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ULTRAVIOLET AND RADIO FLARES FROM UX ARIETIS AND HR 1099

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

We present simultaneous observations of the RS CVn systems UX Ari 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 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.
Subject headings: stars: binaries — stars: flare — stars: individual (UX Ari, HR 1099) — stars: radio radiation — ultraviolet: spectra

I. INTRODUCTION

The RS CVn systems like UX Ari 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 been associated, respectively, 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 Ari and HR 1099), and the fact that essentially all RS CVn systems have been identified with soft X-ray sources suggests the presence of high-temperature coronal plasmas (Walter *et al.* 1980).

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 λ And), and similar asymmetries during an ultraviolet flare from UX Ari 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 or around (as in mass loss) 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 volume (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 Ari and HR 1099).

In this paper we present simultaneous observations of UX Ari 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 Ari (HD 21242) and HR 1099 (HD 22468, V711 Tau) were observed simultaneously with the *International Ultraviolet Explorer* (*IUE*) satellite and the Very Large Array (VLA) on 1987 January 6 and 7. UX Ari was observed with the VLA from 0251 to 0757 UT on January 6 and with the *IUE* during the 8 hr US 2 shift on the same day (roughly 0000–0800 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 hr US 2 shift 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. 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 ($3''.7 \times 4''.3$ at 6 cm and $12''.7 \times 14''.4$ at 20.4 cm). 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. Because the fluxes at the two closely spaced IF's at 6 cm and 20 cm showed no evidence of narrow-band structure, they were averaged together to improve the signal-to-noise ratio. For a 6.6 s integration time the 3 σ rms noise level on the averaged maps is ~ 10 mJy at 20.4 cm and ~ 7 mJy at 6 cm.

The *IUE* observations were made by alternately using the short-wavelength (1150–1975 Å) SWP camera and the long-wavelength (1910–3300 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). In both cases the stars were observed through the large 10″ × 20″ aperture. Observations with the SWP camera consisted of two or three multiple exposures placed side-by-side in the large aperture and perpendicular to the spectral dispersion. Each SWP exposure was about 10 minutes long, while the LWP observations consisted of a single 15 minute exposure. During these observations the background radiation level was moderately low and fairly constant with flux counts, DN, of 18–25 for the SWP camera and 32–45 for the LWP camera.

The spectra were extracted from the photometrically corrected images, and the absolute flux calibration of Bohlin and Holm (1980) was applied to the SWP data. Because the absolute calibration of the high-resolution LWP spectra is still controversial, we decided to analyze relative spectral values only. We also examined the spectra for cosmic-ray events or "hits," but none were found.

In Figures 1–4 we show the *IUE* spectra for both stars. Here, third order polynomial baselines have been removed from the data. The SWP spectra contain a number of chromospheric and transition region ($T_e = 10^4$–2×10^5 K) lines, of which the most prominent are C IV, O I, and C II. The LWP spectra show the relative intensities of the Mg II *k* line at a wavelength of ~ 2796 Å. Each spectral feature was fitted, using a least-squares procedure, with a Gaussian profile in order to determine the peak intensity, ΔI_L, the full width at half-maximum, $\Delta\lambda_L$, and the central wavelength, λ_L, of the line. The integrated line intensity was then taken to be equal to 1.06 ΔI_L $\Delta\lambda_L$, appropriate for a Gaussian function. When no variations were detected, the spectrum from each 10 minute SWP exposure was averaged to give an integrated line intensity over an interval of 30 minutes.

The combined VLA and *IUE* data are shown in Figures 5 and 6. An intense ultraviolet flare was observed from UX Ari at about 0530 UT on January 6 (Fig. 5), but there was no detectable radio burst at either 6 cm or 20 cm. Here, we have plotted the variations in the integrated line intensity of the C IV line at 1549 Å, but similar variations were observed from some of the other prominent SWP lines (Fig. 1). Our analysis of the LWP spectra (Fig. 2) also indicates that the relative intensity of the Mg II *k* line increased more or less monotonically by about a factor of 1.6 ± 0.1 during the 5 hr period of observation.

In Table 1 we give the intensities of the SWP lines during the quiescent period preceding the flare (spectrum A at 0005 UT) and at the flare peak (spectrum D3 at 0522 UT). We note that the intensities of these lines are in reasonably good agreement with those given by Simon and Linsky (1980), also during a period of quiescence.

