A correlation between Balmer and soft X-ray emission from stellar and solar flares

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Summary: Simultaneous optical spectroscopy and X-ray monitoring of stellar and solar flares shows that a well-defined linear correlation exists between the integrated $H\gamma$ and soft X-ray flux that extends over four orders of magnitude. The existence of this relationship implies a direct proportionality between the emission from the cooler and denser regions ($T \approx 10^4 K$) responsible for Balmer lines and the emission from the hot plasma ($T \approx 10^7 K$) responsible for soft X-rays. The consequences are considered for (a) several models which have been proposed for solar flares, and (b) the suggestion that the Balmer emission results from irradiation by soft X-rays.

1 Introduction

It is important, when trying to unravel the complex phenomena involved in stellar flares, to be able to assess where the emission in the different spectral regions arises and to what other parts of the spectrum it is related. For instance, the currently accepted picture of the evolution of a flare involves two basic phases; first the impulsive phase seen in hard X-rays and the optical continuum, and secondly a gradual, or thermal, phase involving a slow decline in soft X-rays and emission lines. The first phase is usually associated with heating by very energetic particles (electrons or protons) and the second is associated with a hot plasma cooling by radiation and expansion. The radiation emitted by the two phases may, or may not, correlate, depending on how closely they are linked energetically. To investigate which parts of the emission from flares correlate with one another requires observations of different spectral regions with many different instruments simultaneously. This paper concerns a search for a correlation between Balmer flux and soft X-ray flux involving several different satellites and ground-based telescopes.

Whilst $H\alpha$ has traditionally been the favourite Balmer line for solar work, the importance of the near ultraviolet continuum and the greater number of strong lines available there, has lead to a preference by stellar astronomers for the 3500-4500 A wavelength region. The strongest Balmer line in this wavelength region is $H\gamma$ which also has the advantage that it is less optically thick than $H\alpha$. Where $H\gamma$ has not been the preferred option and $H\alpha$ observations have been obtained (e.g. in the case of solar flares) we have converted the $H\alpha$ to $H\gamma$ using an average Balmer decrement from several solar and stellar flares: $H\gamma = 1/3H\alpha$. As this ratio will vary somewhat, according to the temperature and pressure in the region of formation of the Balmer lines, (see Drake and Ulrich, 1980), we have preferred to use a mean value determined empirically from observation.

2 Observations

A coordinated observation campaign by Kahler et al. (1982) on YZ CMi was one of the first to obtain good simultaneous optical and X-ray coverage of a stellar flare. Ground-based telescopes provided fluxes for the $H\beta$ and $H\gamma$ Balmer lines and the Imaging Proportional Counter (IPC) of EINSTEIN provided soft X-ray fluxes over the 0.2-4 KeV range. Integrated fluxes, above the normal 'quiet' level for the entire flare event, were determined. As, to our knowledge, this was the only flare seen by EINSTEIN which had simultaneous Balmer line coverage, whereas a number were observed by EXOSAT, we have converted the EINSTEIN IPC

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flux (0.2-4KeV) to the equivalent EXOSAT LE flux (0.04-2KeV) by multiplying by a factor of three. This value was determined by Pallavicini et al. (1986,1988) from observations of dMe stars by both satellites. The use of this factor implicitly assumes that the spectrum of the emission from flares is the same as that for the quiet stars; an assumption which appears to be reasonably well justified by the determination of temperatures of flare plasmas by the EXOSAT ME experiment, (see Doyle et al. 1988a and Haisch et al. 1987) and the lack of any correlation of the ratio of IPC/EXOSAT flux with the derived temperature of the emitting plasma, (see figures 1 and 2 of Pallavicini et al. 1986).

Three other sets of data, all of which involve EXOSAT observations of stellar flares, have been analysed. These include the flares on YZ CMi and Gl 644AB observed by Doyle et al. (1988a,b) and the small flares recorded on UV Ceti by Butler et al. (1985, 1986). The flare on YZ CMi was unusual in that there was no strikingly obvious event in LE X-rays simultaneous with the 1.3 magnitude optical event. Simultaneous spectroscopy showed a two-fold increase in the $H\gamma$ flux during the U-band flare. The existence, or non-existence, of an X-ray event at this time is problematical, as although Doyle et al. concluded that there was no simultaneous event, there was a clear increase in LE X-ray flux about eleven minutes after the peak of the U-band flare. The X-ray enhancement at this time reached a peak of twice the normal level and lasted for about ten minutes, (see figure 1). Although the delay between the rise in X-rays and the rise in the U-band is rather longer than is normally encountered in solar flares, we are inclined to believe that this was in fact the X-ray event associated with the prominent U-band flare at 19.55 UT, and that the apparent delay in the X-ray enhancement is due, in part at least, to the spiky nature of the optical event. Assuming that this is indeed the case the integrated $H\gamma$ and LE soft X-ray fluxes for this event were 3×10^{29} ergs and 5.5×10^{30} ergs respectively.

