

## THE GREAT FLARE OF 1985 APRIL 12 ON AD LEONIS

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### ABSTRACT

Photometric and spectroscopic observations covering the wavelength range 1200–8000 Å are presented for a giant flare on the M dwarf star AD Leo. The flare radiated more than  $10^{34}$  ergs in this wavelength region and lasted for more than 4 hr. The magnitude and duration of the flare allowed us to obtain an unprecedented view of the response of the lower atmosphere. For the first time, a flare energy budget over the entire optical and ultraviolet wavelength region is constructed as a function of time during the flare. The continuum radiation is shown to be the dominant source of energy loss during both the initial “impulsive” phase and the later “gradual” phase. The emission lines contribute less than 10% of the total flare energy in this wavelength region but are about 4 times more important during the gradual phase than in the impulsive phase. The energy budget is compared in detail with another, less energetic, flare on AD Leo and found to be quite similar. A sample of nine well-observed flares on stars with spectral type ranging from dM3.5e to dM5.5e was then used to investigate the relationships between the integrated properties of several flare emission features. Good correlation between H $\gamma$  and Ca II K emission, and H $\gamma$  and U filter emission was found, extending the previously known correlation of H $\gamma$  with soft X-ray emission. These correlations suggest that the observed emission features are produced under similar atmospheric conditions regardless of the total flare energy emitted. The range in total emitted energy may thus be primarily a function of flare area and duration, and not of large differences in flare heating rate and resulting atmospheric structure. In addition, the time evolution of the emission features is qualitatively similar for a large number of flares, and quantitatively similar for the two flares studied in detail. This suggests that the energy source and deposition mechanisms which operate during the impulsive and gradual phases are causally connected, in agreement with current models for solar flares.

*Subject headings:* stars: flare — stars: individual (AD Leonis) — ultraviolet: spectra

### 1. INTRODUCTION

The first stellar flare observations were a serendipitous result of studies of solar neighborhood M dwarfs for other purposes (e.g., Joy & Humason 1949). Since then, photometric and spectroscopic flare monitoring campaigns (e.g., Kunkel 1970; Bopp & Moffett 1973; Giampapa 1983; Worden et al. 1984; Nelson et al. 1986; Butler et al. 1986; Phillips et al. 1988; Doyle et al. 1988) have yielded an increasingly rich lore concerning the dramatic response of the M dwarf atmosphere to flare activity. In the past decade, satellite studies in the ultraviolet and X-ray bands (e.g., Haisch et al. 1981; Kahler et al. 1982; Haisch et al. 1983; Baliunas & Raymond 1984; Bromage et al. 1986), in concert with radio observations of nonthermal flare emission (White, Kundu, & Jackson 1986), have provided new insights into the nature of dMe flares.

Despite these new diagnostics, we still are at the beginning stages of an understanding of how the sudden release of energy that defines a flare affects the stellar atmosphere in each of its temperature regimes (photosphere, chromosphere, transition region, corona). For example, we do not know if flares of low ( $10^{28}$  ergs) and high ( $10^{34}$  ergs) energy on the same star result in simply scaled versions of the same emission (e.g., U filter enhancements of 1 or 5 mag), or if fundamentally different emission mechanisms operate in the two cases. Further, we do not know whether a flare of the same energy on stars with

different spectral type (hence different quiescent atmospheric structure) leads to similar emission characteristics. In particular, the connection between solar and stellar flares still is obscure, primarily because of the very different kinds of data (and analysis) available in the two cases. Although flares on dMe stars may be several orders of magnitude more energetic in their (observed) radiation, several investigators have suggested that stellar flares might be simply scaled-up versions of their solar counterparts (Mullan 1977; Zirin & Ferland 1980). Another puzzle has been the absence of some types of emission during a flare, as in the case of observing optical continuum without corresponding emission-line enhancements, or soft X-ray emission. It is not clear whether the few reported cases (Kahler et al. 1982; Doyle et al. 1988; Ambruster et al. 1989) are the result of differing detection limits in the various wavelength regions or whether flares have significant intrinsic variations in their emission properties. By answering these questions we hope to gain insight into the flare energy source and method of flare energy deposition (are they always the same?) and ultimately into how flares are produced.

The reason for our rudimentary knowledge is clear: to make effective comparisons, and thus develop a quantitative understanding, requires an extensive set of measurements encompassing the range of possible flare energies and environments. The data set should include well-resolved temporal and spec-

tral information in the important emitting regions of each atmospheric component, for flares of a range of energy on stars of different spectral type. Such a data set is not currently available, primarily because of the difficulty of organizing simultaneous observing campaigns with many instruments, and then actually observing a flare (a randomly occurring event) when the campaign is underway. However, approximately 10 flares have now been observed with multiwavelength campaigns, and a few attempts have been made to quantify relationships between flare emission features. These include a possible relationship between hydrogen line emission and soft X-ray emission (Butler, Rodonò, & Foing 1988);  $H\beta$  emission and C IV emission (Phillips et al. 1988), and optical  $B$  and  $V$  filter emission with  $U$  filter emission (Lacy, Moffett, & Evans 1976), a measure of the shape of the optical continuum.

Here we present results of a multiwavelength observing campaign on the M dwarf star AD Leo in the spring of 1985, during which we recorded a giant flare. Our data include optical photometry and spectroscopy and ultraviolet spectroscopy with the *International Ultraviolet Explorer* (IUE) satellite. Excellent weather and seeing conditions allowed us to photometrically calibrate the spectroscopic data so that we are able to derive a detailed description of the absolute energy released during the flare over a large wavelength range. The observations and data reduction procedures are discussed in § 2. In § 3 we present the results of the observations, including continuum measurements from 1200–8000 Å and fluxes in the important optical and ultraviolet emission lines. § 4 contains our analysis of the total energy released in various emission features as a function of time during the flare. Solar flare investigators (Kane 1969; Dennis & Schwartz 1989; Svestka 1989) have found that solar flares can usually be divided into two phases: an initial short-lived period of “nonthermal” energy injection resulting in copious hard X-rays, microwave bursts, and occasionally white-light continuum radiation, and a longer lived “thermal” phase characterized by soft X-ray and chromospheric emission line radiation. The very different emission characteristics suggest that the flare atmosphere also is quantitatively different during the two phases (termed “impulsive” and “gradual”), but the distinct emission phases might well be manifestations of the same energy source (Dennis & Schwartz 1989). To facilitate the comparison with the solar case, we partition our flare measurements into an impulsive phase and a gradual phase and investigate the relative importance of line and continuum radiation in each phase and in the total energy budget. In § 5 we compare our flare with an earlier

well-observed but less energetic flare on AD Leo described by Rodonò et al. (1984) and Rodonò et al. (1989). Then we use a sample of nine flares on three dMe stars to examine the correlation between various emission features in light of the previous relation between the time-integrated  $H\gamma$  and soft X-ray fluxes found by Butler et al. (1988). In § 6, we interpret our results and comment on the possible constraints they place on the flare energy source and deposition mechanisms. Finally, in § 7, we summarize our findings.

## 2. OBSERVATIONS

AD Leo is a dM3.5e star located about 5 pc from the Sun. Thanks to its proximity, it is a relatively bright flare star, with visual magnitude  $V = 9.43$ . Equally important, statistical studies have demonstrated that AD Leo produces energetic flares with moderate frequency (Pettersen, Coleman, & Evans 1984). It has therefore been a prime target in coordinated observing campaigns (e.g., Rodonò et al. 1984) and is one of the best observed flare stars in the solar neighborhood. The flare we observed on 1985 April 12 was one of the largest flares ever reported on AD Leo, with a peak  $U$  magnitude more than 4.5 mag above the quiescent level and a total observed radiative energy output of more than  $10^{34}$  ergs. It is by far the largest M dwarf flare ever observed during a coordinated multiwavelength campaign.

We were fortunate to have planned our collaborative effort to coincide with such a prodigious flare, on a night with excellent photometric weather conditions and 1" seeing. Table 1 is an observing log showing the observers, telescopes used, types of data obtained, and duration of the observations. All times are given in Universal Time. Uncalibrated photometric data from Table Mountain Observatory in Wrightwood, California (W. Sandmann 1985, private communication) were used to bridge a short gap in the McDonald Observatory data (due to extinction measurements) that occurred when the flare began at 04:40 UT.

The McDonald Observatory photometric data were obtained with a standard two-star photometer attached to the 0.9 m telescope. Johnson  $UBVR$ , Strömgren  $H\beta$  narrow and wide, and  $H\alpha$  narrow and wide filters were used. A 1 s integration time was used in each filter. Allowing for the 1 s filter wheel overhead during each cycle, the time resolution in each filter was 9 s. Standard stars were observed to obtain the extinction coefficients and to determine the transformation to the standard magnitude scale. The  $H\beta$  and  $H\alpha$  data were reduced to an index similar to an equivalent width by first

TABLE 1  
AD LEO FLARE OBSERVING LOG: 1985 APRIL 12

| Observer              | Telescope                  | Type of Data                   | Time (UT)                                 | Filters/Spectral Coverage                         |
|-----------------------|----------------------------|--------------------------------|-------------------------------------------|---------------------------------------------------|
| B. R. Pettersen ..... | McDonald Observatory 0.9 m | Optical photometry             | 02:00–08:45                               | $U, B, V, R,$<br>$H\alpha(n+w),$<br>$H\beta(n+w)$ |
| S. L. Hawley .....    | McDonald Observatory 2.1 m | Optical spectroscopy           | 02:18–09:02                               | 3560–4440 Å                                       |
| B. N. Andersen .....  | IUE (Vilspa)               | Ultraviolet spectroscopy (SWP) | 03:03–03:31<br>+<br>04:27–04:55           | 1150–2000 Å                                       |
|                       |                            | Ultraviolet spectroscopy (LWP) | 05:00–05:20<br>06:23–06:57<br>07:40–08:15 | 1900–3100 Å                                       |

correcting the raw counts for sky and then dividing the counts in the narrow filter by the counts in the wide filter. The narrow filter is assumed to measure primarily line flux, while the wide filter measures the local continuum flux. These equivalent width indices were formed from the total fluxes observed, since we could not isolate the true quiescent or flare values of the individual filters.

The optical spectra were obtained with the Electronic Spectrograph No. 2 mounted at the Cassegrain focus of the 2.1 m Struve telescope at McDonald Observatory. A thinned, blue-sensitive RCA CCD detector was used in a spectroscopic mode, providing spectral coverage from 3560 to 4440 Å with a resolution of 3.5 Å (1.75 Å per diode) set by the grating and matched by the 3" entrance slits. The spectral region includes the entire Balmer series except H $\alpha$  and H $\beta$  (which we observed photometrically), as well as the Balmer jump at 3646 Å and the Ca II H and K lines. Time resolution ranged from 1 to 3 minutes.

A standard two-slit observing procedure was used, as discussed previously in Petersen & Hawley (1987, 1989). Briefly, the spectra were placed on an absolute flux scale using observations of spectrophotometric standard stars, after sky subtraction and flat-fielding. Mean extinction coefficients for McDonald Observatory were applied. The AD Leo flare data are spectrophotometric to within a calibration uncertainty of about 10%. The wavelength calibration was established with argon and neon lamp observations. A second-order polynomial fit to some 15 lines achieved a calibration accurate to about 0.1 Å.

Ultraviolet spectroscopy was obtained with the *International Ultraviolet Explorer* (IUE) satellite, described in Boggess et al. (1978). The usable spectral range extended from 1150 to 2000 Å in the short-wavelength region (SWP camera) and from 1900 to 3100 Å in the long-wavelength region (LWP camera). The data were obtained in the low-resolution mode through the large aperture. The spectral resolution is approximately 5 Å in the short-wavelength region and 9 Å in the long-wavelength region (Cassatella, Barbero, & Benvenuti 1985; Holm 1982). In addition to the flare data listed in the observing log, one short-wavelength and seven long-wavelength spectra were obtained during quiescence.

The short-wavelength spectra were reduced and calibrated using the standard analysis procedures of the IUE Regional Data Analysis Facility in Boulder. The flare spectrum contains 15 minutes of flare and 41 minutes of quiescent star; the quiescent contribution is negligible. In fact, the flare light saturated the detector at the peaks of the emission lines and in the continuum longward of 1780 Å. The uncertainty in the absolute calibration is about 10% (Bohlin et al. 1980).