As illustrated in Figure 6, 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 atmosphere than the longer 20.4 cm (1465 MHz) wavelength where the flare

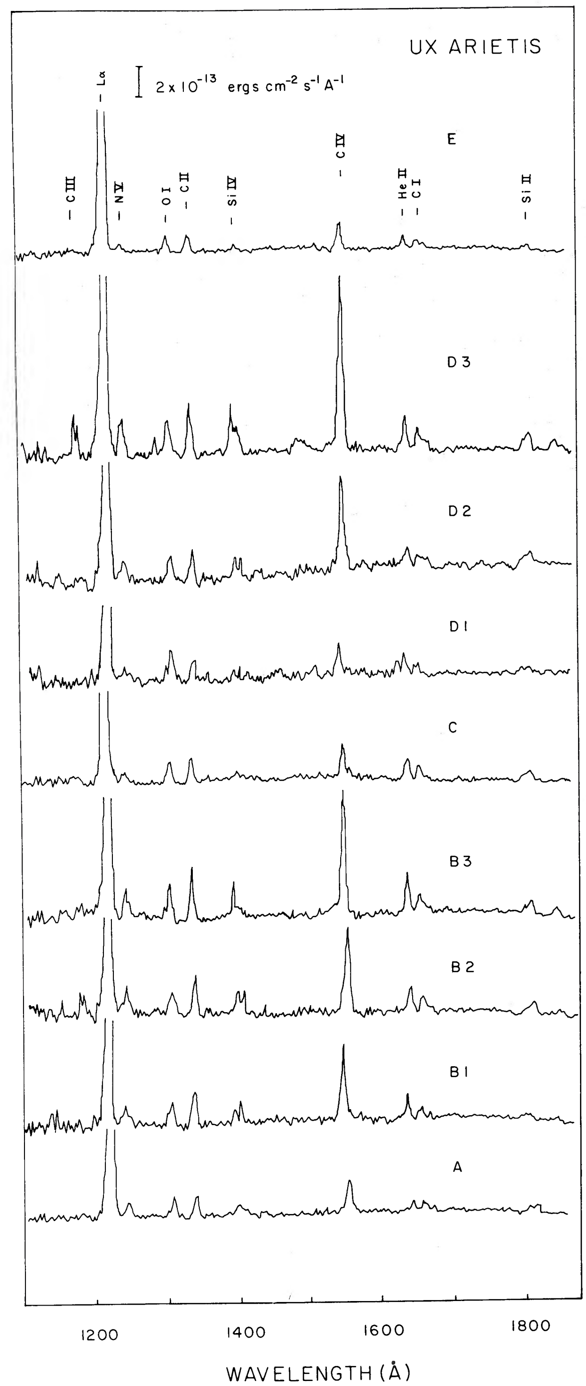

FIG. 1.—Short-wavelength (SWP), low-dispersion spectra of UX Ari on 1987 January 6. The time covered by each exposure can be inferred from Fig. 5, which shows the integrated intensity of the C IV line (1549 Å) throughout the day.

occurred. There is a possibility that the slow 5 hr increase in the integrated intensity of the C IV line (Fig. 3) 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. There were also no detectable variations in the intensity of the Mg II *k* line, to an uncertainty of $\sim 10\%$ (Fig. 4).

