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MILLISECOND RADIO SPIKES FROM THE DWARF M FLARE STAR AD LEONIS

KENNETH R. LANG AND ROBERT F. WILLSON
Department of Physics and Astronomy, Tufts University
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ABSTRACT

The Arecibo Observatory was used to detect two circularly polarized bursts at 1415 MHz from the dwarf M star AD Leonis with total durations of 50 s and 25 s. A sequence of quasi-periodic pulsations with a mean periodicity of $\tau_P = 3.2 \pm 0.3$ s and a total duration of $\tau_D = 25$ s was superposed on the 50 s burst. The strongest pulse was itself composed of a train of quasi-periodic spikes with a mean periodicity of $\tau_P = 32 \pm 5$ ms and a total duration of $\tau_D = 150$ ms. Both the quasi-periodic spikes and individual spikes had rise times of $\tau_R \leq 5$ ms, and they were up to 100% circularly polarized. An upper limit to the linear size of the spike-emitting region is $L \leq 1.5 \times 10^8$ cm, the distance light travels in 5 ms. This size is only 0.005 of the estimated radius of AD Leonis. Provided that the emitter is symmetric, it has an area which is less than 2.5×10^{-5} of the area of the stellar disk and a brightness temperature of $T_B \geq 10^{16}$ K. The high degrees of circular polarization indicate an intimate connection with the star's magnetic field, and the high brightness temperatures suggest a coherent burst mechanism such as an electron-cyclotron maser or coherent plasma radiation. If the electron-cyclotron maser emits at the second harmonic of the gyrofrequency, the longitudinal magnetic field strength $H_l = 250$ G and constraints on the plasma frequency imply an electron density of $N_e \approx 6 \times 10^9$ cm^{-3}. Coherent plasma radiation at the first or second harmonic of the plasma frequency, respectively, require $N_e = 2 \times 10^{10}$ cm^{-3} and $H_l \ll 500$ G or $N_e = 6 \times 10^9$ cm^{-3} and $H_l \ll 250$ G. The quasi-periodic pulsations and spikes may be due to some process that modulates the coherent burst emitter. One possibility is radial oscillations in a coronal loop that are excited by energetic trapped particles or by an impulsive source. In this event, an Alfvén velocity of $v_A = 2 \times 10^9$ cm s^{-1}, a coronal loop of extent $a_1 = 2 \times 10^9$ cm, and a loop inhomogeneity of size $a_2 = 2 \times 10^7$ cm are inferred for the dwarf M star. Energetic particles that are trapped within closed magnetic structures might alternatively modulate the coherent emission.

Subject headings: polarization — radio sources: variable — stars: flare — stars: individual — stars: radio radiation

I. INTRODUCTION

Rare, powerful (10–20 Jy), long-lasting (several hours) radio bursts from dwarf M flare stars have been occasionally observed at meter wavelengths (frequencies of a few hundred MHz) during many thousands of hours of observations in the 1970s (Lovell 1969; Spangler and Moffet 1976; Davis *et al.* 1978). Brightness temperatures of $T_B \geq 10^{12}$–10^{15} K were derived from the measured flux densities under the assumption that the radio emitter was smaller than the stellar disk. Weaker (a few tenths of 1 Jy) radio bursts of shorter duration (tens of seconds) occur more frequently with a rate comparable to that of optically visible flares from the same stars (one every 5.4 hours; Spangler, Shawhan, and Rankin 1974).

The first polarimetric study of these stellar radio bursts was provided by Spangler, Rankin, and Shawhan (1974) who showed that a burst from AD Leonis with a duration of $\tau = 40$ s was as high as 92% circularly polarized. The maximum amplitude of this burst was 520 mJy, which corresponds to $T_B \geq 10^{10}$ K at 430 MHz if the emitter has a radius equal to that of the dwarf M star ($R = 3.0 \times 10^{10}$ cm; Pettersen 1980). This highly circularly polarized burst was also the first radio burst to be observed from AD Leonis.

