case of U Peg, SW Lac, and W UMa the orientation of the subluminous region was different in different epochs. Since the subluminous region would produce a wave-like distortion in the light curve, this would suggest a migration effect such as observed in the RS CVn binaries. In fact Rigterink shows that the wave in W UMa is migrating with a period of about 500 days; and Leung and Jurkevich show that there is a wave in VW Cep migrating through its light curve

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with a period of 718 days. In both cases the migration is towards decreasing orbital phase. Thus the similarity between the RS CVn group and this W UMa group is remarkable.

In addition to the effects attributed to a subluminous region on the surface of one star, large changes in the overall heights of the light curve maxima are observed in SW Lac by Bookmeyer.

Most (6 out of 8) of these W UMa systems are known to undergo large period changes. Despite the fact that half of these binaries are known to have visual companions (AH Vir, AM Leo, W UMa, and 44 ι Boo), it is highly unlikely that orbital motion around a third body can entirely account for the observed period variations. This is because the period variations are very large ($\Delta P/P \sim 10^{-5}$), alternate in sign with a time scale of $\sim$10 years, and are often quite abrupt. One expects that a migrating wave will distort the shape of both eclipses and thereby generate spurious O-C changes which do not represent true period changes. Van't Veer (1973) has demonstrated very nicely that this is happening in VW Cep. But it is clear that these spurious changes are only a small part of the overall O-C changes; hence real period changes are occurring, not only in VW Cep but also in the others. In the case of AH Vir, Binnendijk discussed possible explanations for the observed period variations in terms of mass ejection from the subluminous region, but he was not able to reach a definite conclusion. In the case of W UMa Binnendijk (1966) showed that the flare observed by Kuhi (1964) coincided in time with a large abrupt period increase.

In AH Vir, RZ Com, SW Lac, and AM Leo there were epochs when the subluminous region was absent; at least there were epochs when the light curve appeared normal. This come-and-go nature of the subluminous region suggests something like the "sunspot cycle" which Hall (1972) proposed to explain the variable wave amplitude in RS CVn and which might explain the variable wave amplitudes in the flare star binaries also. In this connection the discussion of 44 ι Boo by Bergeat et al. (1972) is very interesting. They concluded that sudden changes in the orbital period and various irregularities in the light curve indicated the existence of active and quiet epochs, with the interval between active epochs being around 10 years. Light curve characteristics considered by them were (1) unequal maxima, (2) displaced secondary minima, (3) general irregular appearance, and (4) a temporal enhancement or reduction of the light curve occurring at certain phases. They pointed out the similarity between this interval and the 11-year solar sunspot cycle.

H and K emission has been observed in at least one of these systems, namely W UMa itself (Struve and Horak 1950). I am not sure whether or not this will turn out to be a common property of the group. Koch (1974) concludes that his narrow band CN observations indicate an overabundance in the W UMa binaries (which he refers to as strongly interacting binaries), but I am not sure what the ultimate implication of this observation will prove to be.

Milone (1976) has detected very strong infrared excess in one W UMa-type binary, RW Com. This suggests that perhaps infrared excess might prove to be another property which they have in common with the RS CVn binaries.

IV. CONCLUDING REMARKS

A. How to Understand these Properties

Table 5 is provided to illustrate the degree to which binaries of the RS CVn group and the five related groups display similar properties. Such a summary must be somewhat subjective since all of the members of a given group do not always display a given property. A "yes" indicates that all or most do or that accumulation of additional data will probably indicate that they do. A "maybe" indicates that the property is possibly characteristic of that group. A question mark means that the situation is ambiguous at present. Particulars about any entry can be found in the text or in Tables 1, 2, and 3. It is remarkable that several of the properties occur in all or most of the groups. I feel that, with the accumulation of more data, these similarities will become even more apparent.

