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Eclipsing behaviour of the radio emission in the Algol system V505 Sagitarii

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ABSTRACT
We present radio interferometric observations of the EA2 Algol-type binary system V505 Sagitarii made with the ATNF Compact Array at 6 cm and 3.6 cm over one orbital cycle (1.18 days). We obtained a strong detection of the source (1.5 mJy at 6 cm and 1.4 mJy at 3.6 cm) and derive a brightness temperature for the emitting region of $T_b \sim 2.7\ 10^9$ K, a magnetic field strength of 17 G $< B <$ 170 G and an electron density of $N_e \sim 3.7\ 10^8$ cm^{-3}. The radio flux density levels show a clear modulation with evidence of eclipses of the emission region at both conjunctions of the binary. The form of the light curve implies that the radio source involves at least some enhanced emission in the intra-binary region. This has important consequences for the details of coronal formation and field interaction in active close binary stars. We discuss some scenarios for the formation of intra-binary active regions in Algol-type binary systems.

Key words: stars: activity - binaries: close - stars: flare - stars: late type - stars: variables: other - radio continuum: stars

1 INTRODUCTION

The Algol-type binaries (McCluskey 1993; Batten 1981; Shu & Lubow 1981) are a well-studied group of eclipsing systems named after the prototype Algol (β Persei). The classical EA2 Algol binaries (Budding 1986) are semi-detached systems consisting of an early-type primary and a late-type secondary. Photometric investigations reveal that the cooler components of Algols appear to have spectral types, radii and rotation rates similar to the active components of the RS CVn binaries (Hall 1976). 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 RS CVns they also have high rotation rates and therefore also display magnetic activity in the cooler stars. For example, during the primary eclipse of U Cep the hotter star is totally obscured producing a deep nearly flat-bottomed eclipse. 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 shown photometric evidence for cool photospheric star-spots and flare-like events (Olson 1985; Richards 1990).

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. 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 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 coronal temperature distribution ($T_1 \sim$ 1–6 10^6 K and $T_2 \sim$ 2–4 10^7 K). Time-resolved observations of Algol in X-rays by White et al. (1986) and Stern et al. (1990) 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 ($\geq 3R_\odot$). Some RS CVn binaries, notably AR Lac and TY Pyx have been observed to show X-ray eclipses (Siarkowski 1996). 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. However, a comparison of the X-ray emission in RS CVn and Algol systems by Singh, Drake & White (1996) showed similar X-ray luminosity distributions although Algols were less luminous in X-rays by a factor of $\sim$3 when compared to RS CVn stars with the same orbital period.

Not a great deal of work has been done on Algol-type binaries in the radio regime despite the fact that Algol was one

⋆ Present Address: University of Guanajuato, Dept. of Astronomy, Apdo. Postal 144, Guanajuato, CP36000 GTO., Mexico of the first detected stellar radio sources (Wade & Hjellming 1972). 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. 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. Clark, Kellerman & Schaffer (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 VLBI 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.

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 in which optically thick compact regions on the surface of the cool star expand as coronal loops, eventually becoming extended optically thin structures. Such a model is consistent with the evolution of magnetic loops on the Sun.

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 but is not expected for Algols when only one component is thought to be magnetically active. Uchida & Sakurai (1983) suggested that the existence of stellar differential rotation 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. The interacting field hypothesis has recently been superceded by more complex methods although Ferreira (1998) has discussed some possible mechanisms for producing energetic intra-binary flares. However, recent observations by Gunn et al. (1997) at 6 cm and 3.6 cm provided evidence of an intra-binary region of activity in the RS CVn star CF Tuc. Lestrade (1996) recently showed that the preferred site of the radio emission in the RS CVn stars UX Ari and σ^2 CrB is the intra-binary region. These results have important consequences for the details of coronal formation and field interaction in active close binary stars.

Umana, Catalano & Rodono (1991) and Umana et al. (1993) 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 & Rodono (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.

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. In Algols no such mechanism should be possible but they appear to display quantitatively similar behaviour to the RS CVns. 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. In this paper we present and discuss interferometer observations obtained for the Algol binary V505 Sgr simultaneously at 6 cm and 3.6 cm over the orbital period of the system. We present radio images at both frequencies for this binary system and discuss the variation of the observed flux density levels.

2 V505 SAGITARII

V505 Sgr is a classical eclipsing Algol system with a period of 1.183 days consisting of an A2V primary and a G5IV secondary of radii $2.2R_{\odot}$ and $1.15R_{\odot}$, respectively, at a separation of about $7.0R_{\odot}$. Ginestet et al. (1997) recently produced an A9III classification for the primary based on IR spectroscopy. The secondary is believed to be filling its Roche lobe and a tertiary component that orbits the eclipsing pair with a long period has been detected. Mayer (1997) recently considered the orbit of this third body. A preliminary solution for the orbital elements was provided by Slonim (1934) (who found $i = 82.5°$) and the ephemeris was subsequently improved by Lause (1935;1938). Popper (1949) provided a spectroscopic radial velocity curve but was unfortunately only able to determine the elements of the primary component. V505 Sgr has a long history of photometric observations. Times of minima and ephemeris calculations have been provided, amongst others, by Chambliss (1972), Walter (1981a;1981b), Khalesseh & Hill (1991), Rovithis-Livaniou & Rovithis (1992;1994), Walker (1993) and Chambliss et al. (1993). The eclipse of the primary star in V505 Sgr lasts 5.3 hours. A spectroscopic study of V505 Sgr was performed by Tomkin (1992) and recently Worek (1996) studied the Rossiter-McLaughlin rotation effect in this system.

V505 Sgr has not been extensively studied in the radio regime. It was included in the sample of active binaries observed with the Parkes 64-m radio telescope by Slee et al. (1987). They measured a flux density of 11.2 mJy at 8.4 GHz. During a VLA survey of Algol systems Umana, Catalano & Rodono (1991) found a radio luminosity of 5.25 10^{16} erg s^{-1} Hz $^{-1}$ and a brightness temperature of 2 10^9 K suggesting the possibility of a non-thermal emission mechanism. More recently Umana et al. (1993) presented the radio spectrum for V505 Sgr at three frequencies and found it to be characterised by a strong high-frequency component with a much lower flux density at low frequencies. They discuss the possible physical conditions in the radio emitting regions of V505 Sgr and conclude that it is either one order of magnitude larger than the binary system or originates from large magnetic structures in the outer coronal regions. V505 Sgr does not appear to have been observed in the X-ray or UV regions although Arevalo, Antonopoulou & Lazaro (1993) did observe it in the infrared. Some general discussion on V505 Sgr is given by Chambliss (1992) and Giurkin, Mardirossian & Mezzetti (1983).

