RESULTS FROM OPTICAL AND UV STELLAR FLARE SPECTROSCOPY

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ABSTRACT

Optical and ultraviolet spectroscopy can enable the assessment of the physical conditions characterizing a stellar flare atmosphere and thereby potentially elucidate the possible radiative and hydrodynamic transport mechanisms operative during stellar flares. In this review, I present illustrative examples of the spectroscopic diagnostic techniques that can be applied to the analysis of stellar flare spectroscopic data and the resulting inferences concerning stellar flare properties for M dwarf flare events.

INTRODUCTION

High-to-moderate spectral resolution, high temporal resolution spectroscopy of M dwarf stellar flares can yield unique and valuable data that can be utilized to identify the relative roles of lines and continua, and hence the kind of radiative transport mechanisms that operate during the course of flare events. Furthermore, it is possible through spectral line analysis to estimate physical conditions, such as temperature and density, in the flare emitting volume at various depths in the M dwarf flare atmosphere. The atmospheric levels that can be probed depend, of course, on the wavelength coverage of the observations. In this regard, conventional broadband, multichannel photometry can provide extensive wavelength coverage combined with very high (< 1 sec) temporal resolutions. A disadvantage is that the sampling of the flare spectrum is coarse and the relative contributions of lines and continua to the observed flare light is unknown. Thus we cannot rely exclusively on photometry if we seek to thoroughly understand stellar flare activity. For example, the Johnson U and B photometric bandpasses completely encompass the wavelength range of the spectrophotometric flare observation of UV Ceti shown in Figure 1. Thus many of the principal emission lines in the "enhanced chromospheric regions" of the flare are included in these bandpasses. As a result, ambiguity can be introduced into the determination of the operative continuous emission mechanism from photometric colors alone. This

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caveat has been repeatedly stressed by flare star observers. As an example, the temporal evolution of the ratio of total line emission flux to total observed flux for the 8 September 1979 UV Ceti flare event (Fig. 1) proceeded from a quiescent value of approximately 0.06 to a value of 0.18 during flare onset, followed by a decline to 0.03 at flare maximum, and then an increase to approximately 0.3 during the decay stage of the flare. This example clearly indicates that stellar flare spectroscopy is imperative for the understanding of flare colors and flare light curves.

OPTICAL FLARE SPECTROSCOPY

Spectroscopic observations of M dwarf flares, such as that of Figure 1, readily reveal the shape of the flare continuum and thus allow us to explore the possible continuous emission mechanisms that may account for the observed flare light. Several investigators have suggested that the optical flare continuum is composed of bound-free and free-free emission from a two-component thermal model characterized by electron temperatures of $T \sim 10^5$ K and $T \sim 2 \times 10^4$ K. I display in Figure 2 the spectral energy distributions of some of the suggested radiative processes that may give rise to flare continua. The wavelength range corresponds to that of Figure 1 and the vertical scale is arbitrary. The curves represent optically thin emission along a ray and are merely used here to illustrate the potential suitability of a given radiative process as a description of the observed wavelength distribution of stellar flare continuous emission. I have assumed LTE for both H^- and Balmer bound-free emission in the construction of Figure 2. For illustrative purposes, I will discuss the various processes represented in Figure 2 within the context of the UV Ceti optical flare event shown in Figure 1.

The shapes of the free-free curves at $T = 10^5$ K and $T = 5 \times 10^4$ K appear to be reasonable fits to the observed flare continuum shown in Figure 1. However, ultraviolet data are required to determine whether these distributions are truly applicable. Each of the free-free curves exhibits a rise toward the blue. In fact, the $T = 10^5$ K distribution would continue to increase monotonically toward 1000 A while the $T = 5 \times 10^4$ K curve would behave similarly, attaining a maximum near 1800 Å, followed by a slow decline in intensity with decreasing wavelength. However, in essence, both curves are quite flat with no more than a factor of 2 variation from maximum to minimum emission between 1000 Å and 5000 Å.

