THE RELATION BETWEEN RS CVn AND ALGOL

Douglas S. Hall
Dyer Observatory
Vanderbilt University
Nashville, Tennessee 37235
U.S.A.

(Received 20 October, 1988)

ABSTRACT. Late-type secondaries in Algol binaries are rapidly rotating convective stars and thus should be chromospherically active (CA). They are examined with respect to observational manifestations which characterize already known CA stars: Ca II H and K emission cores, photometric variability attributable to starspots, soft x-ray emission, non-thermal radio emission, ultraviolet and infrared excess, and alternating period changes. The conclusion is that they can be regarded as another class of CA stars. In most respects they are literally indistinguishable from other CA stars. Ca II H and K emission cores are observed in the lobe-filling component of six semi-detached binaries: U Cep, RT Lac, RV Lib, AR Mon, S Vel, HR 5110. Alternating period changes are shown to occur only in Algols containing a late-type (convective) star. It is proposed, therefore, that the Matese-Whitmire mechanism explains these changes. Specifically, the interval from one increase (or decrease) to the next can be equated with the star's magnetic cycle. Cycle lengths for 31 stars, derived in this way, range between 7 years and 109 years, with a median of 50 years.

1. INTRODUCTION

The RS CVn binaries, originally defined by Hall (1976), are just one example of stars displaying the phenomenon of chromospheric activity (CA). Stellar CA includes all of the features of solar activity, but with greater intensity: chromospheric emission lines such as Ca II H and K, far-ultraviolet emission lines such as Mg II h and k, spots, coronal x-ray emission, radio emission, flares, anomalies in the continuum energy distribution (ultraviolet and infrared excess), mass loss in a wind, and magnetic fields. For CA stars in binaries we add orbital period changes to the list.

As pointed out by Hall (1987), CA is found in ten groups of stars: (1) RS CVn binaries of the short-period, regular, and long-period subgroups, (2) stars like AY Ceti, 29 Dra, and HD 185510 which most people would consider RS CVn binaries but, because of their white dwarf secondaries (Fekel, Moffett, Henry 1986), fail the Hall definition by a tech-

Space Science Reviews **50** (1989), 219–233.

nicality, (3) BY Dra variables as defined by Bopp and Fekel (1977), some of which are in binaries and some of which are single, (4) flare stars = UV Ceti variables, which are found generally to overlap with the BY Dra variables, (5) solar-type (mostly G) single dwarfs (Baliunas and Vaughan 1985), (6) T Tau variables, as discussed recently by Appenzeller and Dearborn (1984), (7) W-type W UMa binaries, as suggested long ago by Hall (1976) and more recently by Eaton (1986), (8) FK Com stars (Bopp 1983, table III), (9) single, rapidly rotating giants with CA not strong enough to qualify them as FK Com stars (Fekel et al. 1986), and (10) the cool contact component in semi-detached Algol-type binaries such as U Cep (Olson 1985a).

The purpose of this paper is to review in more detail the assertion that the contact components in semidetached Algol binaries are indeed CA, when they are cool enough to be convective.

In Section **2** it will be shown that, with respect to evolutionary state, the RS CVn binaries are quite distinct from the Algol binaries. In Section **3** it will be shown that, with respect to various parameters which have been proposed as predictors of CA, the late-type contact components in Algol binaries clearly should be CA. In Sections **4** through **9** the various observational manifestations of CA will be reviewed in turn, to see if the cool Algol secondaries can be regarded as indistinguishable from other acknowledged CA stars. Section **10**, the last, will summarize with conclusions and predictions for critical observations which should be made.

Throughout this paper, CA stars are taken from the Catalogue of Chromospherically Active Binary Stars (Strassmeier et al. 1988 = CCABS) and Algols binaries are taken from the compilation of 101 systems by Giuricin et al. (1983).

2. EVOLUTIONARY RELATION BETWEEN RS CVn BINARIES AND ALGOL BINARIES

Although the observational characteristics which originally defined the RS CVn binaries (Ca II H and K emission seen outside eclipse, hotter component F or G, and orbital period between 2 and 14 days) did not explicitly include anything about evolutionary status, it turns out that they happen to comprise a fairly homogeneous group of post-main-sequence, pre-mass-transfer binaries (Popper and Ulrich 1977). Morgan and Eggleton (1979) did an excellent job of demonstrating why this apparent coincidence naturally occurs.

The very different evolutionary state of the RS CVn's and the Algols appears dramatically in Figure 1, a plot of lobe-filling fraction (f) versus mass ratio (Q). Here Q is in the sense M(ca)/M(other) for the RS CVn's and M(contact)/M(other) for the Algols. The RS CVn's plotted are all those with radii and masses given in the CCABS; not plotted, however, are the short-period RS CVn's, because they probably are not post-main-sequence, nor those with white dwarf companions (FF Aqr and V471 Tau), because their evolutionary history must be more complicated. The Algols plotted are all those with secondaries later than F; a lobe-filling factor of f = 1 is assumed (Hall 1974, 1975b).

There are four RS CVn binaries which probably are semidetached and hence can be considered Algol binaries as well: RZ Cnc (definitely), RT Lac (probably), RV Lib (possibly), and AR Mon (definitely). Their locations are indicated in Figure 1 with arrows.

The CA star in all the other RS CVn binaries is the more evolved, judging by position in an H-R diagram, and is the more massive of the two, except in a few cases (such as Z Her), where it is slightly less massive. Mass loss by an enhanced stellar wind could explain those few exceptions (Hall and Kreiner 1980).