I think it is almost certain now that the many peculiar properties reviewed in this paper are to be understood with a picture of strong chromospheric activity and large spotted regions on convective stars in binary systems. As indicated throughout this review, such a picture can account for the strong H and K emission, the Hα emission, the correlation of both these types of emission with phase, the persistent wave outside eclipse, the migration of this wave towards decreasing orbital phase (when the spotted star is rotating synchronously), the variable displacement of secondary eclipse and the variable depth of primary minimum and the correlation of both these variations with wave migration, the anomalously shallow depth of secondary minimum, the nonconstancy of the migration rate and the variable ampli-

Table 5. Summary of Properties for the Six Groups

Property	RS CVn	L-P	S-P	W UMa	Flare	V471
a. H and K emission	yes	yes	yes	maybe	yes	yes
b. H α emission	yes				yes	
c. Wave	yes	yes	yes	yes	yes	yes
d. Displaced secondary	yes			yes		
e. Synchronism	yes	no	yes	yes	no	yes
f. Retrograde migration	yes	—	yes	yes	—	yes
g. Evidence of a spot cycle	yes			yes	yes	
h. Irregular light curve variations	yes		yes	yes		yes
i. Flare activity				maybe	yes	
j. UV excess	yes		maybe		yes	
k. IR excess	yes		yes	maybe		
l. Radio emission	yes				yes	
m. Variable orbital period	yes		yes	yes	maybe	yes
n. Period variations correlated with migration	yes		yes	maybe		maybe
o. Mass ratio near unity	yes	no	maybe	no	yes	yes
p. d, sd, or c	d	sd	?	c	d	d

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tude of the wave and the correlation of these two with each other, the period changes and their correlation with wave migration, the depressions in some light curves around first and fourth contact of primary eclipse, the irregular light curve changes, flare activity, ultraviolet excess, infrared excess, and radio emission.

The spot model proposed by Hall (1972) for RS CVn is remarkably similar to the spot model developed by Torres and Ferraz Mello (1973) for AU Mic, by Bopp and Evans (1973) for BY Dra and CC Eri, and elaborated upon by Vogt (1975). Mullen (1974) has shown that starspots can be derived from his convection cell hypothesis which are in fair agreement with the size and temperature of those observed by Bopp and Evans (1973). He further shows that efficient dynamo action is a possible mechanism for generating the required large surface fields and that tidal effects may influence starspot formation. Another interesting paper is that of Worden (1974). Although both Mullen and Worden were interested mainly in the flare stars, their results apply to any late-type star which has a deep convective envelope and hence should be very useful in understanding spot activity in the RS CVn group, the long-period group, the short-period group, the W UMa group, and V471 Tau.

In my opinion the case for strong chromospheric activity and for large spotted regions is very convincing. It should be pointed out, however, that other explanations have been proposed by Evans (1971), by Catalano and Rodono (1967, 1969, and 1974), and by Ulrich (1976). Evans since then has said (Bopp and Evans 1973) that he now believes the spot model is on the right track. Many people object to a spot model on grounds that it is methodologically distasteful, but this objection does not disprove the existence of spots.

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The extreme degree of the chromospheric activity and spottedness might mean that the affected stars are thermally unstable. But, even though the binaries in these various groups may have thermal instability in common, it would not necessarily follow that they got this thermal instability as a result of similar evolutionary histories.

B. The Evolutionary Status of the Related Groups

Figure 1 shows that the various groups, as defined in this paper, occupy different regions in the total-mass versus orbital-period plane, but I am not sure what the significance of this segregation is. It is conceivable that binaries of the long-period group are the long-period counterparts of the RS CVn binaries, that binaries of the short-period group are the short-period counterparts, or that the flare stars are the low-mass equivalents. But it is quite possible that no such connection is true.

Biermann and Hall (1976) have discussed the problem of the evolutionary status of the RS CVn binaries. After considering that they might be pre-main-sequence or post-main-sequence and that their main-sequence counterparts might be either binaries or single stars, they felt the most likely explanation was that the RS CVn binaries are in a thermal phase following fission of a rapidly rotating main-sequence single star. Ulrich (1976) argues, however, that the RS CVn binaries in fact can be understood as products of post-main-sequence evolution of a binary system. This matter has not been settled yet.

