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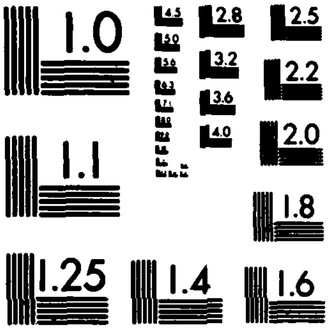

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BRIGHT, RAPID, HIGHLY POLARIZED RADIO SPIKES

FROM THE M DWARF AD LEO

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We have observed a radio burst from the main sequence (dM4.5e) star AD Leo at 1400 MHz from 0536 to 0556 UT on 1983 February 1 at the Arecibo Observatory. A rapid sequence of highly polarized spikes was observed during the gradual rise of a longer lasting, unpolarized event. The maximum flux density of the spikes was $S_{max} = 130$ mJy, and they had rise times $\tau \lesssim 200$ ms. The spikes were all 100% left hand circularly polarized with an instrumental uncertainty of 5%. The rise times provide an upper limit to the linear size

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$L \lesssim 6 \times 10^9$ cm for the emitter. Provided that the source is symmetric, it has an area that is less than three hundredths of the star's surface area. In this case, the lower limit to the brightness temperature of the spikes is $T_B \gtrsim 10^{13}$ K. The high brightness temperatures and high degrees of circular polarization are explained in terms of electron-cyclotron maser emission at the second harmonic of the gyrofrequency in longitudinal magnetic fields of strength $H_\ell \sim 250$ gauss. The unpolarized gradual component did not exhibit any rapid fluctuations, and it was entirely analogous to the thermal emission of solar bursts.

ABSTRACT

We have observed a radio burst from the main sequence (dM4.5e) star AD Leo at 1400 MHz from 0536 to 0556 UT on 1983 February 1 at the Arecibo Observatory. A rapid sequence of highly polarized spikes was observed during the gradual rise of a longer lasting, unpolarized event. The maximum flux density of the spikes was $S_{max} = 130$ mJy, and they had rise times $\tau \lesssim 200$ ms. The spikes were all 100% left hand circularly polarized with an instrumental uncertainty of 5%. The rise times provide an upper limit to the linear size $L \lesssim 6 \times 10^9$ cm for the emitter. Provided that the source is symmetric, it has an area that is less than three hundredths of the star's surface area. In this case, the lower limit to the brightness temperature of the spikes is $T_B \gtrsim 10^{13}$ K. The high brightness temperatures and high degrees of circular polarization are explained in terms of electron-cyclotron maser emission at the second harmonic of the gyrofrequency in longitudinal magnetic fields of strength $H_\ell \sim 250$ gauss. The unpolarized gradual component did not exhibit any rapid fluctuations, and it was entirely analogous to the thermal emission of solar bursts. The Arecibo Observatory has the potential of providing stringent limits on the linear size of "star spots" or "star loops" on active main sequence stars, and it also provides accurate circular polarization measurements.

Subject Headings. Radio sources: variable - stars: coronae - stars: flare - stars: main sequence - stars: late-type - star: radio radiation - Sun: radio radiation

I. INTRODUCTION

Very Large Array (V.L.A.) observations of the quiescent emission from solar active regions at 1400 MHz (21 cm wavelength) delineate looplike structures connecting regions of opposite magnetic polarity in the underlying photosphere. The quiescent emission at 1400 MHz is, in fact, the radio wavelength counterpart of the ubiquitous coronal loops detected at X-ray wavelengths (Lang, Willson and Rayrole, 1982). V.L.A. observations of solar bursts at 1400 MHz (Lang, Willson and Felli, 1981; Willson, 1982) reveal highly polarized (circular polarization $\rho_c \sim 80\pm15\%$) bursts composed of a sequence of spikes with rise times $\tau < 10$ s (the integration time at the V.L.A.). The high circular polarization implies magnetic field strengths of $H_\ell \sim 250$ gauss if the 1400 MHz radiation is at the second harmonic of the gyrofrequency. Spike-like events with rise times $\tau \lesssim 10$ ms have been observed during solar bursts at 1400 MHz (Dröge 1977) and 2600 MHz (Slottje 1978, 1980), indicating high brightness temperatures $T_B \gtrsim 10^{12}$ K that require coherent maser-like emission. The very high brightness temperatures and the high circular polarization of these spikes ($\rho_c \sim 100\%$) have been explained in terms of electron-cyclotron masers in which amplification occurs at the second harmonic of the gyrofrequency (Melrose and Dulk 1982a, b).