Of particular interest are those RS CVn binaries having f ≥ 0.9. These should be the first ones to become semidetached and presumably begin mass transfer through their L_1 point. When this happens it should be extremely interesting because we have the ingredients (a more massive convective star filling its Roche lobe) for the extremely rapid mass transfer (≈ 0.1 $M_\odot$/yr) discussed by Plavec et al. (1973). The system to watch is SS Cam, in which the radius of the more massive K0 IV-III star is 95% of its Roche lobe (Arnold et al. 1979).

3. WHY LATE-TYPE ALGOL SECONDARIES SHOULD BE CHROMOSPHERICALLY ACTIVE

The stars in all 10 groups are linked together by the same two factors (rapid rotation and convection) which almost everyone agrees are funda-

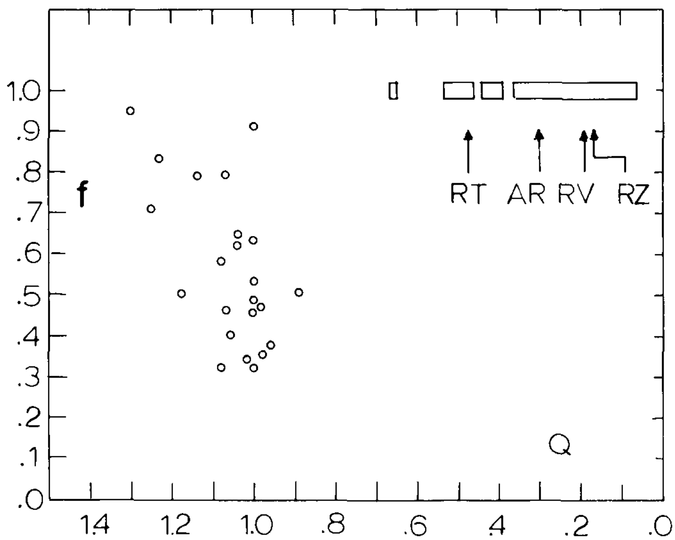

Figure 1. Lobe-filling fraction (f) versus mass ratio (Q). Open circles are known CA stars in RS CVn binaries. Off scale is ε UMi at Q = 2.15, f = 0.4. Late-type secondaries in 73 Algol binaries appear in the upper right at f = 1. Arrows mark four semi-detached RS CVn binaries: RT Lac, AR Mon, RV Lib, RZ Cnc. The two groups (before mass transfer, detached vs. after mass transfer, semi-detached) are well separated.

https://doi.org/10.1017/S0252921100087807 Published online by Cambridge University Press

mentally responsible for CA. To compare observation with theory, various parameters have been used: Ω (angular rotation velocity), V_{EQ} (equatorial velocity), and Rossby number (ratio of convective turnover time to rotation period).

Figure 2 shows that, if we take one of these parameters (V_{EQ}) as an example, cool secondaries in the Algol binaries definitely should be CA. The open circles are all CA components in the CCABS for which the radius and the rotation period are given. The plusses are all secondaries in Giuricin et al. (1983) with spectral types later than F. Three stars which are CA and also fill their Roche lobes (the G9 IV star in RT Lac, the G8 III star in AR Mon, and the K2 IV star in HR 5110) are indicated with circled plusses.

The solid curve corresponds to V_{EQ} = 5 km/sec, which Bopp and Fekel (1977) first demonstrated was the limit for CA. Stars above the curve should be CA, stars below the curve should not. Note the cool Algol secondaries are all above the 5 km/sec line, intermingled with known CA stars. Generally they have even faster equatorial velocities and hence should be even more CA. At this point let us hypothesize that the cool secondaries in Algol binaries <u>are</u> CA, and then look to see if they display the various observational manifestations of CA.

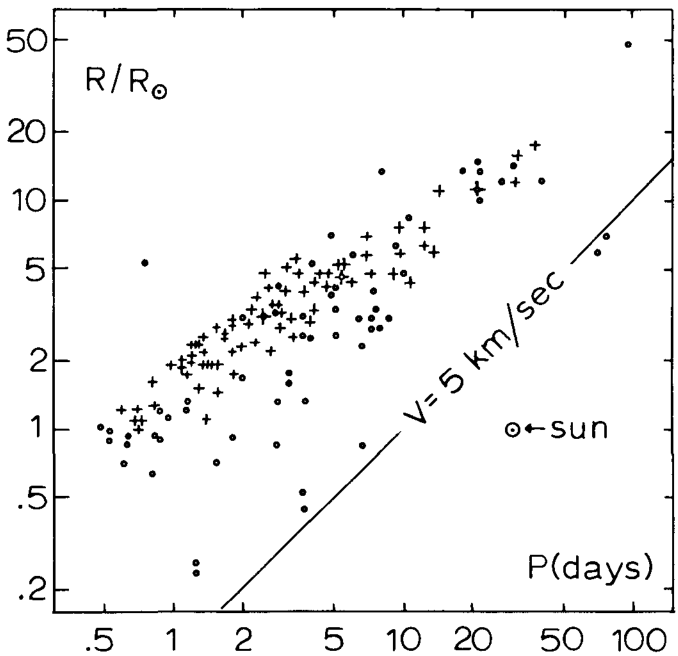

Figure 2. Radius versus rotation period. Open circles are CA stars in the CCABS. Plusses are Algol secondaries later than F. Circled plusses are lobe-filling CA stars. Because stars above the 5 km/sec rotational velocity line should be CA, Algol secondaries should be CA also.

https://doi.org/10.1017/S0252921100087807 Published online by Cambridge University Press

4. Ca II H and K EMISSION

The cool lobe-filling stars in three binaries are already known to show core emission in the Ca II H and K absorption lines, because they appear as such in the CCABS: RT Lac, AR Mon, and HR 5110. Why don't the cores-ponding stars in other Algol binaries display these emission cores also? The answer almost surely is that the far greater relative luminosity of the companion star around 4000 A overwhelms the line profile of the fainter cool star and renders it undetectable.

