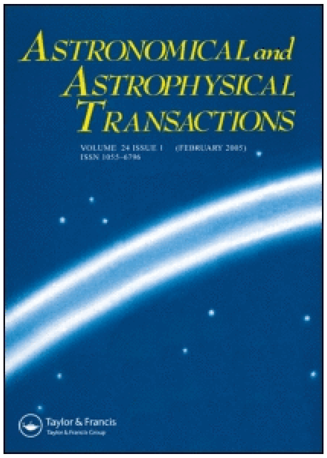

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E. I. Mogilevskii [a]; V. N. Obridko [a]; N. S. Shilova [a]
[a] IZMIRAN, Troitsk, Moscow Region, Russia

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On a probable model of solar flares based on an 'avalanche' of self-organized criticality with energy and matter transport by magnetohydrodynamic solitons

E. I. MOGILEVSKII, V. N. OBRIDKO* and N. S. SHILOVA

IZMIRAN, Troitsk, Moscow Region 142190, Russia

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The problem of energy transport by magnetohydrodynamic (MHD) solitons to the local region of a solar flare is considered within the framework of a new concept on the nature of solar flares as an effect of the unloading of matter and energy under self-organized criticality. The high-resolution observations ($\pm 1''$) by the TRACE spacecraft are used. The characteristics of the small-scale discrete flare elements are shown to correspond to the properties of MHD solitons. Therefore, the above-mentioned concept represents conclusive evidence of the fractal-cluster structure of the solar magnetized plasma.

Keywords: Fractals on the Sun; Self-organized criticality; Magnetohydrodynamic soliton; Solar flares

1. Introduction

A fractal-cluster structure of the solar magnetoplasma (*i.e.* the plasma whose macrostructures are composed of small-scale ($\pm 1''$) initial self-similar discrete elements) was justified recently by both statistical methods and direct observations [1, 2].

The discrete structure of solar atmospheric phenomena has been detected in the last few decades by the high space-time resolution observations by the Yohkoh, SOHO and, in particular, TRACE spacecraft.

The achievements in studying the fine structure of the magnetized solar plasma completely change our previous concepts on the nature of solar phenomena. The structure revealed is a direct consequence of the nonlinear character of the solar medium, dominated by nonlinear wave processes. The observed process of self-organized criticality is treated as reaching the minimum energy for a set of the fractal elements (clusters). This state can be realized in the solar atmosphere by the transfer of energy of magnetohydrodynamic (MHD) solitons formed in the solar plasma.

The fractal paradigm and the related concept of self-organized criticality are universal and independent of the scales of the respective phenomena. As a result, there are a great number of

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*Corresponding author. Email: solter@izmiran.troitsk.ru

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publications where these principles are applied to astrophysics, geophysics, seismology and so on. One of the branches of development of such a study is the problem of the origin of the corona and solar flares [3]. The flare is considered in this approach as an unloading of energy and matter in the active region where self-organized criticality occurs.

Our aim is not to construct a new model of the solar flares on the basis of self-organized criticality but instead to consider a probable process of formation of the self-organized criticality in the solar active region (AR) under the assumption that energy and matter are carried by the flux of MHD solitons. These solitons are created in the upper part of convection zone, which represents a nonlinear medium with weak dispersion (the plasma with a magnetic field). The dynamics of the solitons could be the basic reason for the appearance of self-organized criticality, followed by unloading of substance in the process of motion to the chromosphere, transition layer and corona.

The observational data on fine-structure elements in the flares and before the flares in active regions will be considered in section 2. Next, we shall compare the observed features of the fine-structure elements and solitons in section 3. Finally, the flare will be considered as a phenomenon of self-organized criticality in section 4.

2. Observational data

Our analysis will be based on a series of observations of the AR just before and during the flares. We shall use the films obtained for the most part by TRACE and in some cases by SOHO, which were retrieved from the Internet. The basic aim is to check whether the observed features of complexes of the small-scale ($\pm 10^8$ cm) bright elements correspond to the properties of MHD solitons.

