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Topological Model of the Solar Event Including a Flare and Coronal Mass Ejection on October 19, 2001

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Abstract—Based on the analysis of a strong solar flare X1.6/2B on October 19, 2001 in the active region 9661, accompanied by a coronal mass ejection (CME) of the halo type, a topological model of development of this solar event is suggested. The model considers a unified process of development of CME and a chromosphere flare. According to the model, this process has a common source of energy supply: the turbulent current layer lying between the arcade of flare loops and the surface of CME going away. The structures on the ends of flare bands (SEFB) represent in this model chromosphere feet of the system of large-scale coronal magnetic arches at the initial stage of the dynamic processes whose evolution results in CME. Peripheral structures (PS) of the flare (elongated double bright emission strips beyond the limits of the active region) are interpreted as chromosphere bases of magnetic field lines that form an external shell (braid) of the CME at the late stage of the flare.

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INTRODUCTION

Detailed analysis of the structure of strong solar flares allows one to isolate those its elements that are not described by the existing models. In particular, flare bands (FB) do not exhaust the structure of chromosphere emission details. In addition to them, remote chromosphere brightenings [1] are observed, as well as peripheral structures (PS) of the flare [2], and bright structures on the ends of flare bands (SEFB) [3]. In some cases strong flares are accompanied by powerful phenomena of the type of coronal mass ejections (CMEs). The particular places of their formation and visual manifestations at the chromosphere level at the early stage of development still remain unclear, as well as topological connection with flares in the events associated with them.

In this paper we consider a qualitative topological model of development of a single event including a strong solar flare of importance X1.6/2B occurred on October 19, 2001 in active region 9661 (the time of maximum is about 16:30 UT, Fig. 1) and a quick CME of the halo type. We have used for our analysis 90 digital H_α-images of the flare (the angular resolution of the best pictures is down to 0.7 angular seconds, time resolution of the series is 90 s, the Big Bear Observatory), images of the upper corona provided by the space laboratories *SOHO* and *TRACE*, and the data on variations of the integral flux of solar emission in the X-ray range obtained by the *GOES* spacecraft.

STRUCTURE OF THE FLARE

The following morphological elements of the flare are selected.

The flare bands (FB). This is a bipolar structure of two emission flare bands, typical for strong chromosphere flares and observed in the H_α line. As a flare develops, this structure diverges, and the velocity of propagation of the FB front is 1–5 km/s [2]. The values of contrast with respect to the level of undisturbed chromosphere in H_α line always exceeded 130%.

The structures on the ends of flare bands (SEFB). These dynamic flare emission structures are described for a number of strong flares. They are distinguished by high brightness and irregular form [3–5]. As a rule, SEFB quickly change their brightness, reshape in a ring-like form, and fade away long before the end of H_α-flare development. Each SEFB is unipolar (located in the zone of one polarity of the magnetic field (MF).

The peripheral structures (PS). PS represent bright emission structures on the periphery of active region (AR). Typical contrast values for PS is about 100%, their area is less than the FB area by a factor of 1.5–2 [2]. Starting from the moment of the flare maximum PS were formed in the zone of one MF polarity in the form of thin double emission strips (Fig. 2). Their width is 1.5 to 2 thousand kilometers, which is 4–5 times less than the FB width. The distance between PS strips is from 2 to 10 thousand kilometers. The double strip of PS propagated along the flocculi with an

