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TABLE OF CONTENTS

Page

I. INTRODUCTION 3

II. PUBLISHED PAPERS

A. FLARE STARS AND SOLAR BURSTS; HIGH RESOLUTION IN TIME AND FREQUENCY 5

by Kenneth R. Lang
Solar Physics 104, 227-233 (1986).

B. MILLISECOND RADIO SPIKES FROM THE DWARF M FLARE STAR AD LEONIS 12

by Kenneth R. Lang and Robert F. Willson
Astrophysical Journal 305, 363-368 (1986).

C. NARROW-BAND SLOWLY VARYING DECIMETRIC RADIATION FROM THE DWARF M FLARE STAR YZ CANIS MINORIS 18

by Kenneth R. Lang and Robert F. Willson
Astrophysical Journal Letters 302, L17-L21 (1986).

D. RADIO WAVELENGTH OBSERVATIONS OF MAGNETIC FIELDS ON ACTIVE DWARF M, RS CVN AND MAGNETIC STARS...................... 23

by Kenneth R. Lang
Advances in Space Research, Proceedings of the XXVI Committee on Space Research (COSPAR), Pergamon Press, 1986.

E. MULTIPLE WAVELENGTH MICROWAVE OBSERVATIONS OF THE RS CVN STARS UX ARIETIS, HR 1099, HR 5110 AND II PEGASI...................... 27

by Robert F. Willson and Kenneth R. Lang
Astrophysical Journal 312, 278-283 (1987).

F. SIMULTANEOUS IUE AND VLA OBSERVATIONS OF YZ CANIS MINORIS, AD LEONIS AND LAMDA ANDROMEDAE 33

by Robert F. Willson and Kenneth R. Lang
In New Insights in Astrophysics: Eight Years of UV Astronomy with IUE, European Space Agency, 1986.

III. PAPERS TO BE PUBLISHED 37

G. ULTRAVIOLET AND RADIO FLARES FROM UX ARIETIS AND HR 1099 37

by Kenneth R. Lang and Robert F. Willson Submitted to Astrophysical Journal

IV. FUNDING 50

I. INTRODUCTION

This is the final technical report for the IUE Guest Observer Program entitled "Coordinated Ultraviolet and Radio Observations of Selected Nearby Stars" for the period 1 October 1984 to 30 September 1987. During that period, this program has been successively assigned the program ID FSGKL, FSHKL and FSIKL. It has been funded by a total amount of $37,329 under NASA Grant NAG 5-477 from 1 October 1984 to 30 September 1987.

All of the US2 shifts assigned to this program have been successfully completed with simultaneous International Ultraviolet Explorer (IUE) and Very Large Array (VLA) observations of the proposed target stars. There were no US1 IUE shifts assigned to this program. The target stars included dwarf M flare stars and RS CVn stars. Both classes of stars exhibit slowly varying microwave radiation as well as powerful flares of shorter duration. The combined ultraviolet (IUE) and microwave (VLA) observations have provided important new insights to the radiation mechanisms at these two widely-separated regions of the electromagnetic spectrum. They have also provided information about the physical conditions at different levels in the stellar atmospheres.

The research supported under this grant has been reported in six (6) published papers and one (1) paper submitted for publication. This final technical report contains reprints of these seven (7) papers.

The initial scientific returns of the proposed research dealt largely with the VLA microwave observations, for the IUE did not initially detect any stellar bursts. These VLA results included the discovery of narrow-band microwave radiation and rapid time variations in the microwave radiation of dwarf M flare stars (see the following papers A, B and C). They indicate that conventional radiation mechanisms cannot explain the microwave emission from these stars. It must instead be attributed to coherent radiation mechanisms such as an electron-cyclotron maser or coherent plasma radiation. These mechanisms provide important constraints on both the magnetic field strength and the electron density in the coronae of dwarf M flare stars.

Variable microwave emission from RS CVn stars can provide important constraints on the size of the emitter (see the following papers D and E). A variation of only 30 seconds or shorter rules our emission from both components of these binary stars, and probably limits them to sizes, L, of L $\lesssim 10^{10}$ to 10^{11}cm. We derive a magnetic field strength, H, of H $\lesssim$ 15 G for the varying RS Cvn stars, and attribute the microwave variations to absorption by a thermal plasma located between the binary stars. Curiously, the magnetic Ap stars have intense magnetic fields with no detectable microwave radiation, suggesting that they do not have hot, dense coronae and strong stellar winds (see the following paper D).

Ironically, we detected both slowly-varying ultraviolet radiation and ultraviolet bursts during the final episode of funding for this grant. These results are summarized in the last two papers of this report (see the following papers F and G). In general, ultraviolet variations and bursts occur when no similar variations are detected at microwave wavelengths and vice versa. Although there is some overlap, the variations in these two spectral regions are usually uncorrelated, suggesting that there is little interaction between the activity centers at the two associated atmospheric levels.

In our final section IV, we note that we have spent all of the $37,329 allocated for this research between 1 October 1984 and 30 September 1987, and that we have completed all of the proposed research.

II. PUBLISHED PAPERS

A. FLARE STARS AND SOLAR BURSTS: HIGH RESOLUTION IN TIME AND FREQUENCY*

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Abstract. Coronal loops on the Sun and nearby stars are investigated using observations at 20 cm wavelength with high resolution in time and frequency. Observations of the dwarf M star AD Leonis with high time resolution using the Arecibo Observatory have resulted in the discovery of a quasi-periodic train of circularly polarized spikes with a mean periodicity of 32 ± 5 ms and a total duration of 150 ms. The individual spikes had rise times of ≤ 5 ms, leading to an upper limit to the linear size $L \leq 1.5 \times 10^8$ cm for the spike emitter. This size is only 0.005 of the estimated radius of AD Leonis. Provided that the emitter is symmetric, it has a brightness temperature of $T_B \geq 10^{16}$ K, suggesting a coherent burst mechanism such as an electron–cyclotron maser. Coronal oscillations might modulate the maser output, producing the quasi-periodic spikes. Observations at closely spaced wavelengths, or high frequency resolution, using the Very Large Array have revealed narrow-band structure ($\Delta\nu/\nu \leq 0.01$) in solar bursts and in the slowly-varying radiation of the dwarf M star YZ Canis Minoris. The narrow-band emission cannot be explained by continuum emission processes, but it might be attributed to electron–cyclotron maser radiation. Maser action at the second or first harmonic of the gyrofrequency implies magnetic field strengths of 250 and 500 G, respectively. Thus, observations with high resolution in time and frequency suggest coherent processes in the coronae of the Sun and dwarf M stars. The scientific potential of these discoveries may be best fulfilled by the construction of a solar-stellar synthesis radiotelescope.

1. Introduction

Very Large Array (VLA) observations at widely spaced wavelengths refer to different levels within the ubiquitous coronal loops that are the dominant structural element of solar active regions. The slowly-varying 6 cm emission often originates in the legs of coronal loops, while the slowly-varying 20 cm emission comes from the hot dense plasma trapped within the legs and apex of coronal loops (Lang *et al.*, 1982; Lang and Willson, 1983, 1984; Lang *et al.*, 1983; McConnell and Kundu, 1983; Kundu and Lang, 1985). VLA snapshot maps indicate that the impulsive component of microwave bursts is usually located near the apex of coronal loops (Marsh and Hurford, 1981; Lang and Willson, 1983, 1984; Willson and Lang, 1984; Kundu and Lang, 1985). These bursts may be triggered by temperature enhancements within coronal loops or by changes in the configuration of coronal magnetic fields.

The solar analogy suggests that coronal loops may also play a dominant role in the microwave emission from dwarf M flare stars. These stars exhibit slowly-varying microwave radiation that may be similar to the quiescent, or nonflaring, slowly-varying radiation of solar active regions. These stars also exhibit microwave bursts that are similar to those emitted by the Sun (Linsky and Gary, 1983; Pallavicini *et al.*, 1985).

Recent investigations have revealed two new approaches to the study of coronal loops on the Sun and nearby stars. They involve observations at 20 cm wavelength with high

* Proceedings of the Workshop on Radio Continua during Solar flares, held at Duino (Trieste), Italy, 27–31 May, 1985.

Solar Physics **104** (1986) 227–233.

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resolution in time and frequency. Observations with high time resolution using the Arecibo Observatory have led to the discovery of quasi-periodic spiked emission from the dwarf M star AD Leonis (Section 2). Observations at closely spaced wavelengths, or high frequency resolution, reveal narrow-band structure during solar bursts and in the slowly-varying radiation of the dwarf M star YZ Canis Minoris (Section 3). This paper highlights these recent results that seem to require coherent radiation mechanisms. It also draws attention to their possible implications for a solar-stellar synthesis radiotelescope.

2. Quasi-Periodic Spikes from AD Leonis

If the solar analogy is applicable, slowly-varying emission and stellar bursts from nearby stars ought to be emitted from coronal loops that are a fraction of a stellar radius in linear extent. Thermal bremsstrahlung from coronal loops on nearby stars would, however, be too weak to be detected, and thermal gyroresonant radiation would require impossibly large coronal loops for this radiation to be detected at 20 cm wavelength.

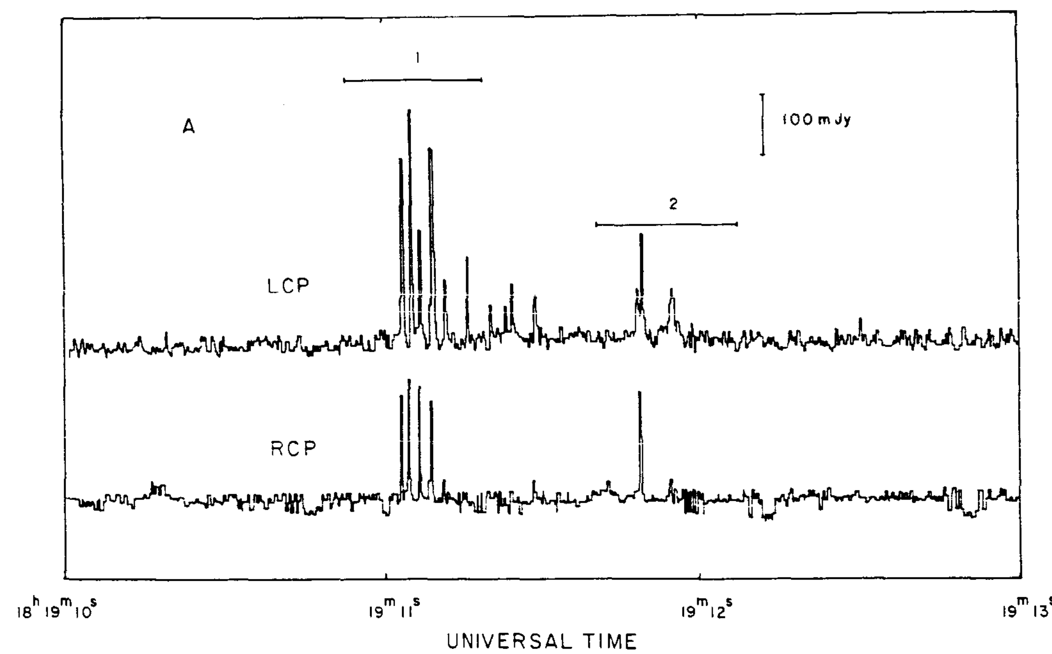

Fig. 1. The total power detected at a frequency of 1415 MHz (21.2 cm) while tracking the dwarf M star AD Leonis. Both the left-hand circularly polarized (LCP-top) and the right-hand circularly polarized (RCP-bottom) signals are shown. Here the integration time is 5 ms. The data exhibit a train of five quasi-periodic spikes with a mean periodicity of $\tau_P = 32 \pm 5$ ms, a total duration of $\tau_D = 150$ ms (horizontal bar 1), and circular polarizations of about 33%. The data also include individual spikes that are 100% left-hand circularly polarized. Each of the 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 and a brightness temperature of $T_B \geq 10^{16}$ K if the spike emitter is symmetric.

Non-thermal and/or coherent emission processes are required if the slowly-varying or burst emission originates from stellar loops or star spots that are similar in size to their counterparts on the Sun.

As illustrated in Figure 1, observations of AD Leonis at 1415 MHz (21.2 cm) indicate a train of quasi-periodic spikes that suggest a coherent burst emitter that is modulated by coronal oscillations. The quasi-periodic spikes have a mean periodicity of 32 ± 5 ms and a total duration of 150 ms. They have a maximum flux density of 300 mJy and circular polarizations of about 33%. Each of the spikes have rise times of ≤ 5 ms, the integration time employed.

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 is only 0.005 of the estimated radius of AD Leonis ($R = 3.0 \times 10^{10}$ cm). Provided that the spike emitter is symmetric, it has an area that is less than 2.5×10^{-5} of the surface area of the star's visible disk. The maximum flux density and linear size can be combined with the star's distance (4.85 pc) to infer a brightness temperature of $T_B \geq 10^{16}$ K from the Rayleigh–Jeans expression.

The high circular polarization of the spikes indicates an intimate connection with strong stellar magnetic fields, whereas the high brightness temperatures suggest a coherent emission mechanism. Similar highly circularly polarized spikes with high brightness temperatures ($T_B \geq 10^{12}$ K) have been observed during solar bursts (Dröge, 1977; Slottje, 1978). The spikes emitted from both the Sun and AD Leonis may be explained by electron–cyclotron maser emission (Melrose and Dulk, 1982). Magnetic field strengths of $H = 250$ and 500 G are inferred if the radiation is at the second or first harmonic of the gyrofrequency, respectively.

But what accounts for the quasi-periodic spikes? Some process must modulate the coherent burst emitter in a quasi-periodic manner. One possibility is coronal oscillations that provide a currently-popular explanation for longer (50 ms to 5 s) quasi-periodic pulsations during some solar bursts (Roberts *et al.*, 1984). An inhomogeneity of size $a = 2 \times 10^7$ cm might account for the quasi-periodic spikes with an Alfvén velocity corresponding to $H = 250$ G and plausible values of density.

3. Narrow-Band Structure in Solar Bursts and in the Slowly-Varying Radiation from YZ Canis Minoris

Recent VLA observations at closely spaced wavelengths near 20 cm have provided evidence for coherent emission processes during solar bursts (Lang and Willson, 1984). One highly circularly polarized (100%) burst exhibited a factor of two difference in brightness temperature (1.5×10^8 K and 0.8×10^8 K) at two wavelengths separated by only 32 MHz (burst 7 of Figure 2 at 1658 and 1690 MHz). The high circular polarization and narrow bandwidth ($\Delta\nu/\nu \leq 0.01$) of this burst are comparable to those expected from electron–cyclotron masers. Although the burst source was apparently resolved, the 10 s integration time of the VLA may have integrated several briefer, spatially-separated coherent spikes.

Narrow-band, slowly-varying microwave radiation has been detected from the dwarf

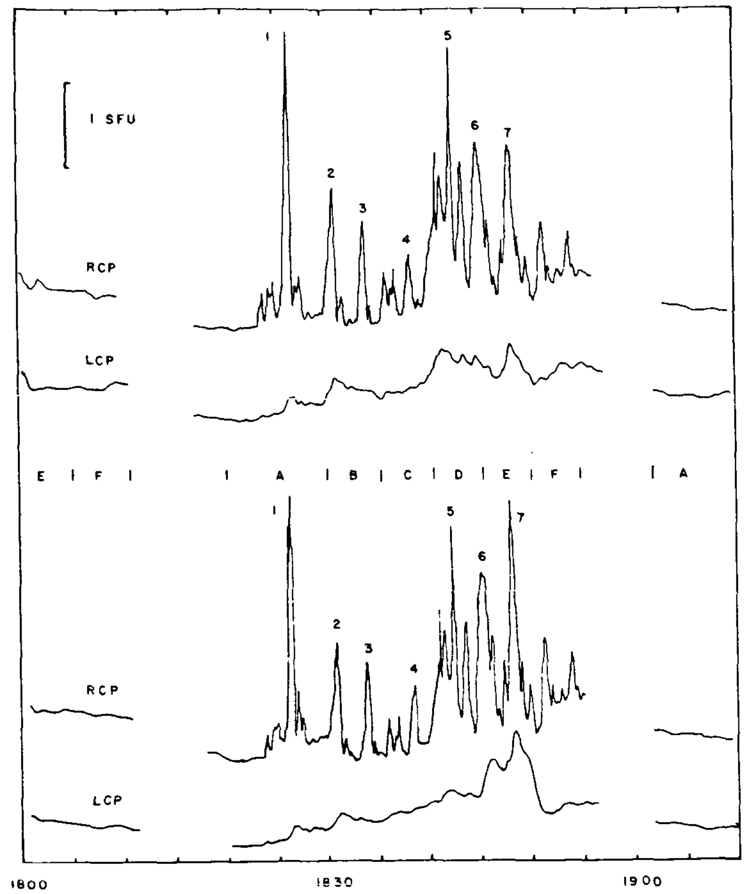

Fig. 2. A sequence of right circularly polarized (RCP) impulsive bursts from a solar active region observed at wavelengths near 20 cm (1400 MHz). The top and bottom profiles are separated by only 30 MHz; burst 7 has a factor of two difference in brightness temperature over this narrow frequency interval, suggesting coherent burst emission. This figure originally appeared in Lang and Willson (1984).

M star YZ Canis Minoris at frequencies near 1465 MHz. Slow variations over time-scales of an hour and as much as 20 mJy in strength peak at different times for frequencies $\nu = 1415$ and 1515 MHz (Figures 3 and 4), indicating narrow-band structure of bandwidth $\Delta\nu \leq 100$ MHz, or $\Delta\nu/\nu \leq 0.1$. Cyclotron line structure from gyroresonant radiation can be ruled out because the high flux density and large observing frequency would require coronal loops that are more than one hundred times larger than the star.