The improvement in sensitivity made possible by the large collecting area of the Very Large Array (VLA)[1] led to the detection of relatively weak (10 mJy), highly circularly polarized bursts from dwarf M flare stars at decimetric wavelengths. For example, nearly 100% right-hand circularly polarized bursts have been observed at 1420 MHz at about the same time from both components of the dwarf M binary star system UV Ceti (L726−8B) and L726−8A (Fisher and Gibson 1982); one 100% right-hand circularly polarized 6 cm burst from L726−8A exhibited quasi-periodic flux variations with a period of $\tau_P = 56 \pm 5$ s (Gary, Linsky, and Dulk 1982). The VLA has also been used to detect relatively weak, highly circularly polarized bursts from the single dwarf M star YZ Canis Minoris (Fisher and Gibson 1982; Pallavicini, Lang, and Willson 1985), as well as slowly varying quiescent, or nonflaring, emission of a few mJy from YZ Canis Minoris (Lang and Willson 1985), both components of the binary star system EQ Pegasi (Topka and Marsh 1982), and the binary dwarf M stars YY Geminorum and Wolf 630 (Linsky and Gary 1983). Two 6 cm bursts with nearly 100% left-hand circular polarization have also been observed from the single dwarf M star AD Leonis (Gary 1985); these bursts showed significant structure at the limiting 3.3 s time scale provided by the fastest VLA integration time.

This suggests a serious limitation for the VLA and most other large radio telescopes. The large integration times of ~10 s that are used to detect weak signals prohibit the detection of rapid bursts. In fact, individual microwave bursts, or variations within microwave bursts, from dwarf M stars are often unresolved in time when observed with the VLA. We have therefore begun a program of monitoring these stars with

[1] The VLA is a facility of the National Radio Astronomy Observatory, which is operated by Associated Universities, Inc., under contract with the National Science Foundation.

high time resolution (better than 1 ms) at the Arecibo Observatory.

After several hours of observation, a stellar eruption was observed from AD Leonis at 1400 MHz with a maximum flux density of 130 mJy. This burst was composed of highly left-hand circularly polarized (100%) spikes with rise times of $\tau_R \leq$ 200 ms (Lang *et al.* 1983). An upper limit to the linear size $L \leq 6 \times 10^9$ cm and a brightness temperature of $T_B \geq 10^{13}$ K were inferred from these rise times. Twenty hours of subsequent observations led to the detection of two other bursts at 1415 MHz that are discussed here.

In § II of this paper we present observations of highly left-hand circularly polarized (up to 100%) spikes from AD Leonis at 1415 MHz with rise times $\tau_R \leq 5$ ms. These rise times provide an upper limit of $L \leq 1.5 \times 10^8$ cm, and a lower limit to $T_B \geq 10^{16}$ K for a symmetric emitter. Some of the spikes were part of a quasi-periodic train of spikes with a mean periodicity of $\tau_P = 32 \pm 5$ ms and a total duration of $\tau_D = 150$ ms. This spike train was itself one pulse in a quasi-periodic sequence of pulsations with a mean periodicity of $\tau_P = 3.2 \pm 0.3$ s and total duration of $\tau_D = 25$ s; the pulsations were superposed upon a longer lasting (50 s) burst. In § III we interpret the high brightness temperatures and high circular polarization of the spikes in terms of coherent maser emission processes. The quasi-periodic trains of pulses and spikes are discussed within the framework of similar effects that have been observed during solar bursts. One possible explanation of the quasi-periodic pulsations and spikes is magnetoacoustic oscillations in a coronal loop that modulate the maser action.

II. OBSERVATIONS

On 1985 July 15, we observed the dwarf M star AD Leonis (Gliese 388, dM3.5e) at a frequency of 1415.0 MHz from 1745 to 1917 UT at the Arecibo Observatory. At this frequency the antenna beamwidth is 3'.3, and the system sensitivity is 8 K per Jy at zenith (1 Jy = 10^{-23} ergs s^{-1} cm^{-2} Hz^{-1}). Both the left-hand circularly polarized (LCP) signals and the right-hand circularly polarized (RCP) signals were recorded using separate receivers. Linear polarization was not obtained. The ellipticity was 0.95, and the uncertainty in circular polarization due to cross talk between the two receivers was 5%. A bandwidth of 4 MHz was employed, with an integration time of 5 ms. The flux density scale was established by calibration observations of PKS 0453+22 (3.25 Jy at 1415 MHz) and PKS 0333+12 (1.8 Jy at 1415 MHz) immediately before and after the observations of AD Leonis.

