QUIESCENT AND FLARING RADIO EMISSION FROM dMe STARS

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1. INTRODUCTION

In reviewing radio studies of M-dwarf flare stars one is struck by the curious way in which the field developed. Indeed, that is twenty years old may be the greatest surprise, for if one imagines the largest solar flares occurring at distances comparable to the nearest stars the expected flux densities would be < 10 mJy. Yet, despite the fact that detection thresholds in 1963 were about two orders of magnitude higher than the expected value, Lovell et al. (1963) made extensive observations and reported the detection of UV Ceti. This remarkable discovery was followed immediately by detections of V371 Ori (Slee et al., 1963) and EV Lac (Lovell et al., 1964). One might have thought that these unexpected discoveries would have spurred significant interest in this new field but they did not.

Why? Three reasons seem most apparent: 1) The "mainstream" of astronomers in the late 60's and early 70's never fully appreciated these data. Cross-fertilization especially with solar astonomers was virtually non-existant. 2) The data were obtained at very slow rates; e.g., Lovell (1972) reported an average of only one flare of a few Jy amplitude (at 240 MHz) on UV Ceti per 35 hours observation. In an era of radio studies of "glamorous" new objects as quasars and pulsars such an investment of time was difficult to justify. 3) Credibility. As Lovell and his colleagues wrote, "(detections) were difficult because of the sporadic and transient nature of the phenomena, and the danger of interference. (In general, interference monitors were not used). In several thousand hours of observation there are only a few cases where the existence of individual flares of long duration has been unambiguous" (Davis et al., 1978). I cannot over emphasize the problem interference causes. My own experience with total power records showed many "events" (later shown to be interference by simultaneous interferometric observations) which had levels similar to flares reported earlier and their "typical" fast-rise, slow-decay morphology. To add to the feelings of mistrust it seemed that observations made with different instrumentation (e.g., telescopes, frequencies, bandwidths,

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integration times and polarizations) yielded qualitatively different results.

The path toward a resurgence in radio studies of flare stars was paved in 1976 and 1977 by the Jodrell Bank group using an interferometer successfully for the first time (cf. Davis et al., 1978). Later, groups at New Mexico Tech (cf. Fisher and Gibson, 1982), Colorado (cf. Gary and Linsky, 1981) and Caltech (cf. Topka and Marsh, 1982) began extensive microwave observations of flare stars using the recently completed VLA. These interferometers provided unambiguous interference and background rejection as well as unparalleled sensitivity. Not only was quality data available but complementary studies at X-ray, UV, and optical wavelengths provided the radio observations a new context within the framework of the new field of stellar activity.

I will discuss the meter-wave (Section 3) and the microwave (Section 4) flaring separately for several reasons. In general, the former were obtained with single-dishes and are subject to confusion with background objects and interference, whereas the latter were obtained with interferometers which reject both. The reported meter-wave flares differ from the microwave flares in that flux densities are typically several orders of magnitude greater than their microwave counterparts. As is the case for the un, there may well be a difference between microwave and meter-wave phenomena. In addition to the flare levels and morphology I will also review the extremely important spectral and polarization observations which are the true keys to developing adequate theories for the emission mechanisms. I will also discuss correlated observations at other wavelengths (primarily optical) in section 5. In section 6, I will review the observations and theory of quiescent stellar radio emission which has recently been detected on UV Ceti (Gary and Linsky, 1981) and several other objects. Like the detection of flaring in 1963, the detection of quiescent emission was quite unexpected. Nevertheless, it has been put to advantage as a sensitive probe of the coronal environment in these objects.