Figure 3 is a plot of blue magnitude difference ΔB (in the sense other star minus CA star) versus spectral type of the other star. Open circles represent known CA stars for which the CCABS gives M_V for both it and its companion star; ΔB was computed by adding the difference in B-V. Plusses represent Algol secondaries later than F in binaries for which Koch et al. (1970) gave blue light curve solutions; ΔB was computed with - 2.5 log (L''_h /L''_c). As in Figure 2, the lobe-filling CA stars in RT Lac, AR Mon, and HR 5110 are shown as circled plusses.

There is quite a clear separation between the known CA stars and the cool Algol secondaries. The former have ΔB ≈ 0^M whereas the latter

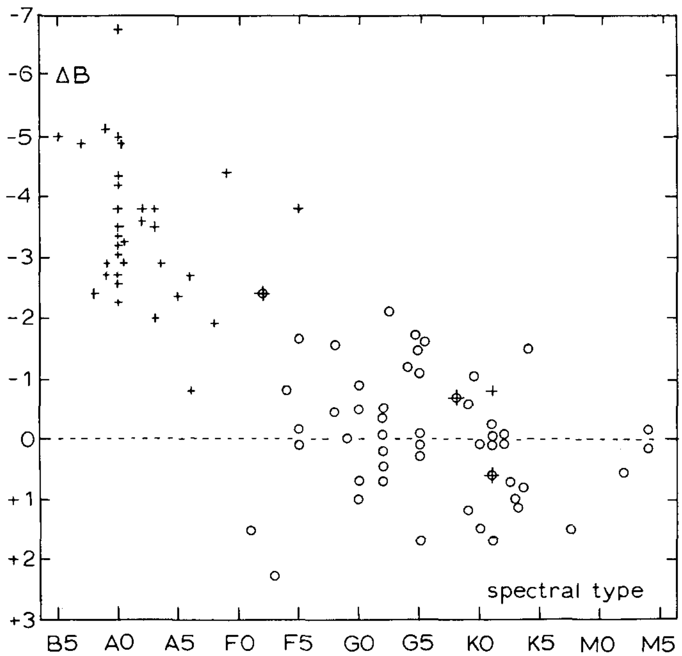

Figure 3. Blue magnitude difference (companion star minus known or suspected CA star) vs. spectral type of companion. Known CA stars (o) have generally late-type companions of comparable brightness. Algol secondaries (+) have generally early-type companions which are several magnitudes brighter. In three cases (⊕) the Algol secondaries are CA.

https://doi.org/10.1017/S0252921100087807 Published online by Cambridge University Press

have $\Delta B \approx -3^{M}_{\cdot}5$. Thus CA has been seen in binaries where the other star is not much brighter, of comparable brightness, fainter, or (in the many SB1 cases, which could not be plotted in Figure 3) too faint to be seen at all. CA has not been seen where the other star is much brighter in the blue part of the spectrum. There is another relevant consideration. The other star in these Algols is generally of spectral type late-B or A, whereas the other star in these CA binaries is generally of spectral type F or G or K. That means Ca II H and K emission must, in the first case, compete with full continuum light (Ca II absorption is weak or absent in A-type and B-type stars) but, in the second case, need only rise above the core of the H and K absorption line of the companion star (Ca II absorption is strong in F, G, and early K stars).

Note the consistent location of the three cases where H and K emission has been seen in a lobe-filling star. For both RT Lac and AR Mon, ΔB is small or positive and the companion star is of late spectral type. HR 5110 (whose H and K emission was observed with difficulty), is intermediate: $\Delta B \approx -2^{M}$ and the companion is an F-type star.

The foregoing discussion makes it clear that, if Ca II H and K emission is to be seen in other Algol secondaries, it must be looked for in totally eclipsing systems when the cooler star can be seen alone. A search of the literature has revealed two other cases: U Cep (Baldwin 1973) and S Vel (Sahade 1952; Bond 1972). There may be others I was not able to find.

There are several reasons why more cases of Ca II H and K emission have not appeared in the literature. First, as shown by Strassmeier et al. (1988, figure 2), one needs extremely good resolution to detect the very narrow emission cores. Even a spectrogram of 2.5 A resolution shows the central emission only 25% as high as it appears on a spectrogram of 0.17 A resolution. There have been very few spectrograms of high dispersion taken during totality of eclipsing Algol binaries. Second, circumstellar matter not eclipsed during totality often produces prominent emission lines, including typically Ca II H and K. Though its profile and the variation of its strength with orbital phase are very different, compared to that associated with CA, its presence can confuse the spectral interpretation. Note that the high-dispersion (40 A/mm) profile of Baldwin (1973) revealed Ca II H and K emission from both circumstellar matter and CA, and could distinguish between the two. Third, recent high-dispersion studies searching for the spectrum of the cool secondaries in Algols have focussed on other portions of the spectrum, for example, where the Na D lines occur. Fourth, the cool secondaries in most of the known eclipsing Algol binaries are very faint in the blue spectral region, many magnitudes fainter on the average than their counterparts in the known RS CVn binaries. Thus makes high dispersion spectroscopy of the Ca II H and K lines very difficult to obtain, especially when exposures must be shorter than the duration of totality.

