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Hard X-ray and Gamma-Ray Flares on the Sun: Stereoscopic Effects near the Limb from Observations on the 2001 *Mars Odyssey* Spacecraft and Near-Earth Spacecraft

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Abstract—We present the first results of data on solar flares detected by the HEND instrument onboard the 2001 *Mars Odyssey* interplanetary spacecraft during its flight to Mars and in orbit around Mars. The instruments carried by the spacecraft, which was developed at the Space Research Institute of the Russian Academy of Sciences, included a scintillation detector with two crystals, enabling the detection of photons with energies from tens of keV to 2.5 MeV with high time resolution. Several dozen flares were detected on both the sides visible from the Earth and back side of the Sun, supplementing other available data in a number of cases. A joint analysis of the HEND data together with data obtained in near-Earth orbits enabled the detection of variations in the integrated fluxes of photons with energies exceeding 80 keV during observations of flares near the limb from various directions. Two events were analyzed in great detail: the setting of a region displaying frequent very short flares on May 20, 2001, and the rising of the group 10486, which displayed numerous flare phenomena on the limb followed by extremely high activity in October–November 2003. These variations appear in simultaneous observations of limb M flares made at angles differing by only 8°–10°. Analyses of observations of rising sources obtained on two spacecraft lead to similar results. This indicates that the vast majority of emission at energies exceeding 80 keV arises at altitudes of no higher than seven to ten thousand kilometers. We briefly consider the powerful solar-disk gamma-ray flare of August 25, 2001. In this case, there are some differences in the behavior of the hard radiation in the decay phase for observations made at angles differing by 25°, which is most likely due to differences in the instrumental responses to radiation with this spectrum. The absence of hard radiation at great heights in the region of the "cusp" places some constraints on our picture of the physical processes occurring in powerful solar flares. © *2005 Pleiades Publishing, Inc.*

1. INTRODUCTION

The high-energy radiation from solar flares contains information about the main energy-release processes and particle-acceleration mechanisms. A review of previous studies, beginning in 1980, using the SMM satellite, is given in [1]. Further, observations of powerful solar flares with $h\nu \geq 300$ keV were carried out using various instruments of the Compton Gamma-ray Observatory, the FEBUS instrument onboard the GRANAT observatory, the Yohkoh BGO detector, and instruments of the GAMMA-1 observatory. For the most powerful events, the gamma-ray emission is produced over 10 min, and some events are accompanied by weak flares occurring over a period of one to several hours. This was found to be the case for flares in June 1991 [2], but is most likely also true for other very powerful events.

This behavior of the gamma-ray emission is probably associated with the fact that the most efficient acceleration of particles on the Sun—apparently of protons as well as electrons—likewise occurs on time scales of several minutes, near spots in the flash phase of large flares; i.e., at the end of or just after impulsive events, at the onset of the formation of coronal flare loops. This conclusion was recently made based on a direct identification of a source of accelerated relativistic particles in the flare of July 14, 2000, based on multifaceted observations and a collection of indirect evidence for other powerful flares during the three last solar cycles [3]. This brought to the floor the question of whether data on the high-energy radiation of flares can be used to reach some conclusions about the sources of the main particle acceleration—their locations and the duration of the processes leading to the generation of high-energy particles in flares.

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The 2001 *Mars Odyssey* satellite was launched on April 7, 2001. Onboard equipment included a Gamma-Ray Spectrometer (GRS) with a High Energy Neutron Detector (HEND). The main task of this satellite is to study Mars. However, the GRS and two scintillation HEND can also be used to detect hard X-ray and gamma-ray radiation from solar flares at various points in the solar system. Thus far, several dozen solar flares have been detected during the flight to Mars from April 7 to October 24, 2001, and during the satellite's orbiting of Mars. The HEND data supplement available data on the hard radiation of solar flares from observations in near-Earth orbits, helping to fill gaps in these data and providing the possibility of studying flares and the activity of groups on the side of the Sun that is not visible from the Earth. In some cases, the flare emission extends to 1.5–2.5 MeV, making it possible to study the physical conditions in high-energy flare sources on the Sun.

Indeed, these data provide a good indicator of particle acceleration on the Sun. This was facilitated by the fact that the energy range of the HEND detector enabled the detection of particles in the transition region from X-ray emission by the beams of electrons with energies of tens of keV that are often present in flares to gamma-rays that arise as a result of interactions between relativistic particles and the surrounding plasma. In the simplest case, the HEND detector can be used like two photometers that detect photons with energies higher than 80 and higher than 330 keV. While the former range includes radiation due to the large number of electrons accelerated to energies of about 100 keV, the second range includes only emission associated with the generation of solar cosmic rays. In addition, in many cases, scintillation and proportional counters enable the detection of not only gamma-rays, but also of solar high-energy particles. This also facilitates studies of the acceleration of particles on the Sun during their propagation in the heliosphere.

In addition, various regions of the solar surface have been observable by HEND at various times. After the *Mars Odyssey* launch, the angle between the Sun and the Earth and the Sun and the satellite changed. For example, in 2002, the satellite was located in a position opposite that of the Earth. The simultaneous use of the *Mars Odyssey* data and data obtained in near-Earth orbits enabled studies of sources of high-energy radiation from different directions. Such "stereoscopic" observations open new possibilities for investigations of flares. This topic is the main focus of the present study.

As is known, stereoscopic observations carried out in 1978–1979, using the Pioneer Venus Orbiter (PVO) and International Sun–Earth Explorer 3 (ISEE-3) spacecraft outside the Sun–Earth line elucidated that 95% of the radiation with energies exceeding 150 keV is produced at heights of less than 2500 km above the photosphere [4]. At the same time, analysis for three flares led to the conclusion that the corresponding radiation arose near the bases of flare loops. Subsequently, numerous images of flares at energies up to 50 keV were obtained, in which sources near the bases of loops were clearly distinguished. However, a third site near the loop apex is also sometimes visible at these energies, as was first identified in [5, 6]. In several impulsive events, the height of this site was close to 10 000 km. A high source in the region of the so-called "cusp" is more often observed in soft X-ray images (see below).

Unfortunately, the poor resolution of images of flares at hard energies has prevented investigation of the structure of the sources, in particular, their heights. The directivity of flare gamma-rays was widely discussed in the 1970s. The main argument for this was the concentration toward the limb of flares with appreciable fluxes of protons with energies exceeding 10 MeV [7, Fig. 9]. This was interpreted as indicating the presence of photons arising near the apices of loops during collisions between relativistic electrons and thermal ions, with the predominant emission of photons in the direction of propagation of the particle beam, i.e., parallel to the solar surface. A softening of the spectra in the transition from limb flares to central flares is sometimes observed at soft X-ray energies (tens of keV) [8], taken to provide confirmation of this view.

However, a subsequent statistical study of 28 flares detected by the SIGNE instrument onboard the *Venera-13* and *Venera-14* spacecraft and the HXRBS instrument onboard the SMM spacecraft demonstrated a near absence of directivity of the radiation at energies from 50 to 500 keV—the ratio of the fluxes did not exceed a factor of 2.5 (see [9] and references therein). This question has now again become topical in connection with the need to interpret the first results obtained by the RHESSI satellite [10].

In principle, the data analyzed here contain information about several large events for which photons with energies up to 2.5 MeV were detected, which can be used to investigate the directivity of this radiation. The high time resolution of these data is an important factor, enabling analysis of the directivity for individual impulsive events or post-eruptive episodes.

Observations of powerful solar flares on the disk have not revealed appreciable differences from the results obtained with HEND and in modern observations in near-Earth orbits. However, such comparisons are not trivial for events near the limb, where stereoscopic effects are most strongly manifested. In the first stage, we aimed to estimate the heights of sources with energies exceeding 80 keV. We then focused our attention on analyzing the set and rise of two groups of spots, on May 20, 2001, and October 22–23, 2003. These groups were accompanied by numerous fairly hard flares. We briefly also discuss the "typical" powerful gamma-ray flare of August 25, 2001, for which HEND data were obtained, together with other numerous observational material. Interpretation of the results enables refinement of the conditions under which hard radiation arises in solar flares.

2. DESCRIPTION OF THE INSTRUMENT

The HEND instrument was developed and constructed at the Institute for Space Research of the Russian Academy of Sciences, and was intended for studies of neutron and gamma-ray emission from the Martian surface. It is one element of the GRS apparatus [11] of the NASA 2001 *Mars Odyssey* project, whose aim was a global study of the elemental composition of the Martian surface via gamma-ray and neutron spectroscopy. The GRS complex includes

—the GRS with a cooled Germanium detector operating at energies of 30–8000 keV;

—a neutron spectrometer (NS) for measuring the flux of thermal and epithermal neutrons;

—the HEND for measuring the flux of neutrons with energies from 0.4 eV to 15 MeV.

HEND has three ^{3}He proportional counters for the detection of epithermal neutrons and one scintillation block for the detection of energetic neutrons and gamma-rays. We will consider here data obtained using the scintillation block, whose main detecting element is a crystal of organic scintillating material.

