INDEPENDENCE OF CHROMOSPHERIC ACTIVITY AND SOFT X-RAY FLARING ON THE FLARE STAR EV LACERTAE

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ABSTRACT

EXOSAT observed the flare star EV Lacertae for 17 hr over 2 days in October 1985. Two flaring episodes were recorded. During a significant fraction of these observations, IUE, photometric and spectroscopic coverage was available. A 2-hour long period of X-ray flaring was observed during which there was no U-band activity and almost no chromospheric activity. On the other hand, two $\Delta U \sim 1^m.5$ optical flares produced normal chromospheric enhancements, but only a weak X-ray response. We suggest that these and a few other observations of stellar flares may imply the occasional existence of magnetically isolated regions in M-dwarf atmospheres.

INTRODUCTION

EV Lacertae is a classical flare star (dM4.5e) with a rather normal rotation period of 4.375 days (Pettersen, Kern, and Evans 1983), which nevertheless showed unusually violent X-ray flaring in HEAO-1 All Sky Survey data (0.5 - 20 keV): 2 flares, both with a factor 50 flux increase and durations of 3-4 hours were seen within 5 days (Ambruster, Snyder and Wood 1984). Optical 'superflares' where $\Delta U \sim 5$ mag have also been observed (Kodaira, Ichimura and Nishimura 1976; Roizman and Shevchenko 1982). In order to search for clues to the unusual flaring activity of this star, multi-wavelength observations involving EXOSAT, IUE, ground-based optical spectroscopy, and UBVR photometry were obtained on 13 October 1985 and 14 - 15 October 1985.

OBSERVATIONS

The EXOSAT observations on both days were made simultaneously with the LE (0.04 - 2 keV) and ME (2 - 6 keV) detectors. EV Lac was observed for 5 hr on 13 October 1985, and for 12 hr on 14-15 October 1985.

The IUE observations were part of an extended program in which the star was observed 4 hours each day for 9 consecutive days between 7 and 15 October 1985; a partial report is given in Ambruster et al. (1986), and a larger paper is in preparation. On each day, alternating low dispersion LWP (2000 - 3000 Å) and SWP (1200 - 2000 Å) exposures were obtained, resulting typically in 2 exposures in each camera per night. The line strengths were measured using a routine of F. Walter which fits a quadratic background and a Gaussian of 6 ÅFWHM, the instrumental resolution, to the lines

Optical spectroscopy was done with the Intensified Dissector Scanner Spectrograph on the 2.7 m telescope at McDonald Observatory. The spectral coverage extended from 3600 - 6600 Åwith an effective spectral resolution of approximately 6 Å. The individual spectra, with exposure times between 15 sec and 1 min, were co-added over the duration of each IUE exposure.

Eight filter photometry was obtained on the 0.9 m telescope at McDonald observatory: U, B, V, R, Hα wide and narrow, Stromgren Hβ wide and narrow). Integration times were 1 sec, time resolution was 9 sec (the time to cycle through all filters plus 1 sec for filter wheel rotation).

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RESULTS

While no X-ray 'super-flares' were seen prolonged, and apparently almost entirely coronal, X-ray flaring activity was seen during a ~ 2 hour period on 13 October. A single X-ray flare, also lasting 2 hours, was seen on 15 October.

13 October 1988: Extended X-Ray Flaring

EXOSAT observations of EV Lac began at 0440 UT during a brief gap in U-band coverage because of clouds. The start of the extended X-ray activity began 10 min later at 0450 UT with a sharp rise in the count rate. The X-ray light curve (Fig. 1) suggests multiple events during the next 2 hours (0440 0640 UT), for example, near 0450 UT, 0550 UT, and 0620 UT. There are also marginal events near 0510 UT and 0535 UT.

The low point at the start of the light curve at 0440 UT may or may not belong to the pre-outburst phase: similar low points between 0550 and 0600 UT are clearly only a brief interlude in the prolonged activity.

U-band coverage began again at 0457, 7 min after the X-ray rise; there was no sign of activity for the next hour. There is another brief gap in coverage because of weather between 0512 and 0524 UT.

Spectroscopic coverage began slightly before U-band coverage at 0447 UT, ~ 3 min prior to the X-ray rise. The $H\beta$ data between 0447 and 0630 UT on this night were co-added over 5 min intervals to search for responses to the X-ray activity. The equivalent widths were normal at 0447 and 0453 UT, high at 0458 UT, and still somewhat high but decreasing at 0503 UT (Fig. 3). The average $H\beta$ EW for this 2 hr period is typical of non-flare values between 7 and 15 October 1985, nevertheless, the high point at 0458 UT and the clear response to the $\Delta U = 1^m.8$ flare 1 hr later are clearly real.