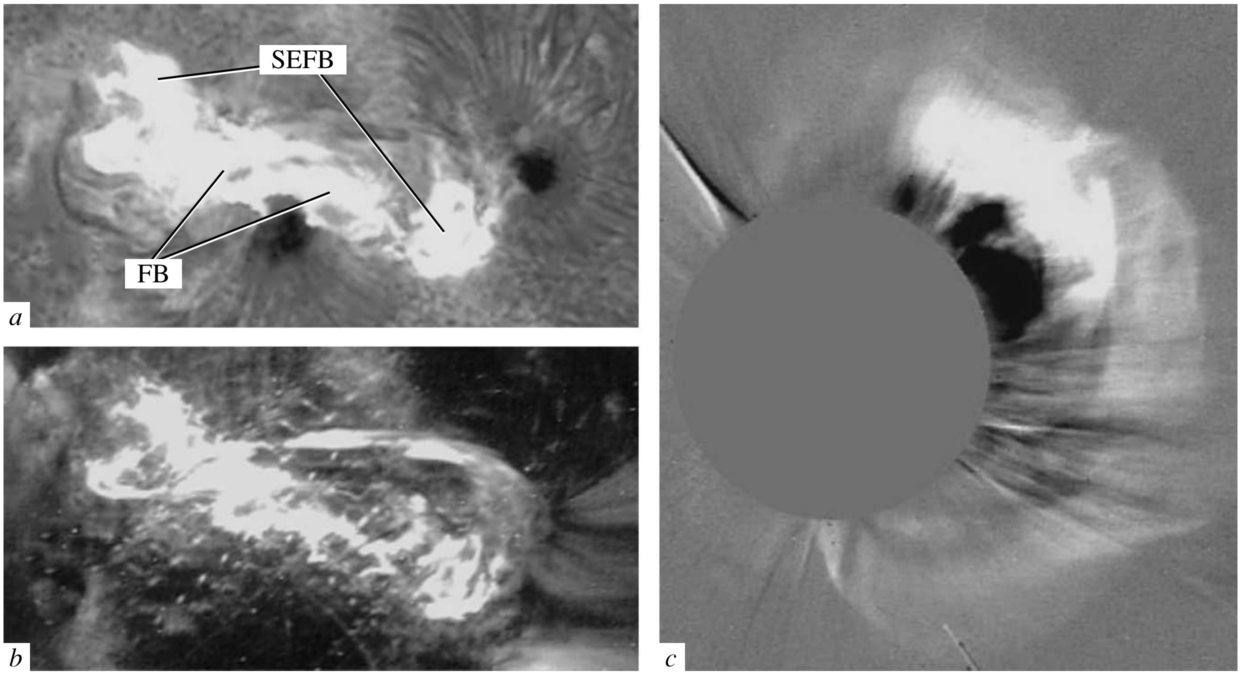

Fig. 1. The flare on October 19, 2001 on before-the maximum stage of its development (16:24 UT): (*a*) the image in the line H_α (Big Bear observatory), (*b*) the image in the waveband 171 Å (*TRACE* spacecraft). (*c*) The coronal mass ejection of the "halo" type detected by the *SOHO* spacecraft starting from 16:50 UT.

average velocity of 150 km/s, the maximum velocity magnitude being about 600 km/s. The maximum brightness was observed in the outer (with respect to the active region) narrow PS strip and on the front of propagating emission.

Casual relationship between the flare and CME. After the flare onset a powerful CME associated with it has been observed by the instruments of the *SOHO* satellite [6–7]. The following additional arguments can be presented in favor of the statement of a close relation between the flare and this CME.

1. Magnetic polarities of the regions where SEFB were developed are opposite, so that a possibility of magnetic reconnection is admitted.

2. In some pictures of available images in different wavelength ranges one can immediately observe extended coronal loops connecting SEFB regions during the phase preceding the CME development.

Within the framework of this hypothesis one can state that the CME started developing immediately in the flare region. The SEFB are bases of a braid of elevating field lines that represent the background for CME development.

TOPOLOGY OF THE FLARE AND CME

Let us consider a three-dimensional topological model of the process of interrelated development of the flare and CME on October 19, 2001. The model describes the event starting from the growth phase of the flare (coinciding in time with the acceleration phase for CME in the lower corona) until the phase of flare decay. The suggested model does not contradict the classical 2-dimensional and 2.5-dimensional models constructed as a part of the CSHKP concept [8–12] and supplements them taking into account a number of new phenomenological details.

The first stage of event development. The arcade of flare loops touches by its chain of tops a quasi-cylindrical shell of a developing ejection (CME) consisting of helically twisted magnetic field lines (Fig. 3). The axial magnetic braid located inside the shell is the spinal arch of the CME. The bases on the braid are closed onto the chromosphere near the SEFB center.

