THE ASTROPHYSICAL JOURNAL, 282:733–740, 1984 July 15

ULTRAVIOLET FLARE ON LAMBDA ANDROMEDAE

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Received 1983 May 31; accepted 1984 January 16

ABSTRACT

On 1982 November 5/6, a luminous, flarelike brightening of the ultraviolet emissions was observed with *IUE* from the active RS CVn type star λ And during the phase of rotation period corresponding to maximum area coverage of the visible hemisphere by starspots and active regions. Enhancements during the flare in the ultraviolet emission lines as large as factors of several and in the ultraviolet continuum up to 80% persisted for over 5 hours. The bulk of the radiative output of the flare occurred in Mg II *h* and *k* and H I Lyα. Because of the long duration and extreme luminosity of the event, the energy radiated by the flare alone is in excess of 10^{35} ergs just in the ultraviolet region. This is the most energetic stellar flare ever recorded in the ultraviolet. In addition, it is the first ultraviolet flare observed from a giant star. In comparison to the largest solar flares, the flare on λ And is at least three orders of magnitude more energetic in similar emission lines.

Subject headings: stars: binaries — stars: flares — stars: individual — ultraviolet: spectra

I. INTRODUCTION

Flares have been observed on active, M dwarf emission-line stars in X-ray, ultraviolet, visible, and radio-frequency wavelengths (cf. Haisch 1983). Stellar flares are observed in the photometric *U* passband of many dMe stars at rates as high as a large flare every few hours (cf. Kunkel 1973). Energies in this passband can often be up to 10^{34} ergs, two orders of magnitude larger than the radiative output in large solar flares.

For G–K type stars, the detection of flares in visible, disk-integrated light is difficult because of the low contrast of the flare relative to the bright photosphere. Chromospheric emission-line variations on short time scales suggested that flares occur on active stars of these spectral classes, most notably the RS CVn type binaries for which Weiler *et al.* (1978) detected Hα flaring. In several active G–K stars, Baliunas *et al.* (1981) determined that fluctuations of a few percent over the time scale of minutes in the Ca II H and K emission lines translated into energies comparable to those of flares in photospheric light of dMe stars. Flare signatures are also apparent in the X-ray, ultraviolet, and radio wavelength regions of the RS CVn stars: an X-ray flare coincident with radio brightening has been seen on HR 1099 (Gibson 1979) and a flare was detected in the ultraviolet on UX Ari (Simon, Linsky, and Schiffer 1980). There are also two reports of isolated radio flares on λ And itself (Bath and Wallerstein 1976; Spangler, Owen, and Hulse 1977).

We report on a large flare episode in the long period RS CVn type binary system λ And. The spectral type of the visible star is G8 IV–III; the spectroscopic orbit is 20.5 days (Gratton 1950). This evolved star rotates once every ~ 54 days, as deduced from broad-band *V* magnitude variations that can be as large as 30% (Hall 1976; Boyd *et al.* 1983). Rotation is marked by these visibly darker surface inhomogeneities, bright in chromospheric and coronal emission and consistent with the idea of starspots (Baliunas and Dupree 1982). The surface fluxes of the ultraviolet emission lines are typically at least as bright as those in solar active regions (Baliunas and Dupree 1979, 1982).

We observed λ And on 1982 November 5/6, at the darkest photometric phase of its rotational modulation (Dorren and Guinan 1983; Hall 1983). During this time an abrupt enhancement, by factors of up to 2–3 in the ultraviolet emissions, persisted for at least 5 hours. This is the first flarelike event detected in the ultraviolet on a star as luminous as λ And, and it appears that its total energy is at least three orders of magnitude greater than that of the largest solar flares. Observations of stellar flares are important because they can test predictions of magnetic phenomena ascribed to stellar flare mechanisms that are extended from theoretical solar flare models.

II. OBSERVATIONS

We monitored the ultraviolet spectrum of λ And with the *IUE* satellite (Boggess *et al.* 1978*a*, *b*), the visible Ca II K chromospheric emission-line profile with the 1.5 m telescope for 2 hours at the Whipple Observatory and the visible brightness with the 38 cm telescope at Villanova University Observatory.

The satellite spectra were spaced over two contiguous 8 hour shifts; details of the exposures are given in Table 1. During the long exposure for a high-resolution, short-wavelength spectrum, we obtained Ca II K line profiles with a resolution of about 0.02 Å with the echelle spectrograph and intensified Reticon detector on the 1.5 m telescope. These profiles were reduced by our standard procedure to calibrate the electronic sensitivity variations, the echelle blaze, and the wavelength scale (cf. Baliunas and Dupree 1982). Exposure times for the visible spectra were 10 minutes. The ultraviolet spectra have been corrected for background irradiance, while the high-resolution spectra have been additionally corrected for the echelle blaze with the Goddard ripple function (Ake 1982). The fluxes in the high-dispersion data reduced with this ripple correction have been multiplied by a factor of 108 to bring into agreement the fluxes between two nearly simultaneous high- and low-resolution spectra (Bohlin and Holm 1980; Cassatella, Ponz, and Selvelli 1981). For the Mg II $h + k$ emission, the flux above zero has been summed over the emission core. For the Ca II K emission, the calibration of Baliunas *et al.* (1979) was applied to determine the stellar

[1] Guest Observer, *International Ultraviolet Explorer Satellite* (*IUE*).

