Non-thermal electrons and stellar radio emission

S. M. White and M. R. Kundu

Astronomy Program, Univ. of Maryland, College Park, MD 20742

ABSTRACT

Radio emission from dMe flare stars has both a flaring and a quiescent component. When we compare stellar radio emission with the Sun, however, we find that the apparent brightness temperature of the quiescent component often exceeds the temperature of non-thermal solar radio flares, and so it is likely that stellar quiescent emission also comes from non-thermal electrons. The duration of stellar quiescent emission is much longer than solar non-thermal emission. Obvious questions to ask are, what is the source of the non-thermal electrons, where do they reside, and how can non-thermal emission last so long? Here we briefly review the observations of quiescent emission, argue that the emitting regions are small, show that such small regions can still account for the observed fluxes, and discuss the source of electrons.

1. Quiescent emission from UV Ceti and EQ Peg

The first observation of flare stars at the VLA detected quiescent emission from UV Ceti at 6 cm, corresponding to a brightness temperature of about 10^8 $(R/R_*)^{-2}$ K (Gary and Linsky, 1981). The flux from this star at 6 cm has never been seen below 0.9 mJy, and the quiescent component varies up to 3 mJy. The quiescent flux is unpolarized and slowly varying (i.e., variable on a timescale of an hour or so). Quiescent flux may also be detected at 20 cm, but seems to be much more variable there than at 6 cm. In particular, while the ratio of 6 cm flux to 20 cm flux is usually in excess of unity, indicating optically thick emission, there have been a number of occasions on which the apparent 20 cm quiescent flux exceeds the 6 cm quiescent flux. Since flaring is more common at 20 cm than at 6 cm, it is often difficult to decide what part of the observed 20 cm flux is actually quiescent.

Normally EQ Peg A is a reliable quiescent source at a level of about 0.5 mJy at 6 cm, corresponding to a brightness temperature of 3 10^8 $(R/R_*)^{-2}$ K. However it has shown one large outburst which was clearly quiescent emission at a level 20 times normal. This was during simultaneous X-ray and radio observations by Kundu et al. (1988) on 1985 August 6. At the beginning of the observation EXOSAT detected the largest X-ray flare seen from this class of star. The VLA began observing half an hour later, and found the 6 cm flux from EQ Peg A to be at about 10 mJy at 6 cm. Two days earlier a brief observation showed it to be at 0.5 mJy. The emission was unpolarized (below 5 %) and decayed slowly for about 6 hours. UV Cet has been observed far more frequently, but has never shown such an outburst.

2. Other quiescent sources

UV Ceti is the best observed quiescent emitter. There are unfortunately no other candidates yet identified which are such reliable and strong quiescent sources. We have compiled a list of some 83 M dwarves observed at the VLA, of which 27 have unambiguous detections (here both stars in binaries wider than 1" are counted separately; White, Kundu and Jackson, 1988, in preparation). The ability to decide whether a star is a quiescent source or not depends critically on having both long observations and sufficient flux in order to study the time variability of the source and identify the contribution of flaring to the flux. Most of the detected stars have not had such long observations, and consequently we are unable to reliably identify more than a few good quiescent candidates. Many of the stars could have quiescent emission at a level slightly below that of UV Cet and not be recognized as quiescent sources because they are more distant. Reliable sources of quiescent emission strong enough for detailed study are UV Cet, EQ Peg A, BY Dra, and possibly AU Mic and the northern component of AT Mic. We expect that many more stars will be confirmed as quiescent sources when more observations have been carried out.

3. Range of brightness temperatures

Exact brightness temperatures for quiescent emission cannot be given since the sources are not resolved and we have no good idea of the source size. If we assume a source the size of the star, then UV Ceti is reliably at a brightness temperature of several times 10^8 K at 6 cm. The strongest 6 cm quiescent emission yet seen was from EQ Peg A, which reached a brightness temperature of 2 10^9 $(R/R_*)^{-2}$ K. Brightness temperatures of quiescent emission at 20 cm are often around this value, and values up to 10^{10} K have been claimed, although in that case the emission was variable and may not have been the usual form of quiescent emission addressed here (Bastian and Bookbinder, 1987). At any rate, it is clear that brightness temperatures are often in the range where gyrosynchrotron emission is the likely emission mechanism. In view of the higher brightness temperatures at 20 cm than at 6 cm, a non-thermal electron energy spectrum is implied.