Koch (1970) suggested that RZ Cnc (which I include in the long-period group) is in pre-main-sequence contraction. If so, it would be thermally unstable but not for the same reason Biermann and Hall

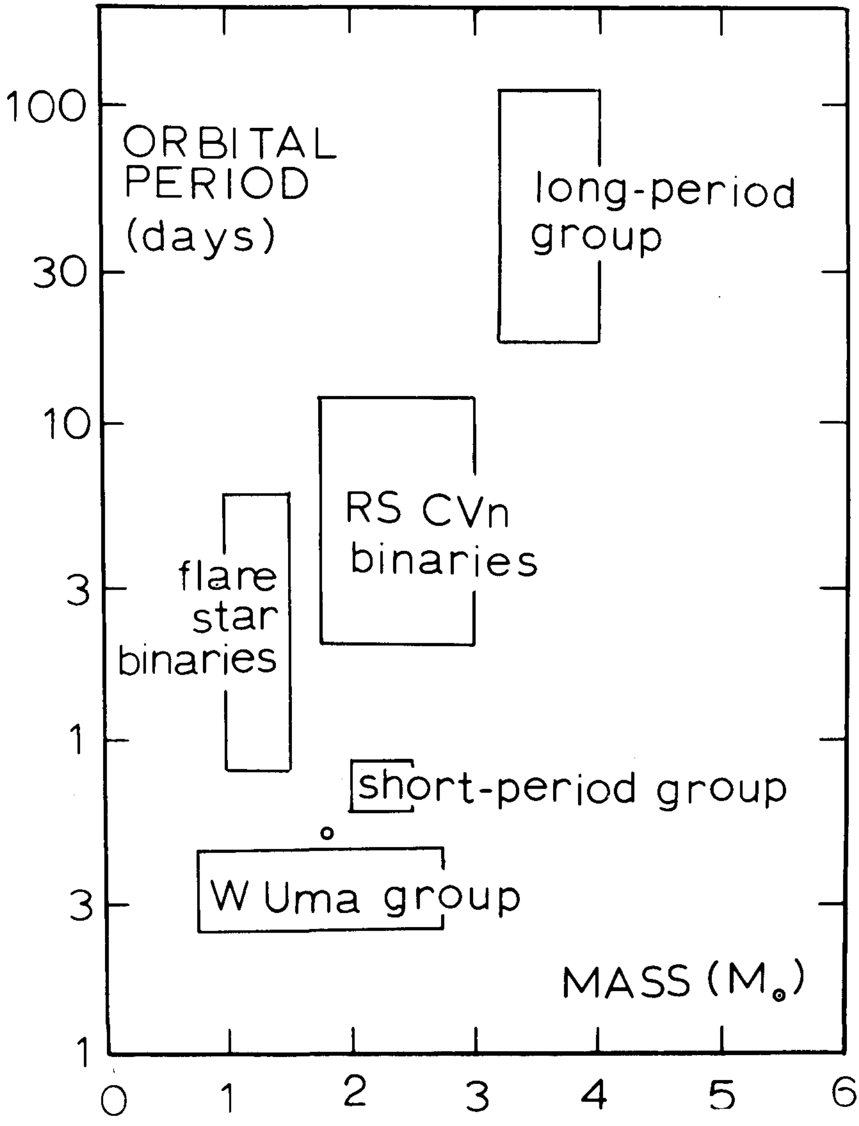

Figure 1. The regions occupied by the six binary star groups in the orbital-period versus total-mass plane. The small circle represents V471 Tau.

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suggested the RS CVn binaries might be. Other people have considered binaries in the long-period group to be the result of post-main-sequence evolution of a close binary. This matter has not been settled yet. Recent observations of Bolton (1975) argue against a pre-main-sequence interpretation. He obtained 16 Å/mm red spectrograms of several stars of this group and compared them visually with spectrograms of stars with known Li line strengths. The indication was that binaries of the long-period group do not have the very strong Li lines characteristic of young stars of the same spectral type.

Wilson and Woolley (1970) examined a large number of dwarf K and dwarf M stars and found a clear correlation between the strength of H and K reversal and various parameters of their galactic orbits. From this they concluded that the dKe and dMe stars are young, whereas the dK and dM stars are old. Bopp (1974b) has detected Li in one dMe star.

It is significant that 7 of the 8 binaries in my W UMa group are known to be of type W, and the one exception (AM Leo) is not yet classified (Rucinski 1974). According to Rucinski the W-type, in contrast to the A-type, are thermally unstable. According to Lucy (1975) the W-type W UMa binaries <u>are</u> evolving on a nuclear time scale but, due to an inability to attain structures in thermal equilibrium, they are condemned to undergo thermal relaxation oscillations about a state of marginal contact. If so, then we have yet another reason for the thermal instability.

