REVIEW OF THE THEORETICAL MODELS OF FLARES OF THE UV CETI-TYPE STARS

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ABSTRACT. The observations of stellar flares in optics, radio and X-ray show the general similarity of the flares on UV Ceti-type stars and on the Sun. At the same time there exist a lot of data showing that the analogy between these processes is not full. From this point of view the analysis of the theoretical models of stellar flares is given.

1.INTRODUCTION.

The first flares on UV Ceti-type stars were observed about 50 years ago and we known now from statistical investigations initiated by professor Ambartzumyan (1988) , that all (or almost all) dMe stars are the flare stars. During this time many different ideas about the nature of the flares were suggested (Gershberg, 1978; Gurzadjan, 1980), but only one of them - based on the community of the physics of the stellar and solar flares - was confirmed by the followed observations. The logical design of this idea was the IAU Colloquium N 104 "Solar and Stellar Flares" at the Stanford University where these two astrophysical topics were presented for the first time as a part of a single whole.

In this review we will discuss from this point of view the problems of the physical modelling of stellar flares with the accent on the models provided by the optical emission. Some questions such as the physics of the primary energy output, dynamics of flare loops and some others are not considered here since they are discussed in the recent reviews by Mullan (1989).

2.THE MAIN STAGES OF THE INVESTIGATIONS OF STELLAR FLARES.

The main characteristics of stellar flares are very different from the solar ones. The energy of strong stellar flares exceeds by the 2 - 3 orders the energy of the strongest events on the Sun. The development of stellar flares is more rapid: at the flares with well-pronounced impulsive phase the brightness of the star increases in tens times on the time scale of about one minute. That is why the analogy with the Sun was not obvious initially and the large efforts of the observers and theorists were needed for its evidence.

L. V. Mirzoyan et al. (eds.), Flare Stars in Star Clusters, Associations and the Solar Vicinity, 299–312.

2.1 OPTICAL EMISSION OF THE FLARES.

The first spectra of stellar flares with the moderate time resolution were observed in the Crimea by Gershberg and Chugainov (1967) and at the McDonald Observatory by Kunkel (1970). They showed, that during the flare the optical continuum is accompanied by the intensification of the Balmer lines, H and K Ca II and neutral helium lines. It meant that the main component of optical flares is the thermal radiation of the gas heated up to the temperature T ≈ 10000 K.

The obtained by Kunkel Balmer decrements of the flares turned out to be unusual: instead of "normal" intensities ratio: $H\alpha > H\beta > H\gamma > \ldots\ldots$ the inverse ones has been observed: $H\beta < H\gamma < H\delta < \ldots\ldots$ at maximum of light. Such decrements are typical for optically thick almost fully thermalized gas.Using their Kunkel estimated the electron number density in the flares: $N_e \approx 10^{13} - 10^{14}$ cm^{-3}. It was the first direct evidence that the flare emission lines are formed at the chromospheric level.

The next important result has been obtained by Bopp and Moffatt (1973) and by Pettersen (1983). They showed that:

1. the development of emission lines in the flares is more extended in time compared to the continuum (see Figure 1), that is typical also for solar flares;
2. the contribution of the emission lines to the total radiation of the optical flares at maxima of light is rather small: 5 - 11% in B - band and hence UBV - observations near the maxima of the flares characteri- -zed the properties of its continuum in main.

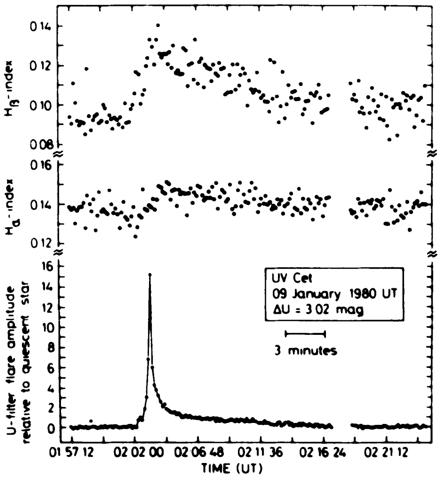

Figure 1. The flare of UV Ceti in $H\alpha$, $H\beta$ and U - band (Pettersen, 1983).

