STELLAR FLARE STATISTICS – PHYSICAL CONSEQUENCES

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Abstract. The observational data permit us to establish clear statistical correlations between different parameters of stellar flare activity and the characteristics of quiet stars. These relations are:
(i) between energies and frequencies of flares on stars of different luminosities;
(ii) between total radiation energies of flares and quiet stars both in X-ray and Balmer emission lines;
(iii) between flare decay rates just after the maxima and flare luminosities at maxima.

1. Introduction

In the vicinity of the Sun, flare activity similar to that of the Sun has been detected on more than 80 red dwarf stars of spectral classes dK0–dM8 (Gershberg, 1978; Page, 1988). About three dozen of these stars have been studied in detail: more than 2000 optical flares were registered during several thousands of hours of photoelectric patrol observations; the luminosities of quiet chromospheres, transition regions and coronal emission in soft X-rays have been estimated.

The analysis of these data permits us to establish some statistical correlations between activity parameters of stars of different spectral classes. Some of these correlations have clear physical consequences; others we need to understand and take into consideration while developing a general theory of flare activity.

2. Flare Energy Spectra

The energy and temporal parameters of stellar flares show an emormous variety in their duration and intensity. As an example, the data of the EV Lac photoelectric patrol observations carried out at Crimea Observatory in 1986–1987 are shown in Figure 1. Indeed, flares detected on one star have time-scales from several seconds (11 September, 1986, $23^h 25^m$) to many hours (10 September, 1987, $18^h 50^m$–$21^h 20^m$), covering a range of about 3–4 orders of magnitude of the total radiation output. There exists a wide variety of flare light curves: from strongly asymmetric with fast rise and slower decay (11 September, 1986, $19^h 20^m$–$20^h 00^m$) to almost perfectly sinusoidal form (12 September, 1986, $17^h 50^m$–$18^h 20^m$).

The variety of flare forms compels us to use statistics to describe the general properties of flare activity on different stars. 'Mean' characteristics do not fit our goal: these are strongly influenced by observational selection effects – only the most powerful flares can be detected on absolutely brighter stars. We must study the distribution of these characteristics instead of the mean parameters in order to eliminate selection effects. Kunkel (1968, 1975) found one of the first important results for statistical properties of

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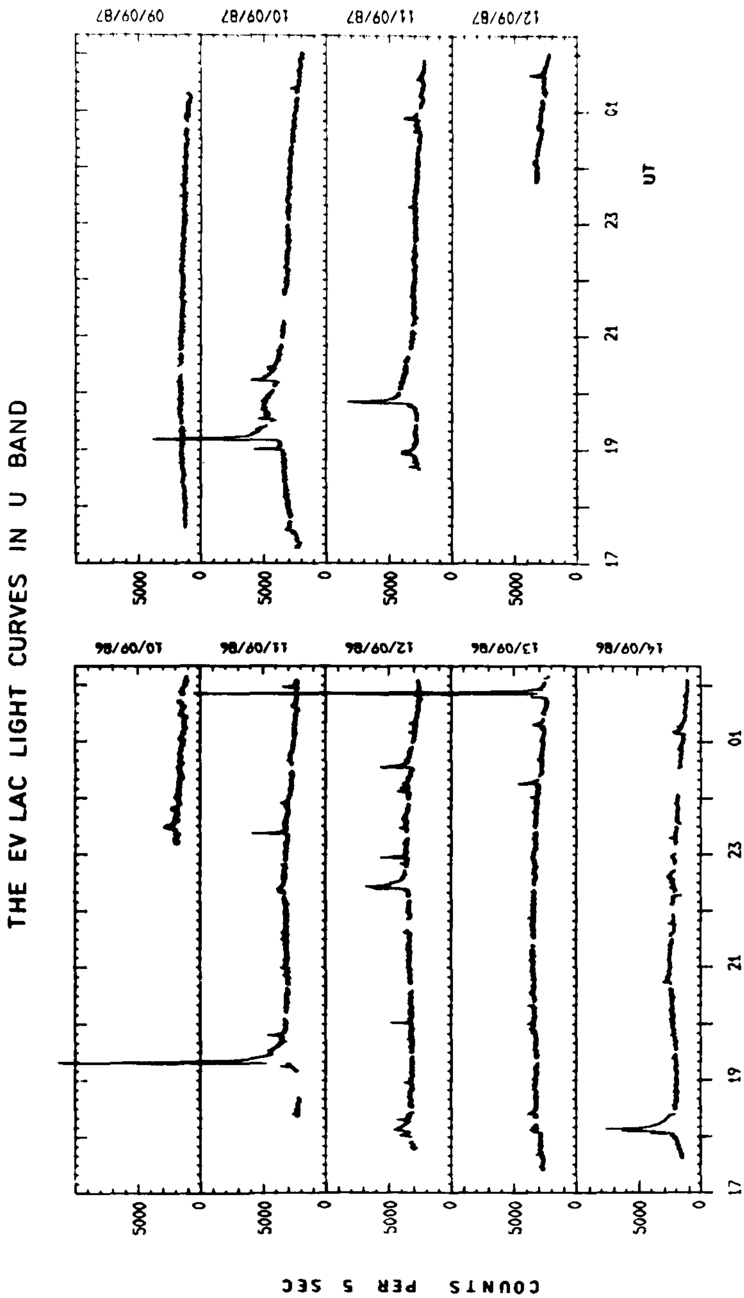

