A REVIEW OF STELLAR FLARES AND THEIR CHARACTERISTICS

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Abstract. We review the flaring activity of stars across the HR-diagram. Brightenings have been reported along the entire Main Sequence and in many stars off the Main Sequence. Some stars are decidedly young, others are in advanced stages of stellar evolution. Flares are common on stars with outer convection zones and outbursts have been reported also on other types of stars, although confirmations are needed for some of them.

Analyses of flare occurrence sometimes find flares to be randomly distributed in time, and sometimes indicate a tendency for flares to come in groups. Preferred active longitudes have been suggested. Recent solar results, where the occurrence rate for flares is found to exhibit a periodicity of 152 days, suggest that stellar flare data should be reanalyzed over long time baselines to see if the present confusing situation can be resolved.

The radiation from stellar flares is dominated by continuum emission and about equal amounts of energy have been recorded in the optical, UV, and X-ray regions of the spectrum. In solar flares strong continuum emission is rarely recorded and a large collection of bright emission lines takes prominence. Small flares occur more frequently than large ones and the latter have longer time-scales. Flare energies can exceed 10^{37} erg. The most productive flare stars are those where the convective envelopes occupy large volumes. Slow stellar rotation rates are believed to reduce the level when the star has been braked significantly from its young rotation rate.

1. Introduction

The term 'flare star' has been used to designate dwarf K and M stars with transient optical brightenings (UV Ceti stars). Objects known to be members of young clusters and star formation complexes were called flash stars or sometimes cluster flare stars. They are mostly of late spectral types, sometimes with affinities to T Tauri stars and related objects. Reports of flaring in a few early spectral type stars gave rise to the term non-classical flare stars (Kunkel, 1975).

In recent years improved detector performance and access to new spectral regions have led to unexpected detections of flare activity in many other kinds of stars. Often the only observation available is a light curve that resembles those seen in classical flare stars. There is only indirect evidence that stellar flares are localized eruptions in magnetic fields as in the Sun, and for some of the flaring objects it is possible that we are seeing atmospheric responses to mass transfer or other dynamical processes. The discovery observations alone never demonstrate beyond doubt that the cause of the observed licht curve is the same as in the Sun. It could be that merely the symptoms are similar.

For these reasons we shall simply apply the principle of recognition when scanning the literature in search of flare stars. Any observation that reminds me, even in an extreme form, of something seen in solar flares or in classical stellar flares is good enough

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to count the star among those that flare. In practice, since we have no spatial resolution when observing stars, I will try to recognize a light curve from its shape, or look for new appearances or enhancements of emission lines on time-scales from minutes to hours. The solar experience allows me to explore many spectral windows: X-rays, UV, optical, and radio. I shall have a relaxed attitude towards the range of some parameters since solar flare analogs on other stars will reflect local conditions there.

In addition to guidance provided by solar flares, a sideview to flaring dMe stars may also prove useful as a background for selection criteria of flaring in other stars. Large stellar flares on red dwarfs last long enough to be time-resolved both spectroscopically and photometrically. In some cases one has succeeded in recording the flare in several spectral windows from X-rays to radio. Several characteristic flare properties have been noted. H I Balmer emission lines are often enhanced over quiescent values before the continuum flux begins to rise in the flare. Emission lines reach their peak flux after the continuum peak. Ca II and Mg II are more delayed than H I Balmer lines. He I follows the higher Balmer lines, while He II emission is very shortlived. During maximum flare emission the lines contribute negligibly to the total flare luminosity in the optical region, beginning at 5% of the U and B band fluxes near flare peak and increasing to 20% during the tail of the flare decay. Only when the continuum component has almost died out does the line flux begin to match that of the continuum, i.e., in the very last stages of the flare. Flare colours show individual changes during the maximum phase, but decay remarkably slowly after flare peak. Stellar flares on red dwarfs are, therefore, predominantly continuum events in terms of energy, but emission lines are enhanced before and well after the continuum component is gone. Contrast effects on the Sun help to mask out the continuum and optical solar flares are studied predominantly in lines.

Estimates from few and scattered stellar flare data in other spectral regions suggest that roughly equal amounts of flare energy are emitted in the optical, ultraviolet, and X-ray windows. *UBVRI* photometry usually gives $3E_U \leq E_{\mathrm{opt}} \leq 5E_U$ (in erg), so $18E_U \leq E_{\mathrm{bol}} \leq 30E_U$ (Pettersen, 1988).

