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CIRCULAR POLARIZATION IN THE RADIO EMISSION OF RS CANUM VENATICORUM BINARIES

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ABSTRACT

A puzzling feature of the polarization of the radio emission of RS CVn binary systems is the observed reversal in the sense of polarization between high and low frequencies. This reversal has been assumed to be a property of the quiescent emission of these systems, which is widely agreed to be gyrosynchrotron emission. However, the reversal has proved difficult to explain in terms of plausible gyrosynchrotron models, and we demonstrate that its location with respect to the spectral peak is not consistent with such models. Instead we propose that a form of coherent radio emission is common at low frequencies in these systems and present several examples in which such a component is clearly present. This coherent component is highly circularly polarized in the sense opposite to that of the higher frequency gyrosynchrotron emission. At low frequencies the gyrosynchrotron component is also present and may be stronger than the coherent component, but is probably weakly polarized so that the polarization of the integrated emission is dominated by the coherent component. Based on the sense of polarization of the coherent component, we suggest that it is probably a form of plasma emission. It can show both rapid variability as well as slower modulation similar to that of the gyrosynchrotron component and has a bandwidth of at least 80 MHz. We also point out that the observed fact that the degree of polarization of the quiescent emission at high frequencies tends to increase with frequency is also inconsistent with gyrosynchrotron models.

Subject headings: binaries: general — polarization — radio continuum: stars — stars: coronae — stars: magnetic fields

1. INTRODUCTION

While progress toward the direct imaging of stellar radio sources with Very Long Baseline Interferometry (VLBI) has been made in recent years (e.g., Mutel et al. 1985; Lestrade et al. 1993), we remain unable to image radio sources which are smaller than a stellar radius. In the absence of imaging information, the information available from radio observations of active stars is contained in several different aspects of the data: in the spectral domain (observations at many different frequencies), the time domain (slow variability of quiescent emission, rapid variation of flares), the spatial domain to a limited extent (VLBI can determine the size of some components of the source), and from polarization measurements. In this paper we address the interpretation of the polarization data. As in the solar case, Faraday rotation in the stellar corona is expected to wipe out any linear polarization present in the intrinsic emission over the signal bandwidths required to detect stellar sources. Thus, only circular polarization information is generally present. Significant circular polarization has been detected in the radio emission from stars as diverse as contracting pre–main-sequence stars, faint red dwarfs, bright evolved subgiant G stars, and magnetic chemically peculiar B stars. But the interpretation of the sense of circular polarization is not always straightfoward, and for this reason it has not been widely exploited.

However, the circular polarization of radio emission from active stars is almost the only diagnostic available for studying magnetic fields in the coronae of these stars, and it is therefore important to try to understand its properties thoroughly. The full use of the information available in the circular polarization data is essential in radio studies of the Sun, both for understanding the magnetic structure of active regions and for analyzing the properties of solar flares. The main complicating factor is the problem of mode coupling, which can reverse the observed sense of circular polarization from that intrinsic to the source, depending on the conditions encountered along the ray path to the observer. However, our understanding of solar radio emission is such that we can actually combine radio images with optical observations of photospheric magnetic fields and use polarization reversal as a diagnostic of the structure of the corona (e.g., Bandiera 1982; Alissandrakis & Kundu 1984; White, Thejappa, & Kundu 1992). As we discuss below, the present observations of stellar radio emission do not imply that mode coupling is an important issue in stellar radiophysics at present.

The RS CVn binary systems, which are evolved close binaries in which one component is typically a K subgiant, are one of the best studied classes of radio stars, and their polarization properties have been measured for a number of years. However, despite the available data, these properties have remained a puzzle. In this paper we address several properties of the polarization of these systems, using both new observations and the results of model calculations. Specifically, we

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propose a new interpretation for the observed reversal of polarization of the "quiescent" emission at low frequencies and point out the discrepancy between all current models and the behavior of the polarization at high frequencies. In the following section we review the relevant radio observations of RS CVn binaries and discuss the current models for the radio emission. It is well established that the quiescent radio emission must be due to the gyrosynchrotron process, i.e., gyroresonance emission by mildly relativistic electrons. Section 3 describes the general properties of the circular polarization which can arise from homogeneous gyrosynchrotron sources, and in § 4 we briefly discuss the differences one might expect in the radio emission of real (i.e., inhomogeneous) sources. Section 5 presents some observations of circular polarization which suggest a specific interpretation for the low-frequency polarization of some systems, and also observations of the behavior of the degree of circular polarization at frequencies above the peak in the flux spectrum. In § 6 we discuss the implications of these results.

2. REVIEW OF CURRENT MODELS

RS CVn binary systems are known to exibit a highly variable radio emission at centimeter wavelengths. Observed values of the flux density range from a few mJy during low-level ("quiescent") activity periods up to 1 Jy during strong flares. Although the radio emission from these stars has been extensively observed since their discovery, only during the past few years have reliable multiwavelength observations of both the intensity and polarization become available in the literature. The first statistical study of the spectrum and polarization properties was made by Mutel et al. (1987), who observed a sample of RS CVn stars at 1.4, 4.9, and 15 GHz during a period of 3 years and compared their results with the few previously published data. Since then, more multiwavelength polarization observations have been made, especially for the most active systems UX Ari, HR 1099, and HR 5110 (Pallavicini, Willson, & Lang 1985; Willson & Lang 1987; White et al. 1990; Massi & Chiuderi Drago 1992; Umana et al. 1993; Fox et al. 1994; Jones et al. 1994).

