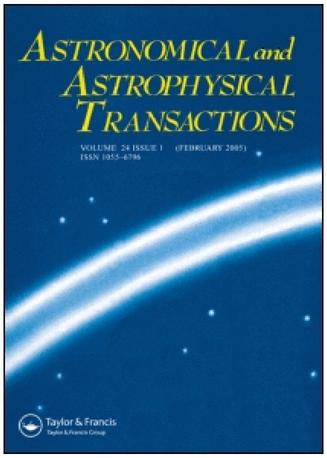

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GENERALIZED CONCEPT OF FLARES ON LATE-TYPE STARS

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Different kinds of stellar flares – very fast flares (0.1–10 s spikes), impulsive flares lasting 100–1000 s and flares with a long decay of the soft X-rays over hours–days – are described. Impulsive flares arises as a consequence of the energy input into the magnetically confined plasma. There is reason to suppose that these flares, which occur mainly on active red dwarfs (UV Cet-type), are a result of evolution of local magnetic fields, and they develop in low-lying loops. The response of the outer atmosphere of a star to impulsive heating is considered. It allows us to understand the origin of the X-ray and optical flare radiation in the framework of a uniform approach. In particular, optical radiation of sources formed during the gas-dynamic process considered does describe the flare observations quite well. Long-decay X-ray flares (LDF), which are more typical for components of RS CVn binaries, especially, for late-type subgiants, are a result of post-eruptive energy release. The duration of LDFs and peculiar features of the temporal behaviour of the temperature can be explained if this process is developed under prolonged heating in giant dense loops. The analysis of gas-dynamic processes in giant coronal loops indicates the existence of sustained heating during the soft X-ray flare. The total energy of such LDFs can reach $10^{35} - 10^{36}$ ergs, that can be supplied by large scale (global) magnetic fields.

KEY WORDS Stellar activity, X-ray flares, magnetic fields

1 INTRODUCTION: THE GENERALIZED CONCEPT

Solar-like flares have been observed on low-mass main sequence stars over the last 50 years in the optical range. Most such flares last from one tenth of a second to an hour. Their total energy covers the energetic range from 10^{27} to 10^{35} ergs. Over the last 20 years stellar impulsive flares have also been investigated in the X-ray range.

Furthermore, extremely powerful non-stationary events with a duration of around one day have been registered with the satellites GINGA, ASCA and BeppoSAX on different active late-type stars, among them subgiants of RS CVn binaries. In the course of such long-decay X-ray flares (LDF) very hot plasmas with temperatures more than 10^8 K have been detected over many hours. As a rule, these events are not seen in the optical continuum. The total energy of these LDFs reaches up to 5×10^{36} ergs.

Solar X-ray observations show that all phenomena developing in the corona during flares can be divided into two groups. The first group includes those processes that are accompanied by free radiation without additional energy input into a coronal flare source. This follows from the observational fact that the soft X-ray emission decreases in a characteristic time $\tau_{\rm decay}$, comparable with the radiative cooling time of plasma: $\tau_{\rm rad} = 3kT/nL(T)$, where n, T are the density and the temperature of plasma, $L(T)$ is the radiative cooling function and k is the Boltzmann constant.

On the Sun, as a rule, a whole flare or isolated phases of a complicated phenomenon are impulsive events. During such a pulse non-thermal, hard X-ray emission is registered. A criterion for division of flares into these two groups is well fulfilled by red dwarfs: $\tau_{\rm decay} = \tau_{\rm rad}$ during most non-stationary events which are mostly impulsive ones. Note that total duration of impulsive phenomena does not exceed a few hundreds of seconds.

The second group of phenomena with a long-duration decay of soft X-rays, LDF where $\tau_{\rm decay} > \tau_{\rm rad}$ is characterized by an additional heating of a coronal flare source, lasting from tens of minutes to one–two days. As a rule this event arises after a significant outflow of matter as a surge or CME, that allows one to refer this phenomenon (or the phase of a whole flare) as an event with a post-eruptive energy release. Such post-eruptive processes are developed in the course of some two-ribbon flares on the Sun (cusp-like events) and dynamic flares with the development of a system of giant arches.