5. STARSPOTS

Of the previously known (CCABS) lobe-filling CA stars, there is no air-tight photometric evidence of starspot activity, although it remains a

https://doi.org/10.1017/S0252921100087807 Published online by Cambridge University Press

possibility in all. (1) In RT Lac the observed starspot wave is assumed to arise from the other star (Eaton and Hall 1979), which also happens to be CA. (2) In RZ Cnc there is a $0^{m}_{\cdot}05$ starspot wave in the light curve outside eclipse but H and K emission has not yet been observed in the lobe-filling star (Popper 1976). (3) In AR Mon the only available photoelectric photometry makes for a sparsely covered light curve in which photometric peculiarities outside eclipse are not obvious (Popper 1976, figure 5). (4) A $0^{m}_{\cdot}06$ starspot wave is seen in RV Lib (Popper and DuMont 1977) and Ca II H and K emission is seen in both stars, but only circumstantial evidence indicates that one of the stars fills its Roche lobe, namely, its position in Figure 1. (5) In HR 5110 the other star is $1^{m}_{\cdot}7$ brighter in V and $2^{m}_{\cdot}3$ brighter in B (Eker 1985), thus making it very difficult to detect any starspot wave which the CA star might produce (Burke et al. 1980).

In six Algol binaries with late-type secondaries (U Cep, RV Oph, U Sge, XZ Sgr, RW Tau, X Tri) photometric variations at totality have been observed and attributed to that star. References are Knipe (1974) and Olson (1981, 1985a, 1987). Although one must deal with the possibility that circumstellar matter can cause such variability, Olson has used multicolor photometry to prove that the changes should be attributed to the cool star itself. The amplitudes are as large as $0^{m}_{\cdot}2$ in V.

Two different interpretations have been considered for this variability: a general warming of the photosphere, possibly as a precursor to an epoch of mass transfer (Olson 1981), and cool starspot activity (Olson 1985a, 1987). If starspots are present, then the variability could be caused either by the migrating wave so well known in CA binaries (Hall 1987) or by changes in mean brightness which also are common in CA stars (Hall 1987, table II).

Both migrating waves and mean brightness changes have amplitudes ranging between a few hundredths and a few tenths of a magnitude, thus consistent with the above-mentioned photometric variability observed in Algol secondaries.

6. X-RAY EMISSION

Strong soft x-ray emission is a well known characteristic of CA stars (Pallavicini et al. 1981) generally attributed to a corona denser and hotter than the solar corona as a consequence of more rapid rotation. The question is whether the cool secondaries in the Algols share this characteristic. The answer has already been provided by White and Marshall (1983). In a study of nine typical Algol binaries with late-type secondaries, they find soft x-ray emission indistinguishable in an L_X vs V^2_{ROT} relation from that of single stars of various rotational velocity.

In the same relation, they found a sample of RS CVn binaries showing x-ray emission about 3 times stronger, which they attempted to explain. They suggested that magnetic interactions between coronal loops on the two stars make available a larger magnetic volume to contain the x-ray-emitting plasma. Such magnetic loop interactions would not be possible in Algol binaries because the early spectral type of the primary may not involve magnetic loops. See also White et al. (1986).

7. RADIO EMISSION

Extremely strong non-thermal radio emission is one of the outstanding characteristics of CA binary stars, a recent reference being Morris and Mutel (1988). By the late 1970's (Feldman and Kwok 1979) there was general agreement that the emission mechanism is gyrosynchrotron radiation, i.e., magnetic bremsstrahlung by low energy relativistic electrons trapped in a region comparable in size with the semi major axis of the binary orbit. The maximum luminosity at 6 cm ever observed from a CA binary is eight orders of magnitude greater than that ever observed from the sun (Zeilik et al. 1979).

Gibson realized some time ago (Feldman and Kwok 1979) that radio emission observed in Algol binaries can be attributed to their late-type secondaries, which are indistinguishable from the CA components in the RS CVn binaries with respect to spectral type, radius, and rotation. Then, and now, no binary with two early-type components, even those showing significant mass transfer, has ever been found to be a non-thermal radio source (Gibson 1980). Note that the median (of 11 observations) flux at 6 cm is 2×10^{16} ergs sec^{-1} Hz^{-1} for Algol (Mutel and Morris 1987) and the median flux for 53 RS CVn binaries is 2.5×10^{16} ergs $sec^{-1} Hz^{-1}$ (Morris and Mutel 1988, figure 1); they are virtually identical.

The only reason why more Algol binaries have not been detected as non-thermal radio emitters is that they are on average much more distant than most of the known CA binaries. Note that the only other (probable) Algol binary observed as a non-thermal radio emitter, b Per (Hill et al. 1976), is less than three times farther away than Algol. All of the other Algol binaries with late-type secondaries included in the sample of Giuricin et al. (1983) are even more distant.

8. ULTRAVIOLET AND INFRARED EXCESS

Both ultraviolet and infrared excess were included as typical characteristics of CA stars (Hall 1976). Both are now generally attributed to cool starspots on a warmer surrounding photosphere. The presence of two temperature regions will produce a flat spectrum which, if fit to the best single temperature at B-V, will give apparent excess light at U and also at R and I and longer wavelengths. In fact, it is the excess light at I which is commonly used today to derive temperature differences between spotted and unspotted regions (Poe and Eaton 1985).

