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FLARES OF STARS OF THE UV CETI TYPE*

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STARS of the UV Ceti type are red dwarfs whose brightness exhibits abrupt bursts from time to time. The duration of such bursts—flares—ranges from several seconds to several dozen minutes, and the flare amplitude ranges from several per cent of the normal brightness of the star to a 100-fold increase above normal. The red dwarfs, in turn, are in general stars whose mass is approximately one-tenth that of the sun, but their number amounts to 70—80 per cent of the stellar population of the galaxy; they are the most numerous and the weakest stars, weaker than the sun by 2—6 orders of magnitude. Such dwarf stars can therefore be investigated only in the nearest vicinity of the solar system (10—20 parsec), and the number of such known objects is small, about 500. Approximately 30 of them are classified reliably or tentatively as variable stars of the UV Ceti type. It can thus be stated that the flares of these stars are the most prevalent type of stellar variation in the galaxy.

Owing to the low luminosity, and principally the exceedingly short duration of the flares, these phenomena were discovered only some 40 years ago, in spite of the great abundance of stars of this type, and special investigations did not start until 1948. As a result of such investigations it has been possible to establish that flares of the same star can greatly differ from one another both in amplitude and in duration. The characteristic time between succeeding flares amounts to tens of hours, and there definitely exist periods of increased flare activity, in which the frequency of the flares rises to about 5 per hour. The main spectral peculiarity of the red dwarf stars, the surface material of which is not hotter than 3000°K, are strong titanium oxide absorption bands. As a rule, in the case of stars of the UV Ceti type, there is superimposed on this absorption spectrum the emission spectrum of ionized calcium, hydrogen, and less frequently neutral helium. During the time of the flare, the emission lines become much stronger and additional continuous radiation appears, which washes out the absorption details of the normal spectrum and is more noticeable in the short-wave region. Apparently all stars of the UV-Ceti type are parts of binary systems, and in all cases the flaring star seems to be the weaker component of the system, located about 1000 star radii away from the principal component. It was recently observed that powerful flares of the UV Ceti type stars are accompanied by bursts of nonthermal radio emission.

As the observations accumulated, many attempts were made to obtain a theoretical interpretation of the flares of stars of this type. Back in 1924, E. Herzsprung, who was the first to register such an event, proposed, in the spirit of the astronomy of his day, that the observed phenomenon may be connected with the falling of an asteroid on the star. As to the last 20 years, attempts were made to apply to the interpretation of these flares almost any new idea advanced in astrophysics. In the late Forties, when problems involving the interaction between stars and diffuse matter were intensely studied, it was proposed that the flares may be connected with the effects of screening or capture of matter by the star. This was followed by: the hypothesis of the hot spot on the surface of the star, the hypothesis of the occurrence of hot gas formations of the type of giant protuberances over the cold photosphere of these stars, the hypothesis of the emergence of unknown forms of prestellar matter to the surface, the hypothesis of special nuclear reaction on the surface, the hypothesis of synchrotron radiation of relativistic electrons in the upper layers of the atmosphere, the hypothesis of emission of non-equilibrium plasma (with ionization not corresponding to the temperature) when the gas jets are emitted and the ionization state is quenched, and the hypothesis of eruption of powerful streams of superthermal electrons and their Compton interaction with thermal photons in the atmosphere of the star. The mere listing of these hypotheses shows how vital the problem of flaring stars is in astrophysics and how skimpy the observational material is, leaving so broad a vista for theoretical constructions. There is in fact no meeting of mind presently even with respect to the basic question of what is actually observed during the time of the flare. An answer to this question can be obtained only by making detailed observations of the flares.

II

Photoelectric observations of the brightness of stars of the UV-Ceti type have been made since 1960

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*Expanded version of the paper "Spectrographic Investigation of Flaring Stars of the UV Ceti Type", delivered at the scientific session of the Division of General and Applied Physics, USSR Academy of Sciences, in November 1966.

