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Eruptive Processes at the Beginning of Development of Powerful Flare-Active Regions on the Sun

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Abstract—The evolution of large solar activity centers is studied, and the conditions resulting in powerful nonstationary processes are clarified. In addition to the factors that are usually considered (changes in sunspot area, the structure of magnetic fields, the character of motions), we examine to what extent observations of nonstationary processes (flares and associated coronal mass ejections) can be used to predict the development of such processes in the subsequent evolution of the activity center. We considered the example of a powerful group in October 2003, which could be observed before its appearance at the eastern limb using a spacecraft in near-Mars orbit. We plotted for events occurring in 2003 images of flares in various spectral ranges and analyzed high-energy processes in group 486, which was isolated at the beginning of its development, and then in the interrelated groups 486 and 484. The analysis of the peculiar early development of group 486 suggested that an intensification of the activity could be expected due to the emergence of new magnetic flux (and satellite groups), as well as the interaction and synchronization of two and then three large groups of the end of October 2003. In other words, in this case, extremely powerful nonstationary processes are associated with a relatively higher contribution of large-scale magnetic fields. We compare our results to analyses of motions and magnetic fields in this activity center throughout its transit across the disk from October 23 to November 5, 2003.

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1. INTRODUCTION. COMMENTS ON SPACE WEATHER PREDICTION

At some epochs, solar activity becomes very high, and series of powerful flares arise in given active regions or activity complexes. This was the case in August 1972, in June 1991, October 2003, and January 2005; a somewhat lower flare activity was characteristic of November 2000 and a number of other periods. Analysis of the development of activity centers hosting series of powerful flares is of interest both from the point of view of the physics of the processes involved and for space weather prediction.

Many factors determining the geomagnetic situation and the level of high-energy radiation are already known fairly well. Therefore, when a nonstationary event on the Sun is already observed, we can predict fairly accurately the development of events on the Earth and in near-Earth space that follow (by half an hour to about a day) the beginning of the event on the Sun. Of course, this is valid only if solar events are recorded in near real time in several wavelength ranges. For example, recently (in 2003), important information has been provided by the SOHO spacecraft, which recorded coronal mass ejections (CMEs) and coronal sources of extreme ultraviolet (EUV) radiation. Simultaneously, various manifestitations of solar activity were recorded on the GOES satellites, the TRACE and KORONAS-F spacecraft, etc. Successful attempts to formalize this forecasting using specialized computer software are being made both in Russia and worldwide. In leading science centers making short-term forecasts, direct human participation is required only in some atypical and complicated cases.

Space-weather prediction relies on the solution of two serious scientific problems. The first is the strong variability of the B_z component of the interplanetary magnetic field (IMF), which cannot be predicted to the required accuracy even given known conditions on the Sun and in interplanetary space. Therefore, using solar data, we can fairly reliably predict whether or not a magnetic storm will take place on the Earth, but it is difficult to estimate its amplitude. Many scientific publications have been devoted to this issue.

The second problem connected with space-weather prediction, which is of greater importance for forecasting the radiation environment, is the evolution of active regions or complexes where major flares develop. Attention has been focused on this classic problem since the middle of the last century, when magnetographs began to measure magnetic fields. Large hopes were pinned on analyzing variations of the magnetic field in activity centers at the photospheric level, where the magnetic field was actually measured. The first conclusion to come from this work was that flare activity is associated with abrupt changes in the magnetic flux of the activity center: flares arise more frequently during either flux increases or the onset of appreciable flux decreases, usually already during the decay of the associated sunspot group. Though this result is statistically valid and correctly reflects the overall tendency, it is not very helpful for short-term predictions for up to several days. Therefore, it is usually essential to supplement it with the second result relating primarily to the appearance of major flares: the highest flare activity is characteristic of a formed δ configuration; i.e., the appearance of areas with opposite magnetic-field polarities in the penumbra of the dominant spot (we will use here the Mt. Wilson classification of sunspot groups). In recent years, photospheric observations have demonstrated that, in many cases, the development of a more complex magnetic configuration takes place due to shear motions. From the viewpoint of the flare-activity level, motions parallel to the neutral line, but oppositely directed, are most important. Local helioseismology enables the detection of such motions in subphotospheric layers as well, at depths of about 10 000 km [1].

Thus, for space weather prediction over several days to about one month, we must determine the character of the evolution of activity centers. Changes in the sunspot area and magnetic configuration are certainly important characteristics. It is characteristic of most groups of modest size (as a rule, unipolar or bipolar, classes α, β), that the time variation of the sunspot area usually reaches a maximum and then smoothly decreases. In some sense, there is no stage of a stable existence of an active region, as Grigor'ev and Ermakova [2] noted as early as 1986. However, the magnetic-flux variations reach larger values, and remain close to their maximum during several days. This is true of all the specific cases noted above in which series of major flares occurred; the flux variations for group 10486 of October 2003 are given in [3].

For powerful events, the flare itself and the associated CME should be considered to be two aspects of a single nonstationary process. In this sense, there are now some indications that not only do major flares result due to the evolution of the local magnetic fields of activity centers, but some role is also played by large-scale fields. The difference in the characteristics of the flares of November 2000 and October 2003 was probably due precisely to the different locations of the flare active centers relative to the polarity separatrix of the large-scale field.

Can we identify any features of nonstationary processes that can distinguish the development of series of flares in activity centers that have appeared from behind the limb from those appearing on the visible disk? We have attempted to study this problem using all available observational resources. However, this information is frequently missing for groups that have just appeared, making it very difficult to predict how a group that has just appeared from behind the limb will develop. However, it is sometimes possible to use new types of spacecraft observations at different points of the heliosphere.

Below, we consider the development of active phenomena that occurred during a period of work on space-weather prediction that coincided with the appearance of powerful flare activity in group 10486 at the end of October 2003. The *Mars Odyssey* spacecraft observed the rise of this group approximately two days before its appearance at the limb for instruments on the Earth or in near-Earth orbit [4]. In addition to the data we utilized in our current forecast for 2003, we have used all available information, including RHESSI data, in our analysis. Section 2 gives some brief information on the activity during this period, and Section 3 some features of the data and reduction methods used. The results of our analysis of the activity during the rise of group 10486 and the first sequence of flare activity on the disk are given in Sections 4 and 5. We summarize our results and consider possibilities for their further development in the Conclusion.