The long-wavelength spectra were obtained by positioning the star at five different places in the large aperture during a single exposure, in order to achieve a time resolution of 3–8 minutes per position. Reduction of these data required a specialized extraction from the raw "line-by-line" files. Briefly, at each wavelength the spatial extent of the spectral image perpendicular to the dispersion is represented by 11 "lines," each  $2^{1/2}$  pixels ( $\approx 2''$ ) wide on 2" centers. Using the recorded positions of the five individual images and the known combined point-spread function of the telescope, spectrograph, and camera, five Gaussians were fitted to the 11 data points at each wavelength, in order to determine the amplitudes, and thus total integrated intensity, of each of the five spectral traces at each wavelength. In that manner the five individual spectra

were recovered. Tests on quiescent data indicate that the sum of the five individual spectra and the spectrum obtained using all 11 lines in the standard extraction procedure are identical to better than 5% over the entire wavelength range. This uncertainty is certainly acceptable given the large variations observed in the flare spectra compared with quiescent levels. However, the first two LWP exposures (see Table 1) were saturated at some wavelengths.

### 3. RESULTS

To obtain  $F_\lambda$  (the average flux per Å, a measure of the monochromatic continuum flux) in each of the *UBVR* filters during the flare, we first calculated fluxes from the total observed magnitudes using the calibration of Johnson (1966). The appropriate quiescent flux was then subtracted from each flare observation, an implicit assumption being that the part of the visible hemisphere covered by the flare was small, so that the quiescent flux was essentially unchanged. The resulting fluxes are those of the flare light only. Division by the FWHM of the filter, also taken from Johnson (1966), then gives  $F_\lambda$ , nominally at the central wavelength of the filter. Figure 1 shows  $F_\lambda$  (flare only) as a function of time to illustrate the optical continuum variations during the flare. The continuum fluxes measured at two ultraviolet wavelengths in the LWP spectra are also shown. In this and subsequent figures, zero on the time axis corresponds to 04:40 UT, the flare start time.

In Figure 2  $F_\lambda$  is plotted versus central wavelength of the filter for several times during the flare, illustrating the changing continuum color with time. The flare continuum is distinctly "blue" during the initial phases of the flare, then flattens before fading completely about 2 hr after the flare started. We consider the continuum shape in more detail in § 4, when we construct the flare energy budget.

The equivalent width indices during the flare for H $\alpha$  and H $\beta$  are shown in Figure 3. Also included for comparison is a similar index computed from the observed spectra for H $\gamma$ . It was formed by taking the total flux in a 25 Å band divided by the total flux in a 200 Å band, both centered on H $\gamma$ . The procedure to obtain line fluxes from these photometric equiva-

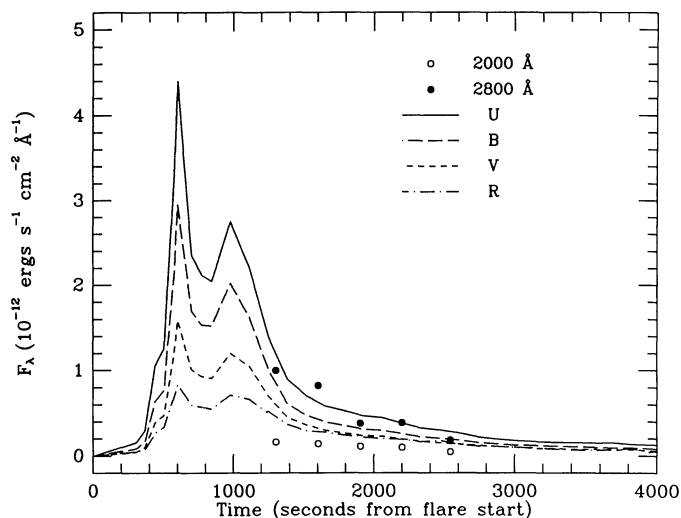


FIG. 1.—Flare light curves as measured in U, B, V, and R.  $F_\lambda$ , the monochromatic continuum flux in each filter, is plotted against time. The continuum  $F_\lambda$  at two ultraviolet wavelengths measured in the IUE LWP spectra are also shown. Zero on the time axis corresponds to 04:40 UT, the flare start time.

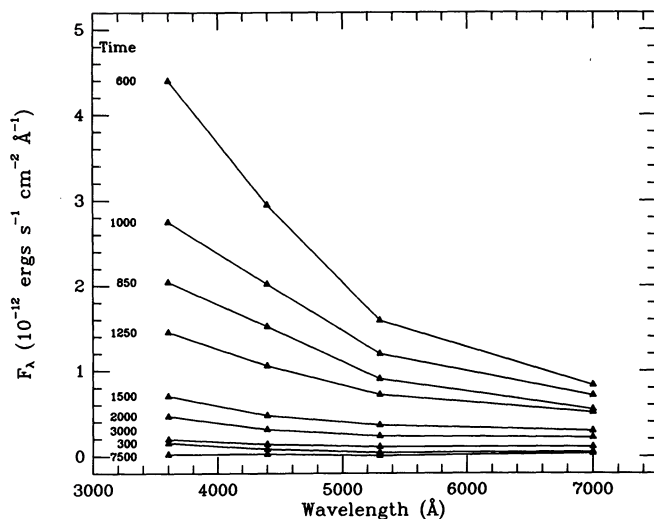


FIG. 2.—The wavelength dependence of the continuum radiation is illustrated at 9 times during the flare. The time refers to seconds from flare start. The points represent measurements taken in *U*, *B*, *V*, and *R*.

lent width indices ( $I_{EW}$ ) is rather involved. We present it in detail in the Appendix with the hope of improving and facilitating future use of narrow-band filters in flare observations. The results for  $H\alpha$  and  $H\beta$  may also be found in the Appendix.

Figures 4a–4c illustrate a time sequence of the optical spectra obtained during the flare. The principal emission lines are identified in the quiescent spectrum which is included in Figure 4c for comparison; it has not been subtracted from the flare spectra. Figures 5a–5b are a similar time sequence of the long-wavelength *IUE* spectra taken during the flare; the quiescent spectrum is shown in Figure 5b and again has not been subtracted from the flare spectra. Figure 6 depicts the short-wavelength *IUE* spectrum obtained during the first 900 s of the flare. The quiescent spectrum is also included. A total of 15 long-wavelength *IUE* spectra, one short-wavelength *IUE* spectrum, and more than 100 optical spectra were obtained during the course of the flare.

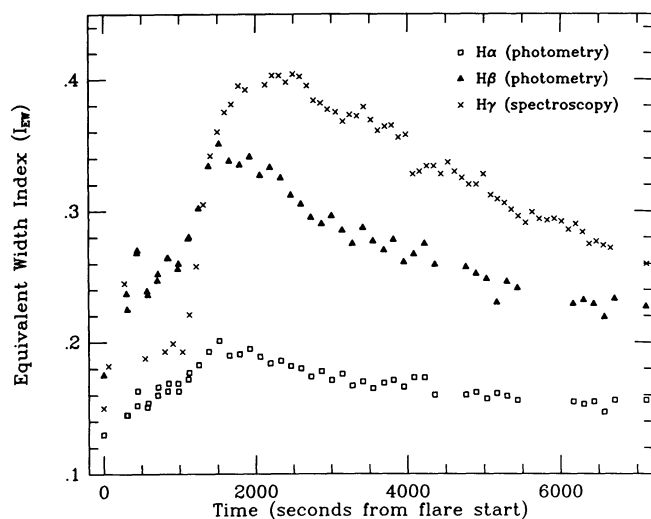


FIG. 3.—Light curves for the photometric equivalent width indices ( $I_{EW}$ ) found by taking the ratio of counts in narrow and wide filters centered on an emission line are shown for  $H\alpha$  and  $H\beta$ . The  $H\gamma$  equivalent width index obtained from the optical spectra is also shown.

We were able to identify more than 30 emission lines in our low-resolution optical flare spectra. Many of these were visible only during the impulsive phase and may provide important information on the changing atmospheric structure, and hence flare heating, if observed at higher spectral resolution. Table 2 gives our line identifications and comments on the individual features. Of particular interest in the spectrum near flare maximum (Fig. 4a) are the very broad wings of the hydrogen lines, some 20–30 Å at the base. The Balmer series lines begin to merge at about H14 due to this broadening, yet the Ca II K line shows very little broadening. Another interesting feature is the rapid filling in of the strong absorption line of Ca I at 4226 Å during the impulsive phase of the flare. The emission core is still visible some 5000 seconds after the flare began. In future work we hope to bring together the Ca I and Ca II data to form an empirical description of the development of the calcium ionization fraction and investigate the constraints this places on the atmospheric structure.

In the long-wavelength *IUE* spectra taken just after flare maximum, there are a large number of individual features visible. We have not identified them in detail, but note that the Fe II edges near 2630 Å and 2750 Å are an order of magnitude stronger than they were in the quiescent spectrum. The complex appearance of the ultraviolet flare spectra, which appear to be made up of many metal lines and recombination continua, may be providing an important clue as to the nature of the blue continuum observed during flares. Detailed atmo-

TABLE 2  
OPTICAL LINE IDENTIFICATIONS NEAR FLARE MAXIMUM

| Wavelength (Å) | Element | Comment                         |
|----------------|---------|---------------------------------|
| 3703.85.....   | H I     | Balmer series H16               |
| 3703.98.....   | He I    | Blended with H16                |
| 3711.97.....   | H I     | Balmer series H15               |
| 3721.94.....   | H I     | Balmer series H14               |
| 3734.37.....   | H I     | Balmer series H13               |
| 3750.15.....   | H I     | Balmer series H12               |
| 3770.63.....   | H I     | Balmer series H11               |
| 3797.90.....   | H I     | Balmer series H10               |
| 3815.84.....   | Fe I    |                                 |
| 3819.61.....   | He I    | Blended with 3820.43 Fe I       |
| 3820.43.....   | Fe I    | Blended with 3819.61 He I       |
| 3835.38.....   | H I     | Balmer series H9                |
| 3856.0.....    | ?       | Also seen by Robinson 1989      |
| 3878.58.....   | Fe I    | In far blue wing of H8          |
| 3888.65.....   | He I    | Blended with H8                 |
| 3889.05.....   | H I     | Balmer series H8                |
| 3906.48.....   | Fe I    | In far red wing of H8           |
| 3933.65.....   | Ca II   | K line                          |
| 3964.73.....   | He I    | In blue wing of Ca II H and He  |
| 3968.46.....   | Ca II   | H line                          |
| 3970.07.....   | H I     | Balmer series He                |
| 4026.19.....   | He I    |                                 |
| 4045.82.....   | Fe I    |                                 |
| 4063.60.....   | Fe I    |                                 |
| 4078.7.....    | ?       |                                 |
| 4101.73.....   | H I     | Balmer series Hδ                |
| 4120.81.....   | He I    | In far red wing of Hδ           |
| 4132.06.....   | Fe I    |                                 |
| 4143.76.....   | He I    |                                 |
| 4226.73.....   | Ca I    | Long-lived emission core, wings |
| 4340.46.....   | H I     | Balmer series Hγ                |
| 4358.51.....   | Fe I    | In far red wing of Hγ           |
| 4375.93.....   | Fe I    |                                 |
| 4387.93.....   | He I    |                                 |
| 4416.1.....    | ?       |                                 |
| 4433.22.....   | Fe I    |                                 |