TABLE 1

SEQUENCE OF *IUE*-ULTRAVIOLET SPECTRA OF LAMBDA ANDROMEDAE, 1982 NOVEMBER 5/6

Image Sequence Number	UT at Midexposure	Dispersion Mode[a]	Exposure Time (min.)
SWP 18479	5 Nov 21.29	L	20
SWP 18480	6 Nov 01.57	H	420
SWP 18481	6 Nov 06.37	L	25
SWP 18482	6 Nov 07.53	L	25
SWP 18483	6 Nov 08.65	L	25
SWP 18484	6 Nov 09.76	L	25
SWP 18485	6 Nov 10.55	L	3
SWP 18486	6 Nov 11.14	L	3
LWR 14567............	5 Nov 21.58	H	5
LWR 14568............	6 Nov 05.63	H	5
LWR 14569............	6 Nov 06.79	H	5
LWR 14570............	6 Nov 07.91	H	5
LWR 14571............	6 Nov 09.02	H	5

[a] All exposures were obtained with the large aperture. Low-resolution is denoted "L," and high-resolution, "H."

fluxes outside the Earth's atmosphere. No correction for the photospheric contribution to the flux was made; the relative contribution, however, is likely to be small compared to the radiative losses in the bright chromospheric emission.

The H I–Lyα feature is overexposed except in the high-resolution and the two 3 minute, low-resolution spectra taken specifically to obtain this feature. In the high-resolution exposure, the geocoronal emission appears inside the deep central absorption predominantly caused by interstellar gas. In order to correct for the geocorona in the low-resolution exposures, the "sky" adjacent to λ And was observed. The Lyα fluxes have been corrected for geocoronal emission; no correction was made for the interstellar hydrogen absorption.

The flare episode occurred around 0600 UT on 1982 November 6, when many of the ultraviolet emission lines strengthened dramatically (Fig. 1). The fluxes in the high-resolution image, integrated over about 7 hours, were as faint as those of the first low-resolution spectrum. These low fluxes, along with the lack of a substantial brightening of Ca II K emission as late as 0400 UT, indicate that the flare enhancement did not occur until late into or even after the long exposure. Maximum enhancement of the fluxes occurred near 0700 UT (see Fig. 2).

These spectra were obtained during minimum brightness of the light curve, when the V magnitude was $+3.86 \pm 0.015$ mag, monitored at Villanova University and also determined with the *IUE* FES differentially from the comparison star, ψ And. In determining the V magnitude of λ And, the values of $V = +4.95$ mag and $B - V = +1.16$ were adopted for ψ And (Nicolet 1978). At minimum light, maximum chromospheric emission is observed corresponding to maximum coverage of stellar sunspots and associated active regions; in general the light level is anticorrelated with the strength of the chromospheric and coronal emissions (Baliunas and Dupree 1982). According to Dorren and Guinan (1983) λ And is currently in a spot cycle minimum of a possible ~6 year spot cycle in which relatively rapid changes in the light curve and photometric period are occurring that could indicate a redistribution of the active regions. It was during a similar phase on 1976 November 9 that Spangler, Owen, and Hulse (1977) observed a small radio flare from λ And at the 15 mJy level at 5 GHz. It is interesting to note that the stellar flares observed on V711 Tau (=HR 1099) in the X-ray and radio-frequency continuum also occurred at a time of rapid changes in its visible light curve morphology and hence spot configurations (Dorren and Guinan 1982).

Compared to the light level and emission-line strengths observed for maximum and minimum light in 1978–1979, this currently observed minimum is about 0.14 mag brighter, and the ultraviolet and visible Ca II K fluxes in the preflare state are correspondingly fainter, than those of the deeper light minimum of 1978–1979. The flare-level fluxes in the ultraviolet, however, are substantially brighter than those of the deep 1978–1979 light minimum when the star was more heavily spotted (Baliunas and Dupree 1982). Thus, the initial ultraviolet spectrum and the strengths of the Ca II K emission of November 5 represents the contemporary light curve minimum, while the later, brighter spectra on November 6 are an ephemeral enhancement, rather than, for example, the sudden appearance over the limb of a large active area. That the Ca II K emission represents the photometric minimum but not the flare is discussed further below. The star's slow rotation (~54 days) would be inconsistent with the sudden appearance of an active area in all ultraviolet lines in times scales as short as an hour. Moreover, the FES magnitude remained constant (within