Kunkel (1970) has argued that hydrogen free-bound emission is the principal component of the observed continuous emission in M dwarf flare events. According to Figure 2, the shape of the bound-free curve, like the free-free curves, approximates the shape of the flare continuum displayed in Fig. 1 well in the "red" portion of the flare spectrum but not in the blue. Of course I cannot conclude that free-bound hydrogen emission is not a constituent of the emission; but it may not be the sole component and additional continuum processes originating in higher temperature layers in the flare emitting volume, such as free-free

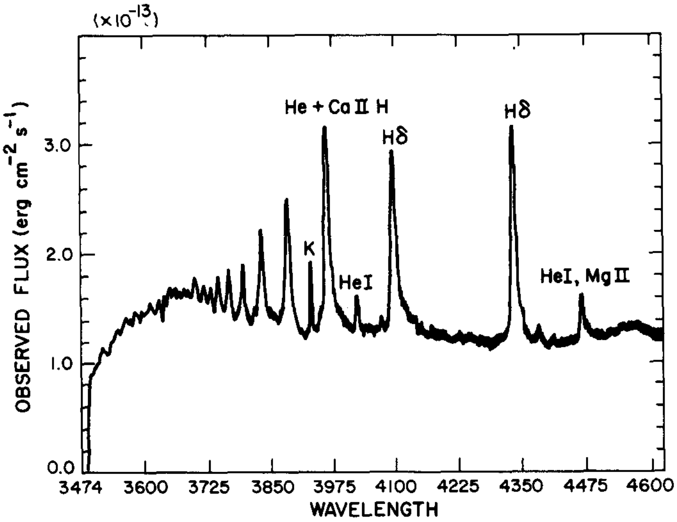

Figure 1: Spectrum during flare maximum for a 5 magnitude (U-band) event observed on UV Ceti (taken from Giampapa et al. 1982).

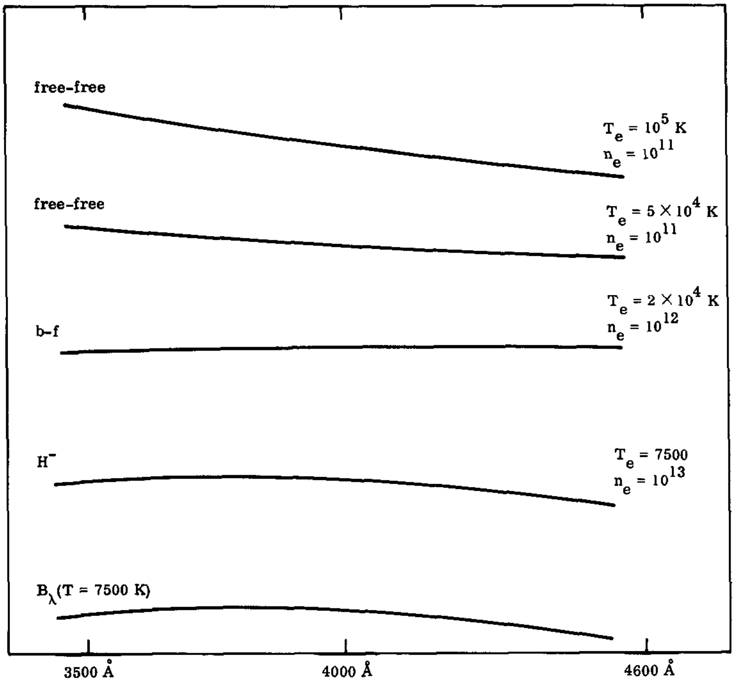

Figure 2: Spectral energy distributions of radiative processes that may give rise to flare continua. The wavelength scale is identical to that of fig. 1. The vertical scale is arbitary.

emissions, are likely present. In this regard, however, I note the caveat that the density of emission lines (especially the higher members of the Balmer series) increases toward the blue and this effect can, in turn, artifically enhance the apparent continuum level in moderate resolution spectra, particularly in the vicinity of the Balmer jump.

An additional mechanism that may participate in the formation of stellar flare continua is H^- emission. Svestka (1966) originally suggested that H^- emission emanating from the temperature minimum region could account for the continuous emission of *solar* flares as observed in the optical. This suggestion has been recently verified by Neidig (1982 and references therein) in the case of a solar white light flare. Grinin (1976) has applied this suggestion to M dwarf stars to demonstrate that upper photospheric heating by a flare blast wave could enhance the formation of negative hydrogen ions and thereby increase the importance of H^- emission as a component of stellar flare optical continua. There is reasonable agreement between the H^- spectral energy distribution in Figure 2 with the flare continuum shape in Figure 1 in the red region. But, as in the case of hydrogen bound-free emission, there is less agreement in the blue. In fact, H^- emission would decline rapidly toward the UV in those spectral regions currently accessible to the camera on board the *International Ultraviolet Explorer* (IUE) satellite.