We might speculate that the slowly-varying radiation from YZ Canis Minoris is due to continuous low-level, coherent burst activity. High circular polarization would be expected to be occasionally observed if the coherent mechanism is associated with

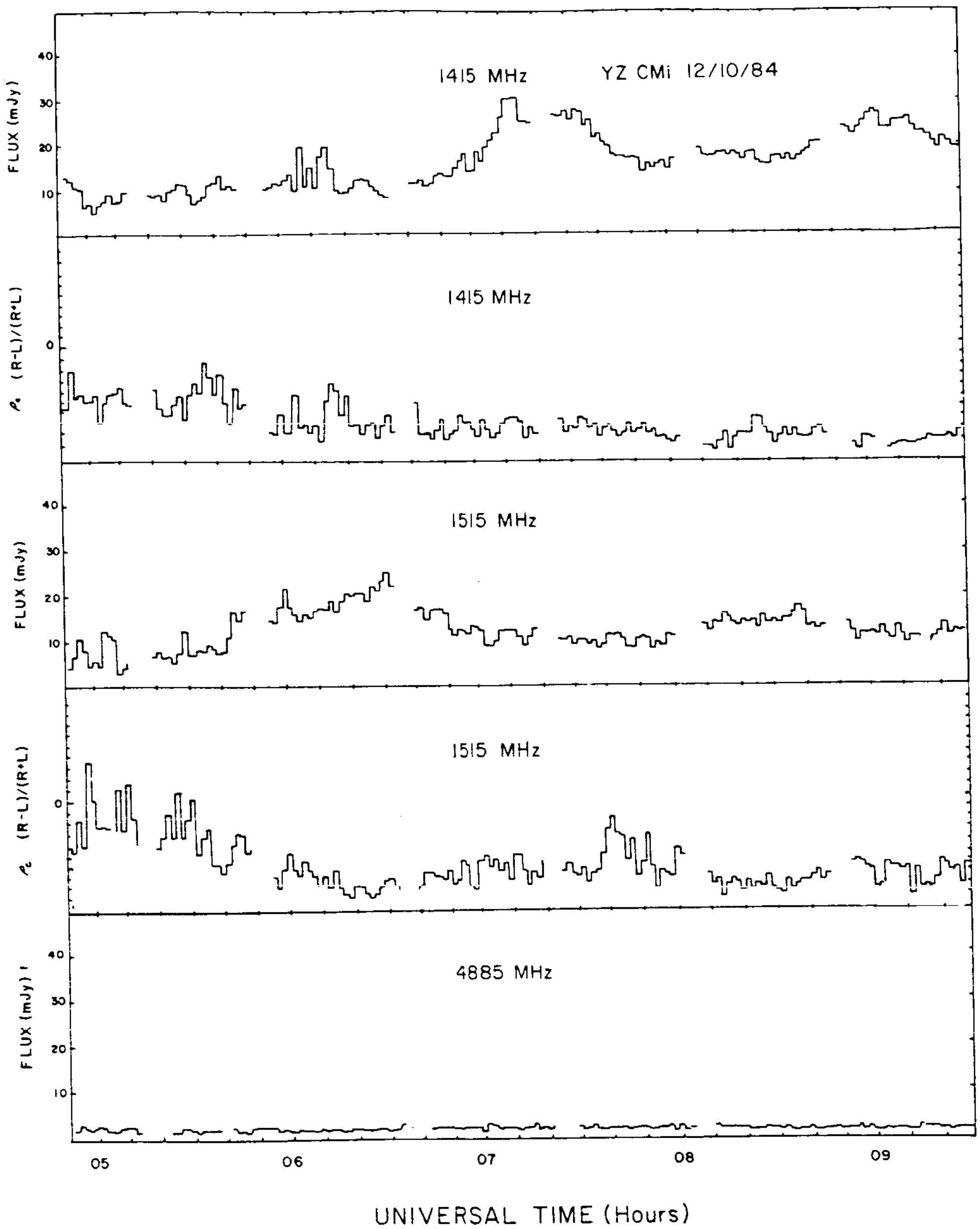

Fig. 3. Slowly-varying emission from the dwarf M flare star YZ Canis Minoris at two closely spaced frequencies of 1415 and 1515 MHz and at 4885 MHz. The emission at the two frequencies peaks at different times, suggesting a coherent emission mechanism with a bandwidth of less than 100 MHz. There are no detectable fluctuations at 4885 MHz.

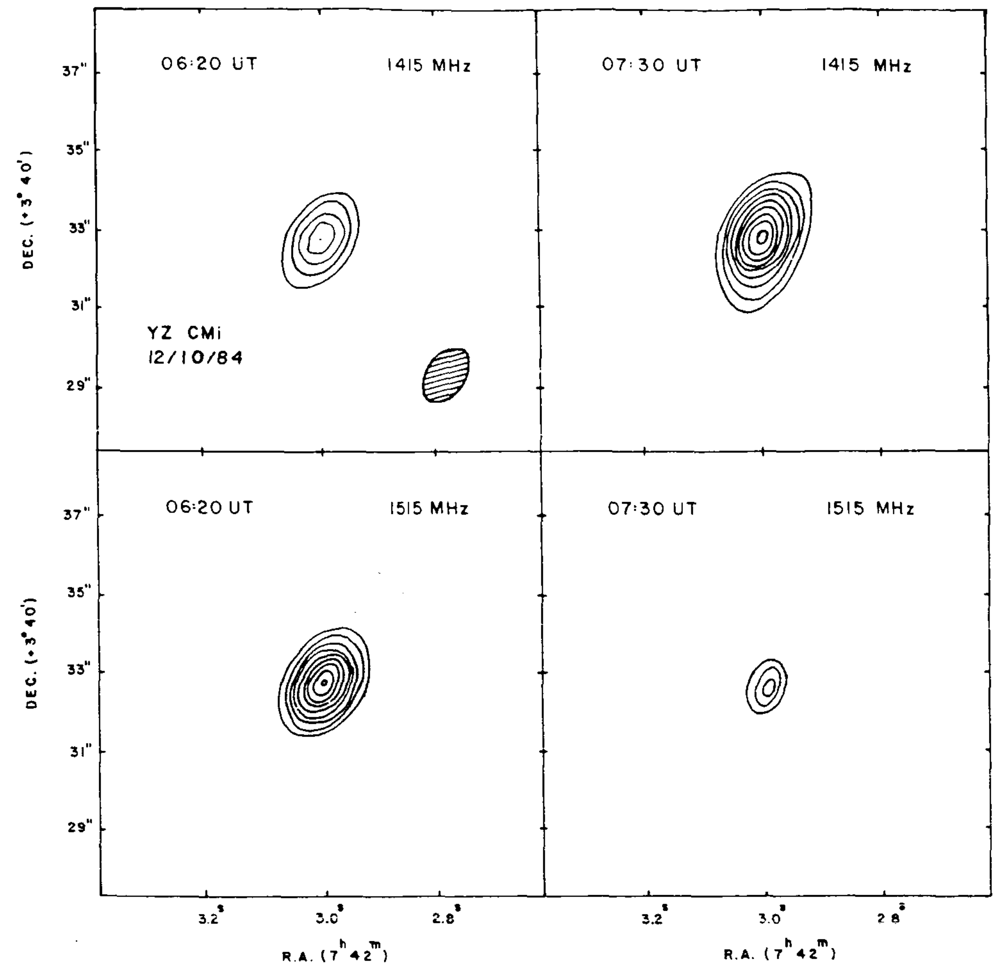

Fig. 4. VLA snapshot maps of the emission from the dwarf M flare star YZ Canis Minoris. The unresolved emission peaks at different times at two frequencies separated by only 100 MHz, suggesting a coherent burst mechanism. The contours are at intervals of 6, 8, 10, 12,... Jy/beam area, with maximum values of 14 and 22 Jy/beam area at 06 : 20 UT and 1415 and 1515 MHz, respectively, and 25 and 10 Jy/beam area at 07 : 30 UT for the same respective frequencies.

intense magnetic fields, and the stochastic nature of continued bursts might explain the variability of the observed microwave radiation.

4. Conclusions

Observations at 20 cm wavelength with high resolution in time and frequency have provided evidence for coherent emission mechanisms on the Sun and nearby stars. However, observations are limited by infrequent use of the Arecibo Observatory and the Very Large Array for solar and stellar observations. The scientific potential suggested by the data presented here can only be fully realized by the development of a solar-stellar synthesis radiotelescope. Such an instrument would be dedicated to solar and stellar observations with high angular, temporal and frequency resolution.

Acknowledgements

Radio astronomical studies of the Sun at Tufts University are supported under Air Force Office of Scientific Research grant AFOSR–83–0019 and contract N0014-86-K-0068 with the Office of Naval Research. Investigations of flare stars at Tufts University are also supported by NASA grant NAG 5–477, and our simultaneous VLA and Solar Maximum Mission observations of the Sun are supported by NASA grant NAG 5–501.

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B. MILLISECOND RADIO SPIKES FROM THE DWARF M FLARE STAR AD LEONIS

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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 Δt = 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

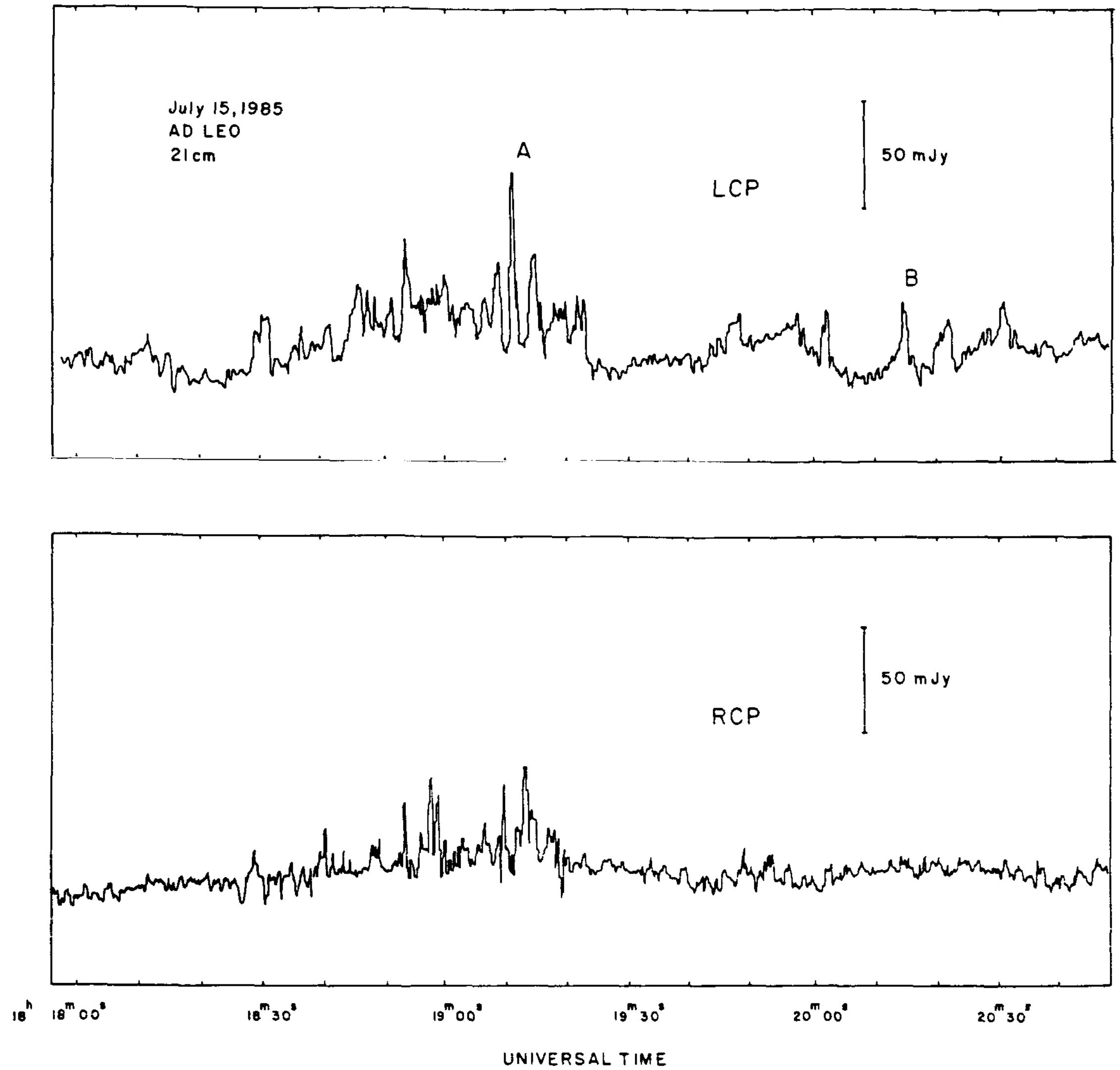

FIG. 1.—Total power detected at a frequency of 1415 MHz (21.2 cm) while tracking the dwarf M star AD Leonis. Both the left-hand circularly polarized (LCP, *top*) and the right-hand circularly polarized (RCP, *bottom*) signals are shown. Here the data have been smoothed by running means to give an effective 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

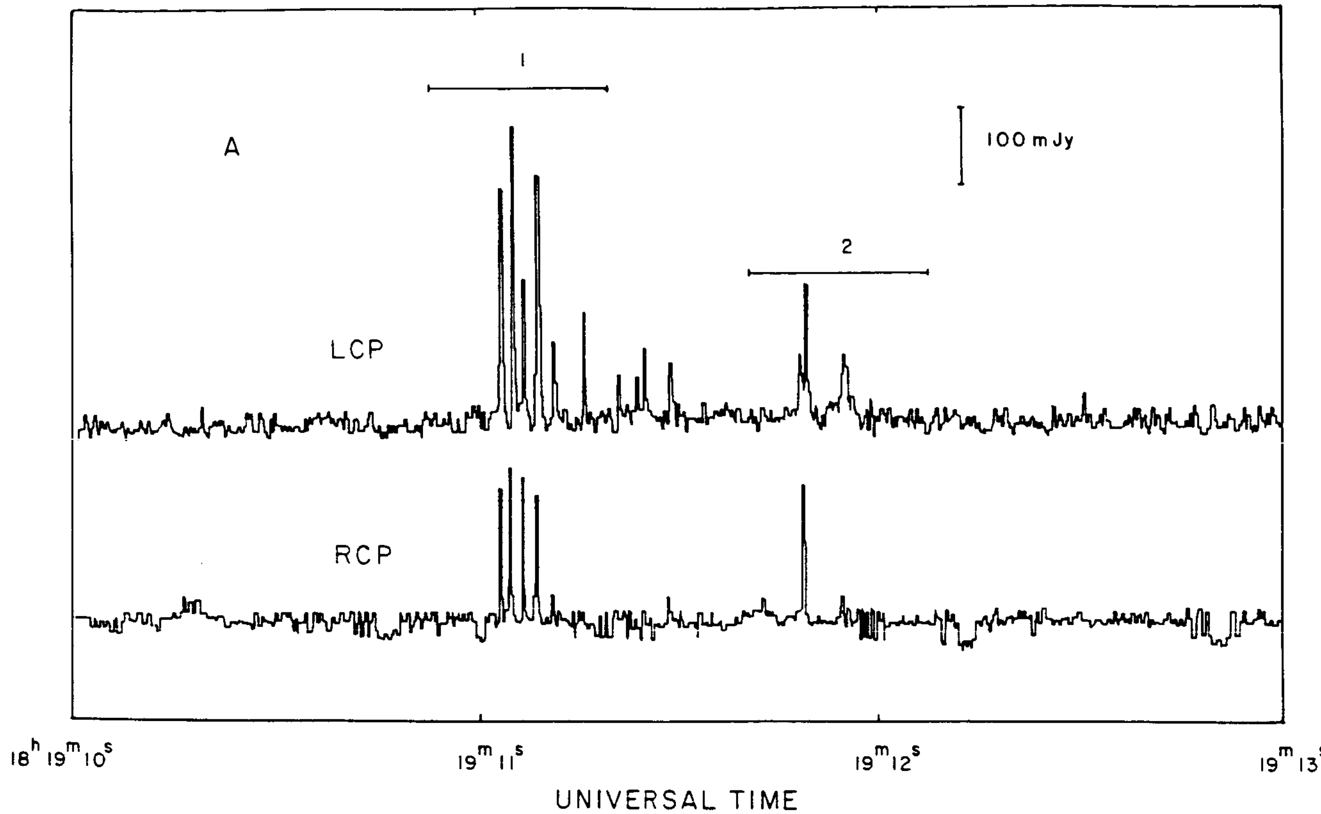

FIG. 2.—The strongest pulse marked A in Fig. 1 is displayed with a 5 ms integration time. Here the background level of the longer burst has been subtracted from the data, and the flux density scale is with respect to this background. Pulse A is composed of a train of five quasi-periodic spikes with a 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.

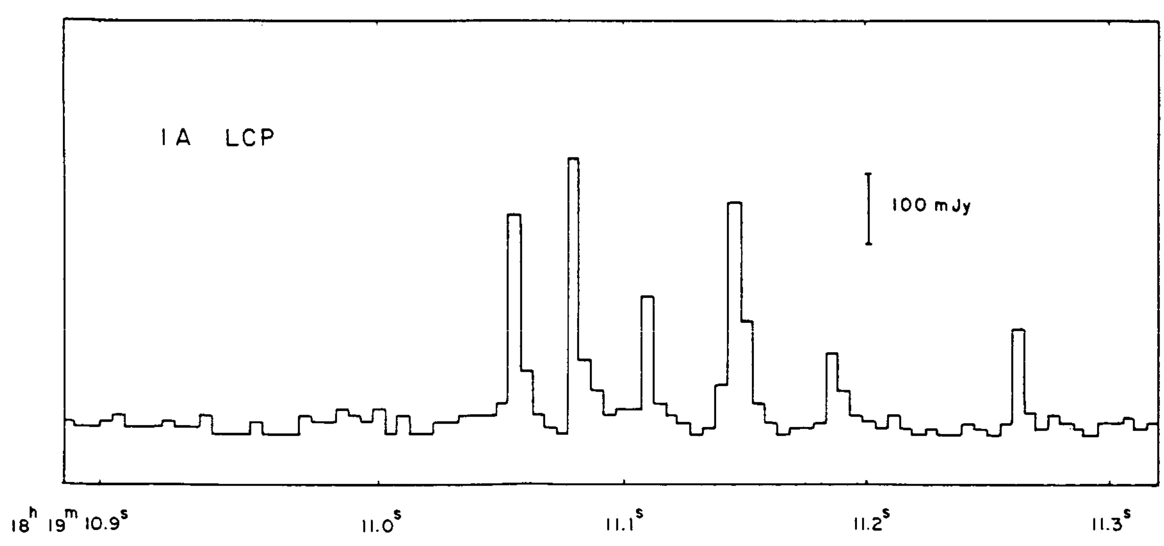

FIG. 3.—Quasi-periodic spikes from pulse A are exhibited on an expanded scale with 5 ms integration time. Each of these spikes had a rise time of $\tau_R \leq 5$ ms, leading to an upper limit to the linear size $L \leq 1.5 \times 10^8$ cm for the spike emitter.