For the evolution of V471 Tau, Nelson (1976) suggested fission of a rapidly rotating main-sequence star, while others at the same symposium suggested the spiral-in of a post-main-sequence binary which originally had a much longer period. There is no consensus on this

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matter yet.

An answer to the question of a possible evolutionary connection between the groups should involve careful consideration of space densities, mass ranges and ratios, angular momentum, luminosity fuctions, relative ages, kinematical properties, and any real abundance anomalies.

C. Comparing Migration Rates

It is interesting to examine the ratio P(migr.)/P(orb.). Excluding those examples where it appears we do not have synchronous rotation, we are left with SS Boo, SS Cam, RS CVn, Z Her, RT Lac, AR Lac, WY Cnc, CG Cyg, V471 Tau, VW Cep, and W UMa. The range for the RS CVn group is about 350 to 6000. The two examples in the short-period group range between about 2400 and 5800. V471 Tau is around 700. The two examples in the W UMa group range between 1500 and 2600. Thus, with no exceptions, binaries in the related groups fall within the range of P(migr.)/P(orb.) shown by the RS CVn group.

It is particularly interesting that binaries of the W UMa group fit also. They are contact (or supercontact) binaries whereas most of those in the other groups are certain to be detached.

D. Explaining the Amplitude of the O-C Variations

There is a simple way to understand why some of the binaries in these groups have such extraordinarily large O-C variations and, at the same time, to check the basic idea that mass loss is causing the period changes.

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Let us assume, for the purposes of this discussion, that the relative mass outflow per year is roughly the same for binaries in all of the different groups. Further let us assume that, whatever the detailed mechanism for the resultant period changes proves to be, the coefficient relating $d \ln P / dt$ with $d \ln M / dt$ is also roughly the same. With these two assumptions $d \ln P / dt$, which is the degree of curvature in the O-C curve, is roughly the same for all. It can then be shown that the semi-amplitude of the up-and-down deviations in the O-C curve is determined only by the migration period, the relation being

$$\Delta(O-C) : P^2(\text{migr.}) \quad . \tag{1}$$

This relation can be checked by using data and sources already referred to in this review and plotting log Δ(O-C) versus log P(migr.) in Figure 2. No period variation has been detected in 3 of the systems, but we can place an upper limit on the amplitude of the O-C variation. Because the migration rates are not constant in all, their periods have been indicated with a range. The straight line has a slope of 2, as would be required by equation (1). The data adhere to this line surprisingly well, indicating that this simple-minded understanding is on the right track. Let me emphasize what a huge range of O-C variation is hereby accounted for: from Δ(O-C) = ± 17 sec in V471 Tau to Δ(O-C) = ± 0.25 days in SS Cam.

If mass loss is indeed producing the period changes, then there would be some net loss of orbital angular momentum and hence there should be a tendency for the orbital period to decrease. If we look at the overall trend of the O-C curves we see a secular period decrease in RT And, RS CVn, CG Cyg, AR Lac, and possibly Z Her. There is a secular increase in RT Lac. There is no clear trend in SS Cam,