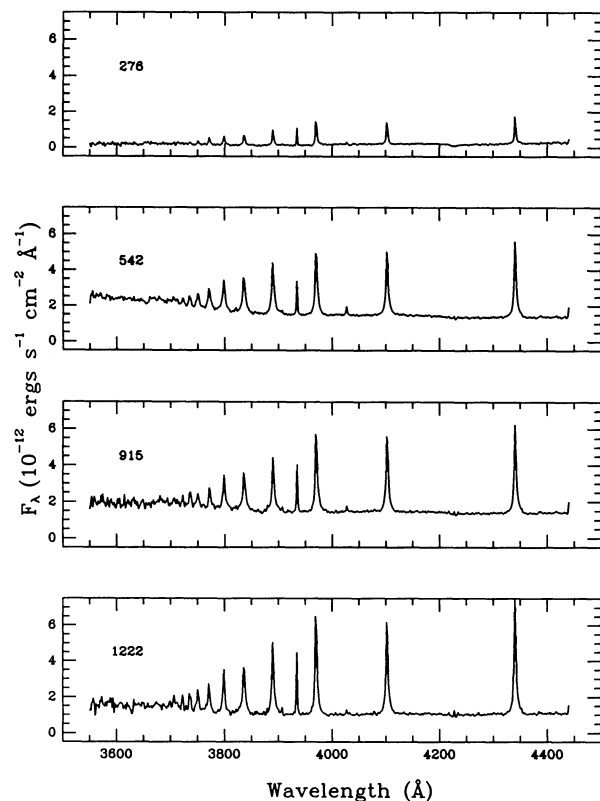


FIG. 4a

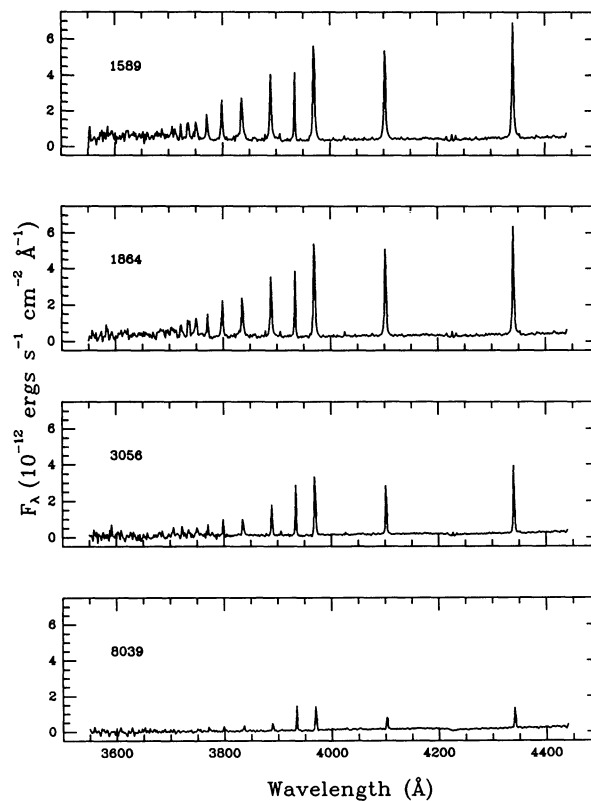


FIG. 4b

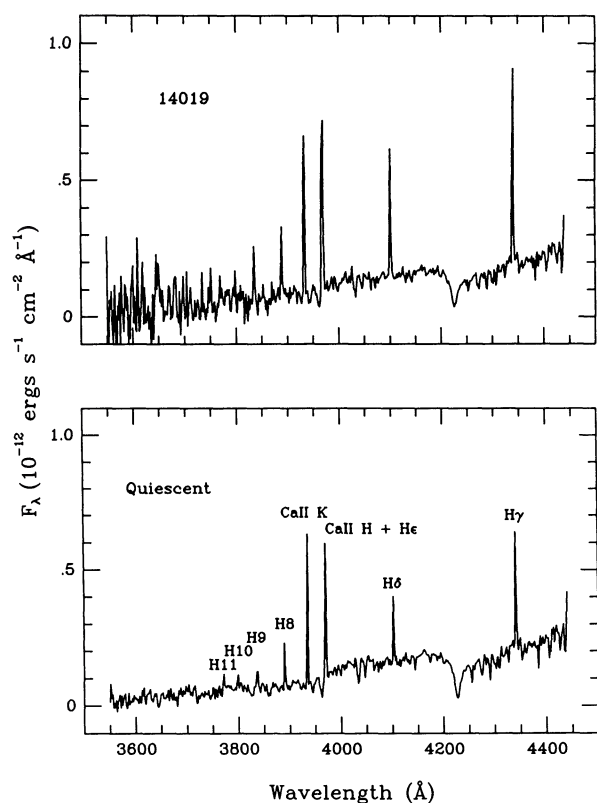


FIG. 4c

spheric modelling is necessary to determine whether a significant fraction of the blue and ultraviolet continuum radiation could be explained by these collisionally excited, optically thin metal features, as discussed in Hawley (1989). High-resolution spectra would also be valuable, in order to identify individual features and provide much-needed constraints on the models.

In the short-wavelength *IUE* spectrum, which was taken during the first half of the impulsive phase, a large number of high-energy species typical of elevated “transition region” temperatures were visible. These included Lyman- $\alpha$ , N v, C ii, C iv, and He ii enhanced by factors of 10–20 over the quiescent values, and C iii, Si iii, O i, and Si iv which were observed only in the flare spectrum.

Emission-line fluxes were measured as a function of time for the important contributors to the radiative losses in the optical and near ultraviolet, including the hydrogen Balmer lines from H9 to H $\gamma$ , the Ca ii H and K lines, and the Mg ii *h* and *k* lines. To analyze the optical spectra, the quiescent spectrum was first subtracted from the spectra taken during the flare. The emission-line fluxes were then determined by numerically integrating the flux under the line, using carefully chosen windows to set the local continuum level. The long-wavelength *IUE* spectra were measured directly, and the quiescent flux sub-

FIG. 4.—(a) Time sequence of optical spectra obtained with the McDonald Observatory 2.1 m telescope during the impulsive phase of the flare. The time of the midpoint of the exposure (in seconds from flare start) is given in the upper left of each spectrum. (b) Same as (a) during the gradual phase of the flare. (c) A spectrum taken almost 4 hr after the start of the flare is shown together with the quiescent spectrum. The flux scale is expanded compared to the flare spectra. The hydrogen line emission is still noticeably enhanced in the flare spectrum. The principal emission lines in this wavelength region are identified in the quiescent spectrum.

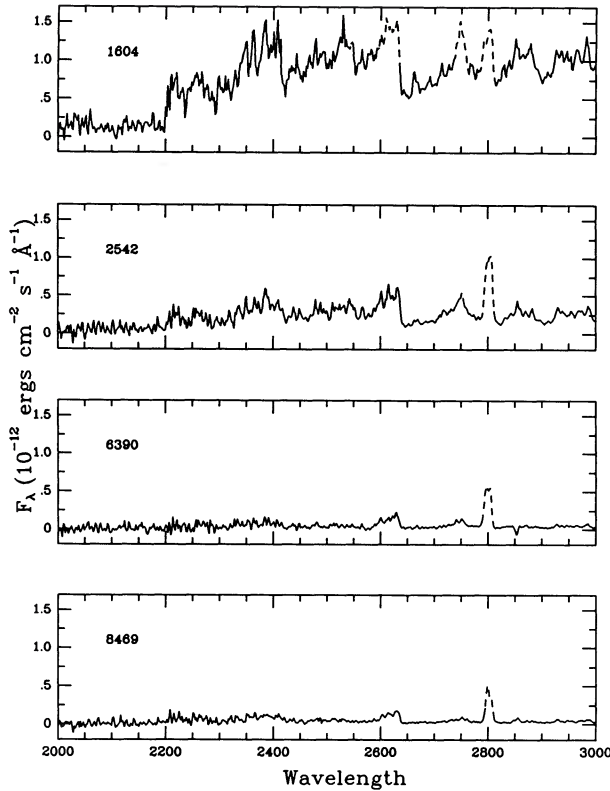


FIG. 5a

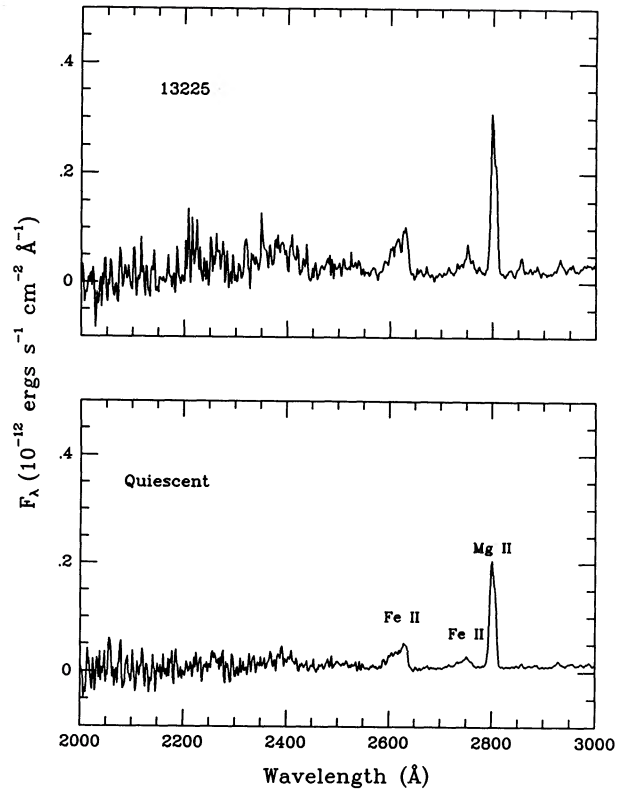


FIG. 5b

FIG. 5.—(a) A time sequence of ultraviolet spectra obtained with the LWP camera of the *IUE* satellite during the gradual phase of the flare. The time of the midpoint of the exposure (in seconds from flare start) is given in the upper left of each spectrum. Saturated portions are indicated with a dashed line. (b) A spectrum taken almost 4 hr after the start of the flare is shown together with the quiescent spectrum. The flux scale is expanded compared to the flare spectra. The Fe II and Mg II features identified in the quiescent spectrum are still enhanced in the flare spectrum.

tracted later, as the first few spectra were saturated in the peaks of the Mg II lines. The line fluxes obtained from those spectra are lower limits to the true values. The results for H $\gamma$ , H $\delta$ , Ca II K, and Mg II  $h+k$  are shown in Figure 7.

Many of the emission lines in the short-wavelength *IUE* spectrum were saturated in their peaks, as shown in Figure 6.

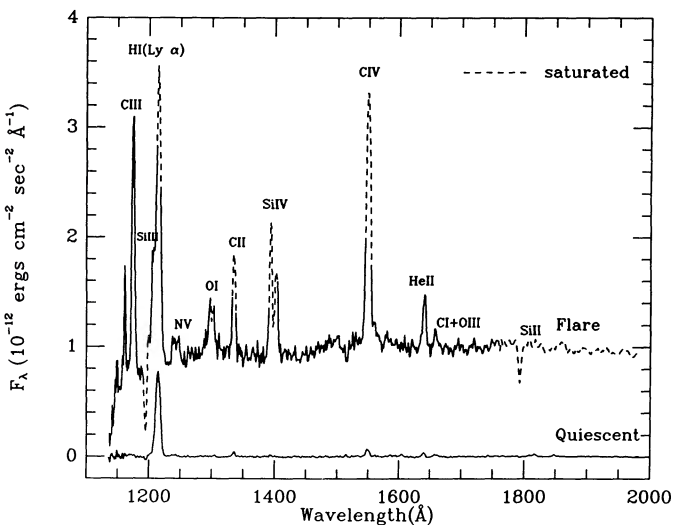


FIG. 6.—Spectra obtained with the SWP camera of the *IUE* satellite during quiescence and during the first 900 s of the flare are shown. The principal emission lines are identified. Saturated portions are indicated with a dashed line.

Estimates of the line fluxes were made using Gaussian fits to the unsaturated portions of the lines. The geocoronal portion of the Lyman- $\alpha$  flux was removed (J. Neff 1987, private communication). The short-wavelength region quiescent spectrum was also analyzed and the quiescent line fluxes were subtracted from the flare values. The results for the quiescent and flare line fluxes are given in Table 3. We estimate the uncer-

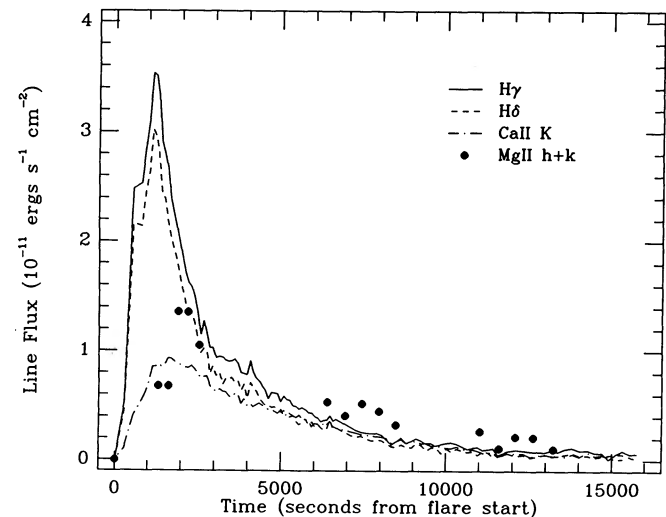


FIG. 7.—The flux emitted in the emission lines H $\gamma$ , H $\delta$ , Ca II K, and Mg II  $h+k$  is shown as a function of time from flare start. The first five Mg II  $h+k$  measurements are lower limits as the lines were saturated in their peaks.