2. FLARE ACTIVITY IN OCTOBER 2003 AND COMPARISON WITH PHENOMENA IN OTHER SIMILAR PERIODS

We consider here mainly the origin of flares in large activity centers. During the last several solar cycles, there have been some periods when active regions have transitted the disk when series of powerful nonstationary processes have been observed. These cases can tentatively be divided into several groups, which differ in the location of the activity center relative to the neutral line of the large-scale magnetic field and the character of the interaction between the main, large activity center and other centers that developed at the same time on the disk. Cases when a large-area sunspot group is located far from a neutral line of the large-scale field, in the middle part of a hill of unipolar field occupying a large region, are rare. One example may be the events of November 2000 (see, e.g., [5]), when activity near a large sunspot group resulted in a series of fairly powerful but fast flares. Most often, a huge activity center is located just at a polarity boundary of the large-scale field. In this case, the appearance of satellite groups with opposite-polarity sunspots in the vicinity of the main center results in a strong increase in the flare-activity level. An extreme situation here is when small activity centers rotate around the main center, as was true, e.g., in August 2000 [6] and December 2005 [7]. In this case, powerful flares consisting of a large impulse and a prolonged post-eruptive phase develop.

However, unusually high flare activity can also arise from the interaction of activity centers located far from each other at a neutral line of the large-scale magnetic field. We consider one such example here. In particular, three sunspot groups were observed on the solar disk in October 2003: 10484, 10486, and 10488 (designated below without the month number). During the transit of the most active group, 486, across the disk, 17 flares of magnitude C, 18 of magnitude M, and 7 of magnitude X were observed, including four flares with magnitudes of X10 and higher. Note that this intensification of activity took place far from the maximum, during the decay phase of the cycle.

Many papers have been devoted to the complex phenomena occurring in October 2003. A summary and bibliography of papers on both solar phenomena and Sun–Earth relations published before 2005 are given in [8]. Additional papers have appeared recently; among these, of the most interest for our work are the papers of Chumak et al. [9], who examine the connection between nonstationary processes and magnetic fields, and of Chertok and Grechnev [10], who analyze large-scale features associated with the development of flare activity in detail, in particular, channels with X-ray dimmings linking separate activity centers. The overwhelming majority of papers on this active period have dealt mainly with events after October 26, 2003, when group 486 was near the center of the disk. Our work supplements these studies with an analysis of events occurring at the very beginning of the development of group 486, before its appearance at the eastern limb for an Earth-based observer. We focus primarily on peculiarities in the development of the eruptive processes that preceded the appearance of the group, and the state that led to the extremely high level of flare activity during October 27–29 and November 4–7, 2003. We believe that it is important to identify the conditions that resulted in the formation of shear motions and the maintenance of this state of the activity center for such a long time. The appearance of satellite groups near the main activity center is common, but was not obvious in this case. We discuss the possibility that interactions between groups that are very far from each other, but are nevertheless linked, could have supported vortical motions or helicity in the region surrounding the main sunspots of group 486.

3. OBSERVATIONAL DATA AND OF THEIR REDUCTION

In both our 2003 paper on the prediction of space weather and in the current study, we widely used solar observations obtained with the GOES, SOHO, TRACE, RHESSI, KORONAS-F, and *Mars Odyssey* spacecraft. We present here some comments concerning the usage of these data in our subsequent analysis of the phenomena occurring in 2003.

A large amount of information on solar phenomena has recently been provided by the SOHO spacecraft. We have widely used data from the SOHO/EIT and SOHO/LASCO instruments in the form of both images and digital representations (FITS files). In particular, we have constructed difference SOHO/EIT images at 195 Å for several events observed on the *Mars Odyssey* spacecraft on the side of the Sun that is invisible from the Earth. We used the technique of Chertok and Grechnev [11], which takes into account the solar rotation between exposures. The resulting movie of the flare of October 21, 2003 is available at http://helios.izmiran.rssi.ru/lars/Chertok/0310_11/SPIRIT/index.html. As a rule, the physical parameters of CMEs were taken from the LASCO catalog; however, in some cases, we performed an additional analysis in order to determine the CME velocities and masses.

The 2001 *Mars Odyssey* spacecraft was launched on April 7, 2001. The instrumentation in the GRS gamma-ray spectrometer included a high-energy neutron detector (HEND) developed in the laboratory of I.G. Mitrofanov in the Space Research Institute of the Russian Academy of Sciences. The primary goal of this instrument was the study of Mars. During both the flight to Mars from April 7 to October 24, 2001 and in near-Mars orbit, the two scintillation detectors of HEND incidentally recorded hard X-ray and gamma-ray radiation from solar flares. The first results on stereoscopic near-limb effects observed by *Mars Odyssey* and near-Earth spacecraft were published in [4].

In HEND, a stilbene scintillator is surrounded by an outer detector with anti-coincidence protection based on a CsI crystal. The instrument records photons with energies of 30 keV–1 MeV. We mainly used the temporal profiles obtained by the outer detector with a time resolution of 0.25 s. The maximum of the sensitivity band is near 80 keV. Below we analyze the data from this peculiar X-ray photometer presented in [4]. The temporal profiles for radiation with energies above 330 keV were obtained with a time resolution of 1 s. In addition, spectra were recorded in 16 energy channels in each scintillator every 20 s.

A number of events were recorded by various instruments on the KORONAS-F satellite, which operated from July 31, 2001 to March 2005. We mainly used data from the SPR-N monitoring detector. This instrument includes a system of polarization sensors for measuring the polarization of solar-flare emission and a detector for monitoring the intensity of 15–100 keV solar X-ray radiation. Results concerning the events of October 2003 are reviewed in [12].

The RHESSI spacecraft [13, 14] obtains information on the emission of the Sun in the hard X-ray range, from 3 keV to 7 MeV. RHESSI data can provide information on the evolution of these radiation fluxes, as well as the spectral parameters and two-dimensional images of the radiation sources. The software package created by the RHESSI team for the reduction of RHESSI data is written for the interactive data processing language IDL (version 5.4 and higher). The package is included in the SOLAR SOFT (SSW) library, and is freely accessible at http://sohowww.nascom.nasa.gov/solarsoft/, together with all necessary instructions for the installation and a database containing the information required for running the software (telemetry data, a file directory, a catalog of flares, etc.).

There are two main archives with these data: the GSFC (Maryland, USA; http://hesperia.gsfc.nasa.gov/hessidata) and ETH (Switzerland; ftp://hercules.Ethz.ch/pub/hessi/data). We used the "raw" data with the zeroth processing level (Level-0), as well as the summary observational data with processing level 1 (Level-1).