2. STELLAR RADIO-ASTROPHYSICS

Although the total luminosity of stellar radio emission is insignificant compared to L_{bol} it is probably the most sensitive probe we have of the coronal environment. Thus, a few preliminary paragraphs are needed before we review the observations to enable the reader to better evaluate the data. Radio flux density S_ν measurements are made in Jansky's (1Jy = 10^{-23} erg s^{-1} cm^{-2} Hz^{-1}). Spectral indices are logarithmic ratios between the flux densities at different observing wavelengths

$$\alpha \equiv \frac{\ell n(S_{\nu_1}/S_{\nu_2})}{\ell n(\nu_1/\nu_2)}$$

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Thus, negative (-) spectral indices indicate non-thermal phenomena. Polarizations are usually measured either in circular-mode or linear mode. By convention the percent polarization

$$\pi \equiv \frac{S_1 - S_2}{S_1 + S_2}$$

where 1, 2 correspond to R, L or $||$, $\perp$, as appropriate. But the total flux density is defined as $S = (S_1 + S_2)/2$. The early radio astronomers could not conceive of high percents of polarization and, thus, we have apparent situations where the polarized flux density is greater than the total flux density. Finally the brightness temperature T_B is the equivalent of the electron temperature T_e in an optically-thick thermal source. It is related to stellar parameters as

$$T_B = 2.12 \times 10^7\ S_\lambda \lambda^2\ d_*^2/R_*^2$$

where λ is the observing wavelength (in cm), d_* is the distance to the star (in pc), and R_* is the source radius (in $R_\odot$). Thus a solar-type star could be detected at a distance of 10 pc by today's most sensitive instrument (the VLA operating at 6 cm) provide $T_B > 8 \times 10^6$K.

One can infer a significant amount about the source conditions and emission mechanism(s) by simply examining $S_\nu(t)$, α, π, and T_B and by remembering that $n_e \lesssim 1.1 \times 10^{13}\ \lambda^{-2}$ cm^{-3} ($<10^{11}$ cm^{-3} for the type of sources we discuss here). Several rules of thumb apply:

a) If the source varies rapidly ($\tau <$ 10 minutes) it is probably non-thermal. Conversely if it remains at about the same level for days-to-months, then it is probably thermal or at least the emission mechanism controlled by the thermal environment.

b) If $\alpha < -2$ or $\alpha > +2$ the emission mechanism may be coherent. In the range $0 < \alpha < +2$ the source is probably optically-thick but it is difficult to distinguish if the source is thermal or non-thermal without other information such as rapid time variability.

c) If polarization is observed the emission mechanism is non-thermal. Very high percentages of circular polarization ($\pi_c > 50\%$) usually require a coherent emission process.

d) If $T_B \gtrsim 3 \times 10^8$ K for reasonable estimates of the true source size -- which can be based on either the timescale for variability (assuming the propogation of some excitation phenomena has a characteristic velocity) or the percent of circular polarization (assuming the magnetic field structure is tangled or radial and you know something about the electron energy distribution) -- then the emission mechanism is probably coherent. Wild variability coupled with very high percentages of circular polarization almost certainly indicate the emission mechanism is coherent. Brightness temperatures $>10^{12}$ are incompatible with incoherent emission mechanisms.

3. METER-WAVE FLARES IN dMe STARS

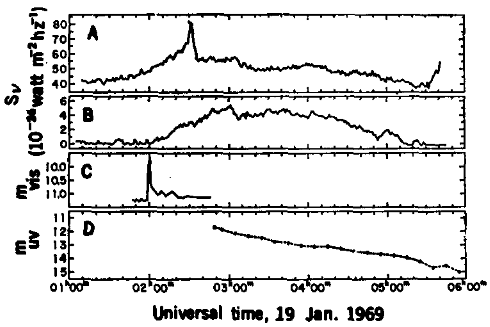

Fig. 1. A large flare on YZ CMi observed simultaneously at 240 MHz (A), 408 MHz (B), the visual (C), and near UV (D) (after Lovell, 1969).

It is very difficult to describe a "typical" meter-wave flare on a dMe star because the observations to date indicate the most believable flares are anything but typical. A classic example is shown in Fig. 1, where total-power flux densities at 240 and 408 MHz obtained at Jodrell Bank by Lovell (1969) are plotted together with simultaneous visual and near-UV photometry by Andrews (1969) and Kunkel (1969), respectively. The difficulty establishing a good baseline is evident in these data. This long three-hour flare had a T_B^{max} ~2×10^{15} K and spectral indices ranging from $-5 < \alpha < -1$. The time delay between the optical and radio peaks suggest phenomena similar to those occurring in solar moving bursts but the peak in the 240 MHz emission would be expected to occur after that at 408 MHz. A good interpretation of this event remains to be offered.