Kunkel (1970) and, more recently, Mochnacki and Zirin (1980) have suggested that stellar optical flare continua can arise from black body emission originating at the footpoints of the flare. This suggestion implies that deep photospheric heating can occur during a stellar flare event. In particular, the point at which $\tau_{5000} = 1$ would be located at higher column mass densities and temperatures in a stellar "flare photosphere" relative to the quiescent stellar photosphere. Utilizing spectrophotometric observations of flare events on the dM4.5e star YZ CMi, Mochnacki and Zirin (1980) concluded that the black body component of the observed continuum emission was the dominant component in the formation of the flare continuum while hydrogen recombination emission was the lesser component. Moreover, these investigators deduced that the black body emission must arise from a projected area that is less than 2% of the area of the visible stellar disk. In a similar analysis, Kahler *et al*. (1982) found that the peak of an optical flare event on YZ CMi was fit well by black body emission characterized by T = 8500 K and extending over an area of 0.5% of the projected stellar disk. This kind of impulsive photospheric heating would result in the ionization of low temperature species, such as molecules and neutral metals, in the upper photosphere-temperature minimum region. Thus absorption line equivalent widths may decline in proportion to the area coverage of the flare footpoints. Unfortunately, a change of less than 2%, as implied by the flare area estimates of Mochnacki and Zirin (1980) and Kahler *et al*. (1982), would be difficult to detect at the high temporal and spectral resolutions required for meaningful stellar flare spectroscopy. Interestingly, Mochnacki and Schommer (1979) obtained a spectrum of

YZ CMi during a flare event in which the photospheric absorption lines were very weak (i.e., filled in by emission or strongly ionized) as compared to the quiescent, non-flare spectrum of YZ CMi in the same wavelength region. In addition, emission lines of Mg I, Fe I and Fe II appeared in the flare spectrum thus indicating (in a schematic fashion) a shift of the chromospheric thermal structure to significantly higher column mass densities at the flare site. The noticeable weakening of the photospheric absorption lines could have resulted from a significant flare area coverage. Alternatively, *intrinsically bright emission* in photospheric lines arising from *small* flare areas would have "masked" or "veiled" the photospheric spectrum arising from the undisturbed portions of the stellar surface. Indeed, small flare areas (< 2%) such as those inferred by Mochnacki and Zirin (1980) and Kahler *et al*. (1982), appear more compatible with the time-scales for M dwarf optical stellar flare events deduced from high-speed optical photometry (see the review by P.B. Byrne in this volume) *if* the characteristic velocity for a stellar optical flare (i.e., collisional excitation of lines and continuum formation) is of the order of the local sound speed.

OPTICAL FLARE LINE SPECTRA

An observed stellar flare line spectrum can provide diagnostics of the physical conditions (i.e., n_e and T_e) that characterize the line emitting regions. For example, we can utilize the classical Inglis-Teller equation which relates the electron density in the Balmer line emitting layers to the highest resolvable Balmer series member before merging of the lines occurs. According to Kurochka and Maslennikova (1970), the relation is $\log n_e = 22.0 - 7.0 \log m$, where n_e is the electron density and m is the principal hydrogen quantum number for the highest resolvable Balmer series member. Enlarged views of Figure 1 show at least m = 15 for this event and hence $n_e \lesssim 10^{13}$ cm^{-3} in the Balmer line emitting regions. Exploiting these high series members further, we can compare observed line ratios to those computed assuming a Boltzmann (LTE) distribution in the level populations. I display in Table 1 the observed and computed ratios of f_m/f_{11}, where f_{11} is the observed flux in the H11 line (the observed fluxes are measured with respect to the nearby flare continuum level). Inspection of Table 1 clearly reveals that the observed flux ratios are in the ratios of the statistical weights. Thus the lines are optically thin and the upper level populations are controlled by collisional processes at the local

Table 1. Observed and Computed Balmer Line Ratios

m	Observed	Computed
11	1	1
12	0.78	0.77
13	0.61	0.61
14	0.52	0.48
15	0.39	0.40

electron temperature and density. The physical significance of this result is that it demonstrates that the mechanism for hydrogen line excitation must be of a thermal nature rather than a non-thermal nature.