The RHESSI Observing Summary Data—Quicklook Data—represent files containing fluxes, which are divided according to the standard energy bands (e.g., 3–6 keV, 25–50 keV) and have a crude time resolution (4 s). This information is written in a daily FITS file. This file can be obtained from one of the archives, together with the zero-level data file for the times of interest.

The following is possible using the Graphical User Interface to HESSI:

—selecting time and energy ranges;

—visualizing the information (fluxes in standard energy intervals corrected for the amplification and changing observing conditions; telemetry data);

—plotting light curves for arbitrary energy ranges and with arbitrary time resolution;

—restoring a two-dimensional image of the source;

—preparing the data for spectral studies with the OSPEX software.

The construction of light curves with a time resolution better than 4 s is complicated if the diaphragms or amplification changed during the observations. The correction for these effects is possible only for a 4-s time interval (one spacecraft revolution). This information can be fetched either from daily files or using the OSPEX software.

To restore the source image, we must know the region where an event was observed. This can be done either using the RHESSI flare catalog or manually. The software suggests various imaging algorithms, from reconstruction without any correction (Back Projection), to the widespread "cleaning" reconstruction (CLEAN), to minimum entropy methods (MEM SATO and VIS) and the PIXON algorithm [15, 16]. The comparison of the results obtained with these different algorithms carried out by Maltagliati et al. [17] shows that the PIXON algorithm yields the best result for sources with complex structures; accordingly, we have used this algorithm in most cases. Unfortunately, one drawback of this algorithm is its slow speed.

The graphic shell of the software enables the preparation of files for further study of the associated spectra. This includes splitting the files into single bands with the required resolution, splitting into time intervals, and calculating the coefficients necessary to calibrate and make the translation from the detector readings to photons. We used OSPEX to construct and analyze the spectra.

4. RISE OF GROUP 10486 AS OBSERVED FROM SPACECRAFT IN NEAR-MARS AND NEAR-EARTH ORBITS

Starting on October 18, 2003, the activity on the disk was related to group 484 (Fig. 1), where several powerful flares were visible before October 21.

On October 21, 2003, regions of the Sun located 24° behind the eastern limb as observed from the Earth were accessible to observations with the *Mars Odyssey* spacecraft. Starting from the beginning of this day, certain differences between the data from this satellite and ground-based information became apparent: weak bursts were observed at times close to, but not precisely coincident with, flares in group 484, being usually slightly delayed. There was the impression that a source of the bursts probably appeared in the softest range detected by HEND, 30–50 keV. About 4^h UT, SOHO/LASCO observed a powerful CME. The first report of this event indicated that this CME was related to an event behind the

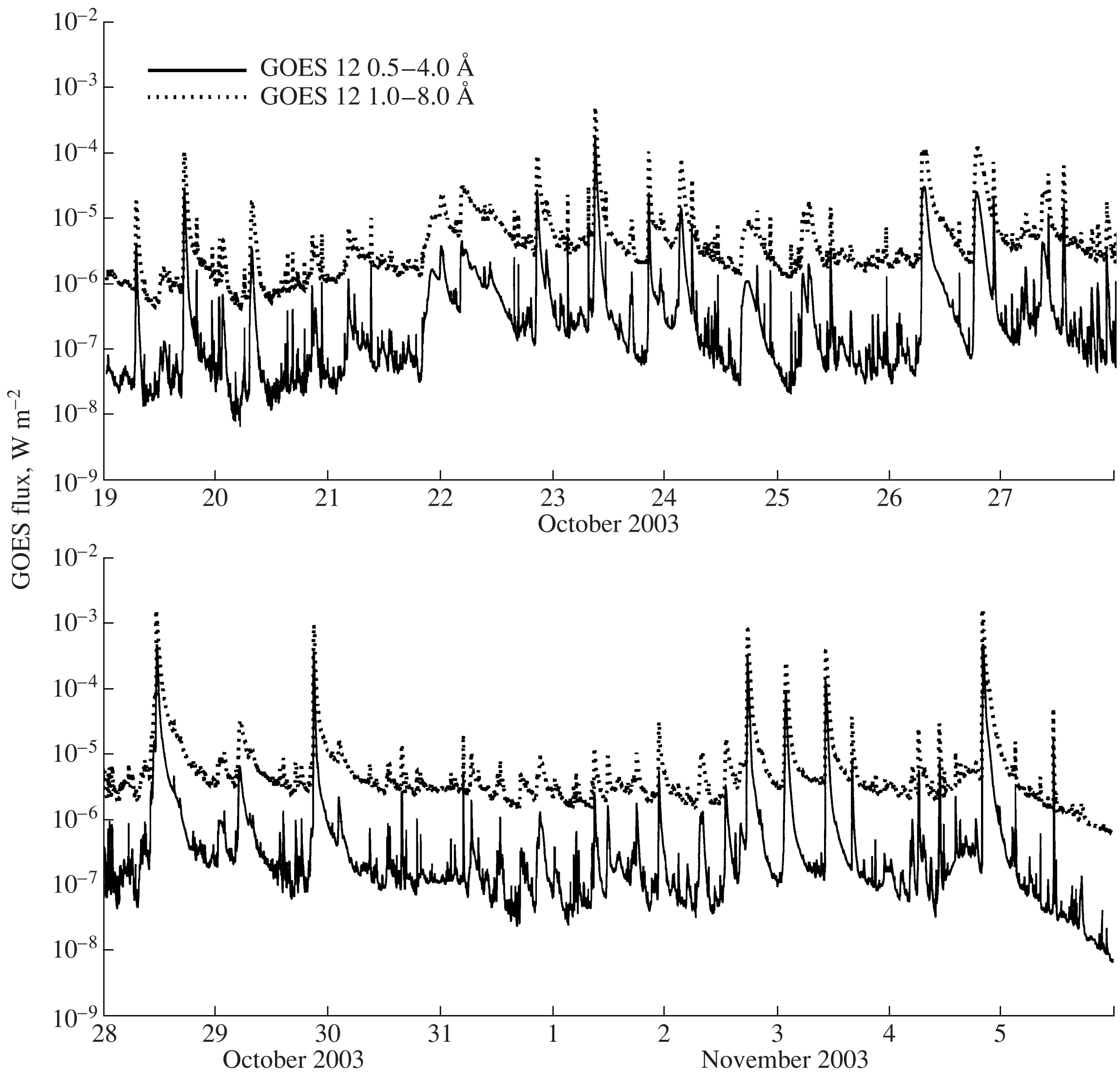

Fig. 1. Soft X-ray radiation (GOES data).

eastern limb. However, this CME was later considered to be a consequence of a flare in group 484. Now, when all LASCO/C2 difference images of this CME are available, it is clear that this event was clearly observed not only behind the eastern, but also behind the western limb; thus, as stated now in the catalog, it formed a full halo. This unambiguously indicates that this event is related to processes on the side of the Sun invisible from the Earth.