2. Which Stars Flare?

A literature search reveals flaring in many types of stars across the HR diagram (see Figure 1). Identifications and references are given in Table I. Flaring has been reported in a few T Tau stars and in star formation complexes, aggregates, and young open clusters with ages from 3×10^5 years to 6×10^8 years. Several hundred flaring objects have been cataloged in Orion and the Pleiades. Many have been observed to flare more than once. Most young flare stars were detected through multiple exposures with Schmidt cameras, but some were X-ray recordings by Einstein and Exosat. Flares have also been seen on stars close to the Main Sequence and in post-T Tauri stars.

Thus, flare activity starts at an early phase in the evolution of stars, and flaring is a common phenomenon in young stars.

On the Main Sequence, flaring has been reported in all spectral classes from Wolf–Rayet stars and B stars to K and M dwarfs. The largest number of flare stars have

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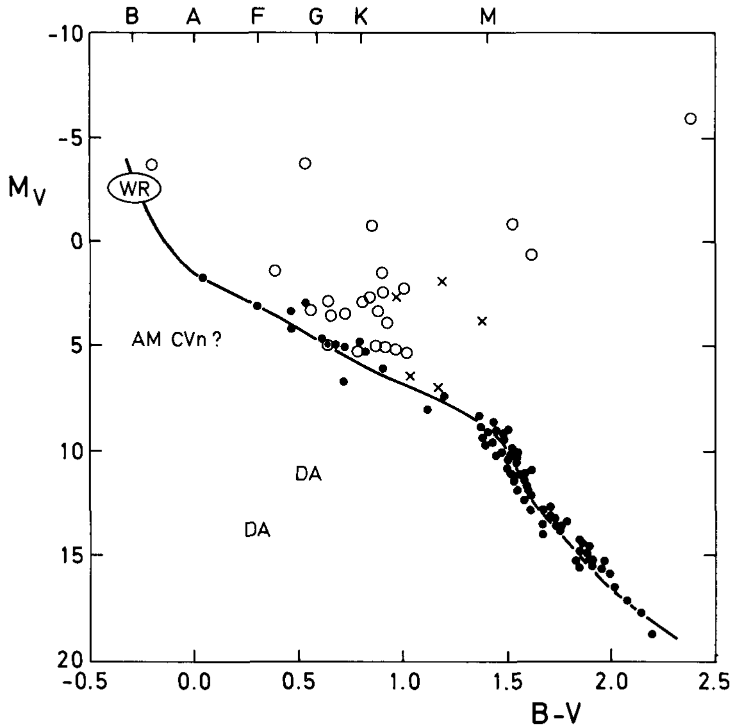

Fig. 1. The positions of some flaring objects in the HR-diagram. Dots are Main-Sequence stars, crosses are young stars and circles are (sub)giants and supergiants at various stages of stellar evolution.

been found among the classical UV Ceti flare stars of spectral types dKe and dMe. Recent years have seen extensions into spectral types G, F, and even A, both in optical and X-ray observations. (Although a couple of the F- and G-type binaries are often referred to as RS CVn systems in the literature (σ^2CrB, SV Cam, XY UMa), we list them here as Main-Sequence stars since both components have luminosity class V. RS CVn stars, where at least one component is a (sub)giant, are listed separately below.) The earliest spectral types on the Main Sequence have flare reports in the optical only, and were listed by Kunkel (1975) as non-classical flare stars.

Thus, flaring has been reported in all spectral classes along the Main Sequence. Flares occur on single stars and on members of multiple systems.

Among the evolved stars and systems the most well-known class of flaring objects are the RS CVn binaries, where at least one component is a subgiant. The presence of chromospheres and coronae have been established by satellite observations, and photospheric starspots are commonly detected by optical photometry. The occurrence of flares in all spectral windows adds to this solar-like picture. In the same region of the HR-diagram we also find stars that are members of Algol and W UMa systems. Both of these are characterized by short orbital periods and small distances between components, so that mass transfer takes place when one component overflows its Roche lobe. FK Com may be an advanced result of this process where one component has

