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# High sensitivity dynamic spectral search for flare star radio bursts

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**Abstract.** We observed ten well-known flare stars with the Arecibo radio telescope at 1.4 GHz and 5 GHz, using a special observing technique to discriminate between real flares and radio frequency interference. With a high sensitivity of 5.5 K/Jy at 1.4 GHz when averaged over a 50 MHz band, we are able to recognize flux enhancements as weak as $\sim$ 6 mJy above the sky background variations.

In about 85 hours of observation, about a dozen bursts were detected, only from AD Leo. All had flux densities lower than 70 mJy, which probably explains their lack of fine structures (except for the strongest one), such as were reported in the literature for stronger flares. Half of the bursts that we recorded are 100% circularly polarized, and half are not circularly polarized. Our results are a first attempt of reliable statistics on dMe flare rates at 1.4 GHz.

The high brightness temperatures we infer for the observed bursts are interpreted in terms of coherent emission processes, either the cyclotron maser instability or plasma radiation. Efficiencies are comparable to those of solar or planetary radio emissions in the case of the cyclotron maser, and higher than the solar efficiency in the case of plasma radiation, with the caveat that there are great uncertainties in the coronal model and the source size.

**Key words:** radiation mechanisms: non-thermal – stars: activity – stars: flare – stars: late-type – stars: variables: other – radio continuum: stars

## 1. Introduction

### *1.1. Flare stars properties*

The term "flare stars" may refer to stars in one of several categories, all exhibiting occasional (or sometimes periodic) rapid, large increases of intensity, in all wavelength domains or some of them. dMe flare stars are red dwarf variables with hydrogen and ionized calcium emission lines. Their optical continuum radiation is $10^2$ to $10^3$ times weaker than that of the Sun (Strohmeier 1972). Hence, individual flare stars are difficult to observe and almost all known flare stars are in the solar neighborhood, not further than 25 pc. They are called UV Ceti-type stars, from the name of their prototype. The strongest flares observed on UV Cet stars are about $10^3$ more energetic than their solar analog, the white-light flares (Haisch 1989).

Simultaneous observations in the optical and radio domains (20 cm to 15 m) have sometimes shown that the radio maximum of a flare occurs at the same time or a few minutes later than the optical maximum, and that its duration is approximately the same in both domains (Hoffmeister et al. 1985). However, usually there is little correlation in the times of occurrence of radio and optical flares. Multi-wavelength observations are not only necessary to understand the flare phenomenon, but they are also one of the means to confirm the reliability of a burst detected in radio.

### *1.2. Difficulties with radio observations of flare stars*

Indeed, at radio wavelengths, there are major difficulties in observing stellar bursts, leading from the fact that they are weak, with microwave flux densities of typically several tens of mJy. Only rarely are bursts stronger than 100 mJy observed, with the record being 940 mJy (Bastian et al. 1990). Hence very sensitive instruments are needed to detect stellar flares, and with single-dish instruments, it is essential to have a reliable method to discriminate between true flares and man-made radio frequency interference (RFI) or small instabilities of the observing system.

Two of the best-known flare stars, UV Cet and YZ CMi were observed at 240 MHz as early as 1958 by Lovell et al. (1963). During 474 hours at Jodrell Bank, 13 events of several minutes remained as "possibly real" flares after the elimination of RFI; here an ON/OFF method was used, observing simultaneously the star and the sky. However, as demonstrated by Bastian et al. (1990), this method is not always reliable.

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Three powerful methods of distinguishing flare emission from RFI are i) independent observations by two widely separated telescopes, ii) use of an interferometer, giving a high resolution in position, and iii) high resolution in the spectral domain, such as is possible with the Arecibo telescope.

The first technique is illustrated by the observations of Güdel et al. (1989), who recorded a flare from AD Leo simultaneously with the Arecibo, Effelsberg and Jodrell Bank radio telescopes: the fact that it had the same characteristics on the three instruments confirmed its stellar origin. On the other hand, they noted long duration, smooth modulations of the background in the Effelsberg data that had no counterparts in the Jodrell Bank data and therefore must be considered as non-stellar events. Such variations generally correspond to the so-called source confusion which appears with single-dish telescopes. Indeed, the primary and secondary lobes of the antenna not only receive the signal arising from the source observed, but it also receive signals from other surrounding sources contributing to the background variations.

Use of an interferometer, such as the Very Large Array, is another method to ensure that the signal recorded is actually of stellar origin, and this is particularly important for emission of long duration.

Bastian et al. (1990) developed a new method to discriminate between RFI and stellar events: the telescope response function (TRF) in the frequency domain. Stellar flares occur in the primary lobe and hence have a TRF spectral shape which is easy to recognize (providing that some of the flare emission has a relatively broad bandwidth), while the RFI, received in the sidelobes, has a different TRF. For the events described by Bastian et al. (1990), this method substantiated their primary method of distinguishing interference – its appearance in the dynamic spectra. They also used a 21 cm flat feed as an interference monitor, but they emphasize that since the sidelobe response of this feed was different from the dual-circular feed's response, the flat feed could not always discriminate against RFI.

Examination of the temporal and spectral characteristics of the signals received is another method that has been used by some authors to distinguish RFI. This relies on the assumption that the flare characteristics resemble those that are well-known, for example, flares on stars might have some common features with those of the Sun. But one must be very careful in applying this *a priori*: it might induce to reject unreported kinds of bursts.

### *1.3. Characteristics of the flare stars radio emissions*

Quiescent emission of a few mJy has been recorded from some flare stars with the VLA. Sometimes this radiation is partially circularly polarized, but generally not (e.g. Kundu et al. 1986). Bastian & Bookbinder (1987) recorded quiescent emission from UV Cet as high as 18 mJy at 1.4 GHz. Added to this slowly varying, broad-band ($\gtrsim$ 40 MHz) and unpolarized component, two intense bursts were recorded, both strongly circularly polarized in opposite senses, with very different characteristics. The first one showed a rapid (10 s) rise and a more gradual decay, and was broad band ($\gtrsim$ 40 MHz). The second exhibited a much slower increase of intensity ($\sim$ 3 min) but a more rapid decrease (1.5 min), and narrow-band components ($\Delta f/f \lesssim 0.2\%$). This case was the first recording of a dynamic spectrum of a flare star at 1.4 GHz; this method has already proven its utility in investigating bursts from the Sun.

Incoherent gyrosynchrotron radiation might be an explanation for the quiescent emission (Dulk 1985). The very high brightness temperatures (up to more than $10^{15}$ K) inferred for the radio bursts show that a non-thermal ($T_b \gg 10^7$ K), coherent ($T_b \gtrsim 10^{10}$ K) mechanism is implied. The origin of the emission could be due to a coherent radiation at the plasma frequency or a cyclotron maser instability (CMI) occurring in the star's corona (Dulk 1985; Bastian & Bookbinder 1987), but the precise mechanism responsible for stellar flares is not understood yet.

Many flares were found to occupy approximately the entire observed bandwidth (Bastian & Bookbinder 1987; Bastian et al. 1990), leaving unconstrained their frequency limits; a possible burst observed by Lecacheux et al. (1993a) had a bandwidth of 135 MHz at 4.75 GHz. One of the highest estimated relative bandwidths for a dMe star microwave burst was more than 6% (Güdel et al. 1989). Hence, observations over a bandwidth of several 100 MHz are of great interest.