Mars Odyssey observed an impulsive flare on October 21 at about 18:45 UT. Figure 2a shows the profile of this flare at an energy near 80 keV. The flare was almost exactly on the limb for the observations from the Martian orbit. Note the presence of two impulsive increases (labeled *1–2–3* and *4*) separated by approximately five minutes. The measured hard radiation and a comparison of the hard and soft X-ray radiation for other phenomena observed on the disk suggest that this event was close to a flare of magnitude M5.

This flare was not observed by near-Earth spacecraft. At about 19^h UT, GOES observed an increase in the soft X-ray background (Fig. 1). SOHO/EIT began to observe activity at 195 Å at the eastern limb early on October 21. We used the SOHO/EIT images to make difference movies, both from adjacent frames and relative to 18:12 UT (to allow for the solar rotation), similar to those plotted and used in [11]. These movies show arches accompanying the development of the event recorded by *Mars Odyssey* after 18:48 UT, in the corresponding position angle. Two such arch systems are clearly visible between 19:13 and 19:48 UT, and one more northern system (Fig. 2c) is outlined. A new event including a CME and a flare is observed at 19:48 UT at that place,

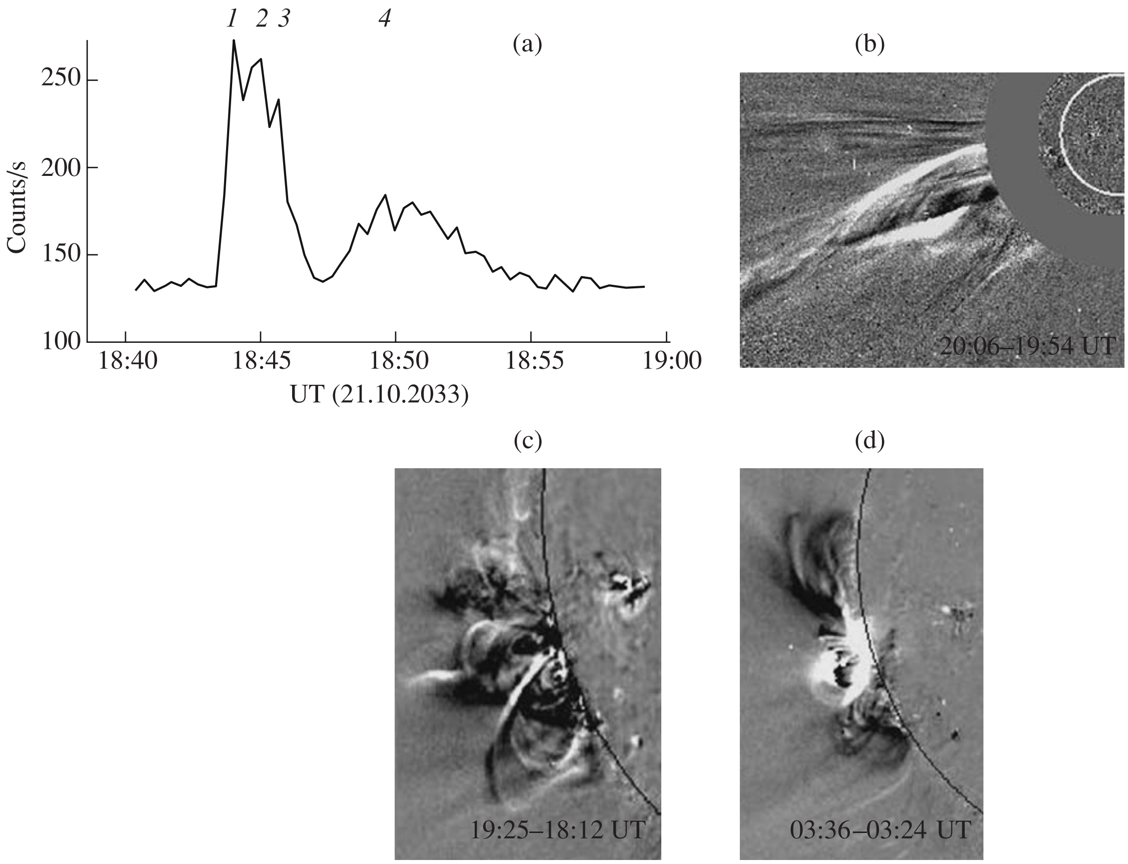

Fig. 2. (a) X-ray photometer record for October 21, 2003 with 20-s averaging (spectrum registration mode). Individual maxima are indicated; the contribution of the 30–80 keV emission dominates in maxima *1* and *4*. (b) LASCO/C2 difference image from the SOHO archive. (c) Difference image for October 21, 2003 at 195 Å. (d) Difference image for October 22, 2003 at 195 Å.

which led to the subsequent acceleration of the ascent of the preexisting two arch systems and a considerable amplification of the third, more northern, system. Three dimmings were detected near these three systems for two hours after 18:12 UT, suggesting the evacuation of gas from these coronal regions.

However, for this case as well as other similar situations, CME were clearly observed. In particular, between 15^h UT October 21 and 4^h UT October 22, six CMEs were found in the LASCO data at a position angle of about 120°, corresponding to the rising group 486. The classification of the CMEs among the narrow ejections in this region of the limb was fairly tentative, and the final catalog included two events. One of these CMEs, marked in the catalog as appearing in the LASCO/C2 field of view at 19:54:05 UT (Fig. 2b) was also related to the event recorded by *Mars Odyssey*.

Thus, though the flares were not obviously observed at the eastern limb viewed from near-Earth orbit, the activity of the rising group 486 was manifest via both a series of CMEs and the ascent of post-eruptive systems. Note also that a noise storm began somewhat earlier, followed by enhanced microwave emission [10]. Systems of loops were associated with the impulsive flare recorded by *Mars Odyssey*: the axes of the first and second system were probably fairly strongly rotated relative to each other. Note that the considerable increase in the limb activity was already related to a powerful CME observed by LASCO/C2 after 20:58 UT on October 21.