TABLE 3  
SWP ULTRAVIOLET LINE FLUXES (AT EARTH)

| Line ID<br>( $\lambda$ in Å)        | Quiescent Flux<br>( $10^{-13}$ ergs $\text{cm}^{-2}$ $\text{s}^{-1}$ ) | Flare Flux<br>( $10^{-13}$ ergs $\text{cm}^{-2}$ $\text{s}^{-1}$ ) |
|-------------------------------------|------------------------------------------------------------------------|--------------------------------------------------------------------|
| C III (1174) .....                  | ...                                                                    | 130                                                                |
| Si III (1206) .....                 | ...                                                                    | 34                                                                 |
| H I (1216) (Lyman- $\alpha$ ) ..... | 5.2                                                                    | 106                                                                |
| N V (1240, 1243) doublet .....      | 1.6                                                                    | 14, 15                                                             |
| O I (1298) .....                    | ...                                                                    | 56                                                                 |
| C II (1335) .....                   | 1.9                                                                    | 55                                                                 |
| Si IV (1392, 1401) doublet .....    | ...                                                                    | 55, 61                                                             |
| C IV (1549, 1551) doublet .....     | 4.4                                                                    | 192                                                                |
| He II (1640) .....                  | 2.2                                                                    | 31                                                                 |
| C I (1657 + O III (1666) .....      | 2.0                                                                    | 11                                                                 |
| Si II (1808, 1816) doublet .....    | 0.7, 1.3                                                               | (saturated)                                                        |

tainties in the flare values to be at least 50% due primarily to the saturation corrections.

Comparing Figures 1 and 7 demonstrates that the qualitative behavior of the emission lines and continuum discussed in Bopp & Moffett (1973) and Worden et al. (1984) also is evident in our data. The continuum flux rises and decays rapidly, while the hydrogen Balmer lines peak later and decay more slowly. There is some indication that the high-order Balmer lines decay more rapidly than the low-order lines. The Ca II K line and possibly the Mg II *h* and *k* lines rise and decay even more slowly than the hydrogen lines. Figure 8 shows the *U* filter, H $\gamma$ , and Ca II K observations normalized to their peak values to illustrate their differing time behavior. The *U* filter is measuring mostly impulsive phase radiation but does have a significant gradual phase component. This is in contrast to the interpretation of Bopp & Moffett (1973), who propose in their Figure 2 that the continuum enhancement ends when the fast decay (what we term the impulsive phase) has ended. Indeed, the generally accepted notion that the white-light continuum is present only during the impulsive phase is certainly not correct during this flare. As we shall see when we compute the flare energy budget in § 4, the majority of the flare energy radiated during the gradual phase is emitted in the continuum. Figure 8

shows that H $\gamma$  has nearly equal impulsive and gradual phase components, while Ca II K is emitted mostly during the gradual phase. Both the hydrogen and Ca II emission lines were elevated for more than 4 hr, while the continuum radiation lasted about 2 hr.

To investigate the broadening of the hydrogen lines during a flare, we measured the full line width at the continuum level for H $\gamma$ . The width at half-maximum was not used, as the emission lines are not clearly resolved at our 3.5 Å resolution. Figure 9 shows the results. Evidently the line broadening continues well into the gradual phase of the flare but ends at ~8000 s, nearly the same time as the continuum enhancements ended. There was no obvious line asymmetry at any time during the flare. While we cannot rule out bulk motions of several hundred km s<sup>-1</sup> as a possible cause of the line wing enhancements (e.g., Doyle et al. 1988), we note that this explanation would require that the amount of radiating material moving in each direction must be approximately equal over an extended time interval in order to produce the observed profiles. This is generally not the case on the Sun, where pronounced redshifts in H $\alpha$  are usually observed during the impulsive phase (Ichimoto & Kurokawa 1984; Zarro & Canfield 1989; Wülser & Marti 1989). Further, the Ca II lines would be expected to show

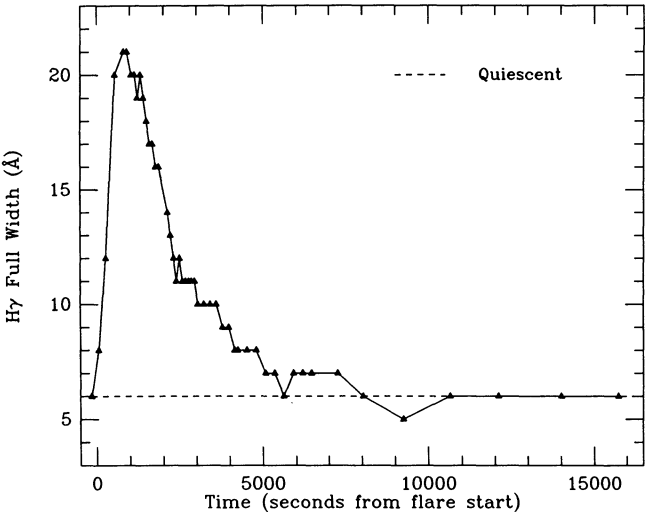
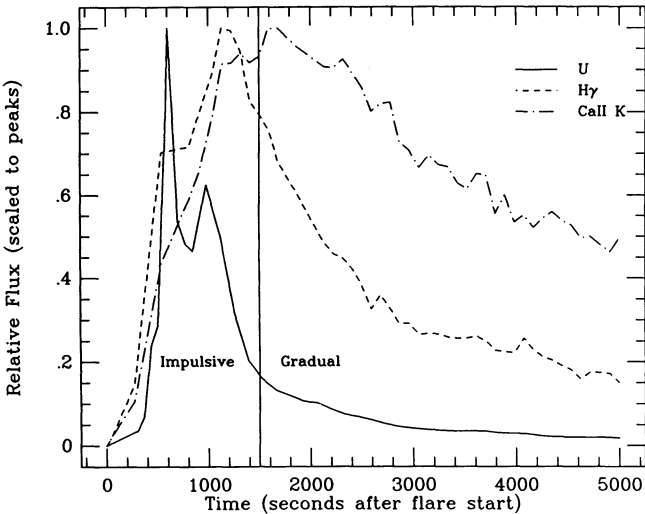


FIG. 8.—The H $\gamma$  and Ca II K lines fluxes and the continuum flux measured in the *U* filter are normalized to their peak values and plotted on the same time scale to illustrate their differing time evolution during the flare. The adopted demarcation between the impulsive and gradual phases is shown.

FIG. 9.—The full width of H $\gamma$  at the continuum level, measured in Å, is shown as a function of time to illustrate the broadening of the hydrogen Balmer line wings during the flare.

similar broadening if hydrodynamic effects were contributing significantly in the chromospheric line forming regions; this broadening was not observed.

If we consider the spectra obtained near flare maximum (Fig. 4), and attribute the extreme broadening seen in the hydrogen Balmer line wings to the Stark effect, the Inglis-Teller relation (Kurochka & Maslennikova 1970) predicts that the electron density necessary to produce series merging at H16, the highest order Balmer line we can detect, is  $N_e \sim 3 \times 10^{13} \text{ cm}^{-3}$ . This value is similar to those found by Giampapa (1983) and Worden et al. (1984) for flares on UV Cet and YZ CMi, two other dMe flare stars. Following Sutton (1978), as discussed in Worden et al. (1984), the predicted increase in broadening at FWHM due to the Stark effect is about a factor of 3 between H $\gamma$  and H9. If the intrinsic FWHM of H $\gamma$  was  $\sim 1 \text{ \AA}$  (as measured for H $\alpha$  during quiescence by Pettersen & Coleman 1981), the predicted 3  $\text{\AA}$  FWHM at H9 is just below the limit of our resolution. We are therefore not able to test conclusively whether the Stark effect could explain the observed line broadening. Observations of flares with better spectral resolution will be necessary in order to fully investigate the line-broadening mechanisms. However, we can definitely rule out line broadening of 8–10  $\text{\AA}$  at FWHM for the hydrogen Balmer lines during this flare, as was reported by Rodonò et al. (1989) for a less energetic flare on AD Leo.

The Balmer decrement normalized to H $\gamma$  for the lines H $\beta$ , H $\gamma$ , H $\delta$ , H8, and H9 is tabulated in Table 4A for several times during the impulsive and gradual phases of the flare. The normalized Ca II K flux also is given. H $\alpha$  is not included due to the uncertainty in obtaining a true flux from our filter photometry, as discussed in the Appendix. The ratios of the flare-only line fluxes were used to compute the decrement. Line flux measurements for the higher Balmer lines (H10 and above) are not included due to the difficulty in assigning the local continuum level. Although the H $\beta$  measurements are uncertain, it appears

that the decrement became quite shallow and stayed nearly constant during the impulsive phase of the flare. The decrement then steepened but did not become as steep as the quiescent value, during the gradual phase.

Table 4B contains average decrements for three other flares; the UV Ceti event reported in Phillips et al. (1988), the YZ CMi event reported in Doyle et al. (1988) and the AD Leo event reported in Rodonò et al. (1984, 1989) (R84) and discussed in more detail in § 5. It is difficult to quantitatively compare the flare decrements since the quiescent decrements on these stars are somewhat different, as shown in the table. In all cases, however, the flare decrement was shallower indicating that the hydrogen emitting regions are systematically different during flares as compared to the quiescent state.

A final observational concern is determining the amount of line flux contained in the photometric bandpasses and hence contributing to the flare magnitudes. If the *UBVR* colors are to be used to define the flare continuum, then the line contamination must be investigated. Assuming a *U* bandpass of 680  $\text{\AA}$  centered at 3600  $\text{\AA}$ , the high-order Balmer lines, beginning at H8, are the only important emission lines contributing to the *U* filter magnitudes. We find that the lines H9 and up contribute a flux about twice that of H8, so that the total contribution is about three times the H8 flux. This value is less than 2% at quiescence and rises to about 15% during the gradual phase of the flare. The *B* filter, centered at 4400  $\text{\AA}$  with a bandpass of 980  $\text{\AA}$ , contains H $\gamma$  and H $\delta$ . Their contribution is less than 1% at quiescence rising to 17% during the gradual phase. The *V* filter, centered at 5300  $\text{\AA}$  with a bandpass of 850  $\text{\AA}$ , does not contain any important emission lines, and the *R* filter, centered at 7000  $\text{\AA}$  with a bandpass of 2080  $\text{\AA}$ , contains only H $\alpha$  which contributes less than 1% at quiescence and rises to 8% during the gradual phase. The line contributions are all smaller during the impulsive phase and do not change the overall shape of the flare continuum during any phase. Nevertheless, we did com-

TABLE 4A  
BALMER DECREMENT: 1985 APRIL 12 AD LEO FLARE

| LINE             | QUIESCENT | FLARE ONLY—TIME OF MEASUREMENT (s) |      |      |      |      |      |      |      |      |
|------------------|-----------|------------------------------------|------|------|------|------|------|------|------|------|
|                  |           | 300                                | 600  | 900  | 1200 | 1500 | 2000 | 3000 | 5000 | 8000 |
| H $\beta$ .....  | 2.01      | 1.20                               | 1.26 | 1.25 | 1.09 | 1.21 | 1.26 | 1.43 | 1.32 | 1.30 |
| H $\gamma$ ..... | 1.0       | 1.0                                | 1.0  | 1.0  | 1.0  | 1.0  | 1.0  | 1.0  | 1.0  | 1.0  |
| H $\delta$ ..... | 0.56      | 0.89                               | 0.87 | 0.86 | 0.84 | 0.85 | 0.84 | 0.82 | 0.82 | 0.72 |
| H8 .....         | 0.40      | 0.66                               | 0.62 | 0.59 | 0.63 | 0.56 | 0.61 | 0.56 | 0.58 | 0.50 |
| H9 .....         | 0.24      | 0.53                               | 0.50 | 0.45 | 0.46 | 0.50 | 0.47 | 0.39 | 0.34 | 0.36 |
| Ca II K .....    | 1.20      | 0.19                               | 0.16 | 0.22 | 0.24 | 0.31 | 0.46 | 0.65 | 0.87 | 0.92 |

