Flares: the Solar-Stellar Connection

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1 Introduction

The systematic study of stellar flares in now more than 30 years old. Throughout that time the solar flare paradigm has been used, highly successfully, to understand various aspects of the stellar phenomenon. In this introductory overview I will attempt to justify the use of the solar model in understanding the stellar equivalent. But I will also point out differences between the two which may require extension of the basic solar model and speculate briefly on what these extensions might be.

There are many excellent previous reviews of stellar flares in the literature (Haisch 1989, Byrne 1983, 1992), to which the reader is referred, along with the other reviews in this volume, for further reading.

1.1 In which stars do we find stellar flares?

The "classical" flare stars are the UV Cet stars, Main Sequence (MS) stars of spectral type later than ~K5Ve (the 'e' suffix indicates the Balmer Hα line in emission). Their characteristic property is rapid rotation, which, in combination with a deep convective zone, generates efficient dynamo action. As in the Sun, the resulting magnetic fields rise through the convection zone and at the photosphere they are locally intensified by surface convection into active regions, within which flares occur in stressed loop structures.

A second class of flare stars are the RS CVn stars. These are close detached binaries with one evolved component which is forced into co-rotation with the orbital period by tidal interaction. The resulting rapid rotation, in combination with a deepening convective zone, results in dynamo-generated magnetic fields which produce flares in the same general manner as in the UV Cet stars.

Flares are also found in a number of other kinds of objects which will not be discussed here, not for lack of interest, but rather lack of space. For instance, FK Com stars are isolated, extremely rapidly rotating field giants whose origin is a matter of vigorous debate. T Tau stars are pre-MS and in the final stages of contraction to the MS but the understanding of whose activity is complicated

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Table 1. Representative parameters for dMe and RS CVn stars

Star	Type	Sp. Type	$R/R_\odot$	P(d)	d(pc)
V711 Tau	RS CVn	G5V/K1IVe	1.3/3.9	2.838	36
II Peg	RS CVn	K2IV/?	2.8	6.724	29
AU Mic	UV Cet	M2Ve	0.6	4.865	9.4
BY Dra	UV Cet	M0Ve/M0Ve	1.3/?	3.827	15.6

by massive winds and/or disks (see Gahm, these proceedings). Flares probably also occur on the low-mass secondaries of Cataclysmic Variables where rapid rotation is again tidally induced.

For the purpose of the present review we will discuss only the UV Cet and RS CVn stars. Representative parameters for members of these two classes will be found in Table 1.

1.2 What is a stellar flare?

At optical wavelengths a stellar flare appears as an impulsive heating resulting in a monotonic rise in light output, followed by a quasi-exponential cooling. Rise times of dMe flares can be as fast as several seconds or as slow as several tens of minutes, while they decay in times between 1 min and several hours (Fig. 1). In general, total energy and light curve complexity is correlated with time scale. Slower flares are usually more energetic and have more complicated light curves.

2 Comparison between dMe and solar flares

2.1 Optical

Optical spectroscopy of fast stellar flares shows that the rise and initial decay is dominated by broad-band continuum and high-excitation emission in such lines as He I and He II. The slower part of the decay shows strong emission in chromospheric lines, mainly H I Balmer and Ca II H&K (Bopp & Moffett 1973). This duality of time scales is also characteristic of solar flares. Continuum emission in solar flares was considered extremely rare until recently (Neidig 1989) but is now associated with the initial heating phase in large solar flares. The heating which gives rise to the observed continuum solar flares is believed to arise in the region of the temperature minimum between photosphere and chromosphere (Aboudarham & Henoux 1986). Typically the chromospheric flare, seen for example in Hα, evolves on a much longer time scale then the continuum.

