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MULTIPLE WAVELENGTH MICROWAVE OBSERVATIONS OF THE RS CANUM VENATICORUM STARS UX ARIETIS, HR 1099, HR 5110, AND II PEGASI

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ABSTRACT

The VLA was used to observe the RS CVn stars, UX Arietis, HR 1099, HR 5110, and II Pegasi with a time resolution of 6.6 s at two pairs of wavelengths near 4835 MHz and 1415 MHz. Variable emission was detected from UX Arietis at 4835 MHz on time scales ranging from 30 s to more than 1 hr, but there were no detectable variations at 1415 MHz. From the rise time of the shortest variation of ~ 30 s, we use the light-travel time argument to obtain an upper limit to the source size of $L \leq 9 \times 10^{11}$ cm, or about 4 times smaller than the halo size determined from VLBI techniques. More plausible Alfvén velocities of 2×10^8 cm s$^{-1} \leq V_A \leq 7 \times 10^9$ cm s^{-1} imply source sizes of 6×10^9 cm $\leq L \leq 2 \times 10^{11}$ cm for the 30 s variations. These sizes are smaller than the binary separation and most-likely smaller than the size of an individual star. Here we also derive a magnetic field of $H \leq 15$ G for the varying source and show that the relatively rapid time scales of the variations cannot be due to synchrotron radiation losses. Instead we suggest that the variations may be due to absorption by a thermal plasma located between the stars.

Subject headings: stars: binaries — stars: individual — stars: radio radiation — radio sources: variable

I. INTRODUCTION

Observations of RS CVn stars at centimeter wavelengths have shown that some of these objects exhibit strong and variable emission on time scales of minutes to several days. Among the more active and well studied RS CVn stars are UX Arietis (G5 V + K1 IV) and HR 1099 (G5 IV + K1 IV). Gibson, Hjellming, and Owen (1975) showed that the flux from UX Arietis at 2095 MHz and 8085 MHz decreased by about a factor of ~ 2.5 over a 24 hr period. Feldman *et al.* (1978) subsequently discovered variations on a time scale of a few hours from HR 1099 at 10.5 GHz. Shorter variations were reported from HR 1099 by Brown and Crane (1978); the 2695 MHz flux underwent rapid, and possibly periodic, fluctuations on a time scale of about 4 minutes.

The microwave radiation from UX Arietis and HR 1099 is often highly circularly polarized, especially, but not exclusively, during periods of little variation (Brown and Crane 1978; Mutel and Weisberg 1978; Mutel *et al.* 1985; Pallavicini, Willson, and Lang 1985). During a variation, the radio spectrum is usually inverted, with a spectral index, $\alpha \approx 1$. These properties suggest that the emission mechanism is gyrosynchrotron radiation from mildly relativistic electrons radiating in magnetic fields of a few tens of gauss (Owen, Jones, and Gibson 1976).

Recent VLBI observations have provided information about the sizes of a number of RS CVn Stars. Mutel *et al.* (1985) and Lestrade *et al.* (1985) have shown that UX Arietis contains an unresolved core (size $L \leq 3 \times 10^{11}$ cm) embedded in extended halo of about 3.2×10^{12} cm in size and that HR 1099 contains a single unresolved component whose size is $L \leq 1.1 \times 10^{12}$ cm. The separations between the binary components of UX Arietis and HR 1099 are, $\sim 1.5 \times 10^{12}$ cm, and 8.4×10^{11} cm, respectively. Observations of HR 5110 at 8.4 Lestrade *et al.* (1984) indicate a source size of 1.1×10^{12} cm, comparable to the overall size of the binary system. The VLBI size estimates, together with the observed flux densities indicate peak brightness temperatures of $T_B \geq 4 \times 10^8$ K for HR 5110 and $T_B \geq 10^{10}$ K for UX Ari and HR 1099. A temperature of 10^{10} K is not inconsistent with the idea that the radio emission is due to gyrosynchrotron emission, but significantly higher brightness temperatures might indicate a coherent emission mechanism such as an electron-cyclotron maser (Melrose and Dulk 1982).

More stringent limits to the size and brightness temperature can be obtained by measuring the rise time of the variable emission using the light-travel time argument to place an upper limit to the size. This approach has, for example, recently been used to derive brightness temperatures of $T_B \geq 10^{16}$ K from intense millisecond spikes emitted by the dwarf M star AD Leonis (Lang and Willson 1986).