Several small flares were seen on the prototype UV Ceti during a coordinated campaign in 1985 by Butler et al. (1986) involving EXOSAT and ground-based telescopes. These events, which followed one another in the space of three hours, were referred to as micro-flares by the authors, not because of any similarity to the hard X-ray bursts seen by Lin et al. (1984), and also termed micro-flares, but because they were small by comparison with the stellar flares commonly observed. In fact Butler et al (1986) and Collura et al (1988) have pointed out that these flares are roughly equivalent in size and duration to compact solar flares. For this study only the four largest of the small flares seen on UV Ceti, those termed A,B,C and D in figure 2, have been included. As with all the flares included here a correction has been made for the background 'quiet' emission.

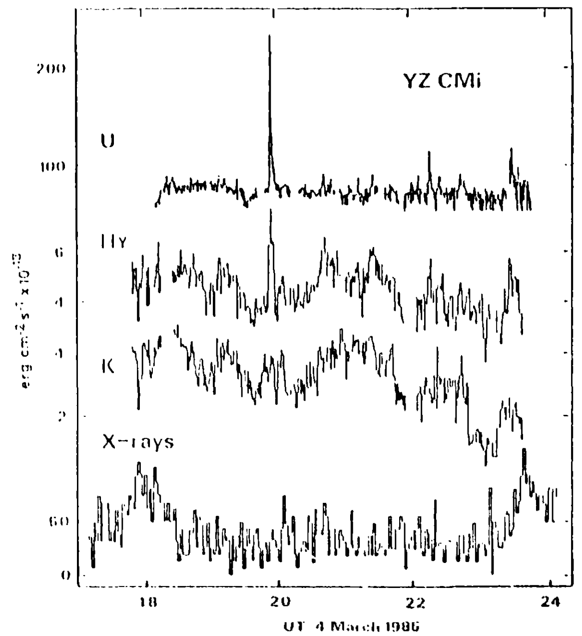

Figure 1. Fluxes observed in $H\gamma$, CaII K, Johnson U-band and soft X rays from YZ CMi on 4 March 1985. Note the 1.3 magnitude flare in U at 19.55 UT and the subsequent increase in X-rays at 20.06 UT.

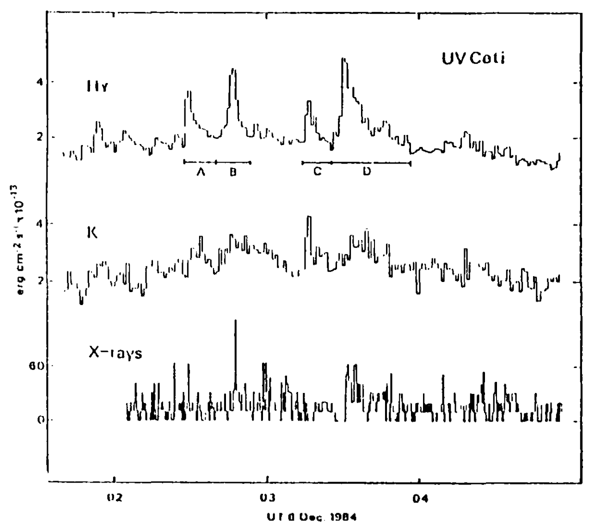

Figure 2. Fluxes observed in $H\gamma$, CaII K and soft X-rays from UV Ceti on 6 December 1984. The four small flares A, B, C and D are indicated.

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One further stellar flare was observed by EXOSAT in soft X-rays and in Balmer emission ($H\alpha$), on the bright dMe star Gl 644AB, by Doyle et al. (1988a). This is by far the most energetic of the flares discussed here with integrated fluxes an order of magnitude greater than the fluxes from the YZ CMi flare by Kahler et al. (1982).