The **goal** of this talk is to show that impulsive events on the Sun and on late-type stars differ from LDFs not only by their durations, but that they present two different classes of physical processes. Impulsive events occur in one or several low-lying confined magnetic loops, while LDFs take place in giant coronal loops, where force lines in the upper part of a magnetic configuration are open, i.e. expand into the heliosphere. If, during impulsive events, the primary energy release is situated in a very compact low-lying volume above a penumbra of spots, then during LDFs the energy is released high in the corona. Of course, there are some, most often powerful, flares with a complicated spatial-temporal structure. If, during their impulsive phase, the magnetic configuration turns out open, then the energy release becomes post-eruptive, and henceforth, the primary and secondary processes will develop differently from impulsive phenomena.

We discuss in more detail a comparison of observations with the theory and gas-dynamic processes; MHD and plasma astrophysical problems as well as features of radio emission will be apart of this talk.

2 IMPULSIVE FLARES

An impulsive flare is the result of a sudden powerful energy release which occurs above the chromosphere (on the Sun at heights of ≤ 10000 km) near spots or regions with strong magnetic fields. At present the mechanism of the primary energy release is not yet clear, but a few ideas are discussed. A pioneering idea by Alfven and Carlqvist (1967) was that the energy is released in a large-scale current in a small volume as happens in the current interruption model. Another idea by Sakai and de Jager (1996) discusses collisions between current-carrying loops and their coalescence. Analogous studies of reconnection of oppositely directed magnetic fields (see, for instance, Syrovatskii, 1966) is often proposed for the primary energy release of impulsive flares. However, there is still a problem to find direct observational evidence for this mechanism in such events.

Every act of primary energy release is accompanied by a standard response of the chromosphere to the impulsive heating by fluxes of heat or of accelerated electrons. This secondary process often includes explosive evaporation, when a downward moving shock wave is formed, and the hot gas evaporates into the coronal part of the loop. Between this radiative shock wave and the flaring transition region, the chromospheric, low-temperature condensation forms. It moves toward the photosphere and becomes a source of the flare optical continuum as well as Balmer and Ca II line emission. Hot gas with $T = (2\text{–}3) \times 10^7$ K flows outwards, to the corona with velocities up to 1000 km/s (see the gas-dynamic model by Katsova *et al.*, 1997).

Many features of this gas-dynamic model for an elementary pulse are confirmed observationally not only in solar, but also in the stellar case. Due to the quite complicated distribution of physical parameters inside the chromospheric condensation versus the height, only recently has it become possible to compute exactly the optical line and continuum flare emission (Katsova *et al.*, 1999); so, the theoretical spectrum is in a good agreement with observations of fast stellar flares.

Thus, it becomes clear that a general feature of impulsive processes is that the main portion of the primary energy is transformed into gas-dynamic motions in the course of the explosive evaporation and heating of the plasma. But during powerful impulsive phenomena a significant part of the primary energy is spent on formation of the optical continuum.

Observations of the flare optical continuum simultaneously with the soft X-rays during impulsive stellar flares allow one to estimate reliably the area of the low-temperature source and the size of a coronal loop. For instance, for the UV Cet 30-s flare (Haisch, Schmitt, and Barwig 1993) the flare area is 3×10^{17} cm^2, and the length of a flare loop is 15000 km. So, our gas-dynamic model allows us to interpret at the same time optical and X-ray observational data for fast impulsive flares on red dwarf stars.