On October 22, the activity at the eastern limb increased appreciably. Against the background of the developing systems of loops in the SOHO/EIT images, flares were distinguished in group 486 (03:28 UT, *M*3.7; 08:30 UT, *M*1.7; 09:37 UT, *M*1.7; 15:06 UT, *M*1.4; 15:57 UT, *M*1.2; 19:47 UT, *M*9.9; 21:56 UT, *M*2.1), which were detectable in the GOES records only with appreciable uncertainty (Fig. 1). One of these flares is shown in Fig. 2d. The X-ray spectrum observed by *Mars Odyssey* was fairly soft, and two pulses were observed with a separation of four to five seconds [4, Fig. 5a]. This was probably due to the fact that the hard radiation is generated at low heights, and only the feet of a low loop are observed. The second foot of the high coronal loop of this flare, and probably one more source of soft radiation, were located behind the limb as viewed from near-Earth orbit. It is characteristic that, together with flare loops, which reached heights of 20 000–30 000 km, dimmings were observed to the North and South. This probably resulted in an underestimation of the importance of this partially post-limb flare. SOHO/EIT observed an arch system at 195 Å after 04:24 UT.

The M9.9 flare at about 20^h UT on October 22 had already been observed by satellites in near-Earth orbit, in particular, the KORONAS-F spacecraft [12]. Most likely, the loop feet were only partially accessible, and this influenced the hard X-ray observations. The CME associated with this flare was rather powerful, in contrast to the flare-associated CME series in the second half of October 21.

Summarizing, the rise of a new activity center was observed on October 21–22. The corresponding sunspot group was not observed in the previous Carrington revolution. The activity in a group that arose on the invisible side of the Sun increased considerably on October 21–22. By analogy with many small groups, whose development was observed in the visible hemisphere, it is highly likely that there was a considerable increase in the sunspot area on those days. This conclusion is based on a large number of weak eruptive events accompanied by a large number of ejections. This is usually characteristic of flare activity in developing groups, but series of narrow CMEs do not arise so frequently. In this case, this was a peculiarity associated with new local magnetic field.

However, the narrowness of the CME vanished after a powerful, fast flare, and the CMEs began to occupy a major part of the eastern limb. The flare arch systems of October 21–22 were complex, and probably similar to those associated with sigmoid flares. Ejections in the equatorial direction became observable on October 22, from group 484 to group 486, leading to the development of new, though also weak, nonstationary phenomena (see Fig. 8a below). This suggests that the nonstationary processes had already begun to develop in the large-scale magnetic configuration.

Thus, the powerful impulsive event that occurred on October 21 at about 19^h UT, observed only by *Mars Odyssey*, was important in the development of flare activity. Subsequently, the series of weak flares of October 22 and the development of powerful CMEs characterized the flare activity of the large-area group that appeared. This activity could then either decrease or considerably increase for some reason; subsequent observations of this group give some indication of why the development of the group followed this second path.

5. FLARES ON THE DISK ON OCTOBER 23–24, 2003

The observations of October 21–22 gave reasons to expect an appreciable increase in the activity of group 486. The first powerful flare of the series took place on October 23 at about 08:30 UT. We know from the GOES data (Fig. 1) that this X5.7 flare was fairly short: the intense soft X-ray radiation lasted only half an hour. Post-eruptive loops began to appear only when the flare emission had virtually completely ended. This also follows from the 195 Å SOHO/EIT data, which show the ascent of the arcades beginning at 12:24 UT and lasting several hours, until 17:30 UT, after which it gradually slowed. The next powerful flare began at 20:24 UT.

The conditions for observing the flare of October 23 at about 08:30 UT were much better on *Mars Odyssey* than in near-Earth orbit, because RHESSI and KORONAS-F observed only its final stage. Figure 3 shows the temporal profile of the X-ray radiation near 80 keV. The data were acquired in the profile-acquisition mode of the HEND outer scintillator with a time resolution of 0.25 s. The burst consists of two peaks separated by two to three minutes, with several maxima being achieved 15 min after the main maximum [4]. A reliable signal was also distinguished during the first part of the burst at 08:25–08:29 UT and in the data from the inner scintillator at energies above 300 keV.

In spite of the fact that the RHESSI observations began only at 08:44 UT, the radiation fluxes at energies up to 100 keV were recorded reliably, enabling the construction of the images for several times. Figure 4 presents the images for the initial stage of the RHESSI observations restored using the PIXSON method. Several loops are clearly visible in the 12–25 keV images. The foot of the brightest and highest loop in the figure coincides with two sources of harder 50–100 keV X-rays. Other loops of the arcade are also visible, in particular, to the North of the main loop, and formed at heights of about 20 000 km (Fig. 4). Our 12–25 keV image and 195 Å SOHO/EIT observations of the high arcade from 12^h to 17^h show that the loop height later increased.

Radio emission from this flare was observed at the Institute of Terrestrial Magnetism, the Ionosphere, and Radio-wave Propagation of the Russian Academy of Sciences (IZMIRAN). The temporal profiles are presented in [4, Fig. 6]; we see the two bursts considered here separated by 15 min and a flux maximum at about 09:00 UT superposed on the profile of the radio burst at 10 cm; further, a gradual decrease in the emission over an hour was recorded. The post-eruptive phase was clearly recorded after 09:00 UT.