Low arches of the flare are positioned at an acute angle to the line dividing magnetic polarities (LDP). Helical magnetic field lines of the CME shell (in what follows, helical lines) touch the chain of loop tops of the flare arcade in the lower part of the CME. As a result, the magnetic field at tops of the flare arches turns out to be anti-parallel to the field at lower points of helical lines on the CME shell.

On the line of contact between loop tops of the flare arcade and the lower CME surface, according to [13], a high-temperature turbulent current layer (CL) is developed. In contemporary flare models this layer is described as a region of magnetic reconnection (release of MF potential energy). The vertical cross section perpendicular to the axial magnetic braid of the CME gives the so-called *X*-point (Fig. 4).

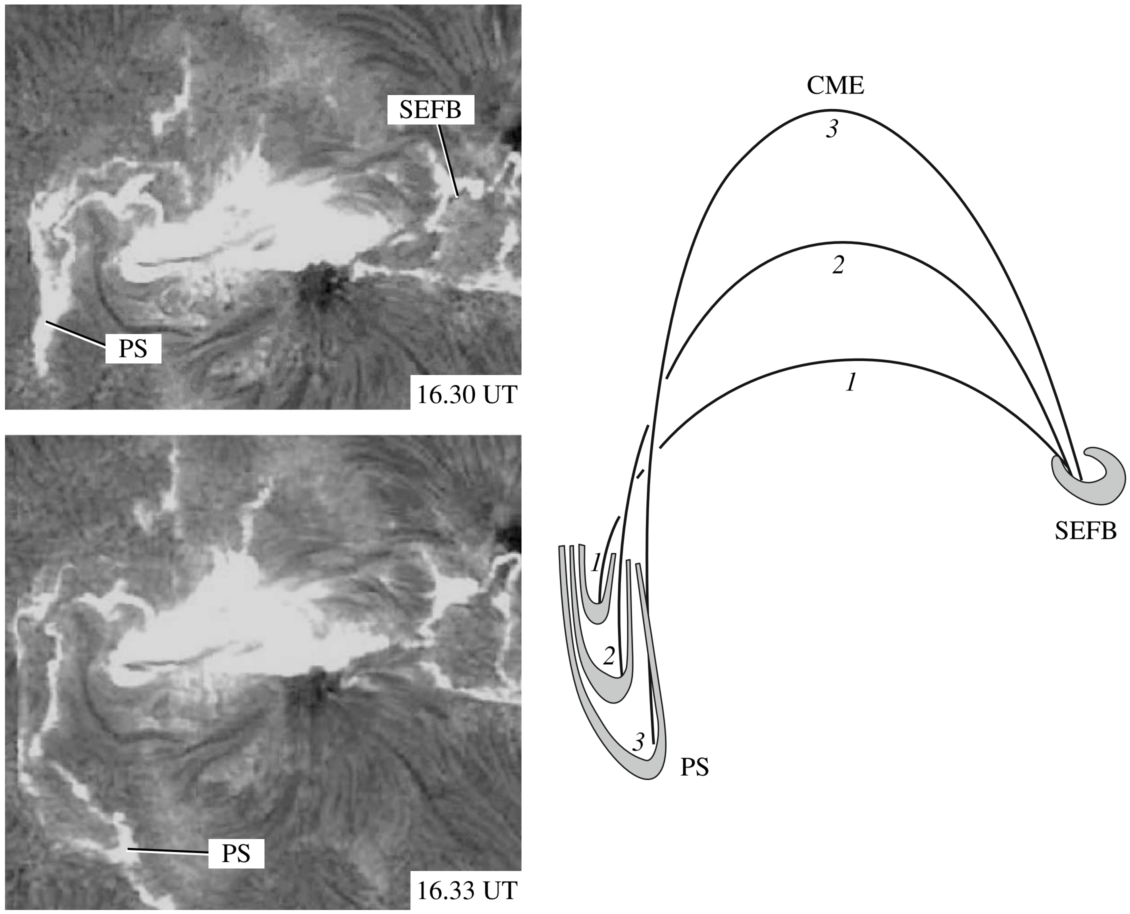

Fig. 2. Development of periphery structures during the flare (on the left) and presumable scheme of the system SEFB–PS (on the right).