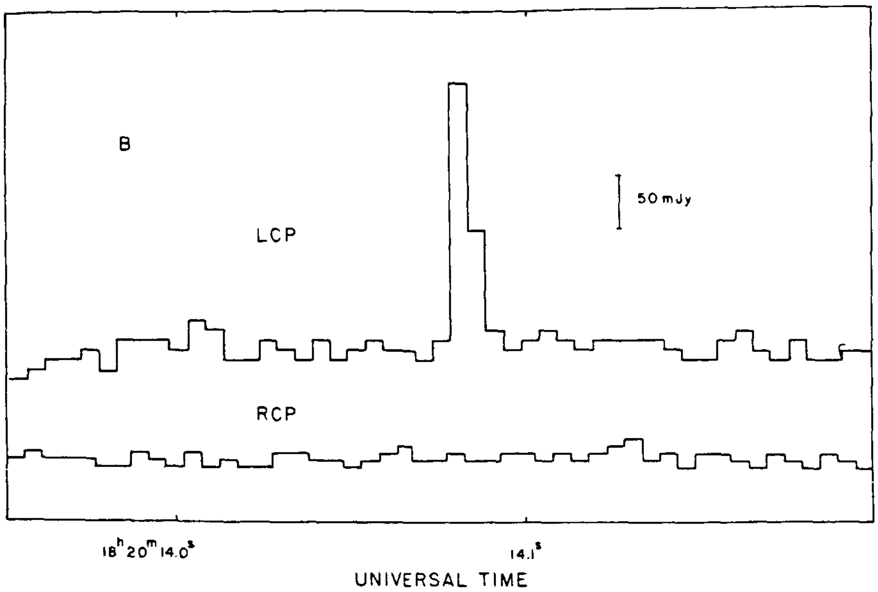

FIG. 4.—The burst feature marked B in Fig. 1 with 5 ms integration time. It is a single spike that is 100% left-hand circularly polarized. The spike has a rapid rise time of $\tau_R \leq 5$ ms, providing an upper limit to the linear size $L \leq 1.5 \times 10^8$ cm for the spike emitter.

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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C. NARROW-BAND, SLOWLY VARYING DECIMETRIC RADIATION FROM THE DWARF M FLARE STAR YZ CANIS MINORIS

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ABSTRACT

Narrow-band, slowly varying microwave radiation has been detected from the dwarf M star YZ Canis Minoris at frequencies near 1465 MHz. This quiescent, or nonflaring, emission cannot be attributed to gyroresonant radiation from coronal loops; the loops would have to be more than 200 times the stellar radius in size with magnetic field strengths of $H \geq 100$ G at this distance. The narrow-band structure ($\Delta\nu/\nu \leq 0.1$) of the slowly varying radiation cannot be explained by continuum emission processes such as thermal bremsstrahlung, thermal gyroresonant radiation, or nonthermal gyrosynchrotron radiation. Our observations may be explained by coherent burst mechanisms like electron-cyclotron masers or coherent plasma radiation. Maser action at the second harmonic of the gyrofrequency implies a longitudinal magnetic field strength of 250 G and an electron density of $N_e \approx 6 \times 10^9$ cm^{-3}. Coherent plasma radiation at the second harmonic of the plasma frequency similarly requires $N_e = 6 \times 10^9$ cm^{-3} but a longitudinal magnetic field strength of $H_l \ll 250$ G. The slow variation of the narrow-band emission might be explained by the stochastic nature of continued low-level, coherent burst activity. There are possible analogies with narrow-band decimetric bursts observed on the Sun.

Subject headings: stars: coronae — stars: flare — stars: radio radiation

I. INTRODUCTION

Nearby main-sequence stars of late spectral type exhibit quiescent, or nonflaring, X-ray emission whose absolute luminosity may be as much as 100 times that of the Sun (Johnson 1981; Vaiana *et al.* 1981). This suggests that these stars may have hot stellar coronae and large-scale coronal loops with strong magnetic fields. Quiescent microwave radiation might be emitted by electrons trapped within stellar loops or by electrons spiraling about magnetic fields above starspots.

Quiescent microwave emission has, in fact, been detected from six dwarf M stars using the Very Large Array (VLA). They are UV Ceti (Gary and Linksy 1981), both components of the binary star system EQ Pegasi (Topka and Marsh 1982), YY Geminorum and Wolf 630 (Linksy and Gary 1983), the suspected spectroscopic binary AU Microscopii (Cox and Gibson 1985), and YZ Canis Minoris (Pallavicini, Willson, and Lang 1985; Kundu and Shevgaonkar 1985). YZ Canis Minoris is curiously unique in being the only single, or nonbinary, dwarf M star that is know to exhibit quiescent microwave radiation.

The quiescent radiation from dwarf M stars is slowly variable over time scales of hours (Linsky and Gary 1983; Pallavicini, Willson, and Lang 1985). An example is shown in Figure 1 where the 6 cm flux density from YZ Canis Minoris rises to 7 mJy over periods of half an hour. Kundu and Shevgaonkar (1985) have pointed out that the microwave radiation from this star is highly variable with a flux density that varied by a factor of 5 in 2 days and reached a peak value of 3 mJy at 20 cm wavelength, but their 2 hr synthesis maps may have underestimated the peak flux density of the slowly varying component that varies on time scales shorter than 2 hr. In addition, Rondonò *et al.* (1984) have reported variable microwave radiation from YZ Canis Minoris at 6 cm wavelength with a peak flux density of 5 mJy and a duration of ≥ 30 minutes. If this was the slowly varying radiation illustrated in Figure 1, its association with an ultraviolet flare that occurred 7 minutes earlier may have been purely coincidental.

Most of the dwarf M stars detected at microwave wavelengths exhibit X-ray radiation with absolute X-ray luminosities of $L_x = 10^{27.5}$ ergs s^{-1} (UV Cet), $10^{28.8}$ ergs s^{-1} (EQ Peg), $10^{29.6}$ ergs s^{-1} (YY Gem), $10^{29.3}$ ergs s^{-1} (Wolf 630), and $10^{28.5}$ ergs s^{-1} (YZ CMi). By way of comparison, the Sun has an average $L_x = 10^{27.0}$ ergs s^{-1} that is attributed to thermal bremsstrahlung of hot electrons trapped in the ubiquitous coronal loops that dominate the structure of the solar corona. This suggests that the slowly varying, quiescent microwave radiation of dwarf M stars may be due to thermal electrons trapped in extensive coronal loops.

The X-ray observations rule out detectable thermal bremsstrahlung at microwave wavelengths; the temperatures and emission measures inferred from the X-ray data indicate that the microwave bremsstrahlung flux density is at least two orders of magnitude below the detection threshold of the VLA. Thermal gyroresonant, or cyclotron, radiation might nevertheless account for the quiescent microwave emission from dwarf M stars. This process explains most, if not all, of the quiescent microwave emission from coronal loops on the Sun (Kundu and Lang 1985). However, gigantic coronal loops with intense magnetic fields (several hundred gauss) and enormous heights of three stellar radii are required to explain the

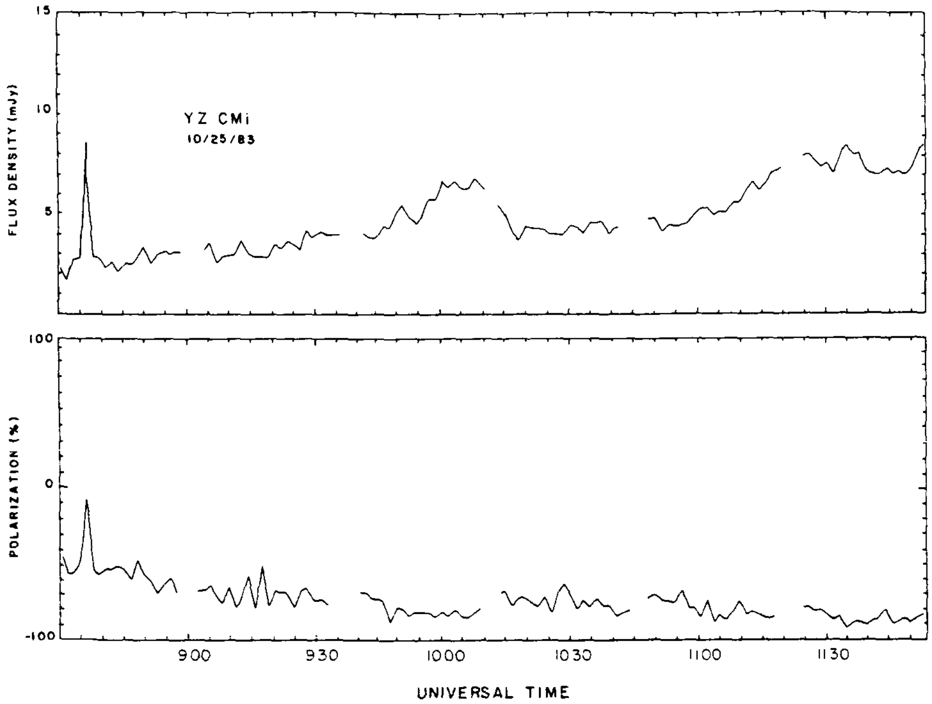

FIG. 1.—A plot of the total intensity I (*top*) and degree of circular polarization, ρ_c (*bottom*) observed at 4885 MHz from the dwarf M star YZ CMi on 1983 October 25. A circularly polarized impulsive ($\leq$ 20 s) burst and circularly polarized, slowly varying (~ 1 hr) radiation are observed. The visibility data were phase shifted to source center and then averaged, baseline by baseline, over a 30 s interval. They were then vector averaged to produce these time profiles. The theoretical 3 σ noise level of these data is ~ 1.35 mJy.

6 cm (or 5000 MHz) emission from dwarf M stars. Gyroresonance radiation of thermal electrons in extensive coronae was nevertheless once believed to be the most likely explanation for the slowly varying quiescent emission from these stars (Gary and Linsky 1981; Topka and Marsh 1982).

An alternative microwave emission mechanism is nonthermal gyrosynchrontron emission by mildly relativistic electrons (Linsky and Gary 1983; Pallavicini, Willson, and Lang 1985). An attractive aspect of this mechanism is that the emitting sources can be relatively small with sizes comparable to those of starspots. The unattractive aspect of the nonthermal gyrosynchrotron hypothesis is that the mildly relativistic electrons must be accelerated more or less continuously in the magnetic fields of starspots.

Our recent VLA observations of YZ CMi indicate that neither thermal gyroresonant radiation nor nonthermal gyrosynchrotron radiation can account for the slowly varying, quiescent microwave radiation of this star. In § II we present observations of the slowly varying radiation with a maximum flux density of 20 mJy and narrow-band frequency structure ($\Delta\nu/\nu \leq 0.1$) at frequencies near 1465 MHz. Possible explanations for this radiation are examined in § II. Thermal gyroresonant radiation would require impossibly large coronal loops and magnetic field strengths. The narrow-band structure cannot be explained by continuum emission processes such as thermal bremsstrahlung, thermal gyroresonant radiation, or nonthermal gyrosynchrotron radiation. Coherent burst mechanisms seem to be required.

II. OBSERVATIONS

The dwarf M star YZ Canis Minoris (GL 285, dM4.5e) was observed with two subarrays of the VLA on 1984 December 10 in the A configuration. One subarray of 13 antennas had signal frequencies of 1415 MHz and 1515 MHz, and the other subarray of 14 antennas had signal frequencies of 4835 MHz and 4885 MHz. The bandwidth at all four frequencies was 50 MHz. The total intensity, I, and circular polarization, ρ_c or Stokes parameter V, were sampled for every 10 s, and the data were calibrated by observing 3C 286 (14.51 Jy at 1415 MHz and 7.4 Jy at 4885 MHz) and 0735+178 (2.2 Jy at 1415 MHz and 2.1 Jy at 4885 MHz).

The calibrated visibility data were used to construct a 4.5 hr synthesis map of the unresolved source. The calibrated data were then phase shifted to bring the microwave source exactly at the center of the 4.5 hr map. There were no confusing sources in the field of view.

The calibrated, phase-shifted visibility data were then averaged, baseline by baseline, with running means over a 1.5 minute time interval, and then vector averaged. The theoretical 3 σ noise level obtained in this way was 2.3 mJy at 4885 MHz and 2.9 mJy at 1415 MHz. The total intensity at 1415 MHz and 1515 MHz exhibited slowly varying fluctuations of as much as 20 mJy, which is well above the noise level (see Fig. 2). However, there were no detectable variations at 4885 MHz for this observation.

An examination of the calibration amplitudes at the times of the gaps in Figure 2 indicates that they are constant and

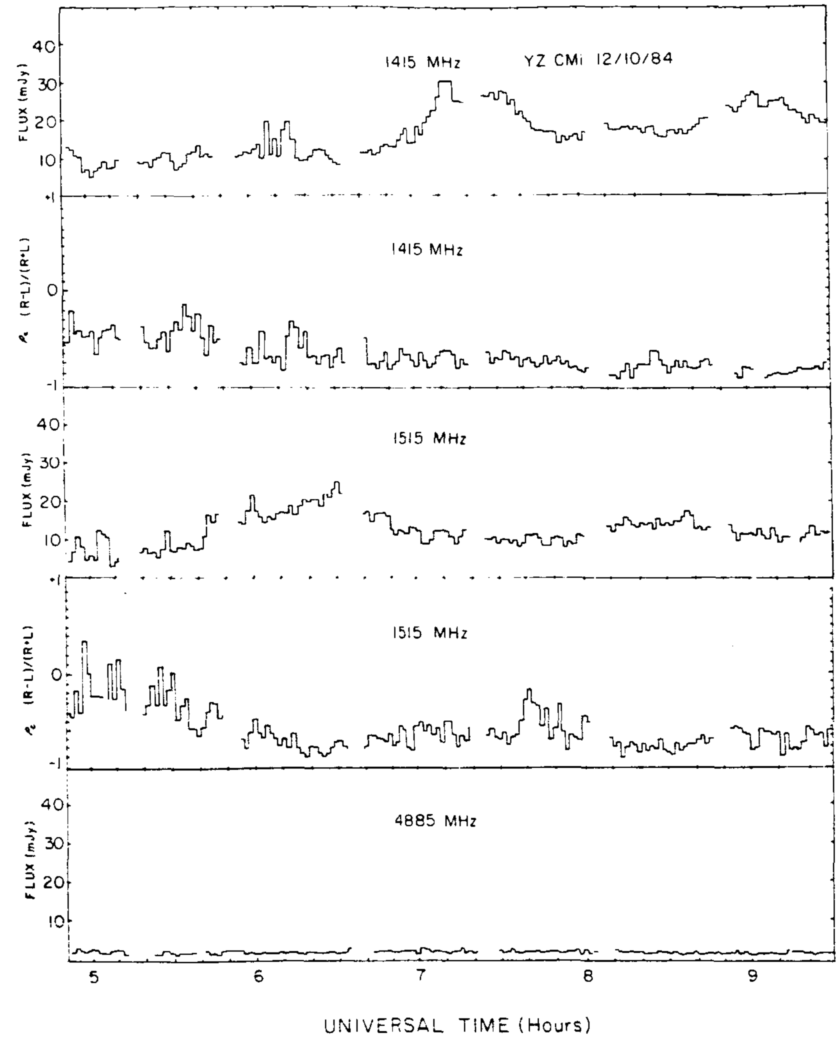

FIG. 2.—Plots of the slowly varying emission from the dwarf M flare star YZ CMi observed at two closely spaced frequencies of 1415 MHz and 1515 MHz and at 4885 MHz on 1984 December 10. Both the total intensity (flux) and degree of circular polarization (ρ_c) are plotted as a function of time. Notice that the total intensity at two frequencies separated by 100 MHz near 1465 MHz peak at different times, indicating a narrow-band radiation mechanism. Also notice that there are no detectable variations at 4885 MHz on this day. Here the visibility data were phase shifted to source center and then averaged, baseline by baseline, over a 1.5 minute interval. They were then vector averaged to produce time profiles with 3 σ noise levels of 2.9 mJy at 1415 MHz and 1515 MHz and 2.3 mJy at 4885 MHz. No quiescent emission was detected at 6 cm where the plot represents the nonzero vector-averaged noise level.

have the same value at 1415 MHz and 1515 MHz within the 5 σ noise level of 3.3 mJy for the 3 minute calibration interval. Changing calibrator amplitudes therefore do not produce the flux variations shown in Figure 2. This is confirmed by the unchanging peak-to-peak noise level of about 3 mJy depicted in the figure.

The interesting aspect of Figure 2 is that the slow variations in total intensity peak at different times for frequencies ν = 1415 and 1515 MHz, indicating narrow-band structure of bandwidth $\Delta\nu \ll 100$ MHz, or $\Delta\nu/\nu \ll 0.1$. This narrow-band structure was confirmed by constructing snapshot synthesis maps over time intervals of 1.5 minutes centered at 06:20 UT and 07:30 UT (Fig. 3). The snapshot maps had an effective half-power beamwidth of 1''.0 × 1''.6. The maximum flux values at 06:20 were 14 and 22 mJy per beam area at 1415 and 1515 MHz, respectively, while at 07:30 they were 25 and 10 mJy per beam area at 1415 and 1515 MHz, respectively.

Although 1415 MHz and 1515 MHz lie outside the protected band for radio astronomy, there was no indication of interference. This is reflected by the unchanging calibrator amplitudes and the absence of interference patterns in the 1.5 minute maps (Fig. 3) and in a 2 hr map (not shown).

III. DISCUSSION

What accounts for the observed narrow-band structure? Continuum emission processes like thermal bremsstrahlung, thermal gyroresonant radiation, or gyrosynchrotron radiation will not normally exhibit such spectral features. Of course, thermal electrons gyrate around magnetic fields, emitting

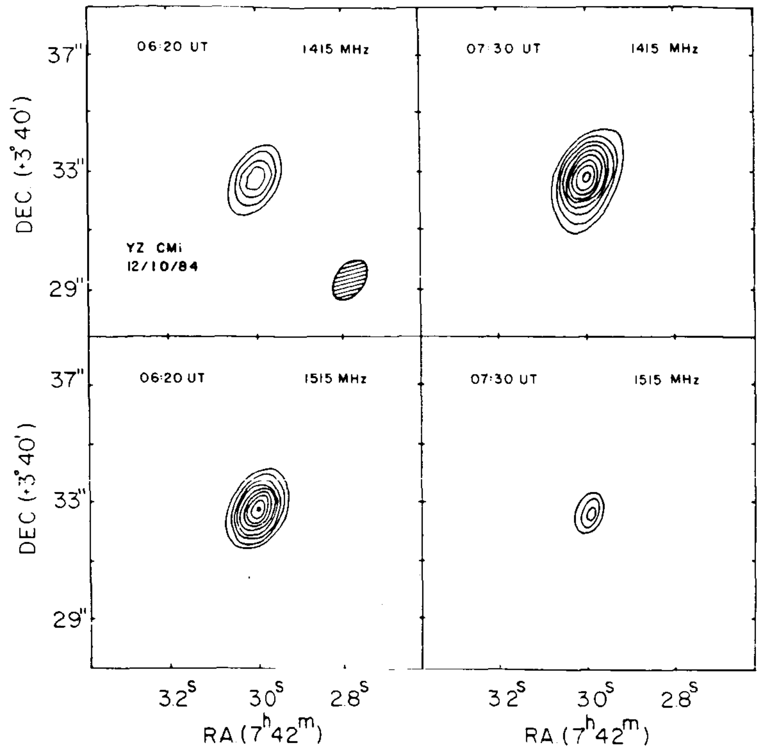

FIG. 3.—VLA snapshot synthesis maps of the total intensity over a 1.5 minute time interval centered at 06:20 UT and 07:30 UT for signal frequencies of 1415 MHz and 1515 MHz. The contour intervals of these maps are 6, 8, 10 ... mJy per beam area, and the synthesized beam (1".0 × 1".6) is illustrated by the cross-hatched ellipsoid at the upper left. Notice that the unresolved emission peaks at different times at two frequencies separated by only 100 MHz near 1465 MHz, indicating a narrow-band radiation mechanism.

cyclotron lines at harmonics of the gyrofrequency. Current sheets could lead to enhanced gyroresonant radiation from relatively thin coronal layers where the magnetic field is constant, and in this case, individual cyclotron lines might be observed. In fact, the VLA has been used to resolve individual coronal loops on the Sun, thereby detecting individual cyclotron lines (Willson 1985*a*). However, when an entire star is observed, the complex magnetic geometry should lead to varying magnetic field strengths and the cyclotron lines ought to be smoothed into a continuum.

