# FLARES OF RED DWARF STARS AND SOLAR ACTIVITY

R. E. GERSHBERG
*Crimean Astrophysical Observatory, U.S.S.R.*

**Abstract.** The UV Cet-type star flares and the chromospheric flares of the Sun have many important common features. Both types of events are very transient; they occupy only small parts of the stellar surfaces; in both cases the optical as well as the radio emissions of the flares have strong similarities in temporal and spectral characteristics. Evaluations of electron temperatures, electron densities and the general character of mass motions within radiating gas in the stellar flares also display similarities to solar flares. The solar and stellar atmospheres where the flares develop have many important common characteristics too: the existence of hot chromospheres and coronas above much colder photospheres, the absence of noticeable dust envelopes, the photospheres patched with dark short-lived spots, and some periodicity in spot appearance over several years. The facts permit one to identify the processes which take place during separate solar and stellar flares and which are responsible for the solar and stellar activities in total. From this point of view some general problems of physics and evolution of red-dwarf flare stars are discussed.

The idea of a physical similarity between the flare activity of red dwarf stars and the solar activity is not a new one. It has being discussed since the very beginning of flare star study – see Kron (1950); Greenstein (1950); Unsöld (1955); Petit (1958); Struve (1959); Schatzman (1959). Some general considerations on the physical relationship between processes that lead to high excitation emission lines to appear in spectra of cold stars and a mechanism which is responsible for the very existence of the solar chromosphere and corona have been suggested by Shajn (1945) even before the beginning of spectral investigations of red dwarf flares; apparently, he was one of the first who realized clearly the inadequacy of the radiation transfer theory within an LTE-hypothesis framework to understand a situation on a stellar surface and who connected a mass motion within outer regions of cold stars and the Sun with a non-equilibrium radiation from these layers of stellar atmospheres.

Since that pioneer work a lot of new important observations of flare stars have been carried out. On the other hand, during the last 20–30 yr, mainly under the influence of solar researches, astrophysics has been enriched with new ideas and conceptions: the convective envelope theory, magnetohydrodynamics, plasma theory, and now many events of the solar activity have relatively complete physical interpretations. This stimulates an attempt to construct a flare star activity model that would be able to represent the total variety of up-to-date observations of these nonstationary objects.

In this introductory report on flare stars, I should like firstly to compare stellar and solar flares, secondly to compare conditions in stellar and solar atmospheres where these violent events originate, and finally to consider some common problems of the solar and red dwarf flare activity. I intend to describe the up-to-date state of problems and to touch on their formation history to a small extent only.

In starting a comparative examination of stellar and solar activities, I must remind you that at optical frequencies we receive from the Sun energy $10^{14}$ times greater than that from the nearest flare stars. Therefore the investigations of the solar activity and

*Sherwood and Plaut (eds.), Variable Stars and Stellar Evolution,* 47–64. *All Rights Reserved.*

stellar variability have been carried out with highly different techniques; as a result, estimations of the same parameters have usually been obtained with highly different methods and therefore we cannot in all cases approach the required degree of comparability for such estimations.

## 1. Flares on Red Dwarf Stars and Chromospheric Flares on the Sun

### 1.1. TRANSIENCY AND LOCAL ORIGIN OF FLARES

A transiency of a solar chromospheric flare and its localization on a small part of the solar disc are detected immediately by visual observations in a proper spectral line: during $10^2$–$10^3$ s a bright region ranging from $10^{-4}$ to $10^{-3}$ of the solar disc appears (de Feiter, 1973), the brightness and the area of a flare increasing roughly in synchronous manner. When observing a star photometrically, we have no possibility of separating the effect of a brightness increase within some regions from the effect of the increasing of the area of the flare and we fix only a total brightness variation of the star. Such light curves of stellar flares correspond to integral light curves of solar flares that have been obtained recently by Tallant (1970) with a special television 'videometer'.

As a rule a stellar flare approaches maximum for several seconds or several tens of seconds; however in some known cases, a photometer with a time constant of about 1 s has registered momentary culminations of flare brightness (Gershberg, 1972). Immediately after a flare maximum, the brightness decay rate is usually 1.5–3 times smaller than the brightness rise rate before the maximum, but a total brightness decay time for a typical stellar flare is usually one order of magnitude longer than the brightness rise time. The same situation exists for the solar flares. Although among flares on considered UV Cet-type stars we have flares with rise times more than 10 min and with total durations of an hour and longer; in general flares on UV Cet-type stars are characterized by a time scale that is one order of magnitude less than the solar flare time scale.

We do not see the disc of a flare star, therefore all arguments in favour of local origin of stellar flares are indirect ones. The main among them is the existence of cold stellar atmosphere characteristics (strong absorption TiO bands, Ca I 4227 Å line, etc.) in stellar spectra during a flare. These spectral features cannot originate in the same volume where helium and hydrogen emission lines of the flare are generated, and the general character of spectral variations of UV Cet-type stars during flares suggests the idea of a photometric addition of an independent flare spectrum to a permanent spectrum of a quiet state of the star. Therefore, either a flare occupies a small part of the stellar surface or it develops within high layers of the atmosphere and does not affect the cold photosphere. However sizes of flare stars' surfaces are not less than 1–2 light seconds, but several flares have been noted to approach maxima quicker than for a second, and so stellar flares are really local events.

Another important argument in favour of local origin of the stellar flares is the existence of nearby flares that are reminiscent of solar sympathetic flares. Moffett

(1973a) has recently registered 4 separate flares within 12 min on the star Wolf 424; Bopp and Moffett (1973) have suspected a connection between two strong flares on UV Cet itself. Statistical investigations by Oskanian and Terebizh (1971) also give support in favour of the existence of stellar sympathetic flares: in general, the times of UV Cet's flares occur according to Poisson's law, but the number of very close flares is noticeably higher as compared to the expected number for such a distribution.

It should be noted that Gordon and Kron (1949) were the first to propose the local origin for the UV Cet-type star flares – 'a hot spot on a cold star' hypothesis. Evaluations of spot sizes and spot temperature have been obtained many times in the framework of this hypothesis and on the basis of photometric and colorimetric observations of flares. However, in these calculations, an equilibrium of the radiation from a quiet and an excited stellar photosphere has been assumed, and later spectroscopic evidence on non-equilibrium flare radiation undermined confidence in these evaluations.

### 1.2. NON-EQUILIBRIUM OF FLARE OPTICAL RADIATION

The optical radiation of solar and stellar flares is highly non-equilibrium: it cannot be even approximately represented by black-body radiation since numerous strong emission lines and a noticeable emission Balmer jump are displayed in flare spectra. In contrast to such classical objects with non-equilibrium radiation as planetary nebulae whose spectra can be represented correctly enough by radiation of an isothermal steady gas of a small optical thickness, in stellar and solar flares case we have no ground to suppose either isothermity or stationarity of radiating gas, or its transparency at optical frequencies.

Really, stellar flares' spectra obtained at the McDonald Observatory and in the Crimea (Kunkel, 1967; Gershberg, 1970; Gershberg and Shakhovskaya, 1971; Kulapova and Shakhovskaya, 1973; Bopp and Moffett, 1973) display essential variations during flare developments. At the UV Cet-type flare brightness maxima, hydrogen, calcium and neutral helium emission lines are very strong; sometimes He II 4686 Å and Mg I 5184 Å are seen in emission. During a flare fading, helium lines disappear first of all but enhanced Ca II lines are observed sometimes for an hour after wide-band photometry traces of the flare have disappeared. At flare maximum, emission lines are wide and often asymmetrical; continuum emission is strong and in the most powerful flares it fills the absorption spectrum to such an extent that the strongest absorption line Ca I 4227 Å disappears completely. All these variations have analogies in optical spectra of the solar flares (Severny, 1964; Švestka, 1972; de Feiter, 1973).