There was no IUE coverage prior to 0557 UT, 1 hour after the X-ray rise.

No impulsive phase event was observed at the start of the X-ray activity because of lack of coverage. The only constraint that we can set is that there could have been no major U-band flare near the X-ray rise at 0450 UT: such flares take many minutes to decay and the decay phase would still have been visible in the U-band light curve which began 7 min later. Generally both the soft X-ray and $H\beta$ emissions represent the gradual phase of a flare; if that is true here, there is consistency with the chromospheric evaporation model in that an increase is seen in coronal emission before a rise is seen in chromospheric emission.

The time between 0450 and 0548 UT is clearly a time of considerable coronal activity, yet there is no associated photospheric (U-band) activity; nor, as mentioned above, could the X-ray activity have been precipitated by some unusually large U-band impulsive event prior to the start of observations. Furthermore, except for the one unambiguous high point at 0458 UT, there is also no chromospheric ($H\beta$) response to this prolonged X-ray activity.

13 October 1985, Flare ($\Delta U = 1^m.8$) at 0548 UT

More normal flare behavior was seen in simultaneous observations of a strong flare at 0548 UT when the U-band light curve recorded a $1^m.8$ flare.

The X-ray light curve (Fig. 1) shows a single high point at this time followed by 2 low points at the quiescent level; although soft X-ray flux is generally associated with the gradual phase of a flare, in this case it seems possible that we have detected a soft X-ray impulsive event.

The chromospheric layers responded to this flare in all observed lines: $H\beta$, Ca II K, and Mg II (2800 Å). The $H\beta$ EW's at 0548 and 0553 UT were higher than at any time prior to 0630 UT; these 2 points were followed by a drop and then a smaller but extended enhancement at 0615 UT (Fig. 3). Co-added over the concurrent IUE exposure (LWP 6900L: 0557 - 0629 UT), the $H\beta$ EW shows a 2.6 σ enhancement. A stronger response was evident in the Ca II K EW's averaged over this same time period, which show a 6 σ increase (error bars are too large in 5 min co-added exposures for meaningful results). Mg II (2800 Å) was saturated in LWP 6900L: this occurred only twice in 17 LWP spectra obtained over the 9 nights of the campaign, and in both cases significant U-band flares occurred during the exposure.

There are no significant enhancements in the transition region C IV (1550 Å) line in 2 exposures on this night (SWP 26926L, SWP 26926L). However, the first SWP exposure began almost 1 hour after the $1^m.8$ U-band flare at 0548 UT, and no response would be expected.

The only remaining activity on this night was a tiny $0^m.2$ U-band flare at 0633 UT, about 13 min after the final X-ray rise of the night at 0620 UT; there is no noticeable response at other wavelengths.

There is, however, a probably significant 1 σ enhancement in the U-band continuum starting at about 0617 UT, at the start of the final decay in the X-ray light curve, suggesting some heating of the photosphere from above.

Finally, it is interesting that when the extended X-ray activity between 0440 and about 0720 is over, the quiescent level is quite constant: an analysis for quiescent, non-periodic variability using the method of Collura et al. (1987) shows no significant variability above 20% amplitude from 0720 to 1027 UT.

15 October 1985, X-Ray Flare at 0500 UT

The EXOSAT light curve (Fig. 2) shows a sharp rise at 0500 UT, following 6.5 hr of variable quiescent flux (2216 0440 UT). The variability was significant at the 99.9% level with a characteristic timescale > 1 hour (Collura et al. 1987; for an extensive application of this method to active cool stars, see Ambruster, Sciortino and Golub 1987). Significant quiescent variability continued after the flare had subsided (0640 - 1001 UT) at a slightly lower, but still significant, level (95%).

The pre-flare and flare count rates in the ME are the same within errors (0.54 q 0.06 and 0.61 q 0.09, respectively), so that this flare was quite soft: the combined LE and ME data yield kT = 1.4 q 0.2 keV (90(the distance of EV Lac is 5 pc). The quiescent spectrum is essentially the same, but less well determined: kT = 1.5 q 0.2 keV, and chi-squared $\sim$ 2. These temperatures agree with those found by Schmitt et al. (1987) for other M dwarfs observed by EXOSAT.