The interpretation of continuum emission especially in the peaks of the flares is extremely important for the understanding of the flare process and has been considered by many authors (see the review of Kodaira, 1983). The initial suggestion, according to which the continuum emission has a purely recombinational origin and is formed in the optically thin gas faced with two problems: a) the observations showed that the Balmer jump at the maxima of light is rather small and systematically lower than the values observed by Kunkel. b) the colour indexes at the peaks of the flares appeared to be in disagreement with the theory. The cloud of the observational points on the two-colour diagram is markedly concentrated near of values: U - B ≈ - $1^m.0$ and B - V ≈ $0^m.2$

These important observational facts were interpreted as the direct evidence for bremstrahlung radiation of a hot gas with the temperature $T \approx 10^5 - 10^7$ K as the main component of the optical continuum of flares at the maxima of light. Such interpretation explained the mentioned above properties of continuum emission but was in conflict with the "low-temperature" composition of emission lines in the optical spectra of the flares at the maxima of light.

Another interpretation was proposed by Grinin and Sobolev (1977): we argued that the main part of the optical continuum at the flare maxima is formed in the deeper layers of the stellar atmosphere where the number density of atoms is about $10^{15} - 10^{17}$ cm^{-3}. At these conditions two additional factors effected the energy distribution of the flares: at low temperature ($T < 8000$ K) the H^-- emission is added to the recombinations of hydrogen atoms; at larger T the gas becomes optically thick beyond the Balmer jump and its radiation is quasi-black-body. The last conclusion has been confirmed by the followed observations of Mochnacki and Zirin (1980), Kaler et al. (1982), Chugainov (1987), de Jager et al. (1989).

Such approach permitted us to draw a direct analogy between stellar flares and solar white flares, whose optical continuum arises also in transition region between photosphere and chromosphere (Neidig, 1989). We estimated also the area of continuum formation region of strong stellar flares (at the maxima of light): $S_{con} \approx 1 - 2\%$ of stellar disk area.

Summarizing the data on the optical spectra of the flares let us note briefly some properties of the emission lines profiles. The observations show that near the maxima of strong flares the hydrogen lines are broadening by several angstroms as a rule. On the spectra with high signal to noise ratio the broad wings are well pronounced in the Balmer lines, that might be due to a classical Stark- effect or plasma turbulence broadening. In a set of the flares a redward asymmetry of the line profiles was observed near the maximum of light. On the spectrogrammes obtained with high spectral resolution Shneeberger et al. (1979) observed the absence of central reabsorption in $H\alpha$ at the flare of EV Lac. It means that the excitation temperature of the atoms and consequently the electron temperature in the flare increases outward.

2.2. THE ULTRAVIOLET SPECTRA.

The existence of hot gas in upper layers of the flares follows from IUE spectra (see review by Giampapa, 1983). They showed the intensive emission lines of C II, Si II, C IV, Si IV and some others. For the ionization of latter the electron temperature of about 10^5 K are needed. However the ultraviolet continuum of flares may be connected with the radiation of deeper layers heated ut to $(1 - 2)*10^4$ K as was suggested by Baljunas and Rymond (1984) and Butler et al. (1981). It is noteworthy that the exposure time of the flare spectra obtained with IUE was usually about several dozens of minutes . That is why they can be hardly used for quantitative analysis.

Two short-living flare bursts of EV Lac were registered on board the ASTRON station with high time resolution (0.6 s) and a pass-band $\Delta\lambda$ = 28 Å (Gershberg and Petrov, 1986; Burnashova et. al 1989).One burst was observed in the spectral region centered at λ = 2430 Å, free from the strong emission lines, the other - at the wavelength λ = 1550 Å of resonance transition of C IV. In both cases the UV bursts were accompanied by the flares in longward wavelengths. These data are analyzed in the framework of the hydrodynamical flare model (Katsova and Lifshitz, 1989; see Section 3).

2.3 RADIO OBSERVATIONS.

At the beginning from the work of Lovell et al.(1963) radio observations of stellar flares were carried out by many authors at the meter-waves and microwaves. Their properties are summarized in the reviews by Gibson (1983), Kuijpers (1989) and Lang (this volume). The main difference from solar microwave flares is the absence or poor correlation with optical ones. The observations show that the stellar radio bursts follow usually the optical events (Figure 2.), that resemble the development of solar radio bursts of IV - type. It is possible that better correlation will be observe in shorter radio wavelengths (see Rodono et al. (1989).

