ENVIRONMENTS OF ACTIVE CLOSE BINARY STARS

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ABSTRACT. This review concerns the environments of active close binary stars, namely the RS CVn-type and Algol-type binaries. An introduction to the basics of solar/stellar atmospheric structure is given and a discussion made of the various forms of solar/stellar activity phenomena in relation to close binary systems. The main part of the review discusses recent results in the radio and optical regimes and their consequences for the binary environment and the solar paradigm.

CONTENTS

1. INTRODUCTION

Our present understanding of the stellar machine is essentially an extension of our knowledge of the Sun, supplemented by reasoned theory. Observations of stars have revealed, to a large extent, that phenomena readily observable on the Sun are also present in stars of many types. Because the Sun is so much closer than the stars, its mysteries are so much more easy to unravel. However, although the Sun gives us a framework in which to study stellar phenomena, many questions concerning its structure, evolution and activity are still unanswered and the stars themselves reveal phenomena whose scale is never realized by our closest stellar neighbour. In this respect a study of the phenomena displayed by stars of all types aids in the determination of facts which have a very real bearing on our knowledge of the Sun, its environment and our relationship with it.

This review is concerned with stars which display features very similar to the Sun but at much greater energies. In particular it considers solar-type stars in close binary systems; that is stellar systems in which the proximity of the components may have a significant affect on the solar-like phenomena and the circum-binary environment. In this review an introduction is given to the basics of solar and stellar activity signatures and the assumed cause, namely the magnetic dynamo. The objects under study are then discussed in detail and a review of relevant literature given concerning observations and theories of the environments of these stars. Emphasis is placed on two spectral regions; the radio and optical regimes. The main purpose of the review is to present the basic optical and radio results pertaining to an understanding of the immediate environments of active close binary stars.

2. SOLAR & STELLAR ACTIVITY

2.1. Solar Phenomena

The Sun is a very normal star of spectral type G2 IV. Our understanding of its interior and exterior structure, energy generation, composition, evolution, its rotation, magnetic field, convection and oscillations, although incomplete, is substantial. Most of what is observed from the Sun is radiation leaking from the stellar surface, radiation derived from nuclear processes. The solar *photosphere* is the thin layer of material where the gas turns from almost completely opaque to almost completely transparent. Above this lies the solar *atmosphere* which has a complex structure.

For the quiet Sun (during sunspot minimum) the temperature varies gently through the *chromosphere* but increases rapidly through the *transition region* into the *corona*. This indicates that radiative equilibrium is violated in the outer stellar atmosphere and non-radiative heating mechanisms must be operating. The initial temperature rise occurs in the lower chromosphere in which hydrogen is mainly neutral and metal ions are singly ionised. Heating here probably takes the form of mechanical input and radiative effects such as the photo-ionization of H^- ions by the background photospheric field. Higher up in the chromosphere hydrogen is ionised by the Balmer continuum radiation field and non-radiative heating is balanced by cooling due to emission in optically thin spectral lines such as Ca II, Mg II and the H Balmer lines. Towards the top of the chromosphere hydrogen becomes fully ionised. Here radiative cooling is achieved by emission in the Lyman-α line of neutral hydrogen. The transition region is a relatively thin interface between chromosphere and corona in which the temperature rises sharply to $\sim 10^6$ K. Here radiative losses are due to emission in collisionally excited UV spectral lines of C, N, O, Ne, Mg and Si. Above the transition region lies the solar corona which retains extremely high temperatures. Coronal energy losses are primarily the result of thermal conduction into lower layers, the emission by highly ionised species at EUV and X-ray wavelengths and expansive cooling as the corona dissipates to form the solar wind. A good review of the quiescent solar atmospheric structure can be found in Mariska (1986). Figure 1 shows the temperature structure of the quiet solar atmosphere indicating the position of formation of various atomic lines.

The simple discussion so far has ignored the structural inhomogeneities in the solar atmosphere which are determined primarily by the solar magnetic field geometry. Phenomena which can be attributed to the magnetic field of the Sun include sun-spots, pores, plages, photospheric and chromospheric

Fig. 1. The temperature structure of the quiet solar atmosphere showing the chromosphere, transition region and corona. The regions of formation of various atomic lines are shown. The chromosphere is located between the heights of 500 and 2000 km (after Vernazza, Avrett & Loeser 1981).

networks, spicules, prominences, coronal loops, rays, streamers and the solar wind. Although the basic structure of the solar atmosphere is at least partly understood the details of formation of these examples of *solar activity* are far from clear. Solar activity is a general term for the phenomena which are controlled or produced by enhanced magnetic fields in *active regions*. The commonly accepted theory of solar magnetic activity is that of the *solar dynamo*. This involves the interplay of an otherwise static global magnetic field with differential rotation and convection zone dynamics. A more detailed discussion of the dynamo theory of solar and stellar activity is given below. Here the discussion is concerned more with the manifestations of this activity.

In the photosphere magnetic fields can be concentrated to produce dark *sun-spots* which generally indicate the presence of emerging bipolar magnetic loops. Sun-spots are cool regions (3900 K) located in the hotter (5800 K) photosphere. The relative coolness of sun-spots is evidenced by the existence of absorption bands of TiO molecules which would normally be disassociated at photospheric temperatures (Tandberg-Hanssen 1967). Observational and theoretical data on sun-spots is reviewed by Moore & Rabin (1985). Associated with sun-spots are the bright regions known as *plages*. These are formed by extended magnetic fields permeating the chromosphere and corona giving rise to regions of high electron temperature and density. Since the H Balmer, Ca II H & K and Ca II infra-red triplet (IRT) atomic lines can become collisionally dominated under such conditions they are often seen to be enhanced in plages relative to the quiescent chromosphere. Plage regions are often stronger in Ca II emission than in the Balmer line emission while the converse is true for the quiet chromosphere. This is because Ca II is more sensitive to collisional excitation while the Balmer lines can be dominated by radiation from the photospheric Balmer and Paschen continua (Gebbie & Steinitz 1974). Although not all magnetically active regions on the Sun are accompanied by plage-like material, plages are always associated with enhanced magnetic fields. In fact it has been found that the Hα and Ca II H and K line strength in plage regions is correlated with the local magnetic field strength (Skumanich, Smythe & Frazier 1975). *Prominences* are long-lived structures in the solar atmosphere supported by large magnetic fields. Since they form along the field lines connecting two sun-spots of opposite polarity they are normally located near active regions and typically have a loop-like structure. Since prominence material is cooler than its surroundings it is seen in absorption when viewed against the solar disk and in emission when seen at the limb. *Solar flares* are transitory events (typically lasting several minutes) which are also a direct consequence of magnetic structure. These releases of large amounts of energy are believed to be triggered at the boundary of field lines of opposite polarity. Flares are therefore also found to be associated with sun-spots and plage regions (Svestka 1976). The radiation from the hot solar *corona* is also found to be dependent on the magnetic activity. Magnetic loops from the underlying active regions permeate into the corona and give enhanced X-ray emission along these flux tubes (Zirker 1971; Dunn 1971). Not only are X-ray bright points associated with chromospheric active latitudes (Golub, Krieger & Vaiana 1976) but also track the solar magnetic cycle (Xanthakis 1971). Although the presence of a high-temperature corona in the Sun is not disputed, the mechanism by which it is heated above the photospheric temperature is still undetermined (Kuperus, Ionson & Spicer 1981). A good review of coronal physics is given by Vaiana & Rosner (1978).

The basic mechanisms of solar phenomena are now firmly established with the evolution of the magnetic field. Highly energetic events are dominated by magnetic affects and many of the global and fine structural components of the solar atmosphere are related to interactions of particles and the ambient magnetic field. Furthermore, as will be discussed below, such phenomena are found to occur on other stars. The solar-like phenomena displayed by these *active* stars are therefore often said to be the *solar analogy* or the *solar paradigm.*

2.2. Stellar Activity

Solar-like magnetic activity such as photospheric spots, chromospheric emission and flares are also observed in stars of later spectral type, from about F5 and later. This is to be expected on the basis of the dynamo theory of magnetic field generation since such stars have substantial convective envelopes (see Section 2.3). While the Sun is a useful prototype for active stars, the degree of activity is small in comparison with late-type stars. For example the solar magnetic flux distribution can give rise to sun-spots which cover up to 0.2% of the Sun's surface but some active stars (e.g. dMe stars) can have star-spot coverages of 10-50%. In such stars also the energy release during X-ray, UV and radio flaring can be 10^5 times greater than in solar flares.