Nearby main sequence stars of late spectral type exhibit quiescent X-ray emission whose absolute luminosity may be as much as one hundred times that of the Sun (Vaiana et al. 1981, Johnson 1981). This suggests that these stars have large scale coronal loops and intense magnetic fields. In fact, surface magnetic fields of strength $H_\ell \sim 1000$ gauss covering as much as 60% of the stellar surface have been observed for several nearby main sequence stars of late spectral type (Marcy 1983, Giampapa, Golub and Worden 1983). The nearby dwarf M stars of the UV Ceti type also exhibit X-ray flares in which the X-ray emission can increase by as much as a factor of 30 in a few minutes. This suggests that these stars may exhibit quiescent emission at 1400 MHz which is related to their coronal loops, and that they might exhibit spike-like bursts at 1400 MHz which are analogous to those observed from the Sun. As a matter of fact, V.L.A. observations of the dwarf M stars UV Ceti (L726-8A,B) and YZ Cmi at 1400 MHz (Fisher and Gibson 1982) and L726-8A at 4900 MHz (Gary, Linsky and Dulk 1982) indicate that these stars do emit highly polarized radio bursts. Although these V.L.A. observations were limited by large integration times of 10 s and large instrumental uncertainties in circular polarization of up to 15%, lower limits to the burst brightness temperature $T_B \gtrsim 10^{10}$ to 10^{12} K could be obtained by assuming that the bursts cover an area smaller than the stellar disk.

In §II of this paper, we present observations of a burst at 1400 MHz from the dwarf M flare star AD Leo. Rapid (rise times $\tau \lesssim 200$ ms), highly polarized ($\rho_c \sim 100\%$), spike-like bursts occurred during the gradual rise of a longer lasting, unpolarized event. In §III we interpret the high brightness temperatures ($T_B \gtrsim 10^{13}$ K) and high polarization of the spike-like bursts in terms of electron-cyclotron maser emission at the second harmonic of the gyrofrequency with a longitudinal magnetic field strength of $H_\ell \sim 250$ gauss.

II. OBSERVATIONS

On 1983 February 1, we observed the dM4.5e star AD Leo [$\alpha(1950.0) = 10^h16^m54^s$, $\delta(1950.0) = 20°17'18''$] at a frequency of 1400.0 MHz (21.4 cm wavelength) from 0520 to 0619 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} erg s^{-1} cm^{-2} Hz^{-1}). Both the left hand circularly polarized (LCP) and right hand circularly polarized (RCP) signals were recorded using separate receivers. The ellipticity was 0.95 and the uncertainty in circular polarization due to cross-talk between the two receivers was 5%. A bandwidth of 20 MHz and an integration time of 0.2 s were employed with digital sampling at the Nyquist rate of 0.1 s. The flux density scale was established using a 2 K noise source which was calibrated by observations of 3C 245 (3.06 Jy at 1400 MHz) immediately after the observations of AD Leo.

As illustrated in Figure 1, a highly polarized (LCP) impulsive burst lasting almost three minutes occurred during the gradual rise of an unpolarized event that lasted twenty minutes. When the impulsive burst is examined with higher time resolution (Figure 2), a sequence of highly polarized spikes is detected. This is entirely analogous to the microwave bursts from solar active regions (Slottje 1978, 1980), where the gradual event is interpreted as the bremsstrahlung of a high temperature, thermal plasma, and the spiked emission is attributed to nonthermal radiation that typically occurs during the rise phase of the thermal flare.

The spikes shown in Figure 2 are also similar to those observed in solar radio bursts (Lang, Willson and Felli 1981; Slottje 1978, 1980). The spikes were 100% left hand circularly polarized. The polarization did not change during the emission of successive spikes, suggesting that the magnetic field structure does not change during spike emission. The maximum flux density of the individual spikes was 130 mJy. Here we notice that V.L.A. observations with 3 s integration time would smooth out the individual spikes and lead to an underestimate of their flux density. The data shown in Figure 2 contain "quasi-periodic" fluctuations at time scales of about 2 s, 10 s and

25 s. Quasi-periodic oscillations with a period of about 56 s have been reported for a microwave flare from the M dwarf L726-8A (Gary, Linsky and Dulk 1982); but power spectral analysis of our AD Leo data indicate that no single periodicity dominates the spectrum.