In accordance with the model under consideration, beams of high-energy particles escaping the CL move in four directions: downward along the feet of loops of the flare arcade and laterally along the CME helical lines causing the SEFB appearance.

It is reasonable to suppose that the fluxes of particles from a single source of energy release have close parameters. Consequently, one can expect a similarity in emission development of FB and SEFB on the phase of flare growth. This assumption is confirmed by the fact of correlated development of the area of H_α emission in FB and SEFB (Fig. 5). Accordingly, on this phase of development of a powerful event one should expect, based on the model, also a correlation in the behavior of HXR sources at the bases of flare arches and in the bases of CME.

In the chromosphere regions (FB and SEFB), where the beams of energetic particles precipitating from CL are thermalized, magnetic tubes are filled by evaporating chromosphere plasma [12, 14–16]. The latter, elevating, fills both flare arches and CME. However, because of the substantial difference in volumes the reached density of matter is radically different. The volume of flare arches increases rather slowly, while the volume of rapidly elevating and inflating CME builds up swiftly, providing for significantly lower density of matter in CME in comparison with flare arches. This circumstance can explain distinctions in the emission behavior at the bases of flare arches (FB) and at the bases of CME (SEFB), starting from the flare maximum.

The suggested model also easily explains the HXR-source in the corona described by Somov [13], which correlates with HXR-sources at the bases of FB. As was pointed out above, in the context of the suggested model, particles coming out of the CL move in four directions. The particles having gone to CME move along helical lines that form the outer shell (shield) of the ridge magnetic braid of CME (Figs. 3 and 4) and hit the outer (upper) front of CME. Here, they collide with compacted moving plasma of the outer front of CME and generate emission in the hard x-ray range. The time behavior of the intensity of x-ray emission naturally correlates with that for the emission caused by the fluxes of particles that went down to the bases of flare arches [13]. A part of the particle flux having passed through the CME front continues moving along helical trajectories down to their chromosphere bases (SEFB).