Following Kurochka and Sitnik (1976), we can use the optically thin H11 line to obtain an estimate of the emission measure. The flux in the H11 line averaged over the stellar surface is F(H11) = 6×10^4 ergs cm ^{2} s ^{1}. Assuming $T_e = 2\times10^4$ K, I find an emission measure of $n_e^{2}\ \Delta V = 2\times10^{53}$ cm ^{3} which is a few orders of magnitude greater than the emission measure of the largest solar flares (Moore et al. 1980). The total X-ray luminosity may be crudely estimated from

$$L_x \sim \left[\frac{P(E_1 - E_2)}{n_e^{2}}\right] (n_e^{2}\ \Delta V),$$

where the quantity in brackets has been tabulated as a function of temperature for optically thin gases of cosmic abundance by Raymond, Cox and Smith (1976). Assuming $T = 3\times10^7$ K yields $[P(E_1 - E_2)/n_e^{2}] = 3\times10^{-23}$ ergs s^{-1} cm^{-3} which, in turn, gives $L_x = 6\times10^{30}$ erg s^{-1}

Mullan (1976) has emphasized the importance of the ratio L_{opt}/L_x as a measure of the fractions of the coronal conductive and radiative losses that participate in the (secondary) heating of the underlying, cooler "optical flare region." For the entire bandpass shown in Figure 1, I find that $L_{opt} = 2\times10^{29}$ erg s ^{1} or $L_{opt}/L_x = 0.03$. I regard the ratio as a lower limit since contributions from important lines (Mg II h and k, Fe II, Hα, Hβ, etc.) and continua in the near UV and the optical longward of about 5000 Å are not included in the estimate of L_{opt}.

HELIUM LINES

In addition to the Balmer lines, neutral helium lines are visible in the optical flare spectrum presented in Figure 1. Moffett and Bopp (1976) have noted the appearance of the He I λ4471 triplet line in some M dwarf stellar flare events. The nearby He I λ4026 triplet line was usually not detected except in the strongest U band events reported by Moffett and Bopp (1976). These investigators note that the λ 4026 line is near a strong Mn I absorption feature at λ4030 thus making detection difficult except in the more energetic U band events. According to Robbins (1968), an optically thin recombination spectrum would yield I(λ4026)/I(λ4471) = 0.48. I find for the UV Ceti flare event of Figure 1, an observed ratio of λ4026/λ4471 = 1.0 thus indicating optically thick lines. The He I λ4388 singlet line is also present in this spectrum. The analogous triplet transition is λ4026. The resulting observed triplet-to-singlet ratio is 2.8, which is near the LTE ratio of 3. This kind of triplet-to-singlet ratio is characteristic of active solar prominences with $n_e > 10^{12}$ cm ^{3} and $T_e > 8000$ K (Tandberg-Hanssen 1974; see also Giampapa et al. 1978 for a parallel discussion in the case of the λ6678 and λ5876 singlet and triplet lines).

HIGH-RESOLUTION BALMER LINE OBSERVATIONS

The Balmer lines are very sensitive to temperatures and pressures in the upper chromospheric ($T > 6000$ K) and transition regions of M dwarf stars while the Ca II H and K lines are strictly lower chromospheric diagnostics (Cram and Mullan 1979; Giampapa 1980; Giampapa, Worden and Linsky 1982). As the region of Hα line formation is more nearly in the vicinity of the presumed site of primary flare energy release, the Balmer lines can be expected to be particularly sensitive to flare activity, especially given their sensitivity to transition region pressures in the M dwarf stars. In fact, the Hα profile in the spectrum of a dMe star exhibits a central reversal (Worden, Schneeberger and Giampapa 1981) which is a non-LTE effect related to the presence of an optical boundary that ultimately leads to Hα source function de-coupling from the local Planck function. However, during a flare the Hα central reversal can vanish (see Schneeberger et al. 1979, their Fig. 3). This observation indicates the presence of a high-pressure transition region at the flare site, or schematically, an inward shift of the chromospheric thermal structure to higher column mass densities. This is essentially a description of the "chromospheric evaporation model," such as those discussed by Machado and Linsky (1975). With regard to the Hα line, chromospheric evaporation models show that hydrogen ionization occurs before the Hα source function can de-couple from the local chromospheric Planck function. As a result, we do not observe a central reversal in the flare Hα profile. In addition, enhanced macroturbulent motions can obscure a central reversal. Furthermore, an increased microturbulent contribution to the Doppler broadening will cause Hα line thermalization at increased temperature and densities in the flare chromosphere.