It may seem surprising but there are almost no suitable observations of solar flares which can be compared to the above observations of stellar flares. Most of the published SMM data refer to the hard X-ray region and even for this there are very few simultaneous Balmer line measurements. The soft X-ray region (0.04-4 KeV) in which stellar flares have been observed by EINSTEIN and EXOSAT does not seem to have been popular with solar observers since the early rocket experiments. Indeed the lack of a single spectrum of this region for a solar flare makes it very difficult to scale the flux of SMM instruments to the wavelength range of EINSTEIN and EXOSAT. The problem is compounded by the large number of emission lines that occur in the EUV - soft X-ray region. However, for one solar flare, observed by Acton et al. (1982) in $H\alpha$ and the 1.85 A line of FeXXV, an estimate of the total soft X-ray flux, over the EXOSAT range (0.04-2 KeV) has been made by Doyle et al. (1988a) based on Acton's published emission measure curve and the emissivity function of Mewe et al. (1985). The integrated $H\alpha$ flux has been determined from Acton's time profile and converted to the $H\gamma$ flux using the same factor of 1/3 used for the flare on Gl 644AB.

The data for all the above flares are given in table 1. It is noticeable that the total integrated energies for the flares listed range over four orders of magnitude in both $H\gamma$ and soft X-ray flux. Plotted in figure 3 we see an excellent correlation between the integrated $H\gamma$ and soft X-ray flux for all the flares observed. The

Table 1. Integrated $H\gamma$ and soft X-ray fluxes for flares on dMe stars and the Sun

Star	distance *parsec*	$L(H\gamma)$ $\times 10^{28} erg$	Lx(0.04-2 KeV) $\times 10^{28} erg$	detector
UV Ceti	2.6	3.3	58	EXOSAT
		4.9	260	
		2.4	63	
		12.9	560	
YZ CMi	6.1	320	10800	EINSTEIN
YZ CMi	6.1	30	550	EXOSAT
Gl 644AB	6.4	2300	120000	EXOSAT
Sun	1 AU	0.2	12	SMM

quality of the correlation is particularly striking when it is realised that the slope of the line drawn through the points has not been fitted but has slope unity in the log-log plot. This implies that there is a direct proportionality between $H\gamma$ and soft X-ray flux, Lx = 31.6 L($H\gamma$), for flares separated over four orders of magnitude in energy which includes flares on the Sun and nearby dMe stars. The tightness of the correlation is even more remarkable since observations of the fluxes were made by three different satellites and five different ground-based telescopes. This may well be the first time solar flares have been shown to obey a common relationship with flares on dMe stars.

3 Interpretation

The existence of a direct proportionality between the $H\gamma$ and X-ray flux for all flares for which we have the relevant data is unexpected for the following reasons.

1. Balmer emission arises from a plasma with a temperature of the order of $10^4 K$, whereas the X-ray emission originates in a plasma with a temperature between $10^6 - 10^7 K$. It is not obvious that there should be any correspondence in the emission between the two plasmas.

2. Time profiles of the Balmer emission show an appreciable impulsive phase component (see Kahler et al. 1982), whereas the soft X-rays are predominantly believed to arise from the cooling plasma in the more gradual and later thermal phase.

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3. The lower Balmer lines ($H\alpha$, $H\beta$, $H\gamma$ etc) are optically thick at chromospheric densities and therefore the total integrated fluxes would be expected to be dependent on the projected area of the hydrogen emitting plasma, rather than the volume, as in the case of the X-ray emitting plasma.

The models commonly proposed for flares, and confirmed to some extent by spatially resolved observation of solar flares, suggest that the Balmer emission originates primarily in the footpoints of magnetic loops where the deeper chromosphere and photosphere is heated to a temperature close to $10^4 K$ by the energetic particles which are beamed onto the surface by the magnetic field. The soft X-rays, on the other hand, are supposed to originate from the hot material evaporated from the foot points, which subsequently fills the magnetic loops, and cools gradually by radiation. A simple model by de Jager (1985,1987) pictures the region in the chromosphere where the magnetic loops reach down to the footpoints. In this model the energetic particles burn down into the chromosphere leaving a hole from which the material has been evaporated. It is suggested that the Balmer emission arises from the lower surface of the hole, where the temperature is $\approx 10^4 K$, and $N_e \approx 10^{13} cm^{-3}$. If the Balmer emission were to be optically thick at this density then it would be expected to scale with the surface area of the bottom of the hole whereas the X-ray emission would be proportional to the amount of material evaporated. Thus, one would naively expect, for stars with a similar atmospheric