Moreover, we can rule out gyroresonant radiation for the observations presented here. The gyroresonant layers in a stellar corona will lie fully outside the star and form closed surfaces around it. The observed radiation will be generated at the maximum harmonic, n, for which the corona still remains optically thick, for this outermost layer absorbs underlying radiation at lower harmonics. The maximum observed flux density, S, will be given by the Rayleigh-Jeans law (Lang 1980), and the radius of the emitting source will be given by

$$R^2 \approx 10^{13} \frac{SD^2}{\nu^2 T} \text{ cm}^2, \qquad (1)$$

where S is the source flux density in Jy; D is the distance in cm; T is the temperature in K; and the observing frequency, ν, is given by

$$\nu = 2.8 \times 10^6 \, nH_l \text{ Hz}, \qquad (2)$$

for a longitudinal magnetic field of strength H_l. (Slightly larger values of R will be obtained when the magnetic field geometry and the visible area of the gyroresonant surface are taken into account.) For YZ CMi, we substitute $S = 0.02$ Jy, $D = 5.99$ pc $\approx 1.8 \times 10^{19}$ cm, $\nu = 1.5 \times 10^9$ Hz, and $T \approx 10^6$ K to obtain $R = 5.4 \times 10^{12}$ cm.

Thus, the hypothetical gyroresonant radiator must have a radius of $R = 5.4 \times 10^{12}$ cm which is 200 times as large as the star's radius of 2.6×10^{10} cm (Pettersen 1980). (Smaller values of R amounting to a few stellar radii were previously obtained because lower flux densities were observed at higher frequencies.) Because the gyroresonant layers remain optically thick out to no more than $n = 6$ for normal stellar coronae (Zheleznyakov and Tikhomirov 1984), the required magnetic field strength for radiation at 1500 MHz is $H \geq 100$ G. Such strong magnetic fields at 200 stellar radii are simply inconceivable. Even a well-ordered dipolar field has a strength that goes as the cube of the radius, implying a surface magnetic field strength of 0.8×10^9 G.

Thus, the narrow-band, slowly varying radiation from YZ CMi cannot be explained by conventional radiation mechanisms. We might speculate that the star could be continually radiating coherent bursts. Coherent radiation processes like electron-cyclotron masers have been used to explain some microwave bursts on the Sun and nearby stars (Melrose and Dulk 1982; Holman 1983). Some solar bursts exhibit high brightness temperatures, $T_B \geq 10^{15}$ K, that require coherent mechanisms (Slottje 1978), and other solar bursts have exhibited narrow-band ($\Delta\nu/\nu < 10^{-2}$) structure that suggests coherent emission (Lang and Willson 1984; Willson 1985*b*). In addition, microwave bursts from the dwarf M star AD Leo have millisecond rise times and high brightness temperatures that require coherent emission processes (Lang *et al.* 1983; Lang and Willson 1986). Coherent burst mechanisms might therefore be adopted to explain the observed narrow-band, slowly varying microwave radiation through continuous burst activity.

High circular polarization would be expected to be occasionally observed if the coherent mechanism is associated with intense magnetic fields, and the stochastic nature of continued bursts might explain the variability of the observed microwave radiation.

If the electron-cyclotron maser radiates at the second harmonic, or $n = 2$, of the gyrofrequency as suggested by Melrose and Dulk (1982), then we obtain a longitudinal magnetic field strength of $H_l = 250$ G for a radiation frequency of 1400 MHz. The first harmonic radiation is expected to be attenuated by gyroresonant absorption in overlying atmospheric layers, and second harmonic radiation may dominate the emission when the gyrofrequency is roughly equal to the plasma frequency $\nu_P = 8.9 \times 10^3\ N_e^{1/2}$ Hz, where the electron density is in cm^{-3} (see Dulk 1985). This means that the electron density $N_e \approx 6 \times 10^9\ cm^{-3}$.

The coherent process might alternatively be attributed to plasma radiation. For example, type IV bursts with $\Delta\nu/\nu \leq 0.1$ have been observed at frequencies $\nu = 200–1500$ MHz. Benz and Tarnstrom (1976) have shown that a coherent synchrotron mechanism for the narrow-band type IV bursts requires either an excessively large number of relativistic electrons or an unstable pitch angle anisotropy. They argue that plasma emission processes might explain these bursts. Plasma processes involving electron beams have also been invoked to explain weaker, narrow-band ($\Delta\nu/\nu \leq 0.1$) bursts or blips observed at decimetric wavelengths during other solar bursts (Furst, Benz, and Hirth 1982; Benz, Bernold, and Dennis 1983). However, analogies with these solar features may be constrained by their rapid temporal variations. The narrow-band type IV bursts have lifetimes of several minutes, and the weaker blips last less than 0.25 s. In contrast, the narrow-band slowly varying radiation from YZ Canis Minoris lasts for hours.

If YZ Canis Minoris has a solar-like corona, then the first harmonic of the plasma frequency will be absorbed by electron-ion collisions at frequencies $\nu = 1400$ MHz, but the second harmonic will escape. For this case we obtain $N_e = 6 \times 10^9\ cm^{-3}$, but for plasma radiation to dominate we require $\nu_H \ll \nu_P$ or the longitudinal magnetic field strength $H_l \ll 250$ G.

Radio astronomical studies of the Sun and other active stars at Tufts University are supported under grant AFOSR-83-0019 with the Air Force Office of Scientific Research. Our VLA observations of the Sun are supported by contract N000 14-86-K-0068 with the Office of Naval Research (ONR). Investigations of dwarf M flare stars and RS CVn stars at Tufts University are also supported by NASA grant NAG 5-477. The Very Large Array is operated by Associated Universities Inc., under contract with the National Science Foundation.

Note added in manuscript.—Dr. Ronald D. Ekers (private communication) has pointed out that the narrow bandwidths and long fluctuation times of the decimetric radiation from YZ CMi are comparable to the decorrelation frequencies and decorrelation times of the interstellar scintillation of pulsar radiation. Our observations might therefore be explained by interstellar scintillation, but YZ CMi is about 100 times closer than the scintillating pulsars. The fluctuating electron number density would therefore have to be 100 times greater than that detected along the line of sight to these pulsars if the observed decorrelation is attributed to interstellar scintillation. Multiple-wavelength VLA observations can be used to test the scintillation hypothesis; the decorrelation frequency and time, respectively, scale as the fourth and first power of the observing frequency. An emitter located at the distance of YZ CMi must have a linear size smaller than 10^4 km in order to give rise to detectable scintillation in this dense interstellar medium (see Lang 1971 for relevant formulae and pulsar data). If a source of this size accounts for the decimetric flux density from YZ CMi, then its brightness temperature is $T_B \geq 10^{14}$ K, which may again require a coherent radiation mechanism.

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D. RADIO WAVELENGTH OBSERVATIONS OF MAGNETIC FIELDS ON ACTIVE DWARF M, RS CVN AND MAGNETIC STARS

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ABSTRACT

The dwarf M stars YZ Canis Minoris and AD Leonis exhibit narrow-band, slowly varying (hours) microwave emission that cannot be explained by conventional thermal radiation mechanisms. The dwarf M stars AD Leonis and Wolf 424 emit rapid spikes whose high brightness temperatures similarly require a nonthermal radiation process. We attribute them to coherent mechanisms such as an electron-cyclotron maser or coherent plasma radiation. If the electron-cyclotron maser emits at the second or third harmonic of the gyrofrequency, the coronal magnetic field strength $H = 250$ G or 167 G and constraints on the plasma frequency imply an electron density of $N_e = 6 \times 10^9$ cm^{-3}. Coherent plasma radiation requires similar values of electron density but much weaker magnetic fields. Radio spikes from AD Leonis and Wolf 424 have rise times $\tau_R < 5$ ms, indicating a linear size of $L < 1.5 \times 10^8$cm, or less than 0.005 of the stellar radius. Although Ap magnetic stars have strong dipole magnetic fields, they exhibit no detectable gyroresonant radiation, suggesting that these stars do not have hot, dense coronae. The binary RS CVn star UX Arietis exhibits variable emission at 6 cm wavelength on time scales ranging from 30 s to more than one hour. The shortest variation implies a linear size much less than that of the halo observed by VLBI techniques, and most probably sizes smaller than those of the component stars. The observed variations might be due to absorption by a thermal plasma located between the stars.

DWARF M FLARE STARS

The dwarf M flare stars exhibit relatively weak microwave bursts (a few tenths of one Jy) with a rate comparable to that of optically visible flares from the same stars. Quiescent, or nonflaring, microwave emission has also now been detected from several dwarf M stars using the Very Large Array (VLA). These stars exhibit quiescent X-ray emission whose absolute luminosity may be as much as 100 times that of the Sun. Both the microwave and the X-ray emission suggest that dwarf M stars have hot stellar coronae and large-scale coronal loops with strong magnetic fields. In this section we will demonstrate that both the quiescent microwave emission and the microwave bursts from dwarf M stars cannot be attributed to thermal radiation mechanisms. The required non-thermal emission processes can provide stringent constraints on the electron density and magnetic field strength in the stellar coronae.

What accounts for the slowly varying microwave emission from dwarf M stars? The X-ray observations rule out detectable thermal bremsstrahlung at microwave wavelengths; the temperatures and emission measures inferred from the X-ray data indicate that the microwave flux density is at least two orders of magnitude below the detection threshold of the VLA. Thermal electrons gyrating about large-scale magnetic fields might emit detectable gyroresonant, or cyclotron, radiation. The radiation will be emitted in gyroresonant layers that lie outside the visible star at a radius, R, given by the Rayleigh-Jeans law /1/

$$R^2 = 10^{13} \frac{SD^2}{\nu^2} \text{ cm}^2 , \qquad (1)$$

where S is the source flux density in Jy; D is the distance in cm; T is the temperature in K; and the observing frequency ν, is given by

$$\nu = 2.8 \times 10^6 \text{ nH Hz} \tag{2}$$

where n is the maximum harmonic for which the stellar corona still remains optically thick.

Gyroresonance radiation of thermal electrons in extensive coronae was once believed to be the most likely explanation for the slowly varying quiescent emission of dwarf M flare stars. Values of R amounting to a few stellar radii were obtained following detection of low flux densities at 6 cm wavelength, and gigantic coronal loops of about three times larger than the visible star were envisaged. However, we have now detected stronger slowly-varying emission at longer wavelengths (20 cm) from YZ Canis Minoris /2/. Substituting the relevant data ($S = 0.02$ Jy, $D = 5.99$ pc $= 1.8 \times 10^{19}$ cm, $\nu = 1.5 \times 10^9$ Hz and $T = 10^6$ K) into equation 1, we obtain $R = 5.4 \times 10^{12}$ cm, which is 200 times larger than the visible star's radius. Strong, large-scale magnetic fields extending out to 200 stellar radii are inconceivable.

Our observations of narrow-band structure from YZ Canis Minoris additionally rule out a thermal radiation mechanism for its slowly-varying microwave emission /2/. Moreover, other observers subsequently found narrow-band structure in hour-long variations from AD Leonis and shorter bursts from UV Ceti /3/. The narrow-band radiation has bandwidth $\Delta\nu < 0.1\ \nu$. Continuum emission processes like thermal bremsstrahlung, thermal gyroresonant radiation or gyrosynchrotron radiation will not normally exhibit such spectral features. Coherent radiation processes like electron-cyclotron masers can give rise to the observed narrow-band structure, but before explaining these processes we will provide additional evidence for coherent burst emission from dwarf M stars.

After several hours of observation at the Arecibo Observatory, a stellar eruption was detected from AD Leonis at 20 cm wavelength with a maximum flux density of 30 mJy. The burst was composed of highly left-handed circularly polarized (100%) spikes with rise times of $\tau_R < 200$ ms. An upper limit to the linear size $L < 6 \times 10^9$ cm, and a brightness temperature of $T_B < 10^{13}$ K (symmetric emitter) were inferred from these rise times /4/.

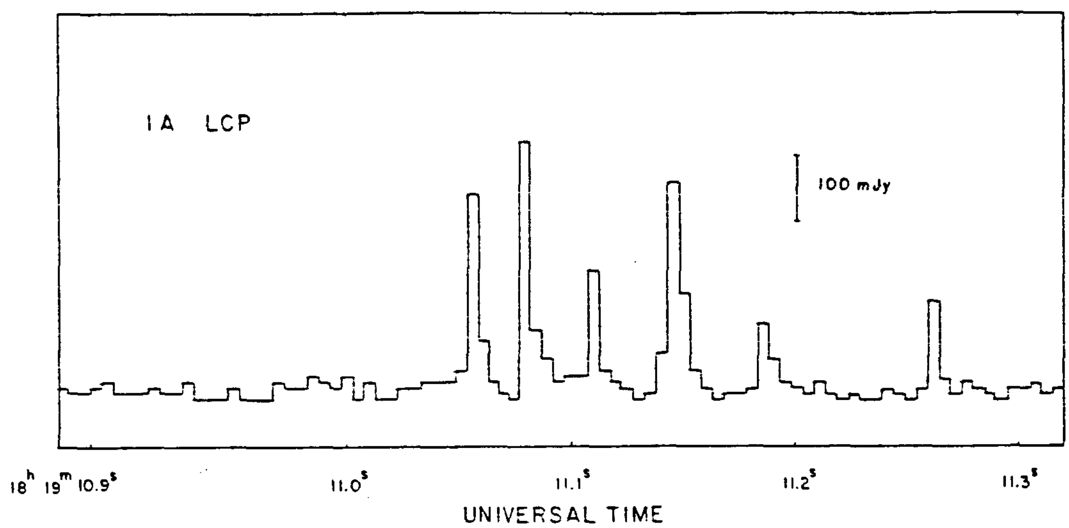

Fig. 1. The total power detected at a frequency of 1415 MHz (21.2 cm) while tracking the dwarf M star AD Leonis. The left-hand circularly polarized (LCP) signal has been displayed with a 5 ms integration time. There are five quasi-periodic spikes with a mean periodicity of $\tau_P = 32 \pm 5$ ms and a total duration of $\tau_D = 150$ ms. Each of these spikes had a rise time of $\tau_R < 5$ ms, leading to an upper limit to the linear size $L < 1.5 \times 10^8$ cm for the spike emitter. A symmetric source of this size would have a brightness temperature of $T_B > 10^{16}$ K, requiring a coherent radiation mechanism.

As illustrated in Figure 1, subsequent Arecibo observations resulted in the detection of quasi-periodic, highly polarized spikes at 20 cm wavelength from AD Leonis /5/. The spikes had rise times of $\tau_R < 5$ ms. An upper limit to the linear size of the spike emitting region is $L < 1.5 \times 10^8$ cm, the distance that light travels in 5 milliseconds. This size is only five hundredths of the estimated radius of AD Leonis. Provided that the emitter is symmetric, it has a brightness temperature greater than 10^{16} K.

We have subsequently detected spikes of shorter rise time $\tau_R = 0.1$ s from AD Leonis that are 100% right-hand circularly polarized, as well as spikes from Wolf 424 with rise times $\tau_R < 5$ ms. All of these spikes require high brightness temperatures in excess of 10^{13} K. The high degrees of circular polarization (up to 100%) indicate an intimate connection with the star's magnetic field, and the high brightness temperatures suggest a coherent radiation mechanism such as an electron-cyclotron maser or coherent plasma radiation. The coherent process provides constraints on the electron density, N_e, and the magnetic field strength, H, in the stellar coronae /6/. If the electron-cyclotron maser emits at the second or third harmonic of the gyrofrequency, the longitudinal magnetic field H = 250 G or 167 G and constraints on the plasma frequency imply an electron density of $N_e = 6 \times 10^9$ cm^{-3}. Although we do not know the harmonic with certainty, the high circular polarization requires a strong magnetic field, and high harmonics provide slow growth and insufficient optical depth. Coherent plasma radiation at the first or second harmonic of the plasma frequency respectively require $N_e = 2 \times 10^{10}$ cm^{-3} and $H \ll 500$ G or $N_e = 6 \times 10^9$ cm^{-3} and $H \ll 250$ G.

MAGNETIC STARS

Although we have ruled out thermal gyroresonant radiation from dwarf M stars, such radiation might be detected from the magnetic stars that have large, strong magnetic fields /7/. These stars have magnetic field strengths of a few hundred to a few thousand gauss. The observed field strengths vary in a roughly sinusoidal fashion with periods in the range of 1 to 10 days. Most of these magnetic stars also vary in brightness and have spectral lines that vary in strength; the period of variation is always the same as the magnetic period. The magnetic variations are explained by a dipolar magnetic field that is frozen into the rotating star. As the star rotates, the observer sees different aspects of the magnetic geometry. It is typically dipolar with two magnetic poles of opposite sign and unequal strength.

Detailed calculations indicate that the gyroresonant layers lie fully outside the star and form closed surfaces around it /8/. The degree of circular polarization depends on the angle between the line of sight and the axis of the magnetic dipole. The magnetic field strength can be inferred from the harmonic of the gyrofrequency. As an example, the magnetic stars ε Ursae Majoris and α^2 Canum Venaticorum have maximum magnetic field strengths of 960 and 3,500 gauss respectively, and respective distances of 20.0 and 43.5 parsecs. For these parameters and assuming an electron temperature $T_e = 10^7$ K, and electron density $N_e = 10^9$ cm^{-3}, the computed flux density for gyroresonant emission at $\nu = 10$ GHz is 0.8 mJy.

We have observed the 11 magnetic stars listed in Table 1 with the VLA for at least one hour each at 6 cm wavelength. No emission was detected from these stars at a 3 sigma level of about 0.2 mJy (see Table). The results indicate that strong surface magnetic fields are not sufficient to produce detectable radio emission. The magnetic Ap stars probably do not have the hot, dense coronae and stellar winds required to produce significant radio luminosity. In contrast, radio emission has been detected from at least two helium-rich, magnetic variable Bp stars with kilogauss photospheric fields (σ Ori E and HR 1890) /8/.