Fig. 1. The photoelectric photometric monitoring of EV Lac in the *U*-band.

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optical flares on UV Cet-type red dwarf stars. He showed that the mean frequency of stellar flares whose luminosity at maximum exceeds the brightness corresponding to the stellar magnitude m, can be given by the simple relation

$$R(m) = 10^{a(m - m_0)},$$

where m_0 is the magnitude of the brightest flare that takes place on the star during a given time interval and a is a coefficient close to a unity.

Later, the time-integrated flare energy at optical wavelengths was considered as the main characteristic of the flare (Lacy, Moffett, and Evans, 1976; Gershberg, 1972) instead of amplitude. In Figure 2, taken from Gershberg and Shakhovskaya (1983), the

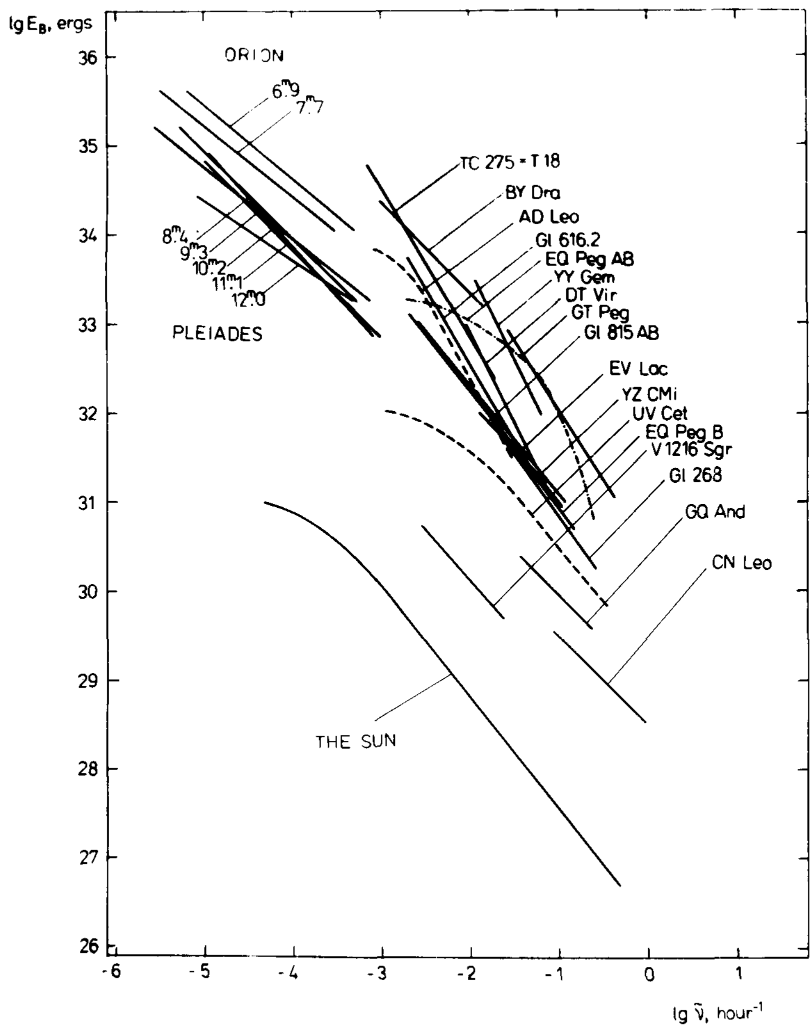

Fig. 2. Energy spectra of flares on red dwarf stars and the Sun. Total energy in the B-band flare radiation, E, is plotted versus frequency $\tilde{\nu}$ of flares with energy exceeding E.