These new data confirm the general properties of the flaring and quiescent components that were derived by Mutel et al. (1987). During strong flares the spectrum has a positive spectral index $\alpha \simeq 1$ (defined as $S_\nu \propto \nu^\alpha$) up to 8–15 GHz, while for moderate flares generally there is a peak at lower frequencies and the spectrum is flatter. Mutal et al. (1987) have shown that the spectral index between 1.4 and 5 GHz is strongly correlated with the radio luminosity, decreasing from positive to negative values as the flux density decreases. Typical quiescent spectra are flat, with $\alpha \lesssim 0$ between 1.4 and 15 GHz. In some cases very similar values of α have been observed during different low-level activity periods.

The emission is circularly polarized, with the degree of polarization π_c anticorrelated with the flux density: while the quiescent component can reach values of π_c up to 40%, flares are generally unpolarized or weakly polarized ($\pi_c \lesssim 10\%$). No evidence for significant linear polarization has been reported: this is presumably because, even if there were significant linear polarization intrinsic to the source, large Faraday rotation destroys it as the radiation propagates through the stellar corona.

For noneclipsing systems such as HR 1099, HR 5110, and UX Ari, there is often a reversal in the sense of circular polarization between 1.4 and 5 GHz (HR 5110 has always been found to be unpolarized at 1.5 GHz); for the best studied objects, the sense of polarization at a given frequency has been observed to be nearly always the same over more than 15 years. Generally at frequencies above 4 GHz, the sense is right-hand for HR 1099 and HR 5110, and left-hand for UX Ari.

The presence of circular polarization together with high brightness temperatures ($T_b = 10^8$–10^9 K for the quiescent component and $T_b \gtrsim 10^{10}$ K for flares) has generally been interpreted as due to gyrosynchrotron emission from mildly relativistic electrons. Owen, Jones, & Gibson (1976) first suggested that emission from an optically thick, self-absorbed source could explain the observed properties of flares, such as the low degree of polarization and the shape of the spectrum; in particular the polarization reversal can be explained as the transition from an optically thin source at higher frequencies to an optically thick one at lower frequencies. A strong flare observed on HR 1099 in 1978 (Feldman et al. 1978) was very well reproduced with inhomogeneous gyrosynchrotron models by Borghi & Chiuderi Drago (1985) and by Klein & Chiuderi Drago (1987). The calculations of Borghi & Chiuderi Drago (1985) show that both the shape of the spectrum and the observed polarization reversal between 1.4 and 5 GHz can be obtained with a simple model with uniform magnetic field and a density of relativistic electrons which decreases with the distance from the star. However, this model cannot be applied to the quiescent emission, since it predicts that the polarization should change sign at a frequency where the spectral index is positive, whereas at low activity levels the reversal is observed to occur with a flat or decreasing spectrum.

Several VLBI observations of RS CVn stars (Mutel et al. 1984, 1985; Lestrade et al. 1984a, b; Massi et al. 1988) have shown that while flares are generally associated with a compact bright source of size comparable to the stellar radius, the quiescent component arises from an extended halo, whose dimensions are of the order of the binary separation; sometimes a core-halo structure is observed. Based on these characteristics of the source structure, Mutel et al. (1985) suggested a qualitative time-dependent model, in which the quiescent emission is regarded as the final phase of the decay of a flaring event. In their scenario, electrons are accelerated in a compact active region with high magnetic field, which is initially optically thick: the emission has therefore a positive spectral index and a low degree of circular polarization. The source then expands outward in regions of lower field strength while the electrons lose their energy by synchrotron radiation; when the source becomes optically thin due to the expansion, giving the halo emission, the spectral index becomes negative and the degree of polarization increases (despite the lower field strength).

Detailed numerical calculations of the time evolution of the emission from an ensemble of relativistic electrons losing their energy by synchrotron and collision losses have been performed by Chiuderi Drago & Franciosini (1993) and by Franciosini & Chiuderi Drago (1995), who reproduced very well both the spectral index–luminosity correlation found by Mutel et al. (1987) and the evolution of the source structure from a core-halo to a halo component. However, no attempt was made to reproduce also the observed polarization properties.

Simple core-halo models consisting of two homogeneous sources of different size and magnetic field strength have been used by Umana et al. (1993) to fit the flat spectra of a sample of Algol-type binaries. As pointed out by Mutel et al. (1987), a two-component model can explain the presence of a polariza-

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tion reversal together with a flat spectrum, provided that the magnetic fields in the two sources have opposite orientations with respect to the line of sight.

Recently Morris, Mutel, & Su (1990) have proposed a two-dimensional magnetospheric model to interpret the radio emission from late-type active stars. The source is assumed to be a toroidal region, threaded by dipolar field lines, which contains thermal plasma and a trapped power-law distribution of relativistic electrons emitting gyrosynchrotron radiation. For the special case of a pole-on view, they find that only a few sets of parameters are consistent with the observations of the flaring and quiescent emission; in particular, the only way to obtain, for the quiescent component, a reversal in the sense of circular polarization with $\alpha \lesssim 0$ is to assume that the relativistic electron density increases strongly with radial distance.

A similar conclusion is reached also by Jones et al. (1994) in the case of a three-dimensional dipole field with a spherically symmetric relativistic electron density. In order to reproduce also the observed degree of circular polarization, they find that the magnetic field geometry should be an arcade of loops, with the emitting electrons confined only to a thin shell at a distance of about two stellar radii.

3. RESULTS OF HOMOGENEOUS CALCULATIONS

In order to interpret the observed polarization properties, we have first computed the spectrum and polarization of gyrosynchrotron emission from a homogeneous source, for different values of the source parameters. Emission in vacuo as well as in a medium with uniform thermal plasma density n_e and temperature T has been considered; in the latter case Razin suppression and free-free emission and absorption have been taken into account. A mean value $T = 1.5 \times 10^7$ K for the "hot" coronal plasma component has been used, based on recent X-ray observations of a sample of RS CVn stars (Dempsey et al. 1993).

