FLARES IN LATE-TYPE STARS:

UV AND X-RAY

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Flare in Late-type Stars: UV

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1 Introduction

Early studies of stellar flares were made entirely in the optical regime. It was recognised that flares arose from the generation of hot plasma within the stellar chromosphere at whose temperature (indicated, for instance, by the presence of a strong, blue optical continuum) a substantial emission in the ultraviolet would be expected. It was not until the advent of space-borne instruments of adequate sensitivity, however, that direct confirmation of this prediction was forthcoming. In this review I examine some results of more than a decade of observation of stellar flares in the UV.

1.1 Sources of UV data

The major source of ultraviolet data on stellar flares has been the International Ultraviolet Explorer (*IUE*) satellite (Boggess et al. 1979). In order to understand the limitations of our current understanding in this area it is important to appreciate some of the characteristics of its instrumentation. *IUE*'s telescope is of 40 cm aperture and it is equipped with a spectrograph which can operate at two resolutions, i.e. $\Delta\lambda/\lambda$ ~350 (LORES) and ~17 000 (HIRES). Its detectors are optimised for operation in two wavebands, i.e. ~1150–1950 Å (SW) and ~1950–3200 Å (LW). *IUE*'s small aperture results in a limited sensitivity, a consequence of which is a modest time resolution when studying stellar flares (a long exposure time is needed to gain adequate signal-to-noise). *IUE*'s elliptical 24-hour quasi-geosynchronous orbit and its resulting interactive mode of operation make continuous monitoring feasible, a feature suiting flare star work.

The recent advent of the Hubble Space Telescope (*HST*) (Giacconi et al. 1982) with its 2.4 m aperture represents in some ways such a huge gain in light-gathering power that it might be expected to render *IUE* obselete. Its prime UV spectroscopic instrument is the Goddard High Resolution Spectrograph (GHRS) whose detectors span essentially the same spectral bands as *IUE*. This offers spectral resolutions of $\Delta\lambda/\lambda$ ~2 000, ~25 000, and ~80 000. However, the spectral ranges available at each of these resolutions are ~285 Å, ~30 Å, and ~8 Å

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respectively. Thus while *HST* offers a giant leap in sensitivity, it fails to offer the wide spectral coverage of *IUE*. The orbit of *HST* imposes a further restriction on its use. Its low orbit means that, for objects at low ecliptic latitude, the Earth occults many targets for up to half the observing time.

Thus most of the ultraviolet flare data available to date has come from *IUE*. Observations from *HST* are beginning to appear, however, and will, no doubt, increase in the near future.

2 Flares on dMe stars

2.1 dMe quiescent emission

Quiescent emission from dMe flare stars is characterised by strong line emission from neutral and ionised atomic species arising in temperatures characteristic of the solar chromosphere ($6 \cdot 10^3$ K $leqT_e \leq 10^4$ K) and transition region ($3 \cdot 10^4$ K $\leq T_e \leq 2 \cdot 10^5$ K). A weak continuum is sometimes present in the long wavelength portion of the LW spectra but is entirely absent in SW. An example of a LORES *IUE* spectrum of dMe flare star in quiesence will be found in Fig. 1 and the corresponding mean surface fluxes in Table 1.

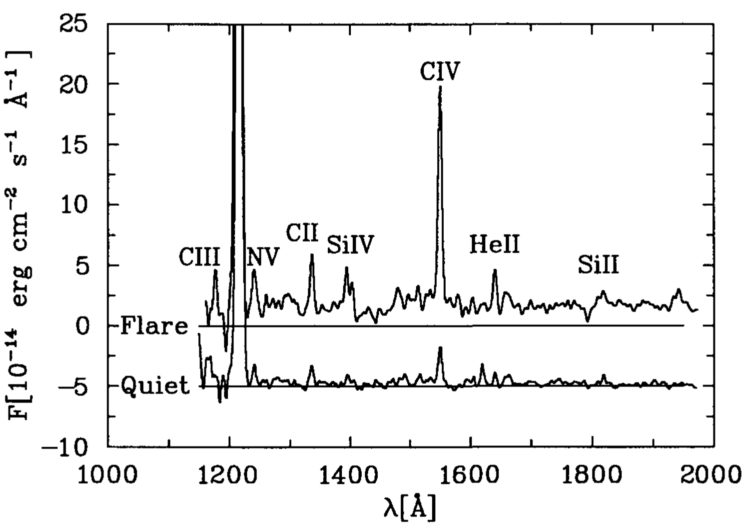

Fig. 1. An example *IUE* SW LORES spectrum of the dMe flare star, YZ CMi, in quiescence and while flaring (J.G. Doyle, *private communication*). Prominent emission lines are indicated. The quiescent spectrum has been displaced to aid visibility of the two spectra. The horizontal line indicates the zero level for each spectrum. Note the strong continuum in the flare spectrum, which is not detectible in quiescence.