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energy spectra of flares of 23 red dwarf stars in the solar vicinity and several groups of flare stars in clusters are given: the total energy of B-band flare radiation – E (ergs) – is plotted versus frequency – $\tilde{\nu}$ (hr^{-1}) – for flares with energy exceeding E. The magnitudes of the quiet stars and their trigonometric parallaxes from Gliese (1969) were used for conversion of the observed counts of flares into flare energies. In Figure 2, the energy spectrum of solar flares is taken from Gershberg, Mogilevskij, and Obridko (1987) and constructed on the basis of 15 500 flares. Only the upper part of the energy spectra of flares beyond the photometric flare detection threshold – E_{lim} – are presented in Figure 2 (the brighter the star, the higher E_{lim}).

As follows from Figure 2, the observed part of energy spectra of flares of different flare stars and the Sun (overlapping several orders of magnitudes in energy) can be represented by a power function with the spectral index β corresponding to the slope of the straight lines in Figure 2. The spectral indices in the energy spectra of flares have a rather narrow range of values: from 0.4 to 1.4.

The flare energy spectra form a rather narrow band in Figure 2. The upper limit of this band seems to be real and determined by the highest attainable efficiency of optical power in a star of a particular type. The reason for this must be explained in any theory of the origin of flares. The lower boundary of the band is the result of observational selection: flare stars with the greatest activity are those usually observed.

In Figure 3, the values of spectral indices β for flare stars of different absolute stellar magnitude (M_V) are given according to Gershberg (1988). If the binary components were not resolved by photoelectrical observations (e.g., UV Cet, V577 Mon, YY Gem, V1054 Oph, AT Mic, Gl 815 AB) then the value of M_v and the parameters of the flare activity refer to the stellar system. For flare stars in the solar vicinity, there exists a slight ($r = 0.60 \pm 0.14$) correlation between β and M_V: the fainter the star, the larger the β. For the flare stars in clusters, Figure 3 shows that β is an age-dependent parameter; the younger the cluster, the larger the β.

Although the physical meaning of the power-law representation of energy spectra is not yet known, its analytical presentation allows us to estimate some important characteristics of flare activity: namely the maximum energy of the most powerful stellar and solar flares, the intrinsic flare frequency, and the total radiation of optical flares of different stars (Gershberg, 1988).

Pustilnik (1988) has recently proposed that the observed energy spectra are determined by the structure of the photospheric magnetic field in the active regions in a regime of turbulent convection. He derived values of the index of the power law β closely matching those observed, assuming that the energy spectrum reflects the dimensional distribution of turbulent elements.

As Figure 3 indicates, this depends more on the age of the star than on its mass. Possibly, a strong influence of stellar rotation on the structure of turbulent convection leads to this dependence. This problem requires further theoretical and observational investigations.

