Astronomy Reports, Vol. 48, No. 8, 2004, pp. 665–677. Translated from Astronomicheskiĭ Zhurnal, Vol. 81, No. 8, 2004, pp. 732–745.


# When and Where are Solar Cosmic Rays Accelerated Most Efficiently?

**M. A. Livshits and A. V. Belov**

*Institute of Terrestrial Magnetism, Ionosphere, and Radiowave Propagation, Russian Academy of Sciences, Troitsk, Moscow oblast, 142190 Russia*

Received September 25, 2003; in final form, March 15, 2004

**Abstract**—The acceleration of particles by solar flares with extremely large proton fluxes whose energies exceed 100 MeV is considered. Most importantly, the location of the source of such acceleration in the flare of July 14, 2000, is determined assuming that the acceleration time coincides with the observed burst of hard line and continuous gamma-ray emission. The onset of this event corresponds to 10:19 UT, when data taken by the TRACE space observatory show that one of the flare ribbons reached a large sunspot in a group. The time interval for the development of the flare, 10:20–10:28 UT, is associated with the beginning of an increasing proton flux at the Earth. The region of efficient acceleration is estimated to be approximately two to three times higher than the height where the hard X-ray pulse usually originates (about 7000 km). The results are generalized for 28 powerful flares with extremely efficient acceleration of relativistic particles—in particular, for the well-studied events of June 15, 1991, and May 24, 1990—and are compared with the results of a statistical analysis of over 1100 increasing-proton-flux events. Efficient particle acceleration seems to be associated with the powerful impulsive episodes of the large flares analyzed. The results suggest that, along with sources of local (as in impulsive flares) and post-eruptive acceleration, there is an additional, very efficient, moderate-scale "accelerator" in tenuous regions with fairly strong magnetic fields and magnetic-field gradients. 

## 1. INTRODUCTION

The problem of particle acceleration is one of the most difficult in the physics of solar flares. The presence of accelerated electrons is revealed in impulsive phenomena by their nonthermal spectra from 10–15 to 100 keV. Extensive data on ions accelerated during solar flares have been obtained over the past 50 years via the direct detection of the particle fluxes at the Earth and in interplanetary space. Catalogs of proton events include all increases in particle fluxes in the above energy range above a few to 10 MeV. The low-energy detection threshold ranges from 0.01–1 particle per square centimeter per second per steradian in periods of deep minimum and maximum solar activity, respectively. The highest proton activity during the last 40 years for which all the necessary data are available was observed in the XXII solar cycle [1]. Despite the availability of multiple records of proton events, the mechanism and sources of the particle acceleration remain unclear.

As follows from studies conducted over the last several decades, particles with energies of 10–80 MeV are probably accelerated by shocks formed by coronal mass ejections (CMEs). A substantial contribution to solving this problem has been made by D. Reams, S. Kahler, and O.C. St.Syr. The subject of the present paper will be more energetic particles, namely, protons with energies above 100 MeV (and electrons with energies above 50 keV). For brevity, we will call such particles relativistic, since an analysis of their motion must be carried out in a relativistic treatment.

A few years ago, shock acceleration was commonly assumed to take place for relativistic particles as well, particularly for protons with energies up to 1 GeV and more, i.e., for solar cosmic rays (CRs) observed at ground-based detectors. However, this view is now in contradiction with new results that follow both directly from observations of high-energy phenomena and from their theoretical interpretation. For example, in some cases, the main shock is formed well after the time when the particles with the highest energies have left the Sun, reaching detectors on the Earth within the following 15–20 min. In addition, it is difficult to explain the acceleration of particles to energies above 1 GeV by shock fronts with the physical parameters of those that are implied by observations of type-II radio bursts in the corona and interplanetary space.