As illustrated in Figure 1, a circularly polarized (LCP) burst with a maximum flux density of $S_{\max} = 30$ mJy, a total duration of $\tau = 50$ s, and a degree of circular polarization of 50%–100% was observed around 1819 UT. Another, weaker burst with $S_{\max} = 10$ mJy, $\tau = 25$ s, and 100% LCP was observed about 20 s after the decay of the more intense burst. Because no similar variations in signal level were observed during this observation or during 20 hours of other observations of AD Leonis, we assume that the variations lasting 50 s and 20 s represent bursts rather than a slowly varying background that would be expected to continue during the rest of the observations. The burst flux densities reported here are therefore absolute values with respect to negligible quiescent radiation from the star. (No other bursts were detected at 1415 MHz during 2 hours centered at transit at the Arecibo Observatory on 1984 November 7–10 and 1985 July 13, 14, 16, 19, 20, and 21.)

A sequence of five quasi-periodic pulsations, or oscillations, with a mean periodicity of $\tau_P = 3.2 \pm 0.3$ s and a total duration of $\tau_D = 25$ s were superposed upon the more intense 50 s burst (see Fig. 1). The strongest pulse had $S_{\max} = 70$ mJy when the data were averaged by running means over 312 ms. The pulses had circular polarizations of 50%–100%. (Quasi-periodic, highly left-hand circularly polarized (100%) burst emission at 1400 MHz with fluctuations at time scales of ~ 2 s, 10 s, and 25 s were previously reported for AD Leonis (Lang *et al.* 1983), but no single periodicity dominated the data.)

When the strongest pulse, marked A in Figure 1, was observed with 5 ms integration time, it was found to be composed of a train of five quasi-periodic spikes with a mean periodicity of $\tau_P = 32 \pm 5$ ms and total duration of $\tau_D = 150$ ms (Fig. 2). These spikes had $S_{\max} = 300$ mJy and circular polarizations of ~ 33% with respect to the longer lasting 50 s burst. The pulses immediately before and after pulse. A (see Fig. 1) were resolved in time with durations of ~ 1 s, and they exhibited no detectable structure on shorter time scales.

Here we also note that higher flux densities are obtained with shorter integration times. The long integration of ~ 10 s at the VLA and other large radio telescopes would smooth out the individual spikes, leading to a serious underestimate of the flux density and perhaps reducing the quasi-periodic spikes to undetectable levels.

As illustrated in Figure 3, the time, Δt, between spikes was not completely regular, but instead showed a tendency to increase with $\Delta t = 25$, 30, 40, and 32 ms for sequential spikes; a sixth spike occurred at $\Delta t = 80$ ms. The individual quasi-periodic spikes had rise times $\tau_R \leq 5$ ms, and isolated, nonperiodic spikes like 2A (Fig. 2) and B (Fig. 1) had similar rise times. Spike B was 100% ± 5% left-hand, circularly polarized, with a rise time of $\tau_R \leq 5$ ms (see Fig. 4).

An upper limit to the linear size of the emitting region is $L \leq 1.5 \times 10^8$ cm, the distance that light travels in 5 ms. This size is only 0.005 of the estimated radius of AD Leonis ($R = 3.0 \times 10^{10}$ cm; Pettersen 1980). Provided that the spike emitter is symmetric, it has an area which is less than 2.5×10^{-5} of the surface area of the star's visible disk.

We can use the maximum flux density, $S_{\max} = 300$ mJy, to infer a lower limit to the brightness temperature $T_B \geq 10^{16}$ K using the Rayleigh-Jeans expression (Lang 1980) and assuming a symmetric source of linear size $L \leq 1.5 \times 10^8$ cm, a distance $D = 4.85$ pc $= 1.55 \times 10^{19}$ cm, and a frequency of 1415 MHz $= 1.415 \times 10^9$ Hz.

III. DISCUSSION

What accounts for the millisecond spikes emitted by AD Leonis at 1415 MHz? The high circular polarization of up to 100% indicates an intimate connection with strong stellar magnetic fields, whereas the high brightness temperatures of $T_B \geq 10^{16}$ K suggest a coherent emission mechanism. Similar short-lived (≤ 20 ms), highly circularly polarized (100%), bright ($T_B \geq 10^{12}$ K) spikes have been observed at decimetric wavelengths during solar bursts (Droge 1977; Slottje 1978, 1980). These spikes have been explained in terms of electron-cyclotron (or gyrosynchrotron) masers at the gyrofrequency and perhaps its low harmonics. (Maser is the acronym for microwave amplification by stimulated emission of radiation.) We know that solar bursts at 1415 MHz occur near the apex of coronal loops (Willson 1983; Lang and Willson 1983, 1984; Kundu and Lang 1985), and we may therefore argue by analogy that the spikes from AD Leonis are due to the maser