Of special interest is the rise time of the individual spikes. As illustrated in Figure 3, the three most intense spikes all had a measured rise time of about 300 ms. Because the integration time was 200 ms, the actual rise time $\tau \lesssim 200$ ms (from the convolution relation). An upper limit to the linear size, L, of the emitting region, estimated by the distance that light travels in 200 ms, is $L \lesssim 6 \times 10^{9}$ cm. A dM4.5e star is expected to have a radius $R = 0.5\ R_{\odot} = 3.5 \times 10^{10}$ cm, and the emitting region therefore had a linear size which is at least six times smaller than the star's radius. Provided that the burst emitter is symmetric, it has an area which is less than three hundredths of the stellar surface area. We can use the maximum flux density $S_{max} = 130$ mJy (1 mJy = 10^{-26} erg s^{-1} cm^{-2} Hz^{-1}) to infer a lower limit to the brightness temperature, $T_B \gtrsim 10^{13}$ K using the Rayleigh-Jeans expression (Lang 1980) and assuming a symmetric source of linear size $L \lesssim 6 \times 10^{9}$ cm.

III. DISCUSSION

The high brightness temperature $T_B \gtrsim 10^{13}$ K of radio bursts from AD Leo and the Sun can be explained by maser emission. The high degrees of circular polarization ($\rho_c \sim 100\%$) are intimately related to the intense magnetic fields of these stars. For instance, Twiss (1958) and Twiss and Roberts (1958) pointed out that both the high brightness temperatures and the high degrees of circular polarization of solar radio bursts might be explained by the masing action of electrons that are trapped within magnetic loops and radiate at the first few harmonics of the gyrofrequency $\nu_H = 2.8 \times 10^{6}\ H_{\ell}$ Hz, where H_{ℓ} is the longitudinal magneti field strength. Melrose and Dulk (1982a, b) have applied this radiation mechanism to solar and stellar bursts having rapid variations with high brightness temperatures and high degrees of circular polarization. Because radiation at the first harmonic of the gyrofrequency cannot escape from such hot, dense plasmas, they attributed the bursts to masers operating at the second harmonic (n=2) of the gyrofrequency, ν_H. At our observing frequency $\nu = 1.4 \times 10^9$ Hz, we obtain a longitudinal magnetic field strength of $H_\ell = 250$ gauss from $\nu = n\nu_H = 5.6 \times 10^6 H_\ell$, where $n = 2$ and the gyrofrequency $\nu_H = 2.8 \times 10^6 H_\ell$. Further evidence for a strong magnetic field is provided by the intense X-ray emission from AD Leo. Its absolute X-ray luminosity is $L_X = 10^{29.0}$ erg s^{-1}, which is at least ten times the Sun's X-ray luminosity. The flare star AD Leo must therefore have a magnetic field strength at least as strong as that of the Sun (cf. Golub 1983), and the electron-cyclotron maser interpretation is consistent with this.

We would also like to point out the potential of using the Arecibo Observatory for studies of active main sequence stars. Accurate circular polarization measurements are one advantage. The rapid time sampling capability of better than 1 ms will allow one to resolve the individual spike-like components of the radio bursts. Measurements of the rise-time of the spikes will establish upper limits to the size of the emitting source, and determine a limit to the fraction of the stellar surface area that is involved in the emission.