The source is assumed to have a cylindrical shape, with projected surface area $A = \pi(L/2)^2$ and dimension L along the line of sight. L has been chosen to be of the order of the binary separation ($L = 10^{12}$ cm), in agreement with VLBI observations of the quiescent emission (Lestrade et al. 1984b; Mutel et al. 1985; Massi et al. 1988). The magnetic field B is assumed to be uniform within the source and makes an angle θ with the line of sight.

The emitting population of electrons is assumed to have an isotropic power-law energy spectrum of the form

$$N(\gamma) = K(\gamma - 1)^{-\delta} \quad (1)$$

with low-energy cutoff $\gamma_0 = 1.1$ ($E_0 = 50$ keV) and $K = N_R (\delta - 1)(\gamma_0 - 1)^{\delta - 1}$, where N_R is the total number density of particles with $\gamma > \gamma_0$. The emissivity $j^{\pm}$ and the absorption coefficient $k^{\pm}$ for the ordinary (+) and extraordinary (−) modes have been computed using the approximate general expressions derived by Klein (1987). We make the common assumption that the modes propagate independently and solve the transfer equation separately for the two modes (Ramaty 1969). The emergent total intensity I and circularly polarized intensity V are then reconstructed from the intensities in the two modes following the usual prescription. We adopt the convention that $V > 0$ when the polarization is in the sense of the extraordinary mode. The degree of circular polarization is then $\pi_c = V/I$.

We have investigated the trend of the spectrum and circular polarization between 1.4 and 15 GHz for different values of the parameters δ, N_R, θ, B, and n_e. Specific examples of how the flux and polarization spectra change when the source parameters are varied have recently been published by Bruggmann & Magun (1990) in the context of solar radio emission and will therefore not be repeated here.

The results obtained for the polarization show the following:

1. The degree of circular polarization has a maximum at a certain frequency near the spectral peak and then decreases at higher frequencies where the source is optically thin, as numerous other studies have shown (e.g., Dulk & Marsh 1982).
2. The polarization is always in the sense of the extraordinary mode ($V > 0$) in the optically thin part of the spectrum and reverses its sense at a certain frequency below the spectral peak.
3. The degree of polarization is greater for greater values of B and δ, while it decreases if θ or N_R are increased. This latter result is consistent with the observation of smaller degrees of polarization at higher flux levels, when presumably the number of radiating electrons in the source is greater than during low emission periods.

Figure 1 shows the relationships between the frequency at which the total intensity is maximum, ν_{pk}, the frequency at which the circularly polarized flux is maximum, ν_{pol}, and the

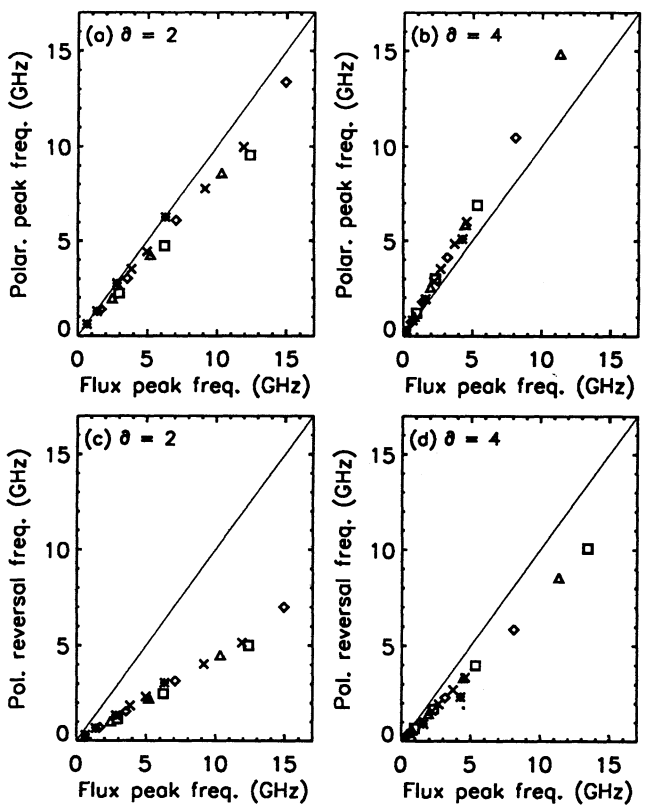

FIG. 1.—This figure presents the behavior of the frequency at which the circularly polarized flux is maximum, ν_{pol}, and the frequency at which the sense of polarization reverses, ν_o, as a function of the frequency at which the total intensity is maximum, ν_{pk}, for a series of homogeneous gyrosynchrotron models of varying δ, θ, B, and N_R: (*a*) ν_{pol} vs. ν_{pk} for $\delta = 2$; (*b*) ν_{pol} vs. ν_{pk} for $\delta = 4$; (*c*) ν_o vs. ν_{pk} for $\delta = 2$; and (*d*) ν_o vs. ν_{pk} for $\delta = 4$. The points shown refer to calculations in a vacuum, with $B = 3$, 10, 30, 100 G, $N_R = 5 \times 10^3$ cm^{-3} ($\delta = 2$) and 10^6 cm^{-3} ($\delta = 4$), $\theta = 10°$ (*asterisks*), 30° (*diamonds*), 50° (*triangles*), 70° (*squares*); and with $\theta = 30°$, $B = 30$ G, $N_R = 10^3$, 2×10^3, 10^4, 2×10^4 cm^{-3} for $\delta = 2$ and $N_R = 2 \times 10^5$, 5×10^5, 2×10^6, 5×10^6 cm^{-3} for $\delta = 4$ (*crosses*).

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frequency at which the sense of polarization reverses, v_o, in the two cases $\delta = 2$ and $\delta = 4$. Several different values of θ, B, and N_R are plotted. The points shown refer to calculations in a vaccum. As may be seen from the figure, for a fixed electron energy spectrum δ there is a very good linear correlation between these frequencies (i.e., $v_{\rm pol} \propto v_{\rm pk}$ and $v_o \propto v_{\rm pk}$) which is largely independent of the parameters θ, B, and N_R. The slopes of the linear relationships do depend on the energy spectrum, being greater for greater values of δ.