Thus, our simultaneous VLA-*IUE* observations of UX Ari

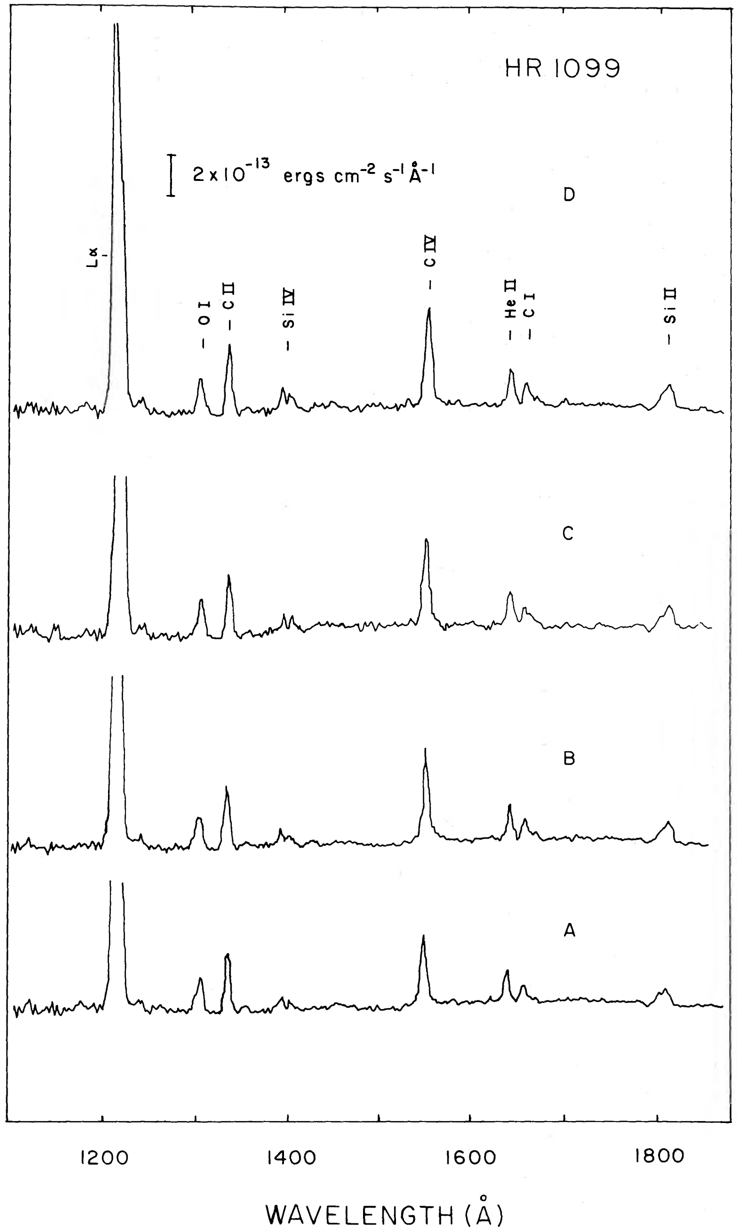

FIG. 2.—Long-wavelength (LWP), high-dispersion spectra of UX Ari on 1987 January 5 and 6, showing the relative intensities of the Mg II *k* line. Here, time increases toward the top of the figure.

TABLE 1

INTEGRATED LINE FLUXES FOR QUIESCENT AND FLARE SPECTRA OF UX ARIETIS

		Flux	
Line	λ (Å)	Quiescent ($\times 10^{-13}$ ergs cm^{-2} s^{-1})	Flare ($\times 10^{-13}$ ergs cm^{-2} s^{-1})
C III	1175	<2	13
N V	1240	<2	16
O I	1304	10	23
C II	1335	10	25
C IV	1549	18	85
He II	1640	5	14
C I	1657	4	16
Si II	1808, 1817	5	9

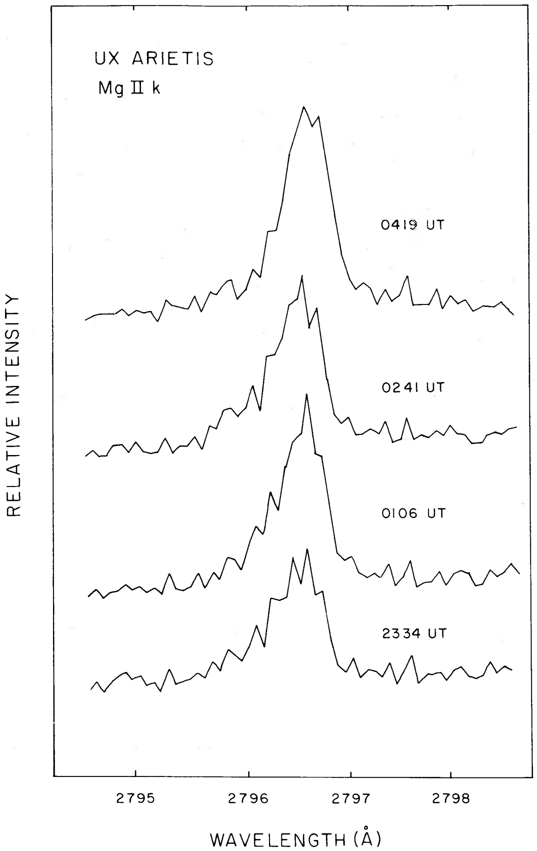

FIG. 3.—Short-wavelength (SWP), low-dispersion spectra of HR 1099 on 1987 January 7. The time covered by each exposure can be inferred from Fig. 6, which shows the integrated intensity of the C IV line (1549 Å) throughout the day.