Late-type stars are known to contain solar-like chromospheres since emission reversals in the Ca II H and K lines are routinely observed. Their spectra also show the Mg II h and k lines as well as the species CII, CIV, SiIV and NV. Transition regions are also evidenced in these stars by the presence of highly ionised atoms in the far ultraviolet. Coronae are also commonly detected in the X-ray and radio regimes. The atmospheres of such stars also display behaviour which is characteristic of activity variations in the Sun. Long-term variability of the Ca II emission in late-type stars was reported by Wilson (1968). In almost all of the 73 stars observed in that survey there was evidence of cyclical variations in activity and these are now thought to be directly analogous to the solar cycle.

Short duration modulations of colour and luminosity seen in many stars are often interpreted as the passage of large cool unevenly distributed star-spots across the stellar disk (Bopp & Talcott 1978; Strassmeier *et al.* 1989). This is borne out by the correlation of the light-curve variations with rotation rates and the strengthening of the temperature-sensitive molecular TiO bands during the spotted phase of the photometric light curve (Ramsey & Nations 1980). Star-spots on tidally synchronized binaries have been observed to display additional modulations at periods close to but not exactly equal to the binary revolution period. Such wave-like distortions in the light-curves of these systems are interpreted as spot migration to higher latitudes (Vogt 1983) and this is again directly analogous to the latitudinal evolution of sun-spots known as *Spörer's law.* The chromospheric Ca II H and K lines of active stars often display a modulation in intensity. It is hypothesised that the emission originates in solar-like plage regions and the modulation is caused by these features rotating in and out of view on the stellar disk (Nations & Ramsey 1986; Buzasi, Ramsey & Huenemoerder 1987). Since Ca II emission is often much stronger in late-type stars, the question arises whether their plage regions are larger than the Sun's or are intrinsically brighter. Determining stellar rotation from the modulation in plage emission has further revealed some evidence of differential rotation (Rodonó, Pazzani & Cutispoto 1983). However, some stars with very strong emission show no modulation and this is thought to be due to an almost complete coverage by plage regions. Chromospheric and transition region line variations in active stars are also interpreted in terms of the solar paradigm. Rodonó *et al.* (1987) conclude that bright regions in the UV occur over cool stellar surface spots as is observed in the Sun (Zirin 1988).

Prominence-like material is generally difficult to observe optically in active late-type stars. Its presence is inferred because active stars also have hot coronae which in the case of the Sun is threaded by cool condensations and prominences. X-ray observations of stellar coronae have revealed phenomena again comparable to that observed in the Sun. In the Sun highly structured loop-like features in the corona at temperatures of $T \geq 10^6$ K are seen delineating closed magnetic field lines rooted in the photosphere. X-ray studies of active stars (e.g. Walter *et al.* 1980) have been interpreted in terms of this solar paradigm. Radio frequency observations also provide evidence of coronae in late-type stars. The inferred temperatures of the coronal gas are $\sim 10^9$ K and these observations are interpreted as gyrosynchrotron emission from material confined in large coronal loops (Linsky 1985). Prominence-like material which is routinely observed optically in the Sun has as yet not been unambiguously observed in late-type stars.

Many excellent review papers exist concerning solar and stellar activity. A review of the characteristics of magnetic activity observed in the Sun and other stars is given by Noyes (1986) whilst Baliunas & Vaughan (1985) review the evidence for long-term stellar activity cycles. Stellar chromospheric diagnostics and empirical atmospheric models are reviewed by Linsky (1980). Flares on the Sun and stars are discussed by Haisch, Strong & Rodonó (1991) whilst the subject of coronal mass ejections are reviewed by Kahler (1992) and Wagner (1984).

2.3. Dynamo Theory

A possible correlation between rotation and chromospheric activity in late-type stars was pointed out by Kraft (1967) and this is now interpreted in terms of the dynamo theory of magnetic field generation. This hypothesis suggests that late-type stars have magnetic fields generated by a dynamo mechanism, that field generation depends partly on the forces produced by differential rotation and that stellar activity is directly influenced by the presence of emerging magnetic flux. The theory of magnetic field generation in the Sun by such a dynamo mechanism is now firmly established and it is believed such a scenario is also applicable to the stellar case. Reviews of the origins of solar and stellar activity in the dynamo generation of magnetic fields have been provided by Parker (1977), Gilman (1986) and Hartmann & Noyes (1987). The classical $\alpha\omega$ dynamo mechanism (Parker 1970) involves the ω component due to differential rotation which drags the poloidal field lines into stronger toroidal fields, and the α component due to the cyclonic motion of convective cells which twists these toroidal fields which then emerge from the stellar surface as active regions.

Fig. 2. Several rotation-activity relations for active close binary stars. The soft X-ray flux (0.2-4 keV) and transition region line fluxes (N V 1240 + C IV 1549 + Si V 1400) normalised to bolometric flux are plotted against an empirically determined Rossby number R. Points and linear fits are plotted for single stars, close binaries and contact binaries. From data by Vilhu (1984).

Noyes (1983) found that stellar Ca II emission levels, when normalised to bolometric emission could be approximated as the product of angular rotation rate and an additional function of spectral type. This function was of the same form as the convective turn-over time-scales derived from interior convection models. This suggested that the inverse of the Rossby number (R_o), the ratio of rotational period (P_{rot}) to convective turnover time-scale (τ_c), may be the governing parameter in determining stellar surface magnetic activity. Hence stellar mass, or equivalently, main-sequence spectral type, is also found to play an important role in the determination of activity since it is this which dictates the properties of the convection zone. It is expected that stars of later spectral type (that is, with higher fractional depths of interior convection) will show stronger dynamo behaviour than stars of earlier spectral type, for a given rotation period.

The theory is at least partly demonstrated for a number of different classes of stars. Coronal relations have been reported by Walter & Bowyer (1981) for RS CVn systems, and by Pallavicini *et al.* (1981) and Schrijver, Mewe & Walter (1984) for mostly single stars. Chromospheric relations were presented by Middelkoop (1981) and Noyes *et al.* (1984). Vaiana *et al.* (1981) found that the ratio of X-ray to bolometric luminosity in K and M dwarfs increases steadily with advancing spectral type, even though surface rotation decreases with advancing spectral type along the lower main-sequence (Vaughan *et al.* 1981). Walter (1981) also found that G8-K5 main-sequence stars show a factor of 10 greater X-ray normalised luminosity than do F8-G5 stars with the same rotation rate, showing the importance of spectral type for field generation. Figure 2 shows several reported rotation-activity relations for active single and close binary stars.

The rotation-activity relation is now firmly established although the details of its operation are at best only partly understood. Although current dynamo models can reproduce many observed properties of the solar magnetic activity cycle and naturally explain more transient phenomena they cannot predict all the observed properties and are in an embryonic stage of application to the stellar case (Gilman & Miller 1981).

3. ACTIVE BINARY STARS

3.1. Activity in Binary Stars

Some of the highest levels of activity are seen in close binary systems consisting of cool (F to M-type) stars. In such systems the components are forced to rotate rapidly due to tidal interactions and often have rotational periods which are synchronized with the orbital periods. Stars of this type are often observed to have high coronal X-ray fluxes and have chromospheric and transition region line fluxes orders of magnitude greater than observed in the Sun. A good review of magnetic activity in close binary systems is provided by Guinan & Gimenez (1993).

Active binary systems, and in particular such systems which display regular eclipsing behaviour, are important for the study of stellar magnetic activity for several reasons. Firstly the physical parameters of the component stars, such as mass, radius and luminosity ratios may be independently derived from orbital analyses. Eclipsing systems can also be extremely useful since they may allow the mapping of the spatial distribution and extent of the chromosphere and corona as well as directly revealing the stellar parameters in the shape of the optical light curve during eclipse. Tidally induced rapid rotation also maintains a high level of activity throughout most of the system's lifetime thereby producing a sample of stars whose magnetic characteristics are essentially unaffected by the decrease in rotation rate with age. Active binary stars are therefore a powerful probe of the currently accepted ideas on magnetic activity generation.

This review is concerned only with the classes of active close binaries known as RS CVn stars and Algol-type binaries but it would be wise to briefly mention several other related classes of object which have a bearing on this field. BY Dra stars (Bopp & Fekel 1977) are similar to RS CVns but generally consist of late dG, dK or dMe stars with short orbital and rotational periods (~0.5-20 days). The photometric and spectral characteristics are similar in nature to RS CVns (Vogt & Penrod 1983). Synchronous rotation is not a defining characteristic of this group and it is believed that some systems are highly active due to their youth rather than spin-orbital coupling. Furthermore some stars defined as BY Dra stars are actually single stars. W UMa binaries are also similar to RS CVns but are generally contact binaries with very short rotation periods (typically 0.25 days). A-type W UMas are characterised by a regular eclipsing light curve and contain stars earlier than F5 while W-type W UMas show evidence of star-spot modulation and contain stars later than F5. Other related objects include X-ray binaries, cataclysmic variables and symbiotic stars although there is no evidence that any of these groups evolves into another. Figure 3 shows the essential properties of both the RS CVn and Algol-type binary systems considered in this review.