In this paper we present 6.6 s VLA observations of UX Arietis at HR 1099, HR 5110, and II Peg at two pairs of frequencies near 1415 MHz and 4835 MHz. The RS CVn stars HR 5110 and II Peg were studied because both are known to vary at radio wavelengths (Feldman 1979; Viner 1979; Spangler, Owen, and Hulse 1977). In § II we present the data and show that UX Arietis exhibited variations on time scales ranging between ~ 30 s to more than 1 hr. In § III we discuss these observations and derive an upper limit of $L \leq 1.98 \times 10^{11}$ cm for the source size. Here we also derive a magnetic field of $H \leq 15$ G for the varying source and show that the time scale of the variations cannot be due to synchrotron radiation losses. Instead we suggest that the variations may be due to absorption by a thermal plasma located between the stars.

II. OBSERVATIONS

The RS CVn stars UX Arietis HR 1099, HR 5110, and II Peg were observed with the VLA (B configuration) on 1985 June 10. One subarray containing 13 antennas was used to observe at frequencies of 1415 MHz and 1465 MHz and another subarray containing 14 antennas was used to observe at frequencies of 4835 MHz and 4885 MHz. In all cases the bandwidth was 50 MHz. The fringe visibilities were sampled at a rate of 6.67 s, and the data were calibrated from observations

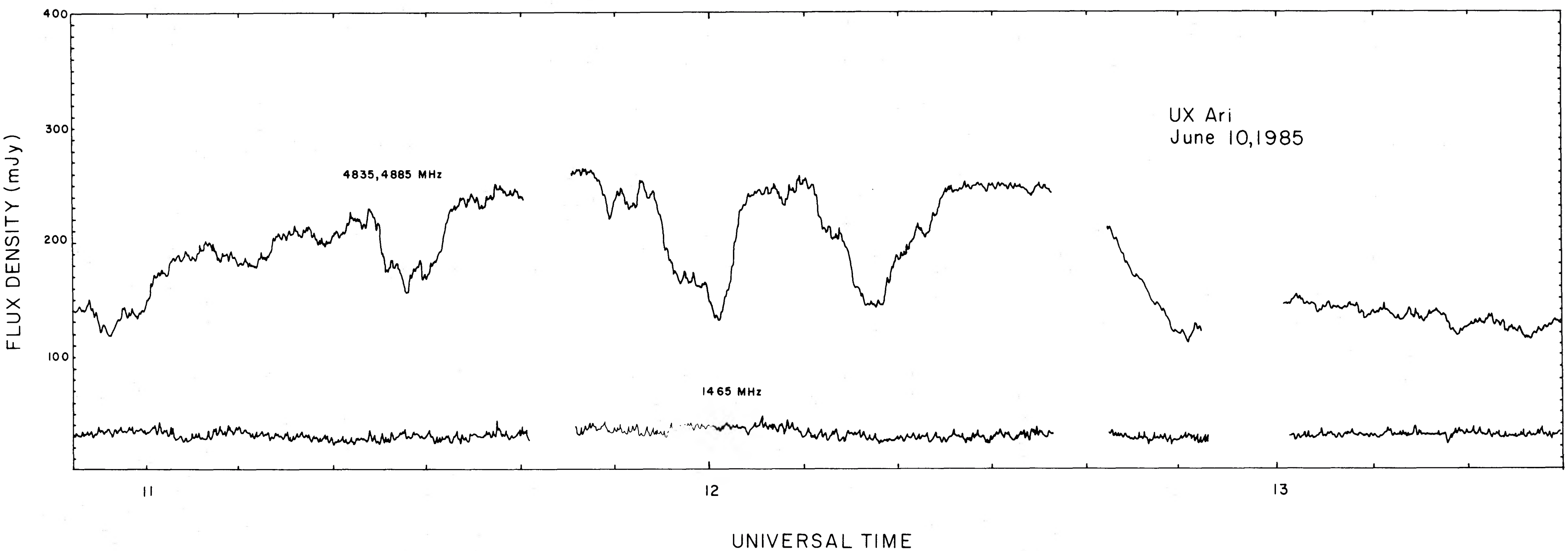

FIG. 1.—A plot of the total intensity, *I*, observed at 1465 MHz, 4835 MHz, and 4885 MHz from the RS CVn star UX Arietis on 1985 June 10. The visibility data were phase-shifted to the source center and then vector-averaged, baseline by baseline, over a 6.67 s interval to produce these time profiles.

of 3C 236 (14.51 Jy at 1465 MHz and 7.4 Jy at 4835 MHz) and 0333+321 (3.14 Jy at 1465 MHz and 2.64 Jy at 4835 MHz). The raw data were first examined, baseline by baseline, for the presence of interference or any obviously bad data.