Finally, the Balmer lines are often considerably more enhanced during a flare than are the Ca II resonance lines. As mentioned previously, the Ca II H and K lines are formed in the lower M dwarf chromosphere in a region that would, during a flare, correspond to the flare footpoints, while Hα is strictly an upper chromospheric-transition region diagnostic. Thus the area of Hα (and Balmer) line emission is greater than that for Ca II emission located at the flare footpoints.

THE BALMER DECREMENT

Investigators have reported observing a "negative decrement" with $EW(H\beta) < EW(H\gamma) < EW(H\delta)$. Kunkel (1970) has shown that this kind of behavior can be explained if the Balmer lines are driven toward LTE conditions with $n_e \sim 10^{13}$ cm^{-3}, $T_e \sim 2 \times 10^4$ K and $\zeta_t \sim 20$ km s^{-1}, where ζ_t is the microturbulent velocity. Recently Drake and Ulrich (1980) computed Balmer line emission from slab geometries for a wide range of conditions. These investigators find $H\beta < H\gamma \underset{\sim}{\sim} H\delta$ for densities in the range $\log n_e \underset{\sim}{\sim} 13\text{-}14$, $T_e \simeq 2 \times 10^4$ K, and $\tilde{\tau}(L\alpha) \sim 10^5$.

LINE WIDTHS AND LINE ASYMMETRIES

The review by S.P. Worden (hereafter SPW) noted that broadening of the Hα and Hβ lines is not a general feature of M dwarf flare spectra.

However, in powerful flare events, such as that shown in Figure 1, the base widths of the Balmer lines are clearly greater than that of the pre-flare, quiescent spectrum (see Fig. 2 of the review by SPW). The broadening in Figure 1 is likely due to Stark broadening. In fact, notice that the Ca II K line is narrow compared to the hydrogen lines in Figure 1. The expression for Stark broadening for Balmer lines shortward of Hα is $\gamma = 0.255\ (n_l^2 - n_e^2) n_e^{2/3}$ (Sutton 1978) while that for Ca II is $\gamma = 2.6 \times 10^{-6}\ n_e$ (Raymer 1979). Assuming $n_e \sim 10^{13}$ cm is approximately applicable for both Ca II K and the neighboring H8 line yields $\gamma(\mathrm{CaII\ K})/\gamma(\mathrm{H8}) = 3.7 \times 10^{3}$. Thus Stark broadening is negligible for Ca II relative to the Balmer lines.

The review by SPW discussed evidence concerning line asymmetries in M dwarf flare spectra. I would add the caveat that blends can mimic asymmetries in moderate or low spectral resolution flare observations. For example, the Ca II λ3968 resonance line can be blended in the wings of the λ3970 Hε line; the He I λ4121 triplet is near Hδ(λ4101); and a Mg II subordinate line at λ4481 resides near the He I λ4471 triplet, as can be seen in Figure 1.

ULTRAVIOLET FLARE SPECTROSCOPY

Unfortunately a paucity of ultraviolet spectroscopic observations of M dwarf stellar flare events is available at the time of this writing and the published (or in press) observations have been summarized by SPW. A principal feature of the UV observations of a flare on Gliese 867A was the presence of a strong, rather flat UV continuum that is reminiscent of free-free emission at $T \sim 5 \times 10^4$ K or 10^5 K. However, Butler et al. (1981) attribute the flare continuum to black body emission at $T = 2 \times 10^4$ K. This value is significantly higher than optical black body temperature estimates given by Mochnacki and Zirin (1980) or Kahler et al. (1982).