3.2. The RS Canum Venaticorum Binaries

The RS Canum Venaticorum (RS CVn) binaries named after the prototype (RS Canis Venaticum) are a particular class of active binary systems which were originally defined by Hall (1976). Good reviews of these objects are given by Linsky (1983) and Montesinos, Gimenez & Fernandez-Figueroa (1988). The prerequisites for membership of this class of stellar systems is that the binaries have orbital periods between 1 and 14 days, contain at least one component of spectral type F-G V-IV and the Ca II H and K lines are in emission outside of eclipse. The cooler component is usually a sub-giant or giant K-type star which is the more massive member. Both stars normally lie well within their Roche surfaces although some systems display evidence of mass transfer (Huenemoerder, Buzasi & Ramsey 1989). Photometric measurements often reveal the presence of low-amplitude quasi-sinusoidal light variations which are interpreted as cool surface star-spots. Migration of the photometric wave in phase relative to the orbital ephemeris is taken as evidence of the latitudinal migration of such star-spots such as is observed on the Sun. Other common features include strong coronal X-ray and radio emission, variable Hα emission, strong UV chromospheric and transition region line emissions (e.g. Mg II h & k and C IV), flaring and orbital period changes, probably due to activity cycles and/or mass loss (Kalimeris *et al.* 1995; Doyle *et al.* 1994).

The RS CVn class is now usually divided into three subgroups, the short-period RS CVns, classical RS CVns and the long-period RS CVns with orbital periods of $<$ 1 day, 1-14 days and $>$ 14 days respectively. For systems with small rotation periods the stars almost certainly rotate synchronously and are tidally locked producing high rotation rates. De Campli & Baliunas (1979) and Scharlemann (1981) considered the tidal forces in such systems in relation to both the circularization of the orbit and to the spin-up of the rotational period resulting in synchronism. Even though the circularization time-scales are much larger than the synchronization time-scales the orbital eccentricities of these systems are close to zero. Linsky (1983) pointed out that the limiting orbital period for synchronously rotating stars among classical RS CVns is about 20 days. It should also be mentioned that the binarity of these systems, apart from producing synchronicity may also influence the dynamics of the convection zone and Roche surface over-filling. For example Young & Koniges (1977) suggest that another relevant parameter for activity studies in binaries is the ratio of the stellar to the Roche radius.

However binarity affects the individual stars in RS CVns, it is clear that their components display many features which by solar analogy are of a magnetic origin. The unambiguous detection of magnetic fields on RS CVn stars is difficult because the rotational broadening dominates over any Zeeman broadening or splitting in spectral lines. However, Donati *et al.* (1990) have found evidence of kilogauss fields and large filling factors (the fraction of stellar surface coverage by magnetic fields) of about 0.14 on the very active HR 1099 system.

A great deal of work has been done on the characteristics of the RS CVns in the optical and the UV. In fact, most of what is known about these systems is derived from the low-amplitude quasi-sinusoidal broad-band light curve modulations attributed to surface star-spots. In general such studies suggest star-spots are 500-1000 K cooler than the surrounding photosphere, can cover up to 40% of the stellar surface (Eaton & Hall 1979; Doyle *et al.* 1988) and can even form in the polar regions. The presence of star-spots is also independently verified by Doppler imaging studies (Vogt & Penrod 1983) in which small distortions in the rotationally broadened spectral lines due to spots are used to recover the surface brightness distribution of the star. Even though this technique requires large amounts of good quality data it has been successful in a number of cases (Strassmeier 1990). In addition, as pointed out by Ramsey (1990), most RS CVn binaries have excess TiO absorption in their spectra which may be ascribed to the presence of star-spots. Evidence for associated plage-like material is also found in the optical and UV, primarily as rotational modulation of activity sensitive lines. For example, Rodonó *et al.* (1987) show that bright active regions on the II Peg system occur nearly over the cool photospheric spots. Localised chromospheric emission was also observed by Neff & Neff (1987) in AR Lac. Measurements in both the optical and the UV (using IUE) of the IM Peg system by Huenemoerder, Ramsey & Buzasi (1990) showed strong modulations in amplitude which appeared to remain for time-scales of up to a year. Hα and/or Ca II (H and K or the IRT) modulations by plages on RS CVn systems have also been seen by Nations & Ramsey (1980) and Barden (1984).

The solar-like structure of the atmosphere of RS CVns extends into the coronal regions. The evidence suggests these regions are very inhomogeneous and consist of hot (10^7 K) thermal plasma confined by closed magnetic loops in the corona. The X-ray emission has been modelled with coronal loop structures using analogous formalism developed for the Sun (Doyle, van den Oord & Kellett 1992; Rosner, Tucker & Vaiana 1978). However, in order to account for the high X-ray luminosities these structures must be much hotter, more numerous and larger than seen in the Sun. Mewe & Schrijver (1986) found an anti-correlation for X-ray flux with optical photometry for

Fig. 3. Schematic representation of the properties of RS CVn and Algol-type binaries. Both types of binaries contain an early K-type star which possesses a deep convection zone and surface starspots (although the latter are difficult to detect in Algols). The evolved K-star has an active chromosphere and high-temperature X-ray/radio corona. In Algol binaries mass transfer takes place via an accretion stream (after Lestrade 1988).

the λ And system and suggested this was due to the spatial correlation between X-ray emitting regions and photospheric spots. Some observations in X-rays require a two-component temperature model. Swank *et al.* (1981) found that their observations were best represented by a bimodal energy distribution characterised by temperatures of 4-7 $\times$ 10^6 K and 2-8 $\times$ 10^7 K. Walter *et al.* (1987) and White *et al.* (1987) also use a two-component X-ray model for the AR Lac system; one component confined near the stellar surface and another extended. It is believed this two-component model may be related to the core-halo morphology required to explain some radio observations of RS CVns (Mutel *et al.* 1985). However Majer *et al.* (1986) have challenged the two-component X-ray models. Work in X-rays by White *et al.* (1990) and Culhane *et al.* (1990) for AR Lac and TY Pyx respectively has provided important evidence on the extent of the coronal X-ray sources in RS CVns. Eclipses visible at lower energies ($<$ 1 keV) during the orbital cycles were not visible at higher energies. This indicates that the high-temperature plasma may be enveloping the entire binary system, confined by interacting magnetic loops between the two active stars (Uchida & Sakurai 1983) while the low temperature plasma originates in regions smaller than a stellar component. Although X-ray observations to date are consistent with the solar analogy, but at much higher energies, the details of coronal X-ray sources in RS CVns are far from clear. An important question that remains is whether the X-ray and radio emission originates from the same cospatial plasma. The radio properties of RS CVn systems are reviewed below.

Flare-like events in RS CVn binaries are difficult to detect optically since the hotter star dominates the system's flux at these wavelengths. Observations of flares at X-ray, UV and radio wavelengths are much easier (Walter *et al.* 1987; Trigilio, Umana & Migenes 1993). In general these events appear to be common in RS CVns and can be explained using the basic solar flare model of localised injection of energy at the base of magnetic loop structures followed by radiative cooling (Doyle, Byrne & van den Oord 1989; Byrne 1989). Such flares indicate high temperature plasma of densities close to 10^{12} cm^{-3} and X-ray energy releases of 10^{37} erg. In the radio the less dense plasma ($\leq 10^{10}$ cm^{-3}) can reach brightness temperatures of about 10^{10} K. Models show that flares on RS CVns, like other types of active stars, resemble solar compact or two-ribbon flares but at significantly higher energies. Flares are also often observed as broadened and shifted UV emission lines (Linsky *et al.* 1989).

Some work has been devoted to the study of rotation-activity correlations in RS CVn binaries. UV line fluxes have been found to be correlated with rotation by Oranje, Zwaan & Middelkoop (1982). Vilhu & Rucinski (1983) similarly found that transition region emissions were correlated with period but noted that these appeared to reach a saturation limit for the short-period systems. Middelkoop (1981) showed that for Ca II emission synchronized binaries behave much like single stars of the same rotation rate. Transition region and coronal correlations have also been reported by Basri, Laurent & Walter (1985). Both these authors and Walter (1987) showed that in general dwarf stars did not display any correlations whilst giant stars of the same rotation period did. Strassmeier *et al.* (1989) noted a similar effect in that Hα and Ca II emission from giant stars in binary systems display higher activity levels than dwarf stars of the same rotation rate. These results demonstrate that it is the surface velocity which is the dominant factor in the dynamo generation of magnetic activity.

