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Large Solar Flares and Coronal Mass Ejections: Their Manifestations in the Chromosphere

V. I. Sidorov[a, b] **and S. A. Yazev**[a, b]

[a] *Astronomical Observatory, Irkutsk State University, Irkutsk, 664009 Russia*
[b] *Institute of Solar–Terrestrial Physics, Siberian Branch, Russian Academy of Sciences, ul. Lermontova 126a, Irkutsk, 664033 Russia*

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Abstract—A phenomenological model of a united (solar flare–coronal mass ejection (CME)) event is briefly described. The model is based on the analysis of the images of the development of some events in various spectral ranges. A modified classification of the chomospheric manifestations of the event is proposed. A phenomenological model describing phenomena in the process of the development of intense solar flare–CME events in the activity complexes on the Sun is briefly presented. The model is based on the analysis of the observation data for some major flares (May 16, 1981, October 19, 2001, July 23, 2002).

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The following morphological features of a flare in the chromosphere are identified.

Flare ribbons (FRs) are observed in the light of chromospheric lines; the bipolar structure typical of intense flares consists of two bright flare ribbons diverging in the process of the development of the flare (the propagation velocity of the front of the flare belt is up to 5 km/s [Altyntsev et al., 1982]). The system of arcs connecting flare ribbons is observed at the post-maximum phase of the flare.

Structures at the ends of flare ribbons (SEFRs) are emission flare structures that rapidly change their brightness and shape [Altyntsev et al., 1982; Banin and Fedorov, 1971; Heyvaerts et al., 1976]. Long before the end of the Hα flare, the contrast of the central parts of the structures at the ends of flare ribbons decreases to the level of the undisturbed chromosphere; as a result, the structures at the ends of flare ribbons are transformed to the quasi-ring structures tracing the boundaries of the cells of the chromospheric grid (see Figs. 1 and 2a).

Peripheral structures (PSs) are flare emission structures at the periphery of the active region differing from flare ribbons in morphology and brightness [Komarova et al., 2004]. Peripheral structures begin to develop at the place of disappearing structures at the ends of the flare ribbons. The process looks like the structuring (increase in the compactness and brightness) of thin chains of flocculi tracing the boundaries of the cells of the enhanced chromospheric gird at the periphery of the active region. Thin double emission belts of peripheral structures are formed with a width of $1.5–2 \times 10^3$ km, which is smaller than the width of the flare ribbons (about 10^4 km). The distance between the strips ranges from 2×10^3 to 10×10^3 km. The double strip is rapidly stretched, propagating along the flocculi with a velocity up to 0.6×10^3 km/s. The maximum brightness is observed in the outer (with respect to the active region) narrow strip of the peripheral structures and in the head of the propagating emission region. The double strip of peripheral structures is observed in the region of one sign of the magnetic field.

Remote brightenings [Yurchyshyn et al., 2004] are the brightenings of the emission nodes of the chromospheric grid in Hα at distances of about $(100–200) \times 10^3$ km from the active region during the flare.

On the basis of the analysis of the images of the listed flares observed both on the disc and on the limb, we propose a topological model of the united event

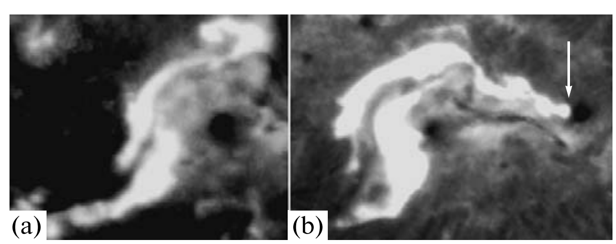

Fig. 1. Flare on May 16, 1981: (a) the pre-maximum stage, the development of the spiral structures at the ends of flare ribbons is seen in the upper part and (b) the post-maximum stage, the development of the peripheral structure is seen in the right part, the arrow marks the section of the emission of the peripheral structure in the spot shadow.

including an intense flare and coronal mass ejection (CME).

First stage of the event development. The chain of the vertices of the arcade of flare arcs connecting flare ribbons adjoins the quasi-cylindrical shell of the CME. The magnetic field of the shell is the set of spirally twisted field lines inside which the axial magnetic pinch, i.e., the central arc of the CME, is located. The bases of the pinch are manifested at the heliosphere level as the emission of structures at the ends of flare ribbons. Flare arcs are located at an acute angle to the magnetic polarity separation lines. As a result, the magnetic field at the vertices of the arcs is antiparallel to the field at the lower points of the shell of the CME. According to [Somov, 2005], the current layer, i.e., the reconnection region (see Fig. 3), which is a source of energy for the entire solar event is developed in the contact line of the vortices of the arcade and the lower surface of the CME. Within the model, particles emitted from the current layer diverge in four directions. The particles leaving to the CME move along the spiral lines of the CME shell and get to the outer (upper) front of the CME where collide with the dense plasma inducing emission in the hard X-ray range. Some particles continue to move in the spiral trajectories to their chromospheric bases (structures at the ends of flare ribbons). As a result, the energy release in the current layer generates six hard X-ray sources in six spatially separated points of the chromosphere and corona. According to the calculations with the method presented in [Sidorov, 2004], the ratio of the energy contributions to the flare and CME is estimated as 0.6 to 0.4 (see Fig. 4 and its caption).