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TABLE I

Stars with observed flare activity

Star type	X-ray	UV	Optical	Radio	References
			Young stars		
T Tau stars	AS 205, DG Tau		DI Cep		7, 21, 27, 68
ρ Oph cloud	several		4 stars		38
Orion ($3–10 \times 10^5$ yr)			482 stars		36
Tau–Aur ($< 10^6$ yr)	several		102 stars		36
NGC 7000 (3×10^6 yr)			67 stars		36
NGC 2264 ($10^5–10^7$ yr)			42 stars		36
Post-T Tau stars	HD 560 B, AB Dor	FK Ser	FK Ser, V4046 Sgr		9, 16, 17, 65, 66
Pleiades (8×10^7 yr)			546 stars		36
Praesepe (3×10^8 yr)			54 stars		36
Coma Ber (3×10^8 yr)			4 stars		36
UMa stream (3×10^8 yr)	π^1 UMa				31
Hyades (6×10^8 yr)	HD 27130		H II 2411, vA 351		45, 53, 64
			Main-Sequence stars		
Wolf–Rayet stars			CQ Cep		26
B-type stars			66 Oph, BD + 31° 1048		2, 42
			HD 160202		4
A-type stars	α Gem		SS 199 II, HD 12211		43, 48, 54
F-type dwarfs	σ^2 CrB		5 Ser, o Aql, HD 137050		1, 5, 41, 64
G-type dwarfs	Sun	Sun	Sun, SV Cam, XY UMa	Sun	44, 74
			κ Cet, RZ Psc, HD 97766		50, 52, 75
K-type dwarfs	BY Dra	BY Dra	BY Dra, EQ Vir^{+++}		46, 47
M-type dwarfs	EQ Peg, YY Gem	AD Leo, V654 Cen	UV Cet, EV Lac^{++}	AD Leo, YZ CMi	46, 47
			Evolved stars and systems		
RS CVn systems	V711 Tau, HD 8357, HD 101379, II Peg, DM UMa	V711 Tau, UX Ari, AR Lac	V711 Tau, SZ Psc, II Peg, AR Lac VY Ari, EZ Peg,	V711 Tau, UX Ari, AR Lac	10, 11, 14, 15, 18, 22, 23, 24, 33, 49, 51, 55, 57, 60, 69
Algols	β Per	(BH CVn)	DI Peg	(BH CVn)	12, 13, (33), 71
W UMa stars	VW Cep		44i Boo, U Peg, W UMa, VW Cep, CN And	VW Cep	19, 20, 25, 30 66, 72
FK Com stars			FK Com		14, 39, 67
Giants			BW Vul, HD 129246/7 α Tau, V654 Her, IU Ori, HD 282773	α Cet	8, 20, 28, 29, 32, 34, 37
Supergiants			ε Aur, μ Cep		3, 40
Systems containing white dwarfs		AY Cet, (λ And)	V471 Tau, G44–32, Case 1, VY Scl, AM CVn		6, 35, 56, 58, 59, 65, 70, 73

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transferred almost all of its mass to the other star. It is not clear whether the flares, seen in X-ray, optical and radio, are directly linked to the mass transfer. Satellite observations again demonstrate the presence of very active chromospheres and coronae, which may be stellar or may be associated with an accretion disk.

A number of late-type giants and supergiants have been reported to flare in the optical and radio. Any event detected on such stars would have to be very powerful (corresponding to flare energies of 10^{34}–10^{39} erg), and none of these stars has been reported to flare more than once.

Other evolved systems are those that contain white dwarfs. The flaring primary star can be a G giant as in AY Cet (λ And could perhaps belong to this class?), or an active K or M dwarf, perhaps with a previous history of mass transfer to the white dwarf companion. From the point of view of atmospheric activity, these stars may be reclassified as (sub)giants or Main-Sequence dwarfs, respectively. The disturbing example is AM CVn, a binary consisting of two helium white dwarfs. It is an open question whether the flares reported have a solar-like nature.

This literature search has demonstrated flaring in young objects contracting towards the Main Sequence, on Main-Sequence stars, and in various types of evolved stars. If we regard reports of single flares as interesting for follow-up studies, but restrict confirmed flare stars to be those where repeated flares have been reported (irrespective of spectral window), the group would be somewhat reduced. Surviving the scrutiny are various age groups among the young stars (T Tau and post-T Tau stars, members of the Orion and Tau–Aur complexes, NGC 7000, NGC 2264, the Pleiades, Praesepe, and the Hyades). On the Main Sequence, 66 Oph (B2e; mass loss instability of disk?) and HD 12211 (A5V + G0V) are early-type stars that have flared more than once. Repeated flaring has been seen in σ^2CrB (F6V + G0V), SV Cam (G3V – K4V), the Sun (G2), HD 97766 (G5), and in a number of dKe and dMe classical flare stars. Among the evolved stars, repeated flaring has been seen in RS CVn systems, Algols, W UMa stars, and FK Com stars, and perhaps in the helium white dwarf binary AM CVn.

