The Ultraviolet Continuum in Solar and Stellar Flares

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Summary. Ultraviolet continua observed in *IUE* spectra of dMe stars in a flaring state are compared with those in solar flares. There is evidence that, as may be the case with solar flares, stellar-flare continua in particularly the $\lambda < 1683$ Å region are due to free-bound transitions in neutral silicon excited by ultraviolet line emission.

1 Introduction

Several *IUE* spectra of UV Ceti (dMe flare) stars show enhanced line emission and so the exposures were most likely taken during flares. In one or two cases this is actually known to be the case from coordinated studies in other wavelength bands. The ultraviolet line emission during flares is generally more enhanced for lines characteristic of the solar transition region, e.g. C IV (λ 1550 Å), less so for chromospheric lines such as Mg II (λ 2800 Å). Nearly all flare spectra to date have been taken in low resolution (FWHM $\sim$ 5 Å).

A continuum has occasionally been observed during some of these flare exposures, mostly in the short-wavelength (1150 – 1900 Å) *IUE* range. Those flares showing the largest ultraviolet line enhancements seem to show the brightest continua. Bromage *et al.* (1986) studied continua seen in *IUE* spectra during a flare on AT Mic, doing a comparison with those in re-extracted spectra of other dMe star flares. By converting line and continuum fluxes to power (assuming durations of 30 minutes for all flares), it was found that flares having the greatest line powers had greatest continuum powers and the flattest spectral dependence. No quiescent flare star spectrum shows any detectable continuum, so that flare continua do not have any significant non-flare contributions. Solar-flare continua have much weaker powers and steeper wavelength dependence.

Machado and Hénoux have proposed that the ultraviolet continuum seen in solar flares at $\lambda < 1683$ Å, due to Si I bound-free radiation, is excited by ultraviolet line emission. We report on evidence, from *IUE* spectra, that the ultraviolet continuum of stellar flares is similarly formed.

2 The Solar UV Continuum

Vernazza, Avrett and Loeser (1981) describe the quiet solar spectrum in terms of various model atmospheres. According to these calculations, the quiet-sun continuum between 1300 Å and 1683 Å is produced by bound-free transitions in Si I, with edges at $\lambda = 1525$ Å and 1683 Å. For a quiet-sun atmosphere, these continua originate in the temperature-minimum layer (about 500 km above $\tau_{5000} = 1$) or low chromosphere. The silicon ionization rate is primarily controlled by photoionizations from upper levels by photospheric radiation, which has a higher characteristic temperature than the local electron temperature. In the ionization balance ratio $n(\text{Si II})/n(\text{Si I})$, only the recombination rate coefficient in fact depends on local temperature. Thus, the Si I continua source functions depart strongly from the Planck function at the local temperature, and despite what had been previously thought, the λ1683 Å continuum in particular is not therefore a reliable indicator of the solar minimum temperature.

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A further contribution to the photo-ionization rate of neutral silicon in the temperature-minimum region is made by photo-ionizations due to the ultraviolet line radiation of the transition region, especially for active solar conditions. Machado and Hénoux (1982) and Machado and Mauas (1986) have calculated this for flare conditions, when the ultraviolet line emission is strongly enhanced: it is found that the continua source functions show a much larger departure from the Planck function at the local electron temperature. The C IV doublet at 1548, 1551 Å is particularly effective in the case of the λ1683 Å continuum.

3 Ultraviolet Continuum in dMe Star Flares

Examples of *IUE* spectra of dMe stars showing continuous emission are given in Table 1. The spectra are in the short-wavelength range of *IUE*, covering the 1150 – 1950 Å range, and so including the Si I recombination continua. They are apparently all flare-enhanced; there seem to be no cases of quiescent dMe star spectra showing a detectable continuum. Bromage *et al.* (1986) have already discussed and compared five of these spectra.

To study whether the excitation mechanism for the solar 1300 – 1680 Å continuum mentioned above is applicable to dMe stars, the observed stellar line and continuous fluxes ought to be converted to specific intensity (erg $\mathrm{cm^{-2}\ s^{-1}\ sr^{-1}}$ or erg $\mathrm{cm^{-2}\ s^{-1}\ sr^{-1}\ Å^{-1}}$). If I is the specific intensity of a line or the continuum, and E the total energy in line or continuous emission over the course of a flare, then

$$I = E/4\pi A\Delta t,$$

where A and Δt are the flare emitting area and duration. The measured quantity from *IUE* data is, however, flux F (erg $\mathrm{cm^{-2}\ s^{-1}}$), given by

$$F = E/4\pi d^2\Delta T,$$

where d is the distance to the star, ΔT is the *IUE* exposure duration and it is assumed that ΔT encompasses the entire flare. Knowing d and ΔT, the total energy E can be estimated; in the case of ultraviolet lines, an appropriate amount for emission when the star is in a quiescent state must first be subtracted. However, the specific intensity of lines or continuum cannot be estimated because the stellar flare area A and duration Δt are unknown.

We can make further progress by some assumptions. If the ultraviolet continuum were excited by line emission in a manner similar to that in solar flares, a plot of specific line intensity (I_L) *vs.* that in the continuum (I_C) could be expected to show a particular relationship. If E_L and E_C, the total energies in line and continuum, were instead substituted for I_L and I_C, that relationship would be preserved if (*a*) Δt were equal for lines and continuum; and (*b*) if A for lines and continuum were equal. From the solar flare observations of Orwig and Woodgate (1986), the light-curves of ultraviolet line and continuum are indistinguishably different, down to very fine time structure; this gives some justification for assuming this is so for stellar flares. The solar evidence for the assumption of similar emitting areas is rather less secure, though it is commonly taken that the ultraviolet line and continuous emitting areas and that of the associated Hα flare are all equal, and represent the footpoints of flux tubes forming the flare magnetic-field geometry; this is assumed, e.g., in the *Skylab* analysis of a flare to estimate total radiative energy (Canfield *et al.*, 1980).