Wide band, high frequency resolution and high time resolution observations are required for many reasons: i) identifying most interference – which are generally narrow-band and/or regular in time; ii) increasing chances of recording a narrow-band burst that would have been "missed" by a single continuum channel or narrow-band observations; iii) delimiting the bandwidths of bursts; and iv) observing fine spectral and temporal structures, like any drift (variation of the emission frequency with time), quasi-periodic oscillations as observed by Gary et al. (1982) or rapid spikes as reported by Lang et al. (1983). Measuring both right and left circular polarizations (RCP and LCP) can also be useful in explaining the origin of bursts.

In order to understand the mechanism leading to radio flares, one needs information on the characteristics of individual flares, and also statistical information on the frequency and flux density of flares. To obtain this information we have observed ten dMe stars for a large number of hours taking into account all the requirements described above. In Section 2 we describe our observing techniques, including a solution to the problem of source confusion. In Section 3 we show the excellent reproducibility of the background variations from one day to another, which is useful in rejecting doubtful signals. We also show some true bursts and discuss the reasons why we recorded a few, weak bursts from only one of the ten stars observed. In Section 4 we draw some conclusions on the source properties. In Section 5 we summarize our main results.

## 2. Observational techniques

We observed ten dMe stars in December 1990, May 1991 and February 1993 with the Arecibo 305 m telescope. It was chosen because it is the world's most sensitive telescope for recording radio spectra, hence increasing our chances of observing a flare. We observed at two different frequencies: at 1.4 GHz using the two line feeds with sensitivities reaching $\sim$ 8 K/Jy at zenith when measured at 1390 MHz, and bandwidths of $\sim$ 50 MHz (FWHM), and at 5 GHz using the mini-Gregorian with a sensitivity of $\sim$ 1.5 K/Jy and a bandwidth of 500 MHz. We used the same back-end receiver at both frequencies: an acousto-optical spectrograph (AOS) with a frequency resolution of about 1 MHz and a bandwidth of 500 MHz (Lecacheux et al. 1993a). The AOS recorded a complete spectrum every 20 ms, which is considerably shorter than the 100 s stability time of the AOS for internal integration, as proved by the Allan variance method; furthermore, the AOS instabilities are much smaller than 1% of the system temperature (Lecacheux et al. 1993b).

The data were recorded on Exabyte tapes and regrouped in 5 min scans of 15,000 individual spectra. Two kinds of calibrations were made to monitor the telescope's performances and evaluate the flux density of flares: i) a known calibration signal from a noise tube was added to the signal for three seconds, nine seconds after the beginning of each 300 second scan; ii) ON/OFF scans of calibrator sources were made before and after the observation of a star.

### *2.1. Observations at 1.4 GHz*

At 1.4 GHz, observations were made from 3 to 7 and from 9 to 13 December 1990, on 8 and 9 May 1991, and from 6 to 15 February 1993. The observation of 8-9 May 1991 was made as part of an extensive multi-wavelength campaign: X-ray, UV, optical, IR and millimetric to decimetric range.

#### 2.1.1. Observing technique at 1.4 GHz

As one of several methods to discriminate between real flares and radio frequency interference (RFI), we used one dual-circular polarization line feed to track the source (antenna "ON"), and another dual-circular polarization line feed pointed approximately 42′ away from the source (antenna "OFF"). Thus a signal appearing on the four outputs (two right-circular and two left-circular polarized) could immediately be identified as an interference: either an interference received by the nearly identical sidelobes of the ON and OFF beams, or an interference occurring in the telescope electronics. On the other hand, emission arising from the source is only received by the primary lobe of the ON feed. In 1990-1991, the four bands of roughly 50 MHz were tuned to the same center frequency of 1380 MHz, which is relatively free of RFI. In 1993, the two ON bands were tuned to 1390 MHz, and the OFF bands to 1410 MHz.

The four 50 MHz spectra were converted to different frequencies inside the 500 MHz band of the AOS (see Fig. 1), and simultaneously integrated for 20 ms, side by side, by the 1024 channels of the linear CCD camera. The accumulated charge in the CCD was transferred to a buffer store, while the integration of the next four spectra was recommencing; the buffer store was read out into an A/D converter, and then into the observatory computer for recording on Exabyte tapes. This provided the dynamic spectra on which we searched for bursts, plotting them with an integration time of 1 s. In parallel with the data acquisition, the four 50 MHz signals were detected by a square-law detector and displayed on a chart recorder for monitoring purposes.

#### 2.1.2. Daily comparison

As explained above, source confusion is one of the disadvantages of a single-dish telescope. Signals from many other sources than the observed star are received by the primary lobe and the sidelobes; they therefore appear as background variations which are different on the dynamic spectra "ON" and "OFF". Some of the variations visible on the dynamic spectra "ON" might be taken as possible events. But most of these background variations are very similar from one day to another, hence, they are easily recognized by being present on the dynamic spectra of several days at the same hour angle (HA). This daily comparison is a new, powerful criterion to reject doubtful signals.

#### 2.1.3. Beam shape

The two 1.4 GHz line feeds at Arecibo were tuned to 1390 MHz in 1990-1991, and to 1395 MHz in 1993; each has a bandwidth of about 50 MHz. The telescope response function (TRF) increases from $\sim$ 1360 MHz to $\sim$ 1390 MHz and then decreases in a known fashion (Arecibo Observatory User's Manual 1989). Thus, a broad-band stellar burst observed within the main lobe has the characteristic shape of the TRF, while broad-band interference, entering from a sidelobe or in electronic circuits, has a different shape.

### *2.2. Observations at 5 GHz*

A second AOS was used as the receiver of the mini-Gregorian feed, operating between 4.5 and 5.0 GHz. It recorded alternatively the RCP and LCP spectra of 500 MHz bandwidth each; each spectrum was integrated for 20 ms and data acquisition was identical with that at 1.4 GHz. This observing technique is described with more detail by Lecacheux et al. (1993a) who used it for the first time in July 1989. However, since this system is about five times less sensitive than the 1.4 GHz system described above, we used it only on 8 December 1990.

## 3. Observational results

At 1.4 GHz, we observed ten flare stars: AD Leo, YZ CMi, Wolf 424, Gl 569, VW Com, YY Gem, V371 Ori, EQ Peg and TZ Ari, and the RS CVn UX Ari, for ten days in December 1990, two days in May 1991 and ten days in February 1993 (only AD Leo), and at 5 GHz on 8 December 1990. The number of hours of observation of each star at 1.4 GHz and 5 GHz is listed in Table 1.