Second stage of the event development. The fast development of the peripheral structures begins near the flare maximum. According to the model, the peripheral structures are the chromospheric bases of the outer shell of the CME: the central pinch of the CME is based on the structures at the ends of flare ribbons and shells bungling them are based on the peripheral structures (see Fig. 5). The development of peripheral structures looks like the propagation (expansion) of the double strip of peripheral structures with bright frontal edge (front) connecting the strips, which rapidly moves along the chain of flocculi (see Fig. 5a). At each time (1, 2, and 3 in Fig. 5b), the peripheral structure front is enclosed in the same peripheral structure, but considered at a later time (2, 3, 4, etc.). It is assumed that the loops of the CME based on the previously "emitting" sections of the peripheral structure are inserted into the loops of the CMEs based on the lately emitted sections of the peripheral structure.

At the late stage of the development of the flare–CME event far from the flare active region, the remote brightening phenomenon is observed. According to [Yurchyshyn et al., 2004], under favorable conditions, remote brightenings can be sources of proton fluxes

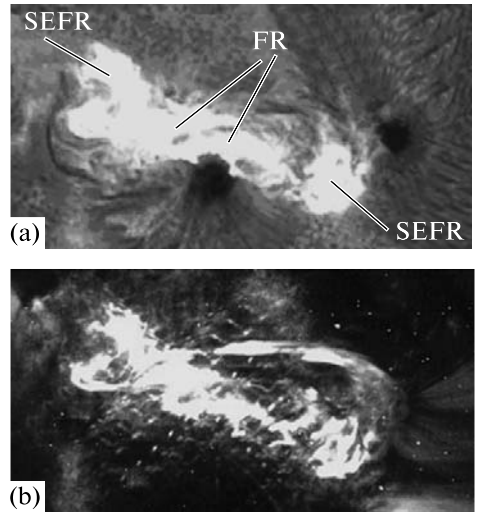

Fig. 2. Flare on October 19, 2001 at the pre-maximum development stage in the (a) Hα line (Big Bear observatory) and (b) 171-Å range (TRACE spacecraft).

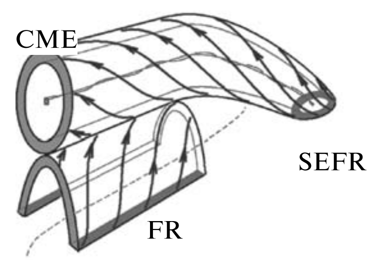

Fig. 3. Topological scheme of the solar flare–CME event at the early development stage.

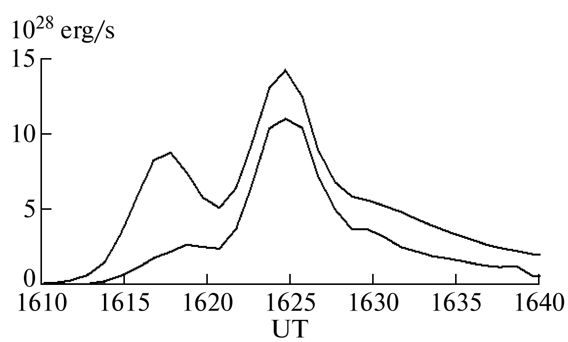

Fig. 4. Time dependence of the energy release in the flare on October 19, 2001. The upper line is the energy released in the current layer. The lower line is the fraction of the energy spent on the flare including losses on radiation, heating, and heat conduction.

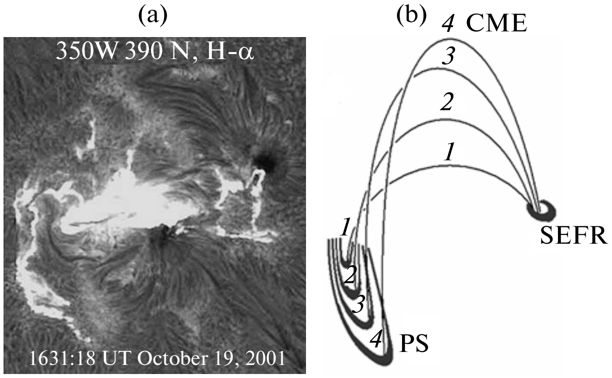

Fig. 5. Development of peripheral structures (PSs) in the flare on October 19, 2001: (a) the image in the Hα line, the arrow marks the section of the emission of the structures at the ends of flare ribbons getting to the spot shadow and (b) the assumed scheme of the SEFR–PS system.