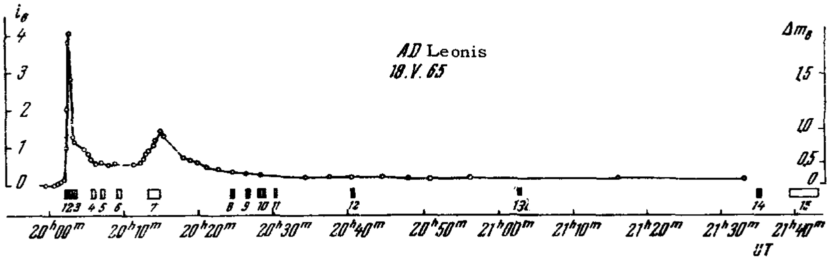

FIG. 1. Variation of the brightness of the star AD Leonis in the blue region of the spectrum during the time of the strong flare of 18 May 1965.

by P. F. Chugaĭnov at the Crimean Astrophysical Observatory of the USSR Academy of Sciences. About 50 flares were registered in several thousand hours of observations. The data obtained indicate that the rising part of the flare brightness curve is much steeper than the falling part, and that immediately following the brightness maximum there is a relatively rapid drop, which then gives way either to a much slower decrease, to a relatively short time interval in which the brightness is approximately constant, or to a secondary brightness maximum. During the course of the observation it became possible to estimate the color of the radiation in the flare, to observe multiple flares and to register, by performing simultaneous observations with the Jodrell Bank Radioastronomy Station (England), several brightness bursts simultaneously in the optical and radio bands. An analysis of these observations has shown the optical properties of flares of stars of the UV Ceti type do not contradict the hypothesis that hot gas is produced over the surface of the star, followed by rapid radiation from this formation, although such a scheme does not necessarily follow uniquely from the indicated observations.

The most information on the nature of the radiation and on the physical parameters of the luminous matter during the time of the flare can be obtained from spectral observations. Unfortunately, until recently all data on the flare spectra were limited to qualitative descriptions of four spectrograms, obtained with exposures on the order of one hour. These observations give only the most general idea of the spectrum of the flare, and yield neither quantitative estimates nor information on the evolution of the spectrum of the flares.

To solve the latter problem it is necessary to obtain spectra of flares with exposures on the order of ten seconds. When classical methods are used to register the radiation, the penetrating power of even the largest modern telescopes is insufficient for such observations. A special spectrograph was therefore connected at the Crimean astrophysical observatory, using electron-optical image amplification. The spectrograph is mounted on the 2.6 m reflector named after Academician G. A. Shain (ZTSH), and makes it possible to obtain flare spectra with short exposures—20 seconds for a star whose spectrum would take 2 hours to register with an ordinary spectrograph.

The first scientific results were obtained with this apparatus in the past year. The observations of flaring stars were made simultaneously with two telescopes: P. F. Chugaĭnov used a 64-cm telescope to register continuously the brightness of the star and the ZTSh to photograph the spectra during the flare. As a result, several dozen spectrograms were ob-