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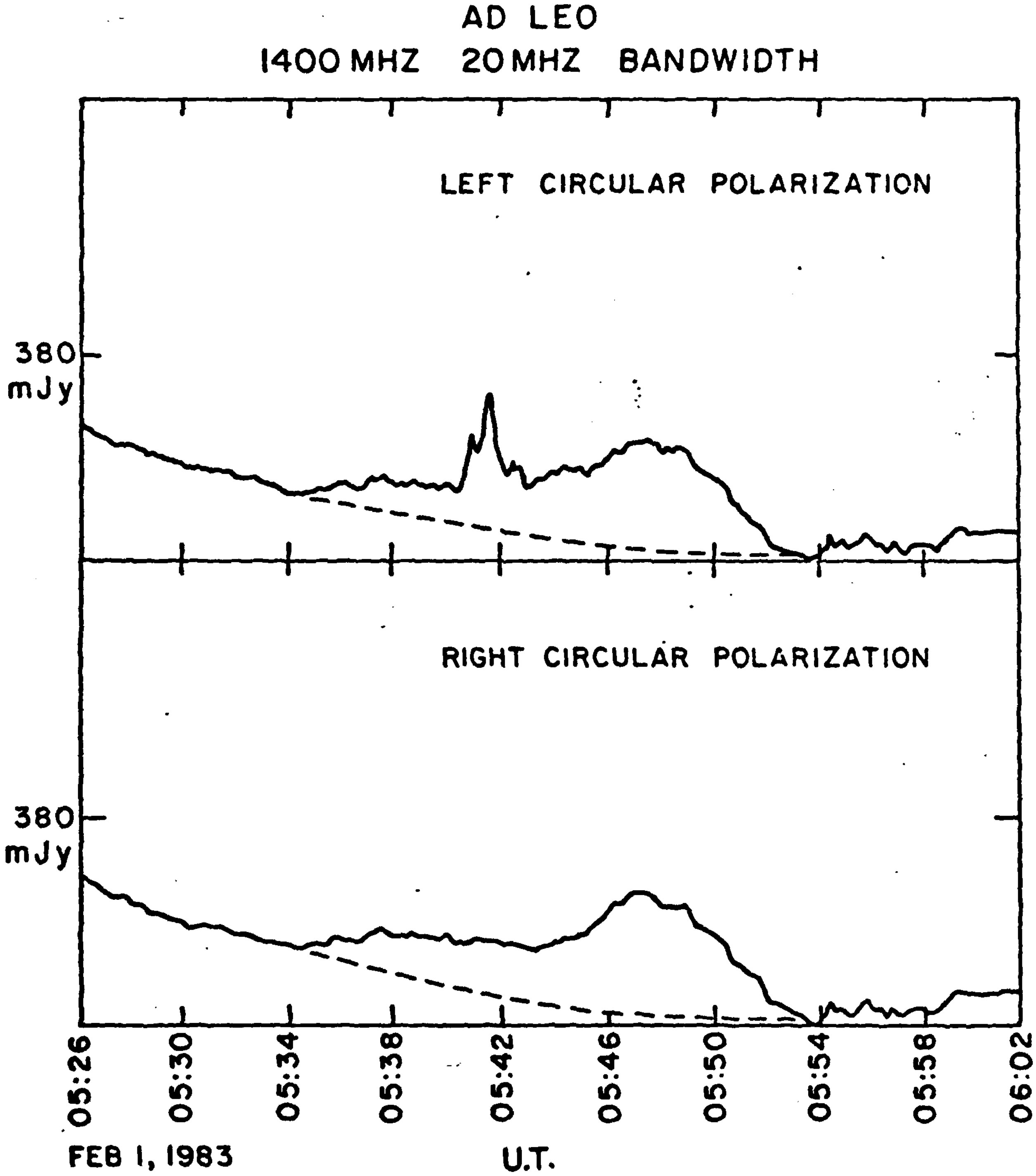
FIGURE LEGENDS

Fig. 1. The total power detected at a signal frequency of 1400 MHz while tracking the dwarf M star AD Leo. Both the right hand circularly polarized (RCP) and left hand circularly polarized (LCP) signals are given. A highly polarized (LCP) impulsive burst lasting almost three minutes occurs during the gradual rise of an unpolarized burst lasting about twenty minutes. Because of the long integration time the rapid-spikes that make up the impulsive burst have been smoothed out and their flux densities underestimated (see Figure 2 for the correct details).

Fig. 2. Rapid, highly polarized spikes observed during a 1400 MHz radio burst from the dwarf M star AD Leo. Both the right hand circularly polarized (RCP) and the left hand circularly polarized (LCP) signals are given. Notice that the burst emission occurs in a sequence of spikes which are all 100% left hand circularly polarized. The time profiles of the spikes denoted by the numbers 1, 2 and 3 are given in Figure 3.