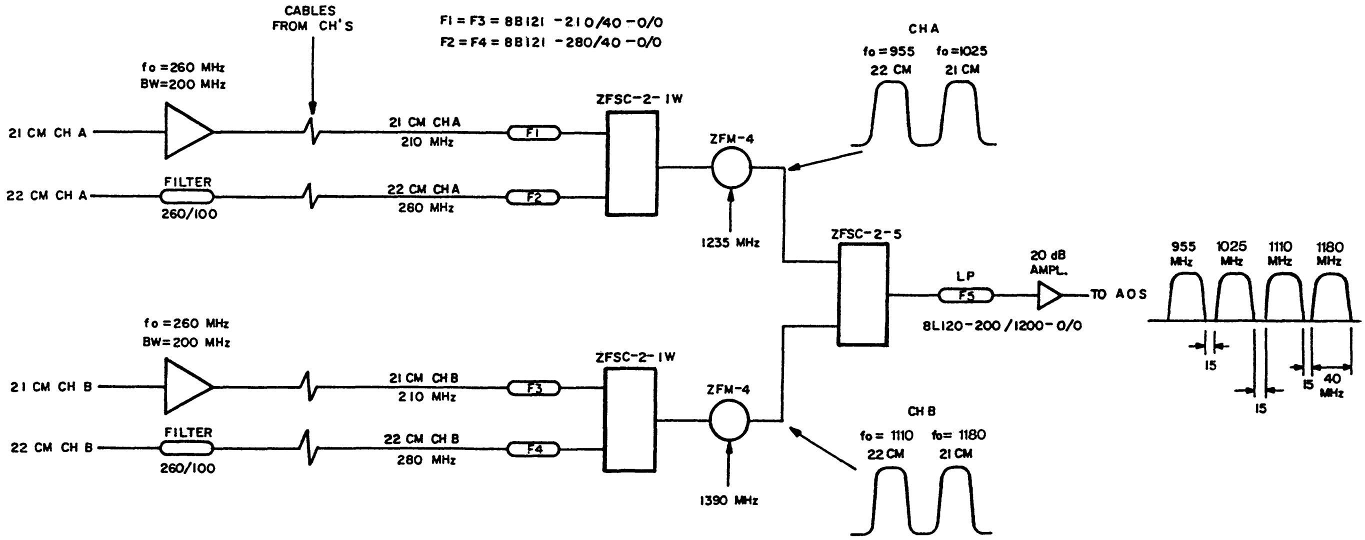



**Fig. 1.** Schematic drawing of the conversion of the four 50 MHz bandwidth input signals (on the left) to four 50 MHz bands at different frequencies inside the 500 MHz band of the AOS (on the right)

**Table 1.** Total number of hours of observation at 1.4 GHz and 5 GHz of each of nine dMe stars and one RS CVn in Arecibo, from 3 to 13 December 1990, on 8-9 May 1991 and from 6 to 15 February 1993.

| Star | Distance (pc) | Observing Frequency (GHz) | |
|---|---|---|---|
| | | 1.4 | 5 |
| Wolf 424 | 4.3 | 10.7 | 1.4 |
| TZ Ari | 4.5 | 3.3 | |
| AD Leo | 4.9 | 38.3 | 2.2 |
| YZ CMi | 6.0 | 7.7 | 0.8 |
| EQ Peg | 6.5 | 3.6 | |
| Gl 569 | 10.4 | 4.4 | |
| YY Gem | 14.5 | 3.1 | |
| V371 Ori | 15.2 | 2.9 | |
| VW Com | 17.5 | 2.0 | 1.0 |
| UX Ari | 20 | 2.8 | |

### *3.1. Results at 1.4 GHz*

#### 3.1.1. The quality of the data

The data demonstrate the excellent technical performances of the telescope and receivers: the system temperature ($T_{sys}$) and sensitivity at zenith were about 35 K and 5.5 K/Jy when averaged over a 50 MHz band. Therefore, the rms fluctuations in a 50 MHz band centered at 1380 MHz are given by

$$\Delta S = 6.4/\sqrt{\Delta\tau\Delta\nu} \text{ mJy},$$

where $\Delta\tau$ is the integration time in seconds and $\Delta\nu$ the bandwidth in MHz. The dynamic spectra plotted with an integration time of 1 s have a sensitivity threshold of a few mJy (for a bandwidth of a few MHz). The dynamic range from white to black chosen for these plots corresponds to several tens of mJy, displayed as a low percentage ($\sim 1\%$) around $T_{sys}$. They demonstrate that the background variations are smooth and very reproducible from one day to another. This is shown on Fig. 2, where

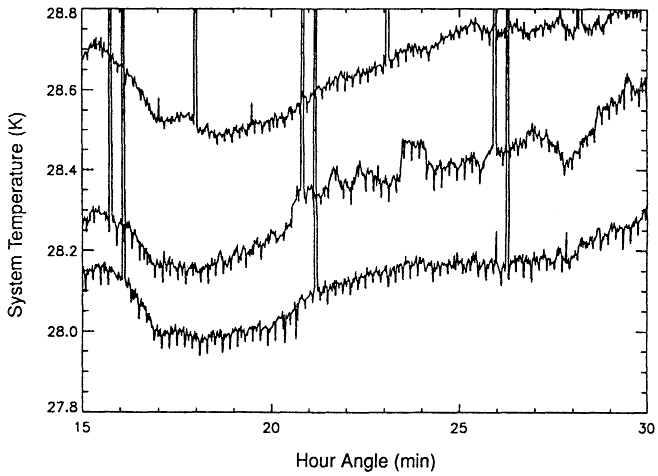



**Fig. 2.** Variation of the system temperature (in Kelvins), integrated over 50 MHz and for 1 s, while observing AD Leo at 1.4 GHz (RCP) on three consecutive days from 11 to 13 December 1990. The horizontal axis is in minutes of hour angle from meridian transit time. The curve of 13 December (in the middle) has been vertically offset by -1.5 K, but the three curves start at the same hour angle (HA = 15 min). The highest fluctuations correspond to about 60 mJy over 5 minutes. Calibration signals are clearly visible every 5 minutes on each day. The first calibration noise tube for the curve of 13 December was made at H.A. $\approx$ 15.6 min. Periodic radar signals "in absorption" are present. In addition, four bursts from AD Leo are visible in the middle curve at 20.5$\lesssim$ $HA\ (min)$ $\lesssim$24.2, among which the strongest reached about 20 mJy

three scans of AD Leo, observed at 1.4 GHz on three consecutive days, are plotted: the system temperature, integrated over 50 MHz for 1 s, is plotted versus hour angle (HA) for the right circular polarization (RCP). In addition, four bursts from AD Leo are visible in the middle curve at 20.5$\lesssim$ $HA\ (min)$ $\lesssim$24.2, among which the strongest reached about 20 mJy.

### 3.1.2. Interference rejection

A number of spurious events, which were obviously not of stellar origin, were eliminated at first sight for various reasons: i) narrow band interference, recognizable thanks to spectral analysis capability, are rejected very easily; ii) many wide band interferences, with evidently artificial temporal characteristics are eliminated without comparison with the "OFF" dynamic spectra; iii) numerous wide band interferences are rejected because they obviously appear in periods of quite rapid ($\lesssim$ 5 min) background variations, which are not clearly recognizable on other days; in particular, they appear when a source passes near zenith (this is the case at -10$\lesssim HA\ (min) \lesssim$10 for AD Leo, whose declination is $\approx 20°$).

After eliminating the above "obviously non stellar events" in the dynamic spectra of the ten stars, about 55 events of stellar appearance remained. Among them, about 12 ($\lesssim 22\%$) are stellar in origin and 43 ($\sim 78\%$) were eliminated for one or several reasons, as shown in Table 2 (no doubtful emission of stellar appearance was found for the five stars not mentioned in Table 2): i) some wide band interferences are easily eliminated by comparing ON and OFF dynamic spectra (an example is shown in Lecacheux et al. 1992); ii) recurrence over consecutive days at the same hour angle is another reason to reject most doubtful emissions; iii) finally, a broad band stellar flare generally reproduces the telescope response function (TRF), while an interference does not; iv) in one case, an event which had not been rejected according to any of the above criteria was found to be present also on CCD pixels that were not used to record the four 50 MHz spectra. One has to keep this last example in mind in order to be careful in accepting some doubtful emissions as stellar events.