Ultraviolet excesses are observed in some Algol binaries when the cool star is seen alone during a total eclipse (Hall 1969). In a few cases this has been attributed to ultraviolet continuum emission from circumstellar matter surrounding the hotter star but larger than the projected diameter of the cooler star (Rhombs and Fix 1976).

Recent multicolor (uvbyI) photometry of several Algol binaries during totality (Olson 1985b) has, however, indicated that the cooler star itself has a flat spectrum in many cases and is responsible for the excess light at both U and I. In the same reference he suggested cool starspots and derived the temperature of and fractional area covered by the spotted and unspotted regions.

9. ORBITAL PERIOD CHANGES

Variations in the orbital period were one of the characteristics Hall (1976) listed as typical for CA binaries, but for an even longer time they have been known to be typical of the Algol binaries as well. Many times in the last two decades mass transfer (both conservative and non-conservative) and mass loss from the system have been proposed as the agent for period changes in the Algols. A few dramatic cases of monotonic period increase have been observed when mass transfer is occurring from the less massive to the more massive during the rapid phase, consistent with the expectation of conservative mass transfer theory (Klimek and Kreiner 1973, 1975). And at least one clear case of monotonic period decrease has been observed when mass transfer is occurring from the more massive to the less massive, again during the rapid phase and again consistent with the expectation of conservative mass transfer (Rucinski 1976).

A long standing unsolved problem with the Algol binaries has been the far more common occurrence of alternating period increases and decreases of comparable size observed in the same binary system (Hall 1975a). It should be realized that a period <u>decrease</u> simply cannot be explained by conservative mass transfer when the loser is the less massive star, as is the case with all but a few percent of known Algols. Similarly, even the typical period increase, examined in isolation, presents a problem. The magnitude of a typical period increase is quite large ($\Delta P/P = 3 \times 10^{-5}$) and would, in the context of conservative mass transfer, imply a mass loss of $\approx 10^{-5}\ M_{\odot}$ or an average mass transfer rate of $\approx 10^{-6}\ M_{\odot}$/yr. This is at least two orders of magnitude larger than what would be expected from losers in the slow phase of mass transfer, as is the case for all but a few percent of known Algols. To explain period decreases and subsequent increases, Hall (1975a) proposed a mode of non-conservative mass transfer involving brief episodes of mass loss on a dynamical time scale and temporary storage of angular momentum in a ring or disk around the gainer. However, a crucial prediction of that theory, namely, evidence of greatly enhanced mass loss at epochs of sudden period decreases, was not confirmed by subsequent observation (Olson et al. 1981). That left the period decreases still unexplained.

Matese and Whitmire (1983) proposed a very different mechanism to explain alternating period changes in binaries, one involving changes in the radius of gyration of one star and subsequent spin-orbit coupling. They said very little about a specific mechanism for their hypothesized radius changes. Van Buren and Young (1985), applying that idea to CA binaries, suggested that the radius increases (or decreases) as magnetic fields strengthen (or weaken). They further showed that CA binaries with relatively short coupling times show period changes whereas those with relatively long coupling times do not. On this last point they did not distinguish between systems with monotonically increasing or decreasing periods or those with alternating period changes.

Figure 4 provides strong support for the hypothesis that the same mechanism, i.e., waxing and waning magnetic fields, can be applied to understand (at long last) the ubiquitous alternating period changes in the Algols. The literature was searched to see which of the 101 Algol systems in Giuricin et al. (1983) show period changes. The various symbols distinguish between monotonic period increase, monotonic period decrease, period changes in both directions, and constant periods. The abscissa is spectral type of the contact component, taken from Wood et al. (1980) or from Giuricin et al. (1983, table 2). Note that all cases of alternating period changes (31 out of 31) are restricted to spectral types later than the boundary line between convective and radiative stars. The few cases of period increase or decrease among the early-type (radiative) stars (4 out of 24, β Lyr being one of them) probably are genuine manifestations of mass transfer, most likely in the rapid phase.

Granting that this explanation is correct, then the time interval between a period increase and the next period decrease can be identified

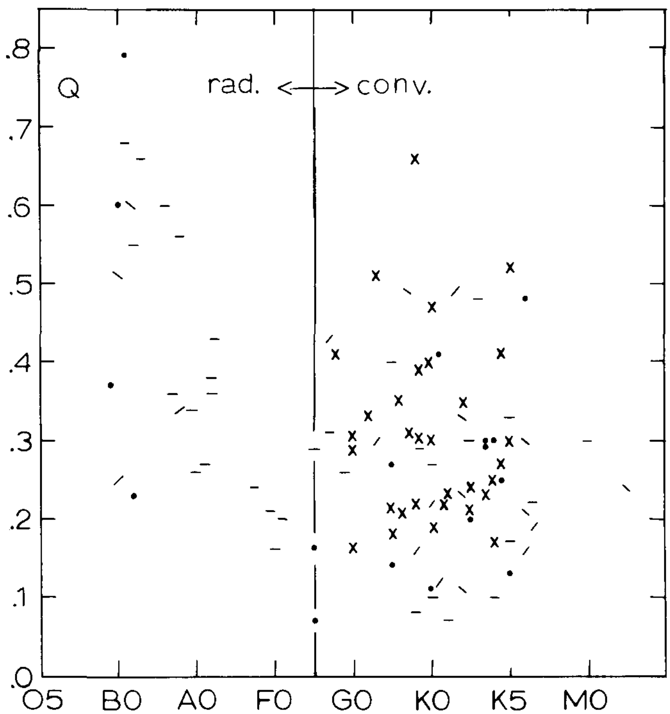

Figure 4. Orbital period changes in Algol binaries with secondaries of various spectral type: constant period (-), increasing period (/), decreasing period (\), increasing and decreasing period (X), inadequate data for judgement (•). Note that all instances of alternating period changes occur when the star is later than F5, i.e., is convective. There is no apparent correlation with mass ratio (Q).