It is necessary to distinguish counts from recoil protons from those made by charged cosmic-ray particles. For this, the scintillator is surrounded by an outer detector with anticoincidence protection based on a CsI crystal. When counts from particles in the outer detector are recorded, the signal is processed and used to reject the corresponding events detected in the inner scintillator.

In addition to the charged particles detected in the inner and outer scintillators, the instrument detects gamma-ray photons. These photons penetrate freely through the anticoincidence protection, so that their counts in the inner scintillator will be mixed with counts from recoil protons. An electronic analog division scheme is used to distinguish the counts from neutrons and photons, based on a comparison of the shapes of the pulses generated in the photomultiplier by the electron produced in the case of a detected photon or the proton produced by the detection of a neutron. Thus, the output of the inner scintillator block forms two independent sets of counts: protons from neutron detections and electrons from gamma-rays. Experimentation showed that the probability of erroneous identification of these counts is very small, $<10^{-3}$.

Thus, two HEND signals arise during the detection of gamma-rays: photons from the outer CsI crystal, which are determined as the counts from this crystal for which there is no simultaneous signal in the inner scintillator, and photons in the inner crystal, which are determined as "electron" counts in this crystal for which there is no simultaneous signal in the outer CsI crystal. The possible energy ranges for gamma-rays that can be registered in the inner and outer devices are 60 keV–2 MeV and 30 keV–1 MeV, respectively.

Two continuous profiles of gamma-ray measurements in the inner scintillator and outer CsI crystal are formed in the instrument, with time resolutions of 1.0 and 0.25 s, respectively. Simultaneously with the recording of these continuous time profiles, a spectrum of gamma-ray counts is formed every 20 s in 16 energy channels in each scintillator.

The data generated each 20 s are transferred to the GRS Central Electronic Board (CEB) and then to the onboard telemetry system, which transmits them to the Earth during tracking sessions. When the HEND data are written to the CEB, they are tied to an onboard timing system with accuracy to better than 1 ms. In turn, the *Mars Odyssey* onboard time system is tied to universal time (UT) with the same accuracy. In addition, positions of the spacecraft for both the flight from the Earth to Mars and in the subsequent orbits around Mars are derived with an accuracy of several tens of meters based on trajectory measurements.

Knowledge of the precise time during the detection of cosmic gamma-ray bursts and solar flares enables the use of the HEND data to localize the sources of the gamma-ray bursts and in stereoscopic observations of the Sun. Our analysis is concerned with the latter task, based primarily on time profiles obtained with the outer detector with a time resolution of 0.25 s at energies of 80 keV–1 MeV and with the inner detector with a resolution of 1 s at energies of 330 keV–2.5 MeV. For brevity, we will refer to these profiles as the signals from the X-ray and gamma-ray photometers.

3. METHODOLOGICAL COMMENTS ON STEREOSCOPIC OBSERVATIONS

Two approaches have been used when analyzing observations near the limb which are schematically illustrated in Fig. 1. First, if some formation is fully visible from one of the spacecraft at a given time and is not visible from the other, its height h cannot exceed the height given by the relation

$$\cos\alpha = \frac{R_0}{R_0 + h},$$

where α is the angle between the two spacecraft (Fig. 1a) and R_0 is the radius of the Sun.

Second, in early X-ray studies of the Sun, the heights of soft X-ray sources were estimated based on observations of their rising and setting. This approach can be reformulated for the case of hard X-ray observations with two spacecraft as follows. Let us suppose that the rising of a flare is observed from a spacecraft near Mars at a time t_1 and from a spacecraft in a near-Earth orbit at a time t_2, after which a limb source is observed from the Earth. With knowledge of the angle

$$\beta = \Omega(t_2 - t_1),$$

where Ω is the angular velocity of rotation of the region at its known heliolatitude, determination of the angle α and estimation of the source height become more reliable. In the case of a very low source, the angle β turns out to be equal to the difference in the longitudes of the two spacecraft. High sources can begin to be observed when they are still behind the limb of the first spacecraft (Mars in Fig. 1b), and arrive at the limb for observations from the Earth after the expected time corresponding to the equality of β and the difference of the longitudes of the two spacecraft. In a number of cases, information from the second spacecraft has made it possible to determine the expected time for the appearance of a flare source behind the limb of a rising group (as was the case at the end of October 2003) which can then be used to estimate the height in the case of simultaneous observations (Fig. 1a). It is obvious that this reasoning operates well in the case of a nonvariable source or observations of similar events that repeat fairly often. Such series of homologous events are sometimes observed, one of which is discussed in the following section.

We calculated the longitudes of the spacecraft in the plane of the ecliptic on the path to Mars using the flight ephemerides; when the spacecraft was in orbit around Mars, we took the longitude of the spacecraft to be equal to that of Mars. As an example, Fig. 1c presents the positions of the Earth and Mars in their orbits on October 28, 2003, at 12^{h} Moscow time. In this case, when the ecliptic longitude of the Earth exceeded that of Mars, the *Mars Odyssey* spacecraft was able to observe regions on the Sun beyond the eastern limb for an Earth observer; flares in the eastern part of the disk were located closer to the disk center for the HEND observations compared to their position for an Earth observer. The cases discussed below refer to precisely this relative position of the spacecraft, except for the very beginning of the flight, when the situation was reversed.

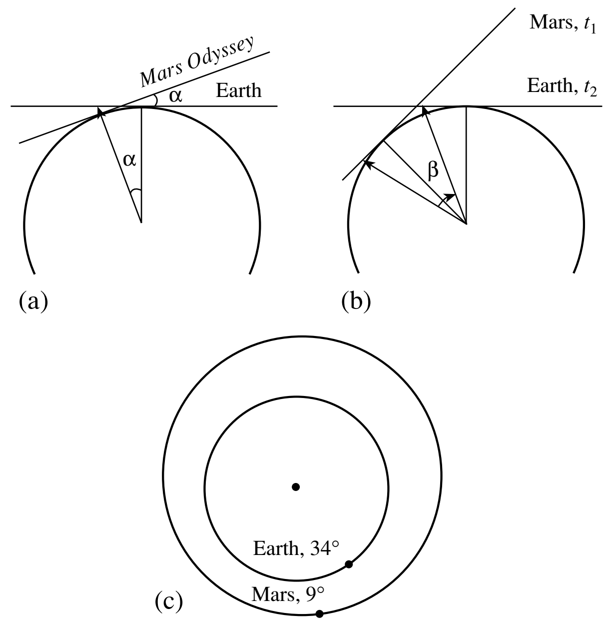

Fig. 1. Schematic depicting the estimation of the height of a source with the use of two instruments: (a) the spacecraft located in the plane of the ecliptic, separated in longitude by an angle α; (b) observations conducted at various times t_1, t_2 (the angle $\beta = \Omega(t_2 - t_1)$, where Ω is the rotational angular velocity of the active region during observations from the Earth); (c) an example of the mutual locations of the two spacecraft (end of October 2003).

4. SETTING OF THE FLARE ACTIVE REGION OF MAY 20, 2001

At the beginning of the flight, HEND detected a flare on May 20, 2001. The observations were carried out in approximately the same direction as those from near-Earth orbit, but, naturally, certain difficulties of subsequent observations of the Sun from near Mars had not yet arisen. Figure 2 shows the variations of the signal of the outer scintillator in the flare-detection regime (time resolution 0.25 s). A hard X-ray flare with its maximum at 6:03 UT (times everywhere have been recalculated to those for an observer in near-Earth orbit) was rapidly followed by the arrival of accelerated protons. We can see that the amplitude of the hard X-ray flare was only slightly smaller than the amplitude of the signal due to the accelerated particles—primarily protons with energies exceeding 60 MeV. In this case, the very rapid arrival of the accelerated particles to both the boundary of the magnetosphere and to the *Mars Odyssey* spacecraft is due to the favorable (western) position of the flare on the Sun and the very quiet conditions in the interplanetary medium on May 20, up until this event. Protons with energies of tens of MeV moved essentially along the force lines of the interplanetary magnetic field connecting the flare with the IMP-8,

