Quiescent Non-thermal Radio Emission from Stellar Systems

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Abstract: Non-thermal radio emission has been detected from dMe stars, RS CVn binaries and W T Tauri stars. Polarisation and intensity measurements of the quiescent (i.e. non-flaring) emission indicate that the emission is gyrosynchrotron emission from mildly relativistic electrons spiralling in a magnetic field. A three-dimensional dipole magnetic field model for the stellar field is presented and the quiescent gyrosynchrotron emission from such a model is calculated and compared with observations. The model can account for many phenomenological features of quiescent emission. Quantitative comparisons of model results with observations indicate that the electron distribution in the emission region may be a magnetic mirroring distribution.

Keywords: stars: flare — radiation mechanisms: cyclotron and synchrotron — radiative transfer

1. Introduction

Many different kinds of stars have been observed to emit non-thermal radio radiation and many properties of the radiation are common to different systems. For example, dMe stars (dwarf M stars with emission line spectra indicating that they have active chromospheres), RS CVn binaries (evolved close binary systems) and weak-line T Tauri stars (low-mass pre-main-sequence stars which lack the envelope of circumstellar material seen in classical T Tauri stars) appear to be very different systems. However, dMe stars and RS CVn systems emit radio flares that are highly circularly polarised and are thought to be produced by a coherent emission mechanism close to the stellar surface (Melrose & Dulk 1982). In addition, all three types of system emit quiescent radio emission, distinguishable from flaring emission by being slowly variable (on timescales of hours), less highly circularly polarised and usually of lower intensity than the flaring emission.

The quiescent radio emission of dMe stars is of order a few millijansky with circular polarisation usually less than 10%. Sometimes the intensities are rising with frequency, sometimes falling, and the spectral indices are usually fairly flat (Jackson, Kundu & White 1989). The quiescent emission of RS CVn binaries is, in general, of higher flux than that of the dMe stars and often, but not always, moderately circularly polarised (Mutel et al. 1987, hereafter MMDL). Direct VLBI measurements have indicated that in some cases the emission region is at least as large as the binary system (Lestrade et al. 1985). VLBI observations of W T Tauri stars have revealed that for these systems also, the source size for quiescent emission is much larger than an individual star (Phillips, Lonsdale & Feigelson 1991). Low circular polarisation has been detected from W T Tauri stars and the intensities usually rise slowly with frequency (White, Pallavicini & Kundu 1992).

For all three kinds of stars the brightness temperatures, spectral indices and degrees of circular polarisation indicate that the emission is gyrosynchrotron emission from a non-thermal distribution of mildly relativistic electrons. In the following sections a three-dimensional calculation of the gyrosynchrotron emission from a large-scale magnetic dipole magnetosphere is presented and compared with observations. This extends and corrects calculations in two dimensions by Morris, Mutel & Su (1990) and complements calculations of the gyrosynchrotron emission from small loops by White, Kundu & Jackson (1989). The emphasis in this paper is not on creating models of individual stars. Models of individual systems have been calculated by Jones et al. (1994), who show that it is very difficult to explain the data from an individual system with a straightforward model. It is, however, worth noting that the modelling of individual systems is probably made more complicated by the fact that only the brightest systems have good enough data to compare with a model, and these systems may be especially bright because they are in some way extraordinary and atypical. As well, detailed quantitative comparisons of models with available data are difficult. White & Franciosini (1995) have shown that at low frequencies a form of high-polarisation plasma emission may be present and may be confusing the low-frequency gyrosynchrotron observations. More data are needed to help distinguish between the two kinds of emission. In this paper the general trends...
of the data are compared with model calculations, with the principal aim of deriving information on the overall magnetic structure. In Section 2 the likely structure of the emission regions is discussed and in Section 3 the model calculation is described and synthetic spectra are presented. In Section 4 model results are compared with observations of the quiescent emission from RS CVn binaries. In Section 5 a magnetic mirroring electron distribution is included in the model to better explain the observed circular polarisation and spectral indices of RS CVn systems, and the conclusions of the work are presented in Section 6.