https://doi.org/10.1017/S0252921100087807 Published online by Cambridge University Press

with $P_{MAGN}/2$, i.e., half the star's magnetic cycle. Figure 5 is a histogram of P_{MAGN} derived in this way for the 31 Algol systems which have shown two or more period changes of alternating sign. This represents extremely valuable information pertaining to magnetic cycles on convective stars other than our sun. The baseline in time is much longer than the 18 years available from observations of Ca II K-line flux variations in solar-type stars (Baliunas and Vaughan 1985). In the extreme case of Algol itself, we have 190 years of data (since the 1700's) defining 12 changes in the orbital period and thereby tracing out 6 of the ≈ 32-year magnetic cycles (Söderhjelm 1980). The median magnetic cycle length, in this sample of 31, is 50 years. Gaps in the record, or intervals poorly defined by relatively inaccurate eclipse timings, must have caused some period changes to go unnoticed and thereby biased the results towards longer values of P_{MAGN}. Thus, the true median is probably somewhat shorter than 50 years.

An important link in this explanation for the alternating period changes in Algol (and CA) binaries is a spin-orbit coupling time which must be shorter than the observed P_{MAGN}, i.e., 1 to 10 years. Van Buren and Young (1985) computed $\tau_{sync} \approx 1$ year but, as pointed out by Hall (1987), they made an error of six orders of magnitude by introducing the factor $\Delta\Omega/\Omega = 10^{-6}$. Their sync/nonsync boundary fell between RS CVn and Z Her; taking dimensions for RS CVn from the CCABS and the formulation of VanBuren and Young (1985, eq. 4) without the factor $\Delta\Omega/\Omega$, one gets $\tau_{sync} \approx 10^5$ years. To explain how τ_{sync} could in fact be as short as 1 to 10 years, one should explore the effects of magnetic coupling between the two stars. DeCampli and Baliunas (1979) estimated that magnetic activity might shorten τ_{sync} by 2 orders of magnitude and that uncertainties in magnetic reconnection theory "may be many orders of magnitude".

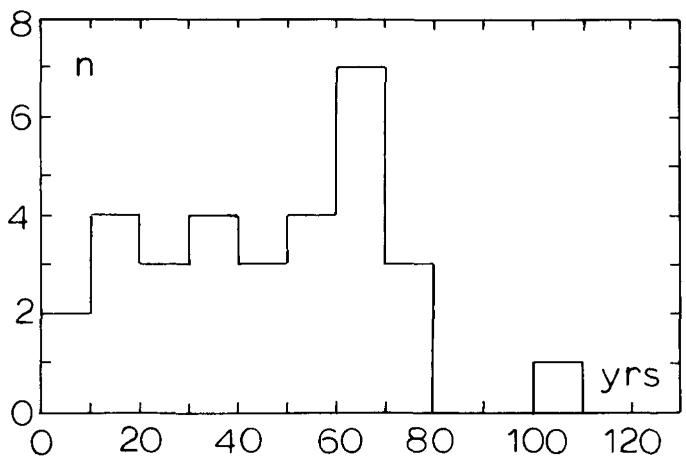

Figure 5. Histogram of magnetic cycle lengths, in years. For 31 late-type Algol secondaries, P_{MAGN} ranges between 7 years and 109 years, with a median of 50 years.

https://doi.org/10.1017/S0252921100087807 Published online by Cambridge University Press

The situation with the Algols is in better shape already. The same formulation of VanBuren and Young, again without the factor $\Delta\Omega/\Omega$, gives $\tau_{sync} \approx 3000$ years, taking dimensions of Algol as an example. Thus, one would need only three orders of magnitude provided by magnetic reconnection theory to make τ_{sync} sufficiently short ($\approx$ 3 years) for the observed magnetic cycle ($\approx$ 32 years). For both the CA binaries and the Algol binaries, the additional effect of mass transfer and/or mass loss, along with the magnetic effects, might act to make τ_{sync} even shorter.

10. CONCLUSIONS

The late-type contact components in Algol-type binaries can be regarded as another group of chromospherically active stars. They display all of the properties characteristic of previously acknowledged CA stars (except, perhaps, flares).

They are convective stars and rapidly rotating, both in angular velocity and equatorial velocity. See Figure 2.

Ca II H and K core emission has been observed in six lobe-filling late-type stars: in U Cep, RT Lac, RV Lib, AR Mon, S Vel, and HR 5110. RV Lib, however, is only presumed to be semi-detached (See Figure 1) because there is no light curve solution in the literature. It is understandable why H and K core emission has not been observed in more such cases. See Figure 3.

Several late-type contact components have been observed to be intrinsically variable, probably as a result of starspot coverage, though it's not clear whether migrating waves or mean brightness changes are the mechanism.

Their x-ray emission is indistinguishable from that of other known CA stars, though binaries containing <u>two</u> late-type rapidly-rotating stars (such as the RS CVn binaries) are about 3 times stronger on the average.