On the other hand, because of the intrinsic limit of sensitivity, the number of stellar bursts is inevitably underestimated. As we will see below, the missed weakest bursts are certainly not the most interesting ones, they do not bring information pemitting to understand the emission process.

**Table 2.** Main motive of rejection of false events. Total number of rejected events per motive and per star: interference present on the dynamic spectra "OFF", identical background variation at the same hour angle on several days, or event with high intensity at both edges of the frequency bands.

| Star | OFF | Daily comparison | no TRF | Total |
|---|---|---|---|---|
| Wolf 424 | 2 | | | 2 |
| TZ Ari | | 2 | | 2 |
| AD Leo | 6 | 26 | 5 | 37 |
| Gl 569 | | 1 | | 1 |
| VW Com | 1 | | | 1 |
| Total | 9 | 29 | 5 | 43 |

### 3.1.3. Bursts from AD Leo

No quiescent emission could be measured from any of the stars observed. No burst was detected from nine of the ten stars observed for a total of $\sim$ 44 hrs. In the $\sim$ 40 hours of observations of AD Leo, about ten events were detected at 1.4 GHz. Table 3 summarizes their main characteristics. We now briefly describe these flares.

The first burst of 11 December 1990 from AD Leo is shown in Fig. 3a. This figure shows the dynamic spectra of 5 minute observations of the four 50 MHz bands (RCP ON, RCP OFF, LCP ON and LCP OFF) recorded simultaneously. They are plotted with an integration time of 1 s and a frequency resolution of 0.5 MHz (corresponding to one pixel). Intensity is represented in grey levels. The event appears clearly in RCP (ON) above the sky background variations. The sky background variations are largely due to source confusion and are not constant with frequency or time, but form patterns which are visible on ON and OFF dynamic spectra, in both polarizations; this pattern reproduces itself from day to day at the same hour angle. Since the antenna "OFF" is not tracking a source, it receives the signal of various sources in the sky and this is why the dynamic spectra "OFF" appear much less smooth than the "ON". The burst reproduces the characteristic shape of the TRF. For this reason, we are confident of the stellar origin of the burst. However, its bandwidth is difficult to estimate, because of the decreasing sensitivity at the edges of our observing band. On Fig. 3b, the same 5 min of the time profile in RCP and LCP "ON", integrated for 1 s over 50 MHz are shown. For $\sim$ 20 s before the $\sim$ 12 s duration burst, an enhancement reaching $\sim$ 12 mJy in RCP is present, which is not of stellar origin because it is also present on the dynamic spectra of another day at the same hour angle.

The second burst of 11 December 1990 (not shown) is less obvious than the first one, but is interesting because it may represent a period of activ:'y, since it occurred about 24 min after the first one. The major part of this event lasts $\sim$5 s and occupies most of the bandwidth. Again, the burst exhibits the TRF, substantiating the stellar origin. At the end of this phase, a second part of the burst, barely visible in the data, starts at $\sim$ 1375 MHz and drifts with time up to $\sim$1390 MHz in $\sim$5 – 10 s. An enhancement of the RCP time profile (not shown) confirms its presence.

Seven events occurred on 13 December 1990 and could therefore also belong to a period of activity. The first one consists of one short peak in RCP and two peaks in LCP (not shown).

The four following bursts are all within a 3.5 min interval. The first of them is more easily visible in the middle curve of Fig. 2, but since it begins at the very end of a 5 min scan and ends a few seconds after the calibration signal of the next scan, its stellar origin is difficult to confirm, its peak flux density cannot be estimated and it is therefore not reported in Table 3. The end of this burst and the next three bursts are visible in Fig. 4a (RCP and LCP dynamic spectra "ON"). Among these three bursts, the first two are very similar with gradual rises and decays. The third is much more credible since it is longer, more intense and clearly reproducing the TRF. Here, as shown by the time profile in Fig. 4b, the rise and decay are rapid.

The two last events of 13 December 1990 are not shown. The second is weak and particularly doubtful.

**Table 3.** Main characteristics of the flares observed from AD Leo at 1.4 GHz with the Arecibo radio telescope (the peak flux densities, $S_M$, are integrated over 50 MHz).

| Date | Starting Time (UT) | Duration (s) | $S_M$ (mJy) in RCP | $S_M$ (mJy) in LCP | RCP(%) | LCP(%) |
|---|---|---|---|---|---|---|
| 11 Dec 90 | 08:41:12 | ~12 | ~20 (9.1$\sigma$) | 0 | 100 | 0 |
| 11 Dec 90 | 09:05:10 | ~12 | ~8 (5.7$\sigma$) | 0 | 100 | 0 |
| 13 Dec 90 | 08:37:55 | ~6 | ~13 (4.8$\sigma$) | ~12 (4.3$\sigma$) | 50 | 50 |
| 13 Dec 90 | 09:40:28 | ~15 | ~12 (5.0$\sigma$) | ~13 (4.8$\sigma$) | 50 | 50 |
| 13 Dec 90 | 09:41:08 | ~14 | ~12 (5.0$\sigma$) | ~12 (4.4$\sigma$) | 50 | 50 |
| 13 Dec 90 | 09:42:19 | ~41 | ~20 (8.3$\sigma$) | ~26 (9.6$\sigma$) | 43 | 57 |
| 13 Dec 90 | 09:51:15 | ~46 | ~12 (6$\sigma$) | ~12 (6.7$\sigma$) | 50 | 50 |
| 13 Dec 90 | 09:53:03 | ~10 | ~8 (4$\sigma$) | ~6 (3.3$\sigma$) | 57 | 43 |
| 12 Feb 93 | 04:40:55 | ~8 | 0 | ~10 (4.0$\sigma$) | 0 | 100 |
| 13 Feb 93 | 04:12:53 | ~90 | ~63 (12.5$\sigma$) | 0 | 100 | 0 |
| 13 Feb 93 | 04:17:22 | ~40 | ~30 (9.0$\sigma$) | 0 | 100 | 0 |

A stronger event was recorded on 9 May 1991. But although it appeared very distinctly above the noise background only in the on-source receiver, it is *not* of stellar origin because it does not have the TRF spectrum. Indeed, the response function of this event appears approximately flat: hence, its flux density at 1360 MHz corresponds to about three times the flux density at 1390 MHz; if the flux density $S$ could be expressed as a power law, $S_\nu \propto \nu^\alpha$, where $\nu$ is the frequency, the spectral index would be $\alpha \approx -54$, which does not seem realistic.

The event of 12 February 1993 (not shown) is weak and must be considered doubtful. Finally, two flares (not shown) were recorded on 13 February 1993 in a 5 min interval. The first one has remarkable structures and will be studied in a further publication.

In summary, among these events, five are 100% circularly polarized and six are not. In general, except for one flare detected on 13 February 1993, their flux density is low (a few tens of mJy), their duration is no more than a few tens of seconds, and their bandwidth is at least 50 MHz ($\Delta f/f \gtrsim 3\%$). Only a few flares appear clearly above the background variations. Moreover, we must be less confident in the presence of RFI, of the stellar origin of non-polarized weak events than of more intense, strongly polarized bursts. Except for the last flare of 13 February 1993, no fine structure in time or frequency was evident within the rather large uncertainties of these weak bursts.