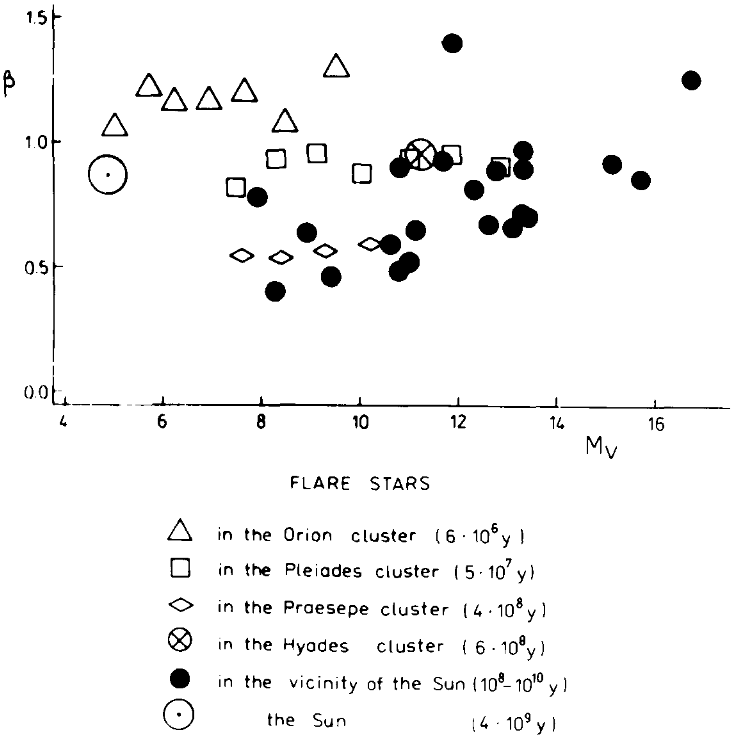

Fig. 3. Spectral indices of energy spectra of flares on red dwarf stars in the solar vicinity and in clusters.

3. Total Radiation of Flares

The time-averaged power of optical radiation of stellar flares L_f(erg s^{-1}) has been computed by the integration of their energy spectra and by conversion of the flare energy recorded in B or U bands into total optical radiation (Gershberg and Shakhovskaya, 1983). If the values of E for the most powerful and weakest flares actually registered in each flare star are used as limiting magnitudes, the integration will yield only the lower limit of L_f. However, if any flare star has a flare energy spectrum from $E = 3 \times 10^{35}$ erg (that is, the strongest flares registered in clusters) to $E = 2 \times 10^{27}$ erg (the weakest flares on the faintest star CN Leo), the real values L_f may be one or two orders of magnitude larger than the lower limits.

In Figure 4, the lower limits of L_f, computed for the stars in the solar vicinity, are indicated by circles together with the time-averaged flares observed by Doyle and Butler (1985) which are indicated by crosses. The symbols corresponding to one star have been connected by straight lines. The lengths of these lines characterize the uncertainty of the L_f values. As in Figure 2, the upper boundary of a region occupied in Figure 4 corresponds to the most active flare stars, while the lower left (unpopulated) corner corresponds to absolutely bright flare stars of low activity, with high thresholds for detection of flares.

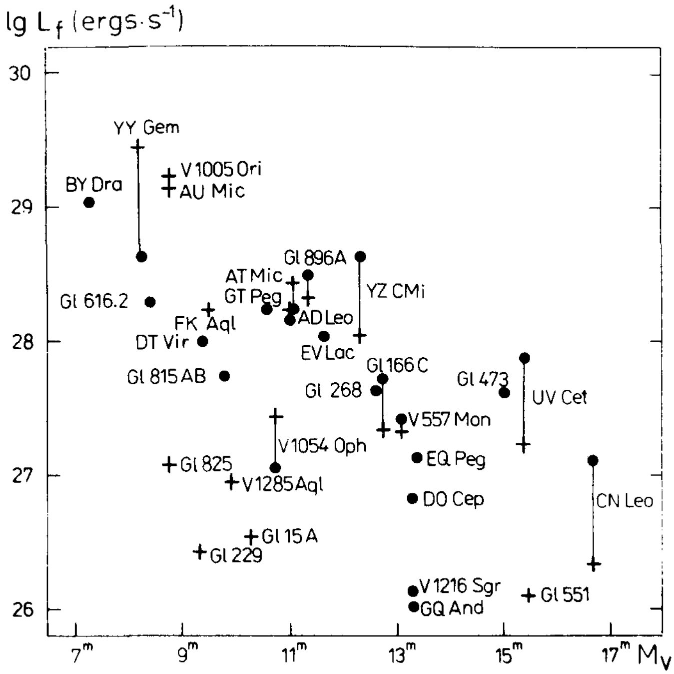

Fig. 4. Time-averaged power of optical radiation of flares, L_f. Circles represent the data by Gershberg (1988), crosses by Doyle and Buttler (1985).

Figure 4 shows that the highest time-averaged optical flare power occurs on the intrinsically bright stars (spectral classes dK5–dM0). According to Gershberg (1985), the intrinsic frequency of flares is also higher for the intrinsically brighter stars, although flares are detected more frequently among fainter stars.

Another important characteristic of a stellar flare activity level is the ratio of L_f to stellar bolometric luminosity: L_f/L_{bol}. In Figure 5, the same symbols as in Figure 4 indicate computed ratios L_f/L_{bol} for the flare stars in the solar vicinity. Values of L_{bol} are taken from Pettersen (1980), when available, otherwise they were computed from M_V using the correlation presented by Agrawal, Rao, and Sreekantan (1986).