As is known, ground-level enhancements (GLEs) of the cosmic-ray intensity are usually associated with the most powerful flares, which often occur in large spot groups or activity complexes. As a result, several successive GLEs are sometimes observed when such a group moves over the disk near the solar-activity maximum. The particles usually come to the Earth from powerful flares in the western part of the disk at longitudes from +20° to +75°,

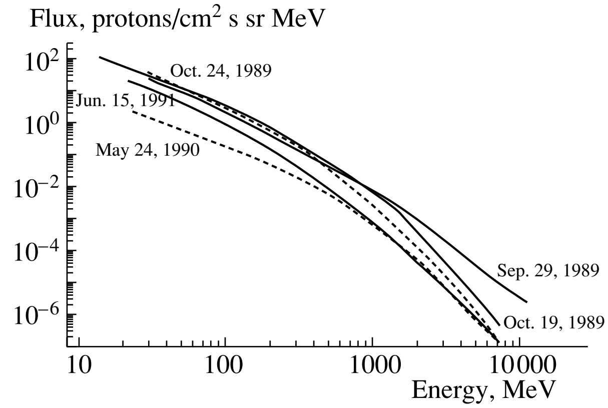


**Fig. 1.** Proton spectra observed at the Earth and in near-Earth orbit at the times of maxima of the most prominent enhancements of cosmic rays in the XXII cycle. The hardest solar cosmic-ray spectrum was detected in a flare behind the limb on September 29, 1989.

although a number of such events are associated with central flares, as well as processes near or behind the western limb. The amplitude of a GLE, the shape of its temporal profile, and its energy spectrum are sensitive to the longitude of the solar event resulting in the GLE. There are sometimes two maxima in the ground-based observations of solar CRs. The first is characterized by high anisotropy: the number of particles leaving the Sun along certain magnetic field lines is considerably greater than the fluxes from other directions. The spectrum of particles arriving directly from the Sun was found to be harder than the spectra of particles arriving later from various directions. The enhancement detected by a particular cosmic-ray station depends on its geomagnetic latitude and can vary from a fraction of a percent to to several thousand percent.

Proton spectra detected at the Earth and in near-Earth orbits are shown in Fig. 1 for the maxima of the largest enhancements in the intensity of solar CRs in the XXII cycle [2]. These spectra are thought to be close to the particle-emission spectra of the source of acceleration. The hardest solar CR spectrum was detected in a flare behind the limb on September 29, 1989. Note that the proton spectrum at energies of about 1 GeV in a short, powerful flare on May 24, 1990, almost coincided with the spectra of prolonged powerful flares in activity complexes. The proton energies in some of these events exceeded 10 GeV. The number of protons with energies over 30 MeV accelerated over the entire duration of the flares presented in Fig. 1 is greater than $2 \times 10^{33}$.

The temporal profile of the solar CR intensity can give us some information about the particles leaving the Sun. Starting from the 1960s, such information was derived using models for the diffusive propagation of high-energy protons. In recent years, it has become possible to utilize additional information about the acceleration process, such as the proton-acceleration time, which is derived from the temporal profile of the intensity of $\gamma$-ray radiation associated with $\pi^0$-meson decays. In [3], the temporal behavior of the intensity of solar protons with $E \leq 100$ MeV was approximated for several flares in the XXII cycle using a diffusive model for the propagation of solar CRs for a chosen proton-injection function on the Sun. In the case of disk flares, the main acceleration takes place during the hard $\gamma$-ray burst (about 10–20 min). The characteristics of the temporal profile of solar CRs in [3] are associated with another one or two phases of acceleration of the relativistic particles. Support for this possibility is provided by the presence of prolonged $\gamma$-ray radiation from powerful flares [4]. Unfortunately, it is not possible to choose a unique model for the acceleration of relativistic protons by elaborating the simplest diffusive models.

In general, we can assume that the relativistic protons are accelerated several times by various mechanisms during a single flare. This could include pulsed acceleration either near spots or in a vertical current sheet in the posteruptive phase and, sometimes, during the interaction of coronal loops. In principle, one can develop a detailed model describing the observations, but there is no guarantee that such a model will correspond to the real situation. There has been little progress in understanding the mechanism for accelerating relativistic particles in the Sun since the 1980s, i.e., during the period of operation of the SMM satellite (see review [5]). This is not due purely to the lack of a sufficient number of observations for the most energetic particles and hard $\gamma$-ray radiation by large flares.