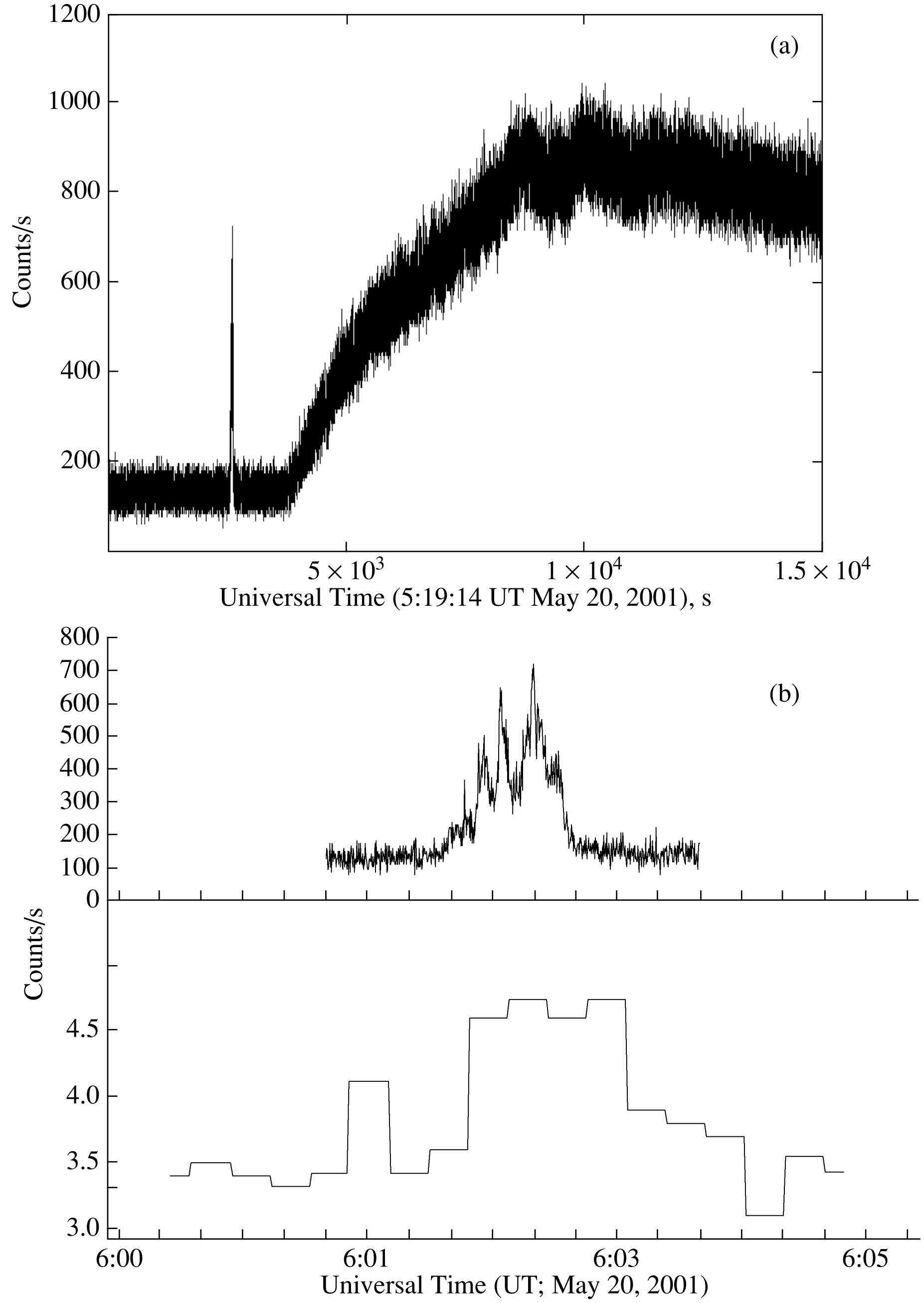

Fig. 2. (a) Count rate for the outer scintillator for the flare of May 20, 2001. The time resolution is 0.25 s. We can see that the amplitude of the hard X-ray flare does not exceed the instrumental response to solar protons with energies exceeding 60 MeV. (b) Count rates for the outer and inner scintillators for the flare of May 20, 2001, after 6^h UT. The resolution of the hard X-ray data is 0.25 s. The gamma-ray emission is presented as the sum of the counts in all the spectral channels; the time resolution here is 19 s.

GOES, and *Mars Odyssey* spacecraft, and were detected by instruments onboard these three spacecraft approximately 20 min after their acceleration. The corresponding time profiles of the accelerated protons turned out to be similar for all three spacecraft, and the fluxes of 10 MeV protons were close to 10 s.f.u., while the fluxes of protons with energies of tens of MeV approached 1 s.f.u. Analysis of the 1100 currently known proton enhancements observed in near-Earth orbit shows that the event of May 20 represents one of the most widespread cases. This is associated with the fact that precisely flares with X-ray strengths of about M5 are related to the weakest events that give rise to accelerated protons that arrive at the magnetosphere [12], and such sources of accelerated protons are the most numerous.

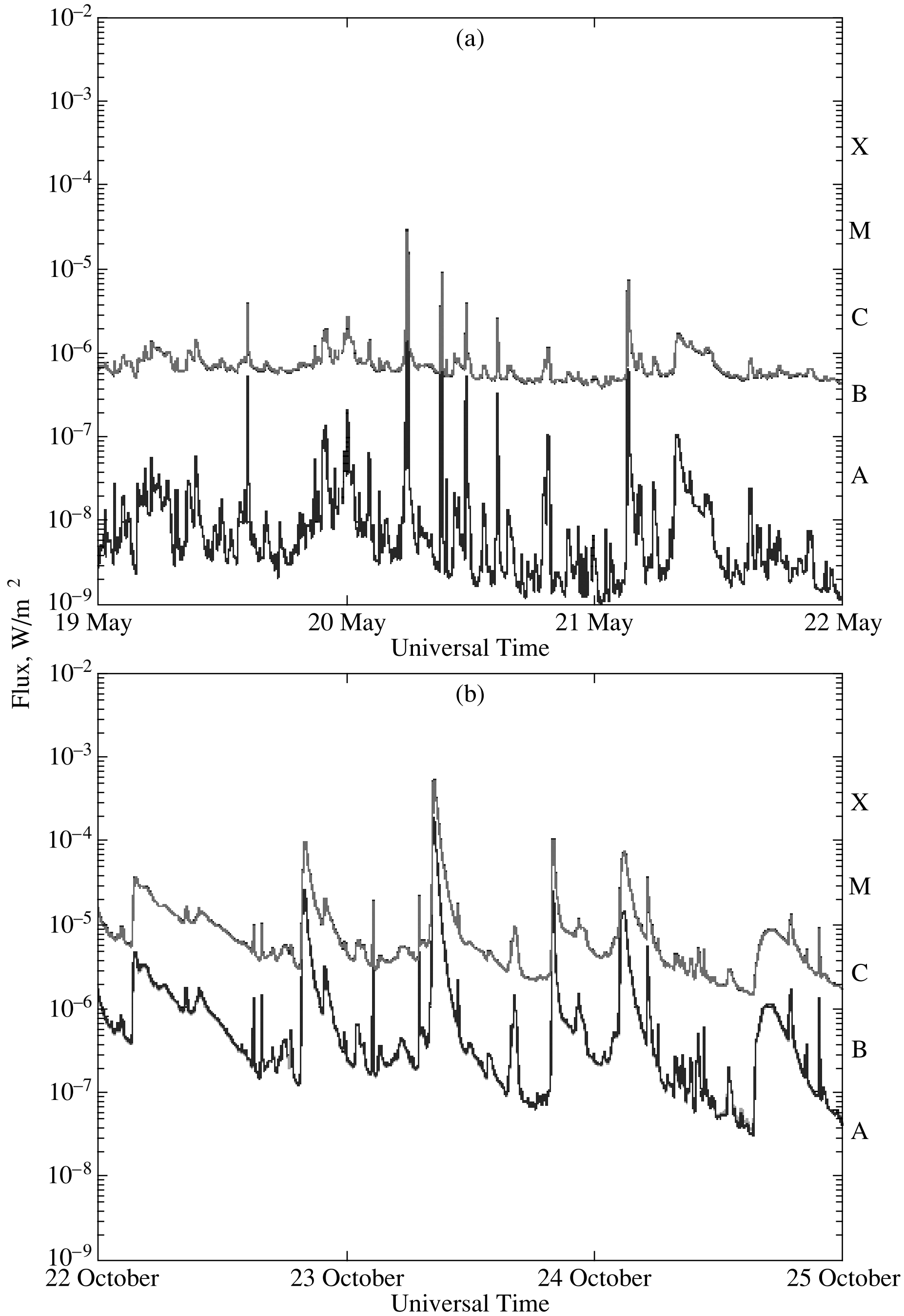

Fig. 3. (a) Setting of an activity center behind the limb on May 20, 2001, and (b) rising of another flare group on October 22, 2003, based on observations in the GOES 1–8 and 0.5–4 Å bands.

Figure 2b shows the responses of the outer and inner scintillators (i.e., the X-ray and gamma-ray photometers) in the flare-detection regime. The high time resolution of the X-ray flare enables the detection of structure: all the events are divided into four to five individual "elementary" events, each of which lasts about 10 s. Such fine structure is observed more often in events near the limb.