3 OBSERVATIONS AND DATA REDUCTION

Observations were performed with the 6-km Australia Telescope Compact Array (ATCA) located near Narrabri, NSW, and operated by the Australia Telescope National Facility (ATNF) for CSIRO. The ATCA consists of five 22-m antennae on a 3-km track together with an antenna located 6 km to the west. A description of the array can be found in Manchester (1991). Observations began at 18:19 UT on 11th April 1995 and consisted of six 7-hour segments of data observed at the same LST each day. The diurnal variations in quiescent flux density levels were assumed to be negligible so that the flux density variation with orbital period could be examined. A total of 42 hours of data were obtained which was adequate to cover the orbital cycle of 28.4 hours although during successive epochs. The array was calibrated in amplitude by convenient observations of the primary flux calibrator 1934-638 with flux densities of 6.33 Jy at 6 cm and 2.59 Jy at 3.6 cm. Phase calibration was achieved by observations of the compact source 1937-101 taken every 15-20 minutes. All observations were conducted at two simultaneous frequencies of 4.8 GHz (6 cm) and 8.64 GHz (3.6 cm) with instrumental bandwidths of 128 MHz. The effective bandwidth was approximately 84 MHz across twenty channels which were then averaged.

The data were processed using the software packages AIPS and MIRIAD. Imaging of the target field revealed four point-like confusing sources with flux density levels significantly above the noise. These were removed by fitting single 2D-gaussian profiles in the image plane and subtracting these models from the visibility data. Analysis of the final data set involved vector averaging the visibilities (taken at the phase center) and plotting these against time. To achieve this the target position was accurately determined by fitting a 2D-gaussian model and then shifting the data to align the peak position with the phase center. This allows the mapping procedure to be by-passed and the data sampled with the full temporal resolution of the array. However, we elected to average the visibilities over several scan lengths. The penalty of directly plotting visibilities is a poorer signal-to-noise ratio and the different temporal weighting gives rise to small discrepancies between the map and visibility determined mean flux densities.

4 RESULTS

4.1 Radio images

Figures 1 and 2 show the restored images of V505 Sgr at 6 cm and 3.6 cm respectively. The AIPS task MX was used to obtain maps 512 × 512 pixels in size. For these observations the synthesized beam had unequal dimensions in the RA and Dec. directions giving differing resolutions in each. The images were produced using RA and Dec. pixel sizes of 0.4 and 2.6 arcsec respectively at 6 cm and 0.3 and 2.0 arcsec respectively at 3.6 cm. The resulting images show unresolved sources at both frequencies. Small extensions of the lowest contour levels are not thought to be real.

Figure 1 shows an unresolved point source with a peak flux density level of 1.53 mJy/beam. The angular extent of this source ($< 1.4 \times < 8.0$ arcsec) is comparable to the size of the synthesized beam ($\sim 2.0 \times 8.0$ arcsec). The mean J2000 position (α=+19^h 53^m 06^s.391, δ=–14° 36′ 11.″40) is consistent with the most accurate optical position allowing for proper motion and the small difference between the optical and radio reference frames. The J2000 position of the phase calibrator is α=+19^h 39^m 57^s.257, δ=–10° 02′ 41.″52. The measured RMS noise level (5σ) in the image is 2 10^{-4} Jy/beam. Also in the field (but not displayed in Figure 1) were four unresolved objects of peak flux density levels 3.6 mJy, 0.6 mJy, 0.4 mJy and 0.4 mJy at positions α=19^h 53^m 00^s, δ=–14° 29′ 10″, α=19^h 53^m 06^s, δ=–14° 40′ 05″, α=19^h 53^m 11^s, δ=–14° 34′ 53″ and α=19^h 53^m 05^s, δ=–14° 41′ 33″, respectively. The strongest of these sources was used as a control source to check the flux density variations of V505 Sgr and to give estimates of random errors.

Figure 2 also shows an unresolved point source with a peak flux density level of 1.37 mJy/beam with an angular size of $< 0.8 \times < 5.0$ arcsec, comparable to the size of the synthesized beam ($\sim 1.0 \times 5.0$ arcsec). This detection is almost exactly coincident with the 6 cm image with a J2000 position of α=+19^h 53^m 06^s.391, δ=–14° 36′ 11.″50. The RMS noise level (5σ) in this image was measured at approximately 2 10^{-4} Jy/beam. Only one of the confusing sources found in the 6-cm image was detected above the noise at 3.6 cm and so could be used as an indicator of flux density error levels. To aid in comparison Figures 1 and 2 are plotted over approximately the same coordinate ranges and with the same contour levels as multiples of the RMS noise in each image. The positions derived from the maps agree extremely well with recent CCD observations by Stone (1997) within the errors of the instruments.

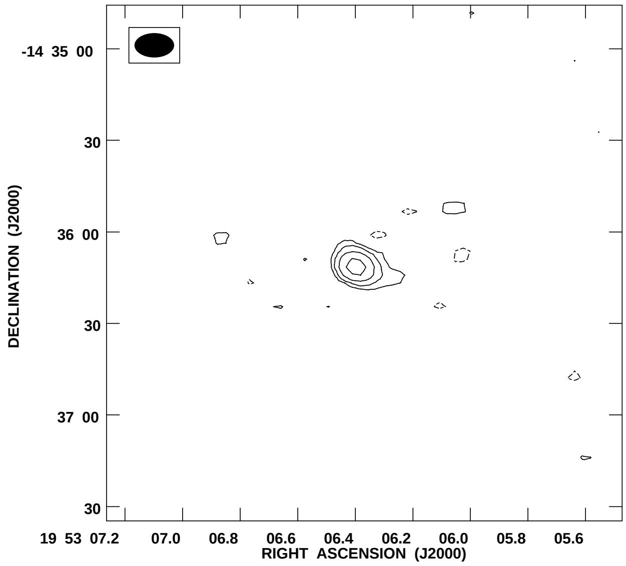

Figure 1. The ATCA radio map of the area around V505 Sgr at 6 cm. The restoring beam (2×8 arcsec) is shown in the upper left hand corner. Plotted flux density levels are at -3, 3, 6, 12, 24, 48 and 96 times the RMS noise level of 0.047 mJy. The source extension to the West is not thought to be real.