TABLE 4B  
BALMER DECREMENTS ON dMe STARS—QUIESCENT AND FLARING

| LINE             | AD LEO    |         |       |           |         |       |           |               |           |               |
|------------------|-----------|---------|-------|-----------|---------|-------|-----------|---------------|-----------|---------------|
|                  | HP85      |         |       | R84       |         |       | UV CET    |               | YZ CMi    |               |
|                  | Impulsive | Gradual | Total | Impulsive | Gradual | Total | Quiescent | Flare Maximum | Quiescent | Flare Average |
| H $\gamma$ ..... | 1.0       | 1.0     | 1.0   | 1.0       | 1.0     | 1.0   | 1.0       | 1.0           | 1.0       | 1.0           |
| H $\delta$ ..... | 0.85      | 0.79    | 0.81  | 0.85      | 0.81    | 0.83  | 0.59      | 0.69          | 0.44      | 0.69          |
| H8 .....         | 0.64      | 0.53    | 0.57  | 0.53      | 0.49    | 0.51  | 0.38      | 0.47          | 0.25      | 0.54          |
| H9 .....         | 0.47      | 0.40    | 0.42  | 0.39      | 0.34    | 0.36  | 0.31      | 0.42          | 0.21      | 0.45          |
| Ca II K .....    | 0.22      | 0.64    | 0.50  | 0.15      | 0.45    | 0.30  | 1.26      | 0.83          | ...       | ...           |

TABLE 5  
ENERGY BUDGET: 1985 APRIL 12 AD LEO FLARE  
A. CONTINUUM REGIONS

| WAVELENGTHS (Å)       | $F_{\lambda}$ INTEGRATED OVER TIME INTERVAL ( $10^{-9}$ ergs $\text{cm}^{-2}$ Å $^{-1}$ ) |            |             |             |               |                 |
|-----------------------|-------------------------------------------------------------------------------------------|------------|-------------|-------------|---------------|-----------------|
|                       | 0–900 s                                                                                   | 900–1500 s | 1500–4000 s | 4000–7000 s | 7000–13,000 s | 13,000–15,000 s |
| 1200–2000 (SWP) ..... | 0.9                                                                                       | (0.3)      | (0.1)       | (0.05)      | ...           | ...             |
| 2000–3260 (LWP) ..... | (0.9)                                                                                     | 0.8        | 0.6         | 0.15        | ...           | ...             |
| 3260–3940 (U) .....   | 1.19                                                                                      | 1.03       | 0.73        | 0.19        | ...           | ...             |
| 3910–4890 (B) .....   | 0.81                                                                                      | 0.75       | 0.50        | 0.13        | ...           | ...             |
| 4875–5725 (V) .....   | 0.47                                                                                      | 0.48       | 0.37        | 0.07        | ...           | ...             |
| 5955–8045 (R) .....   | 0.28                                                                                      | 0.32       | 0.36        | 0.08        | ...           | ...             |

B. EMISSION LINES

| LINE                         | FLUX INTEGRATED OVER TIME INTERVAL ( $10^{-8}$ ergs $\text{cm}^{-2}$ ) |            |             |             |               |                 |
|------------------------------|------------------------------------------------------------------------|------------|-------------|-------------|---------------|-----------------|
|                              | 0–900 s                                                                | 900–1500 s | 1500–7000 s | 4000–7000 s | 7000–13,000 s | 13,000–15,000 s |
| H $\alpha$ .....             | (0.90)                                                                 | (1.58)     | (3.38)      | (1.99)      | 1.51          | 0.45            |
| H $\beta$ .....              | 1.66                                                                   | 2.22       | 4.35        | 1.88        | 1.74          | 0.31            |
| H $\gamma$ .....             | 1.38                                                                   | 1.91       | 3.43        | 1.54        | 0.90          | 0.16            |
| H $\delta$ .....             | 1.19                                                                   | 1.62       | 2.85        | 1.22        | 0.64          | 0.09            |
| H8 .....                     | 0.93                                                                   | 1.16       | 2.01        | 0.74        | 0.40          | 0.07            |
| H9 .....                     | 0.65                                                                   | 0.89       | 1.51        | 0.54        | 0.31          | 0.07            |
| Ca II K .....                | 0.26                                                                   | 0.48       | 1.83        | 1.18        | 0.79          | 0.09            |
| Ca II H + H $\epsilon$ ..... | 1.18                                                                   | 1.67       | 3.71        | 1.79        | 1.13          | 0.15            |
| Mg II $h+k$ .....            | (0.43)                                                                 | (0.79)     | (3.0)       | 1.94        | 1.78          | (0.15)          |
|                              |                                                                        | > 0.36     | > 2.57      |             |               |                 |
| He I 4026 .....              | 0.06                                                                   | 0.05       | 0.10        | 0.04        | ...           | ...             |
| C IV .....                   | 1.7                                                                    | a          | a           | a           | a             | a               |
| All other SWP lines .....    | 5.0                                                                    | b          | b           | b           | b             | b               |

<sup>a</sup> Sum over all time intervals except 0–900 s estimated to be 5.

<sup>b</sup> Sum over all time intervals except 0–900 s estimated to be 15.

pensate for the line contributions in our measurements of the total continuum energy emitted during the flare.

#### 4. THE FLARE ENERGY BUDGET

We next seek to obtain a quantitative description of the energy budget, by investigating the distribution of energy among line and continuum features as a function of time during the flare. We have calculated the energy emitted in the continuum in six wavelength regions covering the range between 1200 and 8000 Å and in the important optical and ultraviolet emission lines within that range. The results are presented in Table 5. The time intervals were chosen to accommodate the actual observing periods for the *IUE* data, and also to provide some time resolution during each phase. As discussed previously, the precise demarcation between the impulsive and gradual phases is subjective. We assume that the gradual phase begins at 1500 s after flare start based on the *U* filter light curve, which shows a turnover from fast to slow decay at that point. Another consideration was that 1500 s falls between the times of peak H $\gamma$  and Ca II K emission, in keeping with the relative importance of the gradual phase components of those lines. Also, the *U* filter flux had fallen to less than  $1/e$  of its peak value. These features may be seen in Figure 8, where the impulsive—gradual phase boundary is shown.

Values in parentheses in Table 5 have been extrapolated from features that were observed, as follows: The 0–900 s flux and the 900–1500 s flux were assumed to be emitted in the same proportion in the long-wavelength ultraviolet region as in the *U* filter, i.e., in the ratio 1.2:1. The short-wavelength ultraviolet flux during the 900–1500 s interval was extrapo-

lated from the measured SWP flux in the 0–900 s interval and the measured 2000 Å flux at 1300 s (see Fig. 1). The SWP flux during the 1500–4000 and 4000–7000 s intervals was determined from the measured 2000 Å flux in the LWP spectra. The H $\alpha$  flux has been multiplied by a factor of 2 during the impulsive phase and by 1.5 between 1500 and 7000 s in an attempt to account for the line-broadening effect on the photometrically measured fluxes. The Mg II  $h+k$  fluxes are assumed to follow the same time evolution as the measured Ca II K flux during those time periods when the observations were saturated or no observations were made. The measured values are shown as lower limits. The extrapolated values are included in the table in order to illustrate their relative importance in computing the impulsive and gradual phase energy budgets given in Table 6.

The evolution of the continuum radiation in Table 5 indicates that the relative contribution of the red (e.g., the *V* and *R* filter) continuum increased well into the gradual phase when compared with the blue (*U* and *B* filter) continuum which showed a monotonic decline. Figure 10 illustrates the effect. The line contributions have not been subtracted, but that would only make the difference more pronounced in the blue, and not remove it in *R*. Since the shift in continuum slope is quite smooth and not marked by obvious breaks in the light curves, it probably indicates that two (or more) competing emission mechanisms, with different spectral distributions, are responsible for the continuum emission. For example, the observed rise in the relative contribution of the red continuum could be explained if the contribution from Paschen-continuum radiation increased in importance as the flare progressed. However, we note that the continuum emission is

TABLE 6  
ENERGY BUDGET SUMMARY: 1985 APRIL 12 AD LEO FLARE

## A. CONTINUUM REGIONS

| WAVELENGTHS (Å)       | F <sub>λ</sub> INTEGRATED OVER TIME INTERVAL<br>AND WAVELENGTH (10 <sup>-8</sup> ergs cm <sup>-2</sup> ) |                  |       |                            |
|-----------------------|----------------------------------------------------------------------------------------------------------|------------------|-------|----------------------------|
|                       | Impulsive<br>Phase                                                                                       | Gradual<br>Phase | Total | Ratio<br>(Impulsive/Total) |
| 1200-2000 (SWP) ..... | 96                                                                                                       | 12               | 108   | 0.89                       |
| 2000-3260 (LWP) ..... | 214                                                                                                      | 95               | 309   | 0.70                       |
| 3260-3940 (U) .....   | 145                                                                                                      | 53               | 198   | 0.73                       |
| 3910-4890 (B) .....   | 147                                                                                                      | 51               | 198   | 0.74                       |
| 4875-5725 (V) .....   | 81                                                                                                       | 37               | 118   | 0.69                       |
| 5955-8045 (R) .....   | 123                                                                                                      | 85               | 208   | 0.59                       |
| Total continuum ..... | 806                                                                                                      | 333              | 1139  | 0.71                       |

## B. EMISSION LINES

| LINES                         | FLUX INTEGRATED OVER TIME<br>INTERVAL (10 <sup>-8</sup> ergs cm <sup>-2</sup> ) |                  |       |                            |
|-------------------------------|---------------------------------------------------------------------------------|------------------|-------|----------------------------|
|                               | Impulsive<br>Phase                                                              | Gradual<br>Phase | Total | Ratio<br>(Impulsive/Total) |
| Total hydrogen lines .....    | 21                                                                              | 40               | 61    | 0.34                       |
| Total Ca II and Mg II .....   | 3                                                                               | 14               | 17    | 0.18                       |
| Total ultraviolet lines ..... | 12                                                                              | (16)             | (28)  | 0.43                       |
| Total lines .....             | 36                                                                              | 70               | 106   | 0.34                       |
| Total energy emitted .....    | 842                                                                             | 403              | 1245  | 0.68                       |
| Ratio (lines/total) .....     | 0.04                                                                            | 0.17             | 0.09  |                            |

always largest in the *U* filter, an indication of the characteristic blue continuum color that is ubiquitous among M dwarf flares. The one reported anomaly (Doyle, van den Oord, & Butler 1989) in which the continuum was found to be *red* in color during the first ~20 s of the flare may be explained by noting that they have presented the data as  $F_v$  versus  $\lambda$ . If the data is plotted as  $F_\lambda$  versus  $\lambda$ , the blue continuum color is evident.

The evolution of the emission line radiation again shows the behavior discussed qualitatively above. The He I line at 4026 Å is the most impulsive, the hydrogen Balmer lines are next and

are very similar to one another (indicating that the decrement remains quite constant), although the higher order lines (e.g., H8 and H9) seem to emit somewhat more in the impulsive phase relative to the gradual phase than do the lower order lines (e.g., H $\gamma$  and H $\delta$ ). The Ca II K line again showed the most gradual evolution.

Table 6 tabulates the total energy emitted in each continuum region during the two phases. The values from Table 5 have been integrated over the filter bandpass in order to obtain the total energy emitted (i.e.,  $F_\lambda$  integrated over time and wavelength); the same quantity that is computed for the emission lines. The energy emitted in the *U*, *B*, and *R* filters has been corrected for the line radiation as discussed above. The correction is small, amounting at most to 17% in the *B* filter continuum during the gradual phase. The ratio of impulsive phase to total flare radiation (a measure of the impulsiveness of the emission feature) has also been computed. Note that the ratio varies from 0.74 (*B*) to 0.59 (*R*) for the continuum emission (though the SWP continuum may be even more impulsive, based on our uncertain extrapolation) and from 0.42 for He I (4026) to 0.16 for Ca II K among the emission lines. The ultraviolet emission lines, which are mostly high-energy species, were assumed to follow the time evolution of the He I line in computing their contribution to the total line radiation. Also, to separate the Ca II H and He contributions from the measured (combined) flux, we assumed that they occurred in the same ratio as Ca II K to H $\delta$  during each time period in Table 5.