2. Source of the Quiescent Emission

The observations indicate that the quiescent emission from the systems mentioned above is gyrosynchrotron emission from non-thermal electrons, but it is not known whether the radiating electrons are continuously injected into the emission region during an observation period, or whether just one injection of electrons occurs. The timescales for most energy-loss processes are too long to affect the energy of radiating electrons during the observation periods of a few hours. However, wave-scattering may be more important and cause significant precipitation of electrons out of the emission region and into the lower atmosphere of the star (Kundu et al. 1987). In the following calculation of the gyrosynchrotron emission, the electron distribution was taken to be constant in time.

The structure of the emission region is also not well understood. It is not clear whether there is a large-scale magnetosphere surrounding the star, or whether the emission comes from ever-changing systems of small loops, as are observed on the Sun. The observational evidence is not clear and has been used to argue both for a large-scale magnetosphere for RS CVn systems (Morris et al. 1990) and against a large-scale magnetosphere for dMe stars (White et al. 1989). The observational evidence is summarised below.

As mentioned above, for some RS CVn systems VLBI measurements have indicated that the emission region is as large as the binary system, and VLBI measurements of W T Tauri stars have also indicated very large emission regions, as large as 10 stellar radii. This is evidence for a large-scale magnetosphere. The circular polarisation of some RS CVn systems is as high as 20% (MMDL) and the polarisation is often observed to change helicity on either side of the observed spectral peak. The helicity of the circular polarisation observed from a particular system is steady over many years, which implies that the emission is from a stable magnetic structure and not from small loops with a short lifetime (MMDL). As well, the emission from both dMe stars and RS CVn systems is constant over long periods of time, implying that the emitting regions are stable structures, changing little.

The stars in RS CVn binaries are tidally locked, i.e. the stars rotate synchronously with the orbit. The orbital axis is roughly parallel to the spin axis of the stars and it is believed that the magnetic axis is roughly parallel to these axes. It has been observed that there is no correlation between polarisation and binary phase or between luminosity and binary phase of RS CVn systems. This observation implies that the emission region is axisymmetric with respect to the star and is further evidence for a global magnetosphere surrounding RS CVn systems (Morris et al. 1990).

On the other hand, the fact that the observed polarisation in dMe stars is low (Jackson et al. 1989) has been thought to imply that there is no overall direction in the magnetic field and the emission must come from many small magnetic loops protruding from the stellar surface. The emission observed is the sum of emission from many different loops at different orientations to the observer, and the contribution to the polarisation from different regions cancels out, resulting in the observed low polarisation.

No Zeeman splitting in emission lines has been observed from dMe stars down to a level of $10^{-2}$ T (100 G) (Vogt 1980). Again, it has been argued that this implies that there is no overall direction to the magnetic field and we are observing the effect of many loops with different orientations. Surface fields higher than $10^{-2}$ T (100 G) have been measured (Saar 1990) and so this points to there being localised regions of high field on the surfaces of these active stars.

The fact that highly polarised, coherent flares are seen has also been used to argue against a large-scale magnetosphere. The most widely accepted interpretation of the flare emission is that it is coherent cyclotron emission from close to the surface of the star (Dulk 1985). Such emission would be very effectively absorbed by a gyrosynchrotron-radiating plasma above it. It has been thought that there cannot, therefore, be such a plasma surrounding the star or the flare emission would not be able to be seen. However, recent work has discussed various escape possibilities (Kuncic & Robinson 1993), indicating that the radiation may be able to escape from the plasma.

3. Quiescent Emission Model

In order to help resolve the question of the magnetic structure surrounding quiescent emitters, in this section a calculation of the gyrosynchrotron emission from a three-dimensional dipole magnetosphere surrounding a star is presented and compared with the observations. A dipole model was chosen as it is the simplest large-scale magnetic field configuration, and a large-scale structure was chosen as it has fewer free parameters than a model incorporating
many small emitting loops. The data are sparse and the more complicated the model, the easier, but less meaningful, it becomes to fit the data.

The star is assumed to be surrounded by a dipole magnetosphere containing radiating electrons. Only the closed field lines contain radiating electrons—the open field lines are assumed to contain no radiating, or absorbing, plasma, as electrons would not be trapped in the open field-line region (see Figure 1). It is not known whether a significant background thermal plasma coexists with the relativistic gyrosynchrotron plasma. For simplicity, in the model calculations the effects of any background thermal plasma in the gyrosynchrotron emitting region are neglected, so that self-absorption by the relativistic electrons is the only important absorption process.