Basri (1987) has further showed that both single and binary stars show rotation-activity correlations but demonstrated that binarity itself was not a significant factor in determining activity levels. Correlations have also been noted in the X-ray (Walter & Bowyer 1981) and radio (Drake, Simon & Linsky 1989; Gunn 1996) regimes for RS CVns. Hence the dynamo generation of activity in these stars is consistently indicated from the lower chromosphere through the corona although the dependence on luminosity class, spectral type and binarity itself requires further work. As mentioned above there is strong evidence that the dynamo mechanism may saturate in short period RS CVns (Vilhu 1987; Fleming, Gioia & Maccacaro 1989). This may be due to rapidly rotating stars becoming completely covered with magnetic fields thus preventing the atmosphere from converting additional mechanical energy into non-radiative heating. However, it has been suggested by numerical calculations (Houdebine *et al.* 1995) that this energy may be simply transfered to other spectral regions (e.g. the UV continuum).

The evolutionary status of active binary stars is crucial to an understanding of their activity levels. Popper & Ulrich (1977) discussed the evolutionary status of RS CVn systems and concluded that emission characteristics develop as they enter the Hertzsprung gap. More recently, Barrado *et al.* (1994) and Montesinos, Gimenez & Fernandez-Figueroa (1988) have confirmed the evolved state of RS CVn components. Their location near the base of the giant branch where hydrogen shells can ignite and envelope expansion can occur shows that the convection zone properties can be significantly altered from main-sequence stars. In fact, it is possible that turnover timescales can increase by an order of magnitude over a very narrow range in spectral types. Furthermore, the temperature at the base of the giant branch depends strongly on metallicity so this increase in convective efficiency can occur at different temperatures in stars of different abundances. Consequently the Rossby number may undergo some quite rapid variations over a narrow temperature range in the RS CVn systems. Although a preliminary analysis of this type was presented by Gilliland (1985) this is an area which has been neglected in studies of the activity in close binary stars.

Although our present knowledge of solar and stellar activity is substantial the study of such phenomena in RS CVn systems may still provide important clues concerning the dynamo mechanism. These systems provide valuable laboratories in which to study stellar plasma magneto-hydrodynamics, the structure and dynamics of stellar atmospheres, and the effects of rotation, evolution, angular momentum loss and mass loss on the activity.

3.3. The Algol-type Binaries

The Algol-type binaries are a well-studied group of eclipsing systems named after the prototype Algol (β Persei). They are generally characterised by relatively simple optical light curves with deep minima and fairly constant brightness outside of eclipse. The classical Algol binaries (Budding 1986) are semi-detached systems consisting of an early-type primary and either a late-type (later than F5) secondary (EA2 Algols) or an early-type (earlier than F5) secondary (EA1 Algols). It was realized early in the study of these stars that they presented an evolutionary problem, the so-called *Algol paradox*. This is merely that in such systems the primary stars are the more massive even though the secondaries appear to be the more evolved components. It was pointed out by Kopal (1955) that this paradox can be resolved if significant mass transfer has occurred from the secondary to the primary. In this model the secondaries were initially the more massive components and in the course of their evolution expanded, came into contact with their Roche equipotential surface and subsequently lost mass which either left the system or was accreted onto the primary. Algols represent perhaps one of the most fundamental types of binary system in which the binarity itself has introduced evolutionary differences between the two components. Optically Algols show strong evidence of mass leaving the secondary components. Spectroscopic perturbations and photometric variability are often interpreted in terms of accretion streams, accretion disks and circumstellar envelopes. Some good reviews of Algol-type phenomena have been presented by McCluskey (1993), Batten (1981) and Shu & Lubow (1981).

Photometric investigations reveal that the cooler components of Algols appear to have spectral types, radii and rotation rates similar to the active components of RS CVn binaries. The main difference is that the active stars in Algols are significantly evolved, invariably contact their Roche surfaces and have lost a substantial fraction of their mass. Since UV, IR and optical spectra of Algols are dominated by their hotter components it is extremely difficult to study the activity signatures of their cooler components. However, because Algols are tidally locked like the RS CVns they also have high rotation rates and should therefore also display magnetic activity in the cooler stars. The totally eclipsing system U Cep (B7 V + G8 III-IV) has given excellent proof of the activity of the cooler components in Algols. During primary eclipse the B7 V star in this system is totally occulted producing a deep nearly flat-bottomed photometric light curve. IUE spectra of this system (Gimenez *et al.* 1990) reveal a rich emission line spectrum similar to those arising from the chromospheres of RS CVn stars. U Cep has also given evidence for cool photospheric star-spots. Olson (1985) presented nine years of photometry for this system and found evidence of a cyclic variability in the brightness of the G8 III star as well as smaller flare-like events. Further evidence of star-spots has been presented by Richards (1990) who analysed the IR light curve of the Algol system and found strong indications of a distortion wave such as those often found for RS CVns. These results could be successfully modelled by star-spots on the cooler (K2) secondary with temperatures several hundreds of degrees less than the photospheric temperature. Hence, although observational evidence in the optical region for solar-like activity in Algols is difficult to obtain, all the available data suggests their cooler components are indeed active. Even though this is to be expected on the basis of the dynamo theory, further observational work is required to confirm this assertion.

A great deal of evidence for solar-like activity in the cool components of Algols can be found in the X-ray and radio regimes. Radio observations of Algols will be discussed further below. Algol itself was first detected as an X-ray source by Schnopper *et al.* (1976). A study of several systems by White & Marshall (1983) indicated quiescent X-ray luminosities of 1-7 $\times\ 10^{30}$ erg s^{-1} which are very similar to those observed on RS CVns. Another similarity with RS CVns is that the X-ray data can be successfully modelled with a bimodal temperature distribution ($T_1 \sim$ 1-6 $\times\ 10^6$ K and $T_2 \sim$ 2-4 $\times\ 10^7$ K). As pointed out by Pallavicini (1981) the early-type components of Algols can not be expected to have such high X-ray luminosities so the emission is thought to arise in the coronae of the late-type stars. Sequential observations of Algol in X-rays by White *et al.* (1986) using EXOSAT revealed that the cool star's corona was not eclipsed by the B-star and so must extend out to at least one stellar radius ($\geq 3R_{\odot}$). This result was later confirmed by Stern *et al.* (1990). These results are extremely interesting because a similar lack of coronal eclipses are found for RS CVns using X-rays. Hence the dimensions of X-ray coronae in close binary systems do not seem to be primarily dependent on the relative activity levels of the components. This has cast serious doubts on the interacting field mechanism proposed by Uchida & Sakurai (1983) for the formation of extended coronae in RS CVns.

As is the case with RS CVns, Algols are known to undergo dramatic flares at X-ray wavelengths. Both White *et al.* (1986) and Stern *et al.* (1992) observed long duration X-ray flares in Algol with an energy release of $\sim 1 \times 10^{39}$ erg s^{-1} in the 0.1-10 keV energy band with a peak temperature of $\sim 6 \times 10^7$ K. Furthermore, the observation of Fe XXV emission confirms that flares are produced by thermal heating of plasma which, by solar analogy, is confined in the coronal magnetic loops of the cooler star. Although such events appear to be more frequent and more energetic than those observed on the Sun, they are again comparable to or less energetic than those observed in the more active RS CVns (Linsky 1990).

It is now beyond doubt that Algol systems display many characteristics of solar-like activity and that these are to be expected from their late-type rapidly rotating components. However, a comparison of the properties of Algols and RS CVns reveals similarities which are unexpected; namely that activity levels and coronal sizes are independent of the relative activity levels of the stellar components. This has important consequences for dynamo theory in general.

4. ENVIRONMENTS OF ACTIVE CLOSE BINARY STARS

4.1. Optical Environments

In recent years evidence has been accumulating that some stars have cool coronal condensations analogous to solar prominences. In many respects these features can be regarded as the remaining phenomenon to be confirmed for active stars which are routinely seen optically on the Sun.