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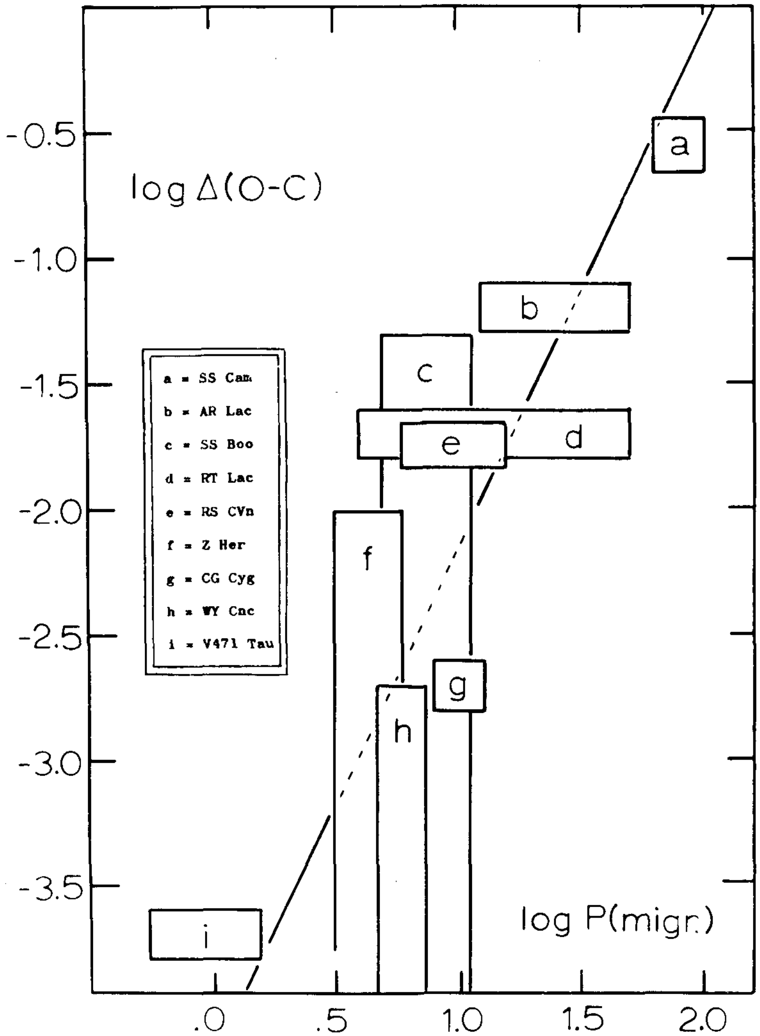

Figure 2. Δ(O–C) is the semi-amplitude of the up-and-down variations in the O–C curve, in days. P(migr.) is the migration period of the distortion wave, in years. Only upper limits to Δ(O–C) are available for SS Boo, Z Her, and WY Cnc. The size of each rectangle includes a nominal ± 10 % accidental uncertainty. The straight line has a slope of 2 and thus corresponds to equation (1).

SV Cam, and V471 Tau. Thus, on the average, there is some indication of the expected net orbital angular momentum loss.

More data would help us understand these interesting period variations better, but it is very difficult to determine the migration rate of an RS CVn binary because one needs light curves fairly complete outside eclipse and distributed without significant gaps over the migration period, which can be decades. Light curves belonging to different migration cycles cannot always be combined in a simple way because the migration rate is not always constant. The amplitude of the wave is usually variable and is sometimes small. And irregular intrinsic light curve changes often complicate the interpretation further. It is even more difficult to correlate wave migration with period changes because, in addition to the migration rate, one must have a well-defined O-C curve covering the same interval of time.

Another difficulty which observers of RS CVn binaries are sadly familiar with is the unfortunate coincidence that many of the orbital periods are near an integral number of days. Of the 24 systems in Table 1, these are AD Cap ($3^{d}.059$), Z Her ($3^{d}.993$), MM Her ($7^{d}.960$), RT Lac ($5^{d}.074$), AR Lac ($1^{d}.983$), VV Mon ($6^{d}.051$), LX Per ($8^{d}.038$), and SZ Psc ($3^{d}.966$). In a random set of irrational numbers greater than unity, fewer than about 12% should have their digits to the right of the decimal greater than 0.960 but less than 0.070. In our sample of 24 we would most reasonably expect about 3. Nature was unkind and gave us 8.

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Discussion to the paper of HALL

SEGGEWISS: You compared the spot activity of the RS CVn stars with that of the sun. I see at least two major differences between the solar spot activity and the RS CVn activity. (1) The light variations of the sun due to spots is on the order of a few thousandths of a magnitude. You need several tenths of a magnitude (i.e., a tremendous activity) for RS CVn stars. (2) On the active sun we find a concentration of spots at certain latitudes, a latitude distribution. For RS CVn stars, you must assume a stable concentration of spots at a certain longitude interval.

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HALL: Concerning the first point, you are entirely correct. In fact if you look at the KO IV component of RS CVn as an example, the brightness of the brighter and the fainter hemispheres are in the ratio 3:2. This must indeed represent tremendous activity. I mention that recently Mullen, in several articles in the Astrophysical Journal, has explored the possibility that the dynamo mechanism, which might be producing spots in our sun, can be scaled up to produce the large-scale spot activity observed in the flare stars and in the RS CVn binaries.