### *3.2. Results at 5 GHz*

At 5 GHz, the system temperature and the sensitivity at zenith were respectively about 45 K and 1.5 K/Jy averaged over the 500 MHz band. A preliminary analysis of the data reveals no burst from any of the four flare stars – AD Leo, VW Com, Wolf 424 and YZ CMi – observed for a total of about 5.4 hrs.

### *3.3. Questions regarding dMe flare rates*

We recorded few and weak flares from only one of the ten stars observed. Were the stars anomolously quiet? We do point out that except for AD Leo, Wolf 424 and YZ CMi, we observed the other seven stars for less than 4.5 hours each. To our knowledge, Gl 569, TZ Ari, V371 Ori and VW Com have never been detected near 20 cm. EQ Peg occasionally exhibits some flares of several mJy at 20 cm (e.g. Bastian 1987), but on other occasions, nothing was reported from several hours of observation (e.g. Güdel 1991). There are many reports of quiescent emission from EQ Peg and YY Gem of typically only a fraction of mJy to a few mJy, measured with the VLA, but mainly at 6 cm: no flare was observed in several hours (e.g. Topka & Marsh 1982; Linsky & Gary 1983). The RS CVn UX Ari was detected near 20 cm on several occasions with a flux density of several tens of mJy, but in many cases it remained at the same constant level (e.g. Willson & Lang 1987); while this can be measured by the VLA, only rapid bursts can be distinguished from the background variations by the Arecibo telescope. To our knowledge, only AD Leo, Wolf 424 and YZ CMi have ever been detected by the Arecibo telescope. There have indeed been reports of radio bursts from these three stars, but not many from Wolf 424. YZ CMi was more often detected as a slowly varying, quiescent source than as a really flaring one, and most reports of flux density are typically of less than 20 mJy at 20 cm. For AD Leo, in ~ 40 hours, we have no event stronger than 70 mJy, half of them are non-polarized, half are 100% circularly polarized, and only one has apparently some fine structures, but no intense spikes, while many previously reported strong events (several 100 mJy) at 20 cm were recorded in Arecibo and were strongly polarized. With the VLA, many bursts of a few tens of mJy were reported for AD Leo, more often at 6 cm than at 20 cm.

The problem is that there have apparently been no reports of what the flare event rate might be at 1.4 and 5 GHz, and this is difficult to estimate from the literature. The apparent high radio activity from dMe stars might be due to several reasons. The total number of hours spent in observing several stars is not systematically reported in a paper showing only one (or a few) burst(s), and in general, a paper is not written only to mention the non-detections from numerous observing hours. For example, Bastian (private communication) reports that in eight days of observation in November 1987, they detected no strong flares from Wolf 424, and only a couple of flares from YZ CMi

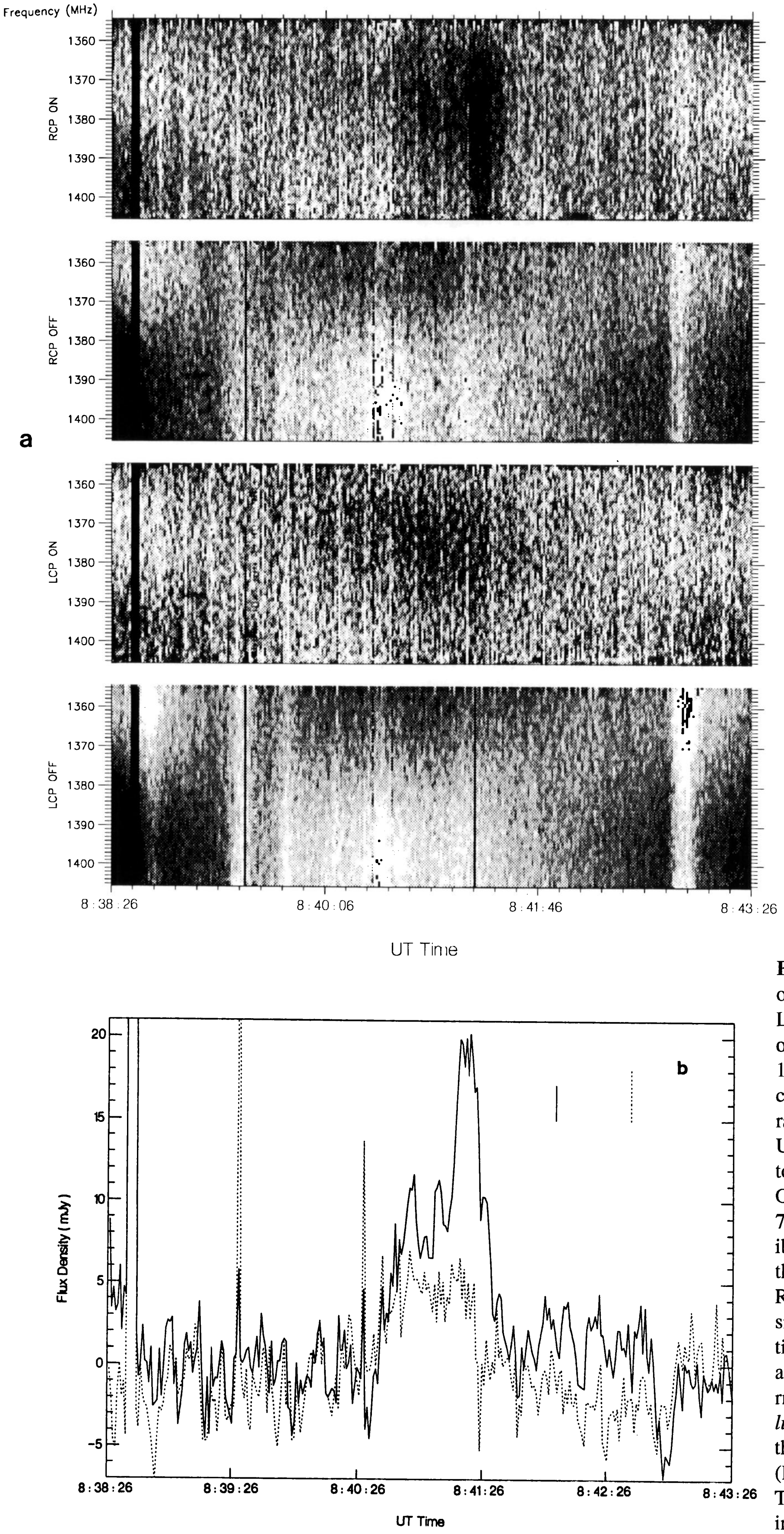
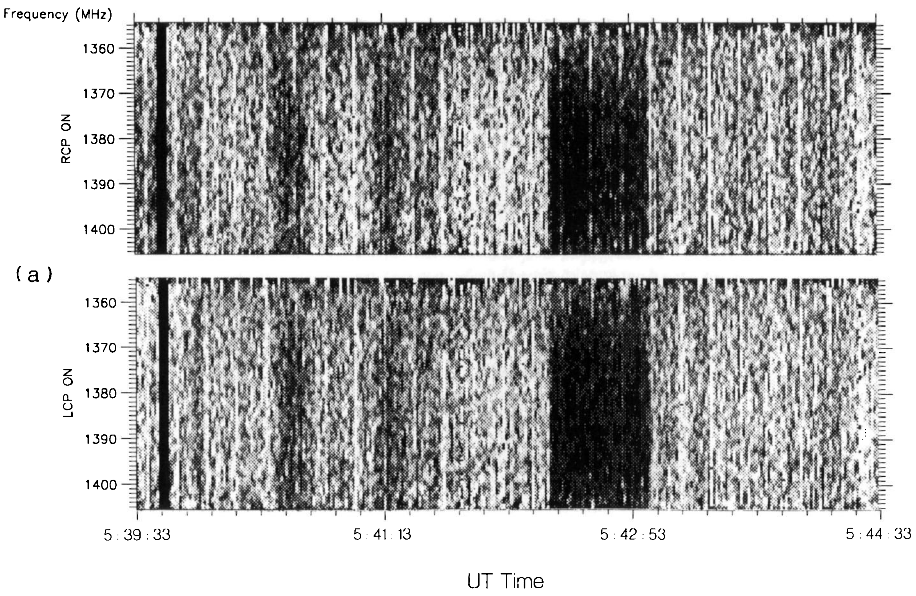