2.1 *Resonant Doublet C IV (λ = 1548 Å and 1550.8 Å)*

An especially high resolution ($\pm 1''$) was achieved by the TRACE experiments in the C IV line. Images of the selected parts of the solar disc (the ARs, etc.) were detected by the high-sensitive multielement matrix receivers using changeable ultraviolet narrow-band filters. The hot coronal lines 171 Å (Fe X-Fe IX) and 195 Å (Fe XIII) were used in the ultraviolet range. Movies of the flares in the region of the resonant doublet C IV, which corresponds to a temperature of 10^5 K, were obtained in the range 1550–660 Å by a 37 Å filter. The respective emission refers to the lower boundary of the transition zone. Gallagher *et al.* [4] studied the flare images of several lines. They found that the specific features of the events have the most contrast for the C IV lines. The brightness increases in the main peak of the flare by a factor of 10 against the background in the C IV line and by a factor of only 2 in the coronal lines (171 Å and 195 Å). Since just the observations of the C IV doublet are the most promising to reveal small-scale structures in both the ARs and the quiet regions, our basic analysis was carried out using the C IV movies.

2.2 *Structure of the solar corona and transition layer in the regions without flares*

A negative picture of the AR of the C IV line is presented in figure 1. There are many points with a size of about 1000 km over the entire field, both inside and outside the AR. As follows from a comparison of several successive pictures, these small-scale self-similar details of the fine structure migrate in a random way and form mesostructure chains, outlining the supergranules. They are magnetosensitive and follow the supergranule cell motions. It is reasonable to suppose

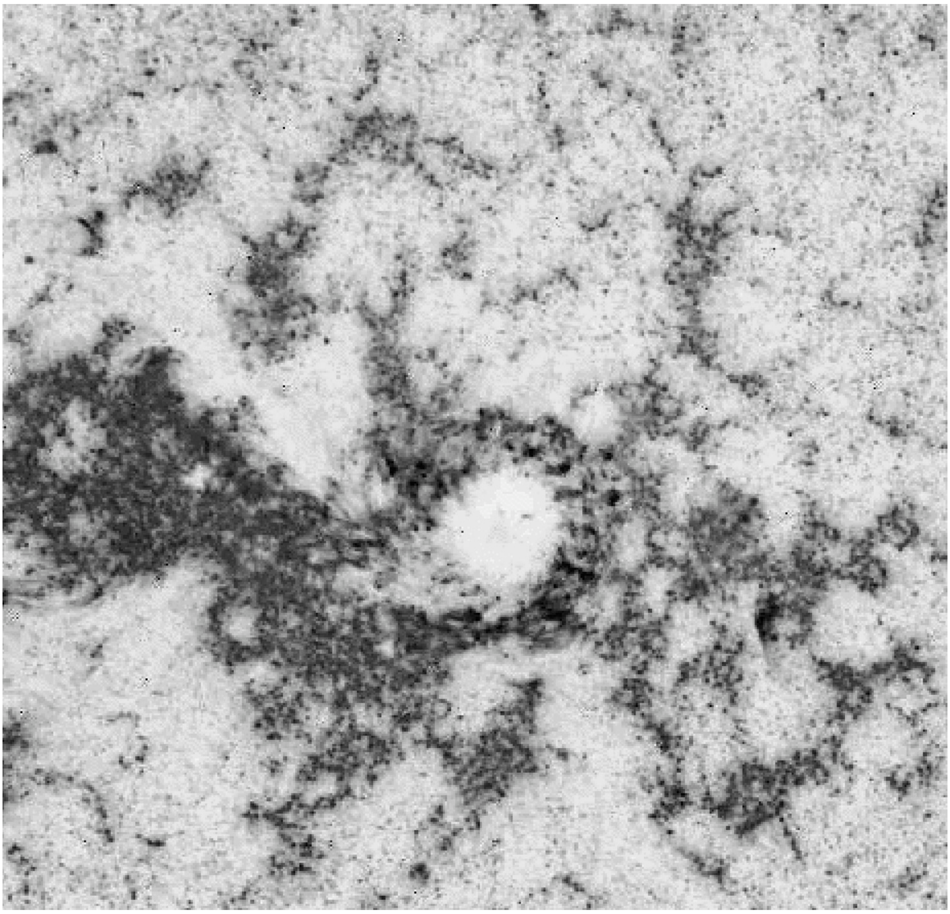

Figure 1. Filtergram obtained by TRACE for C IV on 28 November 2000, near the AR 9240 N09, W02, at 16:32:26 Universal Time (UT).