The number density of radiating electrons was assumed to vary with energy and radius as \( N(E, r) = kE^{-2r^{-7}} \). The steep dependence of electron number density on radius is due to flux tube expansion and adiabatic cooling of the electrons as they expand into the outer magnetosphere. For the results presented below, the electron number density was always constrained so that the energy density in the electrons was less than the energy density in the magnetic field.

Analytic expressions for the gyrosynchrotron emissivity and absorption from Robinson & Melrose (1984) were used [cf. equation (52a,b) of that paper]. The expressions are valid for harmonic number \( s = (\omega/\Omega_c) > 5 \), where \( \omega \) is the observing frequency and \( \Omega_c \) is the cyclotron frequency. Only magnetic fields that satisfied this condition at 1 GHz were considered.

Given these constraints, the gyrosynchrotron radiation emerging from the magnetosphere was calculated for various surface magnetic field values, relativistic electron number densities, system sizes and observer angles. The observer angle is the angle between the magnetic axis and the line of sight to the observer. Gyrosynchrotron radiation in the plasma considered here is emitted in two transverse natural modes (Melrose 1980, p. 104). The total intensity is the sum of the intensities in each of the two modes. For the model parameters considered here, Faraday rotation dominates absorption and the two natural modes are assumed to propagate independently. To calculate the total intensity emerging from the model magnetosphere, the equation of radiative transfer for each of the two natural wave modes (\( \sigma \)-mode and \( \pi \)-mode) of the plasma was solved along paths of propagation assumed to be parallel straight lines in the direction of the observer. The solution was accomplished by dividing the ray paths into small volume elements of dimension \( dz \) along the ray path and assuming that the volume emissivity, \( j_0, \sigma, \pi \), and the absorption coefficient, \( \alpha_0, \sigma, \pi \), were constant within each volume element. Then the intensity of radiation in a particular mode emerging from such an element in the direction of the observer, \( I_0, \sigma, \pi(z + dz) \), is

\[
I_0, \sigma(z + dz) = I_0, \sigma(z) \exp(-\alpha_0, \sigma dz)
\]

\[
+ \left( \frac{j_0, \sigma}{\alpha_0, \sigma} \right) \left[ 1 - \exp(-\alpha_0, \sigma dz) \right],
\]

where \( I_0, \sigma(z) \) is the intensity of radiation passing into the volume element. The size of the volume elements was chosen empirically. They were as large as possible to enable the calculation to take the shortest amount of computer time and yet small enough that making them smaller made no significant difference to the results. The contribution to the intensity from all ray paths and from both natural modes was summed to produce the total intensity from the magnetosphere. At the point of emergence from the magnetosphere the helicity of the circular polarisation of the radiation in a particular mode is determined by the sign of \( \mathbf{k} \cdot \mathbf{B} \) at that point. For example, for the \( \sigma \)-mode and \( \mathbf{k} \cdot \mathbf{B} > 0 \) the emerging radiation is right-hand circularly polarised. To calculate the net circular polarisation, the helicity of the radiation was determined for each volume element at the point of emergence from the magnetosphere. Then the degree of circular polarisation is given by

\[
\rho_c = \frac{I_R - I_L}{I_R + I_L},
\]

where \( I_R \) is the total intensity of radiation emitted with right-hand circular polarisation and \( I_L \) is the total intensity of radiation emitted with left-hand circular polarisation. A derivation of the polarisation calculation under more general conditions will be presented elsewhere (Storey, in preparation). In this paper, preliminary results only are presented.
Examples of synthetic spectra are shown in Figure 2. For reasonable plasma parameters as given in the caption to Figure 2, the model gives appropriate flux values for quiescent emission and a spectral turnover in the observed range. The circular polarisation has opposite helicity on either side of the spectral peak, as is observed for many RS CVn systems, and on the decreasing flux side is less than 10%. The reason for the change in helicity is that the rising part of the spectrum is dominated by optically thick emission. For this emission one natural mode of the plasma, the o-mode, is of higher intensity. As the plasma becomes more optically thin, emission from the orthogonally polarised mode, the x-mode, dominates, as the emissivity is higher for this mode (Dulk 1985). In the model, the change in helicity always occurs on the rising side of the spectrum.