### 1.3. RADIO EMISSION OF FLARES

As known, UV Cet-type flare stars were the first stellar objects after the Sun from which radio emission was detected. To date, strong radio emission from the flares of red dwarfs has been registered in the range from 20 cm to 15 m (Lovell, 1971). According to Spangler *et al.* (1974), a radio receiver sensitivity of about 0.3 f.u. in the meter wave length range is sufficient for a mean occurrence rate of radio flares to approach to a mean occurrence rate of optical flares in the same flare star being monitored with an optical telescope of moderate size.

Assuming that the radio radiating region is comparable to the stellar disc, Lovell has obtained for UV Cet itself a flare brightness temperature at 240MHz approaching $10^{15}$ K. Radio observations of stellar flares in the Orion cluster (Slee and Higgins, 1971) have displayed even higher brightness temperature, up to $10^{18}$–$10^{20}$ K. Spectral indices of radio flares and temporal relations between optical and radio flares for most UV Cet-type star radio flares are similar to solar radio noise storms. However we know cases when the flare radio emission has clearly displayed a frequency drift to lower frequencies that is analogous to the feature of the solar type II radio bursts. The energy ratio $E_{\text{radio}}/E_{\text{optical}}$ within stellar flares is seemingly close to that of the solar flares (Lovell, 1971).

## 1.4. ESTIMATIONS OF PHYSICAL CONDITIONS WITHIN REGIONS WHERE OPTICAL FLARE RADIATION ORIGINATES

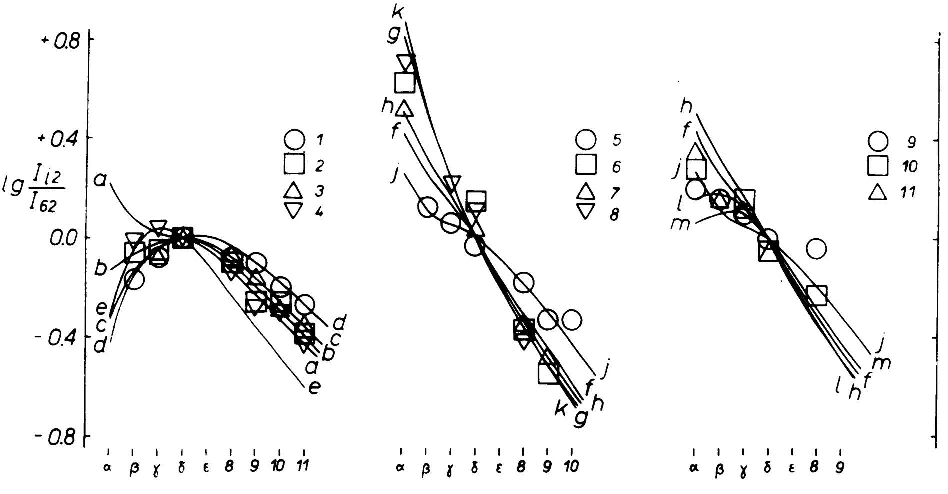
### 1.4.1. *Electron Temperature*

The existence of strong emission Ca II and He II lines in flare spectra leads to the conclusion that the temperature of a radiating gas within flares ranges from several times $10^3$ to several times $10^4$K. In regions where hydrogen radiates effectively, an upper limit of $T_e$ may be found from the magnitude of the Balmer emission jump. Kunkel (1967) has obtained $D_B = 0.64$–$0.76$ for three flares; Crimean spectral and photometric observations (Gershberg and Shakhovskaya, 1971; Chugainov, 1972a) have given for other flares on the same stars AD Leo and EV Lac $D_B \approx 0.15$ near brightness maxima and an increasing $D_B$ to 0.43 during flare decay. If the Balmer jumps observed are interpreted within the framework of a pure recombination emission, then $D_B \lesssim 0.15$ leads to $T_e > 80000$K and Kunkel's magnitudes lead to $T_e$ ranging from 20000 to 25000K. The increase in the Balmer jump during flare decay is naturally to be linked to radiating gas cooling. Therefore in general the temperature regime within stellar flares coincides with temperature conditions within chromospheric flares at the Sun (Severny, 1964; Švestka, 1972).

### 1.4.2. *Electron Density*

Three independent methods have been used to evaluate $n_e$ within stellar flares. In flare spectra of high resolution, the Balmer series have been observed to $H_{10}$–$H_{14}$ (Kunkel, 1967; Greenstein and Arp, 1969; Gershberg, 1974a), and the classical spectroscopic Inglis-Teller method gives an upper limit $n_e$: $3 \times 10^{14}$–$4 \times 10^{15}$ cm$^{-3}$. Another, photometric method is based on the hypothesis that flare decay rates are determined only by a recombination rate in hydrogen plasma that is ionized at the very beginning of a flare; different modifications of the photometric method give $n_e \leqslant 10^{11}$ cm$^{-3}$.

Recently a new method has been proposed to evaluate $n_e$ for a hydrogen plasma from the observed emission Balmer decrement (Gershberg and Shnol, 1974); the method is based on Sobolev's (1947) idea of calculating the amount of radiation from an optically thick gas using escape probabilities. A hydrogen plasma that is not affected by any external radiation field and within which excitation and ionization are determined by electron collisions and by internal radiation field only has been considered; for such a plasma the Balmer emission decrement is determined by three independent parameters: $T_e$, $n_e$ and $\beta^0_{21}$, where $\beta^0_{21}$ is the L $\alpha$ quanta escape probability that is connected to the optical thickness in the lines and to a velocity gradient of inner motions in the radiating gas. It is seen in Figure 1 (from Gershberg, 1974a) that by assuming some $T_e$ one can select pairs ($n_e$, $\beta^0_{21}$) such that calculated decrements will represent observations well enough. During the preparation of the above cited paper, 11 flare spectra for AD Leo, EV Lac and YZ CMi with measured relative intensities for 4 or more lines were available and all these observations are represented using this model. $n_e$ and $\beta^0_{21}$ determinations have a formal precision of about a factor 1.5–2, and $n_e$ is within a range from $10^{12}$ to $10^{14}$ cm$^{-3}$. Recently Bopp and Moffett (1973) have published spectral observations for two flares of UV Cet itself. During the stronger one, they have obtained 2 spectrograms in which they have measured relative intensities for 4–5 Balmer lines; respective observed decrements can be represented within a framework of the theoretical model considered if $T_e = 20000$ K, $\beta^0_{21} = 10^{-4}$ and $n_e = (3\text{–}8) \times 10^{13}$ cm$^{-3}$.