For the stellar flares observed with *IUE* and listed in Table 1, values of E_L were derived for the C IV (λ1550 Å) and C II line features (λ1335 Å), both doublets but unresolved by *IUE* in low-resolution mode. Similarly, values of E_C were derived for the observed continuum at λ1600 Å. Fig. 1 is a plot of E_L *vs.* E_C for the C IV line feature. Added to these values are E_L for the

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same lines and E_C, also at 1600 Å, estimated from the *Skylab* solar flare on 1973 Sept. 5 analysed by Canfield *et al.* (1980). These powers have been approximately converted to total energies by multiplying by a time of five minutes, the half-maximum duration in soft X-rays.

As Fig. 1 indicates, there is a strong linear correlation of E_L and E_C over the very wide range of flare energies. The plot for C II shows the same sort of correlation. This suggests that the ultraviolet continuum radiation is connected with the ultraviolet line emission.

If the solar or stellar continua in this range are mostly due to silicon recombination radiation, there should be some evidence for recombination edges. In the data from the NRL slit spectrograph on *Skylab*, enhanced emission below 1525 Å is apparent in the spectra of not only solar flares but also quiet-sun and active regions and coronal holes (Cohen 1981), indicating the presence of the Si I ^3P recombination edge. The 1683 Å edge is not so apparent, but there is a relative enhancement below this wavelength in solar flare continua over pre-flare emission (Cook & Brueckner 1979). There would be considerable smoothing of these edges if present in stellar flare continua and observed with *IUE*, the resolution in its its low-resolution mode being FWHM $\sim$ 5 Å. Also, to judge from *Skylab* high-resolution solar spectra, some contribution to the apparent continuum in *IUE* low-resolution spectra would be made by numerous weak lines; this is true of the region immediately above λ1525 Å where many Si I lines occur, approaching the series limit, and around λ1680 Å where there are many Fe II lines.

Nevertheless. the 1525 Å continuum edge shows up in at least two of the spectra listed in Table 1. One is of a very intense flare on AD Leo, reported by Pettersen *et al.* (1986), in which many of the chief lines and longer-wavelength continuum are saturated. The other is a very long exposure spectrum of UV Ceti, reported by Linsky *et al.* (1982). In both, there is a very definite drop in intensity with increasing wavelength, short of the C IV λ1550 Å line feature.

4 Conclusion

The strong linear correlation of E_L and E_C, the total energies in line and continuum during dMe star flares, and the apparent visibility of an edge at $\sim$1525 Å, suggest that the continuum in dMe star flares is formed in a similar way to that proposed for solar-flare continua, viz. the excitation of Si I bound-free transitions by ultraviolet line emission.

Table 1. *IUE* spectra of dMe stars showing continua.

Reference	*Star*	E_L (C IV)	E_C	*Continuum visibility*
Butler *et al.* (1981)	Gl 867A	3.4(31)	7 7(29)	Bright
Haisch *et al.* (1983)	Proxima Cen	7.2(29)	1.8(27)	Barely detectable
Baliunas & Raymond (1984)	EQ Peg	6.5(30)	1.0(29)	Visible at longer λ's
Bromage *et al.* (1986)	AT Mic	2.2(31)	3.1(29)	Bright, during 2 stages of flare
		8.5(30)	1.3(29)	
Pettersen *et al.* (1986)	AD Leo	>9(31)	7.2(30)	V. bright

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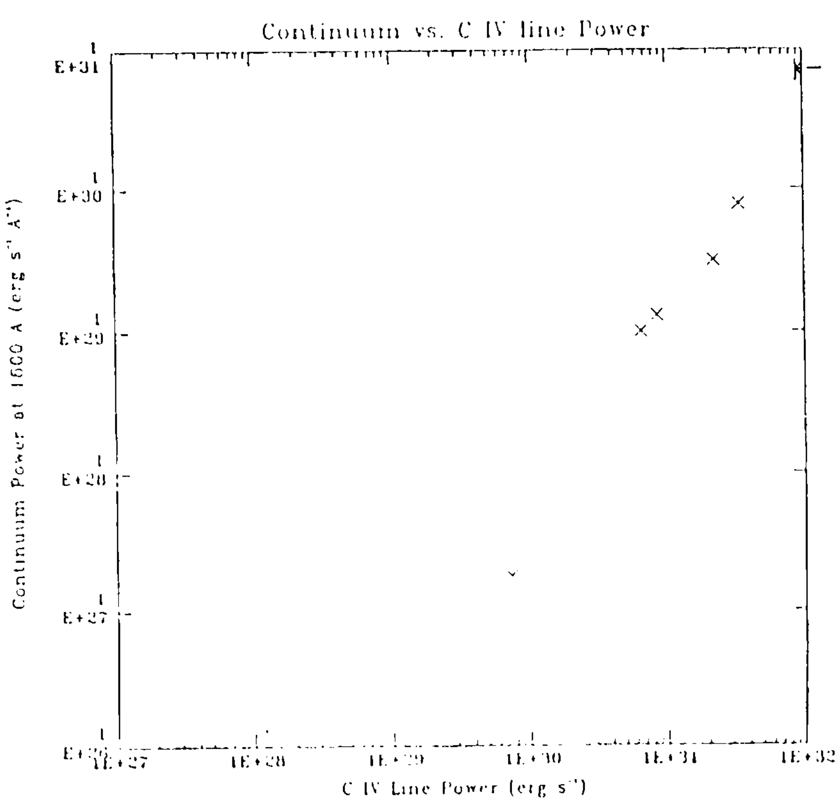

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