![Figure 2](https://www.cambridge.org/core/doi/10.1017/S1323358000020233/9781108594045/image/5.jpg)

**Figure 2**—Synthetic spectra for the dipole field model for two different values of the relativistic electron number density. Squares: electron number density on the stellar surface = $5 \times 10^{10}$ m$^{-3}$. Triangles: electron number density on the stellar surface = $2 \times 10^{10}$ m$^{-3}$. Model parameters: observer angle = 0.4 rad, surface magnetic field = $6 \times 10^{-4}$ T, magnetospheric radius = $5R_\ast = 5 \times 10^{10}$ m$^{-3}$, and distance to the star = 100 pc.

4. Comparison with Observations

The quiescent emission from RS CVn binary systems is the best studied as flux values are highest for these systems. In this section the results of the model calculations are compared with the systematic investigation of the emission properties of RS CVn binaries undertaken by MMDL.

Some of their results have been mentioned above to argue in favour of a large-scale magnetosphere. Their conclusion that there is no correlation between polarisation or luminosity and binary phase is naturally explained in the large-scale dipole model because the magnetic field is axisymmetric with respect to the star and consequently, so is the emission. Similarly, the observation that polarisation features are steady over many years is a natural consequence of a model in which the star is surrounded by a nearly constant magnetosphere. MMDL also found that eclipsing systems appear to be less luminous and have lower circular polarisations than non-eclipsing systems. Eclipsing systems are those for which the observer angle is large. In Figure 3 the model flux density and circular polarisation at the spectral peak are plotted as a function of observer angle. Figure 3 shows that the model is consistent with the observations that eclipsing systems have lower peak fluxes and lower circular polarisations.

![Figure 3](https://www.cambridge.org/core/doi/10.1017/S1323358000020233/9781108594045/image/6.jpg)

**Figure 3**—(a) Model flux density at the spectral peak versus observer angle, (b) Model circular polarisation at the spectral peak versus observer angle. Model parameters are as in Figure 2. Surface electron number density = $5 \times 10^{10}$ m$^{-3}$.

However, the model does not reproduce the observed degrees of circular polarisation or the very flat spectral indices sometimes observed. The observed circular polarisation in RS CVn binaries is sometimes as high as 20% (MMDL), whereas the model values are always less than 10%. MMDL observed a very wide range of spectral indices for different systems and at different times within one system (see, for example, their Figure 3). For different initial conditions, a large range of spectral indices is produced by the model, but the optically thick spectral index produced by the model calculation is never less than 0.8 and the model is unable to account for the very flat spectra sometimes seen by MMDL. However, it is not clear how great a discrepancy there is between model results and observations, as White & Franciosini (1995) have recently shown that the low-frequency observations of quiescent emission may be confused...
by the presence of plasma emission. The presence of low-frequency plasma emission results in a flatter spectral index at low frequencies than that produced by gyrosynchrotron emission alone.

In conclusion, a simple dipole model is able to account very well for many phenomenological features of quiescent emission. On the other hand, the flat spectral indices observed in some RS CVn binaries and often in dMe stars, and the high values of circular polarisation seen in some RS CVn binaries cannot be explained by the simple model, unless the plasma emission detected by White & Franciosini (1996) is a general feature of RS CVn emission.

5. Model Refinements

Assuming that the flat spectral indices and high circular polarisations of RS CVn systems are a property of the gyrosynchrotron emission, a better model is required to explain the observations. In order to refine the simple model it is necessary to decide whether to abandon the idea of a large-scale magnetic structure and consider a more complicated magnetic structure, or whether to retain the original magnetic structure and consider likely changes to the electron distribution. It is worth noting here that the observations imply that the magnetosphere is large-scale, not necessarily that it is a centred magnetic dipole. The dipole model was adopted merely for simplicity.

In Section 2 various arguments against a global magnetic field were presented. For example, it was argued that the fact that low circular polarisation was observed for the dMe stars implies that there is no large-scale magnetosphere. However, model calculations have shown that circular polarisation of less than 10% can result from a global magnetosphere when the magnetosphere is sufficiently optically thin that emission from many field orientations is observed simultaneously. Thus low polarisation does not necessarily imply the existence of many small loops above dMe stars.