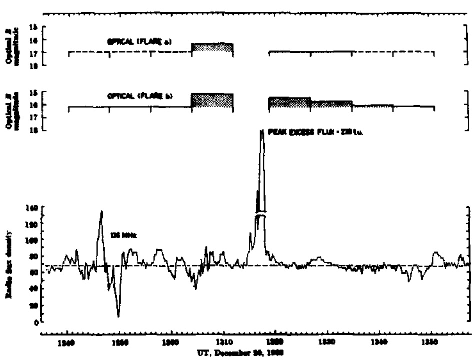

Fig. 2. A "monster" flare presumed to have occurred on one of the nebular variables on the Orion aggregate. T_B^{max} ~10^{20} K! (after Slee et al., 1969).

The most spectacular event which has been reported is shown in Fig. 2. Slee et al. (1969) detected a gigantic flare from what they think may be a flare star in the Orion aggregate. T_B^{max} ~10^{20} K! Two optical flares were seen in different parts of the aggregate at about the time of the radio flare, so it is impossible to identify on which star the flare occurred. The emission would have to be coherent and fully 1% of the total flare energy was estimated to have appeared in the radio band.

The best low-frequency single-dish observations of meter-wave flares on dMe stars are those of Spangler and his colleagues (cf. Spangler et al., 1974b) which were made at Arecibo during 1973-1975. A

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"typical" observation is shown in Fig. 3 in which a flare on Wolf 424 AB lasting about 30 s is shown together with simultaneous U-filter observations (Spangler and Moffett, 1976). The $T_B^{max} \sim 2 \times 10^{14}$ and $\alpha \simeq -4$ again suggest a coherent emission mechanism. The most important of the Arecibo results were obtained for AD Leo (Spangler et al., 1974a) and are shown in Fig. 4. 430 MHz observations using dual circularly-polarized feeds revealed the large polarization of a (small) flare for the first time. T_B^{max} was $\sim 4 \times 10^{13}$ K and the degree of right-hand circular polarization varied from 50% to 80% as the flare evolved. The high degree of circular polarization together with linear polarization in the range of 10-20% and the high T_B imply the circular polarization is not a propogation effect and that the emission mechanism is probably not a coherent plasma process.

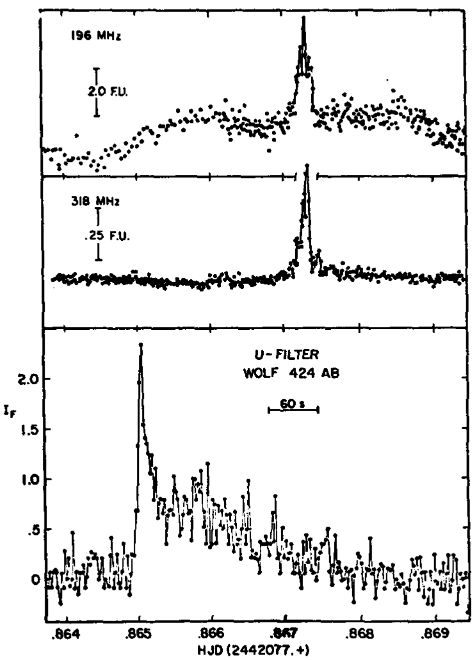

Fig. 3. A typical flare (on Wolf 424) observed at Arecibo, following an optical flare observed at McDonald Observatory (after Spangler and Moffett, 1976).