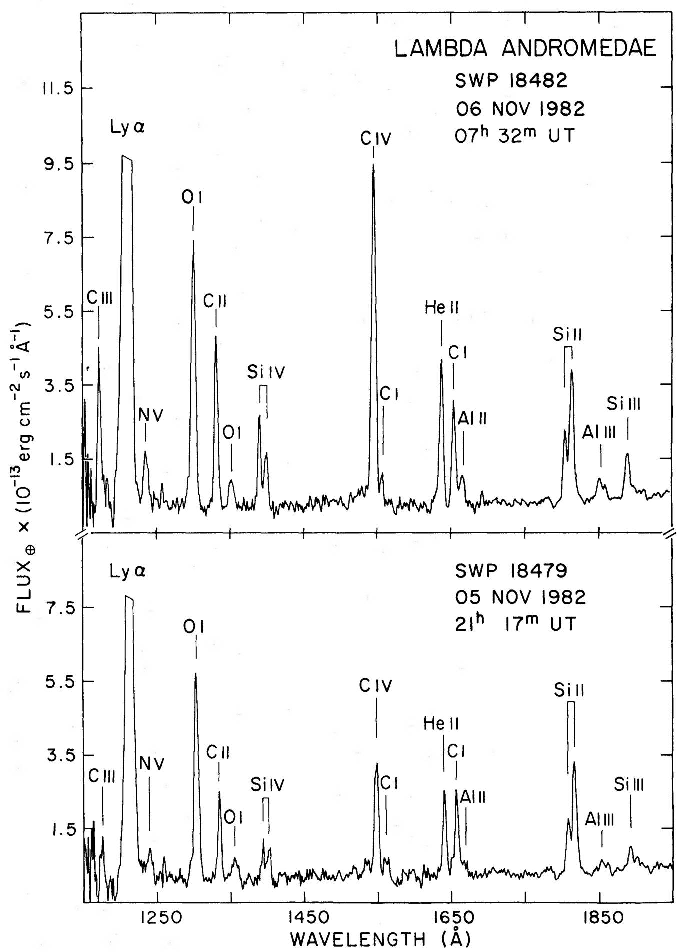

FIG. 1.—Flux observed at Earth (ergs cm^{-2} s^{-1} $Å^{-1}$) of λ And before (*below*) and during (*above*) flare episode that occurred at light minimum, or maximum area coverage by active areas in the rotational modulation period. Lyα is overexposed.

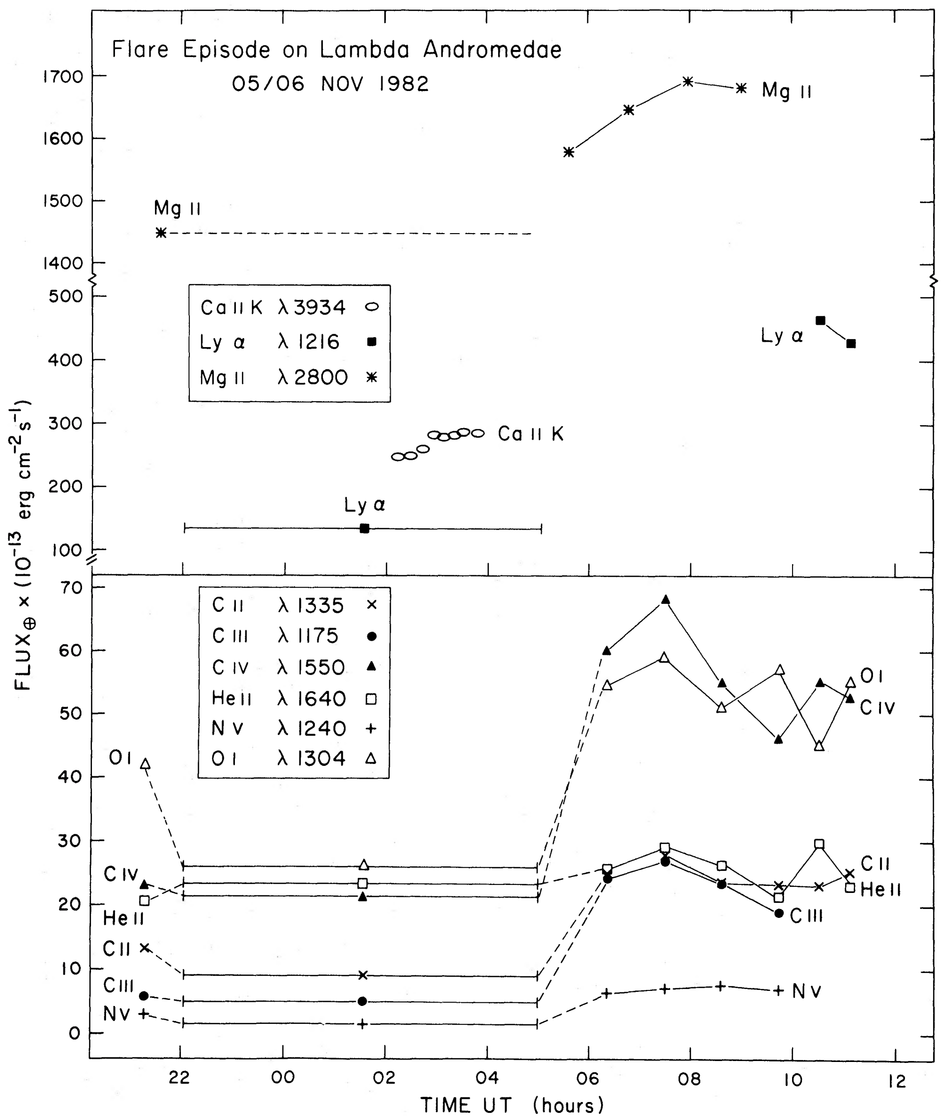

FIG. 2.—Integrated flux observed at Earth (ergs cm^{-2} s^{-1} Å^{-1}) of λ And ultraviolet and visible Ca II K emission features as a function of time. The flare enhancement is greatest at about 0700 UT on 1982 November 6.

$\pm$0.02 mag) through our 16 hours of ultraviolet monitoring; the sudden appearance of a large active area would be accompanied by substantial visible light darkening from its associated visibly darker spotted area. From the photometric light levels, ultraviolet fluxes, and the rapid time scale of the enhancement, we conclude that the ultraviolet brightening is a long-lived flare with a rise time of less than 2–3 hours rather than an active area appearing over the limb.