It was also argued that Zeeman-splitting results imply that there is no global field above $10^{-2}$ T (100 G). The model calculations above have shown that reasonable flux values can be obtained from systems with a surface field of less than $10^{-2}$ T, so the Zeeman-splitting results are not inconsistent with the existence of a global field. In the two-dimensional models of Morris et al. (1990) it was found that surface fields of 0.18 T were required to account for the observations. However, such magnetic field values are not inferred from observations, and the analytic expressions for gyrosynchrotron emissivity and absorption used by Morris et al. (1990) are not valid at such high magnetic field values, as the harmonic number is too low at the relevant observing frequencies.

In the model presented above, flare emission could escape the gyrosynchrotron plasma in the quiescent emission region via one of the escape windows discussed by Kuncic & Robinson (1993), or by propagating out through the open field region of the magnetosphere, which does not contain trapped radiating plasma. Thus the fact that flares are observed does not preclude the possibility of there being a large-scale magnetosphere.

The success of the model in explaining many phenomenological features of the emission from RS CVn binaries, and in providing counter-arguments to the evidence presented against there being a large-scale magnetosphere, provides further evidence that the overall magnetic structure of the quiescent emission region resembles a dipole magnetosphere. The fact that the observed values of circular polarisation and spectral indices are not reproduced in the model more probably indicates that the electron distribution is not as assumed.

Of great assistance in determining what the electron distribution is really like is that there is actually a physical system similar to the model under discussion here, close enough to us that the electron distribution can be, and has been, measured in situ. Planet Jupiter is surrounded by a dipole magnetosphere filled with trapped electrons radiating synchrotron radiation (Carr, Desch & Alexander 1983). It is observed in Jupiter's case that magnetic mirroring is an important effect for the radiating electrons.

Each flux tube segment of a dipole field is a magnetic mirror, with high-field regions at either end and a lower-field region in the middle. Electrons spiralling in the magnetic field are reflected in the high-field regions. The reflection point is determined by the electron's pitch angle in the middle of the flux tube and the magnetic field variation between the middle and the ends. Electrons with high enough momentum parallel to the magnetic field are not reflected. The simplest model for how the electron distribution varies with radius for a dipole field incorporating magnetic mirroring is that the number density becomes constant with radius (Parker 1957).

A magnetic mirroring electron distribution can be taken into account approximately by assuming an electron distribution that is constant with radius and using the model described above to calculate the gyrosynchrotron radiation from a dipole magnetosphere with such an electron distribution. The results are only approximate as the analytic expressions used for the gyrosynchrotron emissivity and absorption assume an isotropic pitch-angle distribution for the radiating electrons. A magnetic mirroring electron distribution lacks electrons with small pitch angles as these particles are not reflected at the mirror points and so are lost to the system.
6. Conclusion

The gyrosynchrotron emission from a large-scale dipole magnetosphere has been calculated and compared with observations of the quiescent emission from several kinds of radio flare stars. A dipole model is able to account for many of the observed features of quiescent emission, and the results strongly support the hypothesis that the emission region of many quiescently emitting stars is a large-scale dipole-like magnetosphere. Model calculations also indicate that magnetic mirroring of the electrons may be important in the emission region.

Examples of model spectra for the constant number density case are shown in Figure 4. Qualitatively, the results are very similar to those for the simple dipole model as the basic structure of the magnetosphere has not been changed. However, model calculations indicate that the circular polarisation can be higher and, as can be seen in Figure 4, the rising part of the spectra can be much flatter. The results for the mirroring distribution are, therefore, in better quantitative agreement with the observations than the earlier results for an isotropic electron distribution, implying that magnetic mirroring may be important in the magnetospheres of quiescent emitters. It is planned to further investigate this preliminary result by taking a mirroring electron distribution properly into account in calculating the gyrosynchrotron emissivity and absorption. There are also other features of Jupiter’s electron distribution, e.g. localisation of the mirroring particles to the equatorial region and different spatial distributions for different electron energies. Further work is being carried out to investigate the likely importance of such effects.