The aim of the present article is to consider the acceleration of these particles, as far as possible, without using any *a priori* assumptions about the acceleration mechanisms or the nature of the source. It is now reliably established that electrons are accelerated to energies exceeding a few tens of keV in numerous flares that are sources of hard X-ray bursts.

This acceleration takes place in one or several episodes of impulsive and flash phases, with the source usually being localized at a small height within a very small region near spots. We will call this case "local acceleration." In other cases, especially in the gradual phase of the flare, when the Kopp–Pneuman model is applicable, the particles seem to be accelerated in a vertical current sheet. We will call this "posteruptive acceleration." The available evidence seems to suggest that these two possibilities—local and posteruptive acceleration for proton energies above 100 MeV (where shock acceleration can be ignored)—are not able to explain the number and spectra of particles in observed phenomena with the maximum fluxes of relativistic particles. Indeed, it is difficult to accelerate a considerable number of particles with energies of several hundreds of MeV with a very small source of pulsed acceleration. In addition, it is known that such sources are localized near spots, in regions of strong closed magnetic fields, making it very difficult for particles to escape. The posteruptive stage is characterized by acceleration in a region of weak magnetic fields that slowly vary in space; this is unfavorable for the efficient acceleration of relativistic particles. In addition, there is direct observational evidence in several cases that considerable fluxes of energetic particles arrived at the Earth before most of the posteruptive phenomena on the Sun had been observed. These facts stimulated us to study a selected group of phenomena with extremely large relativistic-particle fluxes. Physically, we must answer the question of whether there is an additional source of very efficient particle acceleration in these phenomena and, if so, what its properties are.

This formulation of the problem determined our choice of material and the analysis method. We first refine the list of flares in which the acceleration of particles up to relativistic energies is most efficient, using both data on the direct detection of particles and data on radio- and $\gamma$-ray emission. Next, we shall discuss in detail the problem of identifying the source of relativistic particles in the well-studied flare of July 14, 2000. A separate section will be devoted to a retrospective view of all events since 1956 with the largest fluxes of protons with $E \geq 100$ MeV, using the information provided by modern observations of well-studied powerful phenomena. In conclusion, we shall summarize the results of our morphological study of flare particle acceleration in the most powerful events.

## 2. FLARES WITH THE MOST EFFICIENT ACCELERATION OF RELATIVISTIC PARTICLES

Analysis of the accumulated data on the most powerful solar flares suggests that there exist phenomena possessing an anomalously high acceleration efficiency. For example, direct detections of charged particles and neutrons sometimes indicate a total or maximum number of particles that is an order of magnitude greater than the average value for a given class of events. Such events are usually simply identified as GLEs. Nearly 70 GLEs have been recorded since the first measurements in 1942. It has just recently become clear that it is not entirely accurate to identify phenomena with high acceleration efficiencies with GLEs for the following two reasons. First, the probability of detecting a GLE depends strongly on the position of the flare with respect to the Earth. Therefore, even flares that are not very powerful give rise to an appreciable effect if they are localized in a region of the solar surface that is most favorable for observations from the Earth; the opposite is also true: the effect of a powerful flare that is far to the east of the central meridian can be negligible. Second, neutron monitors are sensitive to the hardest particles with $E \geq 1$ GeV. As a result, events with hard spectra are more likely to be detected than other events with the same number of relativistic particles. Therefore, the list of GLE includes both flares with the highest efficiency of the generation of relativistic particles and approximately the same number of ordinary powerful events, whose average fluxes of protons with $E \geq 100$ MeV are not exceptional.

We use here a database of X-ray flares supplemented by uniform material on the fluxes of protons with energies $E \geq 10$, 60, and 100 MeV. Events with fluxes of protons with $E \geq 100$ MeV exceeding 100 cm$^{-2}$ s$^{-1}$ sr$^{-1}$ near the Earth were selected from the above database, which includes data on over 1000 proton flares in 1976–2003. There are only 12 such events. In these powerful flares, the condition of the relativistic particles' escape from the solar corona enabled them to reach near-Earth space, causing the flux of protons with $E \geq 100$ MeV to exceed the above limit.