Thus, the upper boundary of absolute flare activity level increases from the late M stars to the K5 stars, although a portion of the total stellar energy that is released in flare activity is independent of the absolute magnitude of stars in the range from $7^{m}.6$ to $16^{m}.7$ and reaches 0.1% for the most active stars.

4. Flare Activity and Chromospheric and Coronal Emission

Stellar chromospheres manifest themselves in the optical range by strong emission in Balmer lines. The energy released in these lines for the flare stars, according to Linsky *et al.* (1982), exceeds the total radiation of all other observed chromospheric lines. However, according to Grinin and Katysheva (1980), for conditions approximating

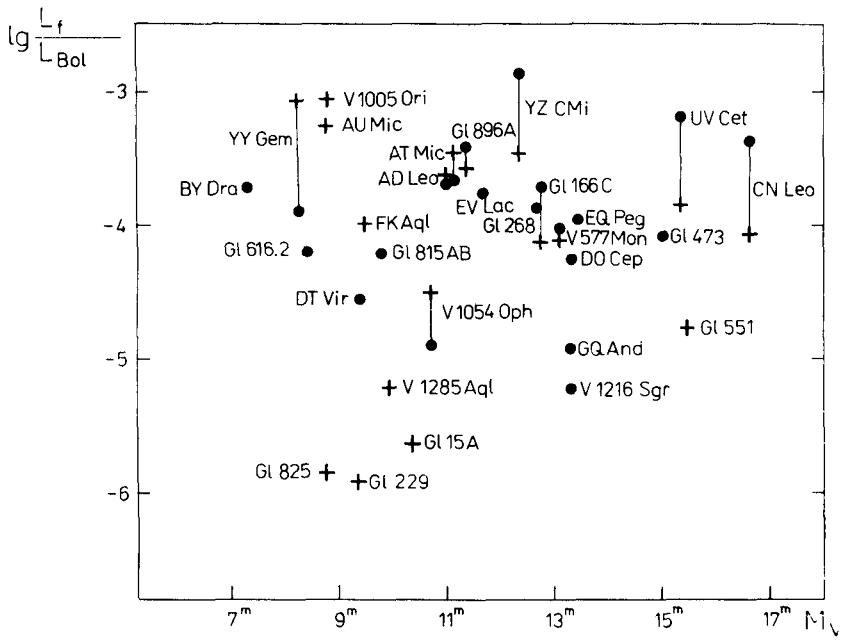

Fig. 5. Ratios of time-averaged powers of the flare optical radiations of flare stars bolometric luminosity. The symbols are the same as in Figure 4.

those of the chromosphere, the Lyman emission may be 1–2 orders of magnitude greater than in the Balmer lines.

For the flare stars, Gershberg and Shakhovskaya (1983) estimated the ratio of energy released in these lines by a stationary stellar chromosphere to the total radiated energy of the star, $L_{\mathrm{Bal}}/L_{\mathrm{bol}}$, and noted that this ratio is close to the value of L_f/L_{bol} and independent of M_V.

We next examine the correlation between L_f and L_{Bal}. In Figure 6, the values of L_f are plotted versus L_{Bal} on a log-log scale for 18 flare stars within the range of M_V, $7^{\mathrm{m}}.6$–$15^{\mathrm{m}}.3$. The symbols are the same as in Figures 4 and 5. The uncertainty of the value $\log L_{\mathrm{Bal}}$ is about ± 0.3 because the flare stars show variability in the intensity of Balmer emission lines, even when photometrically quiescent (Bopp, 1974, Shakhovskaya, 1974b). The symbol $\odot$ corresponds to solar data: the result of Athay (1966) used for the definition of $\log L_{\mathrm{Bal}}$ and L_f has been calculated from the energy spectra of solar flares (Figure 2). The following linear correlation has been found for 18 stars:

$$\log L_f = -6.98 + (1.24 \pm 0.28) \log L_{\mathrm{Bal}}, \tag{1}$$

with correlation coefficient of $r = 0.80$.

The corresponding straight line is shown in Figure 6. The scatter of any star from the line does not exceed the possible observational errors, but the deviation of the Sun from this correlation is significant.