that they form clusters. Comparison of the filtergram of C IV in the disc centre with the respective magnetogram obtained by the Michelson Doppler image (MDI) apparatus (the magnetograph for line-of-sight magnetic field) at the SOHO spacecraft demonstrates excellent similarity between the dimensions and structure of the field in the photosphere and atmosphere of the AR. The supergranulation structure has approximately the same contrast as that of the chromospheric Ca II line. The similarity between the undisturbed atmosphere of the C IV line and that of the MDI–SOHO magnetogram was obtained also by Tarbell *et al.* [5].

The flocculi in C IV filtergrams are also composed of fine structure elements (about 10^8 cm), whose aggregates were called 'moss' by Berger *et al.* [6] and Martens *et al.* [7]. The arches of the filtergrams in the soft X-ray band observed by the Yohkoh satellite are located above the bright points of flocculi in the coronal line $\lambda = 171$ Å. The moss cells have a temperature of about 0.6–1.6 MK and a pressure of about 0.7–1.7 dyn, that is twice the pressure in the undisturbed corona. The velocity of motion of the bright points is about 50–100 km s^{-1}. Martens *et al.* [7] mentioned that heating the loops and pressure in their bases are determined presumably by the chromospheric phenomena. Warren [8] showed that the flares in the filtergrams at $\lambda = 171$ Å are also composed of many fine structures. As will be demonstrated below, some features of the bright moss elements correspond to the properties of the fractal elements, which are composed of smaller objects with magnetic fields of various polarities.

2.3 *The small-scale structures at the initial instants of flare onset*

Let us consider the first instants of the small flare C2.4 in the C IV movie, which was observed on 6 December 2000, near the limb. The interval between frames of the film equals 30 s (figure 2). Within the first 2 min, the flare looks like a spiral with a number of small bright elements in its nodes and an extended glow on the top. The dimensions of the bright local points or elements are close to those of the bright moss elements. These bright local objects will be called blobs hereafter.

The configuration of the spiral changed within 2 min after the above-mentioned instant; a second spiral of smaller cross-section was formed inside the first spiral. Nodes of the second spiral appeared with velocity of about 150 km s^{-1}. As a result, the entire structure of the flare also arose. Not only can we observe the blobs by themselves but also we can reveal their specific localization in some nodes of the changed spatial lattice. From our point of view, every blob is a soliton of sine–Gordon type; that is we observe a kink and a chain of bright points (see section 3 below).

Let us consider the behaviour of the emitting structures in the vicinity of the large spot. A continuous flow of the bright elements from the centre across the perimeter of the large spot