The flare line emission observed by Butler et al. (1981) exhibits interesting behavior as well. I display in Figure 3 a plot of line surface flux (normalized to the quiet Sun) versus temperature of line formation. I constructed these curves on the basis of data given by Butler et al. (1981) and they should essentially represent the run of emission measure in the flare and quiescent stellar atmospheres. The "flare curve" in Figure 3 is somewhat similar to the "quiet curve." An important difference is a relatively shallow emission measure slope for $T > 10^5$ K. The N V λ1240 line ($T \sim 2 \times 10^5$ K) and the He II λ1640 line were not significantly enhanced as would be expected following an initial X-ray flare outburst. Interestingly, Baliunas and Raymond (1982, private communication) recently observed a UV flare event on EQ Peg that is similar to the Butler et al. (1981) GL 867A observations. In particular, the EQ Peg observations reveal flare continuum emission as well as enhanced line emission but no enhancement of N V or He II was seen. Apparently the flare event was confined to atmospheric levels below the region of C IV line formation, or $T \lesssim 1.1 \times 10^5$ K; that is, these kinds of flares may not be associated with coronal events but may originate in the chromosphere of the M dwarf star.

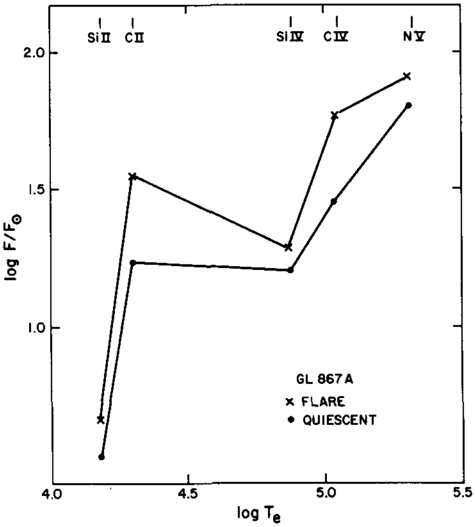

Figure 3: Normalized surface flux versus temperature of formation of the resonance lines of the ions shown during the flare and quiescent state of the dMe star GL867A. Based on data from Butler et al. (1981).

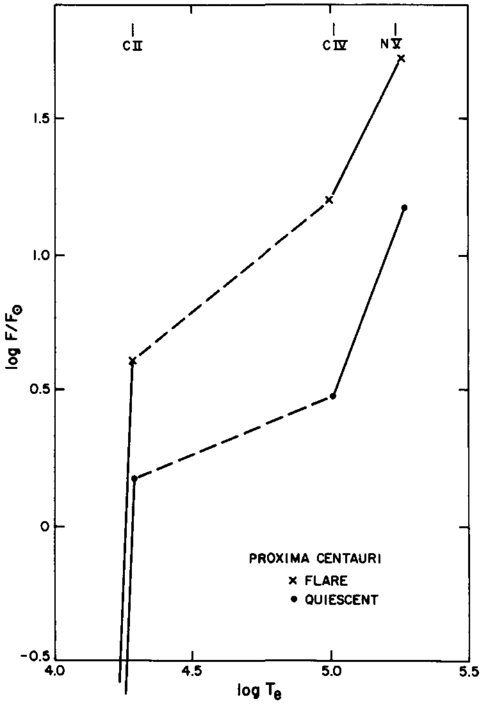

Figure 4: Same as Fig. 3 but for the dMe star Prox Cen. The flare data are taken from Haisch et al. (1982) and the quiescent data are from Linsky et al. (1982).

In juxtaposition to the aforementioned events is the observation of a flare event on Proxima Centauri by Haisch et al. (1982; see the detailed review in this volume). I construct in Figure 4 an "emission measure" curve that illustrates the strong enhancements in the lines (including NV) although the slope between CIV and NV is not quite as steep as in the quiescent spectrum. Haisch et al. (1982) did not observe any UV continuum emission and they concluded that either there was no UV continuous emission during the flare or any continuous emission that occurred was of short duration.

Bromage et al. (1982; see the contribution in this volume) observed a flare event on AT Mic that showed continuum emission increasing toward longer wavelengths in the SWP camera (1100-2000Å) of the IUE. This is reminiscent of bound-free hydrogen emission, H^- emission, or black body emission at $T < 10^4$ K, or, of course, a combination of these radiative processes. A more detailed description of these UV observations appears in this volume (see the contributed paper by G. Bromage and collaborators). In summary, the simultaneous acquisition of additional UV and optical flare data is imperative if we are to progress any further in the understanding of stellar (and solar) flare activity.