**Fig. 3. a** Dynamic spectra of 5 min observations of the four 50 MHz bands (RCP ON, RCP OFF, LCP ON and LCP OFF) recorded simultaneously while observing AD Leo on 11 December 1990. Each pixel represents 1 s of time and one channel of 0.5 MHz bandwidth. The frequency ranges from 1355 MHz to 1405 MHz. Time is in UT. Intensity is represented in grey levels. White to black represents an increase of 30 mJy (RCP ON), 63 mJy (RCP OFF), 26 mJy (LCP ON) and 77 mJy (LCP OFF). The black vertical strip visible on the dynamic spectra at the beginning of the scan is the calibration signal. **b** Same 5 min: RCP (*solid line*) and LCP (*dotted line*) flux densities (in mJy) of AD Leo (same day) versus UT time at $\sim$ 1380 MHz (integrated over 50 MHz), averaged every 1 s. Error bars representing the rms error are shown: $\sigma_{RCP} \approx 2.2$ mJy (*solid line*) and $\sigma_{LCP} \approx 3.1$ mJy (*dotted line*). Again, the strong 5 s signal corresponds to calibration. (Here, periodic radar signal has been removed.) Two strong interferences appear in LCP



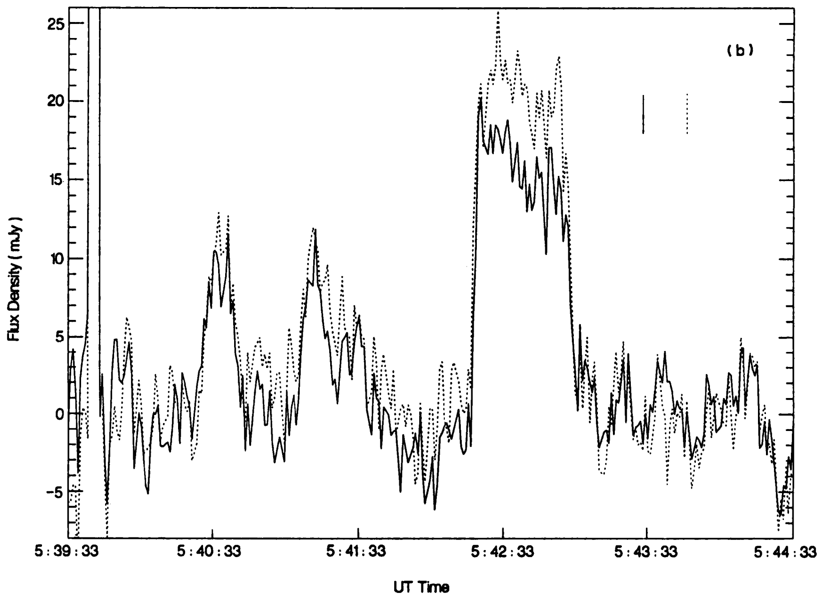




**Fig. 4a and b.** 13 December 1990. **a** 5 min. dynamic spectra "ON" in RCP and LCP. White to black represents an increase of 31 mJy (RCP ON) and 38 mJy (LCP ON). **b** Same as Fig 3b. $\sigma_{RCP} \approx 2.4$ mJy (*solid line*) and $\sigma_{LCP} \approx 2.7$ mJy (*dotted line*)

(both down at 430 MHz); AD Leo exhibited some spectacular activity during the first observing period (4 - 8 November 1987) – see Bastian et al. (1990) – but it produced nothing during the second observing period (14 - 16 November 1987). During their observing run in January - February 1990, they observed for many days and detected only a handful of small events, not published because they thought they had learned nothing new. On the other hand, the criteria used to consider that some of the events recorded with single-dish telescopes are of stellar origin are not always mentioned and the authors sometimes do not prove that they are not RFI. Finally, the impression that intense, fine-structured flares commonly occur might be warped. Indeed, one can reasonably think that only the most interesting bursts were generally reported, because they probably correspond to the most intense bursts, hence, their signal to noise is higher, and fine structures can possibly be observed.

In conclusion, our results might not be in contradiction with the non-published *and* published results mentioned in the preceeding paragraph, as far as flare event rates and flare flux densities are concerned. The weakness of the bursts we detected from AD Leo may be the reason why they contained no fine structures (like intense spikes). Perhaps the late-type stars exhibit strong bursts only rarely, and then, the most interesting events recorded in the past could have been lucky detections or, for some of them, non-stellar events that would have been rejected by the improved methods for discriminating between radio interference and stellar bursts.

## 4. Interpretation and discussion

Assuming a source radius not larger than the AD Leo's radius (0.5 $R_\odot$), we derive a brightness temperature $T_b \gtrsim 10^{10}$ K for the typical bursts reported here ($\gtrsim$ 10 mJy). This value is high and hardly compatible with any incoherent generation mechanism (Dulk 1985). Invoking coherent generation processes is then reasonable. There are essentially two commonly discussed possible candidates: the cyclotron maser instability and the plasma radiation.

### *4.1. The two proposed coherent mechanisms*

#### 4.1.1. Cyclotron maser instability

The cyclotron maser was first proposed to explain the production of planetary and solar radio emissions (Wu & Lee 1979; Melrose & Dulk 1982). Its basic process is a relativistic resonant coupling between electrons in gyromotion and the electromagnetic field of the waves. Letting $v_\perp$ be the velocity component perpendicular to the source's magnetic field, if the electron distribution function $f$ presents an inversion of population in perpendicular velocity $v_\perp$ ($\partial f/\partial v_\perp > 0$), this coupling leads to an amplification of the electromagnetic waves. This process is particularly efficient in highly magnetized plasma ($\omega_p/\omega_c \lesssim 1$), where $\omega_p$ is the local plasma frequency and $\omega_c$ the electron gyrofrequency. The waves are then amplified at frequencies close to $\omega_c$. Letting $\omega$ and $\gamma$ be the real and imaginary parts of the frequency, respectively, and $v_\parallel$ the "parallel" velocity, both the growth rate of the instability ($\gamma/\omega$) and its instantaneous relative bandwidth ($\Delta\omega/\omega$) are scaled by the typical "perpendicular" energy of the emitting electrons (with $v_\perp \gg v_\parallel$):

$$\gamma/\omega \propto (v_\perp/c)^2 \propto \Delta\omega/\omega$$

(Le Quéau & Louarn 1989). The role of cyclotron maser in the generation of the Earth Auroral Kilometric Radiation (AKR) has been confirmed by direct *in situ* measurements (*Viking Experiment*: de Féraudy et al. 1987; Louarn et al. 1990; Hilgers et al. 1991).