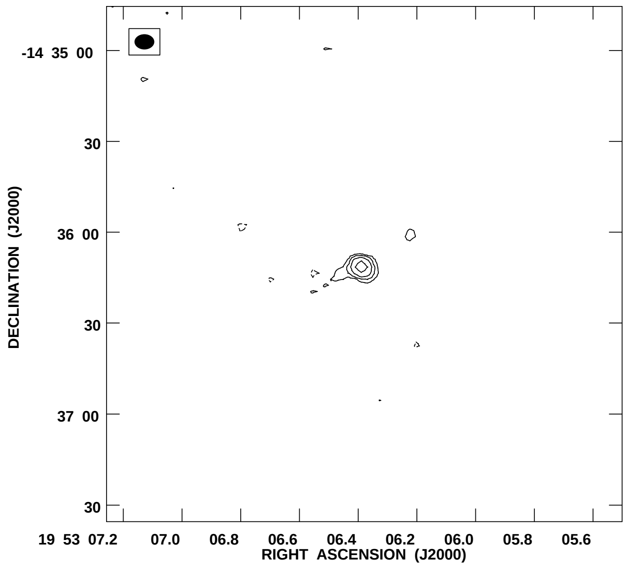

Figure 2. The ATCA radio map of the area around V505 Sgr at 3.6 cm. The restoring beam (1×5 arcsec) is shown in the upper left hand corner. Plotted flux density levels are at -3, 3, 6, 12, 24, 48 and 96 times the RMS noise level of 0.038 mJy. The source extension to the East is not thought to be real.

An estimate of the random error in the flux density levels was made by analysing the strongest confusing source in the image planes at both 6 cm and 3.6 cm for which we assume there is no intrinsic variation. RMS values of 0.2 mJy and 0.3 mJy were found at 6 cm and 3.6 cm respectively. These estimates compare well with the 5σ levels in the map (both approximately 0.2 mJy). The mean 6 cm flux density level derived from the visibilities (1.5 mJy) compares well with the peak flux density in the image shown in Figure 1. The mean 3.6 cm flux density level of 1.4 mJy is also in good agreement with the peak flux density in the image shown in Figure 2. Based on the results of our error estimates we believe that no flux density variation less than about 13% at 6 cm and less than about 23% at 3.6 cm can be regarded as statistically significant.

4.2 Radio light curves

Figure 3 (a) shows the amplitude variation of the target against orbital phase for both the 6 cm and 3.6 cm data. The orbital phase was calculated using the photometric ephemeris of Rovithis-Livaniou & Rovithis (1994). The estimated error in phase using this ephemeris is 0.008. Also shown in Figure 3 (b) is the V-magnitude light curve of the system plotted with data from Chambliss et al. (1993). Note that the data in Figure 3 have been plotted twice (i.e. over two orbital periods) to emphasize the variation of flux density with phase.

We see a clear modulation of the radio flux density of V505 Sgr at both 6 cm and 3.6 cm. The flux density levels appear to decrease at phases centred approximately at 0.5 and 1.0 (i.e. at *both* conjunctions of the orbit). The decrease in flux density is about 75% of the mean level for both wavelengths and for both primary and secondary eclipses. Based on the error estimates this is approximately 6 times the lower limit of detectable variation at 6 cm and 3 times the lower limit at 3.6 cm. The events are also above the 3σ level in the overall flux density variations and so are physically significant. The flux density decrease at primary conjunction (phase 1.0) is slightly broader than that at secondary conjunction (phase 0.5) and appears to be centred symmetrically around the conjunction. The narrower secondary flux density decrease appears to be shifted slightly to phases greater than 0.5.

To investigate the possible geometric location of the emitting regions in V505 Sgr we developed a light curve fitting program. We wish to determine whether the light curve is more conveniently matched by emission from the surface of the active star, from a two-corona system, an intra-binary region or some other combination of simple emitting structures. The purpose of this analysis was not to determine with any accuracy the physical properties of the emitting regions but rather to test which type of model best explains the gross features of the light curve. Hence the results are heavily dependent on the assumed source model and the quality of the data. For each model type a light curve was synthesised by allowing the system geometry to change through an orbital period and calculating the observable flux density at each phase of the observed data. A standard χ^2 test was performed to locate the best agreement between model and observed data. Since the data quality is limited some simplifying assumptions were made. The emitting regions were assumed to be spherically (or circularly) symmetric, homogeneous and isotropic sources. More complex models are not warranted for a comparison to data with inherent stochastic noise.

The results of the model fitting are shown in Figure 4 for the 6-cm data. We do not discuss the analysis of the 3.6-cm data but found similar results. Four models are depicted in Figure 4. These are (a) a circular surface feature on the G-star, (b) a two-corona system where both stars