When analyzing the gamma-ray emission with a time resolution of 1 s, the useful signal was only weakly distinguished, but became more firmly detected in a 19 s integration regime, reaching approximately 80 photons in the entire flare. It is surprising that this relatively strong signal was not detected by Yohkoh, especially in the corresponding channels of the HXT X-ray telescope, which operated at the time of the flare and has a sensitivity that is somewhat

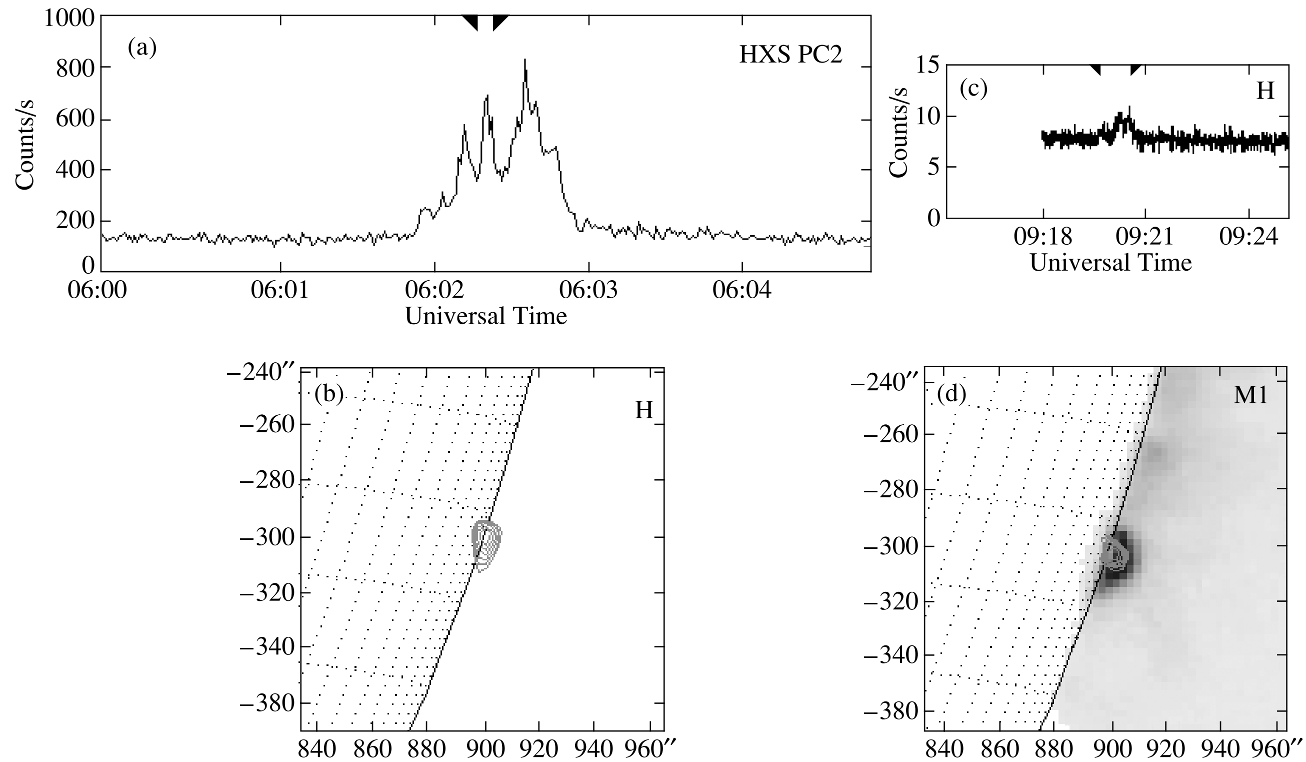

Fig. 4. Left: (a) time profile 75–872 keV in counts per second and (b) image in the Yohkoh XHT H channel (53–93 keV) for the flare of May 20, 2001, near 6^h UT. The time interval for the image is indicated on the upper axis of the flare time profile. Right: (c) time profile in the H channel (53–93 keV) in counts per second per channel and (d) image in the Yohkoh HXT M1 channel (23–33 keV) for the flare of May 20, 2001, near 9^h UT (it was not possible to construct an image in harder channels). The time interval for the image is indicated on the upper axis of the flare time profile.

higher than HEND (this flare was at the detection limit of the Yohkoh gamma-ray telescope).

When analyzing this discrepancy, it became clear that we were dealing with a very rare case of the setting beyond the limb of a group of spots in which rapid (or, as it has recently become popular to call them, "compact") flares arise with some regularity. The analyzed flare was the first, most powerful, flare of a series of events associated with the evolution of this group when it was on the side of the Sun hidden from the Earth. Instruments in near-Earth orbits operating in the soft X-ray and ultraviolet detected photons generated only at the apices of flare loops. This series is also clearly manifest in the regular data taken by the GOES satellite. All five flares visible in Fig. 3, which began on May 20, 2001, at 6:20 UT (M6.4), 9:12 UT (M1.5), 11:35 UT (C6.1), 14:32 UT (C2.9), and 19:30 UT (C1.3), occurred at the western limb during the setting of group 9455.

All these flares are characterized by certain peculiarities, which make them good candidates for gamma-ray flares. For example, the duration of the soft X-ray emission of the first flare of May 20, 2001, was only 6 min, while the growth phase was only 3 min (excluding a precursor at 5:46 UT, which is not shown in the figure). Note that several rapid flares occurred during the passage of this same group across the visible disk of the Sun, in particular, the M3.6 flare of May 13, 2001, beginning at 3:00 UT. This can be considered an example of the half of M flares that do not give rise to proton enhancements at near-Earth orbits and fluxes of hard radiation which are not accessible to measurements with HEND.

Usually, such powerful, bright flare systems of events as the flare beginning at about 6^h UT on May 20, 2001, last an hour or more. The simplest explanation for the brief duration of the flares in this series is that the primary energy release in these flares was so great that the magnetic field could not confine the forming system of loops. However, the idea that the system was completely disrupted is not always in agreement with the observations—often it is simply the conditions for prolonged existence that are disrupted. For example, at the end of the ejection of the flare of May 20, when a shock (type II radio flare) emerged into the middle corona from 6:06 to 6:26 UT, the SOHO data display a wide front with a cavity at its center and with strongly twisted formations at the center and arcades; the large-scale streamer was disrupted. However, the post-eruptive development of this event that is usual for large flares did not occur.

Analogous phenomena with somewhat lower powers were observed in the second flare, which began at 9:12 UT and lasted only 11 min. Type-II radio emission was already detected at large distances at 9:28 UT. The variations of the soft X-ray flux for the last flares in the series and analysis of the radio data suggests that all the flares in the series were homologous (all the characteristic properties of the processes for the first two events were virtually identical).

The first two flares were observed by the Yohkoh HXT instrument (Fig. 4). The most striking thing about them is the extreme similarity of the main properties of the time profiles for the flare of May 20, 2001, obtained for the two instruments, which differed only in their time resolution (Figs. 2b, 4a). The similarity in the absolute values here is due to a chance coincidence in the count rates; in reality, the absolute flux corresponding to the HEND measurements is somewhat higher than the flux for the Yohkoh HXT data. However, after the HEND and HXT X-ray photometer signals were over, the gamma-ray photometer went on to observe another maximum. This delay in the hard emission by approximately 20 s is manifested in the data averaged to 19 s, as can be seen by comparing Figs. 2b (top) and 4a with Fig. 2b (bottom).

This difference between the HEND and HXT data can be expressed in another way. The flare of May 20, 2001, was already powerful at about 6:00, and involved a large number of accelerated particles. Nevertheless, in observations carried out in near-Earth orbit, the spectrum of photons with energies of 50–300 keV displayed a power-law index of −4.3 (according to the HXT spectrum). Such powerful flares usually have harder spectra, with indices from −3 to −2, especially in the case of limb events. This provides additional support for the reality of the inferred differences.

Note that this flare occurred precisely at the limb for an observer at the Earth. This follows, for example, from the SOHO 171 Å frames at $13^{\rm h}$ UT, which show a large loop that is moving behind the limb in the setting part of the active region. In other words, the second base of the loop was probably already located on the side of the Sun that is hidden from an observer in near-Earth orbit; one of the flares with energy exceeding 330 keV was detected from the *Mars Odyssey*, but was not able to be observed from near-Earth orbit.

The second flare was observed on the Yohkoh HXT instrument to energies of about 60 keV, and could already not be distinguished very clearly in the standard H channel (53–93 keV). It was possible to construct images only in two of the four energy channels: L (14–23 keV) and M1 (23–33 keV); the latter image is presented in Fig. 4d. The decrease in the fluxes compared to the first flare is associated with both its lower power and its setting behind the limb over a time of only three hours. Note that, in this case, there is some evidence for a hardening of the spectra of flares near the limb at 20–100 keV, as can be noted in a statistical analysis of hard flares. The flares of May 20, 2001, at 9:12 UT (M1.5), 11:35 UT (C6.1), and probably 14:32 UT (C2.9) were also observed by the *Mars Odyssey*, but the detection of accelerated particles from the western flare at this time prevents a quantitative comparison of the time profiles for the X-ray emission detected by the two spacecraft.