A comparison of the HR-diagrams of confirmed flare stars (Figure 2; stars with more than one flare) in clusters of different ages (Orion $\sim 10^6$ years; Pleiades 5×10^7 years; Hyades 6×10^8 years) to that of field stars (Figure 1) reveals that the majority of flare stars in clusters are on or near the Main Sequence. In Orion they cover the spectral classes K2–M2, in the Pleiades K3–M6, and the Hyades F8 – M4. In the Orion and Pleiades diagrams a few stars appear below the Main Sequence. They are either background stars or grossly subluminous. Foreground stars in the direction of nearby clusters can be identified from proper motion studies. None of the clusters show evolved or early-type flare stars. In the Hyades, stars of $M > 2$–$3\ M_{\odot}$ have begun their post-Main-Sequence evolution, while in the Pleiades the turnoff point is near $6\ M_{\odot}$. Since the observations are predominantly photographic (with low time resolution) this may preclude detection of energetic, but low amplitude flare-ups in early type and other intrinsically bright stars.

Thus flaring is confirmed to take place in stars with outer convection zones, on or above the Main Sequence. This includes both young and evolved stars, singles and

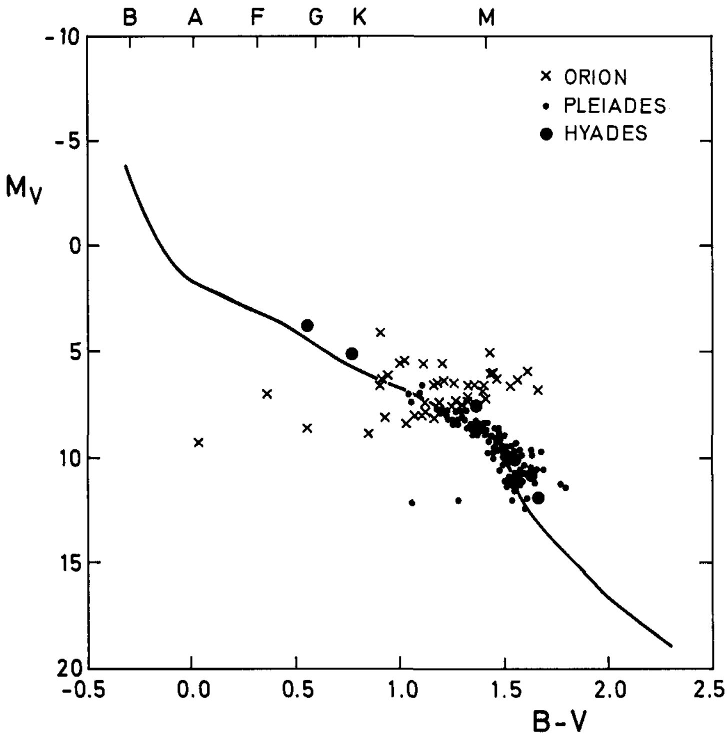

Fig. 2. The HR-diagram for confirmed flare stars in three clusters.

members of binaries. Flaring may take place in other stars as well, but this should be confirmed by further observations.

3. Flare Characteristics

Many stars have been seen to flare only once so typical characteristics can hardly be determined. A similar problem arises for some confirmed flare stars where one flare was seen in optical and another in X-rays or radio. Extensive flare recording has been done for solar neighbourhood dKe and dMe stars, and flare stars in various young clusters and aggregates. These observations show that individual stars span considerable ranges in flare energy, amplitudes, and time-scales. There are notable differences also between some stars. Due to technicalities such as different detection thresholds, limited time resolution, etc., the dominating selection effect in existing observations is that only powerful flares are recorded in intrinsically bright stars. The weak photospheres of intrinsically faint stars allow much smaller flares to be detected, and they occur in much larger numbers than large flares. In what follows we will discuss flare properties in well-observed flare stars, i.e., we consider data for dMe stars, flare stars in clusters, and individual data points for a few evolved stars. The young stars were observed by photographic techniques with Schmidt cameras and suffer from bad time resolution.