Figure 11 illustrates the relative contributions of line and continuum radiation in each phase and in the total energy budget. The emission lines account for only 4% of the total energy during the impulsive phase. Their contribution rises to 17% during the gradual phase and is 9% averaged over the whole flare. The continuum radiation thus is the dominant

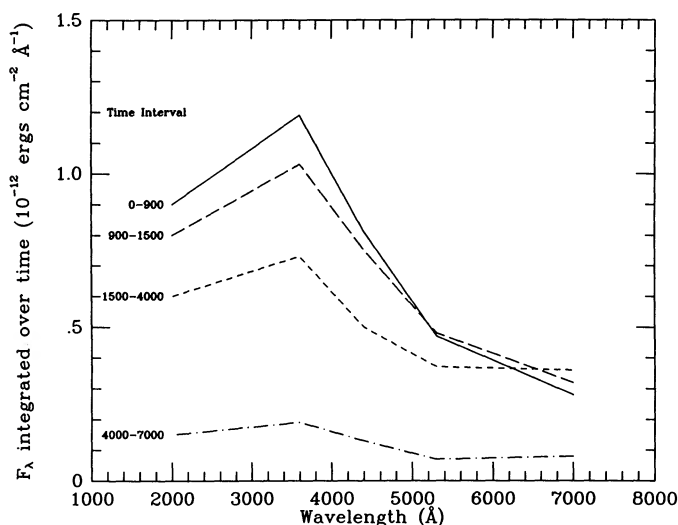


FIG. 10.—The spectral distribution of the continuum radiation as measured in *U*, *B*, *V*, and *R* and at 2000 Å is shown for four time intervals during the impulsive and gradual phases of the flare.

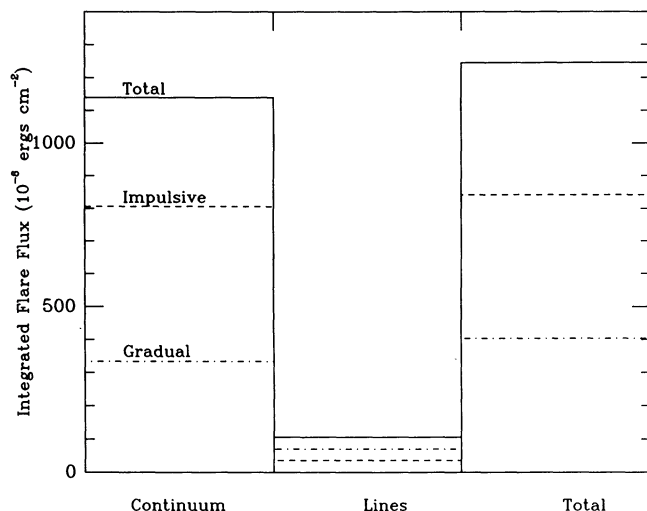


FIG. 11.—The histogram illustrates the flare energy emitted in the continuum, in the lines, and in total (the sum of the lines and continuum). The percentage contribution of each emission component to the total is shown. The emission in each component is also broken down by the phase during which it was emitted, and the percentage of emission in each phase is given.

term in the energy budget throughout the flare. Approximately one-third of the line radiation is emitted during the impulsive phase, while more than  $\frac{2}{3}$  of the continuum radiation is emitted during that phase. Since the continuum accounts for so much of the energy, about  $\frac{2}{3}$  of the total flare energy is emitted during the impulsive phase as well. Of course all of these results refer only to radiation emitted in the 1200–8000 Å wavelength range.

## 5. DISCUSSION

### 5.1. Comparison with Previous AD Leo Flare

One other well-observed flare on AD Leo has been described in the literature: the 1984 March 28 event by Rodonò et al. (1984) and Rodonò et al. (1989), with a  $U$  filter enhancement of some 2 mag and total emitted energy  $\sim 10^{32}$  ergs. Hereafter we refer to it as the R84 flare and to our flare as the HP85 flare. Since the R84 flare occurred on the same star but was a much less energetic event, it is of great interest to

compare in detail the behavior of the various emission features observed in common. We used the published light curves for  $H\gamma$ ,  $H\delta$ ,  $H8$ ,  $H9$ ,  $He\ I\ 4026$ ,  $Ca\ II\ K$ , and the  $U$  filter continuum to obtain an energy profile for the R84 flare. We again determined the impulsive-gradual phase boundary using the criteria of a change in the  $U$  light curve which occurred between the peaks of the  $H\gamma$  and  $Ca\ II\ K$  emission at about 800 s after flare start. The  $U$  filter flux was 0.14 of its peak flux at that time, as compared to 0.16 in the HP85 flare. In fact, we were struck by the remarkable similarity in the behavior of the three emission features between the two flares, particularly considering the complex (double-peaked) nature of the impulsive phase in both cases.

The results of the energy calculations for the R84 flare are shown in Table 7, and the results for the HP85 flare are included for comparison. The  $U$  filter energy is shown both with and without the correction for line emission. It is clear that more line radiation was emitted during the impulsive phase of the R84 flare; approximately one-half of the total (gradual + impulsive) line emission as opposed to one-third for the HP85 flare. In fact, the contribution of all of the flare emission features was greater during the impulsive phase of R84, although the increase in the  $U$  filter was only a few percent. Since the continuum radiation is again the dominant term in the energy budget, the ratio of impulsive phase to total energy emitted did not change much, at least for the emission features being considered. It was 0.74 for R84 and 0.68 for HP85. Furthermore, the ratio of line radiation to total radiation in these features varied only from 0.08 for R84 to 0.14 for HP85, although the difference is larger during the gradual phase where the lines are relatively more important. Figures 12a–12b illustrates the relative contribution of line and continuum radiation in each phase for the HP85 and R84 flares. The HP85 results shown in Figure 12a differ from those shown in Figure 11 in that only the features observed in common with the R84 flare ( $U$  filter,  $H\gamma$ ,  $\delta$ , 8, 9 and  $Ca\ II\ K$ ) are included. The excellent agreement between Figures 11 and 12a indicates that these features faithfully reflect the energy radiated over the whole wavelength range.

Differences of some 30%–50% in the distribution of line radiation over time are evident between the two flares, but the overall behavior of the line and continuum radiation is quite

TABLE 7  
HP85 VERSUS R84 ENERGY BUDGET COMPARISON (FOR FEATURES IN COMMON)

|                            | $F_{\lambda}$ INTEGRATED OVER TIME INTERVAL AND WAVELENGTH |                         |       |                            |                                   |                          |       |                            |
|----------------------------|------------------------------------------------------------|-------------------------|-------|----------------------------|-----------------------------------|--------------------------|-------|----------------------------|
|                            | R84 ( $10^{-10}$ ergs $cm^{-2}$ )                          |                         |       |                            | HP85 ( $10^{-8}$ ergs $cm^{-2}$ ) |                          |       |                            |
|                            | Impulsive<br>(0–800 s)                                     | Gradual<br>(800–3800 s) | Total | Ratio<br>(Impulsive/Total) | Impulsive<br>(0–1500 s)           | Gradual<br>(1500–1500 s) | Total | Ratio<br>(Impulsive/Total) |
| $U$ .....                  | 571                                                        | 184                     | 755   | 0.76                       | 151                               | 63                       | 214   | 0.71                       |
| $U$ (line-corrected) ..... | 553                                                        | 168                     | 721   | 0.77                       | 145                               | 53                       | 198   | 0.73                       |
| $H\gamma$ .....            | 11.14                                                      | 11.01                   | 22.15 | 0.50                       | 3.29                              | 6.04                     | 9.33  | 0.35                       |
| $H\delta$ .....            | 9.43                                                       | 8.97                    | 18.40 | 0.51                       | 2.81                              | 4.79                     | 7.60  | 0.37                       |
| $H8$ .....                 | 5.90                                                       | 5.38                    | 11.28 | 0.52                       | 2.09                              | 3.22                     | 5.31  | 0.39                       |
| $H9$ .....                 | 4.29                                                       | 3.69                    | 7.98  | 0.54                       | 1.53                              | 2.43                     | 3.96  | 0.39                       |
| $Ca\ II\ K$ .....          | 1.71                                                       | 4.90                    | 6.61  | 0.26                       | 0.74                              | 3.88                     | 4.62  | 0.16                       |
| $He\ I\ 4026$ .....        | 0.63                                                       | 0.27                    | 0.90  | 0.70                       | 0.10                              | 0.14                     | 0.24  | 0.42                       |
| Total lines .....          | 33.1                                                       | 34.2                    | 67.3  | 0.49                       | 10.6                              | 20.5                     | 31.1  | 0.34                       |
| Total energy emitted ..... | 586                                                        | 202                     | 788   | 0.74                       | 156                               | 74                       | 229   | 0.68                       |
| Ratio (lines/total) .....  | 0.06                                                       | 0.17                    | 0.08  | ...                        | 0.07                              | 0.28                     | 0.14  | ...                        |

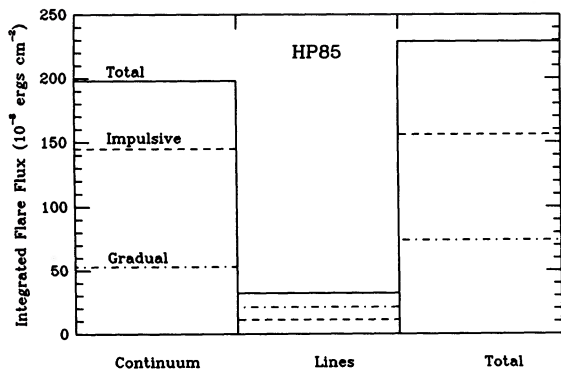


FIG. 12a

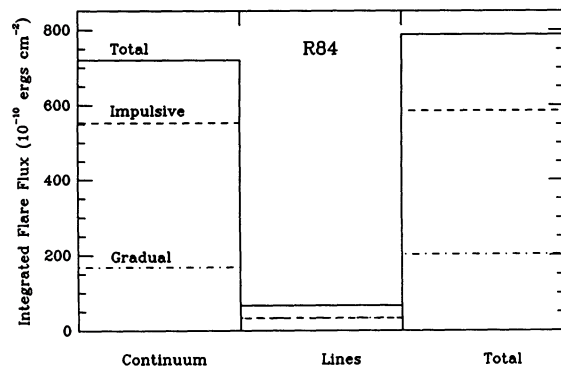


FIG. 12b

FIG. 12.—(a) Same as Fig. 11 except that only the emission measured in the  $U$  filter,  $H\gamma$ ,  $H\delta$ ,  $H8$ ,  $H9$ , and  $Ca II K$  is included. (b) Same as (a) but for the Rodonò et al. 1984 flare.

similar both in time and in energy. The line and continuum radiation appear in roughly the same proportion when summed over the whole flare, and the impulsive and gradual phases contain about the same proportion of the total flare energy in the two flares. Thus, the atmospheric response to the flare energy deposition was nearly the same in the impulsive phase and in the gradual phase of each flare.

### 5.2. Comparison of Four Emission Features in a Sample of Nine Flares

A correlation between integrated (over the duration of the flare) emission features has previously been shown by Butler et

al. (1988) in their study of soft X-ray and  $H\gamma$  emission during flares. They concluded that a linear relation of the form  $E(\text{soft X-ray}) = 31.6 E(H\gamma)$  held over four orders of magnitude in flare energy. Their sample included a total of eight flares on three dMe stars (Gl 644 AB, YZ CMi, and UV Cet) and on the sun. We have used the YZ CMi data from Kahler et al. (1982) and Doyle et al. (1988), the UV Cet data, initially discussed in Butler et al. (1986), data from another flare on UV Cet reported by Phillips et al. (1988), and the flares R84 and HP85 discussed in this paper to investigate further correlations between time-integrated flare emission features. Table 8 compares the total energy emitted in  $H\gamma$ , the  $U$  filter,  $Ca II K$ , and soft X-rays for each of the flares (three dots indicate no measurements were available). The measurements were taken from Butler et al. (1988) and from the original papers whenever possible. We had to estimate the values from the published light curves for the  $U$  filter energy from the Phillips et al. (1988) UV Ceti flare and the  $Ca II K$  energy from the four Butler et al. (1986) UV Ceti flares. Note that  $Ca II K$  data were available for the Doyle et al. (1988) YZ CMi flare, but the published light curve was not of sufficient quality to attempt an estimate of the energy emitted in that line.