Thus, even observations carried out using a single spacecraft contain some information about the location of the X-ray source. Applied to the case considered of a well defined setting source of rapid flares, these soft X-ray data (Fig. 3) enable us to estimate the height of ordinary loops associated with weak compact flares to be $h \leq 20\,000$ km. The Yohkoh HXT data can be used to analyze not only the "ideal setting" of the sources on May 20, 2001, but also some set of such cases. A preliminary analysis of this material suggests that the height of the sources of radiation with energies exceeding 50 keV is lower than the value of 20 000 km for the sources of softer photons. It is clear that the main emission in this range of energies arises near the loop bases, and the question is what contribution is made by high sources near the cusps of typical large prolonged flares.

The variety of geometries and other properties of flares hinders detailed studies of the setting of sources behind the solar limb. The presence of two spacecraft, preferably with identical instruments, fundamentally changes the situation, enabling simultaneous observations of a single event from different directions. The difference in the longitudes in the ecliptic plane for the *Mars Odyssey* spacecraft and the Earth was 8.3° at the time of the maximum of the May 20, 2001 flare. The flare, which was located precisely at the limb for the near-Earth observations, was observed by HEND on the visible disk 8.3° from the limb. In spite of the small difference in the spacecraft longitudes, when the source is located precisely at the limb for one of the instruments, the effect of setting behind the limb will already be manifest for the other. In our view, the most probable explanation is that the second base of a high loop associated with two parts of a bipolar group was not visible in the near-Earth observations. This testifies to a low height for the source, which can be estimated using the method depicted in Fig. 1a to be about 7300 km. Clearly, we are dealing here with a part of the source that is invisible to the near-Earth

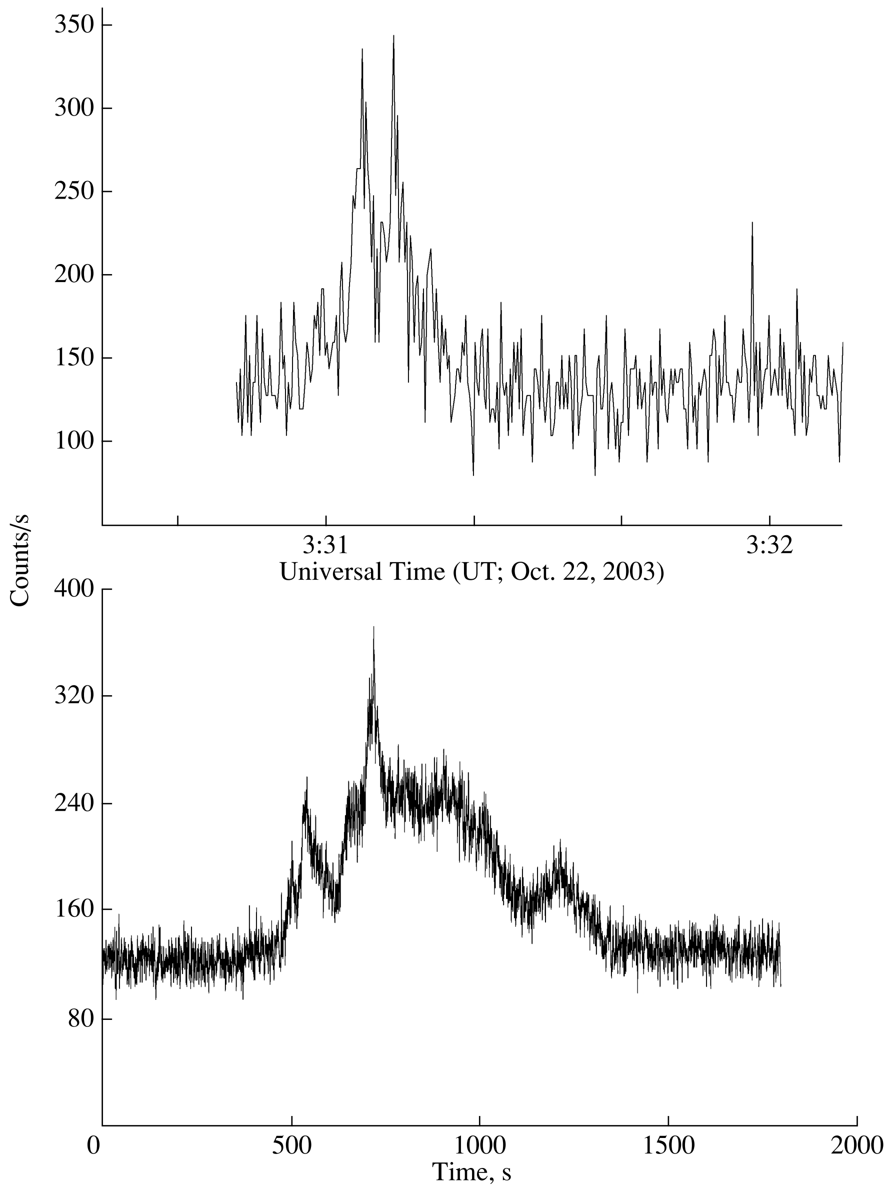

Fig. 5. (a) X-ray flare of October 22, 2003; the time resolution is 0.25 s. (b) The same for the October 24, 2003. Time in seconds, the beginning of the time scale is 2:36:41 UT.

observations and is localized near the base of the loop, rather than at the loop apex.

5. EVENTS DURING THE RISING OF GROUP 10486 IN OCTOBER 2003, BASED ON STEREOSCOPIC OBSERVATIONS

At the end of October 2003, in the decay phase of the 23rd solar cycle, a period of high flare activity began, which has been actively studied with both ground-based observatories and spacecraft in near-Earth orbits. At the beginning of this period, October 23, 2003, the *Mars Odyssey* spacecraft in its orbit around Mars detected nonstationary events on the Sun, which were located 24° to the west of their position for observations from the Earth. Thus, the rising of the groups, above all group 10486, was observed from a near-Mars orbit earlier than from the Earth.

This case is opposite to that discussed above in terms of both type of activity and observing conditions. While the setting of a source of a series of homologous, very short flares was observed in May 2001, in this case, we have the appearance from behind the limb of a source that was transformed over one to two days into a very complex site displaying powerful activity. A large number of weak, nonstationary processes were detected at the eastern limb south of the solar equator in the soft X-ray range by near-Earth instruments. Against the background of the two most powerful flares, which began at 3:28 UT (M3.7) and 19:47 UT (M9.9) on October 22, 2003, a number of weaker events were observed, such as those starting at 8:30 UT (M1.7), 9:37 UT (M1.7), 15:57 UT (M1.2), and 21:56 UT (Fig. 3b). Another difference from the case of May 2001 is that, the observations of these nonstationary events near the eastern limb did not reveal accelerated solar particles traveling in the direction of the spacecraft. Accordingly, there is no flux of particles hindering the detection of X-rays and gamma-rays, as was the case for the western flare of May 20, 2001.

At the end of October 2003, the activity on the disk was determined primarily by group 484, which preceded group 486 (here and below, we omit the 10 before the group number). The effect of a connection between a weak flare in group 484 and the beginning of activity in the following group, 486, can already be seen in the structure of a powerful coronal mass ejection on October 21, 2001 at 4:28 UT at the eastern limb 16° south of the equator. Our data indicate that the enhanced level of soft X-ray emission after 18^h UT on October 21, 2001 (shown by the GOES data) is clearly related to the activity of group 486. Indeed, a large flare with its maximum at 18:41 UT and lasting 12 min in the hard X-ray range was observed by the *Mars Odyssey* spacecraft. The count rate in the outer scintillator reached a maximum of 300 s^{-1}, and the radiation in the first peak remained appreciable at energies of 100–200 keV (see [13] for more detail). Traces of this flare, which realistically could have reached magnitude X but occurred far beyond the limb for an Earth observer, are visible on the 195 Å SOHO image obtained at 18:48 UT.

The following flare occurred at the end of the soft X-ray enhancement that began at about 18^h UT on October 21, 2003, at about 3:30 UT on October 22. According to the GOES data, its class reached M3.7, but in reality the flare was somewhat more powerful due to the invisibility of the dense bases of the flare loops from near-Earth orbit. This also follows from a 195 Å SOHO film, in which the flare loops in the southern part of the region move beyond the limb, in the direction of the main flare site. The time profile of the hard X-ray emission from the data obtained by the HEND outer scintillator is presented in Fig. 5a. There is no corresponding signal in the hard X-ray channels, beginning with energies of about 300 keV, or in the gamma-ray channel. In the data taken in near-Mars orbit (Fig. 5a), two peaks separated by 4–5 s, can be distinguished. This time structure is typical for high-energy phenomena that develop in low loops associated with impulsive events.

This source of hard X-ray emission was located beyond the limb for observations in near-Earth orbit and, thus, so was not visible. Several very weak events associated with phenomena in both groups were observed by HEND on October 22, 2003, but they were softer than the similar weak events on subsequent days. For comparison, the time profile of one of these is also presented in Fig. 5b. The flare of October 24 at 2:54 UT (Fig. 5b) was somewhat more powerful than the flare of October 22 (M7.6); the two X-ray flares were similar, but the hard radiation for the later flare continued for more than 10 min rather than only tens of seconds.