To investigate the effect of the ambient plasma on $v_{\rm pol}$ and v_o, in Figure 2 we present the same relationships for fixed values of B and N_R, with varying n_e, for four different values of θ. Points with the same value of θ are joined by a solid line. Both relationships are practically unaffected by the medium until the plasma density is so high ($n_e = 5 \times 10^8$ cm^{-3}) that the spectrum becomes strongly suppressed at low frequencies due to the Razin effect.

Therefore, in the absence of a significant Razin effect, which should be discernible in the spectrum, the homogeneous model predicts a general linear relationship between $v_{\rm pk}$, $v_{\rm pol}$, and v_o, which is independent of the source parameters, once the value of δ is fixed from the observed spectral index in the optically thin part of the spectrum. In particular we find always $v_{\rm pol} \simeq v_{\rm pk}$ and $v_o < v_{\rm pk}$, i.e., the peak degree of polarization coincides with the spectral peak, but the polarization reversal due to self-absorption occurs in a region where the spectral index is positive.

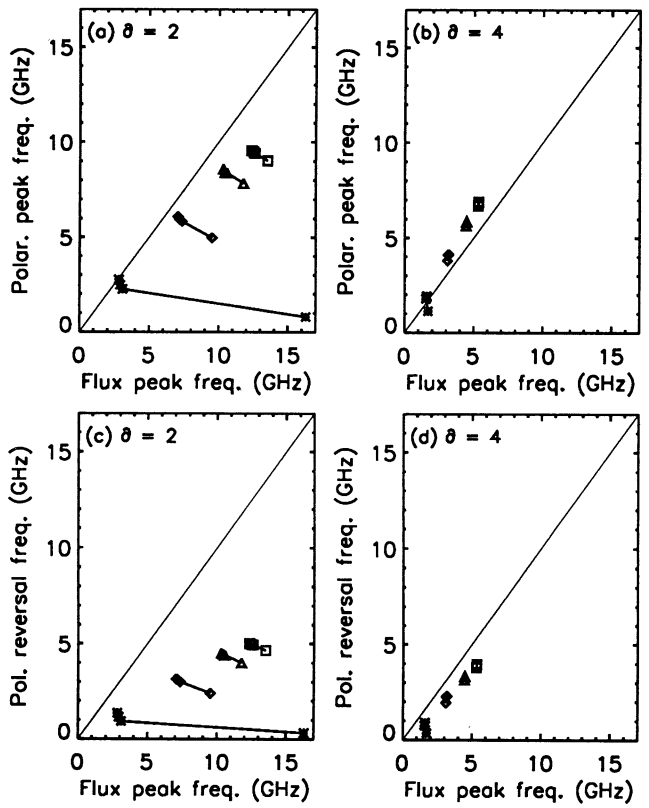

FIG. 2.—Effect of a thermal plasma on the relationships shown in Fig. 1. The panels are the same as in Fig. 1 except that the values of B and N_R are fixed while n_e varies, for four different values of θ. Points with the same θ but differing n_e are joined by solid lines. The parameters are $B = 30$ G, $N_R = 5 \times 10^3$ cm^{-3} ($\delta = 2$) and 10^6 cm^{-3} ($\delta = 4$), $n_e = 0$, 5×10^7, 10^8, 5×10^8 cm^{-3}, $\theta = 10°$ (*asterisks*), 30° (*diamonds*), 50° (*triangles*), and 70° (*squares*). The points most distant from the linear relationship correspond to $n_e = 5 \times 10^8$ cm^{-3}.

This result is inconsistent with the observations of RS CVn stars: in fact, as pointed out in the previous section, the polarization reversal occurs generally between 1.4 and 5 GHz independently of the position of the spectral peak, and in most cases the polarization peaks at a much higher frequency than does the flux spectrum.

4. EXTENSION TO INHOMOGENEOUS MODELS

Homogeneous models are a convenient tool because of their simplicity and the limited number of free parameters they involve, but we do not expect that they are a good representation of stellar radio sources. The appropriate question to ask is, what general properties of the polarization of homogeneous sources also apply to inhomogeneous sources?

In the optically thin limit we see all parts of the source at all frequencies, and it may be helpful to think of an inhomogeneous source as a collection of homogeneous sources. In the optically thin portion of an inhomogeneous source in which the electron energy distribution takes the same form everywhere, the spectral index of every part of the spectrum will be the same, and then the source will be dominated by the region of the source in which $B \sin \theta$ is largest. In such an inhomogeneous source, it follows that the property of homogeneous models that circular polarization decreases as frequency increases above the spectral peak will also hold, with the complication that near the spectral peak some regions of the source will become optically thin at frequencies lower than in other regions.

It is much more difficult to generalize to the optically thick limit, since the observed properties at a given frequency depend on the nature of the optically thick surface at that frequency, and there may be a significant admixture of optically thin flux from above the optically thick surface. Effectively there are more free parameters in the optically thick limit. Jones et al. (1994) analyze a set of dipole models and conclude that it is very difficult to achieve a degree of circular polarization larger than 1% at optically thick frequencies. In their models the degree of polarization peaks near the spectral peak, as in the homogeneous models. In common with other authors, they also find that to explain the very flat spectra one often observes, either the source is optically thin and a very hard electron energy spectrum is required ($\delta \sim 2$), or else the source is optically thick and the nonthermal electron density must *increase* with height to explain the flat spectrum, as was found by Drake et al. (1987). White, Kundu, & Jackson (1989) argued that one can also explain flat optically thick spectra without requiring that density increase with height: such flat spectra are also obtained in models in which both the energetic-electron number density and magnetic field strength fall slowly as height increases.