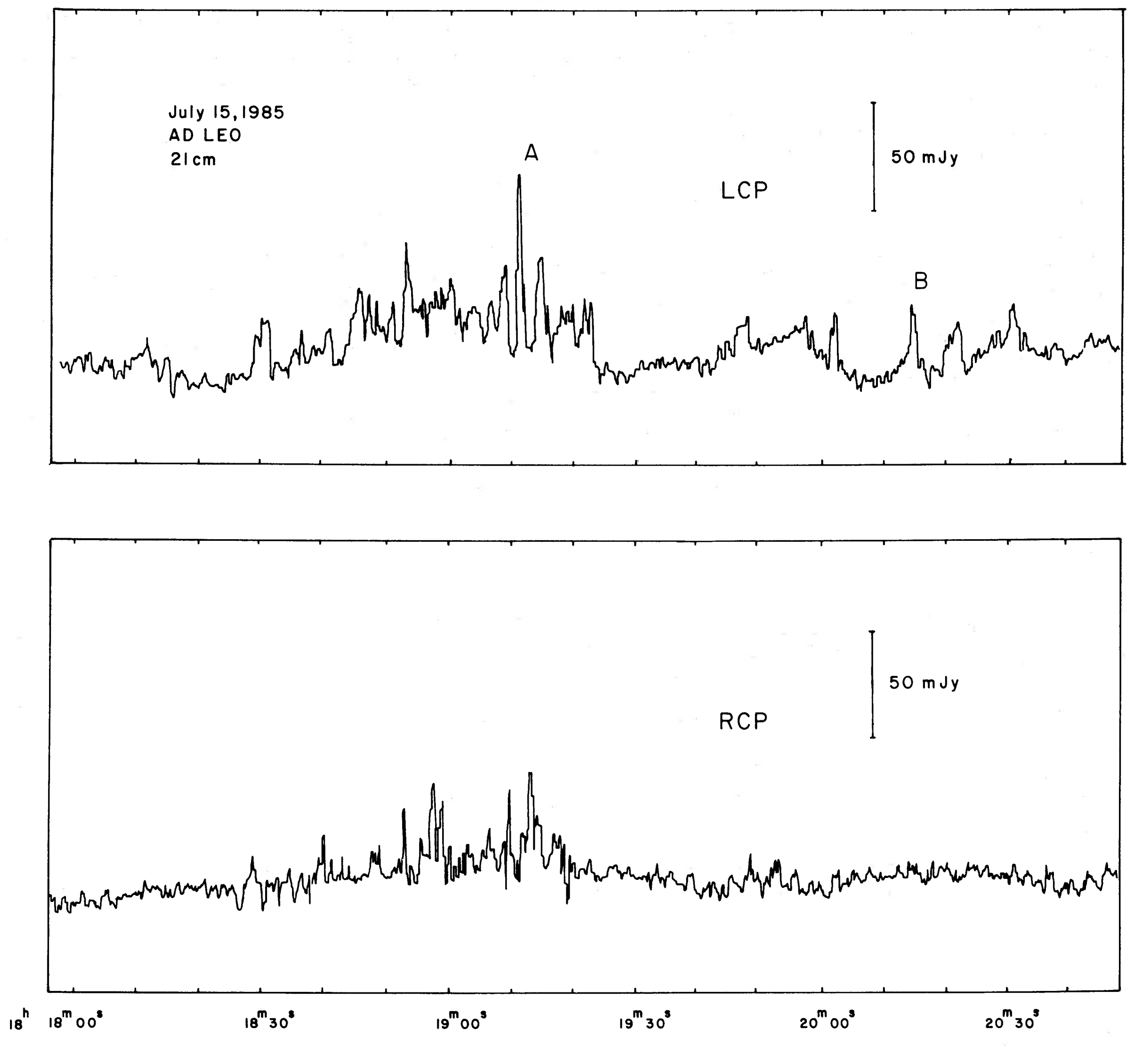

FIG. 1.—Total power detected at a frequency of 1415 MHz (21.2 cm) while tracking the dwarf M star AD Leonis. Both the left-hand circularly polarized (LCP, *top*) and the right-hand circularly polarized (RCP, *bottom*) signals are shown. Here the data have been smoothed by running means to give an effective integration time of 312 ms. The LCP plot exhibits two circularly polarized bursts lasting ~ 50 s and 25 s. A quasi-periodic sequence of five pulses is superposed upon the longer burst near the strongest pulse A. These pulses had a mean periodicity of $\tau_P = 3.2 \pm 0.3$ s and a total duration of $\tau_D = 25$ s. The features marked A and B are shown with a 5 ms integration time in Figs. 2–4.

action of electrons trapped in stellar loops. If this is the case, we would not expect a strong correlation between radio bursts and optical flares of dwarf M stars. In fact, there is no strong correlation between bursts observed in these two spectral regions (Spangler and Moffet 1976).