The X-ray emission from group 486 was first detected firmly in near-Earth orbits was on October 22, 2003 at 19:45 UT at energies near 40 keV. The CORONAS-F monitoring data testify that the detected fluxes were lower than expected for a M9.9 flare, suggesting that the bases of the loops may have been located beyond the solar limb (a more detailed comparison of CORONAS-F data for this flare and data taken in near-Mars orbit can be found in [13]).

Thus, the influence of group 486 began to be felt at soft X-ray energies at the end of October 21, 2003. The situation here is analogous to the setting of the soft source on May 20, 2001: the soft radiation is observed beyond the limb far longer than the hard radiation. In reality, the near-Earth spacecraft CORONAS-F and RHESSI detected at hard X-ray energies the final stage of a large flare that occurred on October 23.

The first large X5.4 flare of a series of powerful events from the end of October through November 4, 2003, occurred on October 23 at about 8:30 UT. Two main maxima are observed on the X-ray light curve (Fig. 6a), which correspond to two impulsive flare episodes separated by approximately 15 min. These two maxima were also observed on the radio at 10 cm (Fig. 6c), confirming the existence of two stages of the event. The fine time structure of the main X-ray impulse is also well defined in recordings with the maximum time resolution of 0.25 s when recordings of only this radiation are separated out.

This flare was detected in the inner HEND scintillator, as can be seen in Fig. 6b, which presents the gamma-ray count rate averaged over 8 s. A comparison of the X-ray and gamma-ray curves shows that radiation with energies exceeding 1 MeV is clearly distinguished not at the time of the first, most powerful X-ray impulse, but instead at the time of the weaker X-ray impulse that occurred 2 min later. It is most likely that this corresponds to the time when

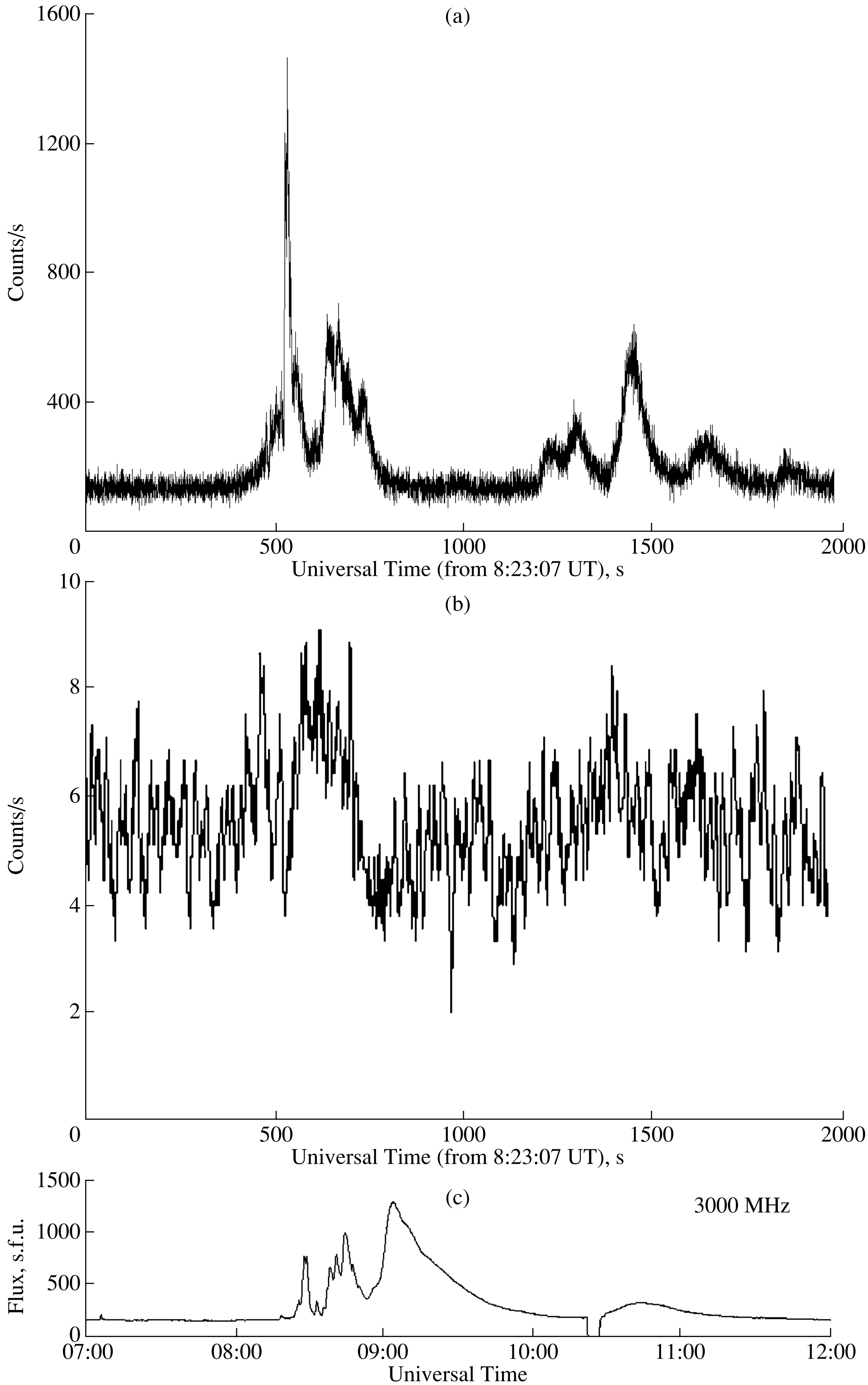

Fig. 6. (a) Hard X-ray emission of the flare of October 23, 2003; the time resolution is 0.25 s, time in seconds. (b) Gamma-ray emission for the same flare and the same time interval, averaged over 8 points. (c) Radio outburst on October 23, 2003, for IZMIRAN data.

the flare particles were accelerated to relativistic energies. The radiation becomes softer at later times, but there is a powerful energy release in both impulsive events. The quasi-stationary development of giant post-eruptive loops whose axis is directed toward another, northeastern, group began after 9^h UT. The development of this post-eruptive phase is clearly expressed and can be traced in both out-of-atmosphere and ground-based data from the ultraviolet to the radio ranges. We are considering this flare in somewhat more detail only because it displayed the main properties of phenomena that were developed in subsequent flares in this series. This event is worthy of a separate, more detailed discussion, all the moreso because other detailed observations from the Earth were hindered by the nearness of the flare to the limb and observations in near-Earth orbits were unsuccessful.

Returning to the main theme of the paper, we assert, based on an analysis of all the available observations, that the activity at the eastern limb of the Sun was first detected on the *Mars Odyssey* spacecraft at photon energies exceeding 80 keV one day earlier than the event was detected in near-Earth orbit. The boundaries of this time interval can be taken to be either the onset of visibility of the hard phenomena to the near-Mars and near-Earth instruments (18:40 UT October 21 and 19:50 UT October 22, 2003), or the movement behind the limb of the group for the two types of spacecraft. This occurred for the Martian spacecraft at 3:30 UT on October 22 (Fig. 5a), while activity at hard energies began to be detected at the beginning of October 23 by the RHESSI and CORONAS-F spacecraft.

Thus, assuming an approximately constant height for the sources of hard radiation associated with flares that are not very strong, we can estimate this height based on simple reasoning (Fig. 1b). The difference in the longitudes of the Earth and Mars at the time of the first flare was close to 22°. The active region shifts by 14° per day in the same direction as the motion of the two planets in their orbits (here, we use data for the siderial rotation of the Sun for an observer on Earth). This means that the base of the second flare was located 8° beyond the limb. Given that the time interval can somewhat exceed one day, it is reasonable to estimate the height of the hard source to be in the range 7000–10 000 km.

6. EVENT OF AUGUST 25, 2001, AS AN EXAMPLE OF A POWERFUL FLARE ON THE DISK

Hard radiation accompanied by particle acceleration on the Sun was detected by both HEND and instruments in near-Earth orbits. First and foremost, we carried out a qualitative comparison of the time profiles of flares occurring on the solar disk observed simultaneously from different directions. For about a dozen cases, such comparisons lead to a surprising coincidence in the shapes of the flares and, most often, fluxes of the radiation for M3–X2 flares. Several examples are presented above. Generally speaking, this supports the conclusion drawn earlier that the radiation of photons with energies exceeding 70 keV for events on the visible disk is not directed (see [9] and references therein).

However, this is not so obvious in the case of the largest events. As an example, let us consider a flare detected during the flight of the *Mars Odyssey* spacecraft to Mars. The powerful flare of August 25, 2001, with well-developed high-energy phenomena occurred on the solar disk at some distance from the southeast limb (class X5.3, onset at the Earth at 16:23 UT, coordinates S17 E34). No flux of accelerated protons was observed from this eastern flare, while a sporadic high-velocity flux of plasma arrived early, after approximately two days. Gamma-ray emission was detected by several spacecraft. In particular, the CORONAS-F and Yohkoh spacecraft detected appreciable fluxes of hard photons with energies up to 40 MeV during this flare [14]. Such events are fairly rare, as can be seen, for example, from an inspection of a list of events detected by FOBOS [15].