and HR 1099 indicate that intense ultraviolet flares are emitted from RS CVn systems when no radio flares are detected and that a radio flare is observed when no counterpart is detected at ultraviolet wavelengths. Previous observations of the RS CVn system λ And also indicated ultraviolet variations that were not detected at radio wavelengths with the VLA (Willson and Lang 1986), and previous radio variations from UX Ari 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 ($\rho_c \leq 20\%$) 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 $S \approx 120$ mJy was superposed upon the weaker, more slowly varying, 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 $T_B = 5.6 \times 10^9$ K (using the Rayleigh-Jeans law with a distance of 33 pc). Similar brightness temperatures are inferred for the radio radiation from UX Ari 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 $H = 10$–100 G (Feldman *et al.* 1978). Such a large radio source size is consistent with VLBI observations of UX Ari and HR 1099 at 4.98 GHz. UX Ari has a radio halo with a linear size, L, of $L \approx 3 \times 10^{12}$ cm and a core of size $L \leq 3 \times 10^{11}$ cm (Mutel *et al.* 1985), and the upper limit to the radio size of HR 1099 is $L \leq 1 \times 10^{12}$ 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 $R \leq 10^{11}$ cm, then the brightness temperatures would be $T_B \geq 10^{12}$ K at our observing frequency of 1465 MHz (for a distance of 33 pc and an assumed flux of 120 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 Leo (Lang and Willson 1986*a*). The

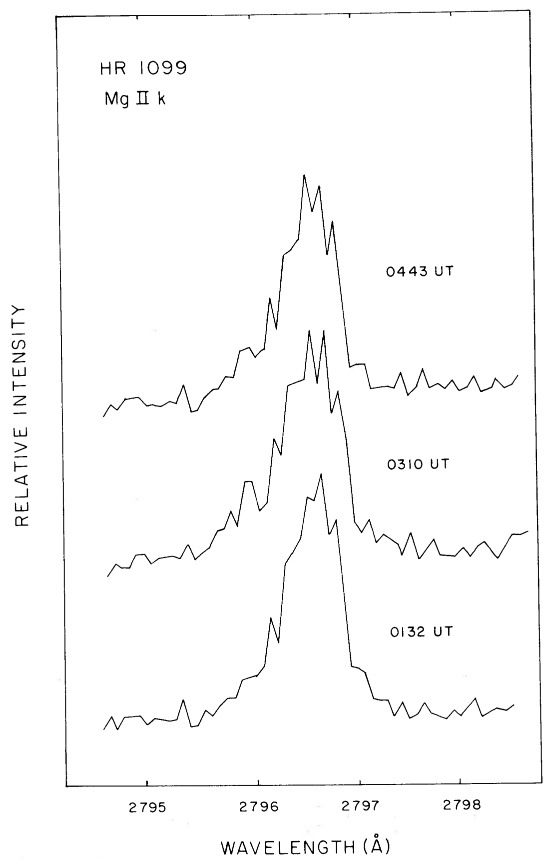

FIG. 4.—Long-wavelength (LWP), high-dispersion spectra of HR 1099 on 1987 January 7, showing the relative intensities of the Mg II k line.

narrow-band structure expected for coherent radiation has also been observed in the radio radiation from other dwarf M stars, including YZ Cmi (Lang and Willson 1986*b*, 1987) and UV Ceti (Bastian and Bookbinder 1987). 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 $\tau \geq 30$ s, suggesting $L \geq 10^{12}$ cm, if the source expands at the speed of light. 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 $N_e \leq 10^{10}$ 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 the ultraviolet flares were not 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).