Fig.3. Time profiles of the spikes marked 1, 2 and 3 in Figure 2. The digital sampling rate was 100 ms, the integration time 200 ms and the distance between fiducial marks on the time axis is 500 ms. Each of these spikes has a rise time $\tau \overset{<}{\sim}$ 200 ms.

Fig. 1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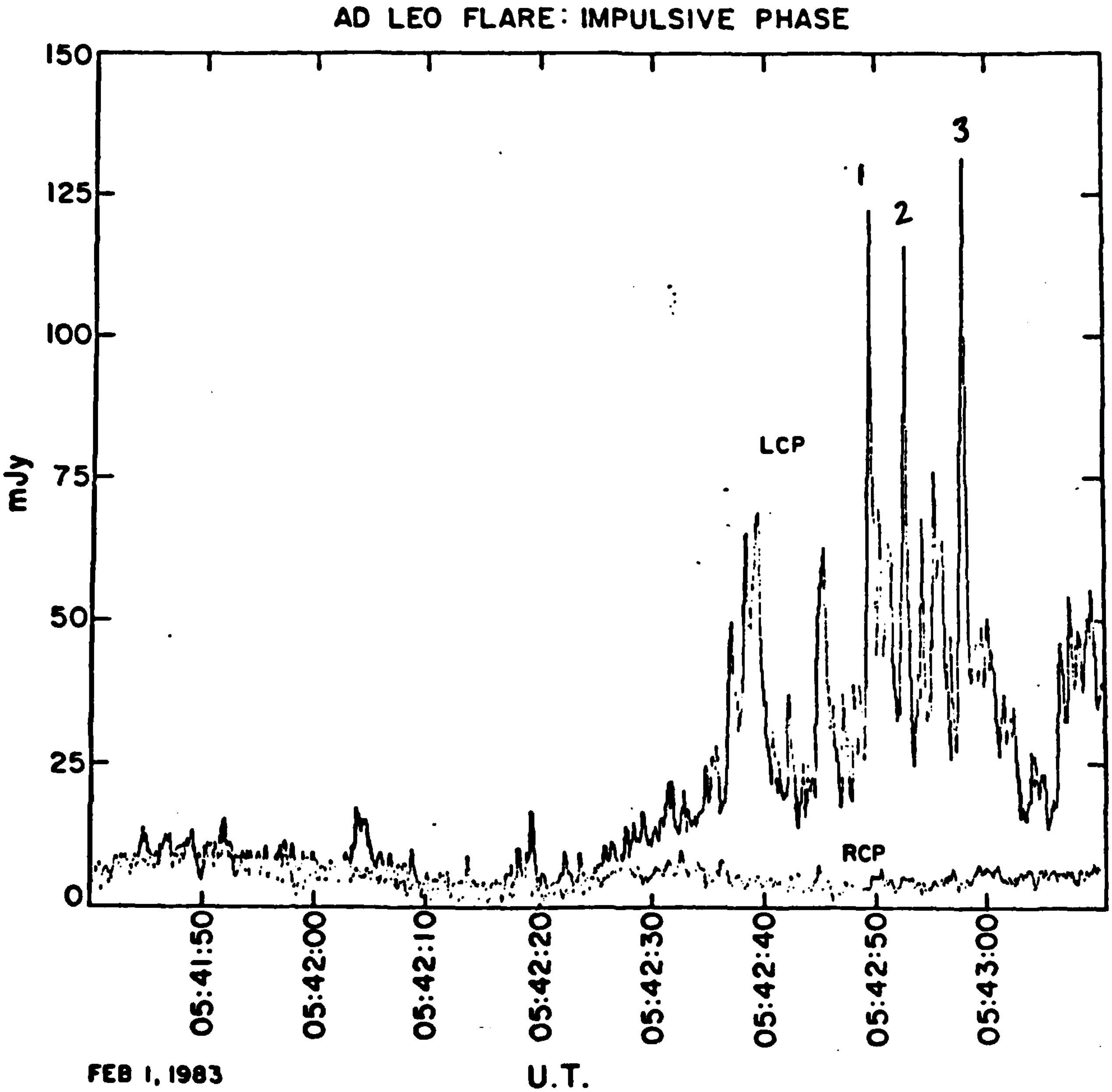
1400 MHZ 20 MHZ BANDWIDTH
LEFT CIRCULAR POLARIZATION
380
mJy
RIGHT CIRCULAR POLARIZATION
380
mJy
05:26
05:30
05:34
05:38
05:42
05:46
05:50
05:54
05:58
06:02
FEB 1, 1983
U.T.