The theory of electron-cyclotron maser emission from coronal loops was first investigated by Twiss (1958) and Twiss and Roberts (1958), and Wu and Lee (1979) delineated the conditions at which the coherent emission will escape from magnetic loops. The theory has been subsequently developed in greater detail and applied to coronal loops by Holman, Eichler, and Kundu (1980), Melrose and Dulk (1982), Sharma, Vlahos, and Papadopoulos (1982), Holman (1983), Melrose, Hewitt, and Dulk (1984), Sharma and Vlahos (1984), and Dulk (1985). The coherent radiation of solar bursts emitted from coronal loops can be generated at the first or second harmonic of the gyrofrequency $\nu_H = 2.8 \times 10^6 H_l$ Hz, where H_l is the longitudinal magnetic field strength.

A relatively strong magnetic field and low-density plasma are required for the electron-cyclotron maser to work. That is, the gyrofrequency ν_H must be greater than or equal to the plasma frequency $\nu_P = 8.9 \times 10^3 N_e^{1/2}$ Hz, where N_e is the electron density in cm^{-3}. For $\nu_H > 3\nu_P$, radiation at the first harmonic of the gyrofrequency grows the fastest and extracts most of the free energy. However, the radiation must pass through overlying atmospheric layers where the radiation frequency is equal to 2 or 3 times the gyrofrequency. The radiation will therefore suffer severe gyroresonance absorption and will most likely never reach the observer.

The problem of gyroresonant absorption may be overcome if the escaping radiation is generated by a maser at the second harmonic where the radiation frequency $\nu = 2\nu_H$ (Melrose and Dulk 1982; Vlahos, Sharma, and Papadopolous 1983; Melrose, Hewitt and Dulk 1984). The much faster growth of the first harmonic must then be suppressed and this is possible for $\nu_H \approx \nu_P$. It is unlikely that significant amplification will