3.1. The time distribution of flares

Statistical analyses of flare occurrence for several stars have concluded that flares are randomly (Poisson) distributed in time (Oskanyan and Terebizh, 1971; Lacy, Moffett, and Evans, 1976; Pettersen *et al.*, 1986; Pettersen, Coleman, and Evans, 1984). In contrast to this there have been repeated claims by observers that flares tend to come in groups, and some have found indications of periodic behaviour from time to time. Some data sets, when subjected to statistical analysis, give the conflicting result that flares are not randomly distributed in time (Pazzani and Rodono, 1981; Melikian and Grandpierre, 1984; Pettersen, 1988; unpublished result for UV Cet). Doyle (1987) even suggested a preferred active longitude for flare production on EV Lac over a certain length of time.

Viewed against recent results for the Sun, where the occurrence rate of flares has been found to exhibit a periodicity of about 152 days in many spectral windows (see Bai and Sturrock, 1987, and references therein), it might prove useful to re-analyze stellar flare data over very long time baselines to see if the present confusing situation can be resolved.

3.2. Flare time-scales

More than 30 years ago, Haro and Chavira (1955) noted that flare duration correlated with the spectral type of the flaring star in a cluster, in that short duration flares occurred preferentially on stars of late spectral type. This was eventually confirmed for dMe stars in the solar vicinity, where longer duration flares occurred mostly on the more luminous stars (Kunkel, 1969, 1974, 1975; Pettersen *et al.*, 1984). The functional relationship between $t_{0.5}$, the average decay time from maximum luminosity to half that level, and the absolute magnitude of the star is such that $t_{0.5} \sim g^{-2}$, where g is the surface gravity of the star. This would imply that the average decay time is proportional to the square of the pressure scale height of the atmosphere, so it follows that the star imposes conditions on the flare region in accordance with its size and mass. Gershberg and Shakhovskaya (1973) considered flare brightness and decay rates, and arrived at the alternative conclusion that large flares last longer than small flares, and only large flares are seen on luminous stars due to contrast effects while small flares dominate in number on faint stars.

Sufficient U-filter flare data are now available at each flare energy level to consider this problem. We have arranged the data in order of flare energy, considering windows of width 1 decade in $\log E_u$ (erg). Flares fainter than 10^{27} erg were seen on the intrinsically faintest stars, while the brightest dKe stars showed flares up to 10^{34} erg. Cluster flare stars and evolved stars showed flares up to 10^{37} erg. Stars with less than about 50 recorded flares showed a range in flare energy of 2–3 orders of magnitude, while stars with about 200 observed flares spanned 4–5 orders of magnitude in flare energy. For each window we determined the average flare time-scale for rise and decay ($t_{0.5}$) in units of seconds. The result is shown in Figure 3, which reveals the same basic properties for rise and decay:

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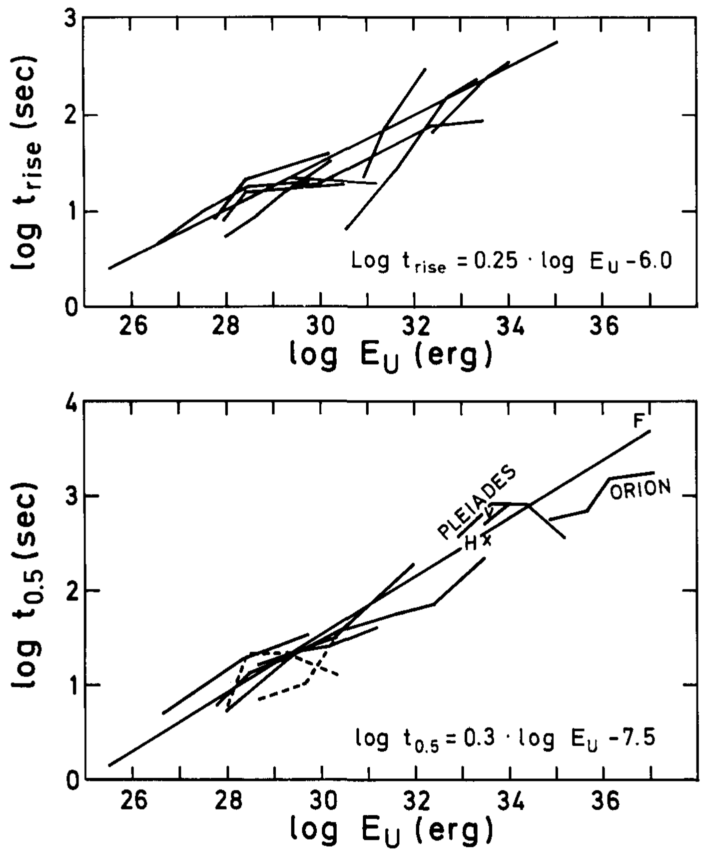

Fig. 3. Relationships between flare time-scales and flare energy. Typical error bars are $^{+0.3}_{-0.7}$ in $\log t_{\rm rise}$ and $\log t_{0.5}$.