The detection of cool material overlying the surface of a star is extremely difficult since in all but the most extremely active stars such material would manifest itself as a small additional absorption feature overlying the global absorption lines. This problem is also exacerbated by the fact that other regions such as plages or lower chromospheric structure, which may also be present, can actually fill-in the global absorption profile due to the increasing collisional domination of the source function for the activity sensitive transitions. An attempt at detecting such prominence-like material must therefore account for a variety of effects. To remove the effect of core-filling of active lines, the technique of *spectral subtraction* is often used. This technique essentially involves subtracting from the spectrum of the active star a synthetic spectrum representing this star in all other respects other than having an inactive chromosphere. The resulting subtracted spectrum then reveals the additional absorption or emission profiles believed to be due only to the active chromosphere of the star. Although this simple technique contains many assumptions it has been used widely in recent years and has revealed many interesting features of active stars. The presence of plage-like or prominence-like material is often shown in subtracted spectra as excess emission or absorption features. In fact, if the absorption by cool material is sufficiently strong it may even be visible in the unsubtracted spectra. The problem with this interpretation is that it is difficult to assign such features unambiguously to absorbing material because they could equally well arise from intrinsic changes in the line-forming regions. Time series of spectra can to a certain extent alleviate this by providing evidence for features which evolve in a self-consistent manner. However, a much more powerful technique is available whereby absorption features can be unambiguously disassociated from the global absorption or emission lines. This technique is to observe active close binary systems which periodically undergo geometrical eclipses. If the geometry is suitable, cool coronal material in the atmosphere of the eclipsing star can absorb the photospheric continuum radiation of the star behind.

The observational evidence for stellar prominences is still very sparse. AB Dor is a well studied single K0 dwarf star for which Robinson & Collier Cameron (1986) reported the presence of transient features in the Hα line. Subsequent work on this star (Collier Cameron & Robinson 1989a; Collier Cameron & Robinson 1989b; Collier Cameron *et al.* 1990) has shown that the most consistent interpretation of these features is of prominence-like condensations of mainly neutral material trapped in corotation with the star by the stellar magnetic field. The variability in the Hα line is consistent with a series of clouds crossing the stellar disk, and by solar analogy these are thought to consist of filamentary structures of cool material. Using such observations it is, in fact, possible to deduce some information on the extent and location of these prominences. Some other single stars are known to show clear evidence for large circumstellar prominences (Collier Cameron & Woods 1992). The main requirement seems to be the presence of magnetic loop structures extending far into the corona with field strengths sufficient to support the material against centrifugal ejection (Byrne, Eibe & Rolleston 1996).

The work mentioned above has all concerned the existence of prominences in rapidly rotating young, single, dwarf stars of spectral types G-K. More has been done on the tidally synchronized evolved giant and sub-giant stars in RS CVn binaries. In such stars excess absorption features are commonly seen in subtracted spectra and arise due to prominence-like material occulting one of the component stars during eclipses (Hall & Ramsey 1992a). Spectral subtraction is used to deconvolve the contributions from individual stars. Hall *et al.* (1990) reported extensive observations of the RS CVn binary SS Boo in the Balmer lines as well as the Ca II H and K and Ca II IRT. An unusual excess absorption occurred near primary eclipse in the Balmer lines and this was attributed to an extended region of 4-4.6$R_{\odot}$. It was further shown that the feature could not be associated with an accretion stream which was seen as an Hα transient feature in similar observations of the UX Ari system by Huenemoerder, Buzasi & Ramsey (1989b). In a follow up campaign Hall & Ramsey (1992b) surveyed 10 RS CVn systems and reported stable prominence-like material corotating with either the primary or secondary stars in eight of their targets. This study concluded that amongst the eclipsing RS CVn stars prominence material was a common feature. Buzasi, Huenemoerder & Ramsey (1991) made a study of the HR 1099 system in which spectral subtraction was performed on optical

Fig. 4. The effect of a prominence-like feature on the optical spectrum of an RS CVn binary. In this Hα observation of the AW Her system the K star is partially eclipsing the G star. The extended region shown obscuring the G star (schematically) is responsible for the excess absorption in the subtracted spectrum while the other extended region leads to excess emission in the blue wing of the Hα line (after Hall & Ramsey 1992b).

spectra in the Hα, Hβ and Ca II lines. When the excess line fluxes were plotted as a function of time a striking discontinuity was found such that the Hα line flux dropped by about 30% for about a third of the orbit. During the drop the Hα line appeared to be phase modulated whereas before it was not. These authors interpreted this as the disappearance of a large stellar structure which was perhaps prominence-like. In fact Buzasi (1989) concluded that extended prominences are the most reasonable explanation for the Balmer line emission from HR 1099. Recently Hall & Ramsey (1994) have provided a first generation model for analysing the characteristics of prominence absorption in the subtracted spectra of RS CVn binaries. Even though this model is by no means sophisticated it generally produces physical parameters in broad agreement with the solar paradigm. Other evidence for extended material has been found in other types of binary system. The BY Dra system DH Leo is known to be non-eclipsing yet was observed to have excess absorption in Hα near conjunction (Barden *et al.* (1985); Newmark *et al.* 1990). This observation implies that a very large region extended from the K-dwarf secondary in DH Leo far enough to occult the K0 V primary. Newmark (1990) also found evidence for extended material near the contact region of the W UMa type system VW Cep. Figure 4 shows the effect of a prominence-like feature in the optical spectrum of an RS CVn binary.

Since the geometry of many of these inferred prominences exceeds the Roche lobes of the components it is reasonable to assume they are magnetically confined. This also lends credence to the hypothesis that they are analogous to solar prominences. As shown by Hall & Ramsey (1994) these prominences are much larger than their solar counterparts. Young, Rottler & Skumanich (1991) have noted the Hα variations in the V471 Tau system which consists of a white dwarf and a K2 dwarf companion. Although this system is certainly more complex than other RS CVn binaries (in fact it may be a pre-cataclysmic binary) it is possible that the white dwarf is occulted shortly before eclipse by a large extended component on the K2 star (Lim, White & Cully 1996). Neff *et al.* (1989) studied the RS CVn system AR Lac with the IUE and found excess absorption in their spectra at phase 0.039 which they interpret as the presence of a large inactive spot on the G component. However, they did note the possibility that such a feature could arise from extended material associated with the K star.

Less direct methods have been used to infer the presence of prominence material in RS CVn binaries. Buzasi (1989) developed an NLTE radiative transfer model to derive values of the Balmer equivalent width ratio of the Hα and Hβ lines in subtracted spectra. A grid of models was used representing plage-like and prominence-like material over a range of appropriate temperatures, densities and optical depths. These results showed that low ratios of $\sim$ 1-2 could be achieved in both plages and prominences viewed against the stellar disk but that values between $\sim$ 3-15 could only be achieved in prominences seen off the limb of the star. Similar conclusions were given by Heasley & Mihalas (1976) who discussed detailed models of quiescent solar prominences. Observational confirmation of these predictions is given by Landman & Mongillo (1979) who observed high ratios in solar prominences seen at the limb, and by Chester (1991) who found ratios of < 2 in solar plage regions. In RS CVn binaries high Balmer line ratios are often found (Huenemoerder & Ramsey 1987; Huenemoerder & Barden 1986; Newmark 1990; Hall *et al.* 1990).

The results discussed above, if real, are significant in that previously the extended coronal regions of active stars were

Fig. 5. The formation of large-scale radio coronae in active late-type binaries. A VLBI hybrid map of the RS CVn binary UX Ari at 4.98 GHz is shown with the dashed circles representing the positions of the binary components at the time of observation. This star shows the typical core-halo radio structure which may be a consequence of the intense magnetic interaction of the two stars (after Mutel *et al.* 1985; Uchida & Sakurai 1983).

the domain of the X-ray and radio observers. They further suggest that there exists cospatial plasma with significant emission measure at both optical and X-ray wavelengths; probably consisting of fine threaded cool regions delineating magnetic loops permeating the hot corona. Since these structures ultimately represent the interface of the stellar atmosphere with the stellar wind they provide important insights into the physics of corona-wind interaction, the eruptive ejection of material into the ambient environment and hence angular momentum and mass loss effects. The unambiguous optical identification of coronal structures in active late-type stars, and in particular in active close binaries, is by no means conclusively proved. However the pursuit of this subject represents one of the last components of the solar paradigm for active stars.

4.2. Radio Environments

Since most of the radio emission observed in the Sun is a consequence of magnetic activity it is not surprising to find that RS CVn and Algol binaries are also radio sources. In fact Algol itself was one of the first radio stars to be detected (Wade & Hjellming 1972). What has become clear in studies to date is that many stars, including close binaries, in which the dynamo generation of magnetic activity is expected to operate, show evidence for large coronal regions similar to but more energetic than those in the Sun. Good reviews of the radio properties of close binaries can be found in Elias & Mutel (1993) and Lestrade (1988).

For RS CVn binaries the emission in the radio is characterised by three distinct phases; (a) *quiescent* emission showing moderately circularly polarized emission with brightness temperatures of 10^8-10^9 K with a nearly flat spectrum, (b) *flare* emission characterised by unpolarized radiation with brightness temperatures of $\geq 10^{10}$ K and a positive spectral index and which typically last a few hours to days and (c) high-intensity short-duration outbursts with high degrees of circular polarization. These three phases of emission are normally attributed to gyrosynchrotron, synchrotron and electron cyclotron maser processes respectively. A good review of radio emission mechanisms in stars and the Sun is given by Dulk (1985).