THE RS CVN STAR UX ARIETIS

As illustrated in Figure 2, the binary RS CVn star UX Arietis exhibits variable emission at 6 cm wavelength on time scales ranging from 30 s to more than one hour /8/. In contrast, the flux at 20 cm wavelength had a nearly constant value of about 30 mJy. From the shortest variations of 30 s, we place an upper limit of $L < 9 \times 10^{11}$ cm for the size of the emitting region under the assumption that the source cannot move faster than the velocity of light. This size is four times smaller than that of the halo component obtained from 6 cm VLBI observations, but comparable to the upper limit given by VLBI for the core component.

Velocities considerably below the velocity of light are most likely. For example, plausible magnetic field strengths of H = 10–100 gauss and electron densities of $N_e = 10^7$–10^8 cm^{-3}, result in an Alfven velocity of 2×10^8 cm $s^{-1} < V_A < 7 \times 10^9$ cm s^{-1}. This implies a source size of $L = 6 \times 10^9$ cm to 2×10^{11} cm and a brightness temperature of $T_B > 10^{11}$ K to $T_B > 10^{13}$ K for the rapid 30 s variations. These sizes are small compared to the separation between the two stars ($L = 1.4 \times 10^{12}$ cm) and to the sizes of the stars themselves ($L = 1.4 \times 10^{11}$ cm and 4.2×10^{11} cm).

A model that might explain the relatively abrupt variations of less than 10-20 minutes is one in which the variable emission is absorbed by a thermal plasma lying between the two stars. High temperature plasma may reside in coronal loops which are comparable in size to the binary system. Absorption of radio emission from one component of UX Arietis by the thermal plasma in coronal loops lying along the line of sight might then explain both the variations at 6 cm and the absence of variations at 20 cm wavelength /9/.

Table 1. Upper limits at the 3 sigma level to the 6 cm flux density, S, of magnetic stars that exhibit no detectable radiation at this wavelength.

STAR NAME	m_V	P (days)	H (gauss)	D (pc)	S (mJy)
α Andromedae	2.1	0.9636	500	41.6	0.23
ι Cassiopeiae	4.5	1.7405	1030	47.6	0.35
53 Camelopardi	6.0	8.0278	17000	7.0	0.21
30H Ursae Majoris	5.0	11.58	1200	25.0	0.20
γ Virginis	3.0	--	436	9.9	0.15
ε Ursae Majoris	1.8	50.0887	960	20.0	0.25
α^2 Canum Venaticorum	2.9	5.4694	3500	43.5	0.20
ι Librae	4.5	—	300	43.5	0.20
β Coronae Borealis	3.7	18.4870	6100	32.3	0.18
χ Serpentis	5.3	1.5958	1840	33.3	0.20
γ Equulei	4.7	—	3500	47.6	0.23

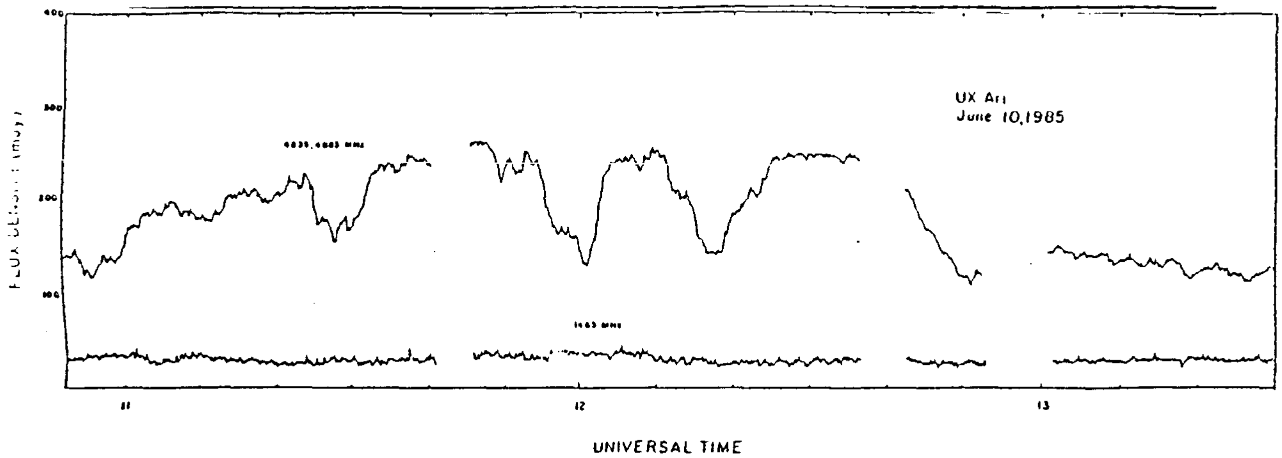

Fig. 2. A plot of the total intensity, I, observed at 1465 MHz, 4835 MHz, and 4885 MHz from the RS CVn star UX Arietis on June 10, 1985. The visibility data were phase shifted to the source center and then vector averaged, baseline by baseline, over a 6.67 s interval to produce these time profiles.

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E. MULTIPLE WAVELENGTH MICROWAVE OBSERVATIONS OF THE RS CANUM VENATICORUM STARS UX ARIETIS, HR 1099, HR 5110, AND II PEGASI

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ABSTRACT

The VLA was used to observe the RS CVn stars, UX Arietis, HR 1099, HR 5110, and II Pegasi with a time resolution of 6.6 s at two pairs of wavelengths near 4835 MHz and 1415 MHz. Variable emission was detected from UX Arietis at 4835 MHz on time scales ranging from 30 s to more than 1 hr, but there were no detectable variations at 1415 MHz. From the rise time of the shortest variation of ~ 30 s, we use the light-travel time argument to obtain an upper limit to the source size of $L \leq 9 \times 10^{11}$ cm, or about 4 times smaller than the halo size determined from VLBI techniques. More plausible Alfvén velocities of 2×10^8 cm s^{-1} $\leq V_A \leq 7 \times 10^9$ cm s^{-1} imply source sizes of 6×10^9 cm $\leq L < 2 \times 10^{11}$ cm for the 30 s variations. These sizes are smaller than the binary separation and most-likely smaller than the size of an individual star. Here we also derive a magnetic field of $H \leq 15$ G for the varying source and show that the relatively rapid time scales of the variations cannot be due to synchrotron radiation losses. Instead we suggest that the variations may be due to absorption by a thermal plasma located between the stars.

Subject headings: stars: binaries — stars: individual — stars: radio radiation — radio sources: variable

I. INTRODUCTION

Observations of RS CVn stars at centimeter wavelengths have shown that some of these objects exhibit strong and variable emission on time scales of minutes to several days. Among the more active and well studied RS CVn stars are UX Arietis (G5 V + K1 IV) and HR 1099 (G5 IV + K1 IV). Gibson, Hjellming, and Owen (1975) showed that the flux from UX Arietis at 2095 MHz and 8085 MHz decreased by about a factor of ~ 2.5 over a 24 hr period. Feldman *et al.* (1978) subsequently discovered variations on a time scale of a few hours from HR 1099 at 10.5 GHz. Shorter variations were reported from HR 1099 by Brown and Crane (1978); the 2695 MHz flux underwent rapid, and possibly periodic, fluctuations on a time scale of about 4 minutes.

The microwave radiation from UX Arietis and HR 1099 is often highly circularly polarized, especially, but not exclusively, during periods of little variation (Brown and Crane 1978; Mutel and Weisberg 1978; Mutel *et al.* 1985; Pallavicini, Willson, and Lang 1985). During a variation, the radio spectrum is usually inverted, with a spectral index, $\alpha \approx 1$. These properties suggest that the emission mechanism is gyrosynchrotron radiation from mildly relativistic electrons radiating in magnetic fields of a few tens of gauss (Owen, Jones, and Gibson 1976).

Recent VLBI observations have provided information about the sizes of a number of RS CVn Stars. Mutel *et al.* (1985) and Lestrade *et al.* (1985) have shown that UX Arietis contains an unresolved core (size $L \leq 3 \times 10^{11}$ cm) embedded in extended halo of about 3.2×10^{12} cm in size and that HR 1099 contains a single unresolved component whose size is $L \leq 1.1 \times 10^{12}$ cm. The separations between the binary components of UX Arietis and HR 1099 are, $\sim 1.5 \times 10^{12}$ cm, and 8.4×10^{11} cm, respectively. Observations of HR 5110 at 8.4 Lestrade *et al.* (1984) indicate a source size of 1.1×10^{12} cm, comparable to the overall size of the binary system. The VLBI size estimates, together with the observed flux densities indicate peak brightness temperatures of $T_B \geq 4 \times 10^8$ K for HR 5110 and $T_B \geq 10^{10}$ K for UX Ari and HR 1099. A temperature of 10^{10} K is not inconsistent with the idea that the radio emission is due to gyrosynchrotron emission, but significantly higher brightness temperatures might indicate a coherent emission mechanism such as an electron-cyclotron maser (Melrose and Dulk 1982).

More stringent limits to the size and brightness temperature can be obtained by measuring the rise time of the variable emission using the light-travel time argument to place an upper limit to the size. This approach has, for example, recently been used to derive brightness temperatures of $T_B \geq 10^{16}$ K from intense millisecond spikes emitted by the dwarf M star AD Leonis (Lang and Willson 1986).

In this paper we present 6.6 s VLA observations of UX Arietis at HR 1099, HR 5110, and II Peg at two pairs of frequencies near 1415 MHz and 4835 MHz. The RS CVn stars HR 5110 and II Peg were studied because both are known to vary at radio wavelengths (Feldman 1979; Viner 1979; Spangler, Owen, and Hulse 1977). In § II we present the data and show that UX Arietis exhibited variations on time scales ranging between ~ 30 s to more than 1 hr. In § III we discuss these observations and derive an upper limit of $L \leq 1.98 \times 10^{11}$ cm for the source size. Here we also derive a magnetic field of $H \leq 15$ G for the varying source and show that the time scale of the variations cannot be due to synchrotron radiation losses. Instead we suggest that the variations may be due to absorption by a thermal plasma located between the stars.

II. OBSERVATIONS

The RS CVn stars UX Arietis HR 1099, HR 5110, and II Peg were observed with the VLA (B configuration) on 1985 June 10. One subarray containing 13 antennas was used to observe at frequencies of 1415 MHz and 1465 MHz and another subarray containing 14 antennas was used to observe at frequencies of 4835 MHz and 4885 MHz. In all cases the bandwidth was 50 MHz. The fringe visibilities were sampled at a rate of 6.67 s, and the data were calibrated from observations

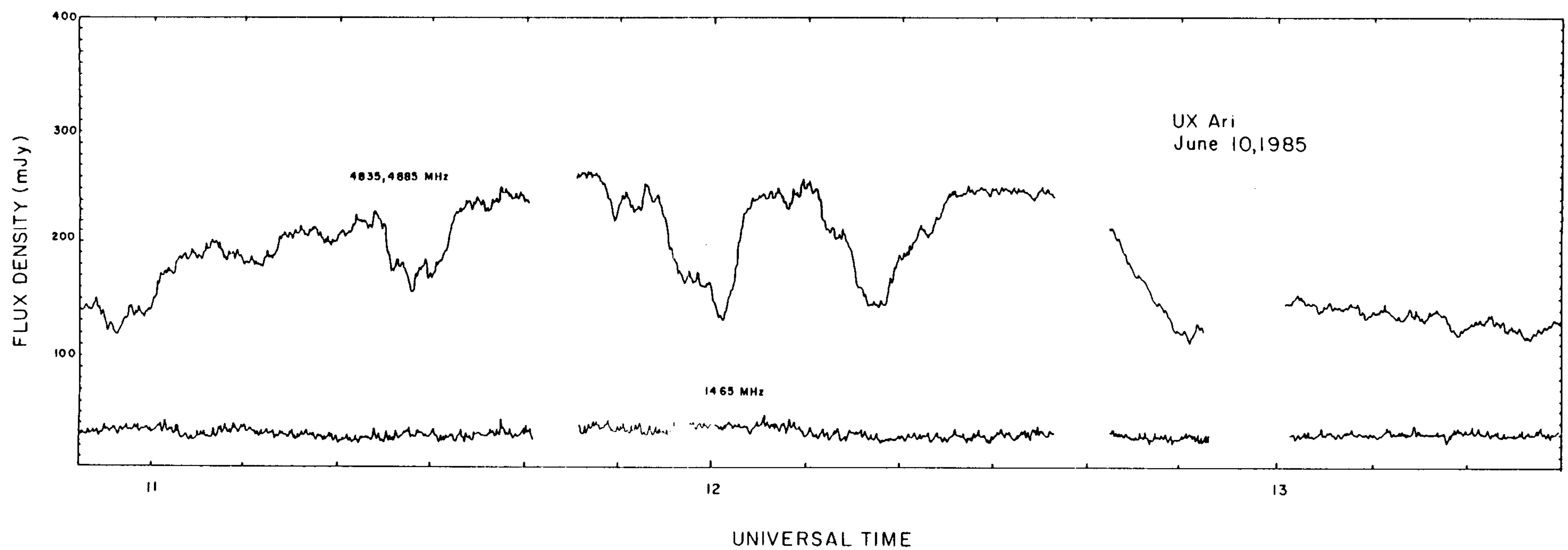

FIG. 1.—A plot of the total intensity, I, observed at 1465 MHz, 4835 MHz, and 4885 MHz from the RS CVn star UX Arietis on 1985 June 10. The visibility data were phase-shifted to the source center and then vector-averaged, baseline by baseline, over a 6.67 s interval to produce these time profiles.

of 3C 236 (14.51 Jy at 1465 MHz and 7.4 Jy at 4835 MHz) and 0333+321 (3.14 Jy at 1465 MHz and 2.64 Jy at 4835 MHz). The raw data were first examined, baseline by baseline, for the presence of interference or any obviously bad data.

The edited data were then calibrated and used to make synthesis maps of the sources which were then cleaned and fitted with two-dimensional Gaussian functions in order to determine their locations to within about one-tenth of the beamwidth (1"9 × 2"0 at 4885 MHz, 3"7 × 5"0 at 1465 MHz). The 6.6 s data were then phase-shifted to bring the sources exactly into the center of the map. Finally, these data were vector-averaged, baseline by baseline, and used to construct plots of total intensity, I, and circular polarization, ρ_c, as a function of time for the 2 hr observation interval. For a 6.6 s integration time the theoretical 3 σ rms noise level is $\sim$7 mJy at 1415 MHz and 1465 MHz and $\sim$6 mJy at 4835 MHz and 4885 MHz.

Our observations indicate that HR 1099, HR 5110, and II Peg exhibited no significant fluctuations in intensity on any time scales ranging from 6.6 s to more than 1 hr, but that UX Ari varied significantly throughout the 2.5 hr period of observation. In Table 1, we give the total intensity and circular polarization at 6 and 20 cm wavelength for each of the four sources. For HR 1099, HR 5110, and II Peg, the 3 σ errors were determined from the rms noise levels on the synthesis maps.

In Figure 1 we show the plots of total intensity for UX Arietis at 4835 MHz, 4885 MHz, and 1465 MHz. These plots indicate that UX Arietis was much more intense and time variable at 4835 MHz and 4885 MHz. There was no detectable circular polarization at any frequency, to a limit of 5%. The major variations in flux occur on time scales of $\sim$10–20 minutes, but faster variations are also apparent in the data. The peak flux occurs at $\sim$1145 UT with an amplitude of $\sim$270 mJy. In contrast, the flux at 1415 MHz and 1465 MHz has a nearly constant value of $\sim$30 mJy. In Figure 2 we show a section of data with variations as short as 30 s. Here, the data at 4835 MHz and 4885 MHz have been averaged together in order to improve the signal-to-noise ratio. The burst denoted by an arrow has an amplitude of $\sim$30 mJy and a rise time of $\sim$30 s. In order to check that these fluctuations are real and not caused by instrumental effects, we constructed a series of 2 minute snapshot maps at both 4835 MHz and 4885 MHz at various times during these observations. Small phase errors, for example, might mimic rapid time variations if the effective phase center varies by a small fraction of the synthesized beam over time scales of a few minutes. Examination of these maps, however, confirmed that the fluxes derived from them were nearly identical at 4835 MHz and 4885 MHz and that they agreed with the values determined by vector-averaging the data.

III. DISCUSSION

Our observations of UX Arietis indicate that the 6 cm flux varied on time scales ranging from $\sim$30 s to more than 1 hr. From the shortest variations of $\sim$30 s, we can place an upper limit of $L \leq 9 \times 10^{11}$ cm for the size of the emitting region under the assumption that the source cannot move faster than the velocity of light. This size is 4 times smaller than that of the halo component obtained from 6 cm VLBI observations (Mutel, Doiron, and Phillips 1984; Mutel *et al.* 1985), but comparable to the size of the core component ($l \leq 3 \times 10^{11}$ cm) found by Mutel *et al.* (1985). With an amplitude of $\sim$30 mJy and a size of $L \leq 9 \times 10^{11}$ cm, we derive a brightness temperature of $T_B \geq 10^9$ K.

Velocities considerably below the velocity of light are most likely. For example, plausible magnetic field strengths of $H = 10$–100 G and electron densities of $N_e = 10^7$–10^8 cm s^{-3} (Gibson, Hicks, and Owen 1974; Mutel, Doiron, and Phillips 1984), result in an Alfvén velocity of 2×10^8 cm s$^{-1} \leq V_A \leq 7 \times 10^9$ cm s^{-1}. This implies a source size of $L = 6 \times 10^9$ cm to 2×10^{11} cm and a brightness temperature of $T_B \geq 10^{11}$ K to $T_B \geq 10^{13}$ K for the rapid 30 s variations. These sizes are small compared to the separation between the two stars ($L = 1.4 \times 10^{12}$ cm) and to the sizes of the stars themselves ($L = 1.4 \times 10^{11}$ cm and 4.2×10^{11} cm).

Dulk and Marsh (1982) have shown that brightness temperatures of up to $\sim 10^{10}$ K may be explained in terms of gyrosynchrotron emission from nonthermal particles radiating in magnetic fields of a few tens of gauss, but that significantly higher brightness temperatures may require a coherent emission mechanism such as an electron cyclotron maser. In principle, the possibility of a brightness temperature as high as 10^{13} K would favor a coherent emission mechanism. However, since electron-cyclotron maser emission is expected to be highly circularly polarized (Melrose and Dulk 1982), the unpolarized variable emission discussed here would seem to exclude this particular coherent emission mechanism.