1 }
2 } EV Lac 11.12.65.
3 }
4 }
5 EV Lac 12.7.66.
6 YZ CMi 15.1.69. I
7 YZ CMi 15.1.69. II
8 YZ CMi 18.1.69.
9 } AD Leo 2.3.70.
10 }
11 AD Leo 18.2.71.

| $T_e$ | 20000° K | | 15000° K | |
|---|---|---|---|---|
| $n_e$ \ $\beta^0_{21}$ | $1 \cdot 10^{-4}$ | $3 \cdot 10^{-5}$ | $3 \cdot 10^{-5}$ | $1 \cdot 10^{-5}$ |
| $1 \cdot 10^{12}$ | g | | k | |
| $3 \cdot 10^{12}$ | f | a | h | j |
| $1 \cdot 10^{13}$ | m | b | l | |
| $3 \cdot 10^{13}$ | | c | | |
| $1 \cdot 10^{14}$ | e | d | | |

Fig. 1. Observed relative intensities of the Balmer lines in spectra of UV Cet-type star flares (numbered signs) and calculated Balmer decrements for optically-thick line hydrogen plasma (lettered solid lines).

Therefore, the range in $n_e$ found spectroscopically in stellar flares overlaps the solar $n_e$ range (Švestka, 1972) and spreads to some higher densities. Optical thicknesses in H$\alpha$ line for solar and stellar flares are also similar.

### 1.4.3. *Mass Motion in Flares*

Chromospheric flares on the Sun are closely associated with very different macroscopic motions in the radiating masses (Öhman, 1968), and we have a vast quantity of information on these motions only because it is possible to study the solar surface with a high space and time resolution. For the UV Cet-type star flares, we have a quite different case: it is not a difficult task to enumerate all the facts that can be used to discuss mass motions in stellar flares.

Joy (1958) has suspected a $+30$ km s$^{-1}$ displacement for flare emissions with respect to permanent stellar emission lines during a UV Cet flare. Greenstein and Arp (1969) have found a $-59$ km s$^{-1}$ displacement for calcium emission and $-23$ km s$^{-1}$ displacement for hydrogen lines with respect to permanent emission lines duirng a Wolf 359 flare. However, in both cases, observers noted uncertainty in the results. Kulapova and Shakhovskaya (1973) have observed for an AD Leo flare, a probable line shift of not more than 1 Å. For a strong UV Cet flare, Bopp and Moffett (1973) have been able to evaluate only roughly an upper limit of a flare line shift: the shift is much less than 8 Å.

All observers who have obtained high resolution flare spectra note an emission line broadening of up to 6–15 Å. During AD Leo strong flares, a noticeable asymmetry of emission line profiles has been discovered and this asymmetry disappears quickly when the flare decays (Gershberg and Shakhovskaya, 1971; Kulapova and Shakhovskaya, 1973); this feature has been confirmed recently by Bopp and Moffett (1973). The ratio $\Delta\lambda/\lambda$ varies from line to line in flare spectra; therefore observed line profiles cannot be represented by the Doppler effect only and self-absorption in the lines must be taken into account.

And that is all. In spite of such scanty data on stellar flares, one can note an essential analogy between the solar and stellar flares. In both cases a gas that contributes the most part to the optical flare radiation does not display noticeable systematic motions, say, of velocities exceeding 100 km s$^{-1}$; however, an agent that excites non-thermal radio emission in the corona spreads with a velocity of about 1000 km s$^{-1}$.

## 1.5. SEVERAL ADDITIONAL REMARKS

It follows from an examination of stellar flare spectra that hydrogen emission is a main contribution in flare radiation over a range of optical frequencies. Figure 2 (from Gershberg, 1974a) confirms this statement quantitatively. In the plot $U-B$ and $B-V$ colours observed near flare brightness maxima are compared with calculated colours for hydrogen plasma models which satisfactorily represent the Balmer decrements of observed flares. It is seen that for the most part, observed flare colours are located within a region corresponding to plasma models with $T_e \gtrsim 15000$ K.

Kunkel (1967) has successfully represented spectral and photometric characteristics

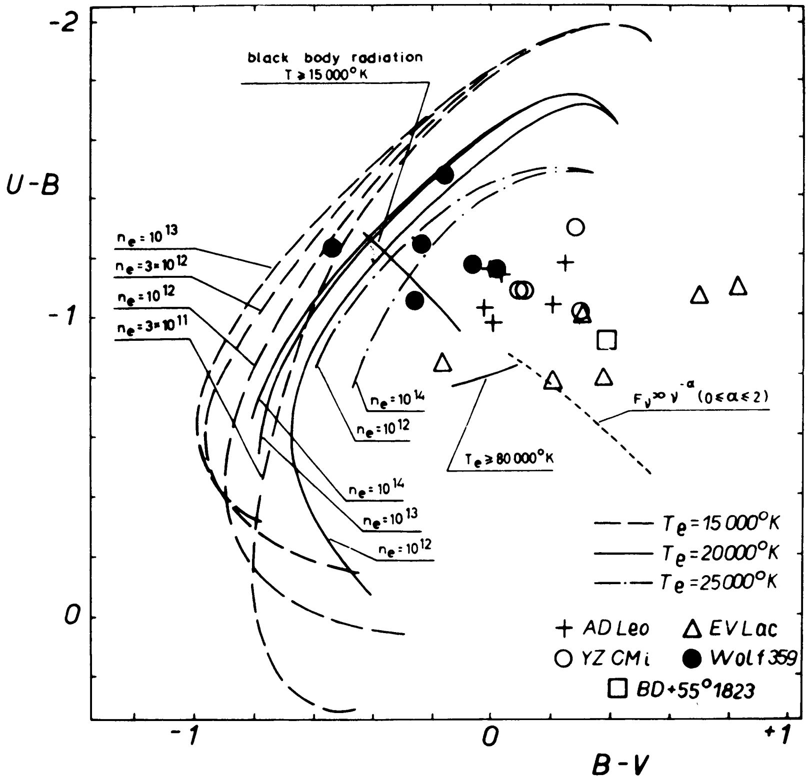


Fig. 2. $U-B$ and $B-V$ colours of UV Cet-type star flares near brightness maxima and calculated colour characteristics of radiation of different types: absolute black body ($T > 15000$ K), optically-thick line hydrogen plasma ($T_e = 15000$, 20000 and 25000 K), optically thin hot plasma ($T > 80000$ K) and synchrotron radiation.

of UV Cet-type star flares observed by himself within the framework of another nebular model: static hydrogen plasma under LTE conditions. Although in both cases, the formal agreement between observations and calculations is about the same, physical preconditions for the Crimean model seem to be more realistic.

To explain observed variations of flare colours during decay Kunkel has proposed to supplement a pure nebular model with a hot photospheric spot originating as a result of a photosphere burn by a flare itself; Grinin (1973) has carried out detailed calculations of the scheme. Such a two-component model really represents the observations better. Then one can assume that during the first several minutes of a strong flare, a short-lived radiation of a hotter plasma with $T_e$ of about $10^5$K is superposed on a colder plasma with $T_e$ of about 20000 K which is responsible for the longer-lived hydrogen emission line radiation. This hotter component would give a noticeable contribution in the continuum only which would decrease the Balmer jump and line emission portion of the total flare radiation. (According to Bopp and Moffett (1973), the line emission portion of the B-band flare radiation does not exceed 20% but calculated models representing the Balmer decrements give up to 40%.) Strictly speaking, the same observational effect may be originated by synchrotron radiation or by some other ultraviolet continuum emission. However, available observations of stellar flares are insufficient for a constructive consideration of such multi-component models. In any case, we have strong evidences in favour of heterogeneous physical conditions in the region where the optical radiation of stellar flares originates, and Moffett's (1973b) proposal to distinguish between two types of flares (fast flares with continuum radiation predominance and slower flares with line emission predominance) may be considered as an extreme form of an affirmation of the heterogeneity. On the other hand, heterogeneity of conditions in chromospheric flares on the Sun is an important feature of these events (Severny, 1964; Takakura *et al.*, 1971; Švestka, 1972).