U-band coverage began at 0459, 1 min before the X-ray rise. A small, $\Delta U = 0^m.4$ flare occurred at 0502 UT at, or slightly after the peak of the X-ray flare. A second small event $\Delta U = 0^m.4$) was observed at 0601 UT, coincident with a small rise in the X-ray flare decay light curve.

Because there was no spectroscopic or IUE coverage till 0550 UT, 50 min after the start of the X-ray flare, no information on the chromospheric response to the main X-ray flare is available. During the first IUE exposure (LWP 6916L; 0550 - 0625 UT), however, the Hβ EW from spectra co-added over this interval is 2.6 σ high, most likely reflecting the $\Delta U = 0^m.4$ flare which occurred at 0601 UT. Probably for the same reason, the Mg II (2800 Å) flux is marginally (1 σ) high.

15 October 1988: Flare ($\Delta U = 1^m.5$) at 0625 UT

An X-ray spike occurred simultaneously with this U-band flare at 0625 UT, punctuating the last stages of the decay of the X-ray flare at 0500 UT. As with the $\Delta U = 1^m.8$ flare at 0548 UT on 13 October, this spike seems to represent an impulsive soft X-ray event.

Like the $\Delta U = 1^m.8$ flare on 13 October, the chromospheric response is seen in both Hβ (6 σ increase) and Ca II K (2.3 σ increase). There was no significant transition region response in the C IV (1550 Å) flux.

DISCUSSION AND CONCLUSIONS

We can summarize the results of the observations as follows:

- Fairly large U-band flares were associated with small, short duration X-ray spikes; significant X-ray flares were associated with small ($\Delta U = 0$ ° m ° .4) optical flares.

- The chromospheric response was greater to U-band (photospheric) flares than to coronal flares (13 October data).

- Most significantly, prolonged X-ray activity can occur with little or no response at other layers of the atmosphere.

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A case has recently been reported of no X-ray response at all to a $\Delta U = 1^m.2$ U-band flare on YZ CMi (Doyle et al. 1986), perhaps because of the absorption of X-rays by an overlying, dense prominence. However, their alternative suggestion, that is, that the event occurred low down in the atmosphere, seems to suggest the best explanation for the present EV Lac results, namely that the lower levels (photosphere and chromosphere) are at times magnetically isolated, or largely isolated, from the corona. Supporting evidence for this view is the association, in the EV Lac observations, of a stronger chromospheric response to U-band, rather than X-ray, flares and, of course, the almost complete lack of response in the photosphere and chromosphere to some 2 hours of X-ray activity on 13 October.

EV Lac is not the only M dwarf to provide evidence for the occasional existence of magnetically isolated regions in the upper atmosphere; the most spectacular case is the 6 March 1979 X-ray flare on Proxima Centauri (Haisch et al. 1981) where there were no related enhancements at all in simultaneous UV, optical or radio coverage. It should be emphasized that most simultaneous observations of cool stars show chromospheric and/or photospheric and/or TR correlates to an X-ray flare: in these cases magnetic loops apparently permeate the various levels of the star's atmosphere in a manner similar to what is seen on the Sun.

On the Sun, in fact, the existence of magnetically isolated regions in the corona has been demonstrated. Flare-like events with no chromospheric ($H\alpha$) counterpart were recorded by the HXIS experiment on SMM (3.5 - 5.5 keV) and by the GOES-2 satellite (0.5 - 4.0 keV) several hours after the November 6, 1980 flare (Svestka et al. 1983). These events were also seen in radio observations of the upper corona, but no TR or lower atmospheric response was found. It is proposed that the coronal events originated in a plasmoid that became magnetically isolated from the lower atmospheric layers following a major 2-ribbon flare. Two-ribbon flares have been observed on M dwarfs (Haisch et al. 1983), so it does not seem unreasonable that an analogous magnetic detachment could also occur.