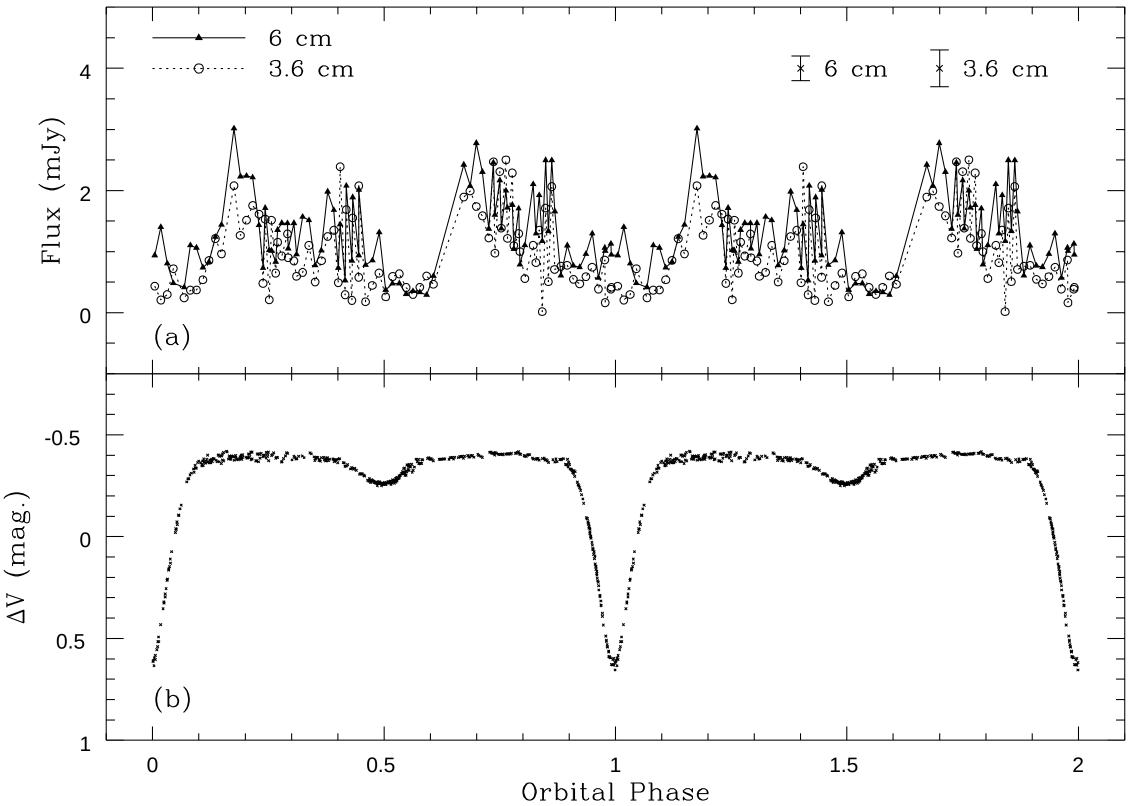

Figure 3. (a) Time evolution of the 6-cm and 3.6-cm flux densities from V505 Sgr folded over the orbital period and plotted against orbital phase. Also plotted are estimated error bars for the radio data. Note that the data have been plotted twice to emphasise phase-correlated variations. (b) The V-magnitude light curve of V505 Sgr observed by Chambliss et al. (1993).

have a spherical corona, (c) a single spherical intra-binary emission region and (d) an intra-binary region and a single corona around the G-star. Where a dual-component model has been fitted the emission variations from the individual components as well as the total flux density variations are plotted. The quality of the model fit is indicated by the reduced χ^2 values for each model. All models replicate eclipses at both conjunctions of the system. We find the worst scenario is a surface feature on the G-star because the geometric constraints will always produce a very broad eclipse when such a feature faces away from the observer and a very narrow eclipse when occulted by the primary star (Figure 4 (a)). This is in fact opposite to that shown by the data. Furthermore, the model results suggest that such a feature would have to be very large ($> 0.9 R_{\odot}$) to produce deep eclipses of this kind. The observed data do not show such dissimilarity between eclipses and we conclude that a surface feature is thus an unlikely source of the emission. However, such a feature may be complex in structure and combined with emission from a larger corona and other active regions so we cannot completely rule out this possibility. A reasonable match to the observations is found using a two-corona model (Figure 4 (b)). However, the results suggest that the emission would consist of approximately equal flux density from both stellar components and that their sizes would be comparable. This is unlikely to be physically meaningful since the early-type components of Algol systems are unlikely to have coronal emission. An intra-binary component also replicates the eclipses in the observed data but the size of such a component is restricted by the separation of the two stars and in this case would display zero flux density at both conjunctions and have equal eclipse depths. The situation is improved when we invoke an additional coronal component around the G-star only (Figure 4 (d)). This replicates two unequal eclipses which have non-zero flux density and indicates that the G-star has a large coronal radius which produces a significant proportion of the flux density but some additional emission originates in the intra-binary region. Although this limited modelling is not entirely conclusive we believe it demonstrates that the most likely explanation of the light curve involves at least some enhanced emission in the intra-binary region. Our subsequent discussion is based on this assumption.

4.3 Characteristics of the radio emission

In this section we derive some characteristics of the radio emission under the assumption that it is due to gyrosynchrotron emission from mildly relativistic electrons. This is generally the emission mechanism invoked to explain the quiescent microwave flux density from active late-type stars.

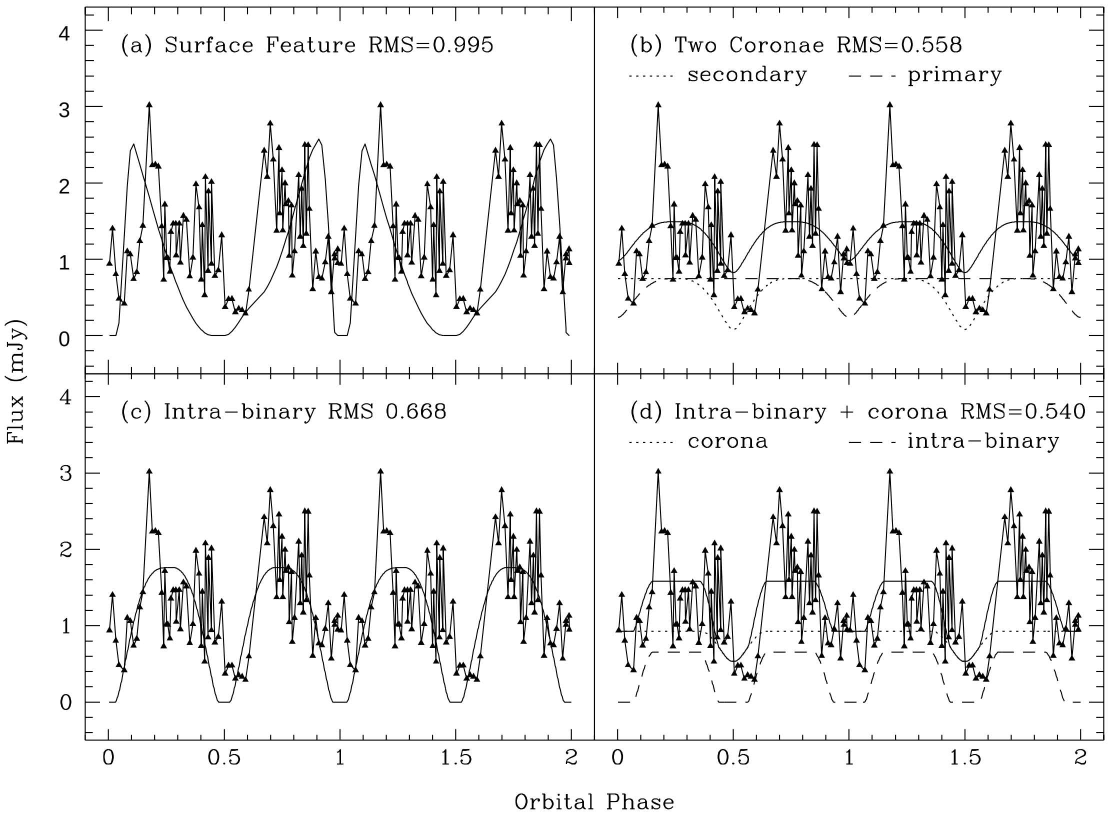

Figure 4. Model radio light curves at 6 cm for V505 Sgr, (a) a circular surface feature on the G-star, (b) a two-corona system where both stars have a spherical corona, (c) a single spherical intra-binary emission region and (d) an intra-binary region and a single corona around the G-star. For dual-component light curves the solid line shows overall variation and the dotted and dashed curves show the variations of the individual components.