However, systematic differences of up to 2–4 orders of magnitude between spectroscopic and photometric $n_e$ evaluations cannot be attributed to heterogeneity within the radiating gas, and this fact forces one to exclude the hypotheses of an ionizing agent acting only at the very beginning of flares, although in the framework of this scheme a lot of theoretical light curves which represent the observations well have been calculated (Gershberg, 1970; Korovyakovskaya and Korovyakovskij, 1971). In other words, for flare stars and for the Sun, the flare decay time is much longer than the recombination time and, in both cases, flare decay is determined not by recombination but by a much slower relaxation of the agent which excites an optical flare. The observed duration of radio bursts also require a long action of an exciting agent (Lovell, 1971).

These common features of solar and stellar flares lead naturally to the question

### 1.6. ARE THERE ANY KNOWN FUNDAMENTAL DIFFERENCES BETWEEN SOLAR AND STELLAR FLARES?

In solar flare spectra, continuum radiation is much weaker as compared to that in UV Cet-type star flare spectra. However, the Balmer emission continuum is not seen in disc flare spectra but is often registered in limb flares (de Feiter, 1973). This fact permits one to state that the matter is not of physical differences between radiating masses in the stars and in the Sun, but in discovery conditions: the solar photosphere is too bright a background to allow flare continuum emission to be observed.

Strong optical flares on the Sun are accompanied by X-ray bursts, but hard radiation associated with stellar flares has not yet been found. It is an essential point since, from the point of view of up-to-date solar flare models (de Feiter, 1973; Kaplan *et al.*, 1974) hard radiation is caused by primary processes in flares and all optical effects are due to secondary ones. An attempt to discover an X-ray emission from stellar flares using Earth ionosphere disturbances has given an upper limit of the ratio $F_X/F_B < 10^5$ (Gershberg *et al.*, 1969). Recently direct X-ray observations with OSO 3 (Hudson and Tsikoudi, 1973) have been carried out during 81 UV Cet-type star flares. No hard radiation from flares has been registered and an upper limit of the ratio $F_X/F_U$ has been evaluated to be $3 \times 10^4$. Since for a typical UV Cet-type star flare the ratio $F_U/F_B$ is about $1.1 - 1.5$, the direct space observations give $F_X/F_B < 4 \times 10^4$. The value is much in excess of the respective ratio for solar flares. In other words, one may think that the available technology is insufficient to record X-ray emission from stellar flares.

Apparently, main differences between chromospheric flares on the Sun and UV Cet-type star flares are quantitative ones in the energy of these events: stellar flares are registered in which the total optical radiation energy is 100–1000 times larger than solar flares, and these stellar flares are much more transient than solar ones.

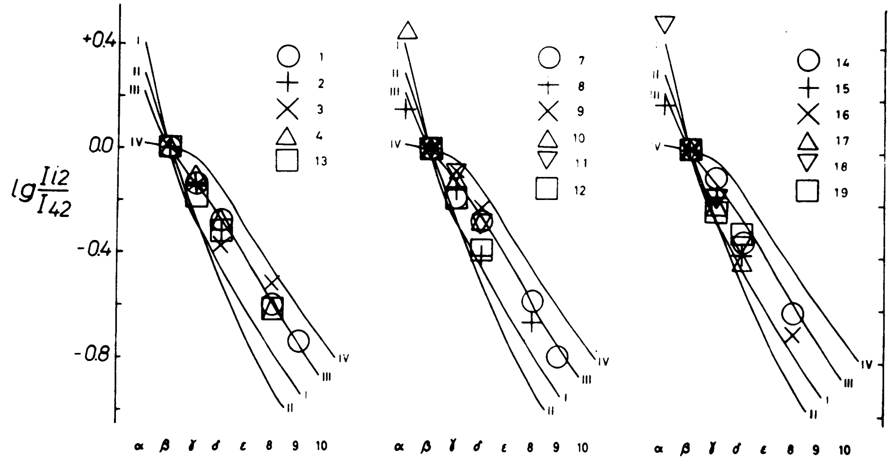
## 2. Outer Layers of Red Dwarf Stars and of the Sun are Birth-Places of Flares

### 2.1. CHROMOSPHERE AND HIGHER ATMOSPHERIC LAYERS

The most important feature of the solar atmosphere is the existence of a temperature inversion: above the solar photosphere with a surface temperature of about 4200 K, there exists the chromosphere with $T_e = 8000–20000$ K and the solar corona with $T_e = (1–2) \times 10^6$ K. This temperature inversion phenomenon was quite inexplicable in the framework of radiative transfer theory but was completely explained when convective envelope theory, cosmic and magnetohydrodynamics developed.

The existence of chromospheres on the UV Cet-type stars was suspected just after the first spectra of these stars in the quiet state were obtained and strong hydrogen and calcium emission lines were discovered against an absorption spectrum background. The EV Lac spectrogram obtained by Wilson (1961) with a dispersion of 9 Å mm$^{-1}$ has confirmed such an interpretation for permanent emission lines: hydrogen line widths have been shown to be comparable to chromospheric temperature and HeI, CaI, FeI and SiI emission lines which are peculiar to the solar chromosphere have been discovered. Then a certain similarity in relative intensities of hydrogen emission lines has been found for the solar chromosphere and quiet state of UV Cet-type flare stars (Gershberg and Shakhovskaya, 1971; Shakhovskaya, 1974). Finally, the Balmer decrements of flare stars have been recently represented within the framework of the above cited non-equilibrium and optically-thick-line hydrogen plasma model with a velocity gradient of inner motions.

In Figure 3 (from Gershberg, 1974b), solid lines correspond to calculated decrements, as in Figure 1, and different signs denote observations of 9 flare stars. Of 19 available observations of Balmer decrements, 17 are well represented by the model under consideration. In the rest (two spectra of EV Lac and AD Leo), the ratios $I_{H\gamma}/I_{H\beta}$ are large, almost such as in flare spectra, and both spectrograms were obtained without simultaneous photoelectric observations of the brightness of the stars. Therefore one may think that these spectra are of excited states of the stars. Theoretical Balmer decrements in Figure 3 are calculated for $T_e = 10000$ K. Real chromospheric temperatures of flare stars scarcely differ noticeably from this value: hydrogen line widths give a limit $T_e < 14000$ K and the existence of HeI emission lines makes $T_e < 10^4$ K to be of very small probability. Therefore, if $T_e = 10000$ K, observed Balmer decrements of 9 flare stars correspond to hydrogen plasma models with $n_e = (1–4) \times 10^{12}$ cm$^{-3}$ and $\beta_{21}^0 = (1–2) \times 10^{-6}$; if $T_e = 15000$ K, $n_e$ will vary by a factor



| | $T_e$(°K) | $n_e$(cm$^{-3}$) | $\beta^{\circ}_{21}$ |
|---|---|---|---|
| I | 10 000 | $1\cdot10^{12}$ | $1\cdot10^{-6}$ |
| II | 10000 | $3\cdot10^{12}$ | $3\cdot10^{-6}$ |
| III | 10 000 | $3\cdot10^{12}$ | $1\cdot10^{-6}$ |
| IV | 10 000 | $1\cdot10^{13}$ | $1\cdot10^{-6}$ |

| | | | |
|---|---|---|---|
| 1-4 | EV Lac | 14 | Wolf 630 |
| 7,8 | AD Leo | 15,16 | Gl 896A |
| 9,10 | YZ CMi | 17 | Gl 896B |
| 11,12 | Gl 815 | 18,19 | Gl 494 |
| 13 | Gl 569 | | |

Fig. 3. Observed relative intensities of the Balmer lines in spectra of UV Cet-type stars in the quiet state (numbered signs) and calculated Balmer decrements for optically-thick line hydrogen plasma (numbered solid lines).

of 1.5. Earlier Grinin (1972) analysed one of our spectrograms using another approach to the problem: he considered Hα-quanta transfer having taken into account electron collisions as a dissipative mechanism. He found $n_e = 3 \times 10^{12}$ cm$^{-3}$ for the AD Leo chromosphere that coincides with the decrement method result.