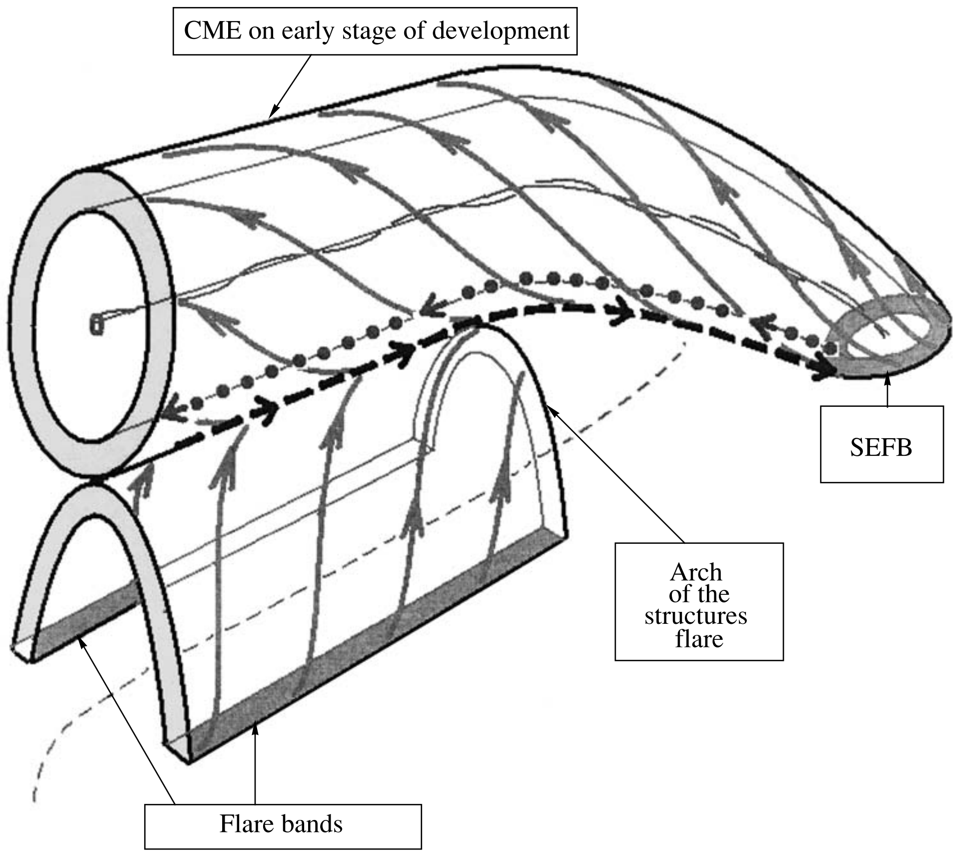

Fig. 3. The topological scheme of the solar event “flare–CME” at the early stage of its development.

Thus, the model predicts the existence of correlation in the behavior of three types of HXR sources: on the CME front, in the bases of flare arches (FB), and in two bases of CME (SEFB) on the early stage of flare development.

In principle, based on the model, it becomes possible to calculate the location of CL region where the main impulsive energy release has occurred.

Let us consider the cross section of the flare arcade and CME in the plane perpendicular to the LDP (Fig. 4). We project magnetic field lines of the flare arcade and CME onto this cross section. Successive involvement in the flare process of the outer (higher and higher) arches is accompanied by a lift of CME and displacement of the *X*-point (of CL cross section) upward, as well as by formation of the new (next) outer shell of CME. The CME lift causes displacement (stretching) of magnetic field lines to the *X*-point in the horizontal direction (shown by double arrows). As a result, reconnection occurs and the cycle is repeated, forming every time a new outer arcade of flare loops and a new outer shell of CME. Involvement into the process increasingly more outer flare arches leads, according to classical conceptions, to the effect of FB divergence [17], and similarly, involvement of new outer shells of CME leads to widening of the SEFB ring. It is supposed that external magnetic field lines approaching from two sides the *X*-point (CL cross section) are closed above a forming CME (not shown in the figure).

Figure 4 shows a displacement of the *X*-point upwards, as well as particle fluxes propagating from the CL in four directions: two downward (forming FB), and two along the helical lines of the CME shell (see Fig. 3). The latter two beams reach the chromosphere level forming two structures of SEFB.

The development of events according to this scheme embraces the time interval including the process of CME acceleration in the lower corona, coinciding with the stage of rapid divergence of FB before the flare maximum. Near the flare maximum the energy flux transported by the beams of accelerated particles originating in the CL drops down. By this time, the central segments of the ring SEFB loss their brightness.

The second stage of event development. Near the maximum phase of a flare a rapid development of peripheral structures (PS) of the flare begins. The process is observed in H_{α} line as fast propagation of emission from SEFB along the chain of flocculi of one magnetic polarity. By this time, emission in the SEFB is observed in the form of thin ring segments with burned

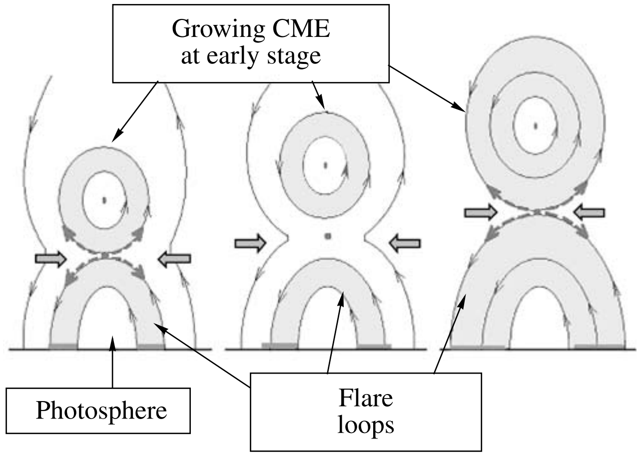

Fig. 4. Cross section of the arcade of flare loops and CME on the early stage. Successive involvement of the outer flare loops and outer shells of CME into the process is shown.