5. OBSERVATIONS

As part of a project to study the long-term evolution of the polarization of RS CVn systems (White 1995), we have been observing three bright and polarized binary systems (HR 1099, UX Arietis, and HR 5110) with the Very Large Array (VLA)[2] on a regular basis. Figures 3 (HR 1099, 1993 July 5) and 4 (UX Ari, 1994 April 23) show two examples of the behavior of the light curves in left (L) and right (R) circular polarization at 1.4 GHz. In each case the observation lasted ~20 minutes and

[2] The Very Large Array is a facility of the National Radio Astronomy Observatory, which is operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation.

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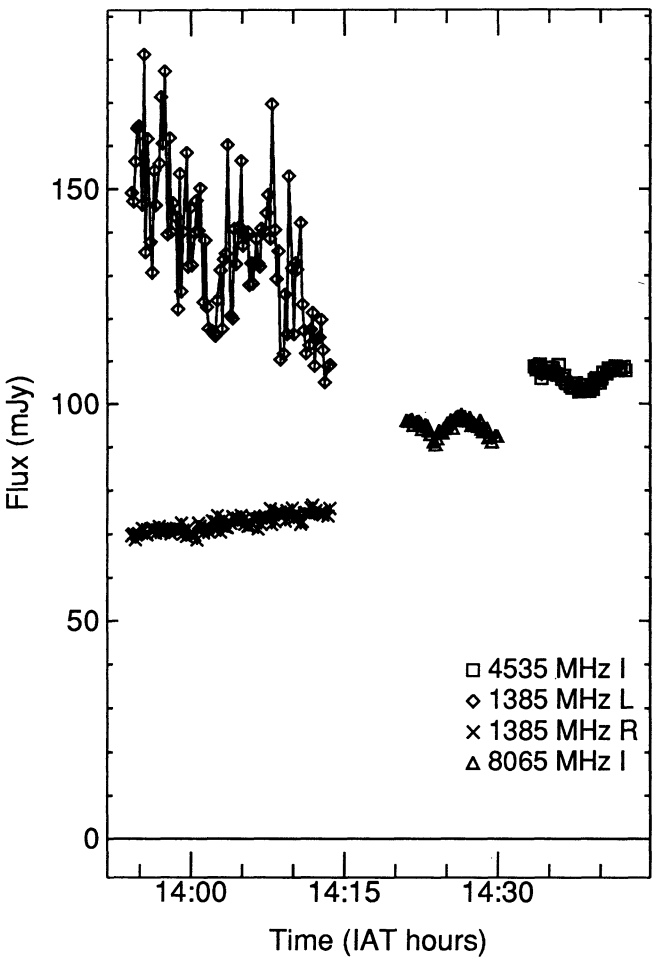

FIG. 3.—The time profiles of right (R; *cross symbols*) and left (L; *diamond symbols*) circular polarization at 1.385 GHz every 10 s during a VLA observation of HR 1099 on 1993 July 5. The total intensity in subsequent scans at 4.5 GHz (*squares*) and 8.1 GHz (*triangles*) are also plotted. Error bars of $\pm\sigma$ are plotted on all points.

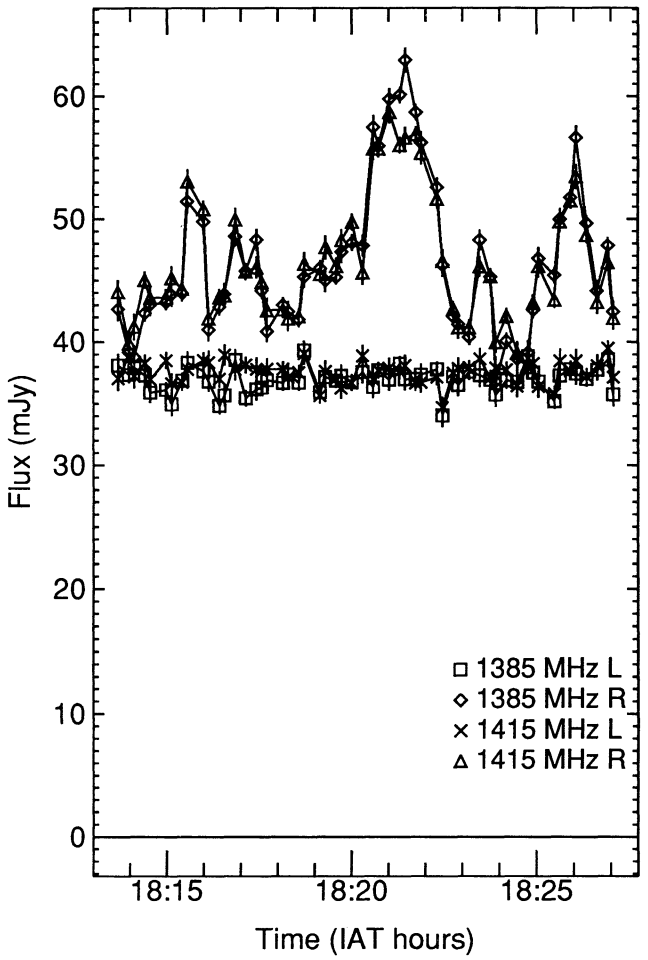

FIG. 4.—The time profiles of right (R) and left (L) circular polarization every 10 s during a VLA observation of UX Ari on 1994 April 23. Two sidebands at 1385 MHz (*squares*: L; *diamonds*: R) and 1415 MHz (*crosses*: L; *triangles*: R) are plotted; each sideband had a bandwidth of 50 MHz. Error bars of $\pm\sigma$ are plotted on all points.

data were obtained at two sidebands, each of 50 MHz bandwidth and centered on 1385 MHz and 1415 MHz, respectively. In Figure 3 we plot R and L for 1385 MHz, together with total intensity data in subsequent scans at 4535 and 8065 MHz. In Figure 4 we display R and L for both 1385 and 1415 MHz, in order to compare the behavior at the two sidebands. The data points are each 10 s apart, and $\pm\sigma$ error bars are plotted. In both these examples the stars were relatively bright. Figure 3 shows that the left circular polarization received from HR 1099 was up to twice as strong as the right, and while R was steadily increasing over the 20 minute observation, L was fluctuating rapidly on timescales as short as 10 s, but overall showed a clear decreasing trend. In Figure 4, UX Ari was steady at L, but showed rapid fluctuations in R. From the similarity of the 1385 and 1415 MHz time profiles in Figure 4, it is clear that the fluctuating component was not narrowband, and this was true of the HR 1099 data also: in each case there appears to be little significant difference between the two 50 MHz sidebands centered 30 MHz apart.