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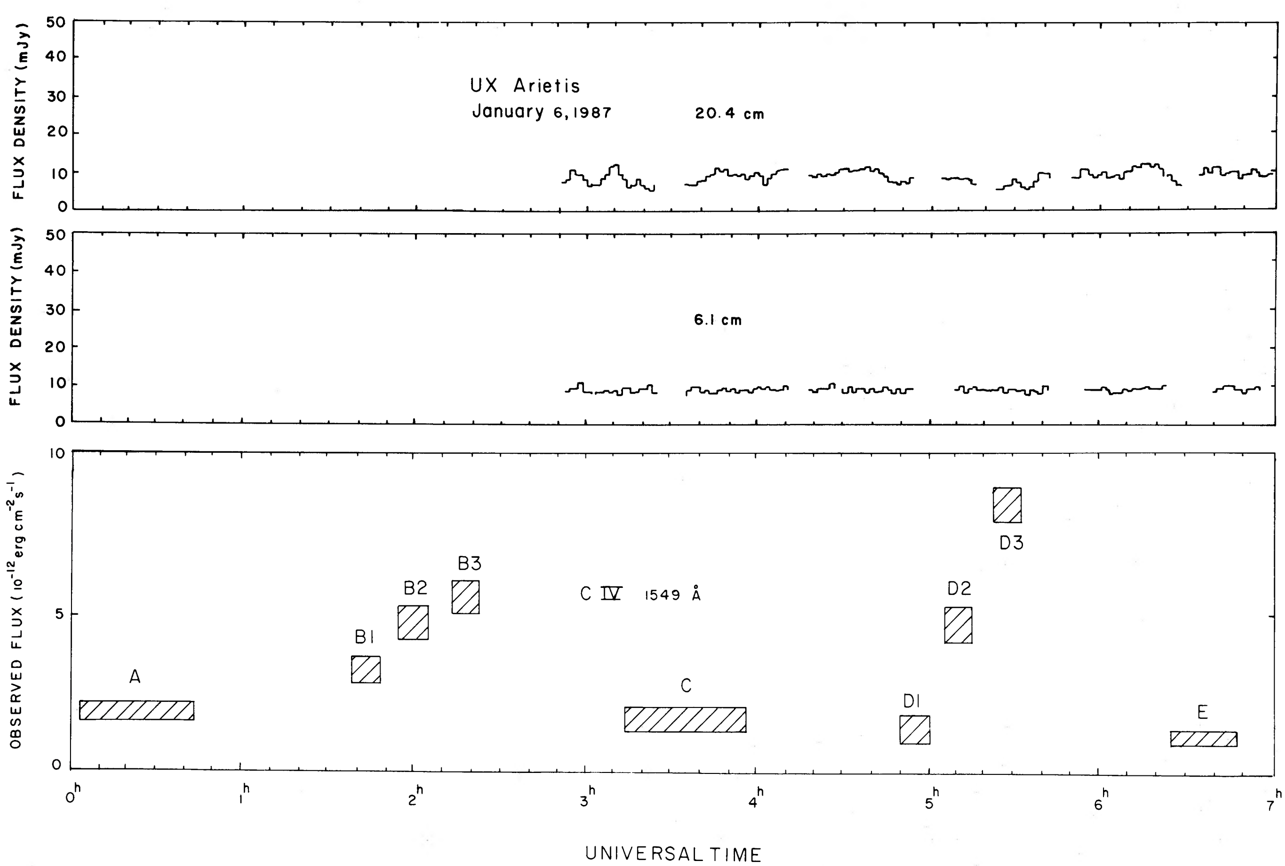

FIG. 5.—VLA and *IUE* observations of UX Ari on 1986 January 6. Plots of the total intensity, *I*, observed with the VLA at 1465 MHz and 1515 MHz (*top*) and 4835 MHz 4885 MHz (*middle*) are compared with a plot of the integrated intensity of the C IV line (1549 Å) observed with the *IUE* (*bottom*). Here the VLA data have been averaged over a time interval of 60 s. The vertical extent of each box corresponds to the 3 σ uncertainty in line intensity, determined by our fitting procedure, while the horizontal extent of each box denotes the time interval for each spectrum. The labels refer to the SWP spectra shown in Fig. 1. In this case, the VLA observations did not begin until almost 3 hr after those with the *IUE*, but they did show that there was no detectable radio emission during the ultraviolet flare occurring at about 0530 UT.