(1) Energetic flares are seen predominantly on bright stars due to selection effects.

(2) Large flares tend to last longer than small flares.

It appears that the time-scales of flares are characterizing the flare region rather than the host star. Within each energy window the time-scales of individual flares may span 1–2 orders of magnitude, and the trend is revealed here by considering average time-scales and a large range in energy. Lack of time resolution for cluster flare stars allow us to include them only for the decay time-scale. A few observations of evolved stars do not contradict the trend in Figure 3.

3.3. Flare luminosities

Photometric U-filter monitoring has resulted in numerous flare light curves on the best observed stars. Integration under the flare portions of such time series measurements and subsequent absolute calibration, yields a time average of the amount of radiative energy emitted during the flare, here referred to as the flare luminosity of a star, $L_f(U)$, in erg s^{-1}. Reliable estimates of $L_f(U)$ require a reasonable number of observed flares

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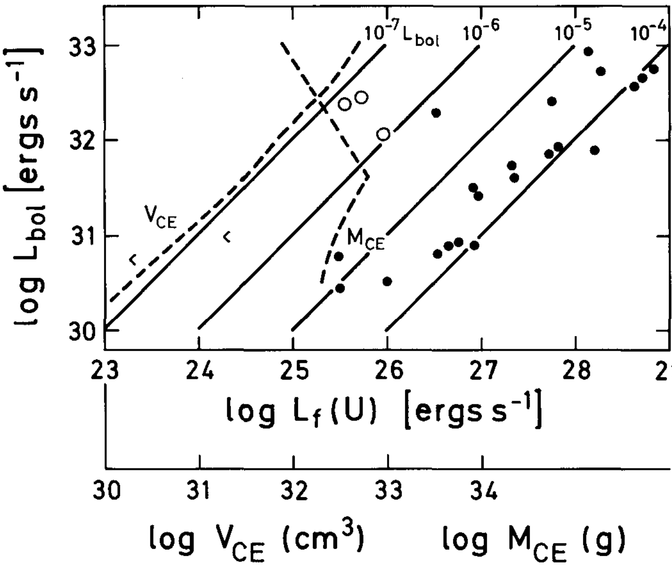

Fig. 4. U-filter flare luminosity of red dwarfs versus their bolometric quiescent luminosities. Also indicated is the run of convection zone mass (M_{CE}) and volume (V_{CE}) for such stars. See text for details.

for each star, say 50. In Figure 4 we have plotted $\log L_f(U)$ for a number of dKe and dMe stars, characterized by their bolometric luminosity L_{bol}. Two important aspects of flare activity are apparent from this figure:

(1) A saturation level for flare activity exists for all stars with $7 \le M_V \le 17$. In the U-filter the maximum amount of flare production is about 10^{-4} of the bolometric radiative output of a star. We estimate that this corresponds to a bolometric flare luminosity of $0.003 L_{bol}$ (Pettersen, 1988).

(2) Many stars are less active than the saturation level. The non-emission line dM stars are 500–1000 times less active than their saturated dMe counterparts. Reduced activity may be a result of age or slow rotation.

It has been shown (Pettersen, 1988) that a change in flare luminosity is due to a change in flare frequency at each energy level, $L_f(U) \sim (N/T)$. It has not been decided if active stars produce larger flares than less active stars. It appears that both classes of stars have the same basic properties, but active stars flare more often at every flare energy level. It, therefore, requires great perseverance (or luck!) to observe a giant flare in a low activity star.

The stars in Figure 4 represent two kinds of structures. Those with $\log L_{bol} > 31.5$ have radiative cores and outer convection zones. Those fainter than $\log L_{bol} = 31.5$ are fully convective. It has been suggested that different types of dynamos are responsible for the generation of magnetic fields on these two types of stars (Rosner, 1980). Flare activity is a result of these magnetic fields, and we note that both bright and faint stars in Figure 4 are capable of producing flares at the saturation level. This suggests that dynamo efficiencies are not very different in the two types of stars, and the smooth decay of the saturation level with bolometric luminosity indicates that the same mechanism is at work in both types of stars. The bolometric luminosity of solar-type stars is proportional to the volume of the star, so it follows from Figure 4 that the saturation level for stellar activity is in some way connected to the size of the star. The often quoted link between atmospheric activity and surface magnetic fields and the convection zone of the star, invites a search for empirical relationships between convection zone parameters and stellar activity parameters.