For a discussion of emission mechanisms the reader is referred to Drake, Simon & Linsky (1992) and Gunn et al. (1997).

A valuable diagnostic of the emission process is the brightness temperature T_b ; the temperature of a black-body which produces the same specific intensity as the source. At 6 cm T_b is given by

$$T_b = 7.1 \times 10^7 S_6/\theta^2, \quad (1)$$

where S_6 is the 6-cm flux density measured in mJy and θ is the source angular dimension in milli-arcseconds. An upper limit to T_b can be inferred using the size of the intra-binary region ($2.7 R_\odot$) since this dimension has been suggested by the form of the light curve. Using a mean 6-cm flux density for V505 Sgr of 1.5 mJy this gives an upper limit of 2.7 10^9 K. Note that if the source size is equal to the size of the active component $T_b \sim 1.6\ 10^{10}$ K and if equal to the overall size of the system is one order of magnitude less than this. Hence, even assuming a large projected area for the emission region in V505 Sgr the brightness temperature is very high.

For gyrosynchrotron emission the frequency at which the emission becomes optically thin, ν_{peak}, depends strongly on the magnetic field strength and the average electron energy. For a thermal population of electrons the flux density S_ν should decrease as ν^{-8} for $\nu > \nu_{peak}$ rather than as ν^α where -0.5 $\leq \alpha \leq$ -5.0 for a non-thermal electron energy spectrum with $2 \leq \delta \leq 7$ (where $N(E) \propto E^{-\delta}$). The dual frequency observations of V505 Sgr at 4.8 GHz and 8.6 GHz have revealed mean flux densities of $\sim$1.5 mJy and $\sim$1.4 mJy respectively. The resulting spectral index of ~ -0.2 is within the range normally found for quiescent active star emission (Lestrade 1988). This is consistent with the flat high-frequency spectrum observed for this system by Umana et al. (1993) and implies that $\tau \sim 1$ over most of the source. Since the spectrum is essentially flat the brightness temperature T_b is determined by the average energy of electrons. This energy (in MeV) is given by

$$E_{eff} = 8.6 \times 10^{-10} T_b, \quad (2)$$

which, assuming $T_b \sim 2.7\ 10^9$ K, is 0.23 MeV. For gyrosynchrotron emission with electrons at this energy the results of Dulk (1985) indicate that the most important emission harmonics lie in the range s = 10-100. Here $s = \nu/\nu_B$ where ν_B is the gyromagnetic frequency and ν is the observing frequency. In this case the magnetic field is given by

$$B = \frac{\nu}{2.8 s}, \quad (3)$$

where B is in Gauss and ν is in MHz. For the 6-cm data the implied range of the magnetic field in the emission region is therefore 17 G $< B <$ 170 G. This field is valid only for the surface or regions of the source where $\tau \geq 1$. Assuming for the moment that the active star is the source of the magnetic field and that this has a dipolar topology given by

$$B = B_o \left(\frac{R}{R_\star}\right)^{-3}, \quad (4)$$

where B_o is the surface induction, $R_\star$ is the stellar radius and R is the radial position of the $\tau \sim 1$ surface from which it is assumed most of the emission originates, then taking R as the radius of the midpoint of the intra-binary region ($R \sim 3.6 R_\odot$) the surface field is of the order 71 G $< B_o <$ 710 G. If the field varies as an inverse square law, rather than being dipolar, then the surface fields are lower (44 G $< B_o <$ 440 G). These surface fields, presumably associated with the active component, are somewhat lower than those derived for other Algol systems by Stewart et al. (1989) but are similar to the spatially averaged plage magnetic fields observed on the Sun (Zirin 1988). One problem with these deductions is that the field topology is unlikely to be dipolar in nature.

It is possible to infer the electron density in the emission region as follows. Again assuming an optically thick source and assuming the emission is gyrosynchrotron from mildly relativistic electrons with a power index of $\delta \sim 3$ then following Dulk & Marsh (1982) the peak in the radio emission is given by;

$$\nu_{peak} \approx 1.5 \times 10^4 (N_e L)^{0.23} B^{0.77} \quad (5)$$

where a nominal viewing angle of $\theta = 45°$ is assumed, L is the length scale of the emission region, B is the magnetic field and N_e is the electron density. Assuming $\nu_{peak} \sim \nu$ (the frequency of observation), $B \sim 17$ G and L is equal to the size of the intra-binary region then $N_e \sim 3.7\ 10^8$ cm^{-3}. Since the emission region is constrained by the binary separation this is a reasonable lower limit and is similar to densities reported in the halo components of RS CVn systems (Mutel et al. 1984; Lestrade et al. 1988).

This density is that of the energetic electron population but there will be in addition a background thermal population with at least this density because no mechanism can accelerate all electrons present. The timescale on which the non-thermal electrons lose their energy through collisions with the thermal population is given by

$$\tau = 1.59 \times 10^{12} E n^{-1} \quad (6)$$

where E is the energy in MeV and n is the density of the thermal population. This expression is valid for energies in the range 0.1-10 MeV (Benz & Gold 1971). An upper limit of $\tau = 17$ minutes follows from taking $n = N_e$ which is too short to assume the source is constant over the timescale of the observations. This result implies the continued presence of an acceleration mechanism to replenish the accelerated particles. A possible explanation for this could be in the relation between the X-ray luminosity and the radio luminosity in the 5-10 GHz range found by Güdel & Benz (1993). This suggests a relationship may be established between the thermal X-ray emission and the non-thermal radio emission if a coronal heating mechanism results in both bulk heating and some run-away acceleration of particles which emit prior to becoming thermalised. Further discussion of this issue was made by Gunn et al. (1997).