As a final comment, it is vital to know the relative importance of the UV and the optical to the total flare energy budget. Unfortunately, simultaneous UV and optical observations are not yet available for M dwarf flares, although solar flares may serve as a guide. The results from the well-observed solar flare of 5 September 1973 reveal that the UV and the optical from 1100Å-8700Å dominated the radiative power output at flare maximum, although soft X-ray observations were unavailable for this analysis (Canfield et al. 1980). Thus the UV and optical may dominate the energy balance in stellar flares as well. However, I note that Wagner et al. (1981) observed that the mass energy flux in a transient associated with the solar flare of 7 April 1980 exceeded the total radiative energy of the flare by at least a factor of 10. Thus we must eventually address the observational problem of measuring the mechanical energy of the material motions in stellar flares in order to discern the relative importance of various flare cooling mechanisms. The answers will ultimately derive from high temporal and spectral resolution spectroscopy.

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DISCUSSION

Basri: I feel compelled to point out that N V may be a deceptive diagnostic. Results from a large survey of RSCVn stars, where hopefully one does not need to worry about flaring, just about "quiescent" active chromospheres, show a different behaviour in N V from other transition region diagnostic lines. As measured by IUE in low dispersion it behaves more like a chromospheric line than a transition region line. So either there is something strange about the formation of N V or, as Linsky pointed out at the Zurich meeting, it may be heavily contamined with chromospheric lines. In particular we do not see the same kind of period/ activity relationship for N V as for other transition lines. As I will show tomorrow the slope of the correlation of N V vs other transition region lines is more like that of chromospheric lines vs the other transition region lines. So one would need to be very careful in using IUE data on N V.

Jordan: May I add a comment on that. I had not heard this result before. It is true that there are a lot of C I lines around the wavelength of N V. It is also true that N V has a very long tail to its ionization curve which extends right out to the corona. So that if in the quiescent state the temperature were only in the region of say 500 000 K then N V would be formed over the entire volume of the corona. So that when a flare went off it would only occupy a tiny fraction of that volume and the total emission would not be enhanced as much. I do not know if that would work or not but it is a thought.

Giampapa: That is a really interesting suggestion. I would add that Bromage saw optical events associated with which there were no UV events. So while N V may well be a deceptive diagnostic, it may also be that there are impulsive events which are confined to cooler regions.

Linsky: I have a question and comment. In the Table which you showed from the Canfield reference there is a lot of emission in the region from 1500-2000 Å. So I would like to make a plea that we try very hard to measure the flux in that continuum. I realize that it is very difficult with IUE because of scattered light and its poor sensitivity and also the fact that we are looking at very weak emission. It is important to measure this in order to understand the mechanism whereby the continuum is formed.

Vaiana: In view of the comments on N V presumably a statement about the possibility of having two types of events, one which peaks around C IV and the other in the X-ray region starting from N V, should be put much less strongly. There is another argument against this and that derives from the recent flare seen by Haisch and Todd in which there is the same decrement in N V even though there is very strong X-ray emission.

Giampapa: I did not mean to make a general statement. As we know from the Sun there is an incredible variety of transient phenomena and may be we are not even sure what we should call a flare.

Vaiana: I know of one without X-ray emission but I do not know of one which stops at C IV.

Kodaira: How high was the time resolution at the IUE spectra?

Giampapa: Time resolution is typically 20 or 30 mins.

Kodaira: In that case it is quite probable that the lines come from the decay phase. It is quite important to decide whether you are dealing with the impulsive or the decay phase. So the emission may be dominated by chromospheric lines.

Giampapa: That is an important point. Haisch made this point also. In the optical the continuum emission is of much shorter duration than the line emission. So one may not be able to see the continuum with IUE anyway.

Rosner: I wonder whether anyone has for the solar case tried to compare the X-ray and UV measurements of compact loop flares, which are fairly small structures low down in the atmosphere, and the prominence-associated flares, which are much more disruptive and where there is a lot of motion associated with cool material. These remind me of the kind of events you have been talking about where you see lots of emission in cooler lines.

Giampapa: I am not aware of any such comparison but that is an interesting point.