Fig. 2a.


AD LEO FLARE: IMPULSIVE PHASE
150
125
100
75
50
25
0
mJy
LCP
RCP
1
2
3
05:41:50
05:42:00
05:42:10
05:42:20
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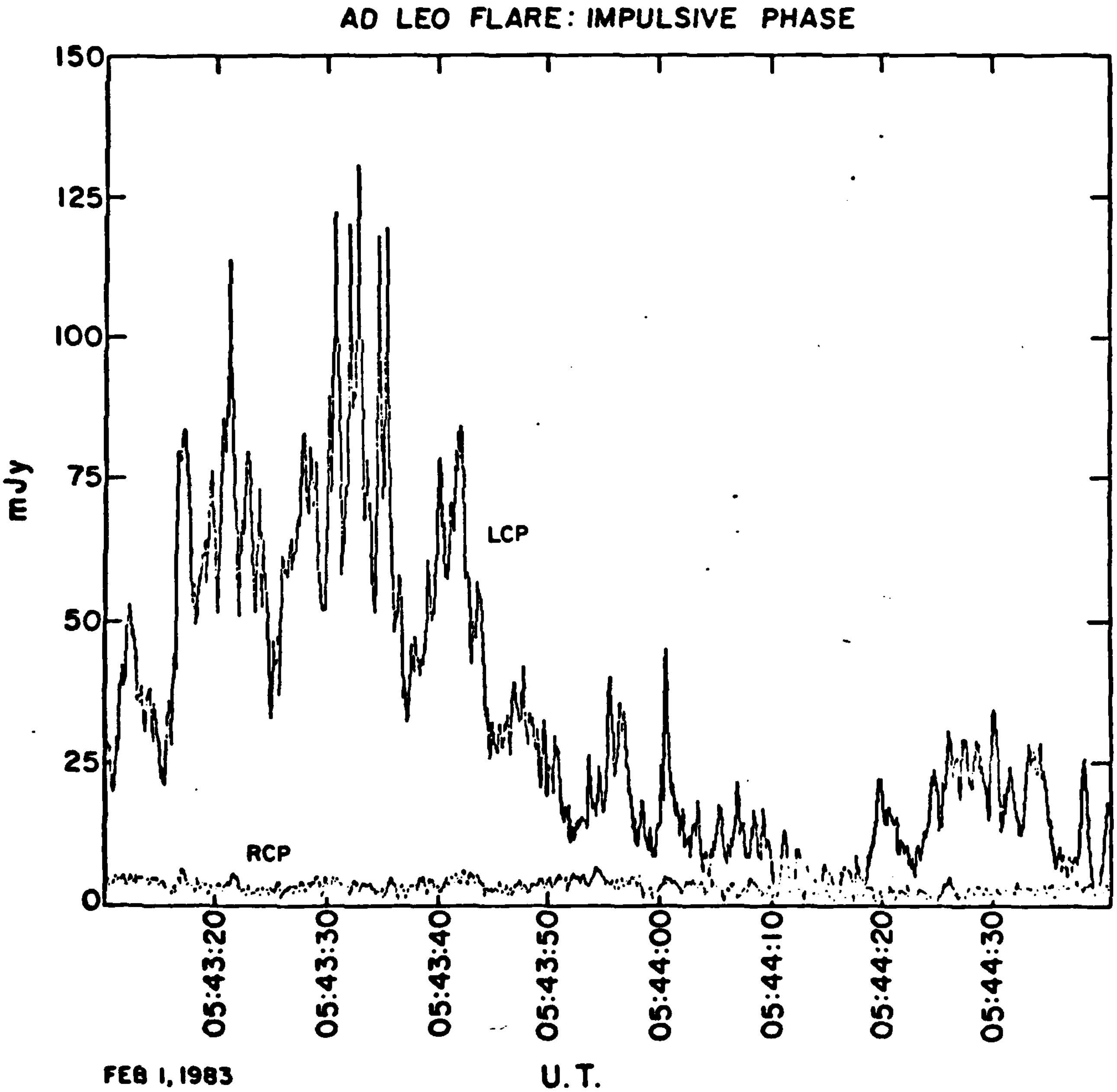
FEB 1, 1983
U.T.