4. Active region emission

The obvious interpretation of the outburst on EQ Peg is that the large flare injected energetic particles into loops above an active region, and these were responsible for the elevated levels of quiescent emission. The only problem with this is that after 6 hours of decay the radio emission suddenly jumped again without any sign of X-ray emission. In any case, we assume that the quiescent radio emission comes from non-thermal electrons trapped in loops above active regions on the surface.

We argue that the true size of the radio-emitting region is of the order of the active region size, which is smaller than a stellar radius. The argument is based on two observational results: the presence of strong magnetic fields covering a large fraction of the surface of these stars (Saar and Linsky, 1988), together with the absence of any net longitudinal magnetic field component above about a few per cent of the average surface field in observations of the Zeeman effect (e.g., see the review by Saar, 1987). This suggests that the magnetic field is present in a number of active regions smaller than a stellar radius, each with cancelling positive and negative flux regions. If the magnetic field were dominated by a single large region, then at least at some phase of stellar rotation we would expect to see signs of polarization due to the Zeeman effect.

Since the active regions should be smaller than a stellar radius, it seems unlikely that the loops extend to any great height above the surface. On this basis, we do not expect that the radio source is several times larger than the stellar surface area, as has often appeared an attractive assumption since it reduces the brightness temperatures.

5. Analytic models for dipolar region emission

Can a relatively small active region account for the observed flux levels? To check this, we have developed simple analytic models for the flux from a buried dipole (White et al., 1988). We use the Dulk and Marsh (1982; Dulk, 1985) formulae for non-thermal gyrosynchrotron emission in the frequency range of 10 - 100 times the gyrofrequency. In the optically thick limit, we assume that the source can be approximated by a uniform brighness temperature and a certain linear dimension. The latter is taken to be the height above the stellar surface at which the emission becomes optically thick, and the brightness temperature is taken to be the brightness temperature in that layer. We then assume that the source area is proportional to the square of the linear dimension, and use numerical integration of the Dulk and Marsh formulae to find the appropriate constant of proportionality. Since this model is only expected to give answers correct to within about a factor of 2, we find that 2π gives adequate results.

One way in which the model is an improvement on previous analytic work is that we allow for non-uniform source regions, i.e., we assume that both the density and the magnetic field have power-law distributions with height above the surface, $B=B_0\ (r/r_0)^{-n}$ and $N=N_0\ (r/r_0)^{-m}$. The fluxes and spectra depend on the power-law indices, and show a greater range of behaviour than the homogeneous non-thermal gyrosynchrotron models. We have treated the cases of monopolar ($n=2$) and dipolar ($n=3$) magnetic fields, and uniform density ($m=0$) and flux-conserving ($m=n$) density models. In Table 1 we show the frequency spectral indices in the optically thick region of the spectrum of a dipolar active region viewed from above, for several parameters: the power-law index of the electron energy distribution, δ; the density index m; and the magnetic field index n.

The interesting feature of this table is that the predicted optically thick spectra are all much flatter than would be expected from the homogeneous formulae, which predict spectral indices in a narrow range near 2.7 - 2.9. Indeed, for very hard energy spectra and a slow fall-off of magnetic field and particle density with height, negative spectral indices can be obtained in the optically thick part of the spectrum.

Similarly simple analytic models can also be developed for the optically thin limit (high frequencies), but these have the same spectral index as the homogeneous formulae (1.2-0.9δ).

We have carried out numerical calculations of the flux from a dipolar region using the Dulk and Marsh formulae with the exact geometry of a buried dipole, both to check the analytic formulae and to see whether a single active region of small size can indeed provide enough flux to explain the observations. We find that, for a range of plausible values of the critical parameters δ, n, m, the surface density N_0, the surface magnetic field B_0, and the scale size r_0 of the active region, the flux depends very strongly on the value of δ, but that the observed fluxes can be easily explained. That is, with true brightness temperatures in excess of 10^9 K, one only needs a source size much smaller than the stellar surface area to explain the observed fluxes, and the observed frequency spectra can easily be reproduced (of course, we have a number of free parameters in the models which can be varied). In fact, the predicted flux can be much larger than observed when $\delta = 2$ (fluxes of around 100 mJy from UV Ceti, from an active region of dimension 10^{10} cm in size), due to the fact that the source becomes optically thick far from the surface in this case, producing both a large source and a large true brightness temperature. In general, the numerical calculations also show that the analytic formulae are accurate to within a factor of better than two, which we regard as surprisingly good.

However one result of these calculations is that for many plausible sets of parameters, particularly when the magnetic field strength is large, the optically thick layers are likely to be in regions where the harmonic numbers are 5 - 10. The Dulk and Marsh formulae on which Figures 1 and 2 are based are not valid in that frequency range. This affects many of the points, both optically thick and thin, at 5 and 15 GHz for $\delta \geq 3$.