The edited data were then calibrated and used to make synthesis maps of the sources which were then cleaned and fitted with two-dimensional Gaussian functions in order to determine their locations to within about one-tenth of the beamwidth (1″.9 × 2″.0 at 4885 MHz, 3″.7 × 5″.0 at 1465 MHz). The 6.6 s data were then phase-shifted to bring the sources exactly into the center of the map. Finally, these data were vector-averaged, baseline by baseline, and used to construct plots of total intensity, I, and circular polarization, ρ_c, as a function of time for the 2 hr observation interval. For a 6.6 s integration time the theoretical 3 σ rms noise level is $\sim$7 mJy at 1415 MHz and 1465 MHz and $\sim$6 mJy at 4835 MHz and 4885 MHz.

Our observations indicate that HR 1099, HR 5110, and II Peg exhibited no significant fluctuations in intensity on any time scales ranging from 6.6 s to more than 1 hr, but that UX Ari varied significantly throughout the 2.5 hr period of observation. In Table 1, we give the total intensity and circular polarization at 6 and 20 cm wavelength for each of the four sources. For HR 1099, HR 5110, and II Peg, the 3 σ errors were determined from the rms noise levels on the synthesis maps.

In Figure 1 we show the plots of total intensity for UX Arietis at 4835 MHz, 4885 MHz, and 1465 MHz. These plots indicate that UX Arietis was much more intense and time variable at 4835 MHz and 4885 MHz. There was no detectable circular polarization at any frequency, to a limit of 5%. The major variations in flux occur on time scales of $\sim$10–20 minutes, but faster variations are also apparent in the data. The peak flux occurs at $\sim$1145 UT with an amplitude of $\sim$270 mJy. In contrast, the flux at 1415 MHz and 1465 MHz has a nearly constant value of $\sim$30 mJy. In Figure 2 we show a section of data with variations as short as 30 s. Here, the data at 4835 MHz and 4885 MHz have been averaged together in order to improve the signal-to-noise ratio. The burst denoted by an arrow has an amplitude of $\sim$30 mJy and a rise time of $\sim$30 s. In order to check that these fluctuations are real and not caused by instrumental effects, we constructed a series of 2 minute snapshot maps at both 4835 MHz and 4885 MHz at various times during these observations. Small phase errors, for example, might mimic rapid time variations if the effective phase center varies by a small fraction of the synthesized beam over time scales of a few minutes. Examination of these maps, however, confirmed that the fluxes derived from them were nearly identical at 4835 MHz and 4885 MHz and that they agreed with the values determined by vector-averaging the data.

III. DISCUSSION

Our observations of UX Arietis indicate that the 6 cm flux varied on time scales ranging from $\sim$30 s to more than 1 hr. From the shortest variations of $\sim$30 s, we can place an upper limit of $L \leq 9 \times 10^{11}$ cm for the size of the emitting region under the assumption that the source cannot move faster than the velocity of light. This size is 4 times smaller than that of the halo component obtained from 6 cm VLBI observations (Mutel, Doiron, and Phillips 1984; Mutel *et al.* 1985), but comparable to the size of the core component ($l \leq 3 \times 10^{11}$ cm) found by Mutel *et al.* (1985). With an amplitude of $\sim$30 mJy and a size of $L \leq 9 \times 10^{11}$ cm, we derive a brightness temperature of $T_B \geq 10^9$ K.

Velocities considerably below the velocity of light are most likely. For example, plausible magnetic field strengths of $H = 10$–100 G and electron densities of $N_e = 10^7$–10^8 cm s^{-3} (Gibson, Hicks, and Owen 1974; Mutel, Doiron, and Phillips 1984), result in an Alfvén velocity of 2×10^8 cm s$^{-1} \leq V_A \leq 7 \times 10^9$ cm s^{-1}. This implies a source size of $L = 6 \times 10^9$ cm to 2×10^{11} cm and a brightness temperature of $T_B \geq 10^{11}$ K to $T_B \geq 10^{13}$ K for the rapid 30 s variations. These sizes are small compared to the separation between the two stars ($L = 1.4 \times 10^{12}$ cm) and to the sizes of the stars themselves ($L = 1.4 \times 10^{11}$ cm and 4.2×10^{11} cm).