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Table 1. Typical mean emission line surface fluxes, in units of $10^4 \mathrm{erg\,cm^{-2}\,sec^{-1}}$, for dMe stars in quiescence and during flare, compared to the mean solar quiescent flux in these lines. Note that the flaring values are lower limits for the reasons discussed in Section 2.2. Figures are also given for continuum surface fluxes in *IUE*'s SW region (1150–1950 Å).

Star	V1005 Ori[1]		BY Dra[2]		YZ CMi[3]		HK Aqr[4]		Quiet
Line	$\log f_q$	$\log f_f$	$\log f_q$	$\log f_f$	$\log f_q$	$\log f_f$	$\log f_q$	$\log f_f$	Sun
C II	7	32	16	24	6	22	12	19	0.5
C IV	11	229	26	33	13	75	22	98	0.6
N V	—	—	8	14	6	18	4	11	0.1
cont.	—	1200	—	—	—	280	—	1200	

[1]Mathioudakis et al. 1991; [2]Butler et al. 1987; [3]Doyle in prep.; [4]Byrne & McKay 1990

2.2 dMe flaring emission

During flares all of the lines visible in the quiescent spectrum are seen to increase, some by factors of up to ~10 or greater. In general the degree of increase is dependent on the excitation of the relevant line, up to mid-transition region ($T_e \sim 10^5$ K). So in the *IUE* wavebands the greatest flux enhancements are seen in the resonance doublets of C IV (λ1548/51 Å) and N V (λ1238/42 Å). An example flare spectrum is shown in Fig. 1 and some representative integrated flare line surface fluxes at source are given in Table 1. It should be noted, however, that, since areas of individual flares are unknown, it has been assumed in Table 1 that they cover an entire hemisphere. Obviously, if a flare covers a fraction $\frac{1}{n}$ of a hemisphere, the fluxes in Table 1 should be increased by the factor n. It will be seen from Fig. 1 that a strong continuum is also present. Such continua are recorded frequently in the more energetic dMe flares, but by no means universally. Lack of continuum detection in some flares may be a matter of *IUE*'s limited sensitivity, however. The origin of dMe flare continua has been discussed by Phillips et al. (1992).

Flaring emission in dMe's is usually only detected in a single spectrum. This is a result of the relatively long exposure times needed by *IUE* to detect flare stars with adequate signal-to-noise compared with the typical duration of a flare as gauged from other wavebands. In practise, exposure times in LW LORES need be longer than ~10 min and in SW LORES longer than ~20 min for flare detection. At the s/n levels attainable by *IUE* the effect of the flare on the spectrum is usually undetectable in subsequent spectra. Thus flare parameters derived from such observations should be judged with this fact in mind. In particular, mean surface fluxes are calculated on the assumption that the flare lasts for the entire exposure time.

Monitoring of active dMe stars for flares has revealed, apart from discrete individual flares, continuous variability in these line fluxes (Butler et al. 1987, Byrne et al. 1991). This has led to the suggestion that, on the time scales resolvable with *IUE*, the most active dMe's flare continuously at a low level. This raises the question as to whether the measured "quiescent" fluxes of dMe's are "quiet" in the same sense as the solar case.