These calculations show that the emission from V505 Sgr is consistent with a region radiating by a gyrosynchrotron process from mildly relativistic non-thermal electrons with inferred field strengths and electron densities comparable to those seen on other active binary stars.

5 DISCUSSION

5.1 Comparison with previous observations

Umana et al. (1993) observed V505 Sgr with the VLA at frequencies of 1.5, 8.4 and 15 GHz and found a spectrum characterised by a strong high-frequency component and a much lower flux density at low frequencies. They found that for all the Algol-type binaries in their sample the observed spectrum could not be explained by homogeneous sources with constant magnetic field strength and uniform electron density for any form of electron energy distribution they considered. They therefore proposed a core-halo morphology. Such a two-component model was derived for Algol itself and the RS CVn binary UX Ari by Mutel et al. (1985) and Lestrade et al. (1988) using VLBI measurements. Those results showed that the emission core was smaller than an individual stellar diameter and the halo was comparable in size to the binary system. The model implies that compact optically thick regions on the surface of the cool star associated with active regions expand as coronal loops, eventually becoming optically thin structures about as large as the binary system. However, based on the shape of the spectrum for V505 Sgr, Umana et al. (1993) suggested the emission was of a thermal origin localized in the extended corona around the active star with typical temperatures of $T \sim 10^6$ K. Using the optically thin part of the spectrum they calculated a coronal size of 1.9 10^{13} cm and an electron density of $N_e \sim 5.9\ 10^7$ cm^{-3}. Assuming a lower coronal temperature of 10^4 K the corresponding numbers are 4 10^{14} cm and 2.4 10^5 cm^{-3}, respectively. Even with the higher coronal temperature this implies the emission region is more than 10 times the size of the binary system and it is unlikely that such high temperatures and densities could be maintained in a region this size. It should be noted that the radio luminosity measured by Umana et al. (1993) is *not* consistent with a thermal emission mechanism and this result was based simply on the shape of the spectrum. They further assumed that the thermal emission was coupled to the typical coronal temperature of 10^6 K deduced for RS CVn systems using X-ray observations (e.g. Swank et al. 1981). Umana et al. (1993) do note, however, that the thermal-like spectrum of V505 Sgr could be due to a core-halo structure if the compact region dominates that of the halo. They calculate a halo size of 7 10^{11} cm ($10 R_\odot$) with $N_e \sim 1.5\ 10^5$ cm^{-3} and average magnetic field of $B \sim 10$ G. For the core component the size was 1.8 10^{11} cm ($2.6 R_\odot$), $N_e \sim 2\ 10^8$ cm^{-3} and $B \sim 40$ G. However, based on the large size of the core component and its low average B they concluded that the radio emission may originate from outer coronal regions involving larger magnetic structures than seen in other Algol systems. Note that not only is the core size derived by Umana et al. (1993) almost equal to the size of the intra-binary region but their values for magnetic fields and electron densities are very similar to those computed above using the gyrosynchrotron assumption. It is therefore possible that Umana et al. (1993) observed the same feature with the VLA but that its spatial location could not be deduced from the observations. The present observations seem to favour an intra-binary site for the emission. The recent discussion by Ferreira (1998) of energetic flares in intra-binary regions may be relevant to the discussion below. The question remains whether the existence of an intra-binary emission region can be reconciled with other radio observations of Algols and RS CVn systems.

5.2 The origin of intra-binary emission

In a previous paper (Gunn et al. 1997) we presented evidence of an intra-binary radio emission region in the RS CVn star CF Tuc and commented on the possible importance of field interaction in these systems. These observations could alternatively be interpreted as a surface feature on the later-type star facing the companion. We have further found evidence of such a region in the V505 Sgr system and faced with other evidence of intra-binary radio emission (e.g. Lestrade 1996) we feel it necessary to comment on the apparent existence of such regions or the coincidental occurrence of active regions on the facing surfaces of active stars in binaries. Numerous models may be proposed for the source of this emission in the intra-binary region of active close binaries. The essential requirement is that acceleration of the electron population in this region is achieved with energies of ~ 0.23 MeV. In this section we explore some of the possibilities for the origin of intra-binary emission.

5.2.1 Interacting fields

It has been postulated that radio emission in RS CVn stars is associated with a volume of large-scale reconnection of magnetic field lines from individual magnetospheres around *both* components of the system (Uchida & Sakurai 1983) although this scenario has recently been superceded by other models.

However, evidence is growing of the existence of the subsequent intra-binary active regions in these stars (Doyle, van den Oord & Byrne 1989; Simon, Linsky & Schiffer 1980; Gunn et al. 1997; Lestrade 1996). This mechanism, however, seems unlikely for Algol systems since the early-type primaries have a very inefficient dynamo mechanism and hence a weak magnetic field. Landstreet (1982) has demonstrated the lack of measurable magnetic fields in a sample of 22 stars of spectral types A0-F5. However, Lestrade et al. (1988) noted that the radial dependence of the magnetic field in Algol was milder than expected for a simple static dipole and concluded that a joint magnetosphere may be present. This possibility certainly requires investigation since Stewart et al. (1989) reported radio emission from EA1-type Algol systems, that is, close binary systems in which *both* components are early-type stars, which appeared to be magnetic in origin. An interacting field mechanism for V505 Sgr is still possible if it is postulated that the A2V star has an *intrinsic* magnetic field which is not dynamo generated, similar to the Ap stars which contain fields up to 20000 G (Borra, Landstreet & Mestel 1982). Observations at 6 cm by Drake et al. (1987) of magnetic Ap and Bp stars showed that the emission was similar to quiescent coronal emission from solar-type stars but the field strengths were generally an order of magnitude greater. The lack of kilogauss magnetic fields in V505 Sgr and the apparently normal optical spectrum (Khalesseh & Hill 1991; Tomkin 1992) indicate that an intrinsic magnetic field in the primary is not the source of the particle acceleration. Furthermore, as pointed out by Kitamura (1980), only one eclipsing binary star is known to contain an Ap component (AR Aur). It is possible that some A2-F0 components of eclipsing binaries are chemically peculiar Am stars (Abt & Bidelman 1969) but none are known to possess magnetic fields. It should be noted that Stewart et al. (1989) used radio data to derive surface magnetic fields comparable to those in Ap stars for a small sample of Algols. However these values were based on single-dish observations at 8.4 GHz and may be significantly affected by noise. In fact the maximum flux density for V505 Sgr reported in this survey (Slee et al. 1987) is almost an order of magnitude higher than that reported here so that the derived magnetic fields are also likely to be over-estimated. We believe that a magnetic field associated with the primary component in V505 Sgr is unlikely to be the origin of the intra-binary emission. However, the concept of a magnetic field in the primary components of Algol binaries and indeed in apparently normal early-type stars in general cannot be completely ruled out by these observations.