#### 4.1.2. Plasma radiation

Plasma radiation is a two stage mechanism: the initial free energy contained in the particle distribution function is first converted into an electrostatic turbulence which is in turn converted by a non-linear wave-wave process into electromagnetic radiation. The resulting emission is generated at frequencies close to the local plasma frequency $\omega_p$ or at its harmonic $2\omega_p$ (e.g. Dulk 1985). This mechanism is the accepted generation process for several types of solar radio emission. For example, type III bursts are associated with semi-relativistic streaming electrons (of velocity $v \approx c/3$) that drive a "bump in the tail" instability in the ambient plasma. In practice, plasma radiation is invoked when the source region of the radio burst is suspected to have a low magnetization ($\omega_p/\omega_c > 1$), a situation which is not favourable to the cyclotron maser.

### *4.2. Comparisons with planetary and solar radio emissions*

Before trying to identify the generation process of the bursts reported here, it is useful to compare, in a quite general way and on the basis of energy considerations, our stellar burst observations to similar planetary or solar observations. The electromagnetic flux density of the Poynting vector is

$$F = \epsilon_0 c E^2 ,$$

where $\epsilon_0$ is the dielectric constant of the medium, $c$ the speed of light and $E$ is the absolute value of the electric field. Assuming that $l$ is the size of the stellar source at a distance $d$, and that the emission is isotropic, we know that the flux density at the surface of the source is

$$F_{S0} = F_{S1}(d/l)^2 ,$$

where $F_{S1}$ is the flux density received. Therefore, an observed flux density $F_{S1}$ = 10 mJy corresponds to a typical spectral amplitude of the waves in the source of

$$E_{S0} = \sqrt{F_{S1}/\epsilon_0 c}\,(d/l) .$$

Putting $d = 4.9$ pc (for AD Leo) and $l$ in units of 1000 km, this is

$$E_{S0} \approx 3 \times 10^{-2}/l \quad \mathrm{V\,m^{-1}\,Hz^{-1/2}} .$$

For $l$ = 1 (1000 km), this is close to the spectral amplitude measured in the most intense sources of terrestrial AKR:

$$E_{E0} \approx 10^{-3} \quad \mathrm{V\,m^{-1}\,Hz^{-1/2}} .$$

#### 4.2.1. Comparisons of efficiencies in the case of the CMI

*Comparison with the Earth*

In the case of the cyclotron maser, if we assume that the emitting electrons have similar energies in the stellar and planetary cases (10 keV, typically), the instantaneous bandwidth of the emission is scaled by the frequency:

$$\Delta\omega \propto \alpha\omega$$

where $\alpha = (v_\perp/c)^2$. The density of electromagnetic energy is then proportional to

$$E_{S0}{}^2\Delta\omega \propto E_{S0}{}^2\alpha\omega \propto (F_{S1}/\epsilon_0 c)\,(d/l)^2\,\alpha\omega .$$

In the case of the Earth, observations at 100 kHz give a density of electromagnetic energy proportional to $10^{-1}\ \alpha$. In the stellar case with $\omega/2\pi \approx 1$ GHz, the value is $10^6\ \alpha/l^2$; the density of electromagnetic energy associated with the stellar burst is then a factor $10^7/l^2$ higher than the AKR one. This ratio corresponds to the density of electromagnetic energy radiated in the band $\Delta\omega$ at a given frequency $\omega$ (the local gyrofrequency) and at a given place in the source. It does not apply to the event as a whole whose bandwidth is dependent on the variation of $\omega_c$ (or $\omega_p$ in the case of the plasma radiation) inside the source region.

In order to compare the efficiency of the generation mechanisms, a meaningful quantity is the ratio of the density of energy calculated above and the density of particles. We then obtain an "efficiency per particle" ($\eta$) of the emission mechanism. For the Earth, the electron density is $\sim$ 1 cm$^{-3}$. For a dMe flare star, the density in flaring loops may be $\sim 10^{10}$ to $10^{12}$ cm$^{-3}$ (Bastian et al. 1990), but probably varies from place to place. In a cyclotron maser source at 1 GHz, with $\omega_p/\omega_c \lesssim 1$, the electron density cannot be greater than $10^8 - 10^9$ cm$^{-3}$, so that the efficiency per particle in the case of AD Leo is:

$$\eta_S \sim (10^{-3} - 10^{-2})\alpha/l^2 ,$$

and then:

$$\eta_S/\eta_E \sim (10^{-2} - 10^{-1})/l^2 ,$$

where $\eta_E$ is the efficiency per particle in the case of the Earth. Except if the typical size of the source is much smaller than 1000 km ($l = 1$), a reasonable explanation for the low efficiency of the stellar process is that only a small part of the electrons is involved in the generation process. This could be an important difference from the Earth for which a large fraction of the electrons in the source (more than 50%) are accelerated to keV energies and can participate to the emission process.
Supposing 100 keV electrons in the stellar case, then:

$$\eta_S/\eta_E \sim (10^{-1} - 1)/l^2 \, ;$$

the efficiency of the stellar process is smaller or of the order of that of the Earth for a source size of ~ 1000 km, and greater if the source is smaller.

In conclusion, despite the huge energy involved in stellar flares compared to planetary bursts, when these events are replaced in their context, the intrinsic efficiencies of the basic generation mechanism seem to be of the same order. It is remarkable that efficiencies of the same order for the Earth and the star correspond to source sizes of a few 100 km, which is the value inferred for the Earth.

However, the above calculations depend on several quantities which are not known precisely. For example, we have assumed a stellar source emitting isotropically in $4\pi$ steradians, but in the case of a cyclotron maser instability, the emission is likely to be anisotropic, and the received flux density comes from part of a hollow cone. The source's solid angle sustained from the Earth ($\Omega$) is then smaller than $4\pi$ steradians; therefore, the total spectral power emitted by the source is a factor $\Omega/4\pi$ smaller than that of an isotropic emission, hence the spectral amplitude is smaller by a factor of $\sqrt{\Omega/4\pi}$. In the case of the Io-controlled Jovian decametric emission, the semi-apical angle of this cone has been estimated at ~ 70°– 80° (e.g. Zarka 1988). With an angular aperture of ~ 10°, we find $\sqrt{\Omega/4\pi} \approx 30\%$. Thus, the spectral amplitude is ~ 30% of the value deduced in the isotropic case, which does not drastically change the preceding conclusion.