In general it is found that emission associated with flare events arises in regions smaller than or comparable to a stellar radius while quiescent emission arises from an extended halo whose dimensions are comparable to the overall size of the binary system. Often both forms of emission are present and such a structure is said to have a *core-halo* morphology. More direct evidence for the large size of radio coronae in RS CVns was presented by Owen & Spangler (1977) and Doiron & Mutel (1984) who both failed to detect a radio eclipse in the eclipsing system AR Lac. VLBI observations by Mutel *et al.* (1985) have also indicated the extensive nature of radio coronae. These authors presented a time dependent model of the emission to account for the core-halo morphology. Electrons are accelerated in a compact region with strong magnetic fields which is initially optically thick and therefore produces a positive spectral index and a low degree of circular polarization. As the source expands radially the magnetic field decreases and the electrons radiate by synchrotron processes. Eventually the source expands enough to become optically thin and appears as an extended halo with a negative spectral index and a high degree of circular polarization. Such a model is consistent with the evolution of magnetic loops in the Sun.

There has been some debate concerning the origin of the

Fig. 6. Results of high-resolution VLBI imaging of the Algol system. A consistent model of the radio emission from Algol involves several radiation processes including coronal gyrosynchrotron radiation and highly circularly polarised microwave bursts. Detailed scrutiny of minute positional displacements in VLBI observations of Algol have also unambiguously demonstrated that the radio emission is associated with the less massive K subgiant star (after Lestrade *et al.* 1988; Lestrade *et al.* 1993).

large-scale coronal structures in RS CVn binaries and the importance of binarity in their formation. Observations indicate the existence of magnetic structures whose geometry is independent of the orbital phase and are symmetrical about the equatorial axis of the system. This may be explained by a single magnetic dipole centred on the active star. Since X-ray observations of RS CVns (e.g. Dempsey *et al.* 1993; Swank *et al.* 1981; Walter *et al.* 1980) also indicate similar large coronal regions it has been suggested that the radio and X-ray emission is cospatial. This contention is supported by the strong correlation between X-ray and 6-cm luminosities in a large sample of RS CVns reported by Drake, Simon & Linsky (1989). The problem with this interpretation is that the X-ray emission is consistent only with a population of *thermal* electrons whereas the radio emission seems to require a *non-thermal* electron population. How such cospatial correlated populations of electrons can exist in the coronae of RS CVns is not clear.

Another possibility for the large coronae of active binaries is that of a joint magnetosphere between the two stellar components. This can form since in RS CVns both stars are expected to develop dynamo-generated magnetic fields. Uchida & Sakurai (1983) suggested that the existence of stellar differential rotation in the radial direction can lead to twisting of magnetic flux tubes and the subsequent reconnection of loops can give rise to the extended coronae. A similar proposition of interacting magnetic flux tubes was used to explain the UV properties of the RS CVn system UX Ari by Simon, Linsky & Schiffer (1980). Currently this model suffers from the observation of similar large radio emission regions in some active single stars (Turner 1985) and Algol-type systems. Figure 5 shows the large-scale core-halo structure observed in the UX Arietis system and the interacting field model which may explain this observation.

Not a great deal of work has been done on Algol-type binaries in the radio regime despite the fact that Algol was one of the first detected stellar radio sources. Elias & Gudel (1993) have observed several peculiar emission line Algol systems while Algol itself was included in a wider survey of stellar radio emission presented by Estalella *et al.* (1993). Clark, Kellerman & Shaffer (1975) showed that the dimensions of Algol in the radio are considerably greater than the size of an individual star and that the emission implied a brightness temperature of 4×10^8 K from a plasma magnetised with fields of $B \sim 10$ G. Mutel *et al.* (1985) applied the core-halo model of radio emission to 5 GHz observations of Algol. This model was found to be successful for both RS CVns and Algols. For Algol they found that the core component was smaller than the size of each star and originated in a high-temperature, highly magnetised plasma ($T_b \sim 10^{10}$ K, $B \sim 100$ G). The halo component was circularly polarized and appeared to originate from a region comparable in size to the binary system with $T_b \sim 10^9$ K and $B \sim 10$ G. A complex model of the Algol system using VLBI observations was presented by Lestrade *et al.* (1988). They suggested that gyrosynchrotron emission arises from an extended coronal region with an almost uniform electron density and magnetic field which decreases slowly with radial distance. They further proposed that flare events were triggered by magnetic reconnection at local sites within the corona producing inhomogeneous self-absorbed synchrotron emission. Conclusive proof that the quiescent microwave emission in Algol is associated with the cooler star was presented by Lestrade *et al.* (1993) who analysed minute positional displacements in their VLBI observations. Figure 6 shows the resulting models from high-resolution VLBI images of the Algol system presented by Lestrade *et al.* (1988) and Lestrade *et al.* (1993).

Umana, Catalano & Rodonó (1991) and Umana *et al.* (1993) also interpret three-frequency spectra of a small sample of Algol binaries with a core-halo model. They found that for all targets the observed spectrum could not be explained by homogeneous sources with constant magnetic field strength and uniform electron density for any electron energy distribution they considered. They concluded that the emission process was non-thermal in origin and showed that the core components were smaller than the size of the active stars with a magnetic field of 60-100 G. They proposed that a search for modulation of the emission with orbital phase would better locate these components. Not only do these results concerning the dimensions of the radio emitting regions in Algols correspond very well to those observed in RS CVns but the levels of emission and the source detection rates are strikingly similar. The average radio luminosity in the Algol survey of Umana, Catalano & Rodonó (1991) was 1.6×10^{16} erg s^{-1} Hz^{-1} while the median value for RS CVns in the survey of Morris & Mutel (1988) was 2.5×10^{16} erg s^{-1} Hz^{-1}. Furthermore brightness temperatures of $T_b \sim 10^8$-10^9 K and magnetic fields of 10-100 G seem to be common for both groups. Another survey of stellar radio emission by Slee *et al.* (1987) detected 30% of the observed Algol systems at 3.6-cm. Stewart *et al.* (1989) analysed these observations and concluded that the emission is probably gyrosynchrotron emission from mildly relativistic electrons gyrating in magnetic fields of 150-300 G. The most significant result of this work was the detection of radio emission from EA1 Algol binaries; that is systems in which both stars are earlier than F5 and therefore cannot be expected to display dynamo-induced magnetic activity.

A comparison of the radio properties of RS CVn binaries and Algol systems provides a viable test of the mechanism originally proposed by Uchida & Sakurai (1983) to explain the intense and extensive emission from RS CVns. As mentioned above this model involves particle acceleration within a large joint magnetosphere. In Algols no such mechanism should be possible but they appear to display quantitatively similar behaviour to the RS CVns. The observations of radio emission in EA1 Algols also confounds this problem. Clearly the details of radio emission in active close binary stars and its relationship with the magnetic dynamo and the binarity of the systems are far from being understood.

5. CONCLUSIONS

Although recent work has eluded to the possibility of cool coronal material being observed optically this must remain a matter of contention. The question of whether this material can be distinguished in active close binaries is still unanswered. Most recently Gunn & Doyle (1996) and Gunn, Doyle & Houdebine (1996) found no evidence of substantial extended regions of absorbing material in a further three RS CVn binaries. Confirmation of these features and their importance in mass loss, angular momentum loss, rotational breaking and in the circumstellar environment must await the development of better observational techniques.

Observations in the radio regime to date have essentially concluded that the coronae in active close binaries are extensive. What is unclear is whether the observed properties of such binary-scale emission is directly influenced by the proximity of the stars and/or their relative degrees of activity. The direct comparison of the location and extent of radio source regions in RS CVn and Algol binaries is a crucial test of the details of magnetic activity in close binaries. In the future the further investigation using VLBI techniques and space-based VLBI (for example the VSOP satellite) and a more detailed investigation of the details of radio emission from active close binaries will hopefully answer some of the remaining questions concerning these stars.

These questions have an important bearing on the study of active stars of all types. Firstly the effects of binarity, the so-called *duplicity enhanced activity* for active stars is still unsettled. The differences inherent in the activity of dwarf and giant stars is an important clue as to its origin. The basic manifestations of activity and their relative levels in stars of different spectral types and rotation rates still require clarification. The possibility of mass loss, either through Roche lobe filling or through impulsive energetic events and its effects on activity, are also not well understood. Finally the magnetic behaviour of stars in the context of stellar evolution are also in need of refinement.