Figure 7 presents the results of gamma-ray observations with a time resolution of 1 s. In this case, a gamma-ray signal with a duration of about 100 s and with its maximum at about 16:31:44 UT was firmly detected. We can see that the entire flare represents a superposition of several impulses with durations of 10–30 s each. The time profile repeats the main properties of the data obtained in the HXT Yohkoh H channel. This suggests that we are dealing with the acceleration of individual beams of particles and their subsequent destruction in dense layers. The shapes of the profiles for higher-energy nonthermal radiation remain similar, reflecting the time dependence of the particle acceleration. However, a more detailed comparison shows that the decrease in the flux in time shown by the HEND data occurs somewhat more slowly than in the HXT Yohkoh H channel. A more detailed analysis is required in order to elucidate whether this is related to the effect of directivity of the radiation for observations at angles differing by 25°. Competition arises from the variations in band sensitivity for the different channel energies when incident radiation also becomes harder.

In many respects, the analyzed event can be considered to be a source of a "typical" powerful gamma-ray flare. Indeed, the flare arose at the point where a bright Hα floccule passed between two large spots in a group with opposite polarities (Fig. 8a). This

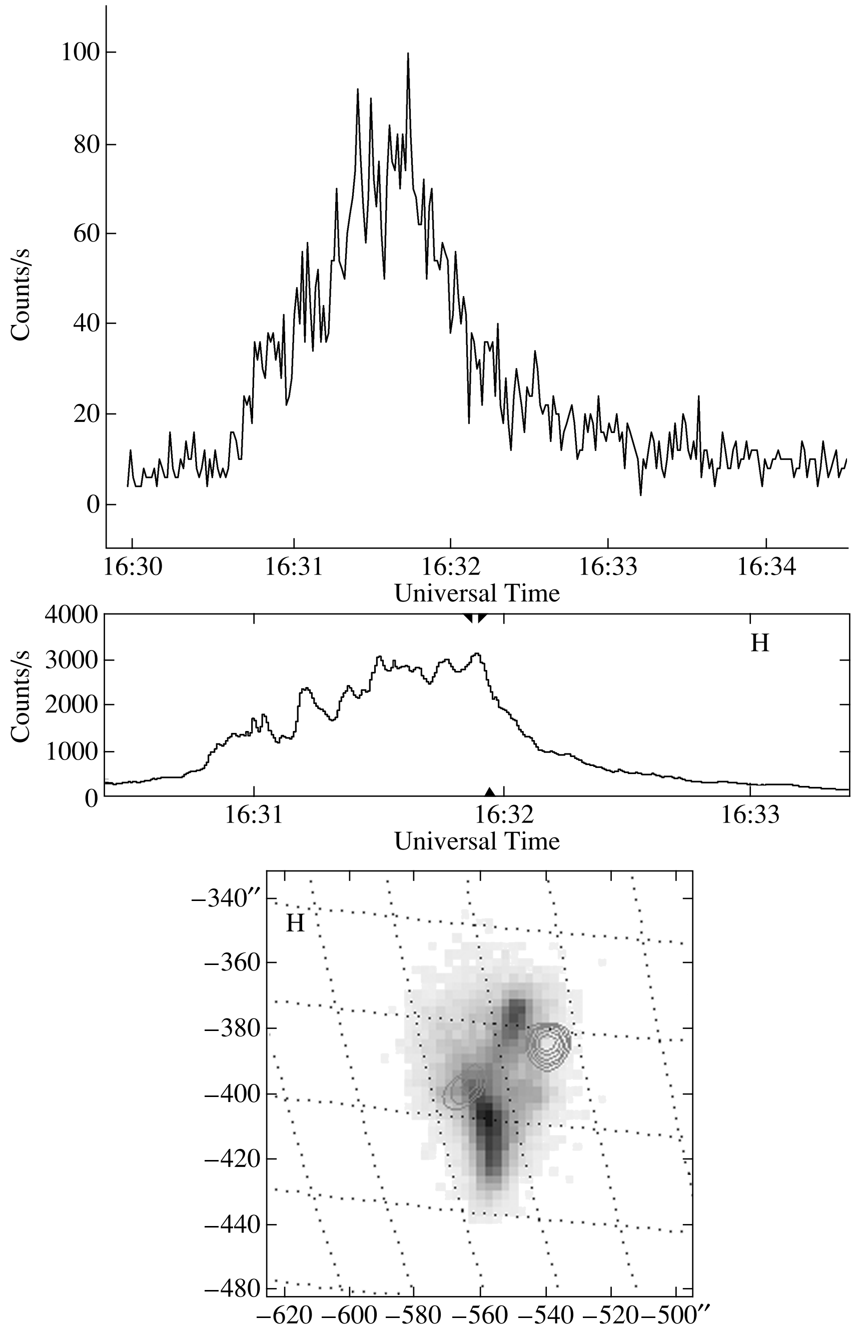

Fig. 7. Count rate for the inner HEND scintillator on August 25, 2001 (upper), time profile for the flare from Yohkoh data in counts/s per channel (middle), and image of the flare in the HXT Yohkoh H channel (53–93 keV) (lower). The map of contours of hard-radiation brightness is shown against the background of an image of the SXT Yohkoh soft radiation. The times when the images were obtained are indicated in the middle plot.

situation is the most favorable for the development of high-energy phenomena, most of which are produced in the penumbra of a single large spot during the rising of small islands with opposite magnetic polarities (i.e., in the presence of large differences in magnetic fluxes of opposite polarity). The extent of the 3B optical flare along the magnetic-field neutral line was modest compared to other flares with comparable powers (for a height of the main loop at the flare maximum of about 20 000–25 000 km; Fig. 7, lower). The compactness of the light sections of the flare in Figs. 8b and 8c is characteristic of gamma-ray flares. The difference images in four lines kindly presented to us by I.M. Chertok enable us to understand the