III. FLARE EPISODE

The flare episode on λ And has several notable features: (*a*) it persisted for over 5 hours, with only a small decrease in intensity during that time; (*b*) the emissions indicative of temperature in excess of about 1×10^5 K (N V, He II) were only slightly enhanced compared to C IV and other lines formed at temperatures of 1×10^5 K and below; (*c*) some continuum regions in the ultraviolet brightened by 30%–80%; (*d*) the greatest amount of energy from observed lines was released from H I–Lyα and Mg II *h* and *k*.

The fluxes observed in the preflare and brightest of the flare spectra are given in Table 2. For the ultraviolet continuum fluxes during the flare and the Ca II K fluxes prior to the flare, mean values are listed. Upper limits to the errors are also tabulated. The relative enhancement of most of the ultraviolet line and continuum fluxes of the flare over the quiet[2] states is highly significant. The photometric precision of the fluxes has been assayed by our calculating the standard deviation of the mean of the fluxes during the sequence of flare spectra. The precision of the ultraviolet fluxes will be at least as good as that indicated by the standard deviations. In fact, any fluctuations present in the flare degrade the precision so that the values in Table 2 should be considered upper limits to the photometric precision. Generally, the standard deviations of the weak lines (for example O I λ1357) are about 10%, while the precision for the stronger lines and continuum intervals are better. For Mg II *h* and *k*, the standard deviation from the mean is 2%

[2] Although the preflare state is referred to as "quiet," it corresponds to a time of relatively strong chromospheric and coronal emission and hence activity, as indicated by the local photometric minimum.

TABLE 2

FLUXES OF PREFLARE AND FLARE SPECTRA OF LAMBDA ANDROMEDAE 1982 NOVEMBER 5/6

Feature	λ (Å)	Flux at Earth ($\times 10^{-13}$ ergs cm^{-2} s^{-1}) Preflare[a]	Flare[b]	Maximum Standard Deviation[c] (%)
Emission lines:				
C III	1175	6	27	7
H I-Lyα	1215	135	444	4
N V	1240	8	14	4
O I	1304	42	59	3
C II	1335	13	28	4
O I	1357	7	9	11
Si IV	1394, 1403	11	26	6
C IV	1550	23	68	8
He II	1640	20	29	6
C I	1657	18	21	3
Al II	1672	5	8	11
Si II	1808, 1817	36	45	3
Al III	1855	2	5	11
Si III	1892	4	8	8
C III	1909	(0.8)	1.2	7
Mg II *k*	2795	852	964	1
Mg II *h*	2802	601	683	3
Ca II K	3934	273	...	2
Ultraviolet Continuum:				
Si I ^3P	1470–1520	11	20[d]	10
Si I ^1D	1580–1630	11	11[d]	9
	1750–1790	12	16[d]	6

[a] Fluxes observed prior to the flare from SWP 18479 and LWR 14567. Lyα, from high-dispersion SWP 18480, has been corrected for geocoronal emission and is the average of the fluxes from orders 113 and 114. The Ca II K fluxes are the average of eight preflare measurements. Parentheses indicate an upper limit to the fluxes integrated over the expected line position.

[b] Fluxes observed during the peak of the flare from SWP 18482 and LWR 14569. Lyα is the average from low-dispersion SWP 18485 and 18486; the flux has been corrected for geocoronal emission. No Ca II K fluxes were measured during the flare.

[c] The maximum standard deviation has been calculated from the fluxes of the short-wavelength ultraviolet fluxes and continua from SWP 18481 through SWP 18484, for Lyα SWP 18485–18486, for Mg II LWR 14568–14571. Ca II K was not observed during the flare, and the standard deviation is from the preflare measurements. See text.

[d] The ultraviolet continuum fluxes are averaged from SWP 18481 through SWP 18484.

of the flux in the line. Therefore, the 15% increase we observe in Mg II is extremely significant. The fluxes from the quiescent low-dispersion (SWP 18479) and high-dispersion (SWP 18480) spectra have not been averaged because of the systematic uncertainty of the low- to high-dispersion calibration that would be introduced. The short-wavelength fluxes at high-resolution are, however, usually within 20% of those in the preflare low-dispersion spectrum.

The behavior of some of the observed fluxes, including those from the high-dispersion, short-wavelength exposure, as a function of time is shown in Figure 2. For clarity, some lines have been omitted, such as the Si IV doublet near λ1400. The increases for all ultraviolet lines can be assessed from Tables 2 and 3.

a) *Ultraviolet Emission Behavior*

i) *Line Emission*

The peak enhancement of the ultraviolet fluxes during the flare compared to the initial quiescent level in λ And and other stars observed with *IUE* are given in Table 3, wherein the

TABLE 3

ULTRAVIOLET EMISSION ENHANCEMENTS IN STELLAR FLARES RELATIVE TO QUIESCENT LEVELS

Feature	λ (Å)	log T_{max} (K)	Flare Enhancement[a] λ And	Proxima Cen[b]	UX Ari[c]	Gliese 867A[d]
He II	1640	>5.3	1.4	3.5	...	1.3
N V	1240	5.3	1.9	4.8	6.1	1.3
C IV	1550	5.1	3.0	6.8	...	2.2
Si IV	1400	4.9	2.4	...	5.4	1.2
C III	1175	4.7	4.6	...	5.8	...
C II	1335	4.3	2.1	>3.1	...	2.1
Lyα	1215	4.3	3.2[e]	...	...	...
Mg II	2795, 2802	3.9	1.17	...	...	...
C I	1660	3.85	1.2	...	...	1.2
	1560	3.85	...	3.2	...	...
Si II	1808, 1817	3.8	1.3	~ 1.7	5.5	1.7

[a] The quiescent spectra have been subtracted from the flare spectra.