For all calculated models representing observed Balmer decrement, one can calculate an effective absolute luminosity for any emission line per cm$^{-3}$ of hydrogen plasma. Comparing an average surface brightness of a stellar chromosphere that can be found from the emission line equivalent width and a specific absolute luminosity calculated for this line, one can estimate a geometric thickness of the stellar chromosphere $h$ multiplied by its surface homogeneity factor $\delta_\lambda$. For the UV Cet-type stars considered, the products $h\delta$(Hγ) have been found to range from 10 to 220 km; $\delta$(Hγ) is a part of the stellar surface with an essential Hγ emission. Note that Bopp's (1974) observations show that a heterogeneity of chromosphere emission over the stellar disc may be large, so that $\delta$(Hγ) may be expected to be rather smaller than 1.

Thus there is reason to affirm that UV Cet-type star chromospheres have a temperature regime that is similar to the solar one and stellar chromosphere densities are in excess by a factor of ten compared to solar ones. There must exist coronae above such stellar chromospheres. However the only up-to-date experimental evidence in favour of the existence of UV Cet-type stellar coronae is a fast downward frequency drift of radio bursts. Kahn (1969) has analyzed the strongest radio flare of such a type and has inferred that the density of the YZ CMi corona is about 20 times higher than the solar corona and a stellar wind originating from such a stellar corona must lead to a secular mass loss rate of about $3 \times 10^{-12}\ M_{\odot}\ \mathrm{yr}^{-1}$.

The important feature of UV Cet-type flare stars is an absence of infrared excesses (Iriarte, 1971). It indicates the absence of dust in higher atmospheric layers and nearby circumstellar space. Although we do not know how dust envelopes of T Tau-type stars originate and develop and why UV Cet-type stars have no such envelopes, observational data draw together UV Cet-type stars and the Sun and separate them from T Tau-type stars. If all stars are born with dust envelopes, their absence in the solar and UV Cet-type star cases may be simply an age effect. However it is not excluded that high surface activity (flares and stellar wind) promotes dust grain destruction and a clearing of circumstellar space (Gershberg and Shakhovskaya, 1974).

## 2.2. SPOTTEDNESS OF PHOTOSPHERE

Sunspots are the manifestation of the solar activity that mankind has known for many centuries and that may be really observed with the naked eye.

The existence of heterogeneities in the photospheres of flare stars has been suspected from visual investigations: many experienced observers (Oskanian, Petit, de Kock, Migach and others) noted slow quasi-periodic brightness oscillations of small amplitude in addition to separate fast flares. Roques (1958, 1961) was the first who recorded such events photoelectrically. Later, during patrol photoelectric observations in Catania and in Arizona, observers have found that flares occurred in minima of these slow brightness oscillations (Cristaldi *et al.*, 1969; Chugainov *et al.*, 1969) and the fact has become a decisive argument in favour of the identification of starspots with activity centres.

Independently of stellar flare investigations, a starspot hypothesis for red dwarfs has been proposed by Kron (1952) to explain secondary variations of brightness which he observed in the eclipsing system YY Gem. Then Chugainov (1966) discovered quasi-periodic brightness oscillations of small amplitude for BY Dra; these brightness variations were not accompanied by noticeable colour variations. A short-lived dark spot hypothesis gave a natural explanation for such photometric features for a rotating star. Later the UV Cet-type flares have been recorded for YY Gem and BY Dra, and now the study of flare and of spotted stars of advanced spectral classes have converged. For the last few years, intensive studies in the field have been carried out in Brazil, in the Crimea, and in Texas (Torres and Ferraz Mello, 1973; Chugainov, 1973; Bopp and Evans, 1973; Bopp, 1973), and about 15 stars with spots are now known. For almost all stars that originally were known as spotted ones, UV Cet-type flare activity has been discovered later: separate strong flares of UV Cet-type and/or a noticeable increase of ultraviolet brightness dispersion at minima that is usually regarded as a summary effect of weak flares. On the other hand, many UV Cet-type stars display slow quasi-periodic brightness oscillations of small amplitudes. It should be kept in mind, however, that observations for starspot discovery and for fast flare registration have some differences; therefore the establishment of the one-to-one link between spottedness and flare activity requires a long observational time.

The spottedness of flare stars has been studied in the most detail for the systems BY Dra, CC Eri and YY Gem (Chugainov, 1973; Bopp and Evans, 1973; Bopp, 1973, 1974; Vogt 1973). According to Bopp and Evans, the main components of these eclipsing systems display starspots at latitudes up to 30–40° and their longitude extent approaches 60–105°; the total area contains about 5–20% of the stellar surface. An effective temperature of starspots is evaluated to be 1500–2000 K lower than the photospheric temperature and therefore spots can make only a negligeable contribution to the total radiation of the star and their appearance on the disc may be accompanied by very small colour variations. Chugainov has analyzed BY Dra observations for 6 yr and has found slow variations in period of small brightness oscillations of the star and small but systematic variations of its mean brightness and colour; Vogt has partly confirmed Chugainov's result. According to Chugainov, a drift in the mean latitude of spots, such as give Maunder's butterflies on the Sun, and a differential rotation of the stellar photosphere are responsible for all these photometric effects.

The obvious analogy between the solar and stellar spots raises a question on magnetic field intensity in flare star spots. There are several independent evaluations of the value; they are based on (i) considerations connected to flare energy (Gershberg and Pikel'ner, 1972), (ii) an idea on the transformation of radiative energy trapped within a spot into magnetic field energy (Bopp and Evans, 1973), and (iii) considerations on the structure of a magnetic tube located in a convective zone of a cold star (Mullan, 1974). All these indirect evaluations give spot field intensities ranging from several kilogauss up to several tens of kilogauss. Unfortunately, to date we have no direct experimental measurements and if the effective temperature of starspots is really very low the possibility in principle to carry out such measurements optically becomes questionable.

In a recent paper, Mullan (1974) considered a spot problem for red dwarfs within the framework of a general conception of cellular convection. He found that the thicker the convective zone, the larger the expected spot sizes, and when the convective zone thickness becomes comparable to the stellar radius spot birth regions approach the poles of the star and the number of spots has to decrease. Therefore one may expect that for brighter flare stars where convective zones are thinner, spots and axial rotation must effectively lead to small and periodic brightness oscillations while for fainter stars with thicker convective zones, slow brightness variations may be due to spots appearing and disappearing at the polar regions and therefore may have no certain periodicity. On average such a regularity is indeed displayed although an accidental distribution of rotation axes of stars in space complicates the picture.