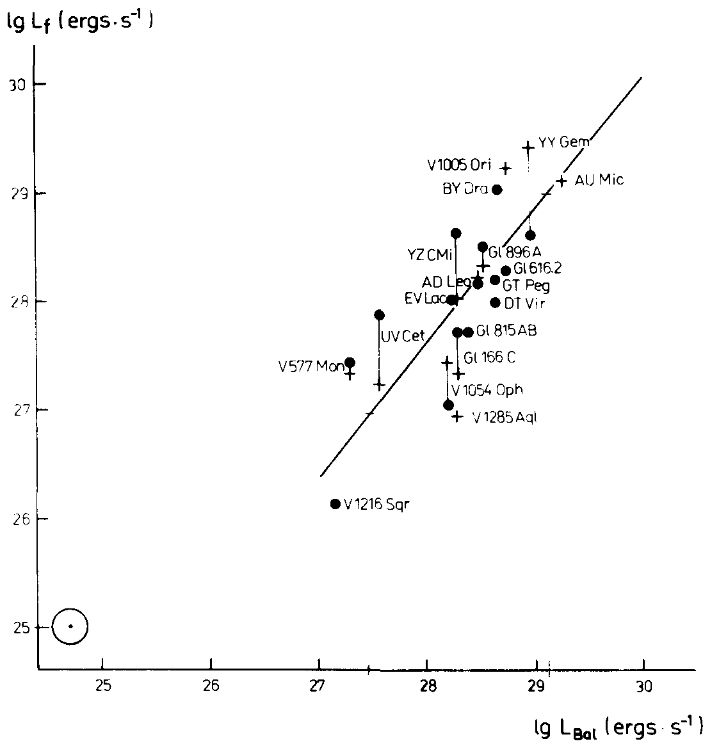

Fig. 6. A plot of the time-averaged powers of optical radiation of flares, L_f, versus the total radiation in Balmer lines of quiet chromospheres, L_{Bal}. The symbols are the same as in Figure 4.

Gershberg and Shakhovskaya (1983) showed, that the ratio of coronal soft X-ray emission L_X (erg s^{-1}) to L_{bol} is close to L_f/L_{bol} and $L_{\text{Bal}}/L_{\text{bol}}$ and also independent of M_V. Later, Doyle and Butler (1985) found a linear correlation between $\log L_f$ and $\log L_X$. In Figure 7, this correlation is presented for a larger body of data than that of Doyle and Butler (1985): the estimates of L_X by Agrawal, Rao, and Sreekantan (1986) and L_f values have been added. The symbols are the same as in Figures 4–6. The L_f value for the Sun has been adopted from Ambruster, Sciortino, and Golub (1987). The following linear correlation has been found for 23 flare stars:

$$\log L_f = 4.8 + (0.80 \pm 0.17) \log L_X , \tag{2}$$

the correlation coefficient being $r = 0.81$. The corresponding straight line is shown in Figure 7.

The deviation of any star from this line does not exceed possible observational errors, although the Sun deviates somewhat from this correlation.

The slopes of lines (1) and (2) are close to unity, so the ratios L_f/L_{Bal} and L_f/L_X are constant within the range of M_V under consideration. This fact was also noticed by Doyle and Butler (1985) for correlation (2), found on the basis of a smaller data sample. To compare the energy losses by flares, Balmer emission of the chromospheres and soft

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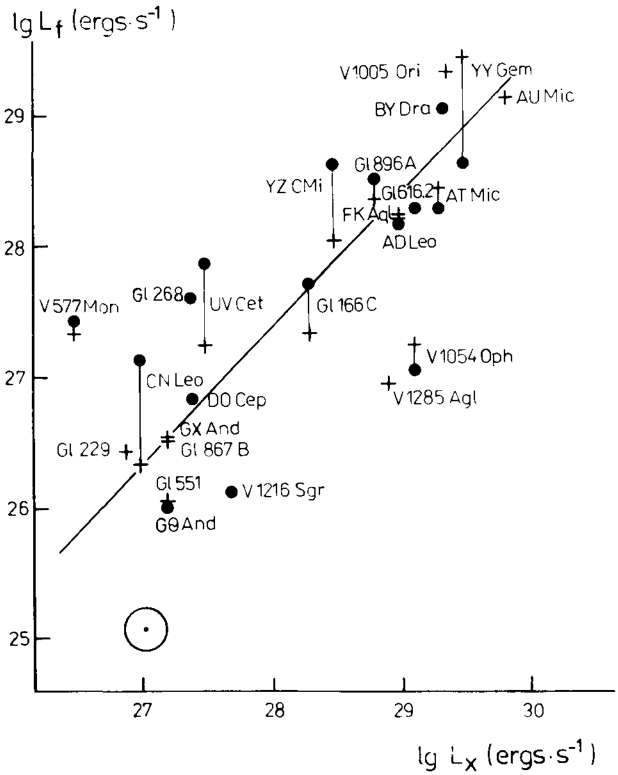