[b] Haisch *et al.* 1983.

[c] Simon, Linsky, and Schiffer 1980.

[d] Butler *et al.* 1981.

[e] Corrected for geocoronal emission.

quiescent emission has been subtracted from the observed flare spectra.

The enhancements during the flare are generally a factor of several. Proxima Cen, Gliese 867A, and λ And all show the greatest enhancement in C IV compared to N V or He II. Because both the initial flux and its enhancement are largest in C IV, more energy was released in C IV than in the higher temperature lines. In the case of the solar flare of 1973 September 5 (Canfield *et al.* 1980), it is also true that C IV and Si IV lines are also more enhanced and hence more energetic than N V and He II.

Unlike previous studies of stellar flares, our measurements also include the ultraviolet continuum, Lyα and Mg II $h + k$ fluxes of both quiescent and flare states. The Lyα and Mg II emission lines showed energies released in the flare that are factors of 10–100 above those in C IV (see Fig. 3). The enhancements in Table 2 belie the very substantial energies released from apparently small relative flux variations in Lyα and Mg II. Because the radiative losses are inherently large in these lines, small relative changes translate into large absolute flux changes.

The total radiative output from the ultraviolet emission lines in the flare alone, including contributions from Mg II and Lyα, is about 6×10^{30} ergs s^{-1}. Over a duration of 5 hours, the energy observed in this event in the ultraviolet is about 1×10^{35} ergs.

A variety of solar flares was well studied in the ultraviolet by the *Skylab* mission. In comparing ultraviolet lines in common to both the Sun and λ And, the flare on λ And was both more luminous and long lived, hence more energetic. This flare was about 10^5 times the power and several million times the energy of the 1973 September 5 solar flare (Canfield *et al.* 1980). One of the largest solar flares studied, the class 2B flare of 1973 September 7, lasted for 2 hours and radiated about 10^{31} ergs in the ultraviolet (Withbroe 1978), four orders of magnitude less compared to the flare in λ And. In the September 5 solar flare, the power in Lyα and other ultraviolet lines, exclusive of Mg II but accessible to *IUE*, represents only about 5% of the total radiative output across the energy

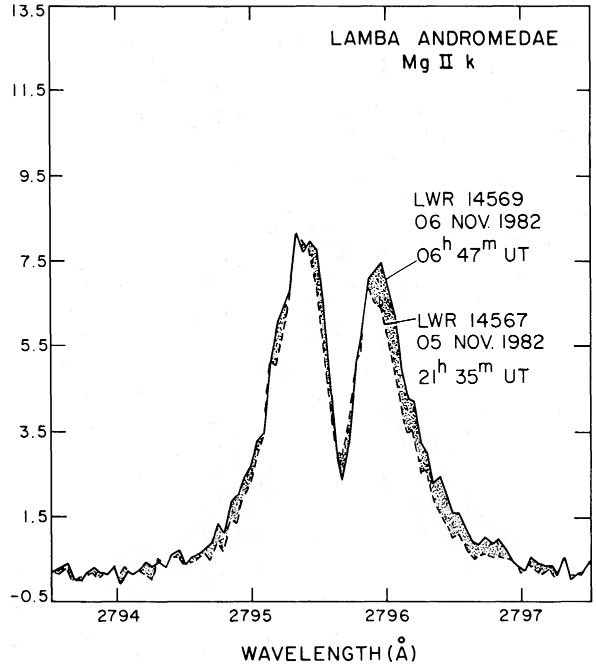

FIG. 3.—The Mg II k profiles observed with *IUE* before (LWR 14567) and during (LWR 14569) the flare event. The total flux in the k emission core increased by about 13%, with most of the enhancement occurring in the long-wavelength portion of the profile.

spectrum from radio through X-ray wavelengths. Thus, the expected total energy at all wavelengths in the λ And flare would be in excess of 10^{36} ergs.

The flare detected in the ultraviolet from the RS CVn binary UX Ari (Simon, Linsky, and Schiffer 1980) is more luminous, for example, 600 times the quiet Sun surface flux in Si IV and 1400 times N V, and at least an order of magnitude brighter in surface flux than in λ And. The duration of the flare in UX Ari, however, is unknown, and the energy cannot be calculated. The most energetic stellar flare observed is probably that detected by *HEAO 1* over several days in the RS CVn system BD +61°1211 with a peak luminosity of about 2×10^{32} ergs s^{-1} and total energy of 4×10^{37} ergs in the low-energy passband 0.2–2.8 keV (Charles, Walter, and Bowyer 1979).

Flares on dMe stars can radiate comparable energies in the visible continuum and observed X-ray regions, for example, on the order of a few $\times 10^{31}$ ergs for YZ CMi (Kahler *et al.* 1982) and Proxima Cen (Haisch *et al.* 1983). The most energetic flares detected on dMe stars, as detected in visible continua, can be as large as 10^{34} ergs (Lacy, Moffett, and Evans 1976). The expected total energy in all wavelengths in the λ And flare is two orders of magnitude larger than that of the most energetic flares detected in dMe stars.