Their strong flare-like non-thermal radio emission seems to be indistinguishable from that of other CA binaries.

Their ultraviolet and infrared excesses, when cases of contamination by circumstellar matter are excluded, can be accounted by a two-temperature source, such as would result from spotted/unspotted regions on the photosphere.

Because alternating period changes occur <u>only</u> in Algols with a late-type (convective) component (see Figure 4), such period changes can be understood by the same physical mechanism which has been proposed to explain similar period changes in other binaries with CA components, i.e., magnetic cycles, consequent small radius changes, and subsequent spin-orbit coupling. More theoretical work is needed to see if the short (a few years) coupling times required by this theory are reasonable. This theory further predicts that TX UMa and U Oph, the only two binaries which exhibit alternating period changes but do not contain a convective star, must prove to show either apsidal motion or to belong to a triple system (Hall 1983).

Conceivably, Algol secondaries which have lost the most mass, and hence probably have relatively shallow convective envelopes, might show

https://doi.org/10.1017/S0252921100087807 Published online by Cambridge University Press

less CA. Note, in Figure 4, that no period changes are seen in the five Algols with $Q \leq 0.10$ (S Cnc, UZ Cyg, AL Gem, RV Oph, DN Ori).

Perhaps the most important finding in this paper is a determination of magnetic cycle lengths for 31 late-type stars. See Figure 5. They range from 7 years to 109 years, with a median of 50 years. Corresponding cycle lengths for six late-type stars in already-known CA binaries (SS Cam, SV Cam, RS CVn, CG Cyg, AR Lac, and V471 Tau) are consistent with these statistics (Hall 1987).

Grants from the Vanderbilt Graduate School and College of Arts and Science, which made presentation of this paper possible, are gratefully acknowledged.

REFERENCES

Appenzeller, I., Dearborn, D.S.P. 1984, Ap.J. **278**, 689.
Arnold, C.N., Hall, D.S., Montle, R.E., Stuhlinger, T.W. 1979, Acta Astr. **29**, 243.
Baldwin, B.W. 1973, P.A.S.P. **85**, 714.
Baliunas, S.L., Vaughan, A.H. 1985, Ann. Rev. Astr. Astrophys. **23**, 379.
Bond, H.E. 1972, P.A.S.P. **84**, 839.
Bopp, B.W. 1983, I.A.U. Colloq. No. 71, 363.
Bopp, B.W., Fekel, F.C. 1977, A.J. **82**, 490.
Burke, E.W. et al. [10 authors] 1980, A.J. **85**, 744.
De Campli, W.M., Baliunas, S.L. 1979, Ap.J. **230**, 815.
Eaton, J.A., Hall, D.S. 1979, Ap.J. **227**, 907.
Eaton, J.A. 1986, Acta Astr. **36**, 79.
Eker, Z. 1985, Wisconsin Astrophysics No. 228.
Fekel, F.C., Moffett, T.J., Henry, G.W. 1986, Ap.J. Suppl. **60**, 551.
Fekel, F.C., Moffett, T.J., Henry, G.W., Simon, T. 1986, Cool Stars, Stellar Systems, and the Sun, edited by M. Zeilik & D.M. Gibson (Berlin: Springer-Verlag), 71.
Feldman, P.A., Kwok, S. 1979, J.R.A.S. Canada **73**, 271.
Gibson, D.M. 1980, I.A.U. Symp. No. 88, 31.
Giuricin, G., Mardirossian, F., Mezzetti, M. 1983, Ap.J. Suppl. **52**, 35.
Hall, D.S. 1969, B.A.A.S. **1**, 345.
Hall, D.S. 1974, Acta Astr. **24**, 215.
Hall, D.S. 1975a, Acta Astr. **25**, 1.
Hall, D.S. 1975b, Acta Astr. **25**, 95.
Hall, D.S. 1976, I.A.U. Colloq. No. 29, 287.
Hall, D.S. 1983, Advances in Photoelectric Photometry **1**, 18.
Hall, D.S. 1987, Pub. Astr. Inst. Czech. **70**, 77.
Hall, D.S., Kreiner, J.M. 1980, Acta Astr. **30**, 387.
Hill, G., Aikman, G.C.L., Cowley, A.P., Bolton, C.T., Thomas, J.C. 1976, Ap.J. **208**, 152.
Klimek, Z., Kreiner, J.M. 1973, Acta Astr. **23**, 331.
Klimek, Z., Kreiner, J.M. 1975, Acta Astr. **25**, 29.
Knipe, G.F.G. 1974, M.N. **167**, 369.
Koch, R.H., Plavec, M., Wood, F.B. 1970, Publ. Univ. Pennsylvania, Astr. Ser. **10**.