As a test to ensure that the observed fluctuations in one polarization were not instrumental, we studied the time profiles of the two polarizations for a strong background source in the field of view of HR 1099. Such background sources are almost always extragalactic objects which should have essentially no circular polarization and should not vary on short timescales. This was found to hold true for the background source we investigated, indicating that the fluctuations observed in HR 1099 were not artifacts.

The features of these observations which are important to note are that the circular polarization is predominantly due to a broadband component which has small variations on short timescales, but on longer timescales appears to be slowly modulated. If the observations did not have adequate signal-to-noise ratio, we would be unable to see the small rapid fluctuations, but the slower modulation would be evident. The rapid fluctuation is characteristic of a coherent emission process, such as plasma emission or cyclotron maser emission (e.g., Dulk 1985; Melrose 1991), which are also known to be able to produce very high degrees of circular polarization. The slower modulation could be mistaken for an incoherent process such as gyrosynchrotron emission.

In both these examples, the sense of the predominant circular polarization of 1.4 GHz was opposite to that at higher frequencies. On 1993 July 5, HR 1099 was -29% polarized at 1.4 GHz, $+7\%$ polarized at 5 GHz, and $+10\%$ polarized at 8 GHz. On 1994 April 23, UX Ari was $+11\%$ polarized at 1.4

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GHz, −1% polarized at 5 GHz, −2% polarized at 8 GHz, and −3% polarized at 15 GHz. This is exactly the behavior attributed to the quiescent emission of these systems by Mutel et al. (1987).

Highly polarized emission has often been seen in these systems previously, and has generally been described as flare-related emission. Mutel & Weisberg (1978) and Fix, Claussen, & Doiron (1980) observed HR 1099 at 1.4–1.7 GHz at Arecibo and saw left circular polarizations of up to 75%, with rapid variability; on UX Ari, Mutel & Weisberg (1978) found right circular polarization of up to 20%. Brown & Crane (1978) measured left circular polarization of up to 40% on HR 1099 at 2.7 GHz and found it to vary on timescales shorter than 1 hr. Gibson, Hicks, & Owen (1978) measured right circular polarizations of order 20% on HR 1099 at 4.9 GHz, and rapid variability at 1.4 GHz (with no circular polarization data). Simon, Fekel, & Gibson (1985) detected a highly left circularly polarized (86%) flare from AY Ceti at 1.5 GHz, while Lestrade et al. (1988) saw up to 70% left circular polarization from Algol at 1.7 GHz. The latter example, also obtained with the VLA, appears quite similar to Figures 3 and 4, with one polarization (R, in the case of Algol) steady while the other shows rapid but small fluctuations superposed on a steady level of emission. It should be noted that, with one exception, all of these examples of highly polarized emission occurred at a frequency below 3 GHz.

In most of the examples cited above, the highly polarized component was attributed to an outburst due to a coherent emission mechanism. On the basis of Figures 3 and 4, it is clear that only a portion of the emission at 1.4 GHz is due to such a mechanism: the steady level of emission seen in the weaker polarization is clearly not related to the rapidly fluctuating component in the stronger polarization. Thus a combination of two sources of emission is present: a possibly weakly polarized component which is steady, and a very highly polarized component, possibly 100% polarized, which has rapid fluctuations on a short timescale, but a more gentle modulation on a longer timescale. We suggest that the most likely mechanism for the highly polarized emission is plasma emission. The main argument in favor of this is that the polarization detected at high frequencies, where the radio spectrum is falling and the source should be optically thin, should represent the x-mode for gyrosynchrotron emission. Since the low-frequency polarization is in the opposite sense, it probably represents the o-mode, which is characteristic of plasma emission. On the Sun plasma emssion comes in many different guises. The form which is closest to that seen here is the noise storm emission common at frequencies between 200 and 500 MHz (Kai, Melrose, & Suzuki 1985): it is broadband, typically 100% polarized in the sense of the o-mode, and can exhibit both rapid fluctuations as well as slower modulation. From the very high degrees of polarization we infer that the o-mode emission is at the fundamental of the plasma frequency, i.e., $\nu = \nu_p = 9000(n_e)^{1/2}$, and hence arises in a region of the corona where the ambient electron density $n_e \sim 2 \times 10^{10}$ cm^{-3}.

Let us now consider the behavior of the degree of polarization at high frequencies. Figure 5 shows the flux and polarization spectra of UX Ari, HR 1099, and HR 5110 obtained from our observations (all those from 1993–1994) and from other previously published observations with measurements of at least three frequencies. The previous data are taken from Pallavicini et al. (1985: the 1984 observations), White et al. (1990: the 1989 January observations), and Umana et al. (1993: HR 5110, 1989 February 18 and 1989 March 6). We have omitted cases in which the fluxes were large and the degree of polarization small. From this figure it is clear that generally the degree of circular polarization π_c tends to increase with frequency (in the R sense for HR 1099 and HR 5110, in the L sense for UX Ari), at least up to 15 GHz, independently of the shape of the spectrum. Only in one of the 15 cases shown in Figure 5 is there a decrease in the degree of polarization at the highest frequency. Another example of the increase in polarization with frequency, observed during the decay phase of a flaring event on HR 1099, is shown in Morris et al. (1990).