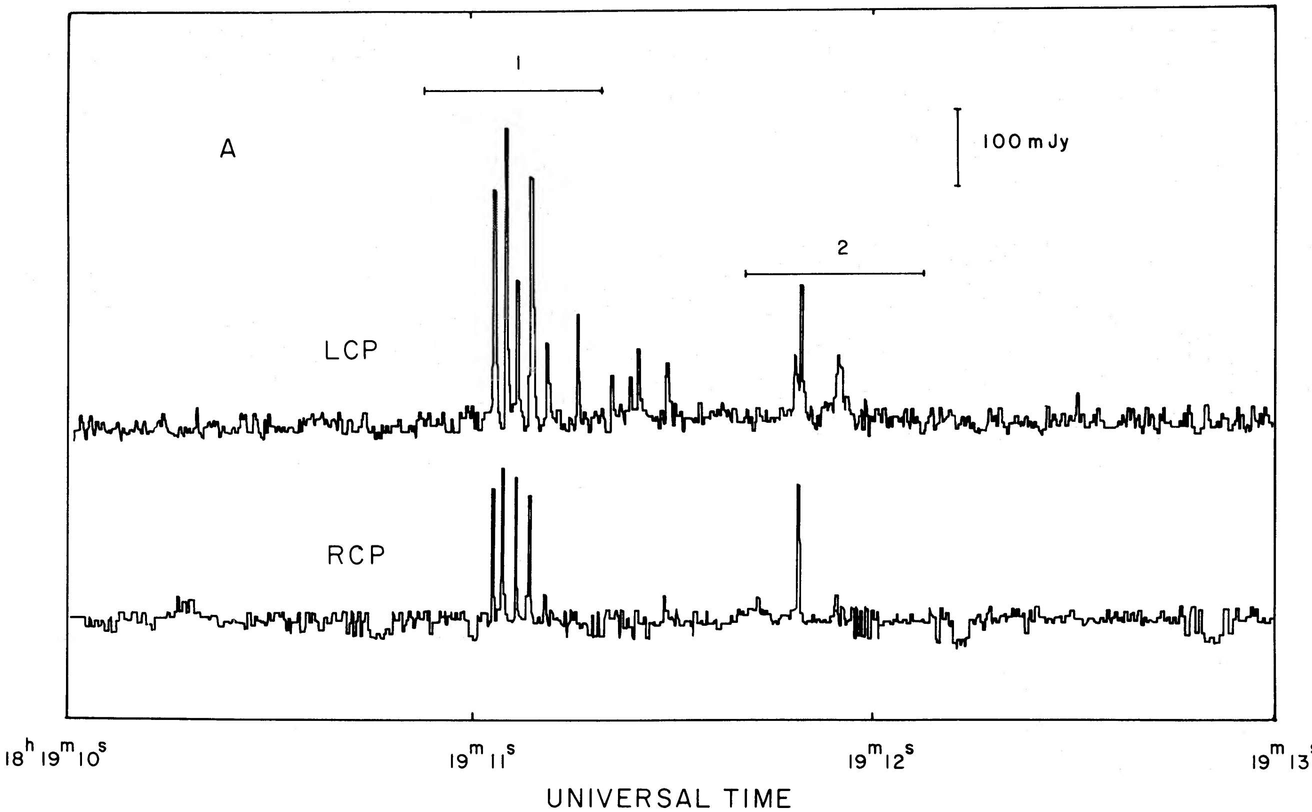

FIG. 2.—The strongest pulse marked A in Fig. 1 is displayed with a 5 ms integration time. Here the background level of the longer burst has been subtracted from the data, and the flux density scale is with respect to this background. Pulse A is composed of a train of five quasi-periodic spikes with a mean periodicity of $\tau_P = 32 \pm 5$ ms and a total duration of $\tau_D = 150$ ms. The emission contained within the horizontal bar marked 1 is shown on an expanded scale in Fig. 3.

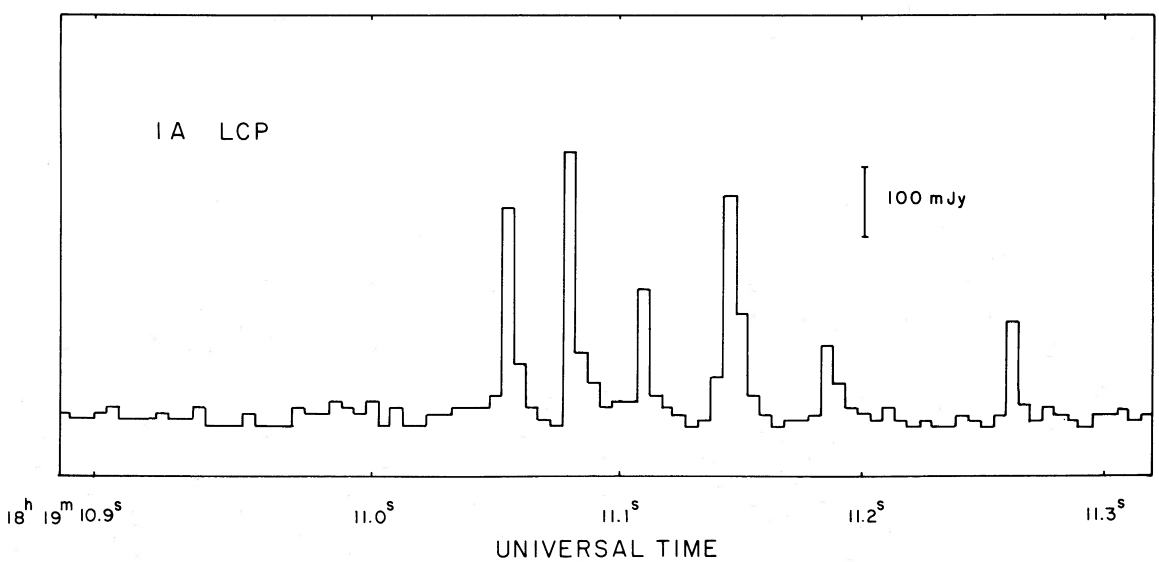

FIG. 3.—Quasi-periodic spikes from pulse A are exhibited on an expanded scale with 5 ms integration time. Each of these spikes had a rise time of $\tau_R \leq 5$ ms, leading to an upper limit to the linear size $L \leq 1.5 \times 10^8$ cm for the spike emitter.