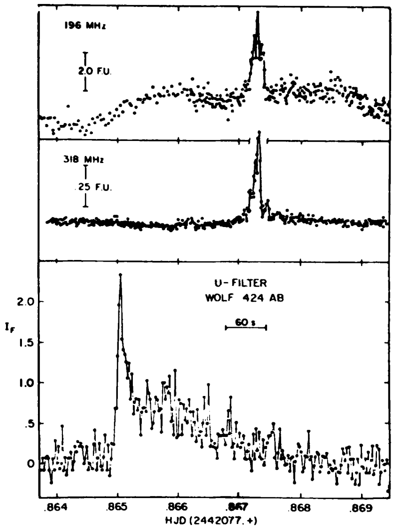

Figure 2. The example of the flare of Wolf 424 in radio and optics from Spangler and Moffett (1976).

The important properties of the stellar radio flares are the high brightness temperature of radiation (up to 10^{15} K) and the high circular polarization, reaching sometimes almost 100%. Both properties are typical for the coherent plasma process. According to Melrose and Dulk (1982) the most probable is an electron-cyclotron maser but other coherent emission mechanisms are not fully excluded (Kuijpers, 1989).

2.4. THE X-RAY OBSERVATIONS.

The first soft X-ray burst was registered by Heise et al. (1975) on red dwarf star YZ CMi on board ANS satellite. Since then the X-ray observations of flare stars have been carried out in a number of specialized space projects. Most of them were observed on EINSTEIN and EXOSAT satellites in the energy ranges 0.2 - 4 keV and 0.1 - 10 keV, respectively. The results of these investigations are summarized in the reviews by Haish (1983), Ambruster et al. (1987) and Pallavicini et al.(1989) The main conclusions are as follows:

The total energies of X-ray bursts on the flare stars are: $E_x \approx \approx 3*10^{33} - 10^{33}$ ergs that is two or three orders higher than on the Sun.

The temperatures of the X-ray flares in both cases are about the same: $T \approx (1 - 3)*10^7$ K. The hardness of X-ray emission is maximal usually at the flare maximum. The electron number density of a hot plasma found from the models of the flare loops is of the order of $10^{11} - 10^{13}$ cm^{-3}.

According to Pallavicini et al. (1989) the stellar X-ray flares can be classified into two main groups: a) the impulsive flares with the dumping time of the order of a few minutes and b) the slow flares with the time decay of about an hour. Their analogies on the Sun are so-called compact and two-ribbon flares.

More informative are the coordinate observations of the flares in X-ray and optics. Unfortunately however only small part of X-ray observations were supported by simultaneous optical photometry and we do not known at present what are typical ratios of the luminosities L_x/L_{opt} at the maxima of light and the total energies E_x/E_{opt} of stellar flares (Byrne, 1989) Some of the optical flares had the X-ray counterparts . The best example of such event is the strong flare of UV Ceti (de Jager et al.1989) which was observed synchronously on the LE and ME detectors of EXOSAT (see Figure 3). Some of flares were observed without X-ray bursts (Karpen et al.1977; Doyle et al. 1988)

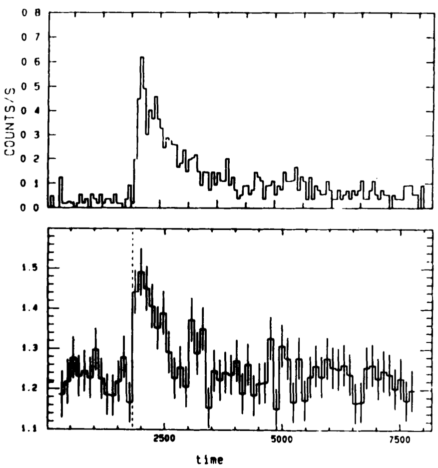

Figure 3. The strong flare of UV Ceti in X-ray (from de Jager et al. 1989). Top: the count rates in the Low Energy detector (40 - 200 Å); Bottom: the count rates in the Medium Energy detector (1 - 6 keV). The abscissa is the time in seconds. The vertical broken line in the lower diagram marks the time of maximum of the optical flare.