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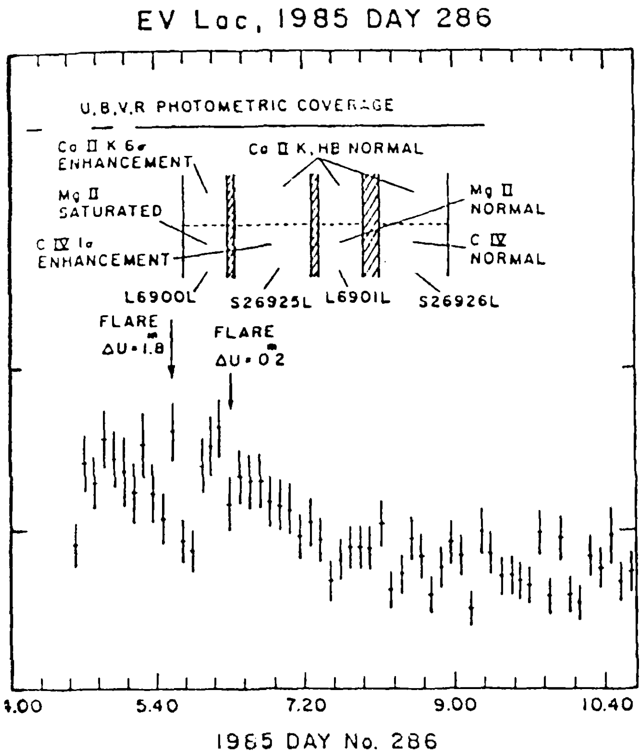

gure 1. EXOSAT LE (0.04-2.0 keV) ght curve for EV Lac, 13 Oct. 1985. mes of the 4 IUE exposures are dicated between vertical lines, ong with important features at tical and UV wavelengths.

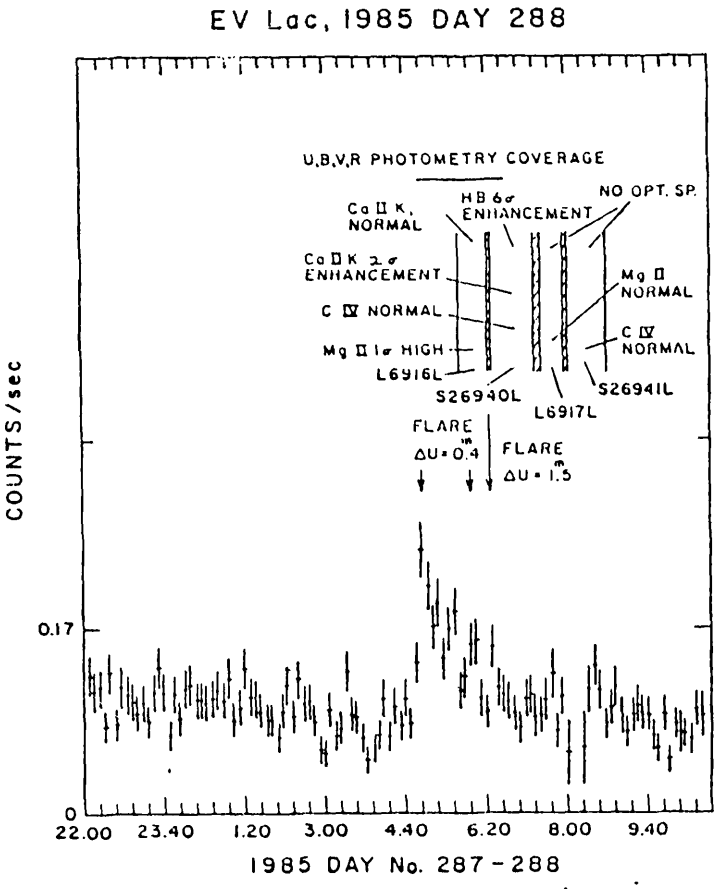

Figure 2. EXOSAT LE (0.04-2.0 keV) light curve for EV Lac, 15 Oct. 1985. Times of the IUE exposures and other important features are indicated.

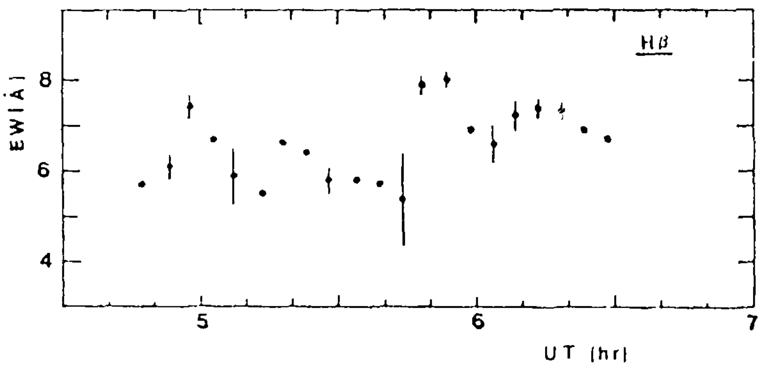

Figure 3. H-beta light curve for EV Lac, 13 Oct. 1985. One-sigma error bars are smaller than symbol size for several points.

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