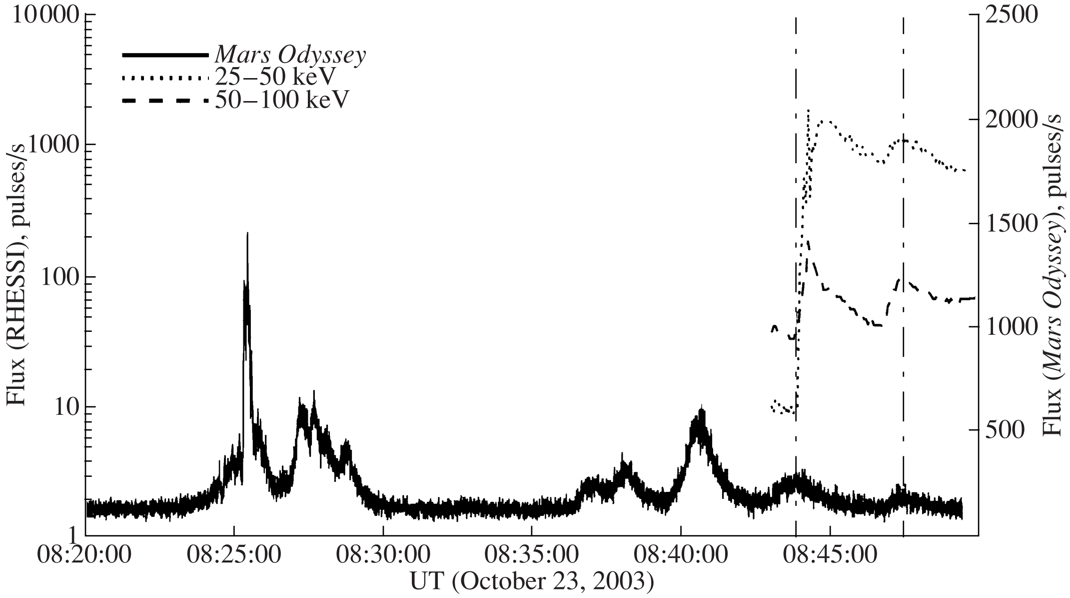

Fig. 3. *Mars Odyssey* and RHESSI records of the flare of October 23, 2003. The time resolution is 0.25 s, and the time is Earth time.

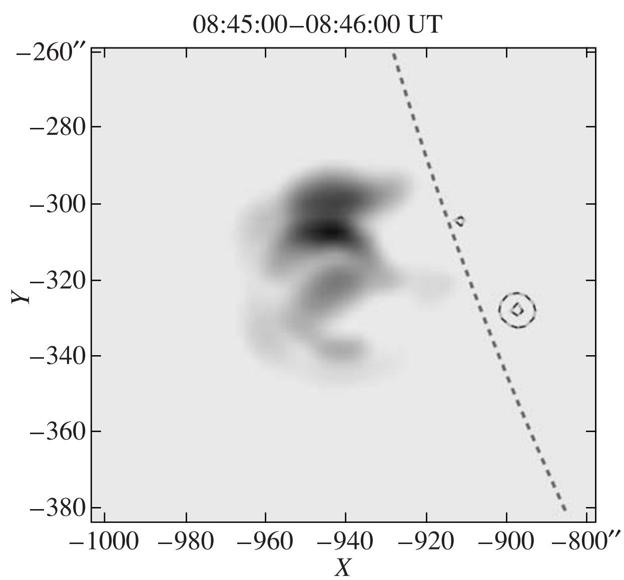

Fig. 4. Image of the flare of October 23, 2003 (in heliographic coordinates), according to RHESSI post-limb observations at 12–25 keV. The contours on the disk show the 50–100 keV emission at 50 and 90% of the maximum level.

The meter-wavelength data from the IZMIRAN spectrograph are shown in Fig. 5. Type III radio bursts began at 08:24 UT and became very intense at 08:25 UT, with a type II radio burst occurring after 08:26 UT. Two harmonics of this burst were observed after 08:27 UT, but this was not pronounced as clearly, as is frequently typical of limb events. Figure 5 shows that the powerful radio emission at 08:27 UT extends to coronal heights.

Thus, the flare of October 23, 2003 demonstrated features characteristic of powerful events. The primary energy release, which began at about 08:25 UT, was then probably manifest at the other end of the coronal loop at about 08:27 UT. This impulsive stage was fairly powerful, and was observed to photon en-

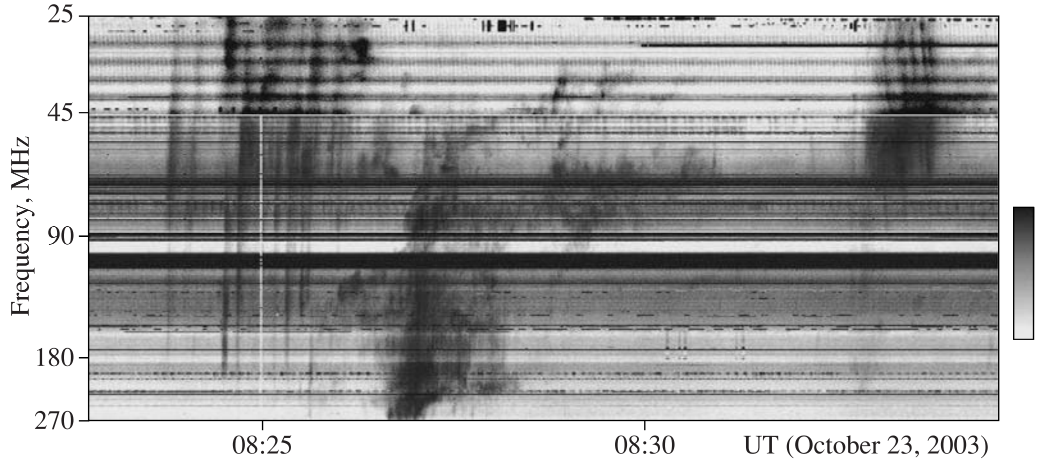

Fig. 5. Spectrum of the meter-wavelength radio emission from IZMIRAN observations of October 23, 2003. In addition to the type III radio bursts at about 08:25 UT and the beginning of type II and IV bursts at 08:27 UT, there is an appreciable increase in the meter-wavelength emission at 08:33 UT.