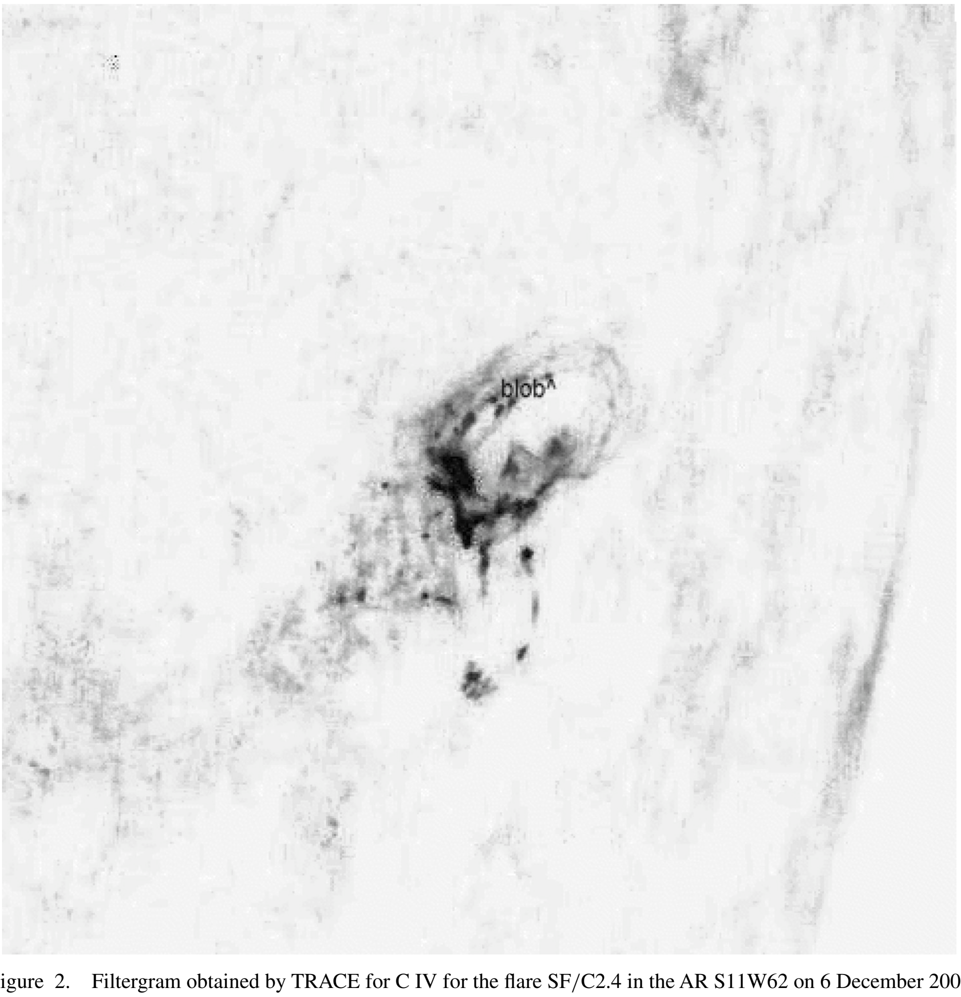

Figure 2. Filtergram obtained by TRACE for C IV for the flare SF/C2.4 in the AR S11W62 on 6 December 2000 at 12:51:31 UT.

was observed in the C IV line. The number of such ejections and their brightness increased considerably just before the flare. The flow of blobs can be interpreted as a chain of small MHD solitons, propagating upwards from the photospheric level and facilitating formation of self-organized criticality in the AR.

On 24 November 2000, a proton flare occurred in AR 9336. This region was studied in the framework of the international program MEOC. Also, three other powerful flares, namely X2.0/3B, X2.3/2B and X1.8/2N, occurred in AR 9336 on the same day. On 25 November, the flares M3.5/2N and X1.9/2B took place in the same region. On 26 November, the flares M2.2/1F and X4.0 occurred again. The region under consideration consisted of a large spot with an extended active core, possessing south polarity with intensity 2600 G. The flare elements with size about 10^8 cm (*i.e.* the blobs) were ejected from the outer boundary of the spot umbra. On 23–24 November (*i.e.* before the flares), a new magnetic field with south polarity arose in the western part of the spot. The small-scale structures in the spot umbra were associated with appearance of new regions of the magnetic field or its redistribution (figure 3). A bright ejection was formed in the spot umbra at 13:28 UT; 5 min later, we could see two ejections; 30 min later, three ejection were observed. Finally, within the next 48 min, one of the ejections sharply expanded, so that the glow area increased. This resulted in the onset of the X2.3/2B flare.

The flare elements (blobs) followed the ambient magnetic field and produced a bright ring around the spot (figure 3). Yet another characteristic feature was the localization of the energy release. The frequency of ejections was considerably less in the eastern part of the spot, which was not involved in the flare. The lifetimes of the bright flare ejections were substantially shorter than those of the low-luminosity elements. The qualitative description of the preflare situation and onset of the flare by itself were presented above in detail because these seem to contain the characteristic stages of development of the activity. For example, the flare on 6 August 2001, presented in the C IV filtergram in many respects followed the same sequence of events. A chain of the cores with north polarity near the southwest boundary of the spot was not covered by the emission. On 5 August 2001, the leader spot of the group 9557, possessing north polarity, was the basic spot for the emission of the subflares at 15:26–15:33–15:55 and 15:03–15:04–15:17 UT. On the other hand, a chain of the cores with south polarity did not produce flare emission. It should be mentioned that bright fragments of the flare can be detected only at the first instants of the glow (not later than 5 min after its beginning), that is before the flare maximum, when the separate emitting fragments merge with each other.