Fig 2b.



AD LEO FLARE: IMPULSIVE PHASE
150
125
100
75
50
25
0
mJy
LCP
RCP
05:43:20
05:43:30
05:43:40
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05:44:00
05:44:10
05:44:20
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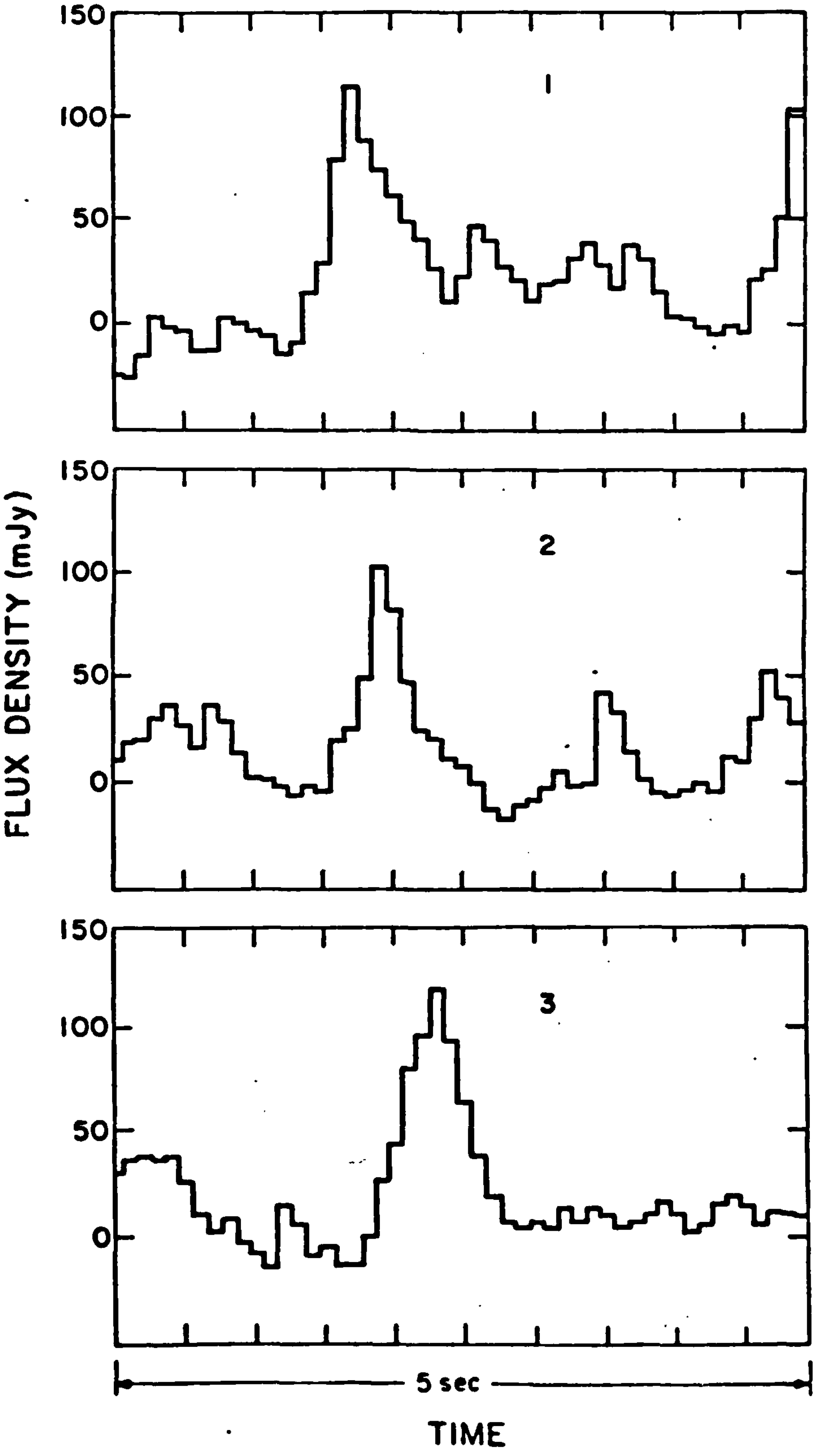
FEB 1, 1983
U.T.

Fig. 3.



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