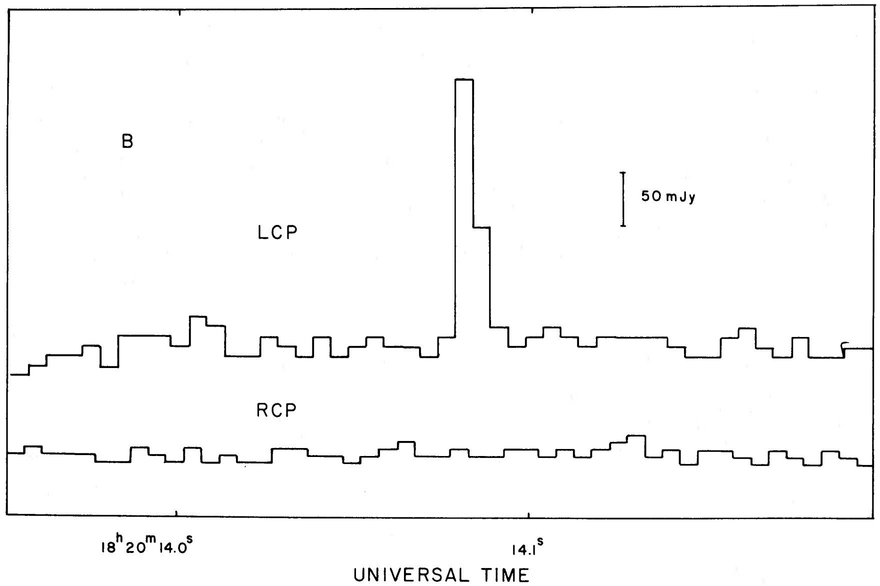

FIG. 4.—The burst feature marked B in Fig. 1 with 5 ms integration time. It is a single spike that is 100% left-hand circularly polarized. The spike has a rapid rise time of $\tau_R \leq 5$ ms, providing an upper limit to the linear size $L \leq 1.5 \times 10^8$ cm for the spike emitter.

occur at harmonics greater than two because faster growth at the first and second harmonics would extract all the free energy (Dulk 1985).

These conditions provide constraints on the electron density, N_e, and the longitudinal magnetic field strength, H_l. For $\nu = 1.4 \times 10^9$ Hz $= 2\nu_H$, we obtain $H_l = 250$ G, and for $\nu_P \approx \nu_H = 7.0 \times 10^8$ Hz, an electron density of $N_e \approx 6 \times 10^9$ cm^{-3} is inferred.

Although electron-cyclotron maser emission at the second harmonic of the gryofrequency may explain the observed spikes from AD Leonis, it is not necessarily the only explanation. For example, under conditions that apply to the low solar corona, second harmonic maser emission may never reach appreciable levels (Sharma and Vlahos 1984).

The high brightness temperature, high circular polarization, and rapid variations of the millisecond spikes might be explained by coherent plasma radiation. For $\nu_H \ll \nu_P$, plasma radiation is favored over electron-cyclotron emission.

Radiation at the first harmonic of the plasma frequency can be seriously attenuated by collisional damping (electron-ion collisions) in the overlying layers of an extensive stellar corona. For the Sun, the first harmonic is strongly absorbed for frequencies higher than 100–500 MHz, whereas the second harmonic is observed up to 2–5 GHz. If solar conditions prevail on AD Leonis, we might be seeing spikes at the second harmonic of the plasma frequency. Nevertheless, we might imagine a stellar corona with less extent and absorption, thereby permitting radiation at the first harmonic of the plasma frequency to escape.

For a radiation frequency $\nu = 1.4 \times 10^9$ Hz equal to ν_P or $2\,\nu_p$ we infer an electron density $N_e = 2 \times 10^{10}$ cm^{-3} and $N_e = 6 \times 10^9$ cm^{-3}, respectively. The condition that $\nu_H \ll \nu_P$ then leads to the constraint $H_l \ll 500$ G for the first harmonic and $H_l \ll 250$ G for the second harmonic.

But what accounts for the quasi-periodic spikes and pulsations? Some process must modulate the coherent burst emitter in a quasi-periodic manner. Here we can draw upon the rich literature on modulations and oscillations of solar bursts.

Quasi-periodic solar pulsations with a mean periodicity of $\tau_P \approx 1$ s have been observed at decametric (Achon 1974), meter (Tapping 1978), and decimetric (Gotwols 1972) wavelengths during type IV bursts. Quasi-periodic fluctuations with periodicities of 0.1–8 s have even been detected during solar bursts at X-ray wavelengths (Dennis, Frost, and Orwig 1981; Orwig, Frost, and Dennis 1981; Kane *et al.* 1983; and Kiplinger *et al.* 1983), and there is some evidence for hard X-ray variations with rise times of $\tau_R \leq 20$ ms.