3.4. Atmospheric activity and stellar convective envelopes

According to Main-Sequence models by Copeland, Jensen, and Jørgensen (1970) the mass of the convection zone increases from less than 0.01 $M_\odot$ for the Sun to a maximum for a fully convective star of 0.3 $M_\odot$. The extent of the radiative core is 0.8 $R_\odot$ in the Sun, decreasing to 0.2 $R_\odot$ (50%) for a 0.4 $M_\odot$ star. The radiative core is nonexistent in stars smaller than 0.3 $M_\odot$. As a result the average density of the convection zone is nearly a linear function of stellar mass and can be approximated by

$$\log \bar{\rho}_{\mathrm{CE}}(\mathrm{g\,cm^{-3}}) = 2.4\text{–}4(M/M_\odot)\,.$$

Thus, there is no correspondence between the mass of the convection zone and the flare luminosity. The run $\bar{\rho}_{\mathrm{CE}}$ is roughly parallel to the run of $L_f(U)$, but in the opposite direction. The most active dMe flare stars have average convection zone densities smaller than those at the lower end of the Main Sequence.

An almost perfect correspondence is found between the volume of the convective envelope, V_{CE}, and $L_f(U)$. The former parameter was computed from Table 2 in Copeland, Jensen, and Jørgensen (1970), using

$$V_{\mathrm{CE}} = \tfrac{4}{3}\pi(R^3 - R_{rc}^3)\,,$$

where R is the radius of the star and R_{rc} is the radius of the radiative core. The latter becomes zero for stars smaller than 0.3 $M_\odot$. When V_{CE} is plotted against the bolometric luminosity of the stars, using the same scales on the axes as in Figure 4, an almost straight line with slope unity results, namely

$$\log V_{\mathrm{CE}}(\mathrm{cm^3}) = \log L_{\mathrm{bol}}(\mathrm{erg\,s^{-1}}) - 0.23$$

for stars between 0.1 $M_\odot$ and 1 $M_\odot$. It appears that the saturated (maximum) flare activity level of a dwarf star is directly proportional to the volume of its convection zone.

Since some stars do not meet such high levels of flare activity, other parameters must also be important in determining the activity levels of individual stars. One such parameter is stellar rotation, since it would influence dynamo action through the component of differential rotation. If stellar rotation slows down with the ageing of stars, this would immediately explain age effects in flare activity.

Figure 5 shows the empirical relationship between flare luminosity and the volume of the convection zone for a number of solar neighbourhood flare stars.

Radii were taken from Pettersen (1980) or relationships derived therefrom, and the sizes of radiative cores were interpolated in the tables of Copeland, Jensen, and

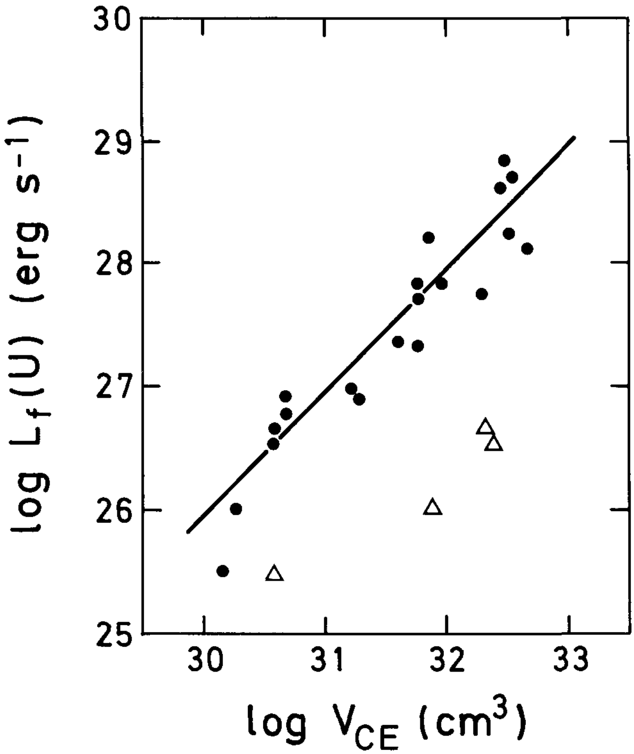

Fig. 5. Relationship between flare luminosity and the volume of the convective envelope, for very active dKe and dMe flare stars. Less active dM stars are indicated by triangles.