The fluxes of relativistic particles reaching near-Earth space are often attenuated because the flare was beyond the optimal longitude interval from $-20°$ to $+90°$. In such cases, we deduced the acceleration efficiency using indirect data, primarily the radio flux at 15.4 GHz and the intensity of the hard $\gamma$-ray burst. These data were compiled in the catalog of proton events [1] and in [4], as well as in some other works. In particular, we analyzed all events with maximum fluxes at 15.4 GHz exceeding $2 \times 10^4$ s.f.u. This approach enabled us to estimate in a first approximation the fluxes of relativistic particles at the Sun for eastern flares, where direct measurements suffer from propagation effects. The extensive observational material for flares in the last two (XXII and XXIII) cycles enabled us to identify events of interest with reasonable reliability—the flares of June 1991 and others, including some cases when the direct detection of the flux of relativistic protons with energies of 100 MeV was problematic, as well as the event with the maximum number of detected neutrons, which occurred on May 24, 1990. A few powerful flares of the previous (XXI) cycle were also included in our final dataset, although the efficiency of their acceleration of relativistic particles was slightly lower than in the most powerful flares of the XXII cycle.

The attenuation of the flux of relativistic protons due to the distance of the source from the optimal longitude zone can also be estimated using the statistical results presented, for example, for GLEs in [6]. In this case, the statistics are based on approximately 50 GLEs and a few hundred proton flares, together with simultaneous measurements of the same events by several spacecraft located at remote points in interplanetary space (see review [7]). Using this approach for small separations from the optimal longitude zone leads to estimates that are close to those derived from indirect data; however, using statistical results is not effective when the flare is considerably shifted to the east from the central meridian.

Our consideration also demonstrates that our estimate of the overall efficiency of the acceleration of relativistic particles from the flux of protons with $E \geq 100$ MeV is much less dependent on the accelerated-particle spectrum than the corresponding estimate derived from the more energetic particles producing GLEs.

Our final results for 28 flares are presented in the table, which lists the date, time of the onset of the flare, X ray magnitude, total duration $dt$, time for the increase of soft X-rays $dt1$ (both times were taken directly from the database of the GOES satellites), optical magnitude, and latitude and longitude of the flare (positive values refer to north of the equator and west of the central meridian). The particle fluxes in near-Earth space are presented for energies $E \geq 10$, 60, and 100 MeV. the presence of GLEs is indicated in the notes.

If the above limit on the dates of the flares were not imposed, the total list of events would include several flares in the 1940s, the well-known flare of February 23, 1956, and the powerful flares of August 1972. A few powerful flares that occurred at the eastern limb (for example, on June 1, 1991) were not included in the final table, because there was not sufficient information about the acceleration processes, especially at low heights. Our analysis indicates that, over approximately the last 30 years, the number of events with extremely efficient relativistic-particle acceleration is about equal to the number of GLEs. However, our sample includes the most powerful flares resulting in GLEs, which is about half our list; the second half represents flares with almost the same efficiency of relativistic-particle acceleration occurring in the eastern part of the solar disk.

Before presenting the main contents of our study, let us make two general comments about the phenomena listed in the table. In many moderate-power flares, the particle acceleration takes place during or just after one burst of the impulsive phase. This is close to the time when the derivative of the flux of soft X-ray radiation is maximum. This is also true for some of the powerful phenomena listed in the table. On the other hand, the most powerful events often represent several successive episodes, in some of which particles could be accelerated. The episodes with the most efficient acceleration in each event will be discussed below.

In addition, detailed data on the hard gamma-ray emission have been obtained in recent years for some flares. These data show that continuum radiation by electrons at 1–10 MeV appears simultaneously with continuum radiation at 60–100 MeV due to $\pi^0$-meson decays and line radiation by nuclei. This was found to be the case when the observations enabled us to carry out such an analysis for large flares: the flares of March 26, 1991 (GAMMA-1) [8], May 24, 1991 (GRANAT, FEBUS apparatus) [9], November 24, 2000 (≈15 UT, Yohkoh) [10], and in some other cases when the observations were not complete. The observed and calculated spectra of high-energy photons for the flare of March 26, 1991, are presented in Fig. 2 [11, 12]. The decay of $\pi$ mesons formed by nuclear reactions between the accelerated protons and background particles produces the observed high-energy radiation at $h\nu \geq 100$ MeV. The onset of the radiation by the electron and proton components is coincident to within an accuracy of a few to ten seconds. In the particular case of the flare of March 26, 1991, the acceleration of the electrons and protons with energies up to 120 and 300 MeV, respectively, took place simultaneously. Therefore, it is reasonable to suppose that the relativistic electrons and ions are accelerated simultaneously, at least in the main episodes discussed here. A weighty argument in favor of the possibility that the relativistic electrons and ions are accelerated by a single process is the tight correlation between the continuum radiation at $\geq 0.5$ MeV and the nuclear line radiation at 4–8 MeV [5, Fig. 4].