Concerning the second point, let me stress that there is one important difference between the sun and the KO IV star in RS CVn: the sun is a single star. It is my feeling that the presence of the other star in RS CVn, which is nearby and equally massive, is the basic reason for the dramatic longitudinal asymmetry. I cannot, however, even begin to suggest a specific mechanism.

A. WEHLAU: Do the unusually shallow secondary minima of RS CVn show a 10 year periodic variation as would be expected on the basis of the mechanism you propose?

HALL: If my model for RS CVn is correct, the depth anomaly in secondary minimum should show a ∿10-year periodic variation, but no one has yet looked into this. The problem is that only one binary - RS CVn itself - has observational material suitable for such a test. The astronomers at Catania have observed RS CVn each year for about 12 years now, but as of now only 4 years of observations have been published.

GEYER: To comment on Dr. Seggewiss' remarks, I would like to mention that on the sun Wolf in Zurich in 1890 observed that sunspots for several years appeared always at the same solar longitude.

KWEE: According to one of your tables, most of your groups are detached systems. Yet you try to explain the period variations by variations in mass. What mechanism do you propose?

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HALL: The basic idea is that there is strong mass outflow preferentially from the fainter hemisphere, induced presumably by the flare activity expected to be associated with spot activity. When the spotted region is on the leading hemisphere, the period should change in one direction; when the spotted region is on the trailing hemisphere, the period should change in the other direction. Ejection velocities associated with flare activity should be $\gtrsim$ 1000 km/sec, so there is no problem getting the mass to escape from these detached binaries. I think this mechanism is on the right track, but there are still problems and details to be worked out.

MATTEI: The properties that you gave for RS CVn variables are very much like those of T Tauri stars. However, you do not put the T Tauri stars with those like RS CVn variables. May I ask why? Few T Tauri stars are known to be spectroscopic binaries.

HALL: I did not include the T Tauri stars in my list of similar systems because they tend to be single stars. But the point you make is an important one. In fact, if you looked at the KO IV component of RS CVn alone, it would be difficult to distinguish from a T Tauri star in its physical characteristics (mass, radius, luminosity, temperature) and various peculiarities (H and K emission, Hα emission, light variations, ultraviolet excess, infrared excess, and mass outflow).

VAN HORN: I have two questions for you. First, if your mechanism is correct, there must be magnetic fields in these stars. Do you have any idea how large these fields are? Second, with respect to Dr. Lomb's question, do you have some idea of how large the mass-loss rate may be?

HALL: First, to my knowledge no one has ever looked for magnetic fields in these stars. This is an important observation which indeed should be made. I have been suggesting this for several years, with no apparent result, and I can only suggest it again at this time.

Second, I can say that if you use a simple impulse-type mass loss mechanism and assume ejection velocities of 3000 km/sec, you require 10^{-6} $M_\odot$/yr to account for the observed period changes in RS CVn. This is very large, certainly too large. But Dr. Peter Biermann has suggested to me that the ejected mass probably co-rotates with the system out to some Alfven radius which is many times larger than the semi-major axis of the orbit. If so, then the required rate of mass loss can easily be reduced substantially.

BUDDING: How sure can we be that the period changes referred to are real and not just the photometric displacement of minima by the "wave" variation? For example, Binnendijk referred to O-C variations in the minima of YY Gem, but later Kron discounted these as being probably effects of the out-of-eclipse light distortions on the precise positions of the minima.

HALL: This is a very important question to raise. The light curve asymmetry can and does distort the shape of primary eclipse and does generate O-C changes which are spurious in the sense that they do not represent real changes in the orbital period. It turns out, however, that in the majority of cases the observed O-C changes are very many times larger than could be produced by such distortion. The clearest example is SS Cam. Here the total range of the O-C variation is more than a half day, which is more than the angle of external contact for primary eclipse! This matter is discussed in detail in a paper which I have submitted to Acta Astronomica. But I want to join you in emphasizing that the spurious component in the O-C variation of every binary must be recognized, treated critically, and removed before any statement is made about true period changes.

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