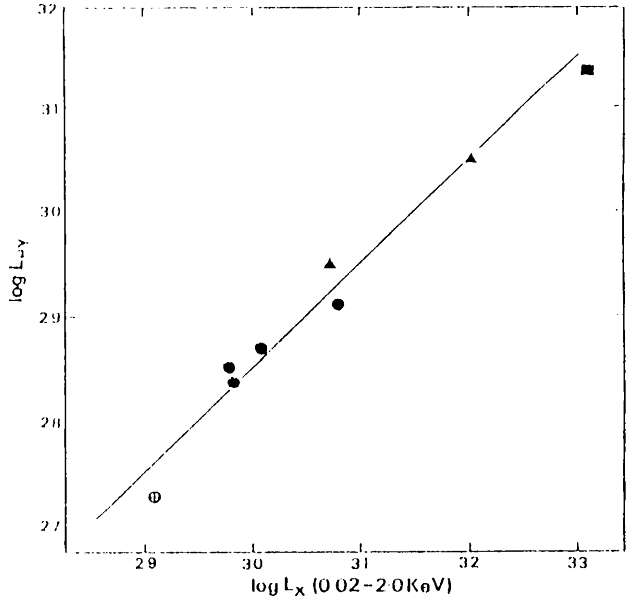

Figure 3. The integrated $H\gamma$ and soft X-ray fluxes for the stellar and solar flares listed in table 1. Symbols: triangles YZ CMi, square Gl 644AB, filled circles - UV Ceti and circle with central cross the Sun.

structure, that a direct proportionality between Balmer and soft X-ray emission would imply that the ratio of the volume of the hole to its surface area, would be constant; i.e. that the well has a constant depth for flares on all dMe stars and the Sun. Similarly, if the Balmer emission were to be optically thin, the proportionality between Balmer and soft X-ray flux would imply a constant ratio of the number of particles in the Balmer emitting region to the number originally contained in the well. Other flare models by McCabe (1973) and Priest (1981) suggest that the Balmer emission arises from loops which lie below the soft X-ray emitting loops but are closely related to them. The proportionality between the soft X-ray and Balmer emission confirms this close association but might impose a tight constraint on their geometry.

A simpler explanation would be that the Balmer flux is a direct consequence of the soft X-ray flux and that the excitation of the hydrogen atoms is primarily due to the soft X-ray radiation rather than heating by energetic particles. In this context it should be remembered that Zirin (1978) noted the simultaneous appearance of X-ray and Balmer emission in solar footpoints. The suggestion that the coronal X-ray radiation is an important contributor to the heating of the upper chromosphere in dMe stars was made by Cram (1982). If this model were to apply to the heating of the lower chromosphere by soft X-rays emitted by flares, and we assume that the downward directed X-ray flux is half the total flux emitted, (where the total flux is emitted

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over 4π steradian), then the total energy emitted in all hydrogen lines should be less than half that emitted in soft X-rays. From Balmer decrement ratios observed in stellar flares by Doyle et al. (1988b) and Phillips et al. (1988) and similar ratios for quiet dMe stars by Gershberg (1973) we would estimate the total Balmer flux to be $\approx 11L(H\gamma)$. The Lyman flux is more difficult to estimate but from the computations of Drake and Ulrich (1980) the Lyman/Balmer ratio may be expected, for $T_e \approx 10^4$, to vary from unity for $log N_e > 13$ to ten for $log N_e < 10$. Thus, at the very least, our total estimated Balmer + Lyman flux would be $\approx 22L(H\gamma)$, i.e. about 2/3 of the total soft X-ray flux. If the amount of Lyman flux exceeded the Balmer flux by a factor greater than 1, then the discrepancy is even greater, and the soft X-ray flux alone would be quite insufficient to explain the total hydrogen emission, let alone the emission in the other chromospheric lines. However, we should also include the flux in the EUV region, $\lambda\lambda 270 - 1216A$ which lies outside the EXOSAT LE range, and will contribute to the excitation of the hydrogen atoms. In the absence of any definitive observations we estimate its energy as roughly 50% of the EXOSAT LE soft X-ray flux. Thus it appears that the observed hydrogen emission flux, $L(H) \approx 22L(H\gamma)$, is approximately equal to the total downward directed soft X-ray and EUV flux, $L_D(X + EUV) = 1/2(32L(H\gamma) + 16L(H\gamma)) \approx 24L(H\gamma)$. We conclude, therefore, that if the soft X-ray and EUV radiation were to be directly responsible for the hydrogen emission, a very efficient mechanism for conversion of the available radiation into hydrogen excitation would be required. Whatever the explanation, if the proportionality between soft X-rays and $H\gamma$ holds, it means that one can predict the soft X-ray flux, which is a sizeable fraction of the total radiated energy from a flare (approx. 30%), from the measurement of the flux of just one Balmer line.

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