Dulk and Marsh (1982) have shown that brightness temperatures of up to $\sim 10^{10}$ K may be explained in terms of gyrosynchrotron emission from nonthermal particles radiating in magnetic fields of a few tens of gauss, but that significantly higher brightness temperatures may require a coherent emission mechanism such as an electron cyclotron maser. In principle, the possibility of a brightness temperature as high as 10^{13} K would favor a coherent emission mechanism. However, since electron-cyclotron maser emission is expected to be highly circularly polarized (Melrose and Dulk 1982), the unpolarized variable emission discussed here would seem to exclude this particular coherent emission mechanism.

Synchrotron self-absorption with a spectral index of $\alpha = 2.5$ has been invoked to explain the inverted spectra often observed during radio bursts from RS CVn stars (Owen, Jones, and Gibson 1976; Spangler 1977; Hjellming and Gibson 1980). The turnover frequency due to synchrotron self-absorption is $\nu_{sa} = 8.1 \times 10^{-4} (S_m/\Omega)^{2/5} H^{1/5}$ (Slysh 1963), where ν_{sa} is given in MHz, Ω is the source solid angle, and H is the magnetic field strength in G. If it is assumed that the absence of burst emission at 21 cm is due to synchrotron self-absorption, then the source size may be estimated. Adopting $\nu \approx 5000$ MHz, $S_m = 270$ mJy, and $H = 100$ G, we derive a source size of $L \approx 10^{12}$ cm, which exceeds the upper limits established from plausible

TABLE 1

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	Date (1985)	UT Time	Wavelength (cm)	Flux (mJy)	Polarization (%)
HR 5110	Jun 9	2308–0411	6	17.2 ± 0.2	+11.7
			20	20.1 ± 0.25	≤5
II Pegasi	Jun 10	0903–0951	6	9.2 ± 0.4	+10
UX Arietis	Jun 10	1052–1330	6	120–270	≤5
			20	30	≤5
HR 1099	Jun 10	2103–2253	6	11.8 ± 0.3	<5
			20	16.8 ± 0.4	−27