## 2.3. LONG-PERIODIC VARIATIONS OF THE ACTIVITY LEVEL

From the very beginning of the UV Cet-type flare star studies, attempts have been undertaken to find a stellar activity analogy to the 11-year solar cycle or, at least, to find variations in a flare activity level from season to season (Oskanian, 1957; Chugainov, 1969). The analysis of photoelectric patrol observations over several years has shown such seasonal variations in stellar activity (Cristaldi and Rodonò, 1972; Gershberg, 1972); however, there is uncertainty in the statistical significance of these variations (Oskanian and Terebizh, 1971; Chugainov, 1972b; Kunkel and Zarate, 1974). Only for BY Dra do the available observations of synchronous variations of the small brightness oscillation period of the star, its mean brightness and colour, and the emission spectrum intensity indicate a 8–9 yr period that is similar to the solar cycle (Chugainov, 1973; Gershberg and Şhakhovskaya, 1974).

## 3. General Discussion

The results of the observations cited above lead to conclusions on the identity of the physical nature of processes in the atmospheres of flare stars and the Sun. There is however an opinion that such 'a comparative astrophysics' is a matter of a little perspective: since we have no complete physical theory either for all the events which take place during a separate chromospheric flare or for all the processes that are responsible for the solar activity in total, the analogy between solar and stellar events does not contain new information. I do not share this scepticism. A comparative analysis of the solar and stellar activities is useful now since it stimulates a new approach to old questions and permits the discussion of some particular problems from a more general point of view.

(1) The traditional way to construct an UV Cet-type star flare model is to represent within the framework of some theoretical scheme all the facts that have been obtained from photometric observations of stellar flares. For the present, without concern as to the essence of physical differences between the quantitative models available, it should be noted that all such schemes – the nebular models (Kunkel, 1967; Gershberg, 1970; Korovyakovskaya and Korovyakovskij, 1971), the fast electron model (Gurzadian, 1973) and the shock-wave model (Korovyakovskaya, 1972) – give good representations for typical light curves and sometimes for flare colour characteristics also. Therefore it is not possible to choose the most probable model on the basis of the best representation of the photometric and colorimetric observations. On the other hand, a perfecting of any theoretical model is connected to an undesirable increasing of the number of unknown parameters that leads to a decrease in critical attitude in a comparison of observations and models. In any case, an examination of complicated structures in consecutive photographs of solar flares for which Tallant (1970) has obtained integral light curves which are very similar to typical light curves of stellar flares must caution against an unwarranted passion for calculations of formal models and must restrain enthusiasm excited by a possibility of fitting these models to observations. The conslusions on the identity of the physical processes that are responsible for solar and stellar flares permit one to abandon the traditional way in UV Cet-type star studies and to pass to considerations of stellar flares on the basis of up-to-date models of solar chromospheric flares.

The problem is one of the necessity of a common approach to different manifestations of the same physical processes. In the case of such an approach, only such a theory of chromospheric flares on the Sun may be regarded as correct and complete enough if this theory also gives a good fit to stellar flares when only numerical values of essential parameters of the theory are varied. In particular, if the most elaborate conception of solar flares based on ideas of magnetohydrodynamical and plasma interactions (de Feiter, 1973; Kaplan *et al.*, 1974) is regarded as an initial scheme, then along the way of 'essential parameter variations' one must raise and answer, for example, the following questions: why, under red dwarf atmospheric conditions do flares develop an order of magnitude faster than solar flares – does plasma turbulence develop quicker or does higher chromospheric density lead to fast particle fluxes dissipating in a shorter time? what causes the larger energy of stellar flare optical radiation – a stronger intensity of magnetic fields of starspots or a higher effectivity of magnetic field energy transformation into optical radiation? to what is due the exclusively high power of non-thermal radio emission of stellar flares – to a larger energy of the agent that excites the coronae, or to a higher coronal density, or to a higher intensity and coarser structure of local magnetic fields which spread from the stellar photospheres into the coronae?

(2) A stellar flare theory must give us not only a physical picture of a typical flare but it must also explain regularities that are obtained from flare statistics. As known (Gershberg, 1972), there are no correlations between the total energy of stellar flare optical radiation and the rate of luminosity increase before maximum. In other words, a flare trigger mechanism is not dependent on a quantity of accumulated

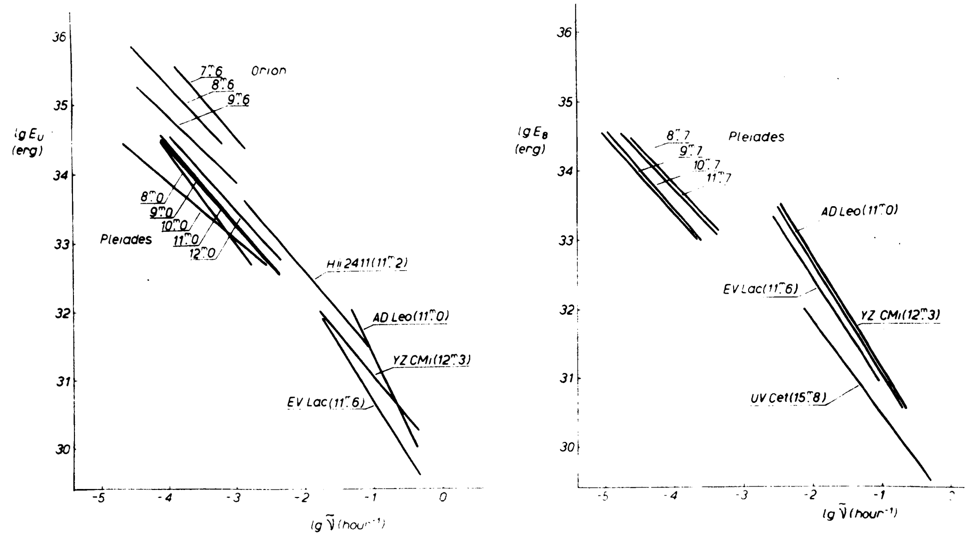


Fig. 4. Distribution of the optical radiation energy for flares of stars in the solar neighborhood, in the Pleiades and in the Orion cluster. $\tilde{\nu}$ $(E)$ is an accumulated flare occurrence rate: the number of flares per hour with optical energy exceeding $E$.

energy which will be released during a flare. Then, in Figure 4 (Krasnobabtsev and Gershberg, 1975), the flare occurrence distribution with optical radiation energy is given for flare stars in the solar neighbourhood, in the Pleiades and in the Orion clusters; $\tilde{\nu}(E)$ is the number of flares per hour with a total energy exceeding $E$. As Figure 4 shows, within wide ranges of age and absolute luminosity, flare stars display a certain grouping in the flare energy spectrum. Apparently, all these regularities must be interpreted in the framework of a common statistical theory of flare activity for the Sun and stars.

(3) Recently Pikel'ner (1974) has shown that the same physical mechanisms – the magnetic field annihilation near a neutral sheet – can give highly different events in solar atmospheric conditions: spicules, 'moustaches' and chromospheric flares for different magnetic field intensities and gas densities. A comparative examination of the solar events shows the larger the total energy of the annihilating field, the larger the fraction of this total energy transformed finally into hard radiation and fast particles. There is reason to think that in the UV Cet-type star flares, the high energy component fraction should be even larger.