The stellar surface fluxes calculated from the angular diameter of 2.54 ms (Baliunas and Dupree 1982) in λ And during the flare are enhanced by factors of 30–60 relative to those of the quiet Sun (Linsky *et al.* 1978). However, these are disk-integrated fluxes that are averaged over the entire visible hemisphere of the star. If the preflare fluxes are subtracted and the flare is assumed to be confined to a small surface area, say 15% of the visible hemisphere, then the ratio of stellar flare to quiet Sun fluxes approaches 100. It is difficult, however, to estimate the surface area of the flare-emitting region. A fractional area coverage of 15% for the flaring region would be reasonable because the light modulation in the visible for the spotted regions was about 0.1 mag, which implies an obscuration of dark spots of about 15% of the quiescent surface. Another estimate of the size of the flaring region can be made from an estimate of the rise time of the flare, and the velocity of propagation of the flare brightening. A rise time of about an hour and speed of a few hundred km s^{-1}, corresponding to the characteristic velocities of, for example, eruptive prominences, flare surges, and coronal transients (Rust *et al.* 1980), results in a few percent coverage of the visible hemisphere.

The Mg II line profile observed before and during the flare is shown in Figure 3. The Mg II profile is centrally reversed, in part by absorption by interstellar gas. Additionally, the line profile is asymmetric, in the sense that the blue peak is more intense than the red. During the flare, it is only the outer, long-wavelength edge of the red peak (near +25 km s^{-1}) that brightens. The asymmetry of these Mg II profiles is the same as that observed at a previous light minimum in both Ca II and Mg II (Baliunas and Dupree 1982). If interpreted as mass motions, then the asymmetry corresponds to differential downflows (Baliunas and Dupree 1982 and references therein) occurring at light minimum, and during the flare.

In the large solar flare of 1973 September 5, Canfield *et al.* (1980) monitored both the Lyα and C II fluxes. During the peak of the X-ray flux, Lyα/C II is lowest, about 4.7, and gradually increases; a typical active region has Lyα/C II $\sim$ 40 and quiet Sun $\sim$ 54 (Vernazza and Reeves 1978). In λ And, we observe that the quiescent and flare Lyα/C II fluxes remain constant, at a value of about 15. It may not be appropriate, then, to predict the Lyα fluxes from C II fluxes in stellar flares from the solar ratios as in the case of Proxima Cen (Haisch *et al.* 1983).

ii) *Continuous Emission*

In the EUV, continuum brightening during a solar flare is especially marked in the Si I photoionization limits at λ1525 (^3P) and λ1683 (^1D), with an increase in the flare compared to surrounding plage areas of 5–16 times for the ^3P and 2–6 times for ^1D (Cook and Brueckner 1979). In λ And, the mean enhancement in the flare is about 1.8 times for the interval $\lambda\lambda$1470–1520 compared to the preflare flux (see Table 2). No significant discernable increase was measured for the $\lambda\lambda$1580–1630 region. A 30% increase in the continuous flux was also noted in the flare spectrum measured between $\lambda\lambda$1750–1790. For this wavelength range, however, the solar flare continuum measurements are uncertain (Cook and Brueckner 1979). The stellar flares on Gliese 867A (Butler *et al.* 1981) and EQ Peg (Baliunas and Raymond 1984) both emitted detectable ultraviolet continua in this wavelength range; however, the continua in the quiescent stellar spectra were beneath the detection threshold.

b) Ca II K *Emission*

That the Ca II K chromospheric emission represents the chromospheric activity level during the photometric minimum but not the flare is based upon two arguments. First, similar to the finding for the ultraviolet emissions, the Ca II K strength is compatible with that expected at a "bright" photometric minimum. We have compared the Ca II K emission strengths monitored over 5 years (Baliunas and Dupree 1982) with coincident photometry (Dorren and Guinan 1983). The average relative emission [K], the integrated flux in the line relative to the base of the emission core on 1982 November 6 is 4.36 ± 0.07, the standard deviation from the mean. The Ca II K emission strength observed here is modest, some 30% weaker than the deeper photometric minimum of 1978–1979. The ultraviolet fluxes in the short-wavelength, high-dispersion spectrum also indicate that the flare had not begun by the start of the Ca II K monitoring at 0200 UT. Since this is about the midpoint of the long-exposure, the ultraviolet fluxes would have been stronger rather than comparable to those in the preflare, low-dispersion exposure.

Second, we expect that the radiative losses during the flare would be similar in Mg II k and Ca II K, formed as they are over a similar region of the chromosphere (cf. Vernazza, Avrett, and Loeser 1981; Avrett 1981). The energy radiated in the flare in Mg II k would imply an accompanying increase of over 50% in the relative Ca II K strength during the flare. A similar enhancement is expected for Ca II K if Lyα and Ca II K losses are scaled from the September 5 solar flare (Canfield *et al.* 1980). The small standard deviations for the Ca II K measurements further suggests that the flare had not yet begun at 0400 UT, the end of the Ca II monitoring.

We conclude from the consistency of the current measurements of Ca II K strength, ultraviolet fluxes, and V magnitudes with historical measurements, and the lack of a large enhancement in Ca II K during our monitoring, that the Ca II K flux is that prior to the flare.