Figure 13 illustrates the resulting correlation of each emission feature with the log of the integrated  $H\gamma$  energy,  $\log E(H\gamma)$ . The upper line is taken from Butler et al. (1988); they note that it is not a fit, but a line of slope unity indicating a direct proportionality between  $E(H\gamma)$  and  $E(\text{soft X-ray})$ . The lower line near the  $Ca II K$  points is also of slope unity. Considering the uncertainty in determining the  $Ca II K$  energies, it appears that a direct proportionality also exists between  $E(Ca II K)$  and  $E(H\gamma)$ . The relation between  $U$  filter continuum and  $H\gamma$  emission is somewhat less certain because of the very low  $E(U)$  reported by Kahler et al. (1982) for a flare on YZ CMi. However, it does appear that within some scatter  $E(U)$  and  $E(H\gamma)$  also are directly related. It is interesting to note that the soft X-ray and  $U$  filter relations appear to be nearly identical, indicating that  $E(\text{soft X-ray}) \approx E(U)$ . A second flare on YZ CMi reported by Kahler et al. (1982) had  $E(\text{soft X-ray}) = 1.3 E(U)$ , which agrees well within the scatter in the present relation. That flare had no reported  $H\gamma$  enhancement; the expected value from the Butler, et al. (1988) relation would have been  $E(H\gamma) = 1.3 \times 10^{29}$  ergs. This is a factor of 20 smaller than that observed in their other flare and may have been below their detection threshold.

Two other relations between flare emission features have

TABLE 8  
TIME-INTEGRATED FLARE ENERGIES IN FOUR EMISSION FEATURES

| Star   | Flare ID | Reference | $\log E(U)$<br>(ergs) | $\log E(H\gamma)$<br>(ergs) | $\log E(Ca II K)$<br>(ergs) | $\log E(\text{soft X-rays})$<br>(ergs) |
|--------|----------|-----------|-----------------------|-----------------------------|-----------------------------|----------------------------------------|
| AD Leo | HP85     | 1         | 33.8                  | 32.4                        | 32.1                        | ...                                    |
|        | R84      | 2         | 32.2                  | 30.8                        | 30.3                        | ...                                    |
| YZ CMi | A        | 3         | 31.1                  | 30.5                        | ...                         | 32.0                                   |
|        | B        | 4         | 30.9                  | 29.5                        | ...                         | 30.7                                   |
| UV Cet | A        | 5         | ...                   | 28.5                        | 28.5                        | 29.8                                   |
|        | B        | 5         | ...                   | 28.7                        | 28.7                        | 30.4                                   |
|        | C        | 5         | ...                   | 28.4                        | 28.7                        | 29.8                                   |
|        | D        | 5         | ...                   | 29.1                        | 28.9                        | 30.7                                   |
|        | E        | 6         | 30.5                  | 29.0                        | 29.0                        | ...                                    |

NOTE.—Distances used: AD Leo (4.85 pc), YZ CMi (6.06 pc), UV Cet (2.62 pc) (Pettersen 1976; Butler, Rodono, & Foing 1988).

REFERENCES.—(1) This work; (2) Rodonò et al. 1989; (3) Kahler et al. 1982; (4) Doyle et al. 1988; (5) Butler et al. 1986; (6) Phillips et al. 1988.

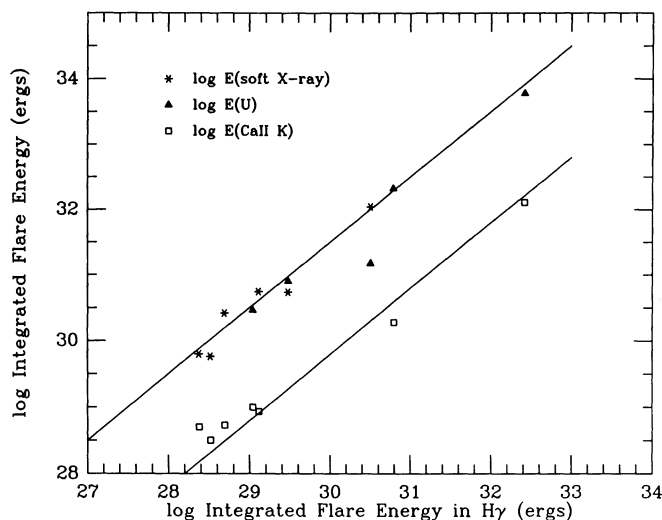


FIG. 13.—The log of the total flare energy emitted in Ca II K, the U filter, and soft X-rays is shown vs. the log of the total flare energy emitted in H $\gamma$ .

been discussed previously. Phillips et al. (1988) found that the ratio of the integrated C IV to H $\beta$  emission was 2.6 during their UV Cet flare, and they report values of 2.9 for a flare on EQ Peg discussed in Baliunas & Raymond (1984) and 1.2 for a solar flare (Canfield et al. 1980). The value obtained for the HP85 flare during the first 900 s is 1.0. Considering the uncertainties in obtaining the C IV and H $\beta$  fluxes and the fact that the HP85 data are available only during the first part of the impulsive phase, our value of 1.0 is quite consistent with the previous determinations.

A second set of data, which relates simultaneously occurring flare emission features, is that of Doyle et al. (1988). They found a good correlation between H $\gamma$  and U filter emission for 245 1 minute observations made in common over a 6 hr period on YZ CMi. During the same observing period, they found a somewhat weaker but still positive correlation of H $\gamma$  with soft X-ray emission, and almost no correlation of U filter and soft X-ray emission. Since H $\gamma$  has nearly equal impulsive and gradual phase components, it follows that a point-by-point correlation on short time scales would show that it correlates with both U filter and soft X-ray emission even during small (microflare) events. The fact that the U filter and soft X-ray emission do not correlate may be evidence of the time delay between impulsive and gradual phase emission from the same event, or of the difference in detection threshold for the emission from such different wavelength regions. Presumably, if the emission were above the detection threshold, and if an effort were made to separate specific events and compute the integrated emission in each feature during each event, there would have been good correlation between all features, as seen in Figure 13 above.

Given the correlations demonstrated in Figure 13, and the results discussed above, it appears that flares are a rather uniform species over several orders of magnitude in energy at least on stars of spectral type dM 3.5 to dM 5.5. While there may be variations of a factor of 2 or so in the ratio of line to continuum contribution between individual flares, and in the relative contributions of the lines to the impulsive and gradual phases, these are small compared to the large energy range covered by the flares themselves. It does not appear, for example, that low-energy flares are more impulsive or have a

less energetic gradual phase, or that flares on later type stars are more impulsive (though the range of spectral type investigated admittedly is small).

Models of the flare energy source thus must explain the following flare characteristics:

1. Flares with a wide range of total emitted energy have well-correlated emission in several features, encompassing both the continuum and emission lines. Small differences in the ratios of flare emission features are observed, but these do not appear to scale systematically with flare energy.

2. The time evolution of the flare emissions, as evidenced by their impulsive and gradual phase behavior, is quantitatively similar in the two flares of AD Leo which have been studied in detail and has been known to be qualitatively similar for many flares. In the two AD Leo flares, the ratio of energy emitted seems to be about  $I:G = 2:1 - 3:1$ .

3. Similar results are found on M dwarf stars with moderately different quiescent structures. Hence, even small flares on these stars must overwhelm the quiescent atmosphere in the region of flare emission.

### 5.3. Further Investigations of Flare Features

There are two aspects of Figure 13 that would be worth further investigation. There is a slight indication that flares of low energy have relatively more Ca II K emission compared to H $\gamma$  emission than the more energetic flares. Since all of the low-energy flares occurred on UV Cet and no high-energy flares were observed from it, we are unable to distinguish between several possibilities for this behavior. Since the flares were of such low energy, and the Ca II K energy was estimated from the published light curves, the uncertainty in the values is quite large and the effect may not be real. Assuming for the moment that it is real, it might be due to the later spectral type of UV Cet compared to YZ CMi or AD Leo, or to the fact that UV Cet is a binary while the others are single stars. Or, it may be the case that low-energy flares on any star have relatively more Ca II emission, in conflict with the proposed uniformity in the flare atmosphere discussed above. In any case, additional observations of Ca II K in flares of both low and high energy would be very helpful in untangling the possibilities.

A second aspect is the precise relation between Ca II K and soft X-ray emission. For example, a tight correlation between not only the integrated energies, but also the time evolution of the emission, might indicate that the Ca II K emission is directly excited by the soft X-rays. Unfortunately, the data in Figure 13 are not yet adequate to test such a correlation since, ironically, only small flares have had both soft X-ray and Ca II K measurements recorded. The obvious similarity in Ca II K and soft X-ray light curves (from different flares)—a smooth gradual phase rise and decay with no strong impulsive phase component—begs for such a comparison to be made. Butler et al. (1988) discussed the possibility that the soft X-rays were the energy source for the hydrogen line emission and concluded that there was only barely enough energy in the high-energy flux to account for the radiation emitted in all of the hydrogen lines; thus, the efficiency of conversion would have to be extremely high. We believe it is unlikely that the soft X-rays are responsible for all of the hydrogen line emission since the time evolution of the features is rather different. Instead, the observed correlation between the integrated soft X-ray and H $\gamma$  emission and the further correlations between the integrated H $\gamma$ , Ca II K, and U filter emission are better explained by supposing that the atmospheric structure in the flare-emitting

region is similar from flare to flare despite the wide range in total emitted flare energy. However, the downward-directed soft X-rays will contribute to the flare heating rate during the gradual phase and may be responsible for the principal heating in the regions of Ca II emission (Hawley 1989; Hawley & Fisher 1991). Simultaneous observations of soft X-ray and Ca II emission are needed to test this possibility.

#### 6. CONSTRAINTS ON ENERGY RELEASE IN STELLAR FLARES

There are two important conclusions of our work. First, large and small flares appear to have emission properties that scale directly with energy. Thus a flare with given  $E(H\gamma)$  will have approximately 30 times that amount of integrated  $U$  filter and soft X-ray emission and approximately one-half that amount of Ca II K emission, regardless of whether  $E(H\gamma)$  was  $10^{28}$  or  $10^{32}$  ergs. The greatly increased luminosity in all features at a given time during a large flare may then be explained qualitatively in at least two ways:

1. The flare area remains fixed but the atmospheric heating is greatly increased, resulting in increased emission. However, the increased heating rate either does not change the structure of the atmosphere significantly, or changing the atmosphere does not affect the relative amount of emission in the observed flare features. While these possibilities seem unlikely, neither can be ruled out until detailed model atmosphere studies (e.g., Richiazzi & Canfield 1983; Hawley 1989; Hawley & Fisher 1991) show whether large changes in the heating rate strongly affect the atmospheric structure, or alternatively, whether large changes in the atmospheric structure strongly affect the observed emission features. The current models unfortunately suffer from the serious drawback that the white-light (hence  $U$  filter) continuum is not predicted in the amount that it is observed. They therefore are not yet sufficiently realistic to test the possibilities.

2. The energy flux being deposited in the atmosphere is fixed (with some scatter) per unit area, in an amount necessary to heat that area to its flare-emitting structure. Increased area coverage and duration of the heating results in more emission but does not change the relative amounts of emission in the various features.

It is well known that flares which are more energetic last longer and hence require heating over a longer period of time. Thus, it is probably some combination of changes in heating rate, greater flare area coverage, and heating over a longer time period that produces large flares. However, we feel that the area coverage and longer duration heating are the most important effects, as there is no evidence for an increased heating rate as a function of total flare energy. In fact, the relatively more energetic impulsive phase observed during the R84 flare suggests that the heating rate was greater than during the impulsive phase of the HP85 flare, which was two orders of magnitude more energetic in total flare emission. Thus, our preferred interpretation is that the similarity in flare emission features is the result of a nearly constant flare heating rate which produces a very similar atmospheric structure in the flare-emitting regions regardless of the total energy emitted by the flare. Variations in the duration and area of flare heating are then responsible for the observed large range in total emitted flare energy.

The conclusion that the flare heating rate is essentially the same during all flares, regardless of their total energy, was also reached by Kane & Donnelly (1971), Donnelly & Kane (1978), and Kane, Frost, & Donnelly (1979) in studies of EUV and

hard X-ray data on the sun (however, McClymont & Canfield 1986 reanalyzed the data and found evidence that the heating rate was larger during more energetic flares). It is difficult to interpret these results in the context of stellar flares because neither EUV or hard X-ray data is available for *any* stellar flare, while white light, Ca II K and  $H\gamma$  data are not available for most solar flares. It may be that the markedly different quiescent structure of the solar atmosphere gives rise to differing behavior in comparison to dMe flares in this respect. On the other hand, it might be that if the same kinds of data were available for both solar and dMe flares such discrepancies could be explained.