Thus relatively small active regions can provide the observed quiescent fluxes from M dwarf stars, and by varying the dependence of density and magnetic field with height above the active region we can also explain variable ratios of the 20 cm to 6 cm flux.

6. From whence the electrons?

In many ways, quiescent M dwarf radio emission has more in common with solar radio flares than with solar quiescent emission: both seem to be due to non-thermal electrons radiating gyrosynchrotron emission in loops above active regions. However, in the solar case the duration of non-thermal radio emission after one injection of electrons is usually less than 30 minutes. In our interpretation of the EQ Peg event above, we suggested that a single episode of electron injection occurred at the time of the X-ray flare, and this episode would then have produced stellar quiescent emission lasting for many hours.

However, we have argued elsewhere based on the analogy with the Earth's radiation belts (Kundu et al., 1987) that one cannot expect electrons to remain in a stellar loop for longer than an hour before they precipitate into the denser lower regions of a stellar corona, and this is consistent with the shorter duration of solar non-thermal events. Thus long-lasting stellar events imply instead continual replenishment of the electrons. If indeed there are many active regions crowding the surface whose magnetic loops jostle one another in the corona, then continual reconnection events in the spirit of Parker's (e.g., 1988) ideas can easily be envisaged as providing a steady supply of non-thermal electrons. The 20 cm observations of EQ Peg during the event discussed above support this, in that they show flaring activity continuing throughout the whole day (although no flaring was evident at 6 cm).

Another seldom-discussed question is how the radio-emitting particles coexist with the X-ray-emitting corona. The X-ray-emitting material is at relatively high density, and if the non-thermal radio particles were to come into contact with it they would rapidly lose their energy. This suggests that the non-thermal radio-emitting particles are on different loop systems, and that their generation mechanism is also different from that which produces the X-ray corona. We are lead to a picture in which flaring occurs essentially independently at different levels of the corona, in agreement with observations that there is little correlation between radio, X-ray or optical flares.

UV Cet has been observed more frequently than EQ Peg, and has shown a three-fold variability in its 6 cm quiescent flux, but no outbursts such as the twenty-fold increase by EQ Peg A. How do we reconcile this? Since it is possible to explain EQ Peg's emission with a single active region, it simply implies that UV Cet's active regions are more uniform in their presence on the visible disc, and more regular in their radio behaviour. Equivalently, we suggest that UV Cet's emission is due to a number of active regions, whereas the large outburst on EQ Peg was due to a single active region.

A prediction following from this is that at optically thin frequencies UV Cet's quiescent emission is less likely to show polarization than an outburst event such as EQ Peg A's, since the former may come from summing over several regions whereas the latter comes from a single active region and any geometric asymmetry in the source structure may well show up as polarization, particularly at optically thin frequencies.

References

Bastian, T.S., and J.A. Bookbinder, 1987, *Nature*, **326**, 678.

Dulk, G.A., 1985, *Ann. Rev. Astr. Ap.* **23**, 169.

Dulk, G.A., and K.A. Marsh, 1982, *Ap. J.* **259**, 350.

Gary, D.E., and J.L. Linsky, 1981, *Ap. J.* **250**, 284.

Kundu, M.R., P.D. Jackson, S.M. White and M. Melozzi, 1987, *Ap. J.* **312**, 822.

Kundu, M.R., R. Pallavicini, S.M. White and P.D. Jackson, 1988, *Astr. Ap.* **195**, 159.

Parker, E.N., 1988, *Ap. J.* **330**, 474.

Saar, S., J.L. Linsky and M.S. Giampapa, 1987, *Observational Astrophysics with High Precision Data*, Liege, Belgium.

Saar, S., 1987, Proceedings of the Fifth Cambridge Workshop on *Cool Stars, Stellar Systems and the Sun*, Springer-Verlag (Berlin), p. 10.

White, S.M., M.R. Kundu and P.D. Jackson, 1988, submitted to *Astr. Ap.*

Table 1

Optically thick spectral indices for a range of electron energy distributions, magnetic field variation and density variation.

v	$\delta = 2$	$\delta = 3$	$\delta = 4$	$\delta = 5$
$n = 2, m = 0$	-0.42	0.04	0.26	0.39
$n = 2, m = 2$	0.70	0.77	0.81	0.83
$n = 3, m = 0$	0.41	0.68	0.82	0.90
$n = 3, m = 3$	1.18	1.21	1.23	1.24