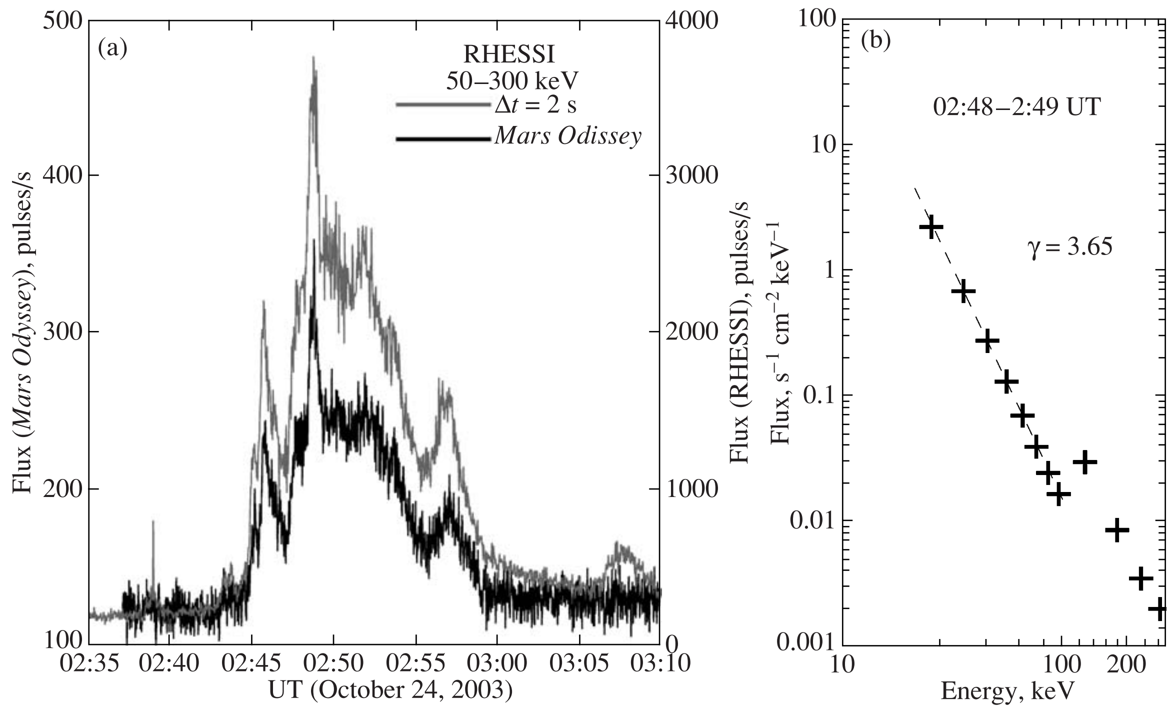

Fig. 6. Left: profiles of the X-ray burst of October 24, 2003 (*Mars Odyssey* and RHESSI data), with a time resolution is 0.25 s; the time is Earth time. Right: spectrum of the burst of October 24, 2003 (RHESSI data).

ergies above 300 keV. Fairly hard X-ray radiation, at 50–100 keV, was observed at the feet of the flare loops throughout the impulsive stage (Fig. 4). The accompanying radio burst was powerful, reaching 10 000 at 1.54 GHz.

The second X-ray maximum at about 08:40 UT resulted in the subsequent development of post-eruptive arch systems. These arches ascended to considerable heights, and we could distinguish three arch systems whose axes were considerably inclined relative to each other. This process subsequently spread above a considerable part of the eastern limb, and then to group 484 [10].

A similar picture was observed in the M7.6 flare of October 24 (after 02:27 UT), which was observed in its entirety by *Mars Odyssey*, RHESSI,

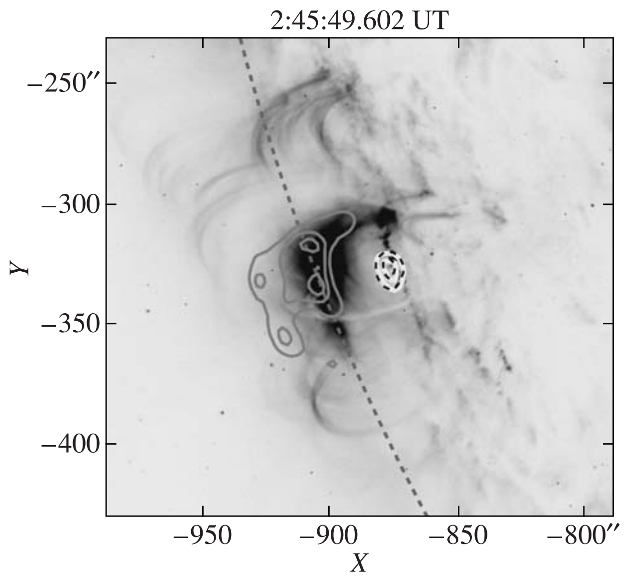

Fig. 7. Image of the flare of October 24, 2003. The background shows the TRACE observations at 195 Å, and the contours the RHESSI observations beyond the limb at 12–25 keV range (10, 30, 50, and 90% of the peak) and on the disk at 50–100 keV and 100–300 keV (dashed contours at 50 and 90% of the peak).

and KORONAS-F. The temporal profiles were very similar on all three spacecraft, with a power-law differential spectrum with the index −3.86 above 20 keV (Fig. 6).

In order not to have to return later to the impulsive stage of the flares, we note here that a characteristic change in the hardness was observed in the flare of October 21. The burst labeled *1* in Fig. 2a was soft, then became hard (*2*), with the radiation remaining fairly hard in the final stage of the burst. This is a well-known scenario for the development of nonthermal emission ("soft–hard–harder"). An interesting description of the spectrum of the hard X-ray radiation and the hardness–X-ray flux hysteresis diagram were proposed recently in [18]. This scenario is considered based on RHESSI observations of powerful flares of 2004–2005. Our data for all three flares of October 21–24, 2003 are consistent with the "soft–hard–harder" scenario, testifying that nonthermal emission contributed a considerable fraction of the total radiation flux above 15–20 keV. It follows that nonthermal processes were clearly pronounced at the onset of the flares in group 486. This is typical of large groups with a δ magnetic-field configuration.

The arch systems in the flare of October 24 discussed above were observed not only by TRACE at 195 Å , but also at 12–25 keV by RHESSI (Fig. 7). Here, also, two systems of loops were observed—the main, southern and weaker, northern systems. However, in contrast to the flare of October 23, the northern and southern systems were much more widely separated. In this flare of October 24, the entire loop system proved to be more complicated than ordinary flares with similar energies.

The events of October 23–24, 2003 can be considered an episode of flare activity in group 486, which later repeated at intervals from 1.5 to 2 d until the disappearance of this group behind the limb on November 5. The main regularities in this activity were already evident in this period, and were manifested through the sympathetic character of the events. In particular, a close correlation between events in groups 484 and 486 was observed during virtually the entire time the groups were present on the disk. An ejection nearly along the line from group 484 to 486 (Fig. 8a) initiated the development of nonstationary processes in group 486 several minutes after the events in group 484. This correlation was also observed in the subsequent days, though the flares in group 486 "initiated" events in group 484.

The second circumstance was the propagation of disturbances along the neutral line of the large-scale magnetic field. In the flares of October 21, 23, and 24, a sigmoid-type form with the formation of three loop systems was visible. The angle between the loop axes gradually changed from one flare to another, probably reflecting the behavior of the neutral line of the large-scale magnetic field near the activity center. This structure was studied in detail outside group 486 in [10] based on the shapes of dimmings. Lin [10] associated it with a "narrow arc with a length comparable to the disk diameter and with convexity directed to high latitudes of the southern hemisphere." This is shown in Fig. 8b (*1–2–3–4*) for October 25, together with information on the large-scale magnetic field. This structure, which existed outside flares and persisted until the disappearance of the group behind the limb, continued to partially exist and display high flare activity even in the subsequent revolution.