*Comparison with the Sun*

For solar millisecond spikes of flux density up to $\sim 2.6 \times 10^2$ SFU (1 Solar Flux Unit = $10^4$ Jy) at 3.2 GHz, Stähli & Magun (1985) conclude that one of the two possible conditions to invoke the cyclotron maser is that the rise times are independent of the source diameters, estimated at ~ 50 – 100 km. We therefore obtain a density of electromagnetic energy proportional to $\sim 10^5\,\alpha$. For an electron density of $\sim 10^9$ cm$^{-3}$, we find a solar efficiency:

$$\eta_\odot \sim 10^{-4}\,\alpha \, .$$

For electrons of 10 keV energies in the solar case too, we find:

$$\eta_S/\eta_\odot \sim (10 - 10^2)/l^2 \, .$$

In addition, quasi-periodic solar pulsations reaching $\sim 10^3$ SFU at 455 MHz are interpreted in terms of the cyclotron maser instability producing emission either at the fundamental ($s = 1$) $o$-mode for $0.3 < \omega_p/\omega_c \lesssim 1.0$ or the harmonic ($s = 2$) $x$-mode for $1.0 \lesssim \omega_p/\omega_c \lesssim 1.4$ (Aschwanden & Benz 1988). The estimated source size is ~ 50 – 500 km; for an electron density of $\sim 10^7$ cm$^{-3}$ and electrons of 10 keV energies, we therefore obtain:

$$\eta_S/\eta_\odot \sim (10^{-1} - 10^2)/l^2 \, .$$

In the above two examples, the stellar efficiency is then of the order of the solar efficiency, or greater if the source size is smaller than 1000 km. The same results are obtained for 100 keV electrons in both the solar and stellar cases, which is plausible.

#### 4.2.2. Comparison with the Sun in the case of the plasma radiation

Assuming that AD Leo's typical bursts (~ 10 mJy) are due to plasma radiation, the electron density in the source can be $\sim 10^{10}$ to $10^{11}$ cm$^{-3}$. Placing the Sun at a distance of 5 pc, its most intense microwave spikes which could be attributed to plasma radiation (Slottje 1978) have a flux density of ~ 0.1 mJy at 2.65 GHz, which is ~ 100 times lower than the stellar bursts at 1.4 GHz, and the electron density is of the same order. Other microwave spikes observed at 6 – 8 GHz (Bruggmann et al. 1990) are $\sim 10^6$ times lower than AD Leo's bursts and, if they can be attributed to plasma radiation, the estimated electron density is $\sim 10^{11} - 10^{12}$ cm$^{-3}$. In the case of the plasma radiation, the intrinsic efficiency per particle of the stellar emission mechanism therefore seems to be much higher than the solar efficiency. One possible explanation could be that the second stage of the mechanism producing plasma radiation, the conversion of electrostatic turbulence into electromagnetic radiation, is more efficient in the stellar coronae than in the solar corona.

### *4.3. CMI or plasma radiation?*

If the above solar examples were due to plasma radiation without any doubt, energy considerations would seem to be in favour of a cyclotron maser instability to explain stellar bursts of ~ 10 mJy. In particular, millisecond fine-structures as intense as AD Leo's bursts (flux density up to ~ 10 mJy at 5 pc, Dröge 1977) are attributed to the cyclotron maser by Holman et al. (1980) and Melrose & Dulk (1982).

Since the value of the ratio $\omega_p/\omega_c$ is poorly known in stellar environments, and it certainly varies with position and altitude, the criterion $\omega_p/\omega_c$ smaller or larger than 1 cannot be used. Indeed, although the mean photospheric magnetic field of dMe flare stars is $\sim 10^3$ time stronger than that of the Sun, one does not know how the magnetic field varies with altitude in the stellar coronae.

For the Sun and planets, the actual generation process is generally determined from the spectral properties and the polarization of the emissions. By analogy with the planetary case for which it is known that in a plasma with low $\omega_p/\omega_c$ ($< 10^{-1}$), the cyclotron maser generates extremely polarized bursts (100% circular polarization, or 100% elliptical polarization in the case of Jupiter's decametric radiation, Lecacheux et al. 1991), the polarized stellar radio emissions could be attributed to this direct generation process.

But there is a controversy on the interpretation of some polarized solar bursts. The intense, 100% LCP, solar microwave spikes attributed to plasma radiation by Slottje (1978) are attributed to cyclotron maser by Melrose & Dulk (1982), who also consider that it is a plausible explanation for some solar decimetric bursts with high circular polarization, but Kuijpers (1980) demonstrated that plasma radiation is plausible too. For example, type I bursts (observed at frequencies $\approx 50-300$ MHz), with a circular polarization $\approx 50-100\%$ and a relative bandwidth $\approx 0.3-2$ % are attributed either to cyclotron maser (Mangeney & Veltri 1976) or to plasma radiation (Dulk 1985).

On the other hand, mildly-polarized or even non-polarized emissions cannot be attributed with certainty to plasma radiation. The cyclotron maser theory was invoked to explain, on certain conditions, solar millisecond spikes with a circular polarization varying from $\sim$ 100 % left to 100% right (Stähli & Magun 1985). Pulsations observed at 455 MHz with a polarization of 10 - 30% for five events and 85 - 100% for five others were attributed to cyclotron maser by Aschwanden & Benz (1988) who suggest that non-polarized emission can arise from individual cells emitting cyclotron emissions of various polarizations.

Furthermore, for the AKR and similar emissions from the giant planets, the emission is produced in a strongly magnetized plasma ($\omega_p/\omega_c \approx 10^{-1}$ for the Earth and $10^{-2}-10^{-3}$ for Jupiter). In the amplification region, the $x$-mode is largely dominant and organized in very fine structures ($\delta f/f \approx 10^{-4}$). But for the less strongly magnetized AKR, after propagation in the inhomogeneous plasma that surrounds the source, a part of the energy is converted on the $o$-mode and the fine structures are mixed. The $o$- and $x$-mode levels are comparable, therefore the resulting emission cannot be strongly polarized and the individual structures cannot be identified except with high temporal and spectral resolutions ($\delta f/f \approx 10^{-3}$ and $\delta f \delta\tau \approx 10^2$ for $f \approx 10^5$ Hz, $\delta f \approx 10^2$ Hz and $\delta\tau \approx 1$ s). In the present case, the spectral resolution is close to this value ($\delta f/f \approx 10^{-3}$), but the temporal resolution is comparatively low: 20 ms. This means $\delta f \delta\tau \approx 10^4$ and then, the fine structures (if they exist) could well have been smoothed.

Finally, bursts with a narrow relative bandwidth ($\lesssim 1\%$) are not systematically explained by the cyclotron maser, as mentioned about type I bursts. Another example is given by Bruggmann et al. (1990), who could not discriminate between plasma radiation and cyclotron maser to explain the solar microwave spikes mentioned above, with a relative bandwidth $\approx 0.8-6$ %.

## 5. Conclusions

In conclusion, given the uncertainties on the coronal model and on the source size, the observations described here can be considered to be compatible with what is known in the planetary or the solar context, especially in the case of the cyclotron maser instability. The intrinsic efficiency of the stellar generation process is typically of the order of the solar or planetary efficiencies, in the case of the cyclotron maser, and apparently stronger than the solar efficiency in the case of the plasma radiation. But as we have no more precise information on the source, the two mechanisms, plasma radiation and cyclotron maser, can explain the stellar bursts.

We have performed $\sim$ 85 hours of observations of flare stars using the best discriminating method against RFI ever used with a single-dish instrument. We recorded about ten bursts, those from only one of the ten stars observed. The measured flux densities are lower than some previously reported values reaching several 100 mJy. A regular survey of the best known dMe flare stars should be performed in order to evaluate their typical intensity and flare rates. For this purpose, highly sensitive radio telescopes like the VLA and the Arecibo telescope are needed. The latter will provide sensitivities as good as the present 1.4 GHz system, but with much wider bandwidths and a wider choice of frequencies when the "Gregorian system" is in operation, thus permitting easier detection of bursts. Wide band observations at 1 – 3 GHz should permit delimitation of their bandwidth. Both improvements are necessary for a better understanding of stellar radio emissions.

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