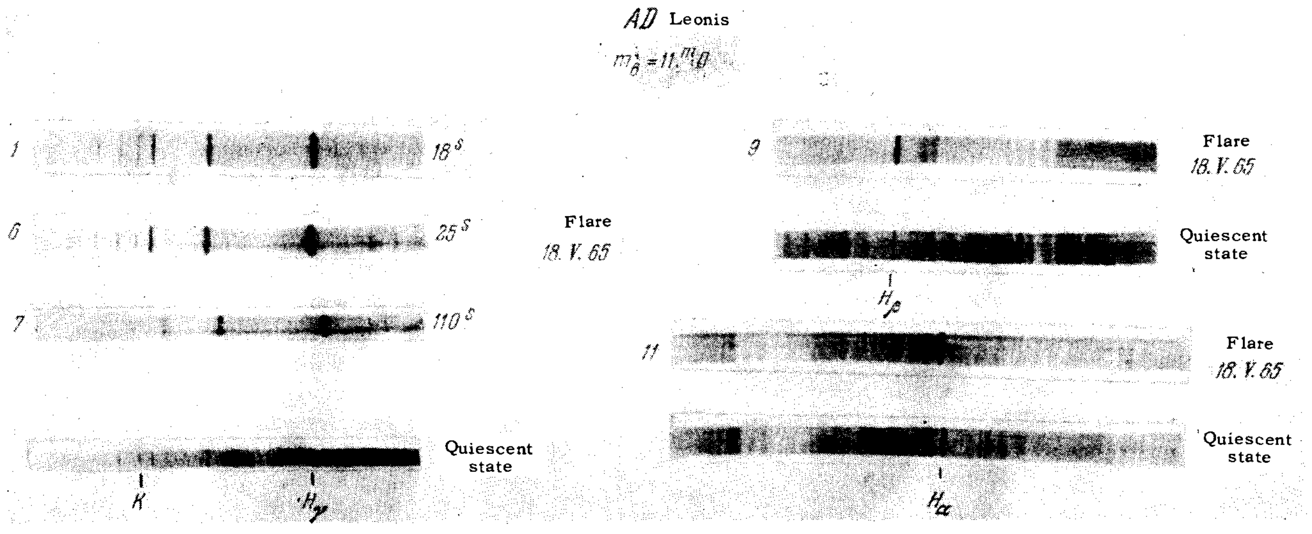

FIG. 2. Reproductions of spectrograms of AD Leonis on 18 May 1965.

tained of ten flares of two stars: AD Leonis—the brightness star of the UV Ceti type, and UV Ceti itself. The figures show the most illustrative of the observation results. Figure 1 shows a plot of the brightness of the most powerful of the registered flares of AD Leonis. At the instant of the brightness maximum, the radiation of the flare exceeded the normal brightness by a factor of 4, and after a rather rapid drop in brightness, a secondary maximum of appreciable amplitude and considerable duration was observed. The different symbols on the figure designate the instants of time when the spectra of the flare were obtained: The first seven light rectangles correspond to photography in the blue region, followed alternately by black and shaded rectangles corresponding to photography in the red and green regions of the spectrum. Figure 2 shows reproductions of several spectrograms of this flare. It follows from this figure that during the time of the flare the spectrum of the star changes in the blue region beyond recognition. Powerful emission lines appear, and the continuous emission washes out the absorption details of the normal spectrum. In the red and green regions, these effects are less noticeable. Figure 3 shows a plot of the brightness of the UV-Ceti flare registered by us, and Fig. 4 shows reproductions of several spectrograms of this flare. It must be borne in mind that UV Ceti is weaker than AD Leonis by a factor of 10, and therefore the spectrograms of UV Ceti were obtained with somewhat longer exposures, without broadening, and have a lower resolution than the spectrograms of AD Leonis; even in this case, however, it is possible to trace reliably the evolution of the emission and absorption details of the spectrum. (On the left of the spectra in Figs. 2 and 4 are indicated the numbers of the photographs, in accord with Figs. 1 and 3, and on the right of the spectra are indicated the durations of the exposures.)

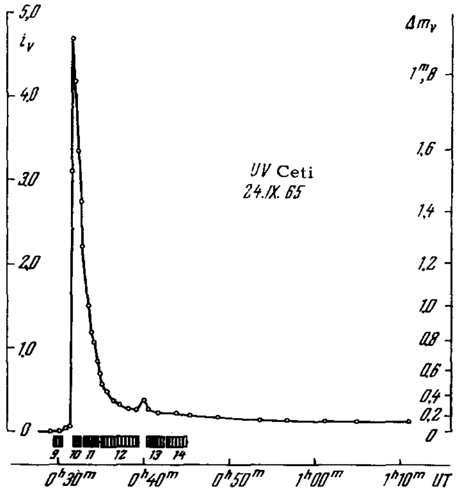

FIG. 3. Variation of the brightness of the star UV Ceti in the yellow-green region of the spectrum during the time of the strong flare of 24 September 1965.

All the pictures were measured photometrically, and yielded the first quantitative data on the intensities and widths of the emission lines of hydrogen, calcium, and helium, on the jumps of the intensity of the continuous spectrum at the limits of the molecular titanium oxide bands, and on the depth of the strong absorption line CaI λ 4227 Å during different stages of development of the flare and in the quiescent state of the star. Information was obtained on the connection between the spectral singularities of the flare and in its overall brightness power, interesting differences were observed in the spectra of the principal and secondary maxima of the brightness, and the local character of the flare in the atmosphere of the star was confirmed.