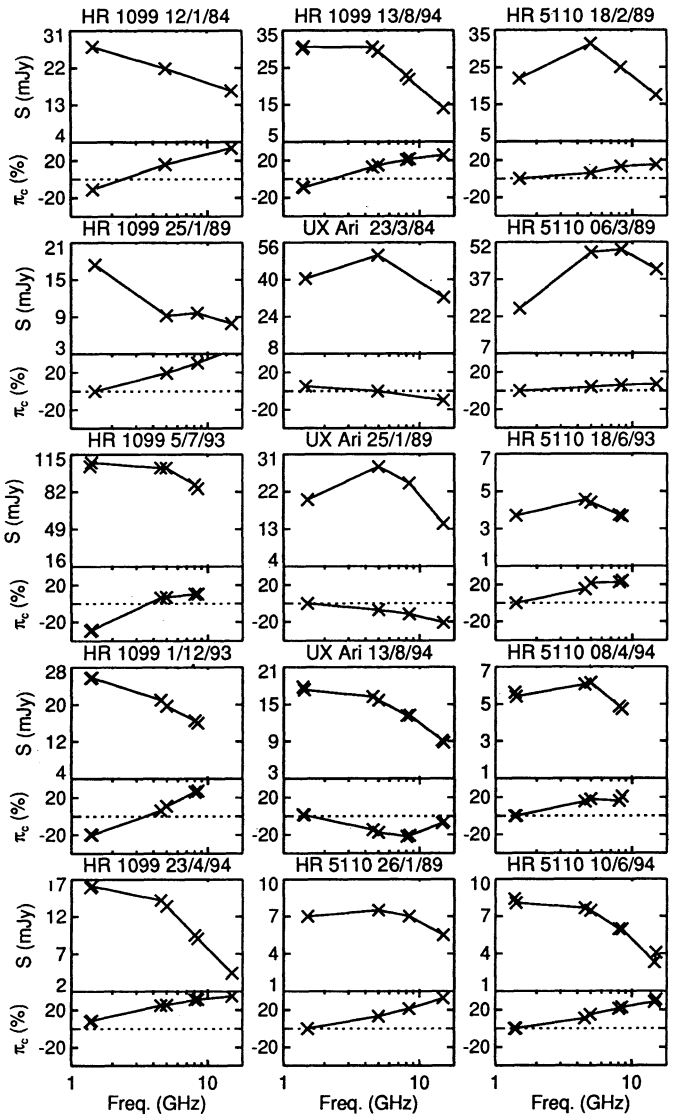

FIG. 5.—The flux spectra S (*upper panels*) and degree of circular polarization π_c as a function of frequency (*lower panels*) for 15 separate observations of the three polarized RS CVn radio sources HR 1099, UX Ari, and HR 5110. The data are taken from the literature and from previously unpublished observations. Only observations with measurements of at least three frequencies are included. The source and the date of the observation are given above every panel.

Moreover, if we separate the observed quiescent emission in the two oppositely circularly polarized components, we see that this increase of π_c is due to the fact that generally the component with higher flux density at high frequency (R for HR 1099 and HR 5110, L for UX Ari) has a flatter spectrum,

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while the other polarization decreases faster with frequency. This behavior is the opposite of that predicted by gyrosynchrotron models: in fact where the source is optically thin, with $\alpha < 0$, we expect a decreasing degree of curcular polarization with increasing frequency, because we obtain a flatter spectrum for the *o*-mode, whereas the emission is polarized in the sense of the *x*-mode.

This problem of obtaining a degree of polarization increasing toward higher frequencies has not been addressed by most earlier published models, which generally have been concerned with the explanation of the spectrum and of the polarization reversal at lower frequencies. Only Jones et al. (1994) have noted that they could not reproduce the behavior of the degree of polarization at high frequencies. One can come up with ad hoc multicomponent models which reproduce this behavior: for example, the sum of an unpolarized steep spectrum component and a polarized, flatter spectrum component can produce a degree of polarization which is increasing over a certain range of frequencies. However, above some frequency, the steep-spectrum component becomes insignificant and the degree of polarization should again decrease with increasing frequency: our observations indicate that this does not generally occur below 15 GHz.

6. DISCUSSION

Based on the observations of low-frequency polarization discussed in the previous section, we suggest a new interpretation for radio observations of RS CVns in which the polarization of the quiescent radio emission below 3 GHz is inverted with respect to the sense of the polarization at high frequencies. Presently this polarization reversal is attributed either to the intrinsic *o*-mode polarization of self-absorbed gyrosynchrotron emission, or to the presence of several gyrosynchrotron components, each with a spectral peak located conveniently to reproduce the observed properties. As noted above, the occasional very large degrees of polarization observed at low frequencies and the location of the inversion with respect to the spectral peak are inconsistent with optically thick models, and the multicomponent models are somewhat ad hoc. We suggest instead that the low-frequency polarization is actually due to the presence of weak but highly polarized coherent *o*-mode emission superposed on a weakly (if at all) polarized quiescent component. When the highly polarized component is strong, it is readily identified as something other than quiescent emission. Often this highly polarized component will be rapidly varying, but on other occasions it may vary only slowly and thus be difficult to distinguish from the true quiescent component on the basis of temporal properties alone.

We cannot determine the true sense of polarization of the quiescent component at 1.4 GHz from the data available; we do have one example which suggests that it is the *x*-mode, not the *o*-mode, for HR 1099 (1994 April 23: +8% at 1.4 GHz, +25% at 5 GHz, +31% at 8 GHz and +35% at 15 GHz). The observation by van den Oord & de Bruyn (1994) that the emission at 0.36 and 0.61 GHz from II Peg is typically very highly polarized is consistent with our interpretation since, based on the solar analogy, we expect the highly polarized coherent emission to become more dominant over the weakly polarized quiescent emission as we go to lower frequencies.