Synchrotron self-absorption with a spectral index of $\alpha = 2.5$ has been invoked to explain the inverted spectra often observed during radio bursts from RS CVn stars (Owen, Jones, and Gibson 1976; Spangler 1977; Hjellming and Gibson 1980). The turnover frequency due to synchrotron self-absorption is $\nu_{sa} = 8.1 \times 10^{-4}(S_m/\Omega)^{2/5}H^{1/5}$ (Slysh 1963), where ν_{sa} is given in MHz, Ω is the source solid angle, and H is the magnetic field strength in G. If it is assumed that the absence of burst emission at 21 cm is due to synchrotron self-absorption, then the source size may be estimated. Adopting $\nu \approx 5000$ MHz, $S_m = 270$ mJy, and $H = 100$ G, we derive a source size of $L \approx 10^{12}$ cm, which exceeds the upper limits established from plausible

TABLE 1

Journal of Observations

	Date (1985)	UT Time	Wavelength (cm)	Flux (mJy)	Polarization (%)
HR 5110	Jun 9	2308–0411	6	17.2 ± 0.2	+11.7
			20	20.1 ± 0.25	≤5
II Pegasi	Jun 10	0903–0951	6	9.2 ± 0.4	+10
UX Arietis	Jun 10	1052–1330	6	120–270	≤5
			20	30	≤5
HR 1099	Jun 10	2103–2253	6	11.8 ± 0.3	<5
			20	16.8 ± 0.4	−27

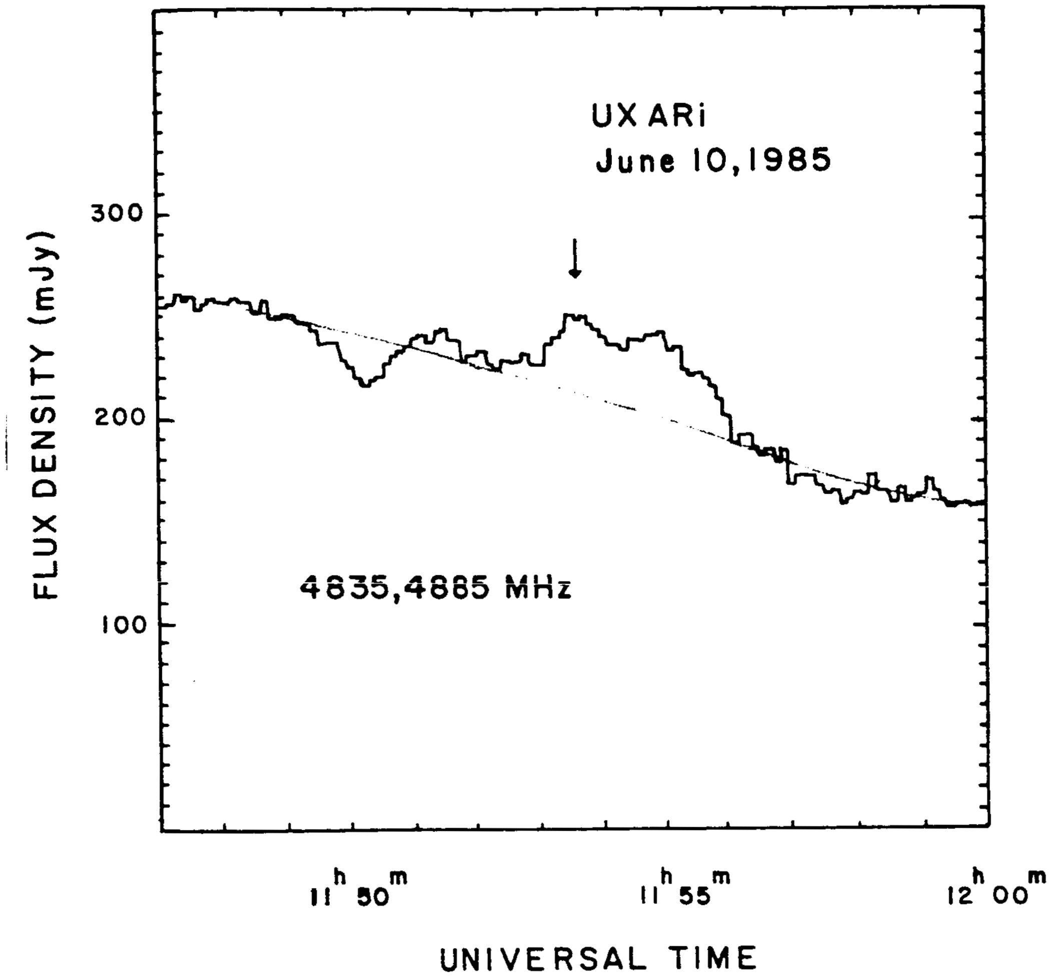

FIG. 2.—A plot of the total intensity, I, observed at 4835 MHz and 4885 MHz from UX Arietis. Here the data at these two frequencies have been averaged together. The time resolution of this plot is 6.67 s; the arrow shows a burst with a rise time of ~ 30 s.

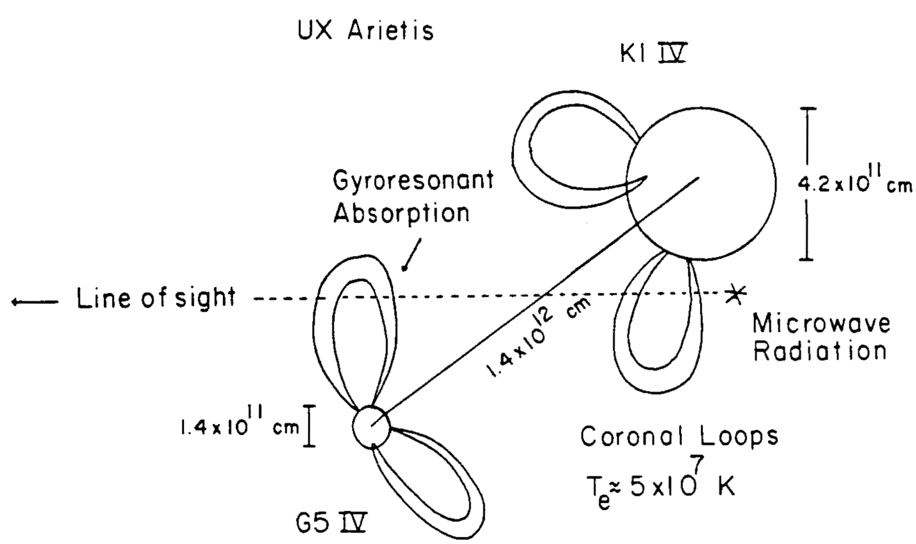

FIG. 3.—A schematic view of UX Arietis showing the orientation of the two components during the time of our observation. Six cm burst emission occurring on the more active K1 star may have passed through a coronal loop located between the two stars, giving rise to thermal absorption. The orbital inclination, $i \approx 55°$, is inferred from the data of Carlos and Popper (1971).

Alfvén velocities for the 30 s variations. However, smaller magnetic fields of $H \approx 10$ G imply a smaller size of $L \approx 3 \times 10^{11}$ cm under synchrotron self-absorption hypothesis.

Fields as small as 10 G are in fact suggested by the lack of polarization of the 6 cm burst emission. Dulk and Marsh (1982) have shown that the degree of circular polarization, ρ_c, of optically thin gyrosynchrotron radiation from mildly relativistic electrons having a power law distribution in energy is

$$\rho_c = 1.26 \times 10^{0.035\delta} \times 10^{-0.071 \cos\theta}\left(\frac{\upsilon_H}{\upsilon}\right)^{[-0.782+0.545 \cos\theta]} .$$

Here, $\upsilon_H = 2.8 \times 10^6 H$ is the gyrofrequency, δ is the electron energy index, and θ is the angle between the magnetic field and the line of sight. For $\delta = 3$–4, we require $H \leq 15$ G and $\theta \geq 70°$ in order to yield a circular polarization of less than about 5%, the approximate upper limit obtained from the VLA observations.

Fields as low as 15 G may, however, present a problem regarding the relatively rapid timescales of the 6 cm variations. According to Mullan (1985), an outburst observed from an RS CVn star has a time scale that is controlled by the evolutionary time scale of a coronal loop that expands outward from the steller surface. Eventually the outburst will "turn off" when the loop de-couples from the steller interior. When this happens it is expected that the burst lifetime will be determined by the synchrotron radiative loss lifetime (Chiuderi and Chiuderi-Drago 1967)

$$t_{1/2} \approx \frac{1.8 \times 10^8}{H^2} \text{ s.}$$

For $H = 15$ G, we find $t_{1/2} = 222$ hr, which is inconsistent with the much shorter time scales of variability reported here.

One possibility is that the major dips in intensity during the peak of the gradual burst are due to absorption by thermal plasma located between the stars. Observations of the Sun at centimeter wavelengths sometimes show "negative" bursts in which the flux decreases abruptly before or during gradual rise and fall bursts (Covington and Dodson 1952; Tanaka and Kakinuma 1960; Covington 1969). These events are sometimes associated with Hα prominences or filament activity that obscure the underlying microwave sources for brief periods of time (Sawyer 1977*a*, *b*).

A model that might explain the relatively abrupt variations of less than 10–20 minutes is one in which the variable emission is absorbed by a thermal plasma lying between the two stars. There is ample evidence for thermal plasma within the UX Arietis system. X-ray observations indicated the presence of two emission components with electron temperatures $T_e \approx 8 \times 10^6$ and $\sim 5 \times 10^7$ K (Swank *et al.* 1981). The lower temperature emission is believed to arise in coronal loops whose lengths are a small fraction of the radius of the more active star. The higher temperature plasma may reside in coronal loops which are comparable in size to the binary system. Simon, Linsky, and Schiffer (1980) have also found evidence for loops which interconnect two stars and which serve as conduits for mass exchange. These loops may provide the mechanism by which particles are accelerated, giving rise to radio bursts (Uchida and Sakurai 1983; Mullan 1985).

The orbital phase of UX Arietis during the time of our observations was $\phi = 0.457$–0.472, as computed from the ephemeris of Carlos and Popper (1971), where zero phase corresponds to the cooler, more active K0 IV star in front. This means that the more active star was situated on the far side of its orbit, as shown schematically in Figure 3, so that burst emission which was generated near that star had a greater probability of passing through material lying between the two stars than at any other time.

Observations indicate that both gyroresonant and thermal bremsstrahlung processes contribute to the centimeter wavelength opacity on the Sun (Lang, Willson, and Rayrole 1982; Dulk and Gary 1983; Lang, Willson and Gaizauskas 1983; McConnell and Kundu 1984). Under the assumption that gyroresonance absorption is the dominant mechanism at 6 cm wavelength, field strengths of 445–595 G are required if the absorption occurs at the third or fourth harmonic of the gyrofrequency. In the present case, however, unless the absorption occurs close to the secondary G5 star, fields as high as these imply surface fields which are much larger than those deduced from starspot analyses of RS CVn and late-type stars (Bonsack and Simon 1983; Marcy 1983). Thus it seems unlikely that gyroresonance absorption plays a role in modulating the burst emission from the active star in UK Arietis.

The optical depth due to thermal bremsstrahlung however does not depend on the magnetic field, and is given by

$$\tau_{\mathrm{TB}} = \frac{9.78 \times 10^{-3} N_e^{\,2}}{\upsilon^2 T_e^{\,3/2}} \ln \frac{(4.7 \times 10^{10} T_e)}{\upsilon} L ,$$

where N_e is the electron density, T_e is the electron temperature, and L is the path length through the absorbing medium. For a temperature of $T_e = 10^7$ K, an electron density of $N_e = 1.5 \times 10^9$ cm^{-3} and a path length $L = 10^{12}$ cm (the approximate size of the binary system) we have $\tau_{\mathrm{TB}} \approx 0.5$ at $\upsilon = 4.8 \times 10^9$ Hz. If the unattenuated flux of the slowly varying emission is taken to be 220 mJy at 1130 UT, for example, then the flux after absorption by the thermal plasma is ~ 140 mJy, in good agreement with the observed value. The relatively rapid dips in total intensity at 1130 UT, 1200 UT and 1215 UT might then reflect changing physical conditions within coronal loops lying between the stars. Absorption by thermal plasma between the active loops might also explain the total absence of variations at 20 cm. Since the thermal optical depth varies nearby as λ^2, where λ is the wavelength, the opacity from this surrounding plasma might be negligible at 6 cm, but not at 20 cm. If the optical depth is high enough, the underlying source of variable emission (as well as the effect of the changing loops) would not be detected. In this case, the quiescent 20 cm emission would likely originate in a larger halo surrounding the stars. High time resolution observations over a range of frequencies at different phases of the 6.43 day binary orbit would provide a useful test of this model.

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F. SIMULTANEOUS IUE AND VLA OBSERVATIONS OF YZ CANIS MINORIS, AD LEONIS AND LAMBDA ANDROMEDAE

57

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ABSTRACT

The International Ultraviolet Explorer and the Very Large Array were used to simultaneously observe the dwarf M flare stars YZ Canis Minoris and AD Leonis and the RS CVn star Lambda Andromedae. Narrow-band , slowly varying radiation near 20cm wavelength was detected from YZ Canis Minoris. This radiation cannot be attributed to conventional emission processes, but may be explained by a coherent emission mechanism. The Mg II h+k line intensities also underwent changes in intensity, although the connection between the microwave and ultraviolet variations is unclear. Impulsive microwave bursts were detected from AD Leonis, but there were no significant variations in the Mg II line intensities. Finally, enhancements in several ultraviolet emission lines were detected on timescales of about an hour from Lambda Andromedae without accompanying variations at 6cm or 20cm wavelength.

Keywords: Active Stars, Stellar Bursts

1. INTRODUCTION

Recent microwave and ultraviolet observations of nearby active stars indicate that these objects exhibit a number of phenomena that may be related to our understanding of physical processes that occur on the Sun. Very Large Array observations of the dwarf M flare stars YZ Canis Minoris and the RS CVn star UX Arietis, for example, have shown that these stars emit microwave radiation that fluctuates on timescales of tens of minutes to several hours (Ref. 1-3) . Variations on similiar timescales have also been detected from the dwarf M flare star EQ Pegasi (Ref. 4) and the RS CVn star Lambda Andromedae (Ref. 5) at ultraviolet wavelengths using the IUE satellite. Quiescent emission as well as bursts of shorter duration have also been observed from a number of active stars at radio wavelengths (Refs. 6-7,.') as well with the IUE and X-ray satellites (Ref. 8).

Both the slowly varying and impulsive emission from active stars may have analogues with fluctuations detected on the Sun. The slowly-varying component of solar radio emission at centimeter wavelengths, for example, is believed to be caused by changes in coronal magnetic loops above active regions, while the more impulsive bursts are thought to be triggered by rapid reconnections of magnetic fileds of inter-connecting loops. VLA observations of solar active regions at 2cm, 6cm and 20cm wavelength, for example, indicate that the emission originates respectively at the feet, legs and apex of magnetic loops (Ref. 9). The 20cm emission is the radio wavelength counterpart of coronal loops detected at X-ray wavelengths and may be attributed to the thermal bremsstrahlung of million degree plasma trapped within magnetic loops. The 6cm emission is attributed to the gyroresonant emission of thermal electrons spiralling around magnetic fields that are connected to underlying sunspots, while the 2cm radiation can be attributed to either thermal bremsstrahlung or gyroresonant emission in the transition region.

Both ultraviolet and X-ray data also provide evidence for plasma and magnetic fields near active stars. Simon, Linsky and Schiffer (Ref. 10) for,for example, showed that enhanced Mg II emission from UX Arietis could be attributed to mass flow in magnetic flux tubes that connect the binary components. The intense quiescent X-ray emission from stars of late spectral type has been attributed to emission from stellar coronae and large-scale coronal loops with strong magnetic fields (Ref. 10-12). Finally,optical wavelength observations of solar-type stars have revealed the presence of starspots with associated magnetic fields of several thousand gauss (Ref. 13-15).

Thus, there is a strong indication that the solar analogy is applicable to other active stars and that simultaneous multiple-wavelength observations might specify conditions in different levels in the stellar atmospheres where burst or slowly varying emission occurs. Since observations obtained at ultraviolet wavelengths refer to physical conditions in the chromosphere or transition region, while observations at radio wavelengths generally refer to conditions in coronal loops, simultaneous observations may provide information about the relative locations of stellar variations and about the physical mechanisms that give rise to them.

2. OBSERVATIONS

2.1 The VLA Observations

In this section we discuss simultaneous IUE and VLA observations of the dwarf M flare stars YZ Canis Minoris and AD Leonis and the RS CVn star Lambda

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Andromedae. In Table 1 we give the date and time that each star was observed with the VLA and IUE. Since one of our objectives was to obtain spectral information about bursts or other variations, the full VLA was divided into two subarrays and used to observe simultaneously within two different wavelength bands. One subarray, containing 13 antennas, was used to observe at frequencies of 1415 MHz and 1465 MHz and another subarray, containing 14 antennas, was used to observe at 4835 MHz and 4885 MHz. The full details of our observing procedure and data analysis are given by Willson and Lang (Ref. 16).

In Table 1 we present the results of our observations, where for each star and observation period we give the total intensity and circular polarization at 6cm and 20cm wavelength.

TABLE 1.

Summary of VLA and IUE Observations

Star	Date	UT Observation Time		VLA Flux			
		VLA	IUE	6 cm		20 cm	
				I	ρ_c	I	ρ_c
YZ Canis Minoris	1984 Sep 30	0935-1435	0651-1356	$\leq$0.50	-	5-42	[illegible]-90
	1984 Dec 10	0450-0930	0205-0845	$\leq$0.50	-	10-30	40-90
AD Leonis	1984 Nov 07	0830-1226	0754-1018	<0.25	-	<0.50	-
	1984 Nov 08	0752-1207	0800-1022	$\leq$0.30	-	3.50±0.15	<25
	1984 Nov 09	0740-1157	0735-1012	$\leq$0.30	-	2.00±0.20	$\leq$30
	1984 Nov 10	0746-1051	0745-1034	0.50	$\leq$40	0.50	-
Lambda Andromeda	1985 Jun 10	1336-2045	1309-2035	2.1±0.15	<20	3.00±0.20	<15
	1985 Nov 11	0226-0850	0333-1033	2.5±0.20	$\leq$25	4.30±0.20	$\leq$15

2.2 The IUE observations

The IUE observations were made using both the short wavelength (1175-2000 Å) SWP camera and the long wavelength (2000-3200 Å) LWP camera. The SWP observations were made at low dispersion (spectral resolution 6 Å) while the LWP observations were made at both low and high (spectral resolution ~ 0.2 Å) dispersion. In all cases, the stars were observed through the large 10" x 20" aperture. In general, each observation consisted of two or three time-trailed exposures of about 10 minutes each. In this way we could search for rapid variations in spectral line intensity such as occur during flares.

In general, only the Mg II h+k lines near 2800 A were detected in the LWP spectra. The SWP spectra of Lambda Andromeda contained a number of chromospheric and transition lines, of which the most prominent are OI, CIII and CIV. In Tables 2 and 3 we give the integrated line intensities for both the LWP and SWP spectra. Since there is currently no adopted absolute calibration for the IUE in the high dispersion mode, the high dispersion LWP integrated line intensities for Lambda Andromeda are relative values only.