Stellar flare light is very blue compared to the background photosphere. Broadband colours of flare light, after subtraction of the quiescent photospheric contribution, are far from blackbody but various models indicate plasma temperatures $\geq 10^4$ K. Lines of He I and even He II suggest that even higher temperatures are present. Furthermore, H I lines are broadened in their cores and may show extended and asymmetric wings (Doyle et al. 1988, Houdebine et al. 1993a,b). Core broadening is attributed, as in the Sun, to Stark effects resulting from heating denser layers to chromospheric temperatures. The asymmetric

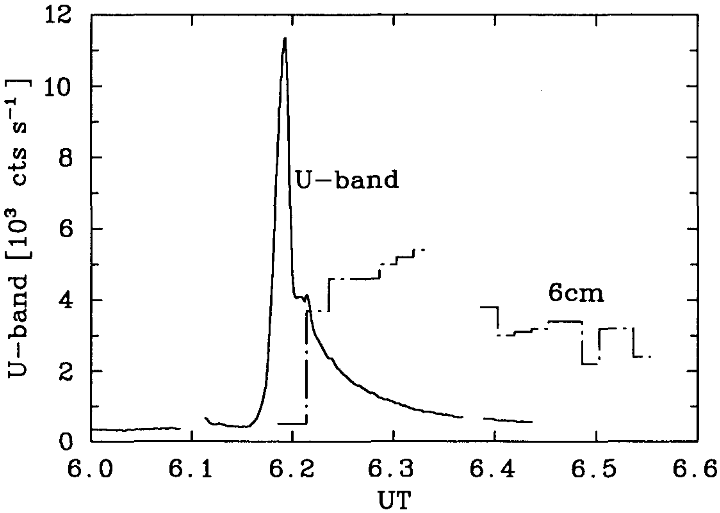

Fig. 1. A typical dMe flare U-band light curve (*continuous line*) (J.G. Doyle, private communication). Note the initially rapid decay followed by a quasi-exponential, and much slower, decay. The 6 cm microwave light curve of the same event is also shown (*broken line*).

wings cannot be explained in this way and gas motions must be assumed. Derivation of unique velocities from optically thick lines, however, must be treated with caution.

2.2 Ultraviolet

All flare stars exhibit quiescent ultraviolet emission line spectra having strong lines characteristic of the solar chromosphere (4,500 K$\leq T_e \leq$10,000 K) and low-to-mid-transition region (10,000 K$\leq T_e \leq$250,000 K) (see Byrne, these proceedinsg). Extrapolating the measured line fluxes at Earth to the star and dividing by the stellar surface area, yields a lower limit to the mean surface flux in each line. Surface fluxes calculated in this way are much higher than the same values for the Sun, even in quiescence.

During a flare all of the lines seen in the quiescent spectrum are enhanced by factors of up to 10. Generally the enhancement factor is greater the higher the excitation of the line, up to the temperature of formation of the C IV resonance lines ($\log T_e \sim 5$). Such behaviour is similar to that seen in solar flares in the same lines (Cohen et al. 1978, Feldman & Doschek 1978) and suggests a generally similar atmospheric structure in stellar and solar flare transition regions.

Stellar UV flares often exhibit strong continua (see e.g. Byrne & McKay 1989, 1990) as in the optical. The integrated energy of such flares may equal that emitted in transition region lines.

2.3 X-rays

dMe flares have mostly been observed in relatively soft X-rays (0.2–2 keV) by satellites such as *Einstein*, *EXOSAT* and, most recently, *ROSAT* and *ASCA*. Where some degree of spectral information is available, spectra may be fitted by 1- or 2-component thermal bremsstrahlung spectra. Maximum derived temperatures of the flaring plasma are similar to solar values and they are seen to cool as the flare progresses. Thus harder X-rays peak earlier than softer.

When simultaneous optical photometry is available, the optical broadband continuum flare is seen to have a faster evolution than the soft X-rays while the variation of the softest X-rays may be even slower than the chromospheric Balmer line component of the light evolution (see e.g. Doyle et al. 1988). This is in general agreement with the schematic behaviour of solar flares (see e.g. Simnett 1986, Fig. 1).