Matese, J.J., Whitmire, D.P. 1983, Astr. Astrophys. **117**, L7.
Morgan, J.G., Eggleton, P.P. 1979, M.N. **187**, 661.
Morris, D.H., Mutel, R.L. 1988, A.J. **95**, 204.
Mutel, R.L., Morris, D.H. 1987, A.J. **93**, 1220.
Olson, E.C. 1981, Ap.J. **250**, 704.
Olson, E.C. 1985a, Interacting Binaries, edited by P.P. Eggleton and J.F. Pringle (Dordrecht: Reidel), 127.
Olson, E.C. 1985b, I.A.P.P.P. Comm. No. 19, 6.
Olson, E.C. 1987, A.J. **94**, 1043.
Olson, E.C., Crawford, R.C., Hall, D.S., Louth, H., Markworth, N.L., Piirola, V. 1981, P.A.S.P. **93**, 464.
Pallavicini, R., Golub, L., Rosner, R., Vaiana, G.S., Ayres, T., Linsky, J.L. 1981, Ap.J. **248**, 279.
Plavec, M., Ulrich, R.K., Polidan, R.S. 1973, P.A.S.P. **85**, 769.
Poe, C.H., Eaton, J.A. 1985, Ap.J. **289**, 644.
Popper, D.M. 1976, Ap.J. **208**, 142.
Popper, D.M., DuMont, P.S. 1977, A.J. **82**, 216.
Popper, D.M., Ulrich, R.K. 1977, Ap.J. **212**, L131.
Rhombs, C.G., Fix, J.D. 1976, Ap.J. **209**, 821.
Rucinski, S.M. 1976, P.A.S.P. **88**, 244.
Sahade, J. 1952, Ap.J. **116**, 35.
Söderhjelm, S. 1980, Astr. Astrophys. **89**, 100.
Strassmeier, K.G., Hall, D.S., Zeilik, M., Nelson, E., Eker, Z., Fekel, F.C. 1988, Astr. Astrophys. Suppl. **72**, 291.
VanBuren, D., Young, A. 1985, Ap.J. **295**, L39.
White, N.E., Marshall, F.E. 1983, Ap.J. **268**, L117.
White, N.E. et al. [7 authors] 1986, Ap.J. **301**, 262.
Wood, F.B., Oliver, J.P., Florkowski, D.R., Koch, R.H. 1980, Publ. Univ. Pennsylvania, Astr. Ser. **12**.
Zeilik, M., Hall, D.S., Feldman, P.A., Walter, F. 1979, S. & T. **57**, 132.

DISCUSSION

Batten pointed out that, since the majority of observations of Algol secondaries still had been made photographically, the limitations of that method were important in assessing the incidence of H and K emission. Totality usually lasted only just long enough to get a good spectrogram - well-enough exposed at a high-enough resolution - to show H and K emission. At some eclipses, no spectrogram can be obtained, at others the transient emission may be invisible despite favourable conditions. In partially eclipsing systems, it would be difficult to see the emission. (Bolton recalled that he had reported emission associated with the secondary star in the spectrum of Algol itself - I.A.U. Symp. 51, pp. 71-2, 1973 - and had subsequently recognized it on McLaughlin's Michigan plates.) Batten continued that this problem provided an excellent example of how observational selection might lead one to a wrong answer. Maybe an observing program with modern detectors might yield many more examples of chromospheric H and K emission in Algols. Hill has a number of suitable Reticon observations of Algols but, having obtained them for other purposes, he would have to check the material for emission.

Chen asked about the differences between chromospheric activity in single stars and in binaries. How could one tell whether emission lines, X-rays or radio emission come from disks and streams or from stellar chromospheres? Hall replied that X-rays and radio emission, even in binaries, come from the corona around the cooler star. Their intensities are consistent with the relation between activity and rotation established from single stars, and, in AR Lac, eclipses of the radio and X-ray fluxes identify their origin. Emission lines could arise either from the stellar atmosphere or the disk, but the radial velocity provides a discriminant. Chromospheric lines must give the same radial velocity as the secondary star itself; stream or disk lines usually give a very different velocity?

Parthasarathy said that, with Tomkin and Lambert, he had obtained Digicon spectra of the secondary components of U Cep and U Sge, with the coudé spectrograph of the McDonald 2.7m telescope, and found emission in the core of the K line. Their Reticon observations of the CaII infrared triplet showed those lines to be weak, in the same spectra.

Andersen commented that Steven Saar (now at the Center for Astrophysics) has developed a spectroscopic method for measuring magnetic fields on late-type stars, by comparing Zeeman-broadened and non-broadened lines in spectra of high-resolution and high signal-to-noise ratio. The method is differential and might be applicable to the brighter secondaries of Algols, despite complications produced by the light of the primary stars.

Rucinski emphasized that flares on chromospherically active stars in binaries may not be the same as white-light flares observed on M-dwarfs. The latter are of short duration because, we think, the magnetic structures are small. In RS CVn stars, and Algol, radio and X-ray flares last much longer - usually some hours. He mentioned that recent VLBI maps of Algol by J.-F. Lestrade _et al._ (_Astrophys. J._ **328**, 232, 1988) show that the radio emission comes from the secondary. Richards said that study also shows magnetic fields of the order of 300 Gauss on the photosphere of the secondary component, decreasing to 10 Gauss some distance away from the star. Rucinski commented that activity cycles _may_ be different from magnetic cycles in synchronized binaries, because differential rotation (in some dynamo models considered to be the driver of activity) is usually assumed, in single stars, to be of the same order of magnitude as the rotation itself. This may not be true in binaries; a comparison of activity cycles in single stars and binary components would be a useful check on theories of the angular-momentum transport inside stars. Olson commented that if the variations of Algol secondaries observed during totality really were caused by spots, the variations were probably not the result of a spot cycle, but of phase migration of an "S-wave" as observed in RS CVn systems. He had once observed the secondary of U Sge brightening and could not explain it by spots, but by a very small hot ($T \sim 14{,}000K$) region on the cool star - another example of a prolonged flare.

In reply to a question from Richards, Hall stated that he had _assumed_ that all Algol secondaries rotate synchronously, because they all fill their Roche lobes.