Therefore the radio and X-ray observations show the existence of a hot phase of stellar flares. At the same time they demonstrate one important difference between solar and stellar flares: at the flares on the Sun the strong correlation between optical, microwave and soft X-ray events exists.

In conclusion of this Section let us note two important results connected with the solar - stellar analogy. These are: a) the discovery by Saar et al. (1987) of the strong magnetic fields (4 - 6 kgs) on the flare stars, and b) the evidence of the similarity of the energetic spectra of stellar and solar flares (Gershberg, 1989; Schakhovskaja, 1989). According to Pustylnik (1988) this similarity may be due to a turbulent character of the magnetic energy output on the surface of the stars by the convective elements of different scales. It means, that starting from the microflares (Beskin et al. 1988) up to giant flares with the total energy of the order of 10^{35} ergs, we are dealing with the physical phenomena of the same nature.

3. THE THEORETICAL MODELS

The general similarity between solar and stellar flares means, that the processes of the primary energy release in both cases are qualitatively the same. As in the solar case we will distinguish two main phases of stellar flares: impulsive and gradual. The impulsive phase is undoupted-ly the key for the understanding of the flare mechanism. At the solar flares the primary process is realized in upper part of the magnetic loops and is due to magnetic reconnection *). Many important details of this process are unknown at present. But it is well known from the hard X-ray observations that this phase is accompanied by rapid acceleration of the charged particles.

The energy spectrum of fast electrons at the strong solar flares has the cut-off energy $E_1 \approx 10 - 20$ keV and the spectral index $\gamma \approx 3$ (Lin, 1974). The interaction of electron beam with the chromospheric plasma provides the heating of the gas up to coronal temperatures. From this hot region the energy penetrates into deeper layers of atmosphere by the conductivity, the shock front or X-ray and UV radiation. Simultaneously the hot plasma is evaporated into corona and provides the gradual phase of the flares.

These processes were considered from different points of view at the modelling of stellar flares. Mullan (1977) was the first who noticed the important role of conductivity in the energy transfer from a hot region of stellar flares. According to his very simplified model the main component of the optical continuum in the impulsive phase of stellar flares is the bremstrahlung radiation of a hot ($T \approx 10^7$ K) plasma that as has been mentioned in the Section 2.1 is in disagreement with the properties of the flare spectra.

3.1. THE HYDRODYNAMIC MODEL OF THE FLARES

Another flare model was considered by Katsova et al. (1981). They calculated the hydrodynamical response of the chromosphere of the red dwarf on the impulsive heating by the electron beam (taken into account the energy transfer by the conductivity). The parameters of the beam in their model was adopted as for strong solar flares: $E_1 = 15$ keV, $\gamma = 3$ and the initial energy flux $F = 10^{12}$ erg/s cm^{-2}. The duration of impulsive heating was equal to 10 seconds.

According to this model the optical flare arises in the dense layer beyond the shock front (see Figure 4). This layer is moving down into denser part of stellar atmosphere with the initial velocity of about 100 km/s which is in agreement with the observed red asymmetry of the emission line profiles in flares spectra.The parameters of optical flare in this model correspond to the parameters of the weak stellar flares.

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*) In principle another mechanism of the primary energy output at the stellar flares based on the idea of Z - pinch was suggested recently by Hayrapetyan et al. (1988) (see Hayrapetyan, this volume).

The further investigations of this type models are needed in the connection with the recent observations of ultra-short flare events (see Tovmasyan and Zalinyan, 1988).