Extensive observations of quasi-periodic solar oscillations have been carried out at meter wavelengths for nearly two decades. Trains of pulses with a range of periodicities of $\tau_P =$ 50 ms to 5 s and durations of $\tau_D = 1$–50 s have been observed. Tapping (1978) showed that the duration times, τ_D, decrease systematically with decreasing pulsation period τ_P. Moreover, Pick and Trottet (1978) showed that enhanced pulses recurring with $\tau_P = 1.7$ s contain trains of spikes of mean periodicity $\tau_P = 0.37$ s. The pulses and spikes that we have observed from AD Leonis exhibit analogous behavior, with τ_D decreasing with decreasing τ_P, and rapid spikes occurring within a pulse of slower periodicity. Moreover, Gary, Linsky, and Dulk (1982) observed quasi-periodic oscillations with $\tau_P = 56 \pm 5$ s during a circularly polarized 6 cm burst from L726−8A, the dwarf M companion of UV Ceti.

One currently popular explanation for the quasi-periodic solar bursts is magnetoacoustic oscillations in a coronal loop. According to this theory, small amplitude radial oscillations are excited in a magnetic flux tube with periods on the order of the tube radius, a, divided by the Alfvén velocity, V_A (Rosenberg 1970, 1972). Meerson, Sasorov, and Stepanov (1978) noticed that the fast magnetohydrodynamic waves in Rosenberg's theory are radiatively damped to such an extent that they cannot account for the long-lasting solar oscillations. They proposed that energetic protons trapped within closed magnetic structures provide the energy to feed the waves and continually excite them. Roberts, Edwin, and Benz (1983, 1984) have alternatively argued that density enhancements in coronal loops support and trap the fast waves that are naturally excited by an impulsive source such as a stellar burst.

Regardless of the exact mechanism of excitation, the maximum periodicity of these coronal oscillations is given by $\tau_P = 2.6a/v_A$. For sizes $a \approx 10^8$ cm and Alfvén velocities $v_A \approx 3 \times 10^8$ cm s^{-1}, maximum periodicities of ~ 1 s are obtained.

For impulsively generated oscillations, the onset time and duration of the quasi-periodic phase can be related to the size, a, and the height, h, of the emitter (Roberts, Edwin, and Benz 1983, 1984). Moreover, the duration time, τ_D, is related to the pulsation period, τ_P. At fixed h and v_A, the duration time τ_D will decrease with decreasing τ_P.

Our observations of quasi-periodic spikes and pulsations indicate that τ_D decreases with decreasing τ_P, as predicted by the theory of coronal oscillations. In addition, plausible physical parameters can be obtained from the observed periodicities. For a magnetic field strength of 250 G, as inferred from coherent emission at the second harmonic of the gyrofrequency, we obtain an Alfvén velocity of $v_A = (H^2/4\pi\rho)^{1/2} = 2 \times 10^9$ cm s^{-1} for a plausible density of $N = 10^9$ cm^{-3} (ρ is the mass density). Pulsation periodicities of $\tau_P = 3.2$ s and 32 ms then require sizes $a_1 = 2 \times 10^9$ cm and $a_2 = 2 \times 10^7$ cm, respectively.

Coronal loops on the Sun have sizes on the order of 2×10^9 cm, and the smaller size of 2×10^7 cm for the faster spikes is well below that inferred from the light travel time argument. We might view the smaller size as an inhomegeneity in a larger stellar loop. Duration times of 0.15 and 25 s are consistent with a constant height of $h = 2 \times 10^9$ cm and a time of ~ 1 s between the generation of the disturbance and the onset of the quasi-periodic phase.

Gary, Linsky, and Dulk (1982) reasoned that the 56 s oscillations observed in the 6 cm burst from L727−8A might be caused by a periodic modulation of the source by an external agent or by a periodic modulation of the energy release mechanism. We agree with their conclusion that flux tube oscillations might modulate coherent maser action. However, this is not the only plausible mechanism for producing apparent periodicities. Energetic particles might be trapped within closed magnetic structures, bouncing between magnetic mirrors at times $\tau \approx L/c$, where L is the size of the magnetic trap and c is the velocity of light. Perhaps mirroring energetic particles interfere with and modulate the coherent maser action.

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Kenneth R. Lang and Robert F. Willson: Department of Physics and Astronomy, Robinson Hall, Tufts University, Medford, MA 02155