The flaring process in one high coronal loop extends quickly to a whole arcade. Development of processes in a particular impulsive flare on the Sun depends on the rate of particle acceleration, features of their propagation in the loop and the evolution of their spectrum. A distinction between these impulsive flares is manifested in the hard X-ray radiation: for example, at the range around 20 keV the non-thermal to the thermal radiation ratio can vary in some cases from a few percent to 100%.

A hot plasma, evaporating from the chromosphere near one footpoint of the loop, together with low-energy particles gradually fill up one or more high coronal loops. The volume and correspondingly the emission of hot gas increase significantly. The soft X-ray emission reaches its maximum; its absorption in lower dense layers can lead to the appearance of a second, more uniformly distributed over the surface source of line and continuum emission. Many loops with cool plasma are also formed during this gradual phase. For this time the model of the optical source is characterized by a smoother variation of physical parameters, i.e. by the temperature plateau. For this case it also becomes possible to give an interpretation of the optical spectrum of a stellar flare (see Poster by Baranovsky *et al.* presented at this meeting).

Unfortunately, the hard X-ray radiation of stellar flares is still not observed, except for a registration at the onset of one LDF (Pallavicini and Tagliaferri, 1998), therefore details of these processes in stellar coronae can not be investigated.

In solar two-ribbon flares the loop arcade is situated above the inversion (neutral) line of the longitudinal magnetic field. In some cases, a closed magnetic configuration can transform to an open one, and the magnetic force lines will be extend into the interplanetary medium. For parts of the neutral line, located inside an active region (i.e. in the region of strong local magnetic fields), large surges or CME can open the magnetic configuration. However, in strong magnetic fields it only happens sometimes, apparently, in cusp-type flares. At the impulsive phase of the most powerful flares a transformation of the closed magnetic configuration into an open one can be caused not only by a surge or CME but also by the extremely powerful evaporation of plasma from the footpoints of the loops.

Propagation of the flaring process along the arcade to a region of weak magnetic fields (outside the active region or during flares which occur in regions without spots) also leads to opening of the configuration. All this is the cause of a subsequent post-eruptive energy release.

3 LONG-DECAY X-RAY FLARES

Our overview of LDFs will consider both observational and theoretical aspects. Although cool giant arches have long been observed in the H_α line, investigations of dynamic flares on the Sun in soft X-rays by Svestka *et al.* (1997) (see also references therein) made possible a subsequent theoretical analysis. Systems of giant post-flare arches are observed either at the final stage of strong flares or during ejection of giant filaments in large outspot flares similar to the event on April 14, 1994 (McAllister *et al.*, 1996) or September 12, 2000. These arches ascend very high, up to $0.5R_\odot$, and have a much longer lifetime compared with typical post-flare loops. The ascension and development of giant arches occur quite slowly often with a constant speed of growth. Then cusp-type flares like on February 21, 1992 were studied, in particular, by Tsuneta (1996); they demonstrate the role of reconnection in the current sheet. This sheet is situated vertically nearby a plane of the magnetic equator of a large-scale dipole, whose axis is parallel to the solar surface. One observational indication of the realization of reconnection is the shrinkage-effect (Forbes and Acton, 1996).

Thus, the solar investigations led considerable advances in the understanding of the nature of long duration solar flares. The ideas by Sturrock, Kopp and Pneuman about the post-eruptive energy release are confirmed by the Yohkoh results. Indeed, it is possible to distinguish an active phase from the whole LDF, which lasts from 0.5 to 2–3 hours after the LDF onset. During this phase the reconnection arises at increasing heights in the vertical current sheet. New loops form and shrink during this active phase, and a plasmoid is ejected to the outer corona simultaneously with this process. At the end of the active phase, one or several giant loops form and exist from 12 hours to one day.

The active phase of the LDF was extracted by Getman and Livshits (1999, 2000). It is best seen in the elementary LDF on January 24, 1992, where the shrinkage-effect was observed directly. This event, as well as the flare on October 28–29, 1992 (Svestka *et al.*, 1997) led to the formation (or re-formation) of a streamer. In these weak X-ray events the vertical current sheet apparently existed prior the flare, and only the speed of plasma inflow into this current sheet increases when matter is ejected and subsequent post-eruptive processes develop.