6. DISCUSSION AND CONCLUSION

Together with ground-based observations of the Sun, extra-atmospheric studies over the last decade have supplied qualitatively new observational data relating to nonstationary processes and the activity centers in which they develop. Most important here is imaging of flares, which was actively initiated by the Yohkoh spacecraft and continued by SOHO throughout cycle 23. The TRACE spacecraft obtained images with high temporal and spatial resolution, and RHESSI produces images in a broad energy band, including gamma-rays. Episodic observations of some phenomena occurring on the side of the Sun

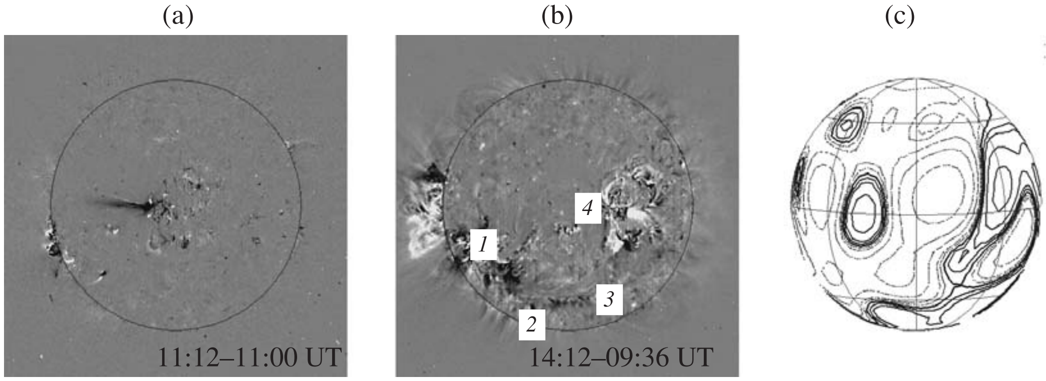

Fig. 8. (a) Difference image of the two adjacent 195 Å SOHO/EIT frames for the ejection of October 23, 2003. (b) Difference image for October 25, 2003, with the position of the dimming channel shown *1–2–3–4*. (c) Distribution of large-scale magnetic fields 1.1 solar radii from the center of the Sun on October 25, 2003. Group 486 had coordinates S15, E43 and group 484 coordinates N05, W13.

that is invisible from the Earth have now become regular thanks to the launch of the STEREO spacecraft.

The flare activity of the Sun in October and then in November 2003 was extremely high. The literature devoted to its analysis is extensive. We decided to supplement these results by considering the onset of the development of the main group 486. This study was aided by the fact that the HEND instrument designed at the Space Research Institute and mounted on the *Mars Odyssey* spacecraft recorded hard radiation associated with events in this group approximately 2 d before the appearance of the group at the eastern limb as observed from the Earth. These data, together with measurements in near-Earth orbit, enabled us to reconstruct the development of the group. A series of small, narrow CMEs in the second half of October 21, a fast flare at about 19^h on that same day, which was not yet visible from the Earth, and a series of weak limb flares on October 22 indicate that the group approached the usual maximum flare activity of fairly large groups.

It is very difficult to observe the development of magnetic fields and motions in the photosphere of an activity center for limb phenomena. Therefore, we must make predictions based mainly on information about nonstationary processes at the limb. As our analysis here has shown, two points could be important here. The first refers to the fairly high hardness of the studied three flares of October 21, 23, and 24. The corresponding hard X-ray bursts followed the same "soft–hard–harder" scenario; the flare of October 23 was recorded by *Mars Odyssey* at energies above 300 keV, and was characterized by a high radio flux. The CME's character changed after October 22: after the flares of October 23 and 24, fast, partial-halo ejections with masses exceeding 10^{16} g were observed. This testified to a fairly powerful process of primary energy release in an ascending group, as is usually typical of processes associated with the complication of local magnetic fields.

However, there was another circumstance that could intensify the activity of this group. In spite of the fact that the flares of October 21–24 were fairly fast, post-eruptive phenomena were clearly visible in them. This began to manifest itself in the limb flares of October 22 observed by SOHO at 195 Å , then in the corresponding 10 cm radio emission after 09:00 UT in the flare of October 23, and in the TRACE movie at 195 Åin the flare of October 24. There is every reason to believe that, if observed on the disk, the events of October 23 and 24 would be similar to sigmoid flares, with the propagation of processes outside the activity center along the neutral line of the large-scale magnetic field.

The propagation of nonstationary processes along the neutral line of the large-scale field passing through groups 486 and 484 was already demonstrated in [10] based on the behavior of dimmings. This is confirmed in our work, both by the behavior of flare loops and our analysis of ejections and the sequence of the onsets of the development of nonstationary phenomena in both groups. This suggests that both circumstances (the complication of local magnetic fields and the interaction of centers of activity located at large distances from each other on the same neutral line of the large-scale magnetic field) can jointly result in a period of extremely high flare activity. We have shown that the prerequisites for such a development of flare activity arose at the very beginning of the development of group 486.

Let us present some thoughts about the physical origins of such a powerful intensification of the flare activity of group 486. Chumak et al. [9] have demonstrated, already quantitatively, that the origin of powerful flares is related to an accumulation of the energy of the nonpotential magnetic-field component above a photospheric activity center. The corresponding currents in coronal sheets probably arise from shear motions. The relation of these currents to shear motions has also been demonstrated for the phenomena of October 25–28, 2003 in [9]. The presence of high vorticity and anomalously high helicity of the velocity field at a depth of about 7000 km beneath group 486 was shown by Thomson [1] based on helioseismology data. As a rule, centers with unusually high flare activity are characterized by the appearance of satellite groups in their immediate proximity, which move in opposite directions on either side of the neutral line of the magnetic field. In some, fairly rare cases, vortical motions around the main sunspot are observed at the photospheric level, [6, 16]. In the case analyzed by us here, a huge vortex that appeared at large depths was probably due to the slow evolution of the large-scale magnetic field. This is indicated observationally by the change in October 2003 of the shape of a channel [10], which probably reflected the neutral line of the large-scale magnetic field. Note that post-eruptive phenomena were becoming more and more prominent in the powerful flares of October 2003, in contrast to the events at the onset of the development of group 486.

It is clear that information on events behind the eastern limb is extremely useful for space-weather prediction. We hope that the STEREO spacecraft will still be operating when the solar activity becomes much higher, and will demonstrate all the advantages of such observations.

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