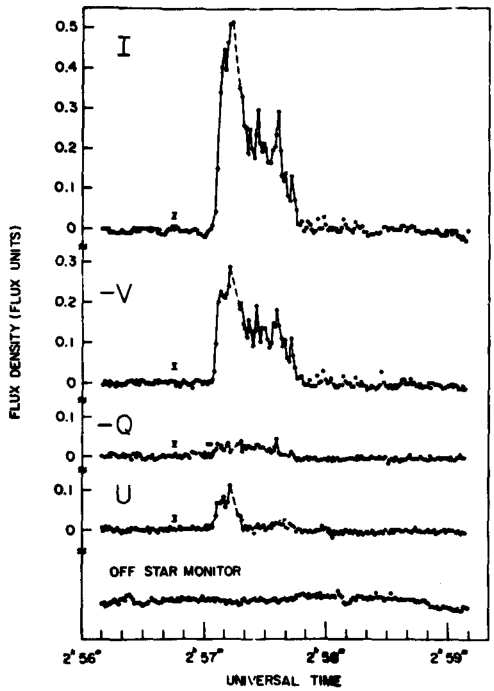

Fig. 4. The first detection of the remarkable polarization seen in flare stars. This flare on AD Leo was as much as 80% right-hand circularly polarized at 430 MHz (after Spangler et al., 1974).

Very real improvement in the low-frequency detection of flares on the dMe stars came at Jodrell Bank with the use of the Jodrell Bank-Defford Radio-link Interferometer and is being continued today with the new MERLIN array. Two "typical" events on the YZ CMi are shown in shown in Fig. 5 (Davis et al., 1978). The event of 1977 Dec. 18 had a

T_B^{max} = 3 x 10^{12} K and, conceivably, could be incoherent if the source size is $\gtrsim$ 2R_*. However, lacking spectral or polarization information there is little physical information in these data except to comment that these are weakest meter-wavelength flares reported to date and still they are 10^4 times more energetic than a large solar flare (importance 3) in the same band.

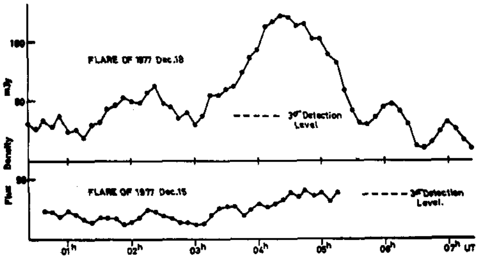

Fig. 5. Two flares on YZ CMi at 408 MHz observed by the Ma IA. Defford interferometer a Jodrell Bank. These are two the weakest low-frequency flares ever observed (after Davies et al., 1978).

4. MICROWAVE FLARES IN dMe STARS

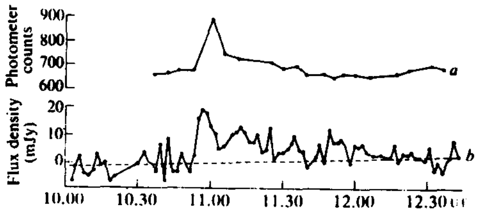

Fig. 6. A weak flare on AT MIC observed at 5000 MHz at Parkes. This flare occurred simultaneously at optical (above) and radio (below) wavelengths (after Slee et al., 1981).

Though studies of the microwave (here defined as λ's < 20 cm) flaring emission from dMe stars have a much shorter history than those at longer wavelengths the body of data is much more useful because of better sensitivity (~10 mJy at Parkes; < 1 mJy at the VLA), less confusion by nearby sources, fewer problems with interference, and, in the case of the VLA, multi-frequency, multi-polarization capabilities. The latter is extremely important because a weak flare, such as that shown in Fig. 6, can have T_B^{max} < 10^{12}K and still require a coherent emission mechanism as stated in the "rules-of-thumb" mentioned before. Thus, the studies by Fisher and/or Gibson and Gary/Dulk/Linsky, are the best for the purpose of physical analyses of microwave flares.

To date, only six objects have been detected to flare at microwave frequencies. Variations in measured flux densities have ranged from a few mJy (Fig. 7) to about 60 mJy (Fig. 8), and flare durations have ranged from a few minutes, for relatively simple events (Fig. 8), to several hours for complex events (Fig. 9). None of the flares at 20 cm shown in Figures 7, 8, or 9 were detected at 6 cm, but since α> -2.5 one can only conclude the events were non-thermal. The only time an event was detected at both frequencies simultaneously is shown in Fig. 10. One cannot be sure if the peaks observed first at 6 cm and then 80 minutes later at 20 cm are in fact due to the same event since we simply do not have enough data to do a proper statistical analysis.

If they are related, then this event is reminiscent of moving solar bursts but is occurring at a higher frequency than those observed on the Sun. This modified solar analogue would be quite apt since the coronal densities in these systems are higher than in the un.