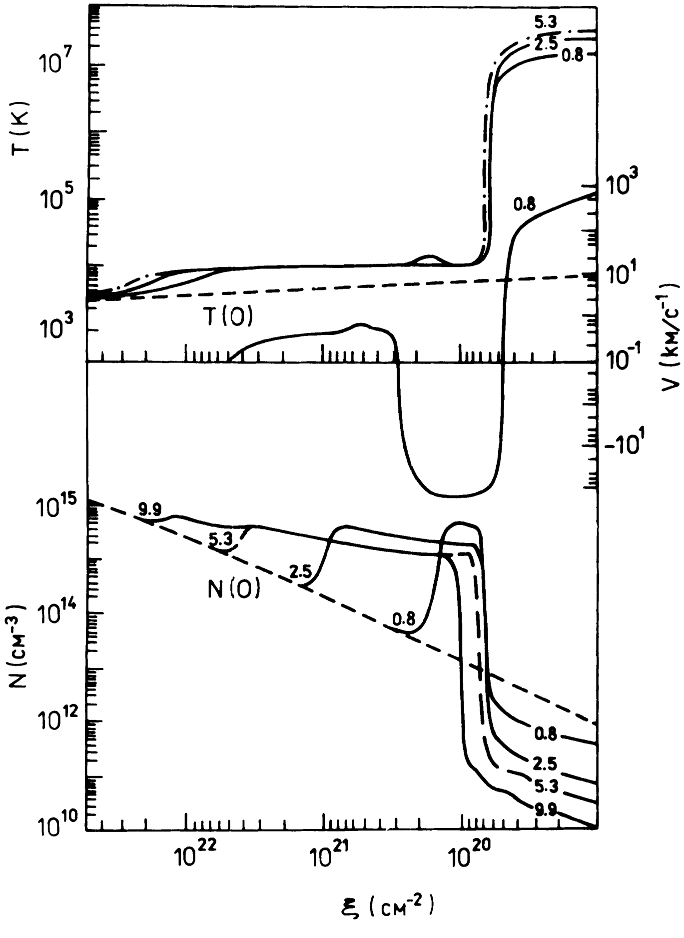

Figure 4. The hydrodynamical response of the atmosphere of a flare star on the impulsive heating by electron beam (from Katsova et al. 1981). (See text for details)

3.2. THE X-RAY HETING MODELS

The soft X-ray emission of the flares is another important mechanism of the heating of the stellar atmosphere. In the solar flare models it was considered by Somov (1975). Recently Hawley (1989) made a detailed investigation of this source of the heating taking into account the accurate non-LTE radiative cooling functions on hydrogen atoms and ions of Ca II and Mg II (see Figure 5). According to her calculations the soft X-ray emission with the parameters close to the observed ones provide the gas heating which explains fully the observational fluxies in the main emission lines of stellar flares. This conclusion is in agreement with the suggestion of Butler et al. (1989) that the Balmer emission lines result from irradiation by soft X-ray, which has been established from the fact of the existence of linear correlation between Hγ and soft X-ray fluxies of stellar flares.

Another important result of Hawley work is the estimation of the area of the flare region responsible for the emission lines formation: $S_{em\,l} \approx 10\%$ of the stellar disc area, that coincides with earlier estimations of Cram and Wood (1982).

Thus, the theoretical modelling of the flare spectra lead us to the following important conclusion: the spatial structure of stellar flares is qualitatively the same as the solar ones: the short-living spots of continuum emission are embedded in more extended region in which the emission lines are formed.

Unlike the Sun on the red dwarf stars due to low backgroung of the photospheric radiation the more extended low-temperature halo of the flares can be observed (Kunkel, 1970). The most probable source of the heating of this region is soft X-ray flare emission also, as was suggested by Mullan and Turter (1977).

The large area of the stellar atmosphere heated by the X-ray radiation of the fares (its size may be about 1/3 of the stellar radius) suggests, that the source of the heating is high over stellar surface. The latter means that the size of magnetic loops on the flare stars (filled by the evaporated plasma) should be compatible with the dimensions of the stars.

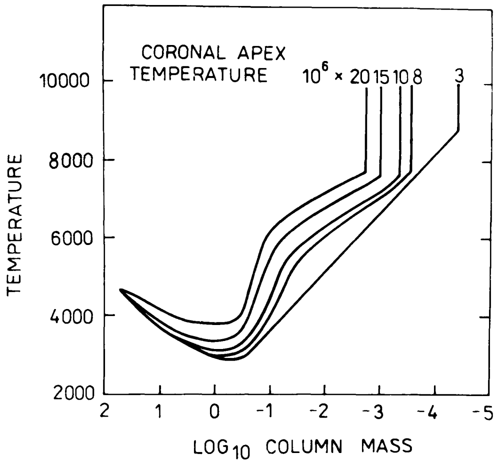

Figure 5. The temperature profiles in the flare model with the X-ray heating from Hawley (1989).