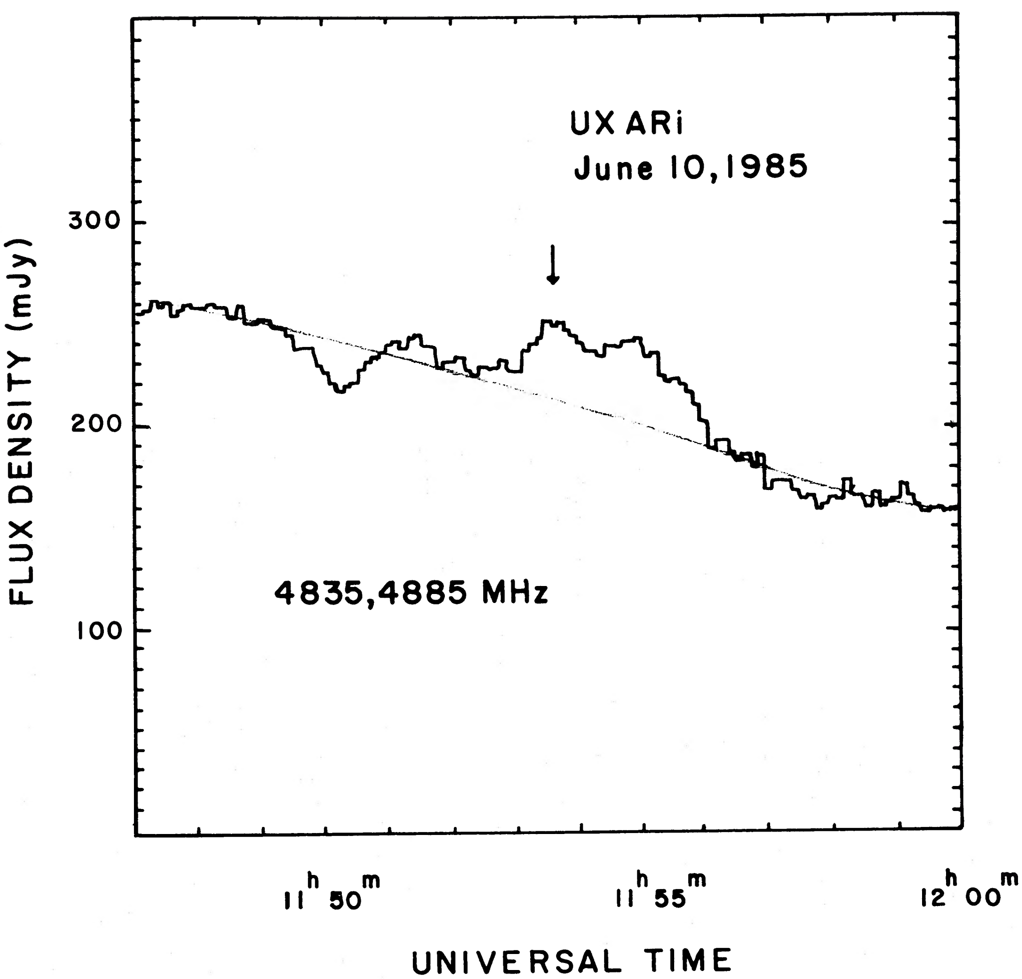

FIG. 2.—A plot of the total intensity, *I*, observed at 4835 MHz and 4885 MHz from UX Arietis. Here the data at these two frequencies have been averaged together. The time resolution of this plot is 6.67 s; the arrow shows a burst with a rise time of ~30 s.

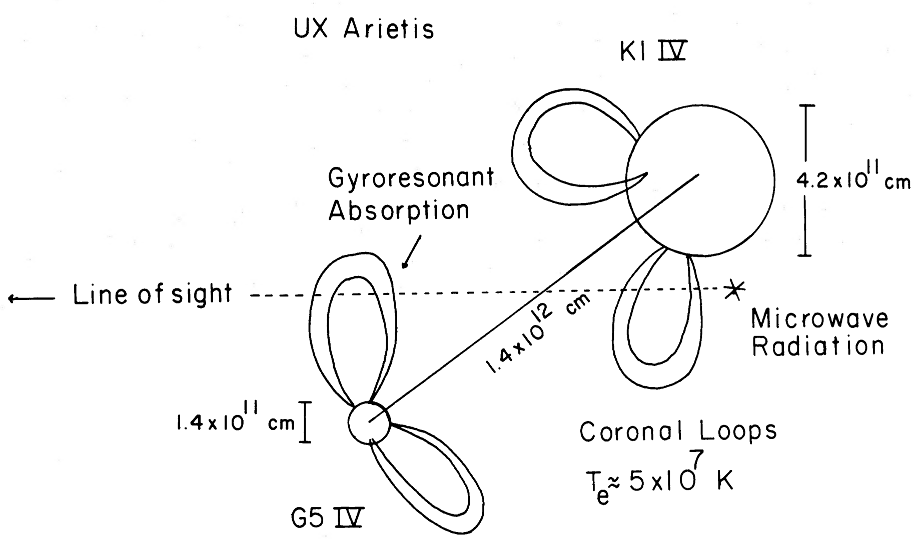

FIG. 3.—A schematic view of UX Arietis showing the orientation of the two components during the time of our observation. Six cm burst emission occurring on the more active K1 star may have passed through a coronal loop located between the two stars, giving rise to thermal absorption. The orbital inclination, $i \approx 55°$, is inferred from the data of Carlos and Popper (1971).

Alfvén velocities for the 30 s variations. However, smaller magnetic fields of $H \approx 10$ G imply a smaller size of $L \approx 3 \times 10^{11}$ cm under synchrotron self-absorption hypothesis.

Fields as small as 10 G are in fact suggested by the lack of polarization of the 6 cm burst emission. Dulk and Marsh (1982) have shown that the degree of circular polarization, ρ_c, of optically thin gyrosynchrotron radiation from mildly relativistic electrons having a power law distribution in energy is

$$\rho_c = 1.26 \times 10^{0.035\delta} \times 10^{-0.071 \cos\theta}\left(\frac{\upsilon_H}{\upsilon}\right)^{[-0.782+0.545 \cos\theta]} .$$

Here, $\upsilon_H = 2.8 \times 10^6 H$ is the gyrofrequency, δ is the electron energy index, and θ is the angle between the magnetic field and the line of sight. For $\delta = 3$–4, we require $H \leq 15$ G and $\theta \geq 70°$ in order to yield a circular polarization of less than about 5%, the approximate upper limit obtained from the VLA observations.

Fields as low as 15 G may, however, present a problem regarding the relatively rapid timescales of the 6 cm variations. According to Mullan (1985), an outburst observed from an RS CVn star has a time scale that is controlled by the evolutionary time scale of a coronal loop that expands outward from the steller surface. Eventually the outburst will "turn off" when the loop de-couples from the steller interior. When this happens it is expected that the burst lifetime will be determined by the synchrotron radiative loss lifetime (Chiuderi and Chiuderi-Drago 1967)

$$t_{1/2} \approx \frac{1.8 \times 10^8}{H^2} \text{ s.}$$

For $H = 15$ G, we find $t_{1/2} = 222$ hr, which is inconsistent with the much shorter time scales of variability reported here.