Fig. 7. A plot of the time-averaged powers of optical radiation of flares, L_f, versus the 'quiescent' X-ray flux, L_X. The symbols are the same as in Figure 4.

X-ray coronal emission, the following mean ratios have been calculated:

$$\log \frac{L_f}{L_{\mathrm{Bal}}} = -0.4 \pm 0.1 \quad \text{(for 18 stars)},$$

$$\log \frac{L_f}{L_X} = -0.6 \pm 0.2 \quad \text{(for 23 stars)}, \tag{3}$$

$$\log \frac{L_{\mathrm{Bal}}}{L_X} = -0.2 \pm 0.2 \quad \text{(for 14 stars)}.$$

The corresponding ratios for the Sun: $\log L_f/L_{\mathrm{Bal}} = -1.7$; $\log L_f/L_X = -2$ differ from (3) significantly. The ratios (3) are compatible with the ones estimated earlier by Gershberg and Shakhovskaya (1983) on the basis of a smaller data sample.

Doyle and Butler (1985) and later Butler *et al.* (1986) proposed that the tight linear correlation of L_f and L_X suggested that stellar microflares might be the dominant heating mechanism of late-type stellar coronae. However, Beskin *et al.* (1988) and Ambruster, Sciortino, and Golub (1987) present arguments against that supposition. The energy

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contribution of microflares can be calculated by integrating the flare frequency power law of the energy spectra of flares down to very low energies. Assuming that the true value $E_{\min}$ is about 10^{25} erg, then the microflare energy contribution to the observed L_f value is significant (about 50%) only for stars later than M5, where $\beta = 1.3$–1.4 (Figure 3). For the brighter stars with $\beta = 0.7$, the contribution of microflares to L_f is less than 10%. According to the ratios (3), it will not be enough to heat the coronae. Furthermore, following Figure 6, a tight linear correlation exists between L_f and L_{Bal} indicating that the energy of microflares is sufficient to heat the chromosphere. But if the contribution of microflares is significant for faint stars, one might expect some decay of the L_f/L_X for bright stars, which is not confirmed by the observations.

On the other hand, Beskin *et al.* (1988) compared the values of the total radiation of microflares and individual flares using direct observations of flare stars with a time resolution of 3×10^{-7} s carried out at the 6-m telescope. The authors selected small patches of light curves, free from any trace of individual flares, and estimated the upper limit of the variable component, assuming that this component has a gradual fluctuation with characteristic time 1–10 s. Compared with the L_f value found for individual flares, the upper limit of the microflare power is markedly lower. Thus, the heating of coronae by stellar microflares is unlikely to be effective.

One might add to the correlation (1) and (2) the tight linear correlations between L_X and the transition region line luminosity, as well as between L_X and the luminosities of chromospheric Mg II lines found by Agrawal, Rao, and Sreekantan (1986). Evidently, all these correlations suggest that in the flare stars, all these kinds of radiation are physically related and that there exists a common heating mechanism in which the portions of energy released in these radiations are dependent neither upon the total energy of this mechanism nor upon the absolute magnitude of the star.

The quantitative similarity between luminosities of optical flares, chromospheres and coronae, proposed by Gershberg and Shakhovskaya (1983), remains to be explained.

5. Flare Decay Rates

Since flares occur on stars of different absolute magnitudes, we have the opportunity to study the correlation between stellar atmospheres and the rate of flare physical processes. The first result in this direction was obtained by Haro and Chavira (1955). They showed that the duration of flares on stars in clusters depends on the spectral class of the star: the later the type of the star, the shorter the flare. Later, Kunkel (1969a, b) confirmed this correlation for stars in the solar vicinity and supposed that this is a consequence of the physical dependence of flare decay rates on physical conditions in the stellar atmosphere. However, Gershberg and Shakhovskaya (1973) and Shakhovskaya (1974a) showed that there exists a strong observational selection effect on these correlations: flares of lower luminosities have been observed on less luminous stars only, and weaker flares are shorter.