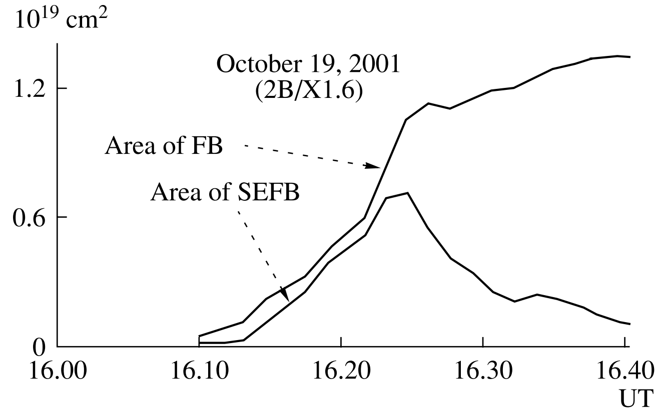

Fig. 5. The time behavior of the area of chromopshere structures, FB and SEFB.

away (nonluminous) central part. Flare bands (FL) reach maximum area and brightness at this moment and go into long, gradually decreasing emission with a slow divergence of the bands. On the background of slowed-down dynamics of FB and SEFB development, a rapid increase of PS with glowing and running over flocculi leading edge of emission (front), common for both bright strips, reflects, apparently, the process substantially distinct from phenomena in the other structural elements of the flare.

Localization of the initial PS detached from SEFB allows one to assume that PSs are also the bases of CME, but of its shells, outer with respect to the central braid. According to this assumption, the central braid of CME rests upon the SEFB, while the outer shells twining it round are supported by PS (Fig. 2).

Changes of PS in the post-maximum phase of a flare look like successive propagation (stretching) of a double PS strip with a bright leading edge (front) connecting the strips, this front rapidly moving along the chain of flocculi. At each moment (*1*, *2*, and *3* in Fig. 2) the PS front seems to be nested inside the same PS, but considered at the later time instant (2, 3, 4, …). Therefore, it is logical to assume that CME loops resting upon PS segments lighted up earlier are nested inside the CME loops resting upon PS segments lighted up later.

Apparently, high brightness of PS front running at the chromosphere level reflects energy processes taking place on the leading edge of CME escaping into the corona. A CME accelerated on the preceding phase of its development, moving with a velocity of 900 km/s, causes a release of energy when the CME front collides with plasma of the undisturbed corona. The fluxes of particles accelerated as a result of these collisions, moving along magnetic field lines, reach PSs which are chromospheric bases of the outer shell of CME. For example, on the phase of quasi-uniform motion of CME, which followed after the acceleration phase, the energy release on the CME front is due to CME collision with the corona plasma rather than due to energy transport from the flare reconnection region, since this source has almost faded [6].

One can suppose that in the process of motion of CME it involves higher and higher outer filed lines rooted in flocculi on the periphery of the active region. These lines going into the corona embrace the top of the expanding cupola of the CME. At the next time inatant, new magnetic lines involved in the CME development and rested upon a shifted PS front encompass from above the preceding CME cupola forming a new CME shell (at a slightly different angle). As a result, the running double strip of emission on the chromosphere level observed in H_α line, reflects the involvement into the process of more and more high and outer magnetic field arches.

SUBSTANCE IN CME

For a CME containing up to 10^{16} g of matter, observed with coronagraphs, the following structure is typical. The bright leading (outer) of compressed plasma edge is observed, the follows a dark cavern of dense, but colder substance. Sometimes, in this cavern one can see fragments of ejected filaments. Such a structure clearly correlates with evolution of SEFB and PS. The central faded segments of SEFB are connected, according to the model, by magnetic field lines with the dark cavern containing cold plasma. This plasma ascended from SEFB on the first phase of a flare. On the second stage, when CME gone away from the Sun by three-six solar radii is observed by coronagraphs, emission of the outer narrow ring of SEFB and PS is connected by magnetic field lines with the bright front of the CME.