Jørgensen (1970). The same kind of relationship can be produced for coronal X-ray luminosity and chromospheric Hα luminosity, outside the flares. It appears that all the common proxies of stellar activity are proportional to the volume of the convection zone for the most active stars. (Similar plots would result if V_{CE} were replaced by the volume of the entire star because the volume of the radiative core is $\leq V_{CE}$ for stars smaller than the Sun, as pointed out by J. H. M. M. Schmitt during the discussion session.) In Figure 6 we have plotted L_x versus V_{CE} for solar neighbourhood flare stars as well as RS CVn stars and one T Tau star. The latter has been assumed to be fully convective, while it is very difficult to estimate the depth of the convection zones in the evolved stars since their ages are not well determined. We have considered their position in the HR-diagram and have interpolated in tables by Novotny (1973). The uncertainties in log V_{CE} must be considerable since even radii are only crudely estimated. There is no doubt that the trend continues to hold for these very active stars, even if the positions in Figure 6 are only approximate. This scenario explains the high level of activity in young pre-Main-Sequence stars since they are rapid rotators, fully convective, and have large volumes since they are still contracting towards their Main-Sequence sizes. On the post-Main-Sequence end of stellar evolution one would expect large convection zones

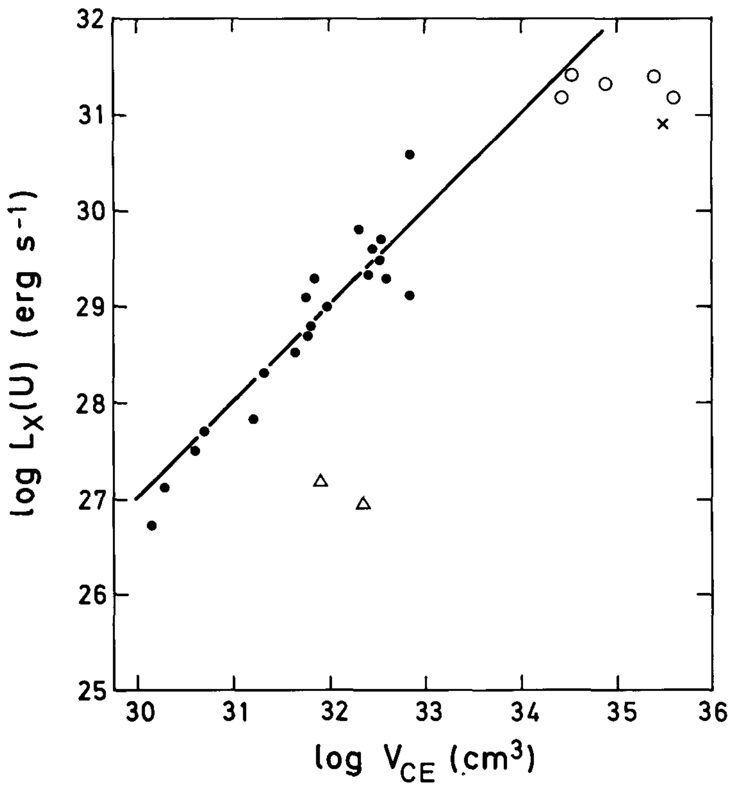

Fig. 6. Relationship between coronal X-ray flux and the volume of the convective envelope. Dwarfs are indicated as in Figure 5. Open circles are RS CVn stars and the cross is a T Tau star.

in giants and supergiants, but volume expansion from Main-Sequence dimensions would greatly reduce stellar rotation rates. Single evolved stars are therefore not expected to show high levels of activity, but members of binary systems that are close enough for synchronization effects to maintain rapid rotation should be very active. One example is the RS CVn class.

4. Conclusions

The main conclusions of this review are:

– Frequent flaring occurs on stars with outer convection zones, on or above the Main Sequence. This includes young as well as evolved stars; singles and members of binaries.

– Flare-like events have also been seen elsewhere in the HR-diagram.

– The time-scales of energetic flares are longer than for small flares, irrespective of host star.

– Studies of flare occurrence as a function of time show contradicting results, sometimes favouring random (Poisson) distributions and sometimes indicating periodic components. Further studies are needed.

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– Atmospheric activity, including flaring, grows with increasing volume of the convective envelope of the host star.

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