If a flare was located far from the limb and was observed only in filtergrams of the coronal line $\lambda = 171$ Å, then, to increase the contrast, we drew difference images. In other words, the filtergram before the flare was subtracted from that taken at the first instant of the flare onset. An example of such picture is shown in figure 4. The C IV filtergrams of the M1.2/2F flare

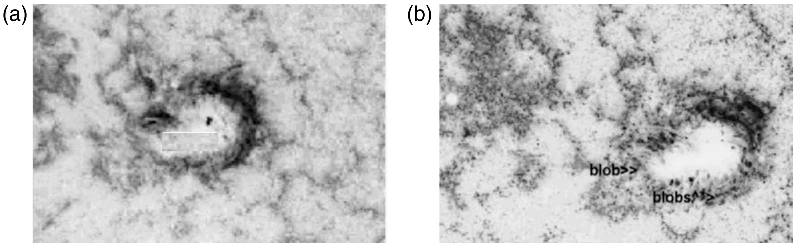

Figure 3. Filtergram obtained by TRACE for C IV on 24 November 2000 at 13:32 UT (negative); showing the bright points (a) in the centre of the spot before the flare MEOC 2B/X2.3 and (b) near the boundary of the umbra.

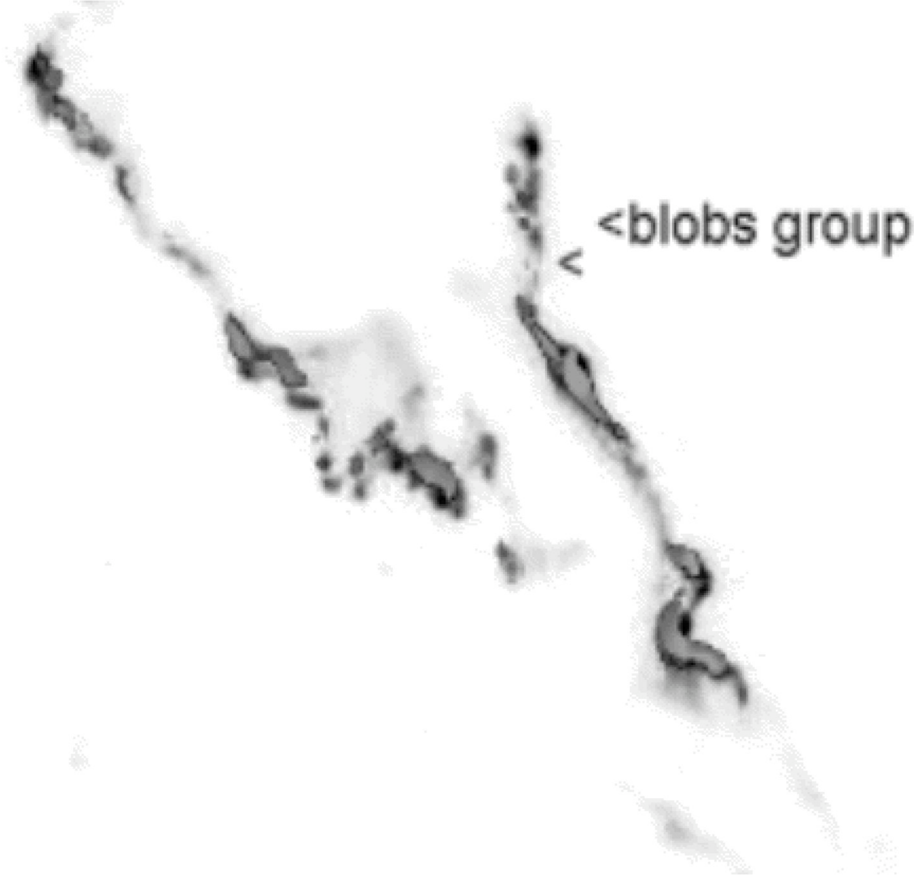

Figure 4. Difference filtergram obtained by TRACE for C IV at the first instants of the flare 2F/M1.2 on 20 January 2001 at 18:42 UT in the region S07, E40.

on 20 January 2001 at 18:40–18:53–20:02 UT in the region S07, E40, and at 18:42 UT were used. We can clearly see a fragmented structure, which is initially weak and then becomes stronger. Each detail consists of several small-scale fragments.