We have also considered whether, perhaps by means of the accretion stream, frozen-in field can be carried from the G-star and diffuse onto the A-star in V505 Sgr and hence create a magnetic connection. The field of the G-star is shielded by a surface current distribution which can be considered in the circuit approximation. The photospheric resistance is $R_p = \eta/H$ where

$$\eta = 4\pi\nu_{ei}/\omega_{pe} = \sqrt{8\pi/9}\sqrt{m_e e^2}\ln\Lambda(kT)^{-\frac{3}{2}} \approx 3.5\times10^{-13} \quad (7)$$

is the resistivity and H is the photospheric scale length. If the self inductance of the surface is

$$L \approx 2\pi R_*/c^2 \quad (8)$$

then the G-star field will penetrate the A-star on a timescale equal to

$$\tau = L/R_p \approx (H/\eta)(2\pi R_*/c^2). \quad (9)$$

With typical values of H, τ is extremely long unless η is somehow raised above its classical value ($approx$ 3.5 10^{-13}) by anomalous effects. Therefore it is unlikely that the magnetic field can diffuse from the G-star to the A-star. This result also has consequences for other mechanisms discussed below.

5.2.2 Stellar wind

Radio emission has been observed in highly luminous stars; generally early-type B and OB giants, Wolf-Rayet stars and some M-type super-giants. These observations are usually associated with stellar winds and variable mass loss rates (Abbott 1985) but radio emission is usually observed from the wind at several hundred stellar radii from the surface and such emission would not show eclipses. For such stars in binary systems particle acceleration as well as magnetic field amplification probably takes place at the interface of the stellar winds or due to the interaction of a wind with the magnetosphere of the companion. Such objects have been shown to display primarily thermal emission or sometimes non-thermal emission derived from shock ionization. This type of process can be ruled out for V505 Sgr since the primary component is not luminous enough to give an appreciable stellar wind. However the radial dependence of magnetic fields in Algol observed by Lestrade et al. (1988) caused them to speculate on the possibility of a stellar wind mechanism. Shock acceleration of electrons due to the impact of a stellar wind from the A-star on the magnetosphere of the G-star is also not possible because this requires the presence of Alfvénic turbulence on both sides of the shock. Since the A-star is not appreciably magnetised, sufficient turbulence is not present on the shock side facing the A-star.

5.2.3 *Accretion stream*

Another possibility that must be considered is whether the radio emission is directly associated with an accretion stream in V505 Sgr. According to the models of Lubow & Shu (1975) V505 Sgr, which has a mass ratio of 1.9, would have an accretion stream which leaves the secondary star at the inner Lagrangian point at an angle of $\theta_s < 20°$. For V505 Sgr the maximum attainable accretion stream angle beyond which there is no impact region on the primary (and an accretion disk forms) is 24.2°. Hence, on the basis of ballistic calculations V505 Sgr is likely to have both an accretion stream and an impact region. It should be noted immediately that the classical noisy photometric signature associated with accretion streams has not been observed for this system. There is also no spectroscopic evidence for such a feature although the system is not well studied spectroscopically.

Using the expression of Pringle (1985) for the cross-sectional area of an accretion stream then the maximum projected area (in cm^2) of the stream is given by

$$A_s = 3 \times 10^6 T_4^{-\frac{1}{2}} R_s \sqrt{\frac{R^3}{MG}}, \tag{10}$$

where R_s is the length of the stream before it impacts the primary, R and M are the radius and mass of the secondary component, respectively, T is the photospheric temperature in units of 10^4 K and G is the gravitational constant. Assuming the accretion stream angle $\theta_s \sim 20°$ for V505 Sgr then we find $R_s = 2.03\ 10^{11}$ cm and $A_s = 4\ 10^{21}$ cm^2. Following Blondin, Richards & Malinowski (1995) this calculation has assumed the temperature of the stream to be comparable to the photospheric temperature of 5700 K and the secondary mass is taken as $1.15 M_\odot$. At the assumed distance of the system (128 pc) this corresponds to a projected solid angle Ω of $2.5\ 10^{-21}$ sterad. At the assumed temperature and with typical stream densities of $n_e < 10^{10}$ cm^{-3} such a source would be optically thick at 6 cm and emit thermally. The maximum expected flux density at 6 cm for V505 Sgr is therefore $\sim 1\ 10^{-8}$ mJy. Hence the radio emission cannot be originating in the thermal accretion stream in this system. The effect of any ambient magnetic field has been ignored in this calculation. If, however, the field is frozen-in in the accretion stream then an electric field $\vec{E} = \vec{v} \times \vec{B}/c$ would be generated where the plasma velocity $\vec{v}$ could be estimated from free-fall from the inner Lagrangian point. Although reasonable fields can be attained the mean free path of a particle corresponds to its gyroradius and the energy gained is very small.

In cataclysmic variables magnetic fields are known to substantially alter the dynamics of accretion streams (King 1983). Since in Algol-type binaries the magnetic fields are generally small compared to cataclysmic binaries it is unlikely they have a significant effect in directing material associated with mass transfer. However, the formation of primary component hot-spots which may be due to magnetic confinement of accretion streams have been reported for a few Algol systems (Kappelmann & Walter 1979; Ammann & Walter 1973; Walter 1976) but it is unclear if this mechanism could produce the 0.23 MeV electron population required to explain the microwave emission. Florkowski (1980) proposed a mechanism for Algol whereby material leaks from the L3 Lagrangian point and forms an impact site with the ambient medium of ionized hydrogen. The acceleration of particles in this region can give rise to gyrosynchrotron emission. However this mechanism requires some correlation with the flaring activity of the active star and assumes an appreciable amount of material in a dense accretion disk. This mechanism is again unlikely for V505 Sgr since such a high density circumstellar disk has not been observed and because the eclipses of such an impact site would not be centred at conjunctions.