A preliminary analysis of these data was recently concluded. During the course of this analysis, principal attention was paid to the ratio of the flare radiation intensity in the Balmer lines to the intensity of the continuous emission of the flare in lines of neighboring frequencies, to the variation of this ratio, and to the variation of the line widths during different stages of development of flares of different strength. As is well known, this ratio (called the equivalent line width) and the line widths depend primarily on the temperature of the material and on the optical thickness at the center of the line. Within the framework of the hypothesis of the hot-gas emission in the flare, the observation data can be interpreted, roughly speaking, with the aid of two models: We can assume, on the one hand, that the material of the flare is at all times transparent in the entire optical frequency band, and its temperature at the instant of the maximum of the brightest flares reaches 10^6—10^7 °K and drops to 10^4 °K as a result of the radiation. Alternately, at the instant of the brightness maximum of a strong flare the optical thickness at the center of the Balmer lines is several units and decreases during the course of the radiation and expansion of the gas, the temperature being of the order of 10^4 °K all the time. Regardless how this dilemma is resolved, the main result of the analysis

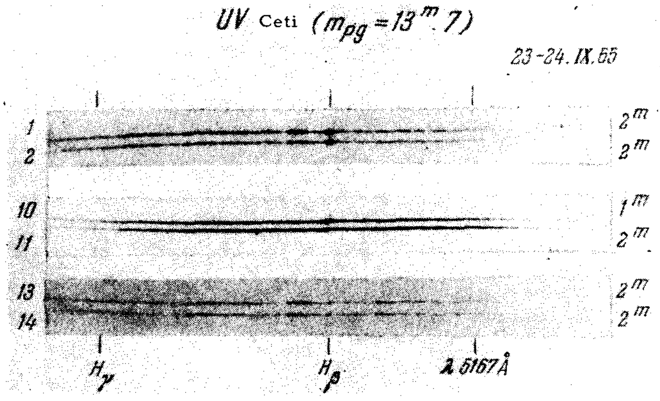

FIG. 4. Reproduction of spectrograms of UV Ceti of 24 September 1965.

can be formulated as an answer to the following question: What is that we observed during the time of the flare? All the observed spectral singularities of the optical emission of the flares of stars of the UV Ceti type can be explained within the framework of the hypothesis of radiating hot gas over the surface of a cold star, without making use of any other exotic emission mechanisms.

III

The experimental data described above allow us to carry out a preliminary examination of the possible mechanism for the formation of hot gas over the surface of stars of the UV Ceti type.

It was noted in the general description of stars of this type that their spectrum obtained in the quiescent state, reveals noticeable emission details. It is natural to interpret the emission observed in the integral spectrum of the star as coming from a powerful chromosphere. The chromosphere of the sun is defined as the layer of gas situated over the photosphere and exhibiting bright lines of hydrogen, Ca^+, and other atoms and ions. Starting with a certain level, the temperature of the chromosphere increases upward. The upper layers of the chromosphere go over into the corona, the temperature of which is still higher, reaching millions of degrees and more. The anomalous heating of the chromosphere is effected by waves traveling from the sun's convective zone, which is situated below the photosphere (for details see the review of S. B. Pikel'ner, UFN 88, 505 (1966), Sov. Phys. Uspekhi 9, 236 (1966)).

In analogy with the solar chromosphere, dwarf stars should also have a chromosphere and a corona, all the more since the convective motions generating the waves should be very strong in these cold stars.

Thus, in light of modern concepts regarding the internal structure of gas and the structure of stellar atmospheres, the very existence of strong permanent emission in the spectra of stars of the UV Ceti type leads to the very likely conclusion that hotter layers of the atmosphere, transparent to optical radiation, are constantly present above the relatively cold photosphere of these stars. The state of the matter in these layers is determined by the flux of non-radiative energy coming from below. If this is so, then we can consider at least three different mechanisms for the production of the hot gas that radiates during the time of the flare in the visible region of the spectrum; the choice between these mechanisms can be formally reduced to the question of localization of the flare in the atmosphere of the star. Indeed, it can be assumed that, owing to the thermal instability (strong dependence of the cooling on the temperature), phenomena of the protuberance-condensation type can develop in the coronas of these stars. Further, we can expect processes such as solar chromospheric flares in the large chromospheres of these stars. Finally, the internal convective motions can produce strong shock waves that emerge to the level of the photosphere. The available data are insufficient to give decisive preference to any of the three indicated localizations of the flares, but it is appropriate to present certain considerations pro and con each of the models.