The recent discovery of $\gamma$-bursts from outside the Solar system (Klebesadel *et al.*, 1973; Cline *et al.*, 1973; Wheaton *et al.*, 1973) suggests a probable connection between these $\gamma$-bursts and optical and radio flares of UV Cet-type flare stars because of similarity in time characteristics. If recorded $\gamma$-bursts are regarded as originating within several parsecs of the Sun, then such a burst releases an energy of about $10^{36}$ erg within the range 0.1–1.5 MeV. In flares of UV Cet-type stars, such large quantities of optical energy have not been recorded to date. It should be noted, however, that the almost 3-yr continuous monitoring of flare stars with isotropic receivers in the $\gamma$ range is 10–100 times longer than the longest series of optical photoelectric observations of these objects, and an extrapolation of the flare energy spectrum, in Figure 4 toward much rarer events support the admissibility of the hypothesis. Recently Karitskaya (1975) has proposed a model of a $\gamma$-burst within the framework of magnetohydrodynamical and plasma processes on the surface of a flare star.

(4) The conclusion of the existence of starspots with magnetic fields of tens of kilogauss on red dwarfs essentially extends the scale of stellar magnetism problems, since flare stars are one of the most numerous types in the galactic stellar population and are the most widespread type of non-stationary stars: the number of flare stars is about $10^4$ times larger than the number of magnetic Ap-stars and about $10^6$–$10^7$ times larger than the number of pulsars. It has been shown (Kunkel, 1973; Shakhovskaya, 1975 that UV Cet-type flares take place not only in young population objects but also in old disc population stars and even in galactic halo objects whose age can exceed $3 \times 10^9$ yr; in other words, the flare activity of red dwarfs dampens rather slowly. Also, flares of the type considered have been observed in binary systems of small and large separation between components, in both bright and faint binary components and in stars for which we have no information on their duplicity. This

fact may have an immediate application to stellar magnetism theory, to ideas on solar magnetic field evolution and to general problems of the solar activity.

(5) To counterbalance the conception of a magnetic field as an energy source for red dwarfs' flares, for the last ten years Gurzadian (1973) has been developing another stellar flare theory which is based on the assumption that a disintegration of a hypothetical pre-stellar matter leads to the origination of short-lived fluxes of fast electrons whose Compton scattering by photospheric photons produces the observed optical flares. In this connection it should be noted that when Gurzadian takes pre-stellar matter from subphotospheric layers, drags out it to a large distance above the photosphere and converts it into fast particles, no astrophysical criticism is appropriate since the existence of unknown forms of matter and new fundamental laws of nature is a question of belief only. But then the hypothesis meets a real difficulty: Compton scattering transforms into optical radiation only a small fraction of the energy of a fast electron and therefore a fast electron energy source must be much stronger than the energy source that produces the stationary luminosity of the star. Thus, Gurzadian's hypothesis excludes the idea of stars as quasi-equilibrium gaseous bodies and suggests that stars are unessential envelopes of receptacles of energy of unknown nature. However, Gurzadian's model must be rejected because it is erroneous in its physical part: energetic losses for a fast electron jet are determined within stellar atmospheric conditions not by Compton scattering but by plasma interaction in the upper atmosphere and by ionization losses in the lower atmosphere.

Nevertheless, there is no reason to have doubts as to the essential role of fast particles in stellar flares: within chromospheric flares on the Sun, fast particles are responsible for non-thermal hard X-ray and meter wave-length range radio emission and are seemingly an immediate agent that excites thermal optical, ultraviolet and soft X-ray radiation (Brown, 1973; Kaplan *et al.*, 1974) as well as gives rise to mass motions within mainly optically radiating gas (Kostyuk and Pikel'ner, 1974). However, it is not necessary to assume hypothetical pre-stellar matter to obtain fast electrons within stellar atmospheres: such particles are effectively produced naturally under plasma turbulent conditions, and the existence of such conditions above solar active regions is confirmed by direct experiments (Gordon, 1973).

(6) Another concept that must be apparently rejected in the light of up-to-date observations is the hypothesis that the UV Cet-type stars are a later evolutionary stage of T Tau-type stars. A recent magnificent flare of V 1057 Cyg has shown that T Tau-type stars evolve into early spectral class stars of high luminosity but not into red dwarfs (Grasdalen, 1973). Stellar statistical data that have been regarded as the basis for this 'T Tau evolution to UV Cet' hypothesis should apparently be interpreted only as evidence that variables of both types originate in the same volume of space but essential differences in masses are responsible for different evolution. There are however communications of observations of UV Cet-type and T Tau-type flares on the same stars (Haro, 1968). Apparently the data should be interpreted as observations of flares on distant binaries consisting of stars of different masses. Perhaps this expla-

nation may be regarded as too artificial. However, according to time characteristics, the flare on the white dwarf G44-32 (Warner *et al.*, 1970) is quite similar to UV Cet-type star flares; if the system 40 Eri containing a white dwarf as well as a UV Cet-type star is moved off to a large distance from the Sun, we shall have a ready model for the flare star G44–32.

So, we have a real paradox: our Sun gives us a key to understanding the activity of smaller and colder K-M-dwarfs but this nearest G-star does not help us to understand other G-stars – T Tau-type variables.

## Acknowledgements

I am very grateful to Prof. S. B. Pikel'ner and participants of the Astrophysical seminar of the Crimean Observatory for useful discussion while preparing this report, and to Miss I. V. Tarasova for the addition to Figure 4 of the 1972–1973 patrol observation data on UV Cet-type flare stars.

## References

Bopp, B. W.: 1973, *Bull. Am. Astron. Soc.* **5**, 399.
Bopp, B. W.: 1974, *Monthly Notices Roy. Astron. Soc.* **166**, 79.
Bopp, B. W. and Evans, D. S.: 1973, *Monthly Notices Roy. Astron. Soc.* **164**, 343.
Bopp, B. W. and Moffett, T. J.: 1973, *Astrophys. J.* **185**, 239.
Brown, J. C.: 1973, *Solar Phys.* **31**, 143.
Chugainov, P. F.: 1966, *Info. Bull. Var. Stars* No. 122.
Chugainov, P. F.: 1969, *Izv. Krymsk. Astrofiz. Obs.* **40**, 33.
Chugainov, P. F.: 1972a, *Izv. Krymsk. Astrofiz Obs.* **44**, 3.
Chugainov, P. F.: 1972b, *Izv. Krymsk. Astrofiz. Obs.* **46**, 14.
Chugainov, P. F.: 1973, *Izv. Krymsk. Astrofiz. Obs.* **48**, 3.
Chugainov, P. F., Havlen, R. J., Westerlund, B. E., and White, R. E.: 1969, *Info. Bull. Var. Stars* No. 343.
Cline, T. L., Desai, U. D., Klebesadel, R. W., and Strong, I. B.: 1973, *Astrophys. J.* **185**, L1.
Cristaldi, S., Godoli, G., Narbone, M. and Rodonò, M.: 1969, in L. Detre (ed.), *Non-Periodic Phenomena in Variable Stars*, D. Reidel Publ. Co., Dordrecht, Holland, p. 149.
Cristaldi, S. and Rodonò, M.: 1972, *Mem. Soc. Astron. Ital.* **43**, 697.
Feiter, L. D. de: 1973, *Utrechtse Sterrenkundige Overdrukken* No. 246.
Gershberg, R. E.: 1970, *Flares of Red Dwarf Stars*, Nauka, Moscow. (English translation by Dr D. J. Mullan is available on request from Armagh Observatory.)
Gershberg, R. E.: 1972, *Astrophys. Space Sci.* **19**, 75.
Gershberg, R. E.: 1974a, *Izv. Krymsk. Astrofiz. Obs.* **51**, 117.
Gershberg, R. E.: 1974b, *Astron. Zh. USSR* **51**, 552.
Gershberg, R. E. and Pikel'ner, S, B.: 1972, *Comm. Astrophys. Space Phys.* **4**, 113.
Gershberg, R. E. and Shakhovskaya, N. I.: 1971, in 'New Directions and New Frontiers in Variable Star Research', *IAU Colloq.* **15**, *Veröff. Bamberg* **9**, 126.
Gershberg, R. E. and Shakhovskaya, N. I.: 1974, *Izv. Krymsk. Astrofiz. Obs.* **49**, 73.
Gershberg, R. E. and Shnol, E. E.: 1974, *Izv. Krymsk. Astrofiz. Obs.* **50**, 122.
Gershberg, R. E., Neshpor, Y. I., and Chugainov, P. F.: 1969, *Izv. Krymsk. Astrofiz. Obs.* **39**, 140
Gordon, I. M.: 1973, *Space Sci. Rev.* **15**, 157.
Gordon, K. C. and Kron, G. E.: 1949, *Publ. Astron. Soc. Pacific* **61**, 210.
Grasdalen, G. L.: 1973, *Astrophys. J.* **182**, 781.
Greenstein, J. L.: 1950, *Publ. Astron. Soc. Pacific* **62**, 156.
Greenstein, J. L. and Arp, H.: 1969, *Astrophys. Letters* **3**, 149.