References

Baliunas S. L., Vaughan A. H., 1985, ARA & A, 23, 379.

Barden S. C., Ramsey L. W., Fried R. E., Guinan E. F., Wacker S. W., 1985, in Zeilik M., Gibson D. M., eds, Cool Stars, Stellar Systems and the Sun. Springer Verlag, p. 241.

Barden S. C., 1984, PhD thesis, Pennsylvania State University.

Barrado D., Fernandez-Figueroa M. J., Montesinos B., De Castro E., 1994, A & A, 290, 137.

Basri G., Laurent R., Walter F. M., 1985, ApJ, 298, 761.

Basri G., 1987, ApJ, 316, 377.

Batten A. H., 1981, in Kahn T. D., ed, Investigating the Universe. Reidel: Dordrecht, p. 207.

Bopp B. W., Fekel F. C., 1977, AJ, 82, 490.

Bopp B. W., Talcott J. C., 1978, AJ, 83, 1517.

Budding E., 1986, Ap & SS, 118, 241.

Buzasi D. L., Huenemoerder D. P., Ramsey L. W., 1991, PASP, 103, 1077.

Buzasi D. L., Ramsey L. W., Huenemoerder D. P., 1987, ApJ, 322, 353.

Buzasi D. L., 1989, PhD thesis, Pennsylvania State University.

Byrne P. B., Eibe M. T., Rolleston W. R. J., 1996, A & A, (in press).

Byrne P. B., 1989, in Haisch B. M., Rodonó M., eds, Solar and Stellar Flares. Kluwer: Dordrecht, p. 61.

Chester M. M., 1991, PhD thesis, Pennsylvania State University.

Clark B. G., Kellerman K. I., Shaffer D., 1975, ApJ, 198, L123.

Collier Cameron A., Robinson R. D., 1989a, MNRAS, 236, 57.

Collier Cameron A., Robinson R. D., 1989b, MNRAS, 238, 657.

Collier Cameron A., Woods J. A., 1992, MNRAS, 258, 360.

Collier Cameron A., Duncan D. K., Ehrenfreund P., Foing B. H., Kuntz K. D., Penston M. V., Robinson R. D., Soderblom D. R., 1990, MNRAS, 247, 415.

Culhane J. L., White N. E., Shafer R. A., Parmar A. N., 1990, MNRAS, 243, 424.

De Campli W. M., Baliunas S. L., 1979, ApJ, 230, 815.

Dempsey R. C., Linsky J. L., Fleming T. A., Schmitt J. H. M. M., 1993, ApJS, 86, 599.

Doiron D. J., Mutel R. L., 1984, AJ, 89, 430.

Donati J. F., Semel M., Rees D. E., Taylor K., Robinson R. D., 1990, A & A, 232, L1.
Doyle J. G., Byrne P. B., van den Oord G. H. J., 1989, A & A, 224, 153.
Doyle J. G., Butler C. J., Morrison L. V., Gibbs P., 1988, A & A, 192, 275.
Doyle J. G., Mitrou C. K., Mathioudakis M., Avgoloupis S., Mavridis L. N., Varvoglis P. P., Graos F., Antonopoulou E., 1994, A & A, 291, 135.
Doyle J. G., van den Oord G. H. J., Kellett B. J., 1992, A & A, 262, 533.
Drake S. A., Simon T., Linsky J. L., 1989, ApJS, 71, 905.
Drake S. A., Simon T., Linsky J. L., 1992, ApJS, 82, 311.
Dulk G. A., 1985, ARA & A, 23, 169.
Dunn R. B., 1971, in Macris C. J., ed, Physics of the Solar Corona. Reidel: Dordrecht, p. 114.
Eaton J. A., Hall D. S., 1979, ApJ, 227, 907.
Elias N. M., Gudel M., 1993, AJ, 106, 337.
Elias N. M., Mutel R. L., 1993, in Sahade J., McCluskey G. E., Kondo Y., eds, The Realm of Iteracting Binary Stars. Kluwer Academic Publishers, p. 335.
Estalella R., Paredes J. M., Rius A., Marti J., Peracaula M., 1993, A & A, 268, 178.
Fleming I. A., Gioia I. M., Maccacaro T., 1989, ApJ, 340, 1011.
Gebbie K. B., Steinitz R., 1974, in Athay R. G., ed, Chromospheric Fine Structure, IAU Symp. 56. Reidel: Dordrecht, p. 55.
Gilliland R. L., 1985, ApJ, 299, 286.
Gilman P. A., Miller J., 1981, ApJS, 46, 211.
Gilman P. A., 1986, in Sturrock P. A., Holzer T. E., Mihalas D. M., Ulrich R. K., eds, Physics of the Sun Vol. I: The Solar Interior. Reidel: Dordrecht, p. 95.
Gimenez A. et al., 1990, in Rolfe E. J., ed, Evolution in Astrophysics: IUE Astronomy in the Era of New Space Missions. ESA SP-310, p. 383.
Golub L., Krieger A. S., Vaiana G. S., 1976, in Bumba V., Kleczek J., eds, Basic Mechanisms of Solar Activity, IAU Symp. 71. Reidel: Dordrecht, p. 145.
Guinan E. F., Gimenez A., 1993, in Sahade J., McCluskey G. E., Kondo Y., eds, The Realm of Iteracting Binary Stars. Kluwer Academic Publishers, p. 51.
Gunn A. G., 1996, IAJ, 23, 33.
Gunn A. G., Doyle J. G., 1996, A & A, (in press).
Gunn A. G., Doyle J. G., Houdebine E. R., 1996, A & A, (in press).
Haisch B. M., Strong K. T., Rodonó M., 1991, ARA & A, 29, 275.
Hall J. C., Ramsey L. W., 1992a, in Giampapa M. S., Bookbinder J. A., eds, Cool Stars, Stellar Systems and the Sun. ASP Conference Series Vol. 26, p. 359.
Hall J. C., Ramsey L. W., 1992b, AJ, 104, 1942.
Hall J. C., Ramsey L. W., 1994, AJ, 107, 1149.
Hall J. C., Huenemoerder D. P., Ramsey L. W., Buzasi D. L., 1990, ApJ, 358, 610.
Hall D. S., 1976, in Fitch W. S., ed, Multiple Periodic Variable Stars, IAU Coll. 29. Reidel: Dordrecht, p. 287.
Hartmann L. W., Noyes R. W., 1987, ARA & A, 25, 271.
Heasley J. N., Mihalas D., 1976, ApJ, 205, 273.
Houdebine E. R., Mathioudakis M., Doyle J. G., Foing B. H. 1995. A & A (in press).
Huenemoerder D. P., Barden S. C., 1986, AJ, 91, 583.
Huenemoerder D. P., Ramsey L. W., 1987, ApJ, 319, 392.
Huenemoerder D. P., Buzasi D. L., Ramsey L. W., 1989, AJ, 98, 1398.
Huenemoerder D. P., Ramsey L. W., Buzasi D. L., 1990, ApJ, 350, 763.
Kahler S. W., 1992, ARA & A, 30, 113.
Kalimeris A., Mitrou C. K., Doyle J. G., Antonopoulo E., Rovithis-Livaniou H., 1995, A & A, 293, 371.
Kopal Z., 1955, Ann. Astrophys., 18, 379.
Kraft R. P., 1967, ApJ, 150, 551.
Kuperus M., Ionson J. A., Spicer D. S., 1981, ARA & A, 19, 7.
Landman D. A., Mongillo M., 1979, ApJ, 230, 581.
Lestrade J. F., Mutel R. L., Preston R. A., Phillips R. B., 1988, ApJ, 328, 232.
Lestrade J. F., Phillips R. B., Hodges M. W., Preston R. A., 1993, ApJ, 410, 808.
Lestrade J. F., 1988, in Moran J., Reid M., eds, The Impact of VLBI on Astrophysics and Geophysics. Reidel: Dordrecht, p. 265.
Lim J., White S. M., Cully S. L., 1996, ApJ, 461, 1009.
Linsky J. L., Neff J. E., Brown A., Gross B. D., Simon T., Andrews A. D., Rodonó M., Feldman P. A., 1989, A & A, 211, 173.
Linsky J. L., 1980, ARA & A, 18, 439.
Linsky J. L., 1983, in Baliunas S. L., Hartmann W., eds, Cool Stars, Stellar Systems and the Sun. Springer Verlag, p. 244.
Linsky J. L., 1985, Sol. Phys., 100, 333.
Linsky J. L., 1990, in Ibanoglu C., ed, Active Close Binaries. Kluwer: Dordrecht, p. 747.
Majer P., Schmitt J. H. M. M., Golub L., Harnden F. R., Rosner R., 1986, ApJ, 300, 554.
Mariska J. T., 1986, ARA & A, 24, 23.
McCluskey G. E., 1993, in Sahade J., McCluskey G. E., Kondo Y., eds, The Realm of Iteracting Binary Stars. Kluwer Academic Publishers, p. 39.
Mewe R., Schrijver C. J., 1986, A & A, 169, 178.
Middelkoop F., 1981, A & A, 101, 295.
Montesinos B., Gimenez A., Fernandez-Figueroa M. J., 1988, MNRAS, 232, 361.
Moore R., Rabin D., 1985, ARA & A, 23, 239.
Morris D. H., Mutel R. L., 1988, AJ, 95, 204.
Mutel R. L., Lestrade J. F., Preston R. A., Phillips R. B., 1985, ApJ, 289, 262.
Nations H. L., Ramsey L. W., 1980, AJ, 85, 1086.
Nations H. L., Ramsey L. W., 1986, AJ, 92, 1403.
Neff J. E., Neff D. H., 1987, in Linsky J. L., Stencel R. E., eds, Cool Stars, Stellar Systems and the Sun. Springer Verlag, p. 531.
Neff J. E., Walter F. M., Rodonó M., Linsky J. L., 1989, A & A, 215, 79.
Newmark J. S., Buzasi D. L., Huenemoerder D. P., Ramsey L. W., Barden S. C., Nations H. L., Seeds M. A., 1990, AJ, 100, 560.
Newmark J. S., 1990, PhD thesis, Pennsylvania State University.
Noyes R. W., Hartmann L. W., Baliunas S. L., Duncan D. K., Vaughan A. H., 1984, ApJ, 279, 763.
Noyes R. W., 1983, in Stenflo J. O., ed, Solar and Stellar Magnetic Fields: Origins and Coronal Effects, IAU Symp. 102. Reidel: Dordrecht, p. 133.
Noyes R. W., 1986, in Sturrock P. A., Holzer T. E., Miha-