Getman and Livshits (1999, 2000) carried out a numerical simulation of gas-dynamic processes in the giant loop at the dynamic stage of the LDF, when the ratio of the gas pressure to the magnetic pressure $\beta = 8\pi p/H^2$ in giant loops becomes greater than 1. They showed that maintaining the X-ray flux for several hours is possible only with an input of the energy into the loop throughout the lifetime of the LDF. The total energy of solar LDFs, which significantly differ in temperatures at the top of the giant loop $(5–25) \times 10^6$ K, turns out to be comparable to the energy of powerful impulsive flares.

As was mentioned in the introduction, the soft X-ray radiation of very powerful LDFs is observed on active late-type stars. Prolonged flares were observed on two red dwarf stars AU Mic and EV Lac (Drake *et al.*, 1994; Katsova *et al.*, 1999; Favata *et al.*, 2000), several RS CVn binaries (Osten and Brown, 1999; Güdel *et al.*, 1999; Pallavicini and Tagliaferri, 1998), a young G0 star AB Dor (Maggio *et al.*, 2000) and Algol (Schmitt and Favata, 1999). In the most powerful of these events, a hot plasma with a temperature $> 10^8$ K and an emission more than 10^{54} cm^{-3} have been detected over many hours.

The previous code for solar LDFs by Getman was modified by Livshits (2000) in order to carry out computations for stellar conditions of various gravity and higher energy of the process. Then numerical modelling of the energy balance in the giant loop was carried out by solving the one-dimensional gas-dynamic equations taking into account the gravity (which varies with height), the thermal conduction and radiative losses. The heating near the top of the giant loop was distributed over time and space (along the mass Lagrangian coordinate).

The computations were carried out for initial densities from 2×10^{10} to 5×10^{11} cm^{-3}, with an initial semi-length of the loop $l = (0.5–5) \times 10^{10}$ cm and the heat fluxes varied over wide ranges. For these processes, the total energy of which doesn't exceed 10^{37} erg, the loop top temperature turns out to be in the ranges of $(10–200) \times 10^6$ K. For similar initial models two sets of solutions can be separated when the density in the loop turns out to be greater or less than the value 4×10^{11}

cm^{-3}; (this density corresponds to the initial model with the temperature 20×10^6 K and semi-length $l = 2 \times 10^5$ km and depends only weakly on these values). In dense coronal loops, after the maximum of heating, the expansion of the giant loop changes to compression.

The typical behaviour of the temperature in a powerful long decay flare on active stars, where the gravity is lower than on the Sun, can be understood only in the case of strong loop expansion. So, for the UX Ari flare, registered on August 29, 1997 by Pallavicini and Tagliaferri (1998), such temporal dependences of the temperature as well as the emission, derived from observations, testifies that this process develops in very dense coronal loops ($n = 10^{11}$–10^{12} cm^{-3}). In this UX Ari flare such dense loops ascend to heights of up to 10^{11} cm, i.e. more than $0.2R_*$. These powerful events are interpreted here in the framework of a model of a set of 8–10 loops, but not of a one-loop model (Livshits 2000).

4 CONCLUDING REMARKS

Thus, the X-ray observations allow to propose the most adequate criterium for rough classification of flares on the Sun and active late-type stars in general. All the above testifies that during these non-stationary events two classes of processes are developed, the first of them is characterized by the energy release in very small volume with comparable strong magnetic fields; in the second type of flares the energy is releazed in a large volume of the corona after significant global changes of the magnetic configuration due to an eruption.

Recent observations of huge LDFs on stars show that their energy can not be provided by evolution of local magnetic fields of active regions on late-type stars. Here the necessary energy is supplied only by large-scale (global) magnetic fields.

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