Table 2.

Integrated Mg II h+k Line Intensities

Star	IUE Image	Date	UT Time	Observed Flux (10^{-12} erg $cm^{-2}s^{-1}$)
YZ Canis Minoris	L4452	1984 Sep 30	07 42	2.03 ± 0.14
	L4452	1984 Sep 30	08 02	2.60 ± 0.10
	L4955	1984 Dec 10	02 05	2.60 ± 0.10
	L4955	1984 Dec 10	02 20	1.38 ± 0.08
	L4955	1984 Dec 10	02 35	1.54 ± 0.10
	L4956	1984 Dec 10	03 56	1.08 ± 0.08
	L4956	1984 Dec 10	04 11	0.94 ± 0.08
	L4956	1984 Dec 10	04 28	1.10 ± 0.10
	L4958	1984 Dec 10	07 58	1.12 ± 0.12
	L4958	1984 Dec 10	08 13	1.26 + 0.14
	L4958	1984 Dec 10	08 27	1.52 ± 0.12
AD Leonis	L4745	1984 Nov 07	08 51	2.40 ± 0.20
	L4750	1984 Nov 08	08 01	3.30 ± 0.20
	L4751	1984 Nov 08	09 48	2.50 ± 0.16
	L4760	1984 Nov 08	07 35	2.50 ± 0.12
	L4761	1984 Nov 09	09 04	2.20 + 0.20
	L4771	1984 Nov 10	07 45	2.30 ± 0.20
	L4772	1984 Nov 10	09 23	2.30 ± 0.20
Lambda Andromeda	L6182	1985 Jun 10	14 59	0.94 ± 0.02*
	L6183	1985 Jun 10	16 36	0.90 ± 0.02*
	L7072	1985 Nov 11	04 21	0.90 ± 0.03*
	L7073	1985 Nov 11	06 00	0.97 ± 0.02*
	L7074	1985 Nov 11	07 31	0.96 ± 0.02*
	L7075	1985 Nov 11	09 02	0.87 ± 0.02*
	L7076	1985 Nov 11	10 33	0.87 ± 0.02*

*Relative flux values

TABLE 3.

FLUXES OF EMISSION LINES FROM LAMBDA ANDROMEDAE

1985 June 10 (10^{-12} erg $cm^{-2}s^{-1}$)

Line	λ (Å)	SWP 26134	SWP 26135	SWP 26136	SWP 26137	SWP 26138
OI	1304	4.53 ± 0.07	4.95 ± 0.11	5.12 ± 0.14	5.44 ± 0.23	4.60 ± 0.09
CII	1335	1.48 ± 0.07	1.78 ± 0.11	1.71 ± 0.14	2.29 ± 0.26	1.82 ± 0.07
SiIV	1394	1.47 ± 0.22	1.38 ± 0.22	1.88 ± 0.33	1.30 ± 0.36	1.19 ± 0.18
CIV	1550	2.15 ± 0.08	2.42 ± 0.13	2.96 ± 0.29	3.32 ± 0.20	2.05 ± 0.12
HeII	1640	1.98 ± 0.10	1.69 ± 0.09	1.10 ± 0.12	1.26 ± 0.12	1.50 ± 0.11
CI	1657	1.15 ± 0.08	1.38 ± 0.09	1.35 ± 0.14	1.37 ± 0.14	1.28 ± 0.11
SiII	1808 1817	3.24 ± 0.25	3.24 ± 0.19	3.09 ± 0.29	3.49 ± 0.29	3.23 ± 0.26

FLUXES OF EMISSION LINES FROM LAMBDA ANDROMEDAE

1985 November 11 (10^{-12} erg $cm^{-2}s^{-1}$)

		SWP 27081	SWP 27082	SWP 27083	SWP 27084	SWP 27085
OI	1304	3.72 ± 0.09	4.64 ± 0.10	3.67 ± 0.08	2.98 ± 0.21	3.72 ± 0.09
CII	1335	1.90 ± 0.09	2.48 ± 0.09	1.92 ± 0.07	1.41 ± 0.19	1.90 ± 0.09
SiIV	1394	1.90 ± 0.17	2.38 ± 0.16	2.20 ± 0.12	1.39 ± 0.29	1.90 ± 0.16
CIV	1550	3/42 ± 0.12	3.81 ± 0.12	3.14 ± 0.13	2.27 ± 0.16	3.42 ± 0.12
HeII	1640	1.68 ± 0.10	1.67 ± 0.09	1.30 ± 0.11	1.20 ± 0.14	1.68 ± 0.10
CI	1657	1.71 ± 0.11	1.30 ± 0.09	1.22 ± 0.10	1.96 ± 0.28	1.71 ± 0.11
SiII	1808 1817	2.25 ± 0.29	2.16 ± 0.29	1.74 ± 0.31	1.74 ± 0.37	2.25 ± 0.29

3. DISCUSSION

Our observations indicate that each of the three stars varied in intensity at ultraviolet or radio wavelengths. In this section we will briefly discuss these variations.

3.1 YZ Canis Minoris

YZ Canis Minoris (GL285) is an active flare star that has been well studied at optical and radio wavelengths. Coordinated optical, radio and X-ray observations have resulted in the detection of a large number of flares, but only a few appear to have been detected simultaneously in all three wavelength ranges (Refs. 17-18).

Previous VLA observations of YZ CMi at 6cm indicate that the source is variable on timescales of tens of minutes to an hour (Ref. 1). The VLA data obtained on December 10, 1984 and shown in Figure 1 have been discussed in detail by Lang and Willson (Ref. 2). This figure shows that the emission at the lower frequencies undergoes slow variations on timescales of about an hour but that the peaks in total intensity at ν=1415 MHz and ν=1515 MHz occur at different times. This behavior seems to indicate a narrow band emission process of bandwidth $\Delta\nu \leq 100$ MHz or $\Delta\nu/\nu \leq 0.1$. The emission is also highly circularly polarized, and becomes more so as the flux level increases. There were no detectable variations at 6cm wavelength. As discussed by Lang and Willson (Ref. 2), the narrow band structure of the slowly varying radiation cannot be explained by continuum emission processes such as thermal bremsstrahlung, gyroresonant emission or non-thermal gyrosynchrotron radiation. It may be explained by coherent emission mechanisms such as an electron-cyclotron maser or coherent plasma radiation.

Our VLA observations at 20cm also indicate that YZ CMi was highly variable on September 30,1984 (Figure 2). On this day, however, the intensities at the two closely-spaced frequencies at ν=1465 MHz and ν=1415 MHz were the same, and for this reason we have averaged the data at these two frequencies. Here, as for the burst shown in Figure 1, the polarization is greatest ($\rho_c \approx 90\%$) at the peak of the burst.

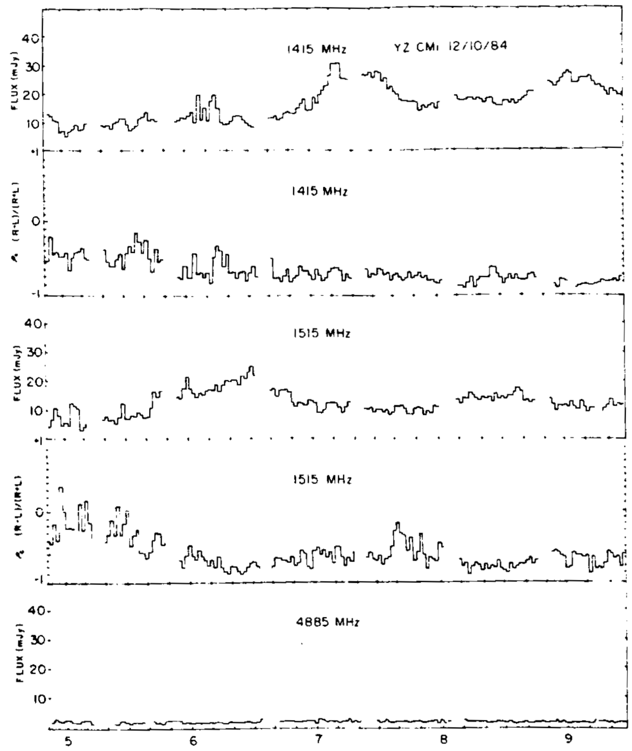

Figure 1.

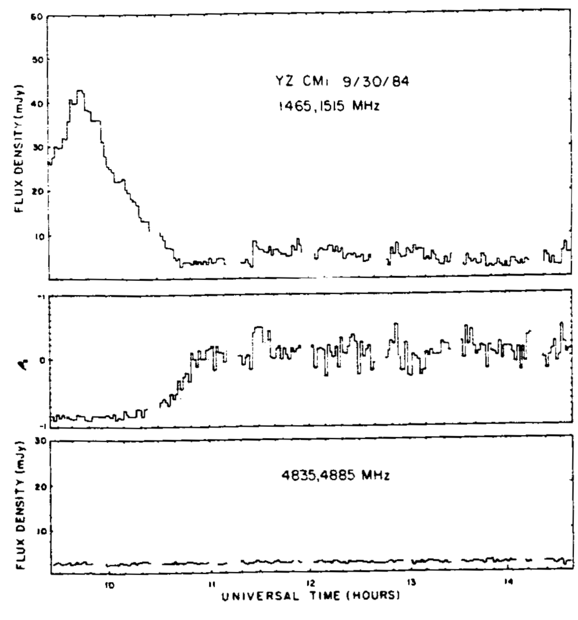

Figure 2.

As shown in Figure 3, the Mg II line intensities were also time variable. In this case, the IUE observations began about three hours before those at the VLA. Figure 3 shows that the Mg II line flux decreased from $\sim 2.6 \times 10^{-12}$ erg cm^{-2} s^{-1} to 1.4×10^{-12} erg cm^{-2} s^{-1} in about 30 minutes, reaching $\sim 1.0 \times 10^{-12}$ erg cm^{-2} s^{-1} about an hour later. Unfortunately, the high level of background noise between 0430 UT and 0730 UT made a direct comparison with the VLA data impossible. The only observation on September 30, 1984 indicates that the Mg II line flux had about the same value as that during the "active" period on December 10, 1984. For comparison, we note that the Mg II flux observed by Linsky et al (Ref. 19) was 1.3×10^{-12} erg cm^{-2} s^{-1}, or about equal to the lowest level on December 10, 1984.

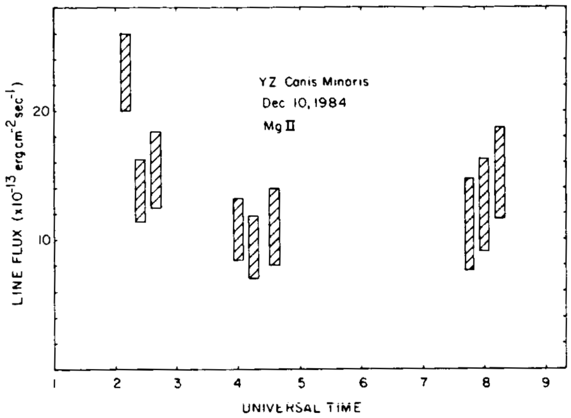

Figure 3.

3.2 AD Leonis

AD Leonis (GL 388) is an active dwarf M flare star known to exhibit frequent and intense bursts at optical (Ref. 20) and radio (Refs. 7,21) wavelengths. Our IUE observations on four successive days failed to show any dramatic changes in the Mg II line flux, although there is some indication of a small enhancement on November 8, 1984. The VLA data, however, indicate that the microwave fluxes did vary considerably from one day to the next (see Table 1). It was on November 8 that three impulsive bursts were detected, of which the most intense is shown in Figure 4. This figure shows that the burst, which was more intense at 6cm, had a rise time of ≤ 6.7 s, and was characterized by two impulsive peaks, each lasting about 20 s. The two weaker bursts, not shown here, were detected only at 6cm and were unpolarized, while the more intense burst shown in Figure 4 was 50% circularly polarized at 6cm and 30% circularly polarized at 20cm.

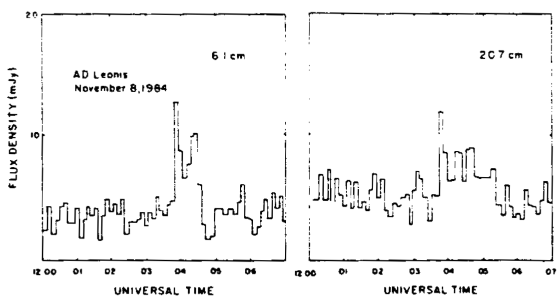

Figure 4.

The lack of of obvious correlation between the intensities of the ultraviolet and radio emission suggests that the activity was confined to the coronal regions of the star.

3.3 Lambda Andromeda

Lambda Andromeda (HR 8961) is an RS CVn system with an orbital period of 20.5 days. Detailed photometric studies show quasi-periodic optical variations that may be attributed to starspots (Refs. 22-23). Analyses of these variations suggest that the evolved, active star rotates about once every 54 days (Ref. 24). IUE observations have suggested a correlation between the intensities of ultraviolet spectral lines and this 54 day period (Ref. 24) and have also indicated that the star exhibits flarelike brightenings on timescales of several hours (Ref. 5).

Our VLA observations indicate that there were no detectable variations on any timescale ranging from 6.7 s to several hours at either 6cm or 20cm, and that the flux levels were about the same on both days of observation. The spectral index, α, between 6cm and 20cm was $\alpha=-0.3\pm0.1$, typical of a source emitting optically thin gyrosynchrotron radiation.

The IUE data, however, indicate variability of some of the emission lines on both days of observation. In Figure 5, we show the integrated line intensity of the CIV $\lambda=1549$ Å transition on June 10,1985. Here, the vertical error bars correspond to the 3-σ uncertainties as determined from the line fitting procedure and the horizontal error bars delineate the length of each SWP exposure. This figure shows that the CIV line intensity gradually increased from ~2×10^{-12} erg cm^{-2} s^{-1} at 1400 UT to ~3.3×10^{-12} erg cm^{-2} s^{-1} at 1900 UT and then decreased again about an hour later. For comparison, Baliunas, Guinan and Dupree (Ref. 5) observed Lambda Andromeda on November 6, 1982 and found that the CIV line intensity increased from ~ 2×10^{-12} erg cm^{-2} s^{-1} to 7×10^{-12} erg cm^{-2} s^{-1} over a period of several hours. The fact that no variations were detected during our VLA observations suggests that the activity occurred in the transition region or chromosphere, rather than in the corona of the star.

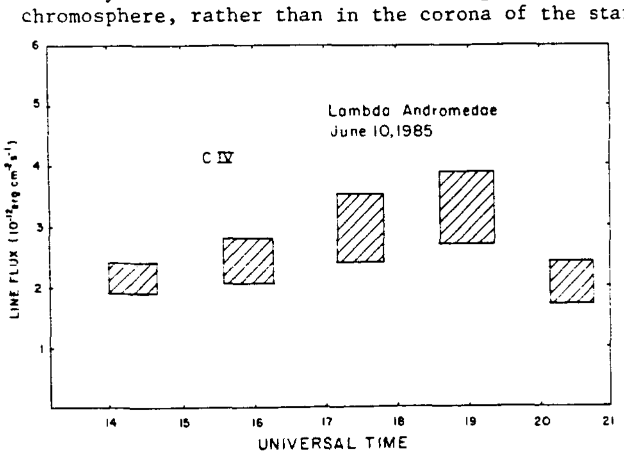

Figure 5.

4. ACKNOWLEDGEMENTS

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ULTRAVIOLET AND RADIO FLARES FROM UX ARIETIS AND HR 1099

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ABSTRACT

We present simultaneous observations of the RS CVn systems UX Arietis and HR 1099 with the International Ultraviolet Explorer (IUE) satellite and the Very Large Array (VLA). Flaring activity is observed at ultraviolet wavelengths with the IUE when none is detected at radio wavelengths with the VLA. We have also observed radio flares with no detectable ultraviolet ultraviolet activity. Thus, flares in the two spectral regions are either uncorrelated or weakly correlated. The flaring emission probably originates in different regions at the two wavelengths. Radio flares from RS CVn stars may originate in sources that are larger than, or comparable to, a star in size. This is in sharp contrast to compact, coherent radio flares from dwarf M stars. The ultraviolet flares from RS CVn stars probably originate in sources that are smaller than a component star.

I. INTRODUCTION

The RS Canum Venaticorum, or RS CVn, systems like UX Arietis and HR 1099 are binary stars whose components are late-type dwarfs or subgiants with spectral type G or K. Variations in their light curves and observations of Ca II H and K lines have respectively been associated with photospheric starspots and chromospheric plages that are probably on the K star [see Gondoin (1986) for HR 1099]. Extended transition regions are suggested by observations of intense ultraviolet emission lines [see Simon and Linsky (1980) for UX Arietis and HR 1099], and the fact that some RS CVn systems have been identified with soft X-ray sources suggests the presence of high-temperature coronal plasmas.

However, the relationship between the starspots, chromospheric activity, and the hypothetical coronal loops is not clear, particularly at times of stellar flares. Observations of asymmetries in the wings of ultraviolet emission lines have been interpreted in terms of mass upflow in unspotted regions [see Baliunas and Dupree (1982) for Lamda Andromedae], and similar asymmetries during an ultraviolet flare from UX Arietis have been interpreted in terms of mass flow along magnetic flux tubes that connect the K star to the G star [see Simon, Linsky and Schiffer (1980)]. Speculations about mass flow between the component stars might at first sight be related to radio flares from RS CVn stars, for they have been interpreted in terms of nonthermal gyrosynchrotron radiation from a volume that is several times larger than a star's size [see Feldman et al. (1978) for HR 1099]. However, previous coordinated ultraviolet and radio observations suggest that the ultraviolet emission is confined to a smaller volume on one star, and that there may not be a causal relation between activity in the two spectral regions [see Weiler et al. (1978) for UX Arietis and HR 1099].

In this paper we present simultaneous observations of UX Arietis and HR 1099 at ultraviolet and radio wavelengths. Flaring activity is observed at ultraviolet wavelengths when none is detected at radio wavelengths, and vice versa. The observations are given in § II where we show that flares in the two spectral regions are either uncorrelated or only weakly correlated. In § III we discuss these observations and use them with other data to argue that the flaring emission originates in different regions at the two wavelengths. Radio flares from RS CVn systems most likely originate in sources that are larger than, or comparable to, a star in size; but this is in sharp contrast to the radio radiation from dwarf M stars that emit coherent radiation from compact sources. Ultraviolet flares from RS CVn systems probably originate in sources that are smaller than a component star.