In Figure 8, the absolute luminosities of flares at maxima $L^{\max}$ (erg s^{-1}) are compared with the decay rates just after flare maximum ($-\mathrm{d}L/\mathrm{d}t$) (erg s^{-2}). Photoelectric observations of flare stars in the U band have been used. To the 28 flares studied by Shakhovskaya (1974) we have added 66 flares observed with time resolution of 3×10^{-7} s by Beskin *et al.* (1988) and 37 flares with time resolution of about 10 s by Bruevich *et al.* (1980) and Iljin (1987). Figure 8 shows the symbols for different stars as a function of their absolute magnitudes M_V and the numbers of flares utilized. Only the observation with time resolution 3×10^{-7} s, marked by the letter R, have been used for the analysis of the correlation between $L_U^{\max}$ and $(-\mathrm{d}L_U/\mathrm{d}t)$. For each of two stars with the most numerous flares (V577 Mon, Wolf 424 = FL Vir), a linear correlation between $\log L_U^{\max}$ and $\log(-\mathrm{d}L_U/\mathrm{d}t)$ was sought. The difference in regression equations obtained was random with a probability of more than 90%. The flares on the other stars, UV Cet and CN Leo, are consistent with these equations. The regression equation for all the 66 flares of these four stars is

$$\log \frac{\mathrm{d}L_U}{\mathrm{d}t} = 3.22 + (0.84 \pm 0.06) \log L_U^{\max} \qquad (4)$$

with $r = 0.77$. The corresponding straight line (4) is represented in Figure 8.

Individual flares, observed with lower time resolution are not inconsistent with this correlation (4), but a thorough analysis shows that there exists a systematic shift of these

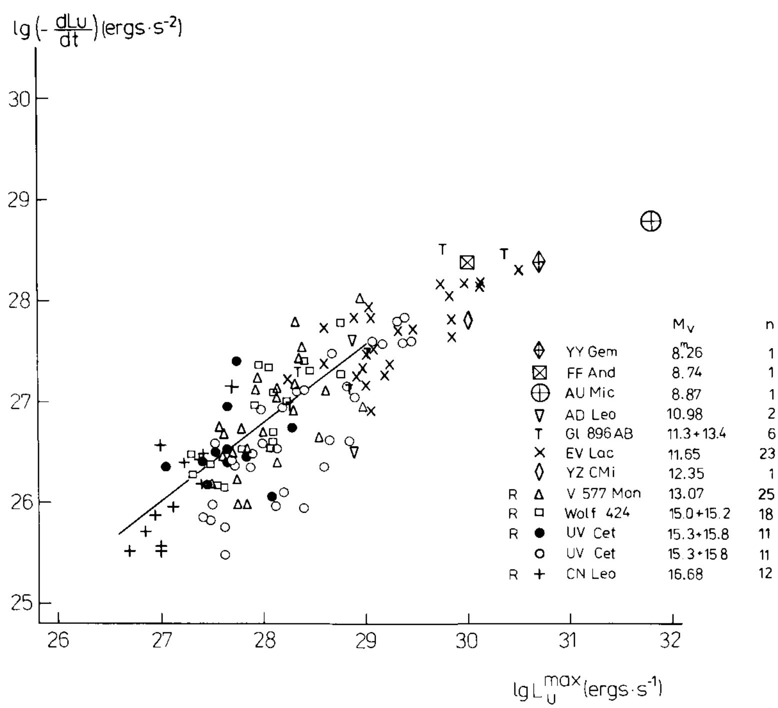

Fig. 8. The comparison of the absolute luminosities of flares at maximum, $L_U^{\max}$, and decay rates just after the maximum, $(-\mathrm{d}L_U/\mathrm{d}t)$, in the U-band.

flares relative to Equation (4) having the value $\log(-\mathrm{d}L_U/\mathrm{d}t) = -0.15$. This spurious displacement is connected by the difference in time resolution.

We conclude that statistical relations between flare luminosities at maxima and flare decay rates exist covering the range of absolute magnitudes of flare stars from $M_V = 8^{\mathrm{m}}.3$ up to $M_V = 16^{\mathrm{m}}.7$. In other words, the flare decay rate is independent of stellar luminosity. The physical implications of this correlation are not yet clear.

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