The other flare 3B on 6 June 2000, at 12:06–15:21–18:43 UT and 12:06–12:09 UT (in the region N10, E18) looks in the TRACE filtergrams like chains of several dozens of fragments, localized near and along the trace of the filament. A general conclusion that can be derived from our analysis is that a flux of the blobs going from the spot cores (or their neighbourhood) precedes the flare. It is just this flux that produces the state of self-organized criticality, which manifests itself as a flare.

3. Comparing the properties of small–scale elements and solitons

The present section is devoted to consideration of some characteristics of the small-scale elements in the flare and in the AR before the flare, which can be used to verify their solitonic nature.

First of all, let us recall the basic properties of solitons.

Solitons can be defined as the solitary pulsed, weakly-damped waves formed in nonlinear media with weak dispersion in the low-frequency or high-frequency spectral ranges, when the effect of the breaking of a nonlinear wave is compensated by the dispersion. In the case under consideration, the respective nonlinear medium is the magnetized plasma at various levels, from the subphotospheric layers to corona. As distinct from linear waves, solitons do not interfere with each other, do not experience diffraction and from a certain point of view behave like particles. The soliton fluxes can be generated in ARs on the Sun and serve as probable agents for energy and matter transport. Really, sonic waves in the medium with decreasing density are transformed into shock waves and dissipate very quickly. Alfvén waves may be the energy carriers, but they also experience resonant absorption in the structured medium as sonic waves. So, solitons are the most suitable agents for energy and matter transport in a nonlinear medium.

Solitons are the solutions of the basic differential equations in a nonlinear medium. They are the Korteweg–de Vries and sine–Gordon equations. Applicability of the respective basic equation is determined by the properties of the medium as well as the spectral range of the phenomenon under consideration.

The formation of MHD solitons in the subphotospheric and photospheric magnetized plasma (*i.e.* at the plasma factor $E_{\text{kin}}/E_{\text{mag}} = 4\pi m V^2/B^2 > 1$) is associated with propagation of the sound wave excited by an increasing subconvective element. The case under consideration refers to nonlinearity at *high* frequencies. The dispersion relation in the medium with decreasing density and weak negative dispersion will take the form [9, 10]

$$\omega = c_0 k - \beta k^3 + \cdots . \tag{1}$$

Here c_0 is the phase speed, k is the wave vector and β is a constant. In a coordinate system moving with speed c_0 the Korteweg–de Vries equation holds:

$$U_t + U U_x + \beta U_{xxx} = 0, \tag{2}$$

where U is the magnitude of the magnetic vector. The solution of equation (2) is the soliton given by

$$U = U_0 \cosh^{-2}\left(\frac{x - ct}{\Delta}\right). \tag{3}$$

Here, cosh is the hyperbolic cosine, and Δ is the soliton width.

A chain of two-dimensional MHD solitons can be formed in the chromosphere and transition zone as a result of solving yet another basic equation, namely the sine–Gordon equation. Nonlinearity at *low* frequencies takes place in the regions of the solar atmosphere with $E_{\text{kin}}/E_{\text{mag}} = 4\pi m V^2/B^2 < 1$. The evolutionary sine–Gordon equation

$$U_{tt} - c_0^2 U_{xx} + \omega_0^2 \sin U = 0 \tag{4}$$

possesses a solution in the form of a chain of weakly coupled solitons:

$$U(\xi) = 4 \arctan\, \exp\left(\frac{\pm\omega_0 \xi}{c_0}\right), \tag{5}$$

where ξ is the current variable.

By using the above-listed mathematical properties and the experimental data discussed in section 2, let us emphasize some common features of the small-scale elements and solitons.

3.1 *Morphological properties*

A characteristic feature of the flare on 6 December 2000 is the lattice whose nodes contain luminous blobs representing the structural elements of the flare. These blobs possess one of the properties of solitons: the greater their brightness, the shorter is their lifetime (because they 'explode').

During the flares near the large spot, the outflux of blobs is followed by a change in the shape of the spot (or its core). This fact points to the subphotospheric origin of the respective structures.

The blobs do not interact with each other. In the same manner as solitons with a fluctuating tail, the blobs stick to one another and form pairs.