Thus the soft X-ray emission of the flares is an important (and probably the main) source of the gas heating at the gradual phase. It should be note however, that the role of this mechanism cannot be decisive at the impulsive phase of the stellar flares. This follows for example from the lack of the X-ray counterpart at the set of optical flares (see Section 2.4).

https://doi.org/10.1017/S007418090018790X Published online by Cambridge University Press

3.3 THE MODEL OF THE IMPULSIVE PHASE OF THE STELLAR FLARES

In the case of solar flares the bulk of accelerated electrons has a non-relativistic energies (tens keV). Such electrons are stopping in the chromospheric layers and heat them up to $T \approx 10^7$ K. Only a small part of the accelerated electrons penetrate into deeper layers of the solar atmosphere and their energy deposition is insufficient to produce the optical emission of white flares (Canfield et. al. 1986), (see, however Aboudarham and Henoux, 1986). There is a strong argument in favour of the fact that in case of stellar flares the situation is opposite and the direct heating of the low-temperature region of the flares by charged particles play more important role.

As was mentioned in the Section 2.1, the gas emitting in the optical continuum at the maxima of strong stellar flares is optically thick beyond Balmer jump. At the same time even the strongest white flares on the Sun are optically thin (Machado and Rust, 1974). Since the electron temperatures in both cases are about the same ($T \approx 10^4$ K), it means that the primary heating agent penetrates into deeper layers of stellar atmosphere (in the units of the column density), that at solar flares.

This idea has been used recently at the modelling of the impulsive phase of stellar flares (Grinin and Sobolev, 1989 a,b). We investigated the direct heating of the low-temperature region of the stellar flares by the beam of accelerated particles taking into account the radiative transfer.

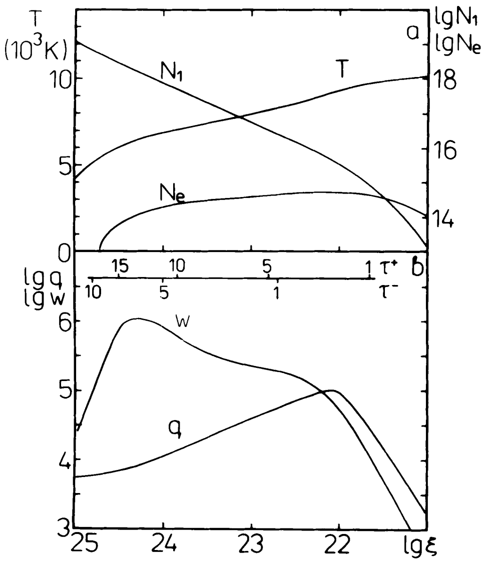

Figure 6 illustrates the parameters of the flare calculated in a thick target approximation at the following assumptions: the primary heating is due to the high energy proton beam with a power-low energetic spectrum. The parameters of the beam: the spectral index $\gamma = 3$, the cut-off energy $E_1 = 5$ MeV, the the initial energy flux $F = 5*10^{11}$ erg/cm^2 s. The free-free and free-bound transitions of hydrogen atoms and H^- in the LTE approach were taken into account at the calculations of the radiative cooling functions.

Figure 6. The model of the low-temperature flare region in the impulsive phase (see text for details). Top: the temperature, electron (N_e) and neutral atom (N_1) number density as a function of the column density ξ. Below: the energy deposition by charged particles (**q**) and by radiation of the flare itself (**w**) in erg/cm^3 s. The optical depths scale beyond (τ^+) and before (τ^-) Balmer jump.

Our main conclusions are the following:

a) The proton beam with the cut-off energy $E_1 \approx 3 - 10$ MeV and the initial flux $F \approx 10^{11} - 10^{12}$ erg/cm^{2}s provides the gas heating, which explains the observational properties of the optical continuum of the stellar flares at the maxima of light. The same results give the heating by the electron beam with the cut-off energy in $(m_p/m_e)^{1/2} \approx 50$ times less and the same spectral index.
b) In both cases the energy deposition by charged particles is maximal near the value of $\xi \approx 10^{22}$ cm^{-2} and the radiation of the flare heats deeper layers of the atmosphere ($\xi \approx 10^{24}$ cm^{-2}) . The role of the radiative transfer is especially important at the energy fluxies in the beam: $F > 3*10^{11}$ erg/cm^2 s, when the flare region is optically thick beyond Balmer jump. The radiation of the flare is quasi-black-body at these conditions in the agreement with the observations (see Figure 7).