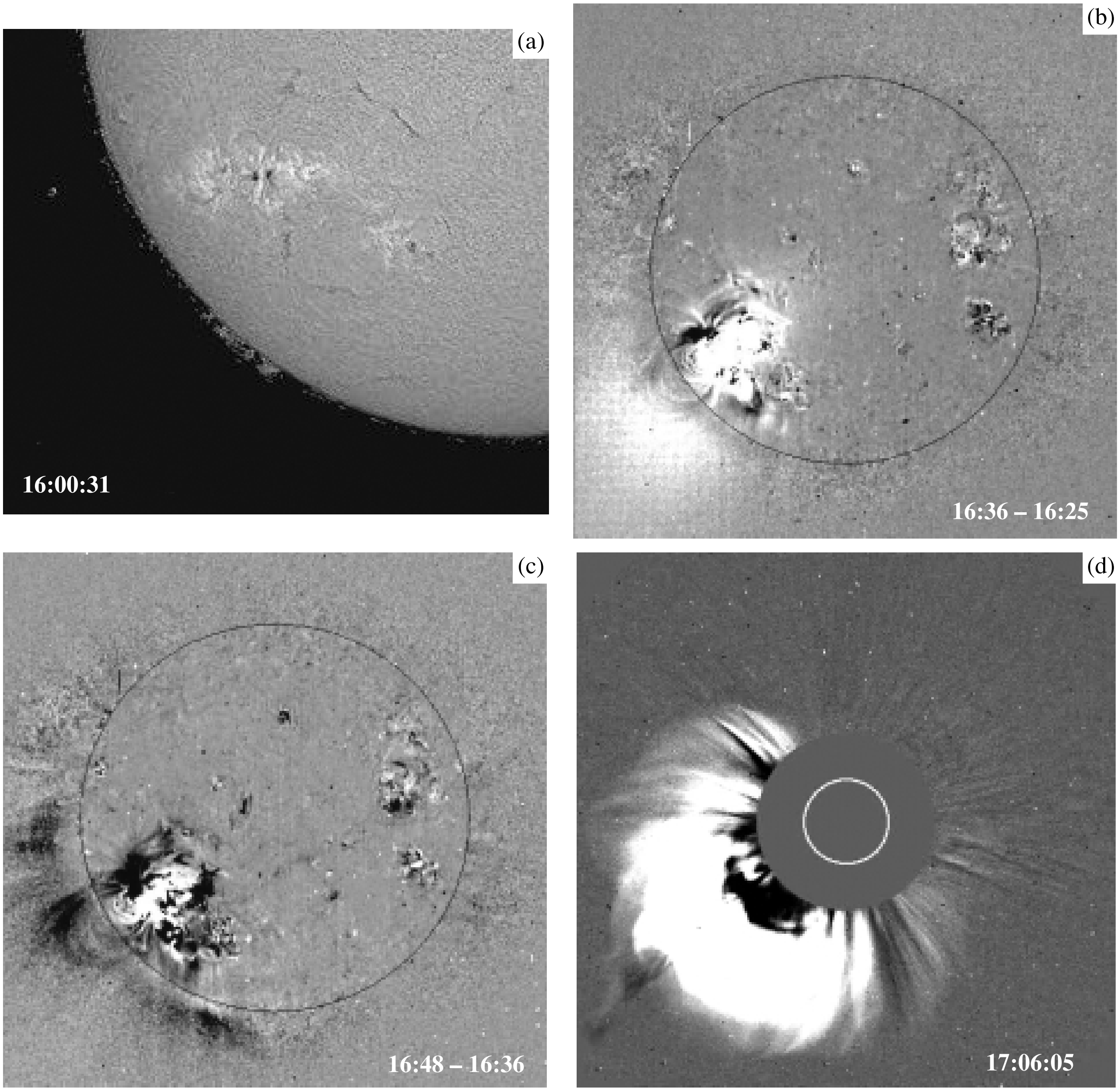

Fig. 8. Flare of August 25, 2001: (a) onset of the flare in Hα (16^h UT); (b) difference image at 195 Å from the SOHO data for the interval of the flare maximum; (c) same as in (b) for the next frame (the darkening/dimming can be noted to the North of the region in which the flare began, which makes a transition to a dark arc above the limb); (d) coronal mass ejection in the middle corona from the SOHO C2 data.

main properties of the plasma ejection, and possibly the outflow of accelerated particles (this analysis is analogous to that applied in [16]). Namely, there are grounds to suppose that a perturbation cone was directed to the Southeast, approximately 30°–40° from the radial direction passing through the flare.

Indeed, the development of the high-energy event of August 25, 2001, lasted over all several minutes. The rapid and dense coronal mass ejection that arose at that time (Fig. 8d) led to the development of the subsequent post-eruptive phase of the flare immediately after the high-energy event (Figs. 8b, 8c). This is quite common, and only in certain powerful events, such as the event of June 15, 1991, is there an interval of 10–20 min between these two phases. As a rule, after a powerful impulse, the system of new flare loops propagates in two directions along the neutral line of the longitudinal magnetic field. The structure of the flare begins to resemble an S shape, referred to as a "sigmoid flare." One peculiarity of the event of August 25, 2001, is that the ejection was asymmetric: it was stronger toward the Northeast than toward the South. This was manifested via the substantial development of the system of giant arches, which was clearly visible on the eastern limb, as well as the stronger dimming to the Northeast. A corresponding darkening that arose due to the ejection of part of the high loops is clearly visible in Fig. 8c to the northeaster of the spots, in the location of the energy release.

Thus, powerful phenomena accompanying large fluxes of gamma-rays represent a combination of compact formations and the very unusual and prolonged subsequent development of nonstationary processes.

7. RESULTS AND DISCUSSION

We have presented the first results of data on solar flares obtained using the HEND instrument onboard the *Mars Odyssey* interplanetary space station during its flight to Mars and its orbits around Mars. The scientific instrument complex of the station includes the HEND, developed at the Space Research Institute of the Russian Academy of Sciences. The scintillation HEND with two independent crystals enabled the detection of photons with energies from tens of keV to 2.5 MeV. In the first stage, we restricted our use of these data to a regime with two "photometers" operating at more than 80 keV (hard X-ray) and more than 330 keV (gamma-ray), with maximum time resolutions of 0.25 and 1 s, respectively. The instrument also detects solar cosmic rays.

Consideration of these data together with the results of measurements made in near-Earth orbits enable the detection of some variations in the integrated fluxes of hard radiation from solar flares in the case of simultaneous observations from two different directions. The most interesting observations of this type are those near the solar limb. We have applied two approaches to the realization of such "stereoscopic" observations. The first consists of simultaneous observations of a source from two different directions, and the second, in determining the moments when a source appears at the limb at different spacecraft as a result of the corresponding rotation of the Sun.

We analyzed two cases as examples: the setting of a flare region on May 20, 2001, which displayed regular brief flares, and the rising of group 10486, which displayed numerous flare phenomena at the limb and extremely high activity in October–November 2003. In both cases, we found that the setting of a modest (class M) flare 8°–10° behind the limb led to an appreciable decrease in the nonthermal radiation with energies exceeding 80 keV. The corresponding height of formation of the bulk of this radiation is located below 7000–10 000 km. This supports the idea that this radiation is generated near the bases of flare loops, with the flux from the loop apices being negligible. We emphasize that this result was based on geometric reasoning, without serious assumptions being made about the structure of the source or the mechanism generating the radiation.

Essentially, the instrument we have used detects flares beginning with class M3, or more precisely, those of them in which a fairly large quantity of particles have been accelerated. If these flares are located in the western part of the disk, or even in the central part, accelerated solar cosmic-ray particles that are generated there can be detected in near-Earth orbits. The new information about these weak sources of proton perturbations is the following. Acceleration occurs in the impulsive or explosive phase of these flares, and continues no more than several minutes. If an ordinary system of high loops forms, it exists for only a very short time. An additional source of X-ray emission usually forms in the post-eruptive phase, high in the region of the cusp. RHESSI data clearly demonstrate that, in the powerful flare of July 23, 2002, this source is located at coronal heights, and moved upward beginning from a height of about 20 000 km [17]. Even in X flares, this radiation is concentrated near energies of tens of keV.

Analysis of HEND data leads us to conclude that the energies of photons arising in the source at high heights near the loop apices do not exceed 80 keV. This contradicts the picture in which the acceleration of relativistic particles occurs during the reconnection of magnetic-field lines in a vertical current sheet or at the front of a large-scale shock in the corona. Strictly speaking, this conclusion can be drawn only for M flares. One of the main problems, therefore, becomes the need to search for mechanisms for efficient particle acceleration at low heights in compact flares.

It is not possible to draw the same conclusion for powerful solar flares based on currently available data. Several examples only confirm the short durations of typical solar gamma-ray flares. We emphasize that comparisons of the HEND data with the results of radio observations indicate a coincidence between many interesting features, especially in the impulsive phases of flares. This is associated with the good time resolution of the HEND data. The meaning of these coincidences is that the radiation at energies exceeding 80 keV is nonthermal, and the appearance of a thermal component is not noticeable, even in such powerful gamma-ray flares as the event of August 25, 2001. Note also that, in a number of cases, HEND data occupy gaps in observations of the hard X-ray radiation of several interesting events, and joint analyses could lead to new results for phenomena such as large solar flares. Our analysis also convinced us of the large diagnostic potential of data obtained with even modest instruments for which regions beyond the eastern limb of the Sun are accessible to observation.

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REFERENCES

1. H. Hudson and J. Ryan, Annu. Rev. Astron. Astrophys. **33**, 239 (1995).
2. G. Rank, J. Ryan, H. Debrunner, *et al.*, Astron. Astrophys. **378**, 1046 (2001).
3. M. A. Livshits and A. V. Belov, Astron. Zh. **81**, 732 (2004) [Astron. Rep. **48**, 665 (2004)].
4. S. R. Kane, Sol. Phys. **86**, 355 (1983).
5. S. Masuda, PhD Thesis (Univ. of Tokyo, Tokyo, 1994).
6. S. Masuda, T. Kosugi, H. Hara, *et al.*, Nature **371**, 495 (1994).
7. E. Rieger, Sol. Phys. **121**, 323 (1989).
8. S. V. Bogovalov, S. R. Kel'ner, and Yu. D. Kotov, Astron. Zh. **65**, 1275 (1988) [Sov. Astron. **32**, 664 (1988)].
9. P. Li, K. C. Hurley, C. R. Barat Talon, and Victoria Kurt, Astrophys. J. **426**, 758 (1994).
10. H. T. Gallagher, B. R. Dennis, S. Krucker, *et al.*, Sol. Phys. **210**, 341 (2002).
11. W. V. Boynton, W. C. Feldman, I. G. Mitrofanov, *et al.*, Space Sci. Rev. **110**, 37 (2004).
12. A. V. Belov, E. Garcia, V. G. Kurt, and E. Mavromichalaki, Kosm. Issled. (2005) (in press).
13. M. A. Livshits, V. A. Chernetskii, A. V. Bogovalov, *et al.*, Astron. Vestn., No. 6 (2005) (in press).
14. S. N. Kuznetsov, K. Kudela, I. N. Myagkova, and B. Yu. Yushkov, in *Proceedings of the 28th International Cosmic Ray Conference* (Universal Academy Press, 2003), p. 3183.
15. O. V. Terekhov, Doctoral Dissertation (Institute for Space Research, Russian Academy of Sciences, Moscow, 1996).
16. I. M. Chertok and V. V. Grechnev, Astron. Zh. **80**, 1013 (2003) [Astron. Rep. **47**, 934 (2003)].
17. S. Krucker, in *Proceedings of the 13th Cool Stars Cambridge Workshop, Hamburg* (2004), ESA SP-560, p. 101.

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