One possibility is that the major dips in intensity during the peak of the gradual burst are due to absorption by thermal plasma located between the stars. Observations of the Sun at centimeter wavelengths sometimes show "negative" bursts in which the flux decreases abruptly before or during gradual rise and fall bursts (Covington and Dodson 1952; Tanaka and Kakinuma 1960; Covington 1969). These events are sometimes associated with Hα prominences or filament activity that obscure the underlying microwave sources for brief periods of time (Sawyer 1977*a*, *b*).

A model that might explain the relatively abrupt variations of less than 10–20 minutes is one in which the variable emission is absorbed by a thermal plasma lying between the two stars. There is ample evidence for thermal plasma within the UX Arietis system. X-ray observations indicated the presence of two emission components with electron temperatures $T_e \approx 8 \times 10^6$ and $\sim 5 \times 10^7$ K (Swank *et al.* 1981). The lower temperature emission is believed to arise in coronal loops whose lengths are a small fraction of the radius of the more active star. The higher temperature plasma may reside in coronal loops which are comparable in size to the binary system. Simon, Linsky, and Schiffer (1980) have also found evidence for loops which interconnect two stars and which serve as conduits for mass exchange. These loops may provide the mechanism by which particles are accelerated, giving rise to radio bursts (Uchida and Sakurai 1983; Mullan 1985).

The orbital phase of UX Arietis during the time of our observations was $\phi = 0.457$–0.472, as computed from the ephemeris of Carlos and Popper (1971), where zero phase corresponds to the cooler, more active K0 IV star in front. This means that the more active star was situated on the far side of its orbit, as shown schematically in Figure 3, so that burst emission which was generated near that star had a greater probability of passing through material lying between the two stars than at any other time.

Observations indicate that both gyroresonant and thermal bremsstrahlung processes contribute to the centimeter wavelength opacity on the Sun (Lang, Willson, and Rayrole 1982; Dulk and Gary 1983; Lang, Willson and Gaizauskas 1983; McConnell and Kundu 1984). Under the assumption that gyroresonance absorption is the dominant mechanism at 6 cm wavelength, field strengths of 445–595 G are required if the absorption occurs at the third or fourth harmonic of the gyrofrequency. In the present case, however, unless the absorption occurs close to the secondary G5 star, fields as high as these imply surface fields which are much larger than those deduced from starspot analyses of RS CVn and late-type stars (Bonsack and Simon 1983; Marcy 1983). Thus it seems unlikely that gyroresonance absorption plays a role in modulating the burst emission from the active star in UK Arietis.

The optical depth due to thermal bremsstrahlung however does not depend on the magnetic field, and is given by

$$\tau_{TB} = \frac{9.78 \times 10^{-3} N_e^{\,2}}{\upsilon^2 T_e^{\,3/2}} \ln \frac{(4.7 \times 10^{10} T_e)}{\upsilon} L ,$$

where N_e is the electron density, T_e is the electron temperature, and L is the path length through the absorbing medium. For a temperature of $T_e = 10^7$ K, an electron density of $N_e = 1.5 \times 10^9$ cm^{-3} and a path length $L = 10^{12}$ cm (the approximate size of the binary system) we have $\tau_{TB} \approx 0.5$ at $\upsilon = 4.8 \times 10^9$ Hz. If the unattenuated flux of the slowly varying emission is taken to be 220 mJy at 1130 UT, for example, then the flux after absorption by the thermal plasma is ~ 140 mJy, in good agreement with the observed value. The relatively rapid dips in total intensity at 1130 UT, 1200 UT and 1215 UT might then reflect changing physical conditions within coronal loops lying between the stars. Absorption by thermal plasma between the active loops might also explain the total absence of variations at 20 cm. Since the thermal optical depth varies nearby as λ^2, where λ is the wavelength, the opacity from this surrounding plasma might be negligible at 6 cm, but not at 20 cm. If the optical depth is high enough, the underlying source of variable emission (as well as the effect of the changing loops) would not be detected. In this case, the quiescent 20 cm emission would likely originate in a larger halo surrounding the stars. High time resolution observations over a range of frequencies at different phases of the 6.43 day binary orbit would provide a useful test of this model.

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