las D. M., Ulrich R. K., eds, Physics of the Sun Vol. III: Astrophysics and Solar-Terrestrial Relations. Reidel: Dordrecht, p. 125.
Olson E. C., 1985, in Eggleton P. P., Pringle J. E., eds, Interacting Binary Stars. Reidel: Dordrecht, p. 127.
Oranje B. J., Zwaan C., Middelkoop F., 1982, A & A, 110, 130.
Owen F. N., Spangler S. R., 1977, ApJ, 217, L41.
Pallavicini R., Golub L., Rosner R., Vaiana G. S., Ayres T., Linsky J. L., 1981, ApJ, 248, 279.
Parker E. N., 1970, ARA & A, 8, 1.
Parker E. N., 1977, ARA & A, 15, 45.
Popper D. M., Ulrich R. K., 1977, ApJ, 212, L131.
Ramsey L. W., Nations H. L., 1980, ApJ, 239, L121.
Ramsey L. W., 1990, in Wallerstein G., ed, Cool Stars, Stellar Systems and the Sun. ASP Conference Series Vol. 9, p. 195.
Richards M. T., 1990, ApJ, 350, 372.
Robinson R. D., Collier Cameron A., 1986, PASA, 6, 308.
Rodonó M. et al., 1987, A & A, 176, 267.
Rodonó M., Pazzani V., Cutispoto G., 1983, in Rodonó M., Byrne P. B., eds, Activity in Red Dwarf Stars, IAU Coll. 71. Reidel: Dordrecht, p. 179.
Rosner R., Tucker W. H., Vaiana G. S., 1978, ApJ, 220, 643.
Scharlemann E. T., 1981, ApJ, 246, 292.
Schnopper H. W., Delvaille J. P., Epstein A., Heimken H., Murray S. S., Clark G., Jernigan G., Doxsey R., 1976, ApJ, 210, L75.
Schrijver C. J., Mewe R., Walter F. M., 1984, A & A, 138, 258.
Shu F. H., Lubow S. H., 1981, ARA & A, 19, 277.
Simon T., Linsky J. L., Schiffer F. H., 1980, ApJ, 239, 911.
Skumanich A., Smythe C., Frazier E. N., 1975, ApJ, 200, 747.
Slee O. B., Nelson G. J., Stewart R. T., Wright A. E., Innis J. L., Ryan S. G., Vaughan A. E., 1987, MNRAS, 229, 659.
Stern R. A., Haisch B. M., Nagase F., Uchida Y., Tsuneta S., 1990, in Wallerstein G., ed, Cool Stars, Stellar Systems and the Sun. ASP Conference Series Vol. 9, p. 224.
Stern R. A., Uchida Y., Tsuneta S., Nagase F., 1992, ApJ, 400, 321.
Stewart R. T., Slee O. B., White G. L., Budding E., Coates D. W., Thompson K., Bunton J. D., 1989, ApJ, 342, 463.
Strassmeier K. G., Hall D. S., Boyd L. J., Genet R. M., 1989, ApJS, 69, 141.
Strassmeier K. G., 1990, ApJ, 348, 682.
Svestka Z., 1976, Solar Flares. Reidel: Dordrecht.
Swank J. H., Holt S. S., White N. E., Becker R. H., 1981, ApJ, 246, 208.
Tandberg-Hanssen E., 1967, Solar Activity. Waltham, MA: Blaisdell.
Trigilio C., Umana G., Migenes V., 1993, MNRAS, 260, 903.
Turner K. C., 1985, in Hjellming R. M., Gibson D. M., eds, Radio Stars. Reidel: Dordrecht, p. 283.
Uchida Y., Sakurai T., 1983, in Rodonó M., Byrne P. B., eds, Activity in Red Dwarf Stars, IAU Coll. 71. Reidel: Dordrecht, p. 629.
Umana G., Catalano S., Rodonó M., 1991, A & A, 249, 217.
Umana G., Trigilio C., Hjellming R. M., Catalano S., Rodonó M., 1993, A & A, 267, 126.
Vaiana G. S., Rosner R., 1978, ARA & A, 16, 393.
Vaiana G. S. et al., 1981, ApJ, 245, 163.
Vaughan A. H., Baliunas S. L., Middelkoop F., Hartmann L. W., Mihalas D., Noyes R. W., Preston G. W., 1981, ApJ, 250, 276.
Vernazza J. E., Avrett E. H., Loeser R., 1981, ApJS, 45, 631.
Vilhu O., Rucinski S. M., 1983, A & A, 127, 5.
Vilhu O., 1984, A & A, 133, 117.
Vilhu O., 1987, in Linsky J. L., Stencel R. E., eds, Cool Stars, Stellar Systems and the Sun. Springer Verlag, p. 110.
Vogt S. S., Penrod G. D., 1983, PASP, 95, 565.
Vogt S. S., 1983, in Rodonó M., Byrne P. B., eds, Activity in Red Dwarf Stars, IAU Coll. 71. Reidel: Dordrecht, p. 137.
Wade M., Hjellming R. M., 1972, Nature, 235, 270.
Wagner W. J., 1984, ARA & A, 22, 267.
Walter F. M., Bowyer S., 1981, ApJ, 245, 671.
Walter F. M., Cash W., Charles P. A., Bowyer C. S., 1980, ApJ, 236, 212.
Walter F. M., Gibson D. M., Linsky J. L., Rodonó M., Gary D. E., Butler C. J., 1987, A & A, 186, 241.
Walter F. M., 1981, ApJ, 245, 677.
Walter F. M., 1987, ApJ, 316, 434.
White N. E., Marshall F. E., 1983, ApJ, 268, L117.
White N. E., Culhane J. L., Parmar A. N., Kellett B. J., Kahn S., van den Oord G. H. J., Kuijpers J., 1986, ApJ, 301, 262.
White N. E., Shafer R., Parmar A. N., Culhane J. L., 1987, in Linsky J. L., Stencel R. E., eds, Cool Stars, Stellar Systems and the Sun. Springer Verlag, p. 521.
White N. E., Shafer R. A., Horne K., Parmar A. N., Culhane J. L., 1990, ApJ, 350, 776.
Wilson O. C., 1968, ApJ, 153, 221.
Xanthakis J., 1971, in Macris C. J., ed, Physics of the Solar Corona. Reidel: Dordrecht, p. 179.
Young A., Koniges A., 1977, ApJ, 211, 836.
Young A., Rottler L., Skumanich A., 1991, ApJ, 378, L25.
Zirin H., 1988, Astrophysics of the Sun, Cambridge University Press, p. 134.
Zirker J. B., 1971, in Macris C. J., ed, Physics of the Solar Corona. Reidel: Dordrecht, p. 140.