A possible scheme of filling CME with plasma ascending into the corona from SEFB is illustrated in Fig. 3. Beams of particles from CL move along the field lines of the CME and reach its bases (SEFB). Cromospheric evaporated plasma much more slowly move back along the same magnetic field lines. These flows of substance are shown by dashed lines (without taking helical motion into account).

If one summarizes the total mass of the coronal substance above some active region and assumes that it is this substance that is carried away with CME [6], then the required mass can easily be accumulated. However, observations show that the coronal condensation above the active region persists even after CME passage. This means that either matter resources above the active region are replenished in a time comparable with the time of CME development in the lower corona (about 3–10 min) or the substance of another origin goes away from the Sun. The model gives arguments in favor of the second assumption.

DISCUSSION AND CONCLUSIONS

In this paper we suggested a hypothesis in whose context we succeeded in finding morphological manifestations of the bases of a rapid coronal mass ejection in the beginning of the process. The phenomenon of SEFB known for long also finds a natural explanation. In addition, the suggested consideration allows one to estimate in a new fashion some strong flares in which SEFB and PS were observed (for example, on May 13 and 16, 1981 [1, 18] and others).

In accordance with the suggested model, PS dynamics directly indicates to rapid passage of the CME front through the corona, which is possible only for fast CME after the phase of acceleration. The high brightness of PS is evidence of high the intensity of processes of collisions of matter on the CME front with the undisturbed corona plasma rather than of high intensity of flare reconnection under CME, as it was the case for SEFB on the first stage of the event. The motion of the leading edge of PS reflects the involvement into CME of the outer magnetic structures of the corona whose magnetic field lines are rested upon the PS front running over the chromosphere. The moment of PS stopping and fading corresponds to termination of intense involvement of outer magnetic fields into the CME. It should be noted that on the second stage the event develops in accordance with basic statements of the CSHKP conception. The model suggests some ways of checking its adequacy based on the analysis of time behavior of brightness of separate elements of a flare and CME and of the general topology of loop systems observed in the process of development of powerful eruptive solar events.

The suggested scheme explains the filling of CME with plasma and the topological relationship between the flare and CME in a joint event. In one variant of the CSHKP model, plasma evaporating from chromosphere flare bands fills not only flare loops, but an overlying plasmoid as well [12]. In the present paper it is demonstrated that, in the context of the suggested scheme, CMEs are filled with matter from special chromosphere elements of the flare (SEFB) adjacent to flare bands and representing the chromosphere bases of CME.

MAIN RESULTS

1. A classification of basic morphological chromosphere elements of the flare on October 19, 2001 is suggested and substantiated. These elements are flare bands (FB), structures on the ends of flare bands (SEFB), and periphery structures (PS).

2. An explanation is suggested to the SEFB phenomenon. It is hypothesized that SEFB are the chromosphere bases of a magnetic braid that forms afterwards a fast coronal mass ejection.

3. The phenomenon of emission flare peripheral structures, including their double structure is explained. In the context of the model suggested PS s are the chromosphere bases of magnetic loops twining round the initial braid which afterwards forms the coronal mass ejection.

4. A topological model is proposed that implies a single source of energy supplying both the flare and CME acceleration in the lower corona. From the standpoint of authors, the model explains a number of important features of solar flares, in particular:

—correlation of increased area of H_α-emission for flare bands and SEFB on the growth phase of the flare;

—specific features (distinctions) of the physical processes observed in SEFB and FB caused by distinctions in physical conditions in flare loops and arches of the CME system;

—correlation of the source of hard x-ray emission on the CME front with HXR-source in the chromosphere during another solar event (on April 15, 2002 [13]).

5. A qualitative scheme is suggested that explains the origin of matter in the coronal mass ejection.

The above considerations can serve as a basis for developments of a modified model describing the process of evolution of an indivisible powerful solar event: a flares accompanied by CME.

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