Grinin, V. P.: 1972, *Radiation Transfer within Envelopes of Non-Stationary Stars, Dissertation*, Leningrad University.
Grinin, V. P.: 1973, *Izv. Krymsk. Astrofiz. Obs.* **48**, 58.
Gurzadian, G. A.: 1973, *Flare Stars*, Nauka, Moscow.
Haro, G.: 1968, in B. M. Middlehurst and L. H. Aller (eds.), *Nebulae and Interstellar Matter, Stars and Stellar Systems* **7**, 141, University of Chicago Press, Chicago.
Hudson, H. and Tsikoudi, V.: 1973, *Nature Phys. Sci.* **245**, 88.
Iriarte, E. B.: 1971, *Bol. Obs. Tonantzintla Tacubaya* **6**, 143.
Joy, A. H.: 1958, *Publ. Astron. Soc. Pacific* **70**, 505.
Kahn, F. D.: 1969, *Nature* **222**, 1130.
Kaplan, S. A., Pikel'ner, S. B., and Tsytovich, V. N.: 1974, *Dynamics of Solar Plasma*, Znanie, Moscow. (English version to be published in *Phys. Reports*, 1975.)
Karitskaya, E. A.: 1975, *Astron. Zh. USSR* **52**, in press.
Klebesadel, R. W., Strong, I. B., and Olson, R. A.: 1973, *Astrophys. J.* **182**, L85.
Korovyakovskaya, A. A.: 1972, *Astrofizika* **8**, 247.
Korovyakovskaya, A. A. and Korovyakovskij, Yu. P.: 1971, *Astrophys. Res.* **3**, 101.
Kostyuk, N. D. and Pikel'ner, S. B.: 1974, *Astron. Zh. USSR* **51**, 1002.
Krasnobabtsev, V. I. and Gershberg, R. E.: 1975, *Izv. Krymsk. Astrofiz. Obs.* **53**, in press.
Kron, G.: 1950, *Astron. J.* **55**, 69.
Kron, G. E.: 1952, *Astrophys. J.* **115**, 301.
Kulapova, A. N. and Shakhovskaya, N. I.: 1973, *Izv. Krymsk. Astrofiz. Obs.* **48**, 31.
Kunkel, W. E.: 1967, *An Optical Study of Stellar Flares, Dissertation*, University of Texas, Austin.
Kunkel, W. E.: 1973, *Astrophys. J. Suppl.* **25**, 1.
Kunkel, W. E. and Zarate, N.: 1974, *Info. Bull. Var. Stars* No. 879.
Lovell, B.: 1971, *Quarterly J. Roy. Astron. Soc.* **12**, 98.
Moffett, T. J.: 1973a, *Monthly Notices Roy. Astron. Soc.* **164**, 11.
Moffett, T. J.: 1973b, *Bull. Am. Astron. Soc.* **5**, 399.
Mullan, D. J.: 1974, *Astrophys. J.* **192**, 149.
Öhman, Y. (ed.): 1968, 'Mass Motion in Solar Flares', *Nobel Symp.* **9**, Stockholm.
Oskanian, V. S.: 1957, in M. A. Arakelian (ed.), *The Non-Stable Stars*, Acad. Sci. Armenian SSR, Yerevan, p. 17.
Oskanian, V. S. and Terebizh, V. J.: 1971, *Astrofizika* **7**, 83.
Petit, M.: 1958, *Cont. Obs. Asiago* **3**, 29.
Pikel'ner, S. B.: 1974, *Astron. Zh. USSR* **51**, 233.
Roques, P. E.: 1958, *Publ. Astron. Soc. Pacific* **70**, 310.
Roques, P. E.: 1961, *Astrophys. J.* **133**, 914.
Schatzman, E.: 1959, in R. N. Bracewell (ed.), 'Paris Symposium on Radio Astronomy', *IAU Symp.* **9** and *URSI Symp.* **1**, 552, Stanford University Press, Stanford.
Severny, A. B.: 1964, *Ann. Rev. Astron. Astrophys.* **2**, 363.
Shajn, G. A.: 1945, *Bull. Acad. Sci. USSR*, Ser. Phys. **9**, 161.
Shakhovskaya, N. I.: 1974, *Izv. Krymsk. Astrofiz. Obs.* **51**, 92.
Shakhovskaya, N. I.: 1975, *Izv. Krymsk. Astrofiz. Obs.* **53**, in press.
Slee, O. B. and Higgins, C. S.: 1971, *Australian J. Phys.* **24**, 247.
Sobolev, V. V.: 1947, *Moving Envelopes of Stars*, Leningrad State University Publ.
Spangler, S. R., Shawhan, S. D., and Rankin, J. M.: 1974, *Astrophys. J.* **190**, L129.
Struve, O.: 1959, *Sky Telesc.* **28**, 612.
Švestka, Z.: *Ann. Rev. Astron. Astrophys.* **10**, 1.
Takakura, T., Ohki, K., Shibuya, N., Fujii, M., Matsuoka, M., Miyamoto, S., Nishimura, J., Oda, M., Ogawara, Y., and Ota, S.: 1971, *Solar Phys.* **16**, 454.
Tallant, P. E.: 1970, *Solar Phys.* **11**, 263.
Torres, C. A. O. and Ferraz Mello, S.: 1973, *Astron. Astrophys.* **27**, 231.
Unsöld, A.: 1955, *Physik der Sternatmosphären*, Springer-Verlag, Berlin, p. 609.
Vogt, S. S.: 1973, *Bull. Am. Astron. Soc.* **5**, 399.
Warner, B., van Citters, G. W., and Nather, R. E.: 1970, *Nature* **226**, 67.
Wheaton, W. A., Ulmer, M. P., Baity, W. A., Datlowe, D. W., Elcan, M. J., Peterson, L. E., Klebesadel, R. W., Strong, I. B., Cline, T. L., and Desai, U. D.: 1973, *Astrophys. J.* **185**, L57.
Wilson, O. C.: 1961, *Publ. Astron. Soc. Pacific* **73**, 15.