II. OBSERVATIONS

The RS CVn systems UX Arietis and HR 1099 were observed simultaneously with the International Ultraviolet Explorer (IUE) satellite and the Very Large Array (VLA) on 1987 January 6 and 7. UX Arietis was observed with the VLA from 0251 to 0757 UT on January 6 and with the IUE during the 8-hour U.S. Shift 2 on the same day (roughly 0 to 8 hours UT). HR 1099 was observed with the VLA from 2219 UT on January 6 to 0805 UT on January 7 and with the IUE during the 8-hour U.S. Shift 2 on January 7.

The VLA (C configuration) was divided into two subarrays of 13 antennas each in order to simultaneously observe at four frequencies. One subarray was used to observe at frequencies of 1465 MHz and 1515 MHz and the other one was used at 4835 MHz and 4885 MHz. The fringe visibilities were sampled at a rate of 6.67 s, and the data were calibrated from observations of PKS 0333 + 321 for 5 minutes every 40 minutes. The flux density scale was established from observations of 3C 286 (7.5 Jy at 4835 MHz and 14.7 Jy at 1465 MHz).

The VLA data were first examined, baseline by baseline, for any interference or obviously bad data that were removed. The edited data were then calibrated and used to make synthesis maps of the sources which were then cleaned and fitted with two-dimensional Gaussian functions in order to determine their locations to within about one-tenth of the beamwidth (3".7 x 4".3 at 4885 MHz, 12".7 x 14".4 at 1465 MHz). The 6.6 s data were then phase-shifted to bring the sources exactly into the center of the map. Finally, these data were vector-averaged, baseline by baseline, and used to construct plots of total intensity, I, and circular polarization, ρ_C, as a function of time. For a 6.6 s integration time, the theoretical 3σ rms noise level is ~ 7 mJy at 1465 MHz and 1465 MHz and ~ 6 mJy at 4885 MHz.

The IUE observations were made by alternately using the short wavelength (1175-2000 Å) SWP camera and the long wavelength (2000-3200 Å) LWP camera. The SWP observations were made at low dispersion (spectral resolution 6 Å) while the LWP observations were made at high dispersion (spectral resolution ~ 0.2 Å). The stars were observed through the large 10" x 20" aperture. Observations with each camera consisted of two or three time-trailed exposures of about 10 minutes each. Integrated line intensities were determined for each 10-minute interval and used to detect flares. When no flares were detected, the data were combined to give integrated line intensities over an interval of about 30 minutes. The SWP spectra of UX Arietis and HR 1099 contained a number of chromospheric and transition region lines, of which the most prominent are O I, C III, and C IV. Here we have plotted variations in the integrated intensity of the C IV line at 1549 Å, but similar variations were observed for the other two prominent lines. No variations were detected in the Mg II h + k lines observed with the LWP camera near 2800 Å.

The combined VLA and IUE data are shown in Figures 1 and 2. An intense ultra-violet flare was observed from UX Arietis at about 0530 UT on January 6 (Figure 1), but there was no detectable radio flare at either 4885 MHz or 1465 MHz (also Figure 1).

As illustrated in Figure 2, a circularly polarized radio flare was observed from HR 1099 at 1465 MHz at about 0500 UT on January 7, but there was no detectable flare at either 4885 MHz or at ultraviolet wavelengths. Both of the latter two wavelengths refer to lower levels in the stellar atmos phere than the longer 20.4 cm (1465 MHz) wavelength where the flare occurred. There is a possibility that the slow five-hour increase in the integrated intensity of the C IV line was related to subsequent triggering of the radio flare observed at higher levels in the stellar atmosphere, but the flare itself was not detected at the lower levels.

Thus, our simultaneous VLA-IUE observations of UX Arietis and HR 1099 indicate that intense ultraviolet flares are emitted from RS CVn systems when no radio flares are detected, and that radio flares are observed when no counterpart is detected at ultraviolet wavelengths. Previous observations of the RS CVn system Lamda Andromedae also indicated ultraviolet variations that were not detected at radio wavelengths with the VLA (Willson and Lang, 1986), and previous radio variations from UX Arietis at 4885 MHz were not detected at either 1465 MHz with the VLA or at ultraviolet wavelengths with the IUE (Willson and Lang, 1987). As discussed in greater detail in the next section, the flaring emission at different wavelengths probably originates in different regions, with shorter wavelengths referring to smaller regions that are deeper within the atmosphere of the active K star.

III. DISCUSSION

Weakly polarized ($\rho_C < 20\%$) radio radiation was always observed during our observations of HR 1099 with flux densities $S \approx 50$ mJy. A circularly polarized ($\rho_c \approx 55\%$) radio flare with $S \approx 100$ mJy was superimposed upon the weaker quiescent, or nonflaring, radiation. If the radius, R, of the radio source is comparable to the separation of the component stars ($R \approx 10^{12}$ cm) then the brightness temperatures, T_B, corresponding to these two values of flux density are $T_B = 2.3 \times 10^9$ K and $T_B = 4.6 \times 10^9$ K (using the Rayleigh-Jeans law with a distance of 33 pc). Similar brightness temperatures are inferred for the radio radiation from UX Arietis if the source is comparable in size to the separation of the component stars (Willson and Lang, 1987).

Thus, plausible brightness temperatures are inferred if the radio radiation originates in sources that are larger than the stellar size and comparable to the binary star separation. The radio flares can then be explained by nonthermal gyrosynchrotron radiation. The low-frequency cutoff of the spectrum of one burst from HR 1099 has been explained by synchrotron self-absorption in a source of this size with plausible magnetic field strengths, H, of H = 10 to 100 Gauss (Feldman et al., 1978). Such a large radio source size is consistent with VLBI observations of UX Arietis and HR 1099 at 4.98 GHz. UX Arietis has a radio halo with a linear size, L, of $L \approx 3 \times 10^{12}$ cm and a core of size $L < 3 \times 10^{11}$ cm (Mutel et al., 1985), and the upper limit to the radio size of HR 1099 is $L < 1 \times 10^{12}$ cm (Mutel et al., 1984). Detailed considerations of the self-absorption of gyrosynchrotron radiation indicate that the source size will increase at lower frequencies (Klein and Chiuderi-Drago, 1987), so even larger sources are expected at our observing frequencies near 1.4 GHz.

If the radio sources were smaller than a star in size, with radii $R < 10^{11}$ cm, then the brightness temperatures would be $T_B > 10^{12}$ K at our observing frequency of 1465 MHz (for a distance of 33 pc and an assumed flux of 200 mJy). Such a high brightness temperature suggests a coherent radiation mechanism. Compact, coherent radio sources have, in fact, been inferred from the rapid, millisecond variations in radio bursts from the dwarf M star AD Leonis (Lang and Willson, 1986a). The narrow-band structure expected for coherent radiation has also been observed in the radio radiation from another dwarf M star YZ Canis Minoris (Lang and Willson, 1986b, 1987) with bandwidths, $\Delta\nu$, of $\Delta\nu/\nu \approx 0.03$ at our observing frequency of $\nu \approx 1465$ MHz. If the RS CVn stars radiate similar narrow-band coherent emission, we might have detected a difference in the radiation observed at 1465 MHz and 1515 MHz. The variations and the signal level observed at these two frequencies were, within the observational uncertainties, identical during our observations of HR 1099. Moreover, the observed variations in the radio radiation had time scales $\tau > 30$ s, placing limits $L < 10^{12}$ cm on the linear size, using the light-travel time argument. Thus, the available data suggest that the RS CVn stars do not emit coherent radio radiation from compact sources that are much smaller than a star in size, and in this respect they differ from the dwarf M stars.

Radio bursts from RS CVn stars may originate in large-scale coronal loops that are anchored in the active K star but exceed it in size. Such loops have been suggested by extrapolations from transition region pressures using a hydrostatic scaling law (Simon and Linsky, 1980). They would be large enough to permit gyrosynchrotron radiation with plausible brightness temperatures and synchrotron self-absorption at low radio frequencies. The hot plasma trapped within these loops could also be of sufficiently low electron density, N_e, to permit the radio radiation to escape. Radiation at frequencies, ν, less than the plasma frequency $\nu_p = 8.9 \times 10^3 N_e^{1/2}$ would be absorbed. In order to detect the radiation observed from HR 1099 at 1465 MHz, the electron density must be $N_e < 10^{10}$ cm^{-3}.

Much higher electron densities are required to account for the ultraviolet emission lines observed during ultraviolet flares from RS CVn stars. This suggests that these flares originate close to the stellar transition region in sources that are most likely smaller than a component star in size. The fact that ultraviolet flares are not usually correlated with radio flares, and vice versa, is consistent with different sources for the radiation emitted in these two spectral regions, and the radiation at the shorter ultraviolet wavelengths most likely originates in smaller sources that lie deeper in the atmosphere of the K star. This suggests that mass flow between stars is not responsible for the ultraviolet flares of RS CVn stars, and that there must be some other explanation for the line asymmetries that led to speculations about such mass flows (Simon, Linsky and Schiffer, 1980).

Radio astronomical studies of the Sun and other active stars at Tufts University are supported under grant AFOSR-83-0019 with the Air Force Office of Scientific Research. Simultaneous observations of active stars with the International Ultraviolet Explorer (IUE) satellite and the Very Large Array (VLA) are also supported by NASA grant NAG 5-477. The VLA is operated by Associated Universities, Inc., under contract with the National Science Foundation.

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FIGURE LEGENDS

Fig. 1. VLA and IUE observations of UX Arietis on 1987 January 6. Plots of the total intensity, I, observed with the VLA at 1465 MHz (20.4 cm - top) and 4885 MHz (6.1 cm - middle) are compared with a plot of the integrated intensity of the C IV line (1549 Å) observed with the IUE (bottom). Here the vertical extent of each box corresponds to the 3σ noise level, while the horizontal extent denotes the time interval for each spectrum. In this case, the VLA observations did not begin until almost three hours after those with the IUE, but they did show that there was no detectable radio emission during the intense ultraviolet flare occurring at about 0530 UT.

Fig. 2. VLA and IUE observations of HR 1099 on 1987 January 6 and 7. Plots of the total intensity, I, and degree of circular polarization, ρ_C, observed with the VLA at 1465 MHz (20.4 cm - top) are compared with a plot of the total intensity observed with the VLA at 4885 MHz (6.1 cm - middle) and a plot of the integrated intensity of the C IV line (1549 Å) observed with the IUE (bottom). Here the vertical extent of each box corresponds to the 3σ noise level, while the horizontal extent denotes the time interval for each spectrum. Although there is a slow increase in the flux from the C IV line between 01 and 05 UT, the circularly polarized burst observed at 1465 MHz around 05 UT was not detected at either 4885 MHz or at ultraviolet wavelengths.

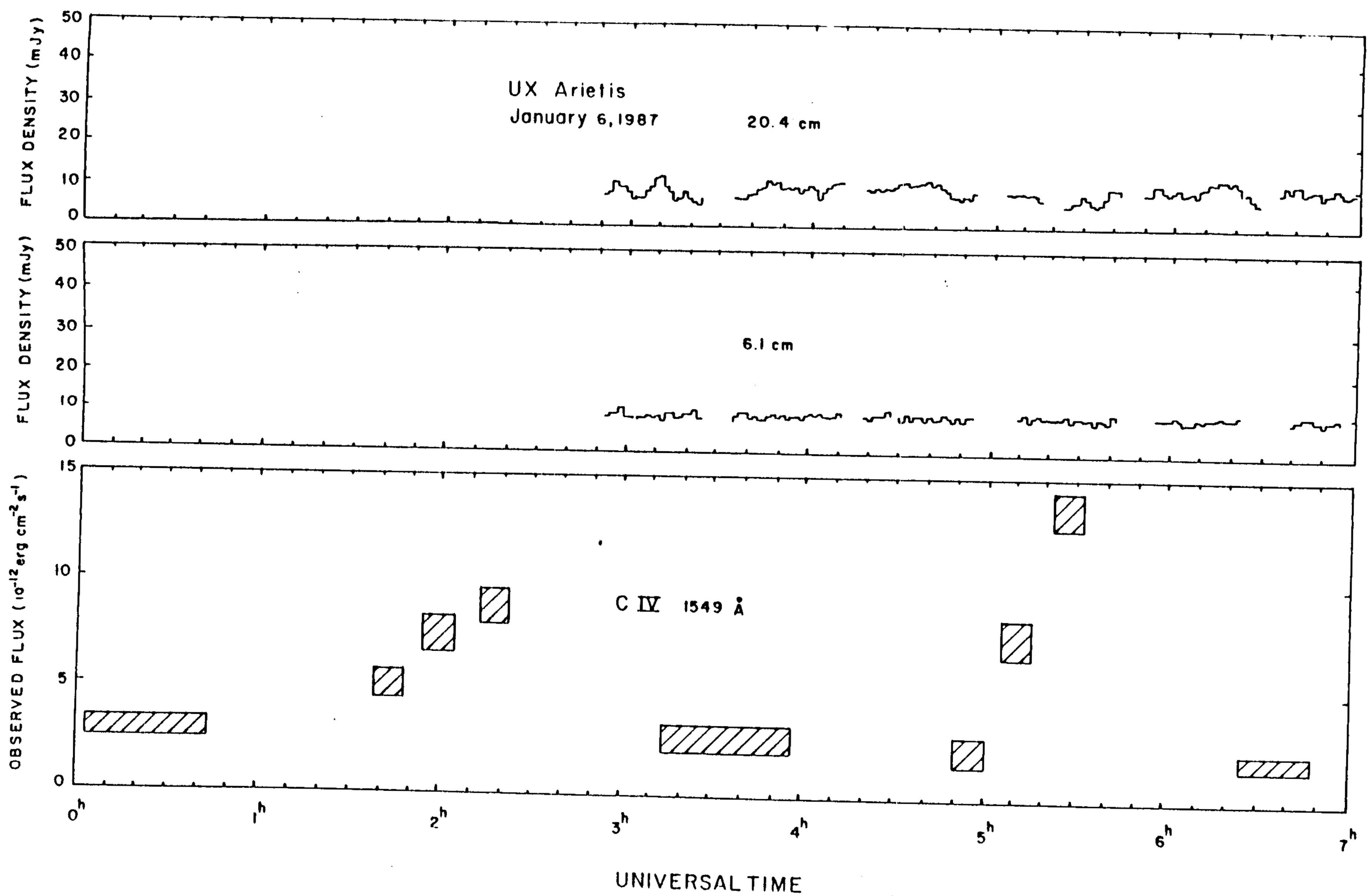
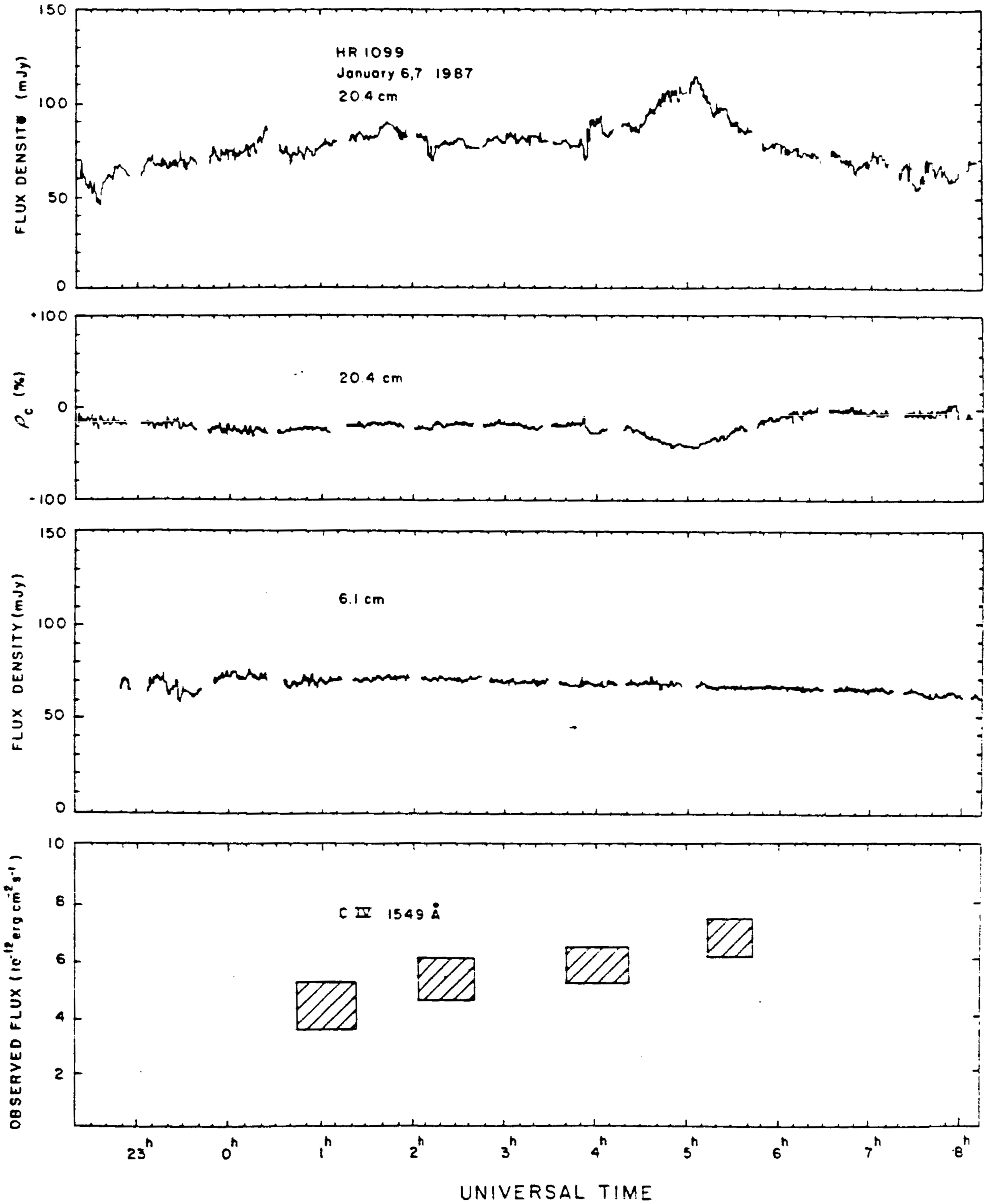

UX Arietis
January 6, 1987
20.4 cm
6.1 cm
C IV 1549 Å
FLUX DENSITY (mJy)
OBSERVED FLUX (10^{-12} erg cm^{-2} s^{-1})
UNIVERSAL TIME
50
40
30
20
10
0
15
5
0^h
1^h
2^h
3^h
4^h
5^h
6^h
7^h

Fig. 1.



HR 1099
January 6,7 1987
20.4 cm
FLUX DENSITY (mJy)
150
100
50
0
+100
0
-100
ρ_c (%)
20.4 cm
6.1 cm
FLUX DENSITY (mJy)
10
8
6
4
2
C IV 1549 Å
OBSERVED FLUX (10^{-12} erg cm^{-2} s^{-1})
23h
0h
1h
2h
3h
4h
5h
6h
7h
8h
UNIVERSAL TIME

Fig. 2.

IV. FUNDING

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