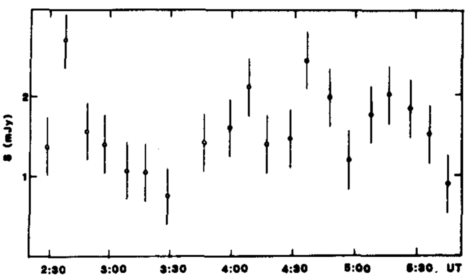

Fig. 7. Very weak flaring on UV Ceti observed at 20 cm with the VLA. The quiescent level of this star is 1.1 mJy (after Fisher and Gibson, 1983).

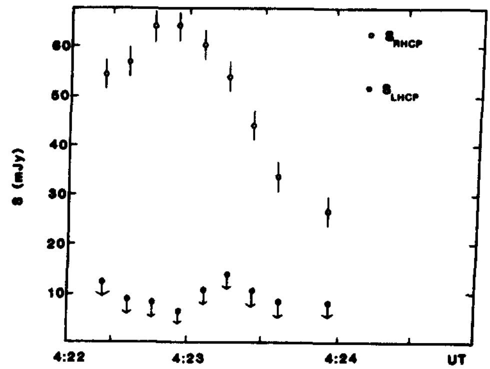

Fig. 8. A short, highly circularly polarized (π_c>85%) flare on UV Ceti observed at 20 cm (after Fisher and Gibson, 1983).

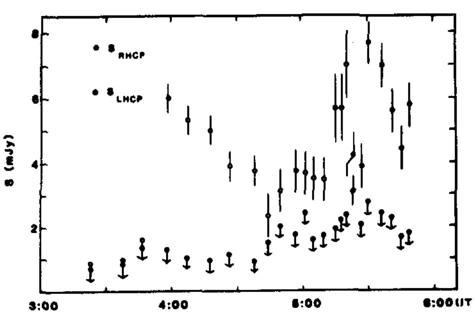

Fig. 9. A complex, highly polarized event on L726-8 A (UV Ceti's companion) observed at 20 cm (after Fisher and Gibson, 1983).

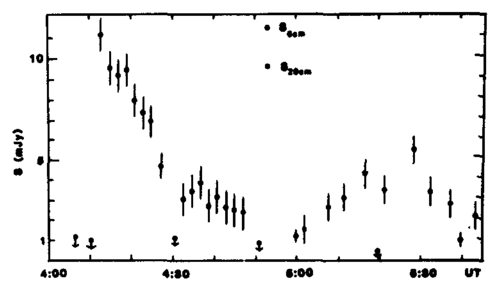

Fig. 10. A 6 cm flare on L726-8 A is followed by a flare at 20 cm. If related, this could be an analogue of a moving Type IV solar burst (after Fisher and Gibson, 1982)

All of the 20 cm bursts observed with the VLA have been highly-circularly polarized, $\pi_c > 50\%$, and in some cases $\pi_c \approx 100\%$. The 6 cm flare of L 726-8 A (UV Ceti's companion) shown in Fig. 10 was not significantly polarized, however. As Melrose and Dulk (1982) have pointed out, large circular polarizations ($\pi_c > 30\%$) and high brightness temperatures ($T_B > 10^9$ K) are not mutually compatable within the framework of incoherent emission mechanisms. Thus, even the relatively weak flares seen here may result from coherent processes. Melrose and Dulk (1982) favor a cyclotron maser mechanism which they estimate can

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achieve $T_B^{max} \sim 10^{16}$ to 10^{17} K and, of course, π_c's~100%. The population inversion (or loss cone anisotropy) to drive the maser develops when electrons injected at the top of a flux tube travel down the flux-tube to regions of higher magnetic field and ambient particle density. The low pitch-angle electrons are thermalized before they can be "mirrored" back leaving only electrons which develop a one-sided loss cone.