2.4 Energetics

dMe flares, while resembling their solar counterparts in both their time and wavelength evolution, differ fundamentally in their integrated energies. Fig. 2 shows a *cumulative frequency diagram* for optical U-band flares on a typical UV Cet flare star. This diagram plots the integrated U-band energy of flares against the frequency of a flare of that energy or greater. It will be seen that the largest flares have energies of $\geq 10^{34}$ erg in optical U-band alone. Furthermore, flares of energy equivalent to the *bolometric* energy (i.e. energy emitted in all wavebands) of the very largest solar flares, $\sim 10^{32}$ erg, occur at a rate $\sim$1–2 d^{-1}. Table 2 gives some details of the most energetic dMe broadband optical flares yet observed.

In general the total energy budget of flaring decreases towards stars of lower mass. However, the luminosity of these low-mass stars also decreases. As a result in some of these active latest type flare stars, the fraction of their bolometric luminosity emitted as flare visible light rises to $\sim$1%, indicating a very high efficiency of convective energy to magnetic energy.

Table 2. Most energetic stellar flares observed in the optical U-band from dMe and RS CVn stars

Star	Type	Sp. Type	Date	ΔU_{max}	t_{rise}	$\log E_U$	Ref.
V1005 Ori	UV Cet	M0.5Ve	2 Oct '81	3.25	40s	$\geq 34.1^*$	Byrne et al. 1984
YY Gem	UV Cet	M0.5Ve	31 Oct '71	0.71	370s	34.1	Moffett 1974
AD Leo	UV Cet	M4.5Ve	17 Feb '74	–	–	34.0	Ichimura & Shimizu 1978
II Peg	RS CVn	K2IVe/?	17 Aug '89	0.72	43min	$\geq 35.3^*$	Doyle et al. 1992
V711 Tau	RS CVn	G5V/K1IVe	14 Dec '89	0.61	138min	34.9	Zhang et al. 1992

*This flare was still in progress when the observation was terminated by dawn.

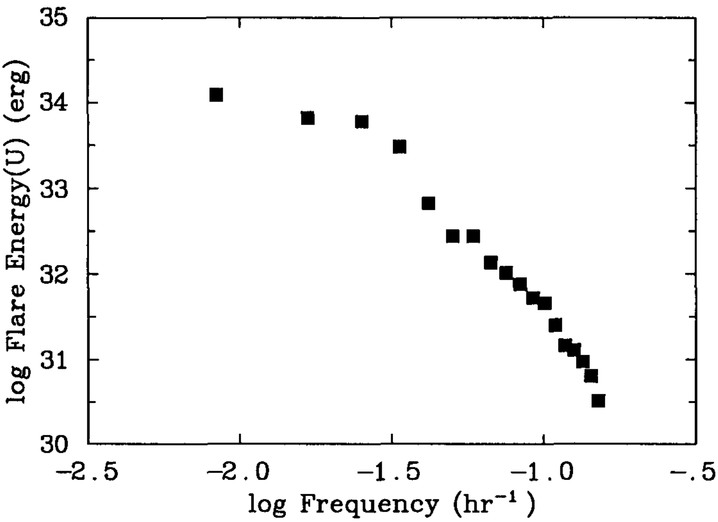

Fig. 2. Cumulative frequency diagram for U-band flares on the dMe flare star, YY Gem, prepared using data from Moffett (1974).

3 Comparison between RS CVn and solar flares

3.1 Optical

Until recently it was believed that RS CVn stars did not flare in broadband optical light. Observations made during the past 5 years, however, have shown this to be false. A small number of very large optical flares have been recorded (Table 2) from a small number of RS CVn stars (Doyle et al. 1992, Zhang et al. 1992). However, the frequency of optical flares is a matter of current debate. Two recent optical studies of the RS CVn star II Peg, appear to be in serious disagreement (Mathioudakis et al. 1992, Byrne et al. 1994). The former claims a rate of optical flaring in agreement with the rate of ultraviolet flares seen with the *IUE* satellite (see below), while the other failed to record any flares in a total observing time about 5 times the mean interval between ultraviolet flares. More recent results (Byrne et al. in prep.) appear to support the latter view, i.e. that broadband optical flares are rare events and are probably only associated with the most energetic flares.