Coronal condensation hypothesis. The temperature of stellar coronas is determined from the condition of approximate equality of the escape velocity in the gravitational field of the star and the average thermal velocity of the proton in the corona; the escape velocity is determined by the ratio of the mass of the star to its radius. Inasmuch of this ratio for the stars of the UV Ceti type is close to the corresponding ratio for the sun, the temperatures of the coronas should be close in both cases. As to the density of the matter, the solar corona and the corona of a star of the UV Ceti type may be quite different.

The localization of the flare in the corona, as noted above, offers a natural explanation for the observed widths and equivalent widths of the hydrogen lines, and also the intensity of the continuous radiation of the flares. If the flares are indeed the result of condensation of coronal gas, then the phase of the largest brightness of the He II lines should precede that of the maximum brightness of the He I lines. Unfortunately the available observations are not sufficient for a check on this conclusion.

The main difficulty with the coronal localization of the flare is the question of the mass of the gas. During the time of the strong flare of AD Leonis on 18 May 1965, 10^{33} erg was radiated in the photographic region; such an energy can be radiated by a gas with mass $\sim 10^{21}$ g. Since the flare is a local phenomenon in the atmosphere of the star (as proved by the conservation of the molecular bands in the green and red regions of the spectrum even during the time of maximum brightness of the strong flares), the total mass of the star's corona should be larger by at least 2—3 orders of magnitude than the estimated gas mass in the flare. On the other hand, the mass of the solar corona amounts to 3×10^{16}—10^{18} g. Consequently, the hypothesis of condensation in a continuously existing corona leads inevitably to the conclusion that stars of the UV Ceti type have coronas larger by 5—6 orders of magnitude than the solar corona. Since the solar corona is weaker by a factor of a million than the solar photosphere, and stars of the UV Ceti type are weaker in absolute magnitude than the sun by several orders, it is obvious that such powerful coronas should be revealed directly by coronal lines in the integral spectrum of the stars of this type. We note that if we forego the pure gas model of the flare and attribute the observed continuous radiation to some other mechanisms (synchrotron radiation, say, or the inverse Compton effect), then the difficulty with the large mass of radiating gas is not eliminated at all, since the line emission still constitutes an appreciable fraction of the total radiation of the flare, and the gas mass determined from the line emission gives at best a value smaller than the foregoing estimate by only one order of magnitude.

The chromospheric flare hypothesis. If the flare is localized at the level of the chromosphere, then the changes of the optical thickness of the radiating and expanding gas can explain the temperal variations of the equivalent widths of the emission lines, and the line widths make it possible to estimate only the upper limits of the true macroscopic velocities. We note that the velocities obtained are of the order of the characteristic velocities in solar chromospheric flares (up to 300—800 km/sec).

In principle, the question of the existence of powerful chromospheres in stars of the UV Ceti type was already discussed above. It should only be added that tidal perturbations, albeit weak (owing to the large distances between the components of the binary system), are neverthelsss constantly present and are superimposed on the internal convective motions, and should produce favorable conditions for the occurrence and intensification of the magnetic fields of these stars. At any rate, the large temporal variations of the flare activity suggest the existence in such objects of a certain analog of the period of solar activity.

It is possible that the large mass of the gas that radiates during the flare will raise difficulties also for the chromospheric localization of the flare, since the total mass of the solar chromosphere is of the same order of magnitude as the mass of the solar corona. But these difficulties cannot be as serious as in the coronal variant, since observation of stars of the UV Ceti type actually reveal that the chromosphere of these stars is much more larger than the solar one.