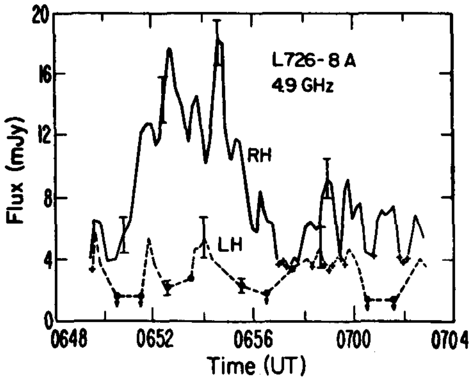

Fig. 11. Possible quasi-periodic oscillations in L726-8 A seen predominantly in r.h.c.p. (after Gary et al., 1983).

The electron-cyclotron maser may have is best application in explaining quasi-periodic 56 sec oscillations seen in L726-8 A (see Fig. 11) by Gary et al. (1982). The key datum here is not the oscillation itself, which remains unexplained but could be due to flux-tube oscillations driven by Alfven waves which modulate the emission. Rather, the very rapid variations suggest the excited region is very small and thus $T_B \gg 10^{12}$ K. A cyclotron maser theory is very attractive because the same electron population that produces the radio flare could also account for flaring in the hard and soft X-rays, the UV line emission, and optical continua as discussed below.

5. CORRELATION OF RADIO FLARING WITH PHENOMENA AT OTHER BANDS

It is most difficult to assess the frequency with which radio flares are accompanied by flares at other bands since the coordinated efforts made to date have varied widely in the bands covered, their sensitivities, and the stars observed. Only the coordinated observations of Proxima Centauri by Haisch et al. (1981) provided more-or-less simultaneous coverage at all four major bands -- radio, optical, UV, and X-ray -- and only two others succeeded in providing simultaneous radio, optical, and X-ray observations of YZ CMi (Karpen et al., 1977; Kahler et al., 1982).

The impression that most radio events were accompanied by quasi-simultaneous optical flares was widely held until the mid-1970's primarily because the single-dish observations had no good way of distinguishing radio flares independently. However, since many of these simultaneous events were among the largest ever observed the probability that strong radio flares have optical counterparts remains high. The best observed events of this type (e.g., Fig. 1) show significant time-delays between the optical and radio peaks, suggesting that

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the radio events could be stellar counterparts of solar type IV-dm bursts. Much more sensitive low-frequency radio/optical studies by Spangler and Moffett (1976) showed the simultaneous occurrence of radio/optical flares about 70% of the time, and occasionally the radio flare preceeded the optical event. A larger survey at still lower-frequencies by Nelson et al. (1979) showed only about 30% of the radio and optical flares were correlated, the radio flares were generally of long duration (>30 min), and all followed the optical flares.

At microwave frequencies the correlation between optical and radio events is virtually non-existent for all stars except Proxima Cen which shows correlated events about 25% of the time (cf. Slee et al., 1982). Otherwise only 2 or 3 correlated events have been reported out of 9 radio and 41 optical events recorded during some 50 hours of coordinated observation in the USA (Fisher and Gibson, 1982) and Australia (Slee et al., 1982).

Two events probably best represent the relation of radio phenomena to those at other bands. At microwave frequencies all coordinated events have shown the optical and radio flares to be co-temporal (cf. Fig. 6) whereas at longer wavelengths the radio emission follows other flare phenomena (see Fig. 12). These two examples support the idea that there are at least two different types of radio flare emission, the former on which the radiating electrons are of the same population as those which "create" phenomena in other bands, and the latter in which the emission probably results from excitation of regions above the flaring loop during the propogation of some outward moving disturbance.

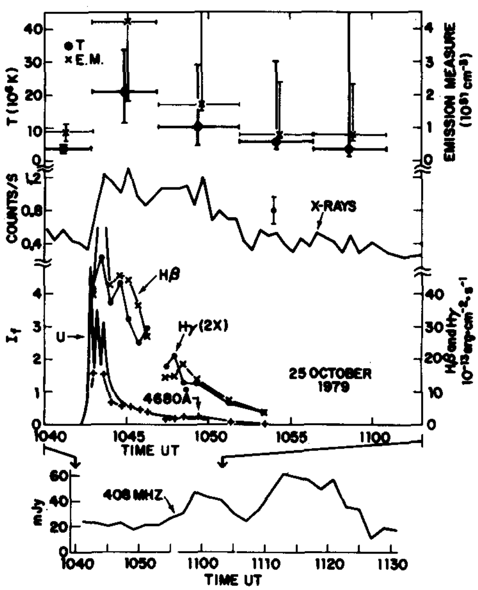

Fig. 12. Multi-frequency observations of a flare on YZ CMi. Note the time delay before the onset of the low-frequency radio emission (after Kahler et al., 1982).