3 Flares on RS CVn stars

3.1 RS CVn quiescent emission

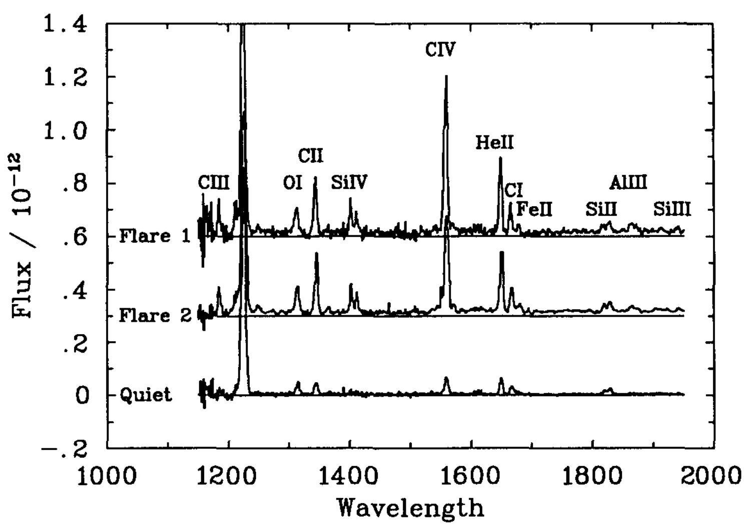

Fig. 2. An example *IUE* SW LORES spectrum of the RS CVn star, II Peg, in quiescence and while flaring (P.B. Byrne, *private communication*). The two flare spectra were separated by ~2 hr in time. Prominent emission lines are indicated. The flare spectra have been displaced to aid their visibility. The horizontal line indicates the zero level for each spectrum. Note the continuum in the flare spectra, which is not detectible in quiescence.

Quiescent ultraviolet line emission from RS CVn systems is qualitatively the same as that from the dMe's except that the sources are more luminous. Some, but not all, of the extra luminosity is accounted for by the greater surface areas of these subgiant or giant stars. The greater brightness of RS CVn's has meant that *IUE*'s HIRES mode can be used, in addition to SW LORES, to study their spectra, at least in the strong Mg II *h&k* resonance lines. An example of such spectra will be found in Figs. 2 and 3.

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Table 2. Typical mean emission line surface fluxes, in units of $10^4\,\mathrm{erg\,cm^{-2}\,sec^{-1}}$, for RS CVn stars in quiesence and during flare, compared to the mean solar quiescent flux in these lines. Figures are also given for continuum surface fluxes in *IUE*'s SW region (1150–1950 Å).

Star	II Peg[1]		V711 Tau[2]		IM Peg[3]		λ And[4]		Quiet
Line	$\log f_q$	$\log f_f$	$\log f_q$	$\log f_f$	$\log f_q$	$\log f_f$	$\log f_q$	$\log f_f$	Sun
C II	9	49	54	112	8	28	20	43	0.5
C IV	20	104	72	194	13	71	35	105	0.6
N V	2	15	8	40	9	18	12	22	0.1
cont	—	4460	—	—	—	—	270	490	—

[1]Doyle et al. 1989; [2]Linsky et al. 1989; [3]Busazi et al. 1987; [4]Baliunas et al. 1984

3.2 RS CVn flaring emission

As with their quiescent emission, flaring emission in RS CVn's is qualitatively the same as in the dMe stars but RS CVn flares are considerably more energetic. This greater energy arises both from a higher specific flux during the flare and from a much longer flare duration. Indeed RS CVn flares may last up to sizeable fractions of a day, arguing in favour of continual heating on these time scales. As a result *IUE* has been able, in some cases, to observe the time evolution of RS CVn flares in ultraviolet lines (cf. Fig. 2).

Use of LW HIRES spectra to study the behaviour of the Mg II *h&k* resonance lines during RS CVn flares has given important indications of long-lived mass flows in material at chromospheric temperatures. In general, as in optical lines, these velocities are seen as red-shifts, but blue-shifts are also recorded (Doyle et al. 1988, 1989, Linsky et al. 1989). However, reports of representative velocities derived from these observations should be treated with caution. The Mg II *h&k* lines are optically thick and, as a result, there is not a simple mapping of velocity onto the line profile.

A few RS CVn's have been monitored for flaring sufficiently often to allow estimates to be made of the frequency and energy distribution of ultraviolet line flares. For instance Mathioudakis et al. (1992), using earlier *IUE* data from a variety of sources, estimated that the RS CVn system II Peg produced a flare of integrated energy in transition region lines of $\sim 10^{35}$ erg every 10 hours.