The shock-wave emergence hypothesis is free of the difficulties with the large mass of the radiating gas, and within the framework of this hypothesis the observed spectral singularities of the flares can be explained by postulating absorption of the radiation from the flare by the matter in the chromosphere, or by postulating self-absorption in the lines. Both in the chromospheric-flare hypothesis and in the shock-wave emergence hypothesis, it is immaterial to the observer whether the absorption takes polace in the upper layers of the chromosphere or in the radiating gas itself, but the dynamic situation in these two cases can be different.

Indeed, according to the hypothesis adopted here, the spectral singularities of a high-power flare near the brightness maximum correspond to emission of gas having an appreciable optical thickness in the Balmer lines, but this optical thickness becomes small during the course of de-excitation of such a flare, or in the case of a low-power flare. If the large thickness for the Balmer quanta in the initial phase of the strong flares is connected with the absorption in the unperturbed chromosphere lying over the flare, a decrease in this optical thickness as the flare becomes extinguished can be regarded as the result of the rising of the radiating gas above the effectively absorbing level of the chromosphere, or as the result of the increase in the degree of ionization and a corresponding "bleaching" of the chromosphere under the influence of the flare. But the optical thickness for weak flares turns out to be systematically lower, and this should mean that weak flares are localized in higher layers of the atmosphere than the strong flares. The physical cause of such a possible stratification of the flares is not clear.

On the other hand, if we deal with self-absorption, then all the flares can be localized at one level of the atmosphere, and we can attempt to attribute the decrease of the optical thickness of the radiating gas to rapid expansion. Obviously, the optical thickness in the lines of the radiating gas can decrease only if the characteristic time of the expansion of the flare l/v is much smaller than the characteristic recombination time $1/nC(T_e)$, i.e., when $n \ll v/lC(T_e)$, where n is the density of the radiating gas, v the expansion velocity, l the characteristic dimension of the flare, and $C(T_e)$ the recombination coefficient. Putting $C(T_e) \approx 10^{-13}$ cm^3/sec, $l \sim 0.1R_* \sim 0.01R_\odot \sim 10^9$ cm, and recognizing that $v < 10^8$ cm/sec, we get $n \ll 10^{12}$ cm^{-3}. Such a density corresponds to the upper solar chromosphere. In other words, the variant with self-absorption leads to the already encountered difficulty with the large mass of the radiating gas.

If further investigations show that we are nonetheless dealing with self-absorption, and not with selective screening of the flare by the chromosphere, then it will apparently be necessary to forego the very simple model of radiation from some initially ionized mass of gas, and consider the motion of a strong shock wave in the atmosphere, with a layer of radiating gas behind the shock-wave front. The radiation intensity of such a gas, its temperature, and its optical thickness should be determined by the strong shock wave and by the structure of the unperturbed atmosphere of the star. Inasmuch as no models have been calculated for the atmospheres of stars of the UV Ceti type, and such a calculation entails fundamental difficulties, it is impossible as yet to consider theoretically a hydrodynamic model of the flare. In particular, whereas it is still possible to use in some manner the analogy with the solar corona when considering the coronal localization of the flare, this can hardly be done at the level of the lower chromosphere, since the atmosphere of red dwarf stars contains a transition layer from molecular to atomic absorption; the solar atmosphere does not have this transition layer, since molecular absorption is negligible under the conditions of the solar photosphere, and the lower layers of the chromosphere of a red dwarf should have a more complicated structure than the lower chromosphere of the sun.

In conclusion, it must be emphasized once more that the aggregate of the observation data and the general theoretical considerations makes it possible to regard the flare activity of stars of the UV Ceti type on the whole as a phenomenon physically related to solar activity. The peculiarities of the internal structure of dwarf stars create favorable conditions for the release of large amounts of energy in such processes, and the absolute weakness of such stars makes such flares stand out in strong contrast against the normal glow of these objects. It is obvious that greatest success should be expected by performing simultaneous comprehensive photometric, spectrographic, polarimetric, and radioastronomic observations of these flares, since such investigations can yield in principle information on the state of the stellar atmosphere over its entire height, from the level of the photosphere, where the molecular absorption bands are produced, to the upper layers of the corona, from which the observed nonthermal radio emission may emerge.

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Translated by J. G. Adashko