Interestingly, on the basis of the expected enhancement of Ca II K with the Mg II k radiative losses in this flare, we conclude that an increase in the ultraviolet activity matching what is observed here might have occurred during the 50% increase in Ca II [K] observed in λ And on 1978 December 16 (Baliunas and Dupree 1982).

c) Transition Zone Pressures

The pressure of the transition zone of the quiescent region and the flare regions has been estimated three ways (see Table 4). First, we use the density diagnostic provided by the ratio of C III λ1176 and λ1909 lines, and the calculations of Cook and Nicolas (1979) that assume an electron temperature of 5.6×10^4 K. Unfortunately, the λ1909 feature is weak, and its marginal detection implies lower limits to the quiescent level density of $n_e > 2 \times 10^{10}$ cm^{-3} and $n_e > 1 \times 10^{11}$ cm^{-3} in the flare region. The lower limits arise by conservatively assuming that the weak C III λ1909 emission in the quiet spectrum is an upper limit to the flux. The precision of the flare emission (Table 2) contributes an uncertainty which is small compared to that of the calculations for the density derivation (cf. Cook and Nicolas 1979).

We have also used the calculations of intensity ratios of Si III λ1296 and λ1892 (Dufton *et al.* 1983). This intensity ratio gives an upper bound to the pressure, because the Si III λ1296

TABLE 4

PRESSURE ESTIMATES FOR QUIESCENT AND FLARING TRANSITION ZONE IN LAMBDA ANDROMEDAE

PRESSURE (dyn cm^{-2})		
Quiescent	Flare Only	METHOD
>0.2	>1	C III (λ1176)/C III (λ1909)[a]
3	5	C IV (λ1550)[b]
4	6	Si IV (λ1400)[b]
<11	<9	Si III (λ1296)/Si III (λ1892)[c]

[a] Cook and Nicolas 1979.
[b] Haisch and Linsky 1976.
[c] Dufton *et al.* 1983.

feature is blended with O I (λ1305) in the low-resolution spectra (the wavelengths of the features in the high-resolution spectrum confirm the identification of this line as predominantly O I). However, by assuming the flux is entirely that of the Si III multiplet, we obtain an upper limit to the density. Further, we assume that the contribution of the Si III λ1296 component to the total emission is in the same proportion observed for this multiplet in a solar flare (Cohen, Feldman, and Doschek 1978). Because the Si III λ1296 to λ1892 intensity ratio is a temperature-sensitive density diagnostic, we assume log $T = 4.7$. The resulting upper limits of the densities are $n_e < 2 \times 10^{12}$ cm^{-3} for the quiescent atmosphere, and $n_e < 1 \times 10^{12}$ cm^{-3} in the flare region.

Finally, we scale the pressure relative to the quiet Sun from the fluxes of optically thin, collision-dominated transition zone features. Models of a constant-pressure, conductively dominated transition zone have emission measures that scale linearly with pressure. We further assume that the emission measures scale similarly from the Sun to λ And. Then the scaling of pressures from the quiet Sun is (Haisch and Linsky 1976)

$$\frac{F_*}{F_\odot} = \frac{A_*}{A_\odot}\frac{P_*}{P_\odot} ,$$

where $F_*/F_\odot$ are the relative and solar surface fluxes, $A_*/A_\odot$ the elemental abundance of the star relative to the Sun, and $P_*/P_\odot$ the ratio of transition zone pressures. For λ And, log $A_*/A_\odot = -0.23$ (Helfer and Wallerstein 1968).

We use the C IV and Si IV emission fluxes. In our high-resolution, quiescent spectrum, the C IV peak intensity ratio of the components of the λ1550 doublet indicates that the line is approximately optically thin, as observed in other active-chromosphere giants, α Aur and β Dra (Ayres *et al.* 1983). We assume C IV remains optically thin during the flare and Si IV is also optically thin before and during the flare. We adopt a quiet Sun pressure of 0.16 dyn cm^{-2} (Dupree 1972). The values of $P_*/P_\odot$ are about 19–25 (quiescent) and 29–34 (flare alone) for C IV and Si IV, respectively.

The pressures and their upper and lower limits are consistent. The range bounding the pressure estimates encompasses uncertainties both in the measured fluxes and in theoretical calculations of density-sensitive line ratios. Although a pressure of 3–4 dyn cm^{-2} for the quiescent atmosphere and 5–6 dyn cm^{-2} for the flare region are indicated, these values are uncertain by about a factor of 2. In comparison, the active Sun has a pressure of about 1.4 dyn cm^{-2} (Dupree *et al.* 1973). The quiescent pressure of λ And is about twice that of the active Sun, although we reiterate that the "quiescent" observations of λ And correspond to maximum spot and active area coverage. Empirically determined pressures in solar flares, 4–50 dyn cm^{-2} (Machado and Emslie 1979), are consistent with our flare pressures. Note that the surface flux of the flare region is determined from disk-integrated values probably giving a lower limit to the pressure derived from scaling the surface fluxes to those of the quiet Sun.

From these densities the radiative cooling time is estimated to be shorter than an hour. The persistence of the flare indicates that a continual input of substantial amounts of energy is required to maintain the bright emission levels.

c) Prediction of X-Ray Fluxes

We can estimate the X-ray flux from the strength of He II (λ1640) following the method of Hartmann *et al.* (1979) and