The second important result is that the time evolution of the heating rate appears to be similar in the flares studied here. This is evidenced by the direct comparison of the flare energy budgets for the R84 and HP85 flares, and by the good correlation of integrated emission features which are produced primarily during the impulsive phase (e.g.,  $U$  filter emission) or during the gradual phase (e.g., Ca II emission). That is, the atmosphere is quantitatively different and produces different flare emissions, during the impulsive and gradual phases of the flare. Yet it is different in nearly the same way from flare to flare, regardless of the total energy emitted by the flares. Thus the integrated flare properties remain similar from flare to flare.

This result is not unexpected if stellar flares are a result of the same energy release and deposition mechanisms that are thought to be important on the Sun. A well-accepted, though schematic, model of solar flare energy release and deposition (see Dennis & Schwartz 1989) is that particle acceleration produced by magnetic reconnection or current driven instabilities provides the energy for heating the lower atmosphere during the impulsive phase and simultaneously heats the corona. This results in an increased heat flux into the lower atmosphere which acts to evaporate chromospheric material into the corona. The resulting hot, dense corona, maintained by continued particle acceleration, or some other energy source, radiates soft X-rays which provide additional heating in the lower atmosphere during the gradual phase (the lower atmosphere may also be heated directly by the continuing energy source). In this scenario, the impulsive and gradual phases are causally connected, and the primary energy source is the same for both. Correlations between integrated flare emission features, even those emitted primarily during only one phase, are a natural consequence of the model.

#### 7. SUMMARY

We observed a major flare on AD Leo in the 1200–8000 Å wavelength region which allowed us to compute a detailed flare energy budget in the optical and ultraviolet spectral regions. A comparison of our measurements with those from other well-observed flares demonstrated that the Balmer decrement, line broadening, and time evolution of the emission in various features were generally similar to those seen previously. To quantify this similarity we compiled integrated  $U$  filter,  $H\gamma$ , Ca II K, and soft X-ray energies for a number of flares. The previously known correlation of the integrated soft X-ray flare energy,  $E(\text{soft X-rays})$ , with  $E(H\gamma)$  was found to hold for  $E(U)$  and  $E(\text{Ca II K})$  as well, for flares strong enough to be above detection limits. Thus, a principal result of our study is that dMe flares have remarkably similar integrated emission characteristics in a variety of features, over a wide range of total flare energy. We considered various interpretations of this

result and the constraints which it places on flare models. Our conclusion is that the flare atmosphere is very similar both in its structure, and in its time evolution, for the flares in our sample. We further speculate that in order to obtain similar flare atmospheres the flare heating rate must be nearly the same for these flares. More energetic flares then are a result of flare heating over a larger area and for a longer duration.

However, we note that detailed atmospheric models must be used to test whether (a) similar emission properties could be produced by atmospheres with significantly different structures and/or (b) the flare atmospheric structure could remain essentially the same despite large changes in flare heating rate. While we regard both of these possibilities as unlikely, either would provide an alternate explanation for our observational result. Additional multiwavelength observations of dMe flares are required to test the validity of the correlations found in the present small sample; observations with higher spectral resolution would also provide more constraints for the theoretical models.

A related result was that the time evolution of the individual features was similar from flare to flare, both qualitatively as has been observed for many years (Bopp & Moffett 1973) and quantitatively, as evidenced by the detailed flare energy budget broken down by phase discussed in § 4. This result can be

explained with a generally accepted, schematic model for solar flares, indicating that flares on dMe stars and on the sun may be the result of the same energy release and deposition mechanisms.

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## APPENDIX

The photometrically determined equivalent width index discussed in § 2 above, was found by dividing the counts obtained in a narrow filter by the counts obtained in a wide filter, both filters being centered on the emission line of interest, and the counts in each having been first corrected for sky. It is easily shown that the resulting equivalent width index  $I_{EW}$  is equal to  $(A + B)/(A + C)$ , where  $A$  is the true line equivalent width, and  $B$  and  $C$  are the equivalent widths of the narrow and wide filters, respectively. If we can determine  $B$  and  $C$ , and measure  $I_{EW}$  then the line equivalent width  $A$  is simply:

$$A = (B - C * I_{EW}) / (I_{EW} - 1) .$$

Note that since the quantity  $(I_{EW} - 1)$  appears in the denominator, accurate photometry to determine  $I_{EW}$  to better than  $\pm 0.01$  mag is essential. The line flux may be obtained from the line equivalent width  $A$  and a measure of the local continuum flux.

To test this method we used the spectroscopic  $I_{EW}$  for  $H\gamma$ , with  $B = 25$ ,  $C = 200$ , to compute  $A$ . The local continuum flux was taken to be the average flux in the 200 Å bandpass. The resulting flare line fluxes (with the quiescent flux subtracted), are shown in Figure 14 along with the true line fluxes obtained by integrating the spectrum directly (using carefully chosen continuum windows). The excellent agreement indicates that the method for determining line fluxes from  $I_{EW}$  works well, provided that  $B$ ,  $C$ , and the local continuum flux are known.

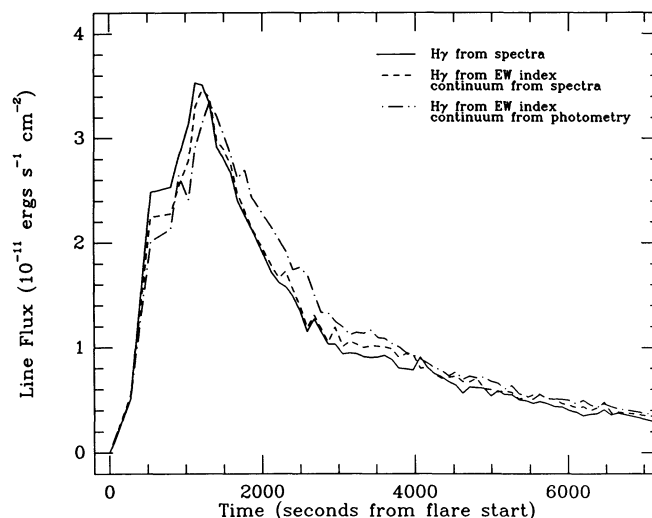


FIG. 14.—Comparison of  $H\delta$  fluxes measured using spectroscopic and photometric equivalent width and continuum estimates

TABLE 9  
PARAMETERS USED TO DETERMINE  $H\alpha$  AND  $H\beta$  FLUXES FROM  $I_{EW}$

| Line<br>(1)     | $I_{EW}$<br>(observed)<br>(2) | Equivalent Width<br>(observed, in Å)<br>(3) | $B$<br>(measured, in Å)<br>(4) | $C$<br>(measured, in Å)<br>(5) | $A$<br>(using measured $C$ )<br>(6) | $C$<br>(adjusted)<br>(7) | Percent Change in $C$<br>(8) |
|-----------------|-------------------------------|---------------------------------------------|--------------------------------|--------------------------------|-------------------------------------|--------------------------|------------------------------|
| $H\alpha$ ..... | 0.13                          | 3.0                                         | 8.4                            | 75.5                           | 1.6                                 | 84.7                     | 11                           |
| $H\beta$ .....  | 0.175                         | 6.0                                         | 21.8                           | 124                            | -0.9                                | 153                      | 19                           |
| $H\gamma$ ..... | 0.15                          | 6.0                                         | (25)                           | (200)                          | 5.9                                 | (200)                    | ...                          |

In principle we could determine  $B$  and  $C$  for the  $H\alpha$  and  $H\beta$  filters by directly integrating the spectral response curves for the filters. We have done this integration and the results are shown in Table 9 (cols. [4] and [5]). When combined with the measured values of the quiescent  $I_{EW}$  for  $H\alpha$  and  $H\beta$ , the resulting quiescent equivalent widths do not agree with the known quiescent values, as shown in columns (3) and (6) of Table 9. Since our response curves are of rather poor quality, and we know that the continuum changes somewhat over at least the width of the wide filters, we decided to adopt the measured values for  $B$ , the narrow filter equivalent width, and compute the value of  $C$  necessary to bring the quiescent data into agreement. These values are shown in column (7) of Table 9 and represent increases of 11% and 19% over the measured values, for  $H\alpha$  and  $H\beta$  respectively. Using these values for  $C$ , we then compute a set of equivalent widths for  $H\alpha$  and  $H\beta$  that are consistent with the quiescent measurements.

To determine the local continuum flux, we use our photometric  $UBVR$  continuum fluxes and interpolate to the wavelengths of the emission lines  $H\alpha$ ,  $H\beta$ , and  $H\gamma$  (as a test case). Again, however, we find that the known quiescent continuum fluxes at the line wavelengths are somewhat different than those found from the interpolation procedure. This is not unexpected but is a well-known difficulty with determining monochromatic fluxes from broad-band measurements. The continuum fluxes from the photometry must be multiplied by the factors (1.16, 0.85, 0.73) at ( $H\alpha$ ,  $H\beta$ ,  $H\gamma$ ) in order to match those determined spectroscopically. The third curve in Figure 14 is that found using the  $I_{EW}$  for  $H\gamma$  and the photometrically determined continuum flux, with the correction factor of 0.73. The line fluxes are more uncertain than those obtained with the spectroscopically determined local continuum flux, but still agree within about 20%.

The entire procedure outlined above was applied to the  $H\alpha$  and  $H\beta$  data, with the resulting line fluxes shown in Figure 15. The  $H\gamma$  line flux (determined spectroscopically) is also included. One final difficulty is evident. Although previous observations (Kunkel 1970; Bopp & Moffett 1973; Worden et al. 1984) have shown the existence of a Balmer increment ( $H\gamma > H\beta > H\alpha$ ) during flares, we do not believe that the greatly reduced  $H\alpha$  flux in our data is real. Although the  $H\alpha$  flux may well be somewhat less than  $H\beta$  or  $H\gamma$  during some parts of the flare, we believe that the low  $H\alpha$  fluxes we measured were a result of using a narrow filter that was too narrow to encompass all of the  $H\alpha$  flux during the flare. The  $H\alpha$  line broadening is likely to be similar to that seen in  $H\gamma$ , with a full width at the continuum of some 20–30 Å at its maximum; this is to be compared with the filter FWHM of about 8 Å. Therefore we regard our  $H\alpha$  line fluxes as lower limits to the true  $H\alpha$  line fluxes during the flare. We do not expect that this is a problem with the  $H\beta$  line fluxes as the FWHM of the  $H\beta$  filter is about 20 Å. Note also that during the flare on AD Leo observed by Rodonò et al. (1984), their  $H\alpha$  photometry showed almost no apparent change, possibly because of the same problem.

In summary, our attempt to use  $H\alpha$  and  $H\beta$  filter combinations to provide information on the line fluxes required detailed knowledge of the quiescent star in order to obtain consistent results. However, with this knowledge and some care in the data analysis, narrow-band filters are potentially a valuable tool to use in determining the chromospheric emission-line response during a flare, photometrically.

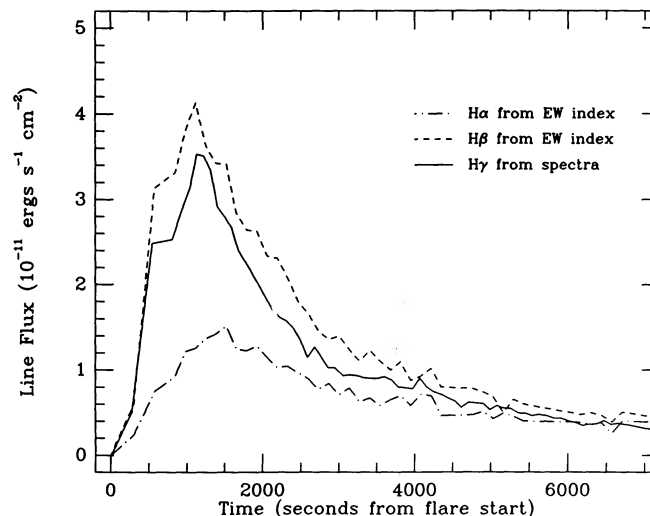


FIG. 15.—The  $H\alpha$  and  $H\beta$  line fluxes obtained using the photometric equivalent widths and the method described here are shown together with the spectroscopically determined  $H\gamma$  fluxes.

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