One issue which needs to be addressed is why plasma emission should be observed to be so common at 1.4 GHz in RS CVn systems when it is largely confined to lower frequencies on the Sun. The conventional explanation for its absence at higher frequencies on the Sun is the fact that the free-free absorption of plasma emission by the thermal plasma in the corona is a very strong function of frequency: since free-free opacity varies as $n_e^2/T^{1.5}$, where n_e is the ambient electron density, and the plasma frequency ν_p varies as $n_e^{0.5}$, the opacity rises as a very high power of ν_p (e.g., Benz 1993). Thus there is a fairly sharp upper limit to the frequency range of plasma emission for a corona of a given temperature, except when very sharp gradients are present in the corona (e.g., Benz et al. 1992). However, as already noted, the typical temperature of coronal material in RS CVn systems is at least an order of magnitude larger than in the solar corona, and this effect will reduce the opacity for plasma emission at a given frequency and allow it to appear at higher frequencies than on the Sun.

The three systems whose observations we discussed earlier are all believed to be observed roughly pole-on from our viewpoint, and this fact is believed to be crucial in making them highly polarized compared with, say, eclipsing systems such as AR Lac (Mutel et al. 1987): most studies of the magnetic field structure on active stars lead to the conclusion that there are large long-lived polar spots (e.g., Donati et al. 1992), and since the systems are pole-on, we always see a spot of the same polarity, which explains the observed consistency in polarization over long timescales (e.g., White 1995). The question arises as to what we expect to see at low frequencies in systems where both poles are visible. At higher frequencies we can expect rough cancellation of the optically thin but oppositely polarized emission from the two poles, which explains why the polarization in these systems is generally lower. However, coherent sources are usually more variable than incoherent sources, so it is unlikely that coherent *o*-mode sources over both poles will have the same strength at all times, and we might expect to see more variability in the observed polarization. It is possible that coherent sources over the poles may be beamed away from us if we are looking at them from the equator rather than looking down on them from above the poles: some low-frequency plasma emission on the Sun is known to be beamed, largely because *o*-mode emission at the fundamental is emitted in a region with refractive index much smaller than unity and must refract as it propagates to lower densities (e.g., Melrose & Dulk 1988; Lim et al. 1994). In a corona with a predominantly radial density gradient, this effect will cause fundamental plasma emission to be radially beamed, in which case radiation originating over the poles will be directed away from observers in the equatorial plane. Another consideration is that not all systems will necessarily show the coherent emission reported here: the system HR 5110 is a very active radio source, is believed to be nearly pole-on and can be highly polarized at 5 GHz (e.g., Mutel et al. 1987), but so far it has never shown any circular polarization at 1.4 GHz.

We also note that the assumptions that the three stars we discuss are seen pole-on and that each has a magnetic field dominated by a large-scale dipole component implies that mode coupling is probably not relevant: mode coupling becomes an issue only when the component of the magnetic field along the line of sight reverses within the stellar corona. For sources located near the pole of a dipolar field and seen nearly pole-on, any such reversal probably occurs very high in the corona. In any case, mode coupling cannot increase the degree of polarization above the fraction intrinsic to the source of the radiation.

In the model derived from VLBI observations, the polarized quiescent component of the radio emission arises in an

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extended source, while the strong unpolarized component seen in ourbursts is very compact. This seems initially counter-intuitive, because polarization is always highest where the magnetic field is strongest, and in an extended component with dimension equal to the size of the binary system we expect the mean field to be rather low. There is a testable corollary of this model, however: since the compact outburst component does not obscure the much larger quiescent component, the total circularly polarized flux should not greatly change during an outburst (this assumes that the outburst is completely unpolarized, which may not be the case).

7. CONCLUSIONS

We argue that the polarization inversion seen at low frequencies in the quiescent radio emission of RS CVn binaries is not a property of the quiescent emission at all, but rather associated with weak coherent plasma emission which is broadband, often slowly varying, and highly polarized in the sense of the *o*-mode. Such emission, when weak, will not easily be distinguished from true quiescent emission, but there are several examples in which this form of emission is clearly present in a stronger form and which show a slower modulation not unlike that of quiescent emission. The rapid low-level modulation which can be detected in the stronger examples of this emission will not be seen when the emission is weak because of limited signal-to-noise ratio in the data.

If this interpretation is correct, it removes the need for models of the quiescent radio emission of RS CVn systems to reproduce the low-frequency polarization, which has proved to be a difficult constraint (e.g., Jones et al. 1994). In particular, it may not be necessary for the energetic electron number density to increase with distance from the star, as some models of the quiescent emission have required in order to reproduce both the flux spectrum and the polarization reversal (e.g., Morris et al. 1990). In some cases, taking the highly polarized component into account will also change the spectrum of the quiescent component considerably: for example, in Figure 3 the spectrum obtained if we assume that the quiescent emission at 1.4 GHz is at the level of the right circularly polarized emission is quite different from that obtained if we use total intensity as the quiescent level (the spectrum peaks between 1.4 and 5 GHz, rather than peaking below 1.4 GHz).

One obvious problem with gyrosynchrotron models for the quiescent emission of RS CVn systems remains: that of explaining how the degree of polarization can continue to increase as one goes to higher frequencies. Inhomogeneous models permit the degree of polarization to increase over some range of frequencies, but above some frequency the source becomes optically thin everywhere and gyrosynchrotron models then require that the degree of polarization should decrease as one goes to higher frequencies. The observations clearly show that it continues to increase at 15 GHz, and we plan future observations to determine whether the increase continues at even higher frequencies.

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