Doyle et al. (1989) have speculated that, in view of the larger atmospheric scale height of the sub-giant active components of the RS CVn stars (compared to dMe's), particle beams, thought to be responsible for heating the chromospheres and photospheres of flares, may be absorbed too high in the atmosphere to yield optical continuum. The exception would be the very most energetic flares, which may produce particles of sufficient energy to penetrate to the upper photosphere/temperature minimum region where white light flare radiation is thought to arise (Aboudarham & Henoux 1986).

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Spectroscopically, as with the dMe stars, chromospheric emission lines such as Balmer H I and Ca II H&K are seen strongly in emission in flare light. They are likewise broadened and show asymmetries, especially to the red. The interpretation of these effects is essentially the same as in the case of the dMe stars.

3.2 Ultraviolet

RS CVn stars are much better observed in the ultraviolet than is the case for dMe stars. This is because of the higher intrinsic luminosity of RS CVn stars, aiding the detection of their quiescent emissions, and the relatively greater energy and longer time scale of their flares.

The quiescent spectra of RS CVn stars exhibit the same chromospheric and transition region emission lines as in the case of the dMe stars. These emissions are enhanced during flares in a qualitatively similar way to dMe flares.

Because of their higher luminosity, even in quiescence, RS CVn stars provide sufficient signal-to-noise to be observed at high spectral resolution in the chromospheric Mg II *h*&*k* resonance lines. This has resulted in the detection of gross line broadening and asymmetries, similar to those seen in optical Balmer lines and usually interpreted as due to systematic mass motions within flares (Doyle et al. 1989). However, because these lines are optically thick, the derivation of velocities from such observations is again highly uncertain.

3.3 X-rays

As is the case in the ultraviolet, the higher luminosity of RS CVn stars has made it easier to observe them in X-rays, both in quiescence and while flaring. It has even been possible to carry out low resolution spectroscopy on some objects.

The general character of RS CVn flares in X-rays is similar to that of the dMe stars. However, as in other wavebands, they are longer in duration and of higher peak luminosity. It is also found that peak temperatures, measured by thermal bremsstrahlung fits to X-ray energy distributions, are considerably higher. This latter result is reinforced by the observation of line emission from very highly ionised species (e.g. Fe XXV) (Doyle et al. 1992).

3.4 Energetics

The most striking difference between solar and RS CVn flares lies in their energy. While dMe flares show total time-integrated energies up to 10^{2-3} times those of large solar flares, RS CVn flare energies are greater by a further factor 10^{2-3}. This has led some authors to consider the possibility that the solar analogue may no longer be applicable in unmodified form. Doyle et al. (1989) have considered the possibility that energy may be extracted from the orbital motions of the binary via tensioning of interconnecting loops between the components of the binary.

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I. Pustylnik: Can you summarize in one ore two sentences whether the observed statistics of flare activity favours more the idea that flares are enhanced by the binary nature of the object or by the rate of axial rotation?

P.B. Byrne: There is no evidence of any difference in the energetics or the frequency of flares between dMe stars in binary systems or in single stars. In RS CVn systems all sources are binaries so the question is nor relevant.

H. Zinnecker: You did not discuss stellar flares with large changes in optical brightness ($\Delta m > 1$). May I ask you to comment on those stellar flares with large amplitudes?

P.B. Byrne: The flares I am discussing ARE large in term of energy. Estimating the energy of flares from the ΔU amplitude alone gives a false impression. This is because the background U brightness changes enormously from the earliest flare stars (=K5 Ve) to the latest (=M6 Ve). Thus, in magnitude terms the same flare on a later type star will have a much greater ΔU.