4 Physical parameters of flares

Under optically thin (*coronal*) conditions a simple relationship exists between the observed line flux $F_{\rm line}$ and a quantity known as the emission measure (EM) of the plasma, i.e.

$$F_{\rm line} = \xi (N_e^2 dV) = \xi\ EM \tag{1}$$

where the quantity ξ contains a number of essentially atomic parameters such as the abundance of the element concerned, the relative abundance of the ionic

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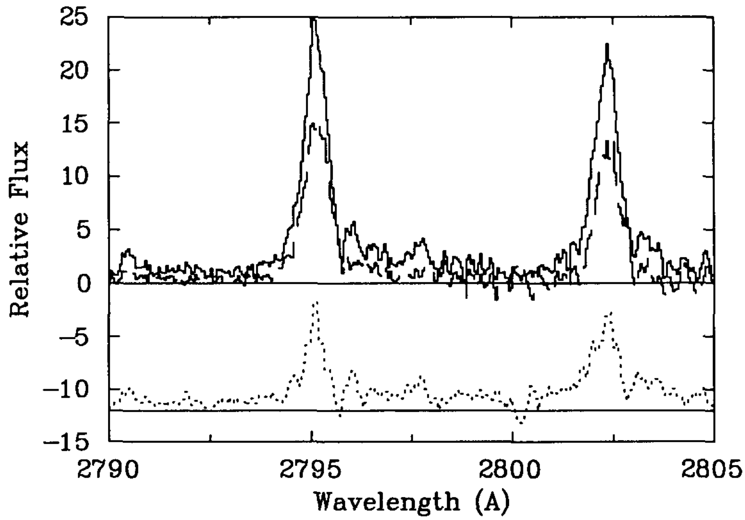

Fig. 3. An example *IUE* LW HIRES spectrum, in the region of the MgII h&k chromospheric emission lines, of the RS CVn star, II Peg, in quiescence and while flaring (P.B. Byrne, *private communication*). The *solid line* is the flare spectrum, the *dashed line* is the quiescent spectrum and the *dotted line* is the difference. Note the excess extended emission in the wings, especially the red wing.

species, etc. The validity of the coronal approximation has been tested by, for instance, checking that the ratio of strong resonance doublets is in the ratio of their statistical weights (see e.g. Byrne et al. 1987). Once the overall distribution of EM has been determined from a number of well observed lines formed over a range of temperature, it can be combined with a suitable radiative loss function to determine the *total* radiative losses, including unobserved lines, over the temperature in question (Byrne et al. 1987, Mathioudakis et al. 1991).

It is also possible to determine local electron density, N_e, in the transition region by observing density-sensitive intersystem line ratios, such as between C III] λ1176 Å, C III] λ1908 Å and Si III] λ1892 Å. In the dMe's these lines are extremely weak and the derived densities correspondingly uncertain (Mathioudakis et al. 1991). Furthermore, it is not known whether flare conditions are constant during typical exposure times as explained above. However, values of $N_e \sim 10^{10-10.5}\,\mathrm{cm}^{-3}$ would appear to be indicated. Signals being much stronger for the closest RS CVn's, intersystem line fluxes can be measured with greater confidence (Byrne et al. 1987). The long duration of RS CVn flares also gives us greater confidence in the applicability of the resulting densities. Typical values are $N_e \sim 10^{10.5-12}\,\mathrm{cm}^{-3}$.

Combining EM and N_e yields the volume of the plasma at that temperature via the relation

$$dV = F_{\mathrm{line}} / \xi\, N_e^2 \qquad (2)$$

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which for dMe's yields values for large flares of $dV \sim 10^{28-29}\,\mathrm{cm}^{-3}$ and for RS CVn flares of $dV \sim 10^{30-32}\,\mathrm{cm}^{-3}$. Assuming that such flares arise within magnetic loops, we can represent such loops as semi-circular in outline with radius R_{loop} and of constant circular cross-section of radius $r \sim 0.1 R_{\mathrm{loop}}$. N such loops would have a volume, V_{loop}, given by the following expression.

$$V_{\mathrm{loop}} \sim 0.04\pi^2 R_{\mathrm{loop}}^3/N \tag{3}$$

Equating this to derived volume leads to a typical loop dimension $R_{\mathrm{loop}}(\mathrm{dMe}) \sim 10^{9-10}\mathrm{cm}$ and dimension $R_{\mathrm{loop}}(\mathrm{RS\,CVn}) \sim 10^{10-11}\,\mathrm{cm}$. Note that R_{loop} is only weakly dependent on N. Such dimensions, at least in the case of the dMe's, are remarkably solar-like. However, we should caution that such dimensions are derived from the volume of material at transition region temperatures only. It is possible, even likely, that the bulk of the flaring plasma may be at X-ray temperatures. Whether the X-ray plasma occupies the same loops as the transition region material is a matter of uncertainty, however, even in the solar case.