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6. QUIESCENT EMISSION FROM FLARE STARS

More surprising to this author than the detection of flaring emission from dMe stars was the detection of quiescent emission (cf. Gary and Linsky, 1982; see Fig. 13). The quiescent solar atmosphere only becomes optically thick at cm-wavelength in the outer chromosphere where temperatures are typically ~20000 K. This implies, by analogy, that the expected flux density from a typical dMe star would be <1 μJy, still about 2 orders of magnitude below today's capability. What is required to make them detectable is that the source be both larger and optically-thick at a higher temperature ($T > 10^7$ K). Gary and Linsky (1981) suggest that gyroresonance absorption can make the coronae about these stars optically-thick at frequencies a few harmonics above the gyrofrequency (see Fig. 14). This implies that field strengths in the coronae must be few hundred Gauss. To be consistent with the Einstein X-ray results the temperatures determined at both bands should be the same. Thus, if the temperatures are few x 10^7 K as suggested by Einstein, the source size inferred by the radio flux densities which are measured imply $R_{radio\ corona} > 3R_*$! This may be pushing the thermal bremsstrahlung/gyroresonance absorption interpretation a bit far. One needs to determine source spectra and polarization characteristics before this model can achieve a full measure of acceptability.

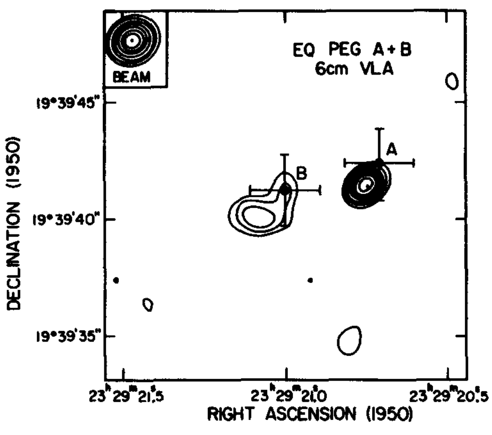

Fig. 13. Quiescent emission from EQ Peg A (0.6 mJy) and B (0.4 mJy) observed by the VLA (after Topka and Marsh, 1982).

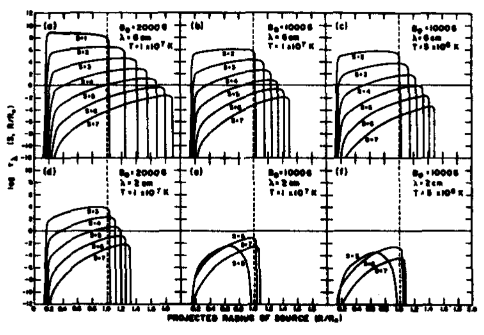

Fig. 14. Optical depths due to gyroresonance absorption as a function of height, magnetic field, wavelength, and temperature. These graphs show it may be possible to make dMe stellar coronae optically thick to a few stellar radii (after Gary and Linsky, 1981).

That the radio corona is thermally controlled, however, is virtually certain. Flux density measurements of UV Ceti show the same levels of emission on timescales of a few hours to 1.3 years. Thus, long-term monitoring of quiescent microwave emission may be a very good way to investigate them for synoptic (solar-cycle type) variations.

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DISCUSSION

Kuijpers: In the case of UV Ceti did you ever observe a flare going off in between the two stars or are they always concentrated on a single individual star?

Gibson: No. As far as we can tell they are all on individual stars.

Venugopal: If one observed the Pleiades at meter wavelengths, then scaling from flare intensities observed in Orion, one should see much higher intensities than are in fact observed. We observed the Pleiades region in 1973 and 1974 for a total of over 200 hours without recording a single flare of intensity greater than 0.75Jy at λ = 92 cm i.e. f = = 327 MHz. During November 1981 we had a further 60-70 hours of observation and again no flares.