5.2.4 *Unipolar inductor*

Significant stressing of the magnetic field of the active star is possible by analogy with the unipolar inductor mechanism proposed for the cataclysmic variable AM Her by Chanmugam & Dulk (1983) and further investigated by Dulk, Bastian & Chanmugam (1983). The mechanism proposes that the primary is embedded in the magnetosphere of the active star. If the system has some degree of rotational asynchronism then, as the field lines cross the surface of the primary, large potential differences are set up across the flux tube connecting the two stars. This drives an electric current from the companion to the polar region of the active star and back again. If this effect takes place then acceleration of particles in the intra-binary region is possible. Kuijpers & van der Hulst (1985) applied the unipolar inductor model to RS CVns. They showed that, although a unipolar inductor can result in potential differences of 100MeV, the particles are only accelerated to energies of $\sim$ 10keV. This is because particles that experience collisions have their average drift velocity much reduced. Another problem with this process is that it requires some degree of asynchronism between the two components which is unlikely for such a closely locked system. Even with reduced magnetic fields and high degrees of asynchronism the required acceleration of electrons to $\sim$1 MeV is probably not possible.

5.2.5 *Field shearing*

The remaining mechanism of particle acceleration is perhaps the most simple because it does not require any *ad hoc* assumptions on the dynamics of the intra-binary region or the characteristics of the primary component. This process is that the non-magnetic companion star alters the magnetic field topology of the active component in the intra-binary region. A model of the inductive generation of fields in binary systems has been presented by Dolginov & Urpin (1978) and expanded by Dolginov & Urpin (1979) and Dolginov (1980). Essentially the mechanism gives field excitation in one star by the currents induced by the second. For the mechanism to work the rotation axes of the stars must be slightly inclined to the orbital plane. The magnetic field topology of the active component in V505 Sgr is certainly quite complex by solar analogy. However, if a dipole model is assumed and the active star has surface fields B_o then the field near the primary component is approximately $B_o(R_c/d)^3$ where R_c is the radius of the secondary and d is the separation. The field penetrating into the surface of the primary can increase due to twisting of the magnetic force lines by an amount $\sim \omega R_c^2/\eta$ where ω is the angular rotation rate of the primary and η is the turbulent magnetic viscosity of the intra-binary plasma. This field in turn induces a field increase near the secondary of order $B_o(R_c/d)^6(\omega R_c^2/\eta)$. The primary can also increase the magnetic field strength by a further amount $\Omega R_c^2/\eta$ (where Ω is the orbital angular velocity) due to orbital twisting of the field lines. However, this field amplification is the equilibrium value reached at the moment the amplification is balanced by diffusion. As has been shown in Section 5.2.1 the timescale for the field to diffuse into the A star and establish a magnetic connection is extremely long so this inductive generation effect will not work well for close binaries.

In the unipolar inductor model of Chanmugam (1983) the two stars have parallel rotation axes but are asynchronously rotating. In the field induction model of Dolginov & Urpin (1979) both rotational asynchronism and non-parallel rotation axes are considered. Unfortunately for close binary systems such as Algols neither of these departures from synchronized behaviour are likely. However, the field topology in these systems may be more complex and dynamic so that substantial magnetic amplification can occur in the intra-binary region without invoking a magnetic field for the A2V star. Rather than rotational effects or accretion stream effects the predominant factors may be plasma motions in the lower atmospheres of both stars and magnetic reconfiguration associated with energy release in the active regions. The photosphere of the inactive star could play a crucial role by cutting magnetic field lines rooted there, thus forming reconnection in the intra-binary region. The subsequent particle deposition events could be the source of the radio emission emanating from between the two stars. Some investigations on how to overcome the field diffusion timescales which preclude these mechanisms would be beneficial.

6 CONCLUSIONS

We observed the EA2 Algol-type binary V505 Sagitarii with the ATNF Compact Array over a complete orbital period. We obtained a strong detection of the source with flux densities of ~1.53 mJy and ~1.37 mJy at 6 cm and 3.6 cm, respectively. The radio flux density variations showed the existence of a decrease of approximately 75% at both conjunctions of the system and these are best modelled as a large corona surrounding the active secondary component *and* a substantial region of emission originating *between* the two stars. The possibility that the radiation originates from thermal plasma in an accretion stream between the stars is discounted. A gyrosynchrotron emission process is considered the most likely explanation with a brightness temperature of $T_b \sim 2.7\ 10^9$ K, a magnetic field strength of 17 G $\leq B \leq$ 170 G and an electron density of $N_e \sim 3.7\ 10^8$ cm^{-3}. These results are in good agreement with observations of this system by Umana et al. (1993).

The existence of eclipsing behaviour in V505 Sgr associates the emission with the intra-binary region. These observations cast doubt on the assertion that the interacting field mechanism for RS CVn binaries, proposed by Uchida & Sakurai (1983), can be discounted merely on the basis that RS CVns and Algols appear to show very similar properties. These results not only demonstrate that field interaction may be important but that it appears to be important in the very systems in which it should not exist. It is possible that the core structures seen in Algols and RS CVns can be associated with activity in the intra-binary region for both classes of object. However this assertion would require a great deal of additional observational and theoretical work before being confirmed.

It has been pointed out that binary stars are more likely to be radio sources than single stars with similar properties (Gibson 1980). The results of this work may provide some clues as to why this should be. A correct picture of the radio activity in close binary stars may then require a detailed assessment of tidal interactions, magnetic field interactions (or induction) and the effects of circumstellar material. In terms of the solar paradigm the radio coronae of active close binary stars seems to be analogous to loop models of emission but the energetics and geometry may be radically different.

In order to fully understand the origin of radio coronae in active stars further observational work is required. Multi-wavelength observations, including circular polarization measurements are the only way forward in this field since these will enable the appropriate radio emission mechanism to be established and provide important constraints on the physical properties of the radiating plasma. Although large scale radio coronae are irrefutably established in active close binary stars further time-resolved observations of eclipsing systems are needed to investigate the extent and location of these regions. In particular it is vital that the existence of intra-binary emission regions in Algol-type systems, and perhaps also in RS CVns, is confirmed with additional observations. A great deal of work is required in order to explain the interaction and/or induction of magnetic fields in late-type binaries which may be the origin of some of the observed structures.

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