5 HST flare observations

As pointed out above, *HST* has disadvantages (spectral coverage, Earth eclipses, etc.) for flare observations, as well as obvious advantages (aperture, spectral and temporal resolution, etc.). Several interesting results have been achieved already. Maran et al. (1994) monitored the dMe flare star, AU Mic, spectroscopically using GHRS in the wavelength region 1345–1375 Å without recording any discrete flares. However, they found that the mean spectrum showed a strong Fe XXI λ1354 Å coronal emission line, whose intensity is comparable to that observed in solar flares. This result would support the conclusion from *IUE* data that the most active dMe's flare almost continually (Butler et al. 1987, Byrne et al. 1991).

Woodgate et al. (1992) also observed AU Mic with the GHRS on *HST* and detected a UV line flare which resulted in a factor 7 increase in the flux of the SiIIIλ1206Å line on the blue wing of Lyα. During this flare they observed a red asymmetry in the wing of Lyα which they attributed to recombining protons from a proton beam.

Perhaps the most dramatic *HST* flare star result to date has been the observation of extended red wings on the C IV λ1548/51 Å resonance lines during the initial stages of a flare on the dMe flare star, AD Leo (Bookbinder et al. 1992). Interpreted as velocities, these imply downflowing material at mid-transition region temperatures of $\sim$2 000 km s^{-1}. Byrne (1993) discussed this result and calculated that the downflowing material's kinetic energy represents $\sim$25 times the energy *radiated* in the C IV lines. Furthermore, the observation of downflows of this magnitude in the optically thin C IV lines lends credence to reports of comparable velocities in optically thick chromospheric lines such as H I Balmer. There is a clear implication that mass flows may be a common and important energy sink in stellar flares.

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L. Pustil'nik: What is the best time resolution in the UV-range for flare observations? And what is the shortest observed time of a flare itself ($t_{\rm rise}, t_{\rm decay}$)?

P.B. Byrne: This answer must distinguish between dMe's and RS CVn's. In dMe's the exposure time of a typical UV spectrum is in general comparable to, or shorter than, the total duration of the flare. In the case of RS CVn stars, the total duration is much longer and it is possible to take multiple spectra during the evolution of the flare.

On the other hand, durations of flares themselves, as derived from optical continuum data, would suggest that the shortest $t_{\rm rise}$ is about 1 sec. In general $t_{\rm decay}$ is longer by a factor 2 or more. The answer may be dependent on waveband, however. For instance, in soft X-rays, the time scales appear to be longer.

R. Minarini: What about estimates of the amount of mass motions during flares from UV data?

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P.B. Byrne: Most indications of mass motions came from chromospheric lines (e.g. Mg II h&k) which are very optically thick. Thus it is very difficult to derive unique velocities from line assymetries. The only case of optically thin line evidence comes from the unpublished profiles of C IV during a flare on AD Leo. These indicate velocities up to 1800 $\mathrm{km\,s^{-1}}$ decaying to 600 $\mathrm{km\,s^{-1}}$ in about 25 sec.

R. Pallavicini: I was surprised to see that these *IUE* observations indicate higher densities for low-gravity RS CVn binaries than for high-gravity dMe stars. Can you comment a little bit more on these density determinations?

P.B. Byrne: This may be in part a result of observational selection. In general dMe flares are much shorter in duration than RSCVn flares. In fact their entire duration is shorter than the typical exposure times. So when we measure densities we measure "averages" over the whole flare. By contrast in the RSCVn's the rise time alone (assumed to be the heating phase) is about equal to the entire duration of a dMe flare. Thus the RS CVn densities may be more meaningful.

Of course, there is a second aspect of flare densities and that is that in flares conditions are far from equilibrium. Thus heating flux and confining magnetic field strength will play a greater role in determining density than gravity.

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