Gibson: That is an interesting result and it again points out the probable problems with the early radio data.

Rodonò: It is quite a difficult problem to achieve coincident observation at more than one wavelength. The very high rate of flaring both in optical and radio on the active objects makes it very difficult to attribute an individual optical flare to a particular radio flare. So I would suggest that future observations should not be confined to the very active objects like YZ CMi, for example, but that the many less active objects be observed which will permit a better determination of optical/radio and other wavelength coincidences.

Gibson: I think that the problem with that approach is that we have observed less active stars and we do not see flares at all, at least in the kinds of total observing times available on an instrument like the VLA. Zirin and I have made attempts at simultaneous observation previously and we do not really know how to resolve this problem. It is obviously necessary to have at least optical observations simultaneous with the radio data if we are to put the flares into a proper perspective. However at present only stars which flare as frequently as YZ CMi and UV Cet yield a sufficient number of flares to make it worthwhile undertaking a project like this given that the total amount of observing time is of the order of 100 hrs yr^{-1}.

Evans: I would like to address two points. The first is that one of the biggest difficulties in arranging simultaneous observations is that of scheduling time at separate institutions. You mentioned the simultaneous radio and optical work by Spangler and Moffett. In that case there appeared to be a convincing argument in favour of a connection between flares in the two regions of the electromagnetic spectrum whereby the radio flare followed the optical flare by 5-8 minutes. The second point concerns the effects of duplicity and you talked about ringing between one star and another. Well, the duplicity characteristics of flare stars vary a great deal, extending from YY Gem with a period of less than a day to UV Cet whose period has been revised from 250 to 26 years. We did an experiment to see if there was an effect of separation on the rate of flaring. The early observations by Moffett happened to be done near periastron. We then observed the star again about 3 years later and found the same rate of flare energy release. There was some suggestion that the star might not have been flaring in quite the same way. Even at their closest however those stars are pretty far apart and if one were looking for mutual interaction one would be better to search for it in YY Gem or CC Eri.

Gibson: Well I would like to thank you for bringing up the correlation between optical and long-wavelength radio which seems well established. There seems to be correspondence about 50% of the time with a distinct time delay. This would seem to agree with models which invoke the optical flare going off at low level and then a disturbance propagating up into the corona where radio emission can escape from the star and be detected. This may be fundamental different from the kinds of things which we are seeing at higher frequencies.

Kodaira: You have said that the correlation between low radio frequency flares and optical flares is a loose one whereas the high frequency flares come "hand-in-hand" with the optical. Yet your results and those from my survey have failed to produce real coincidences. An exception is the Parkes 64m single-dish observations at 5 GHz.

Gibson: There is only one flare which we have detected simultaneously in the optical and with the VLA and here we only saw the beginning of the flare.

Kodaira: But this was impulsive microwave emission.

Gibson: Most of the rest of the data does come from the Parles data, primarily on Prox Cen and there they seem to get good "hand-in-hand" data.

Kodaira: Yes but this data shows effects which only occur in one integration bin and it only barely exceeds the 3σ level. Do you credit these data?

Jordan: I think we are getting a little detailed.

Kodaira: Yes but it is important whether they have really detected microwave bursts or whether the effect is too marginal to credit at this stage.

Uchida: My question relates to the propagation of the low-frequency disturbance. Has anyone tried to estimate the velocity of the low-frequency disturbance. I ask this because in the Sun there are two types of propagation radio sources. The first, Type II, is identified with the magnetohydrodynamic shock which travels at typically about 1500 km s^{-1}. The second, Type IV, is associated with the expanding electron cloud moving with typically 300 km s^{-1} velocity. The blast-type burst might be particularly interesting because of the possibility of sympathetic flaring in binaries.

Gibson: The assumption was made by Spangler for istance in analysing his delays that he was dealing with the shock rather than the expanding cloud. He used more or less arbitrarily in this analysis parameters which are typically solar because nothing better was available at that time. Perhaps these need to be looked at again and the calculations reworked.