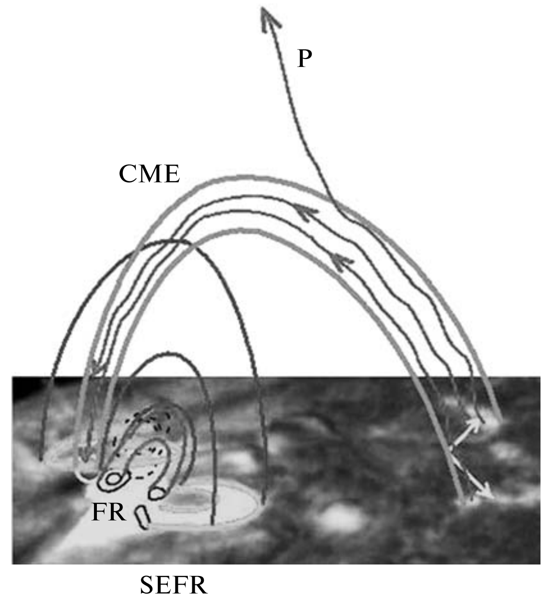

Fig. 6. Scheme of the emission of solar protons to the upper corona in the region of the joint development of the solar flare and CME at the post-maximum stage of the event. Along the magnetic arcs connecting the remote Hα brightenings (shown by white arrows) with the gamma source, fast protons move and generate the gamma source (the centroid of the gamma source is shown by the white circle). Some protons are reflected from the strong magnetic field in the flare active region, move to the upper corona along the CME loops and, then, to the heliosphere (on an example of the flare on July 23, 2002 [Yurchyshyn et al., 2004]).

generating gamma sources (in the event on July 23, 2002, remote brightenings were apparently sources of protons generating a gamma burst near a flare belt, because the latter with a delay of 1 min repeated almost exactly the light curve of the remote brightening [Yurchyshyn et al., 2004]). According to the model, the electron fluxes moving from the active region to the outer arcs of the rising CME to their remote bases (at a characteristic distance of 10^5 km from the active region) initiate shock heating in them, which is manifested as the remote brightening effect (see Fig. 6). As a result, accelerated proton fluxes move along the same arcs in the opposite direction and generate a gamma source in the bases of the arcs in the active region. Necessary conditions for a flare event under which high-energy ions and electrons move to the different bases of the coronal arcs were theoretically derived in [Zaitsev and Stepanov, 2008]. Under these conditions, the gamma source generated by high-energy ions and hard X-ray sources generated by fast electrons are spatially separated.

To explain the acceleration of protons, the model involves the betatron mechanism, which was often used previously by many authors (see [Karlický and Kosugi, 2004] and reference therein). Within this mechanism, protons are accelerated by the electric field E, which is induced by time variations of the magnetic field B according to the Faraday law $\nabla \times \mathbf{E} = -\partial\mathbf{B}/\partial t$. The decrease in the longitudinal electric field in the coronal loops during the flare [Zaitsev and Stepanov, 2008], as well as the decrease in the spiral twisting degree of the loop [Portier-Fozzani and Inhester, 2001], leads to the disappearance of the non-potential part of the longitudinal magnetic field of the loops, which is due to the solenoidal component of the current.

In the event on July 23, 2002, the pitch angles calculated for fast protons, which interact with the dense chromospheric plasma and generate the 2.23-MeV gamma source, are 87°–88°. The calculations indicate that some protons with larger pitch angles and energies of 20–30 MeV can be reflected from the "magnetic mirror" over the spot shadow (we used the method for calculating the coronal magnetic field [Dulk and McLean, 1978] according to which the vertical gradient is $B \sim 0.035$ G/km for $B \sim 500$ G at an altitude of $(14–18) \times 10^3$ km) and return to the upper corona through the coronal loops of the CME. The concentration of almost all the kinetic energy of the protons in the rotational motion enhances the gradient drift on the inhomogneities of the magnetic field and density of the CME front, promoting their emission to the heliosphere.

The proposed scenario does not contradict the known correlations of the proton ejection with the existence of the gamma source and chromospheric emission in the spot shadow; moreover, it explains the possibility of the reflection of protons from strong magnetic fields in the spot shadow and, therefore, emission of protons to the upper corona. Note that the last circumstance is not explained by the scenario of the acceleration of particles in the event on July 23, 2002 proposed in [Zaitsev and Stepanov, 2008], where ions are accelerated from the corona to the chromosphere along the magnetic field of the loop. The mechanisms described in [Zaitsev and Stepanov, 2008] is not likely decisive in the case under consideration.

Within the considered model, it is possible to propose the following criterion of the potential proton origin of an event at its post-maximum development stage:

• in the chromospheric lines, the presence of the remote brightenings and penetration of the emission of structures at the ends of flare ribbons or peripheral structures to the spot shadow (shown by the arrows in Figs. 1b and 5a, respectively);

• in the gamma range, the appearance of the radiation source near the flare development region.

According to the model, the emission structures of remote brightenings indicate the possible localization of the chromospheric source of protons getting to the heliosphere, as well as its topological relation with the CME and gamma source in the flare.

CONCLUSIONS

The analysis of the observation data makes it possible to separate the sequence of the described phenomena that are reproducible in the above solar events and confirm the proposed model or, at least, are consistent with it.

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