Hartmann, Dupree, and Raymond (1982), given their assumptions, a range of emission measure distributions as a function of temperature and an estimate of the fraction of $\lambda 1640$ emission caused by recombination following photoionization by coronal EUV ($55 < h\nu < 100$ eV) radiation. The observed He II flux increased by a factor of 1.4 in the flare spectrum over the preflare observation. We would expect to observe X-ray fluxes of about 5–10 $\times 10^{-11}$ ergs cm^{-2} s^{-1} for the quiescent corona. During the flare we would predict the X-ray flux to increase to 7–14 $\times 10^{-11}$ ergs cm^{-2} s^{-1}. Previous measurements of the observed X-ray flux can be compared to interpolated photometric light levels (Dorren and Guinan 1983). The flux observed at earth with the *HEAO 1* A-2 low-energy X-ray detector of f_x (0.15–2.8 keV) $= 2.5 \times 10^{-11}$ ergs cm^{-2} s^{-1} during 1978 January (Walter *et al.* 1980) was obtained when the optical brightness of the star was $m_v \approx +3.88$ mag. During 1979 June an X-ray flux of f_x (0.2–4 keV) $= 5.2 \times 10^{-11}$ ergs cm^{-2} s^{-1} was reported by Swank *et al.* (1981) from the Solid State Spectrometer on the *HEAO 2* satellite; the extrapolated visible brightness of λ And during this time is $m_v \sim +3.90$ mag. During 1980 January an X-ray flux of f_x (0.15–4 keV) $= 4.9 \times 10^{-11}$ ergs cm^{-2} s^{-1} was measured by Walter and Bowyer (1981) with the IPC on the *HEAO 2*; the apparent visual magnitude of λ And at this time was $m_v = +3.82$ mag. Although the energy responses of the X-ray detectors on the two satellites are not the same, a comparison between the measurements is meaningful because only a small fraction of the X-ray flux of λ And occurs at energies greater than ~ 3 keV. There is no clear correspondence between X-ray emission and V magnitude, although there is a significant correlation of He II with faintness of photometric light, as with other ultraviolet emission (Baliunas and Dupree 1982). Apparently the X-ray emission does not behave as the other chromospheric and coronal emissions do. Either these X-ray measurements involve temporal variations that mask the expected inverse correspondence between light level and coronal emission, or perhaps the X-rays emanate from regions far above the stellar surface, and remain in view, unlike the visible and ultraviolet chromospheric and coronal emissions, which undergo rotational modulation. The prediction from He II emission of the X-ray flux $f_x \approx 5$–10×10^{-11} ergs cm^{-2} s^{-1} during this observed light minimum, for which $m_v = +3.86$ mag, is slightly higher than the previous X-ray measurements during corresponding visible light levels. The agreement however, is within a factor of two, the estimated uncertainty for the He II–X-ray predictions (Hartmann, Dupree, and Raymond 1982). The prediction of X-ray flux is in accord with a luminous stellar flare observed with *HEAO 2* on HD 27130, a binary in the Hyades with G V + K V components and an orbital period of 5.6 days (Stern, Underwood, and Antiochos 1983). On HD 27130 a thirtyfold increase to a peak X-ray luminosity in excess of about 10^{31} ergs s^{-1} is comparable to the X-ray luminosity predicted for λ And during the flare. The ratio of the flare X-ray to ultraviolet transition region fluxes in λ And is about 10. Including the uncertainty in the estimate of the X-ray flux, this ratio is in reasonable agreement with the value of 20 observed during a flare on Proxima Cen (Haisch *et al.* 1983; Haisch 1983).

IV. COMPARISON TO FLARE MODELS

The ultraviolet spectra of this luminous stellar flare have implications for theoretical models of stellar flare–like activity. Several flare models can be discounted because the excess ultraviolet continuum caused by the flare was detected. For example, the model of stellar flares of Kodaira (1977) requires plasma bubbles at much higher temperature than is warranted by the ultraviolet continuum. The color dependence of the ultraviolet continuum also excludes a model which heats the lower stellar atmosphere by bombardment of energetic protons, as predicted from the Sun (Hudson 1981). The continuum might originate in a narrow chromospheric region warmed by a shock wave arising from a beam of accelerated electrons with a hard-energy power spectrum (Katsova, Kosovichev, and Livshits 1981).

As demonstrated by the analysis of solar flares, stellar flare ultraviolet emissions should also be able to discriminate among flare models. For solar flares, Machado and Emslie (1979) compared theoretical models to empirical differential emission-measure curves derived from emission lines in solar flares. In several theoretical models, each characterized by a solution of the energy-balance equation, the expected emission measures were tested. Their model of a static loop, at constant pressure, with the divergence of the thermal conduction flux balancing radiative losses, provides a reasonably good match to the solar observations between temperatures of 2×10^4 K and 2×10^5 K. The empirical differential emission curve declines steeply above 10^5 K and may have a low-lying plateau at temperatures of several hundred thousand degrees, and indicates a narrow transition zone at these temperatures (Machado and Emslie 1979; Underwood *et al.* 1978). The preferential enhancement of C IV relative to N V in stellar flares is thus consistent with the analysis of solar flares. A model predicting strong enhancement of emission in this restricted temperature range is the current-sheet model of Syrovatskii (1976). During the stellar flares, the He II and N V fluxes, the highest temperature indicators available from these *IUE* spectra, become moderately strengthened. The inference, from the ultraviolet fluxes, of the X-ray fluxes and their subsequent measurement, could further test the importance of X-ray heating of the chromosphere and transition region.

We thank the staff of the NASA-*IUE Observatory* for help in obtaining the ultraviolet spectra. We are grateful to E. Horine and J. Peters for acquiring visible spectra from F. L. Whipple Observatory, and Drs. F. Chaffee and D. Latham, for supervising the remote-observing program. S. L. B. and E. F. G. wish to acknowledge support from the Langley-Abbot program of the Smithsonian Institution. This work was supported in part by NASA grant NAG-5-87.

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