The speed of motion of the blobs turns out to be 200 km s^{-1} or less. This is close to the value of the magnetosonic velocity in the solar atmosphere. Such a velocity should be characteristic of the nodes of MHD solitons, according to the sine–Gordon equation. A set of exploding blobs defines the ribbons of the flare. For example, as seen in the flare on 24 November 2000, the ragged boundaries of the flare emission represent thin branches originating from separate luminous blobs.

3.2 *Estimate of the emitted energy*

We tried to obtain an observational estimate for the energy of one term of the chain of MHD solitons, carrying the energy to the flare region. By the use of a small diaphragm, we were able to separate one element in the image and to determine its brightness in arbitrary units. As a result, it was established that the brightness of blobs is approximately the same as the flare brightness. On the average, a flare covers 20–100 pixels, whose sizes correspond to the blobs. The brightness of blobs is three to five times greater than the brightness of the same area of flocculi in C IV and Lα lines. It is difficult to estimate the brightness of flocculi in the 171 Å line because of a great number of fine details. The energy emitted by flare in the 171 Å line was estimated to be 10^{28} erg [11], that is of the same order as the energy in the C IV line. Since the flare area is larger than the soliton area by a factor of 100, then the energy emitted by one soliton in the ultraviolet range can be roughly estimated to be about 10^{25}–10^{26} erg.

4. Flare as a phenomenon of self-organized criticality

As already mentioned above, new attempts at constructing models of solar flares are based on applying the concept of a stochastic effect in nonlinear media with self-organized criticality in the ARs. The flare by itself is considered as an effect of unloading (or avalanches) of matter and energy in various spectral ranges (from γ-rays and X-rays to the infrared and radio emission).

A threshold concentration can be created in the fractal complex under certain conditions of energy influx, which is necessary for generation of the fine-structure elements. Quick unloading occurs if the energy and matter continue to flow to this region. The arising *singularity of threshold concentration* of fractals was called by Robinson [12] and Bas *et al.* [13] *self-organized criticality*. The above-cited workers revealed the effect of self-organized criticality in laboratory experiments with friable substances. The calculations were carried out later using the method of 'cellular automat'. As was shown by subsequent investigations, the respective phenomena are independent of the scales under consideration. Their important feature is also a self-organized restoration of the initial state after threshold unloading.

The self-organized criticality of a medium can be realized in a dynamic system if the respective influx of energy is present. As regards the case considered in our paper, this is the solar AR in the process of development. A local state of self-organized criticality can stimulate a perturbation in the entire system. In the case of the AR on the Sun, this is realized by the changing topology and structure of the magnetic field in a large volume after the flare or manifests itself as a coronal mass ejection.

Self-organized criticality, as the state with minimal kinetic energy and magnetic field, corresponds to *the attractor* of the given system. Phase trajectories of the evolving system tend to this state. In general, the dependence of the *power* of the flare occurrence on their importance confirms the fractal nature of active phenomena on the Sun.

Therefore, a flare can be treated as the effect of unloading energy at self-organized criticality. The entire process can be schematically presented as a nonlinear interaction between the processes of transfer and dissipation of energy. A relatively weak flux of solitons from the subphotospheric layers to the undisturbed regions is completely compensated by dissipative processes in a quite simple quasi-potential magnetic field of the chromosphere and corona. Both the amplitude and the complexity of the magnetic field increase with increasing activity. This results in increasing upward flux of blobs (*i.e.* solitons) to the corona and, simultaneously, in increasing dissipation in the corona. The solitons, which did not interact with each other before, begin to interact in a more complex magnetic field of the corona, particularly as a result of the reconnection. Such magnetic reconnection may occur both between different solitons and inside each soliton. These processes lead to heating of the corona over the AR and to formation of *coronal condensation*. Marik and Erdelyi [14] analysed the magnetic reconnection as a multiple process in subtelescopic fractal elements. A subsequent development of this process results in the phenomenon of self-organized criticality, unloading of energy, and the flare.

In general, the data presented above correspond to the concept of transport of energy to the region where the conditions of self-organized criticality are realized, followed by unloading of energy in the form of a flare composed of a set of solitons.

Acknowledgements

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