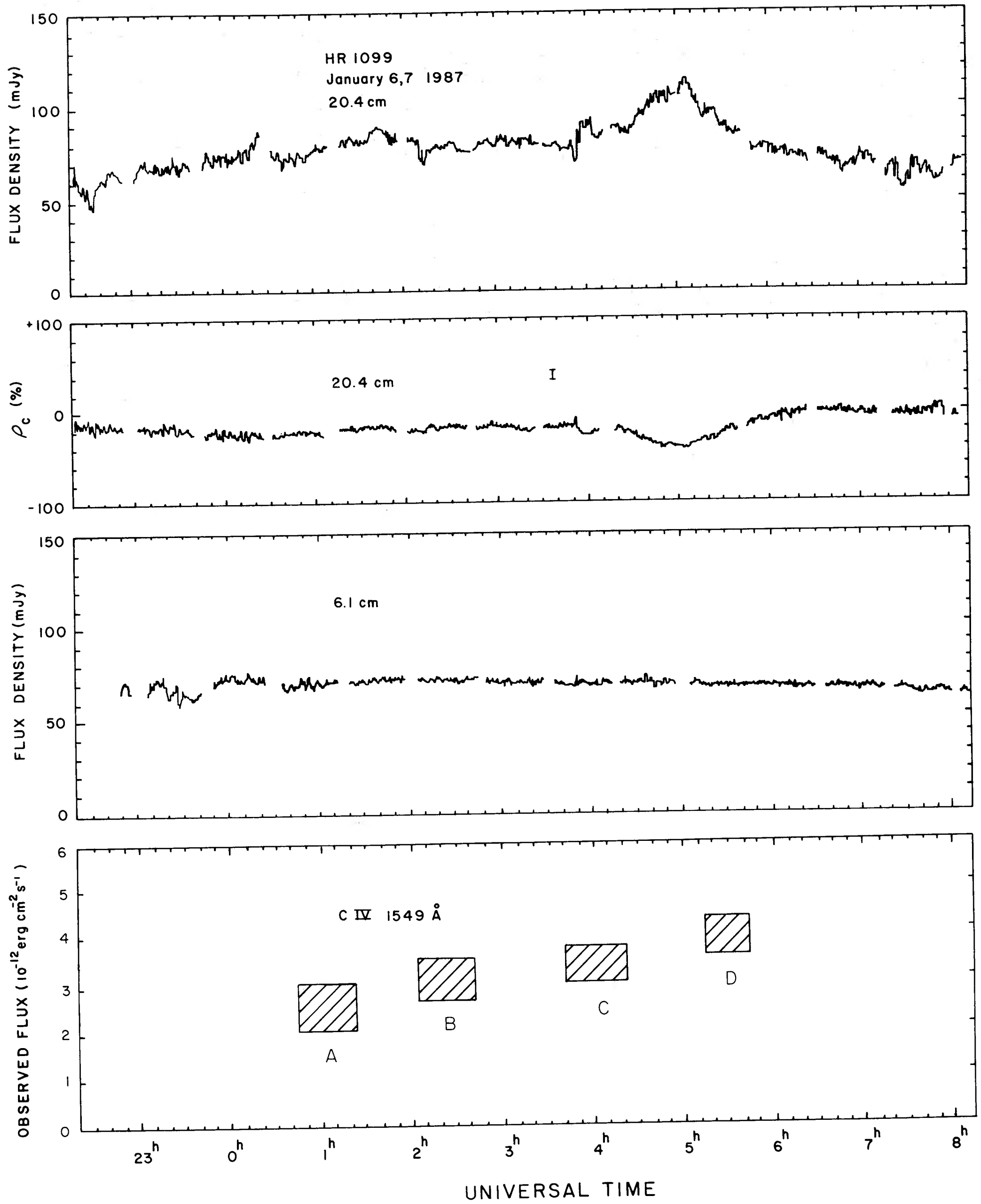

FIG. 6.—VLA and *IUE* observations of HR 1099 on 1987 January 6 and 7. Plots of total intensity, I, and degree of circular polarization, ρ_c, observed with the VLA at 1465 MHz and 1515 MHz (*top*) are compared with a plot of the total intensity observed with the VLA at 4835 MHz and 4885 MHz (*middle*) and a plot of the integrated line intensity of the C IV line (1549 Å) observed with the *IUE* (*bottom*). Here, the VLA data have been averaged over a time interval of 33.3 s, and the vertical bar on the polarization plot is the 3 σ uncertainty of $\sim$10% in ρ_c. The vertical extent of each box corresponds to the 3 σ uncertainty in line intensity, determined by our fitting procedure, while the horizontal extent denotes the time interval for each spectrum. The labels refer to the SWP spectra shown in Fig. 3. Although there is a slow increase in the flux of the C IV line between 0100 and 0500 UT, the circularly polarized burst observed at 20 cm around 0500 UT was not detected at either 6 cm or at ultraviolet wavelengths.

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KENNETH R. LANG and ROBERT F. WILLSON: Department of Physics and Astronomy, Robinson Hall, Tufts University, Medford, MA 02155