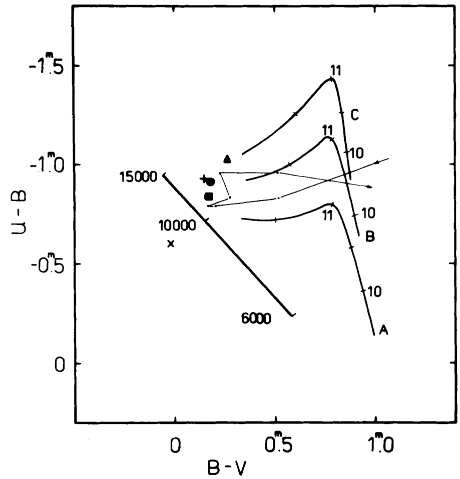

Figure 7. The theoretical two-colour diagram for the set of the models: A, B, C - corresponds to the values of the cut-off energy E_1 = 10, 5, 3 MeV. The values of Log F are given along theoretical lines. The mean values of the colour-indexes of the flares near maxima of light are given on the data by Moffett (1973) and Chugainov (1982): (x) -UV Ceti, (■) - CN Leo, (+) - EV Lac, (●) - - YZ CMi,(▲)-AD Leo. Thin line shows the evolution of the colour-indexes of the strong flare of BY Dra (from the paper of Chugainov, 1987).

Thus, the discussed above model gives the acceptable explanation of the most important phase of stellar flares. Its main difference from the classical models of the solar flares is the quantitative: *the more energetic accelerated particles in the beam.*

This model is insensitive to the kind of the charged particles (the protons or electrons). The arguments in favour of the protons are given in the papers by Van den Oord (1988), Grinin and Sobolev (1988) and Simnett (1989). The main argument is connected with the problem of the neutralization of the electric currents at the flares (Van den Oord, Simnett).

4. CONCLUSION

In the conclusion of this review let us return again to the problem of the solar-stellar analogy. It is well known from the solar physics that the energy spectra of the charged particles generated at the solar flares depend from the power of the events (Lin, 1974): most purely electron events are observed at the weak solar flares (importance 1 and subflares). The proton events are observed mainly at the strong flares (importance 2 and 3). The electron energy spectrum during proton events tends to be harder than for purely electron ones. The simple physical extrapolation of this tendency to the flare stars supports the main conclusion of the previous Section that the more energetic charged particles are generated in the impulsive phase of stellar flares. *This conclusion is not unexpected from the point of view of the solar-stellar analogy.*

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https://doi.org/10.1017/S007418090018790X Published online by Cambridge University Press

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PETTERSEN: Since Suzanne Hawley could not be present at this symposium, I would like to briefly comment on her interesting results, just discussed by Grinin. Her model calculations of the time evolution of hydrogen Balmer lines are in agreement with observations during flares. Energy is transported from coronal to chromospheric levels by radiation and thermal conduction in her model, and she is not able to obtain continuum results of the kind that we observe during flares. For that it is probably necessary to include accelerated particles, electrons and/or protons, directed towards the photosphere.

Suzanne Hawley is now preparing her results for journal publication, and I refer you to this.

RODONO: Your prediction of more energetic electron spectrum for stellar flares does it imply a larger than solar hard-X-ray flux from stellar flares? If so, the detection of hard X-ray emission from stellar flares would become possible.

GRININ: From an extrapolation of gamma given above we may expect a larger ratio of hard X-ray/soft X-ray emission in stellar flares.

MONTMERLE: Your Lx versus electron spectral index extrapolation would indicate delta=2 for flare stars. Could this index be determined directly by radio observations (gyrosynchrotron mechanism)?

GRININ: I believe this would be problematic because of the high sensitivity of the radio maser mechanism to different parameters of the plasma.