## 3. LOCALIZATION OF THE SOURCE OF THE MAIN ACCELERATION OF RELATIVISTIC PARTICLES IN THE FLARE OF JULY 14, 2000

Modern observational data make it possible in some cases to localize the source of acceleration of the relativistic protons ($E \geq 100$ MeV). The present section will be devoted to an analysis of the flare that occurred on Bastille day, 2000. It was observed for several hours by the TRACE satellite during the time when hard X-ray and $\gamma$-ray radiation was detected by Yohkoh. X-ray observations at energies above ≈25 keV were carried out at the beginning of the flare, from 10:05 to 10:14 UT by the hard X-ray spectrograph (HXRS) onboard the Multispectral Thermal Imager satellite, and after 10:19 UT by Yohkoh. Although the time of the maximum derivative of the soft X-ray emission (1–8 Å), 10:18 UT, which

Data on the flares and particle fluxes

| Flare Date | Time, UT | X-ray magnitude | $dt$, min | $dt1$, min | Optical magnitude | Latitude, deg | Longitude, deg | Proton flux, $cm^{-2}$ $s^{-1}$ $sr^{-1}$ | | | Notes |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | $E >$ 10 MeV | $E >$ 60 MeV | $E >$ 100 MeV | |
| Sept. 23, 1978 | 9:47 | X1.0 | 43 | 42 | 3B | 35 | 50 | 1000 | 159 | 48.3 | GLE |
| Oct. 12, 1981 | 6:22 | X3.1 | 55 | 14 | 2B | −18 | −30 | 590 | 84.8 | 26.27 | GLE |
| June 3, 1982 | 11:41 | X8.0 | 105 | 7 | 2B | −9 | −72 | 30 | 0.89 | 0.283 | |
| June 6, 1982 | 16:30 | X12.0 | 162 | 24 | 3B | −9 | −25 | 15 | 1.76 | 0.332 | |
| July 9, 1982 | 7:31 | X9.8 | 53 | 7 | 3B | 17 | −73 | 38 | 2.2 | 0.2 | |
| Dec. 7, 1982 | 23:36 | X2.8 | 71 | 18 | 1B | −19 | 79 | 900 | 111 | 56.1 | GLE |
| Apr. 24, 1984 | 23:56 | X13.0 | 104 | 5 | 3B | −12 | −43 | 1110 | 224 | 5.51 | |
| Aug. 12, 1989 | 13:57 | X2.6 | 134 | 27 | 2B | −16 | 37 | 6000 | 875 | 237 | GLE ? |
| Aug. 16, 1989 | 1:08 | X20.0 | 80 | 9 | 2N | −18 | 84 | 1500 | 171 | 83.7 | GLE |
| Sept. 29, 1989 | 10:47 | X9.8 | 228 | 46 | | −30 | 90 | 4500 | 696 | 559 | GLE |
| Oct. 19, 1989 | 12:29 | X13.0 | 464 | 26 | 4B | −27 | −10 | 2500 | 690 | 400 | GLE |
| Oct. 22, 1989 | 17:08 | X2.9 | 240 | 49 | 2B | −27 | 31 | 4450 | 811 | 380 | GLE |
| Oct. 24, 1989 | 17:36 | X5.7 | 528 | 55 | 3B | −30 | 57 | 5000 | 398 | 272 | GLE |
| May 21, 1990 | 22:12 | X5.5 | 87 | 5 | 2B | 35 | 36 | 276 | 67.1 | 30.9 | GLE |
| May 24, 1990 | 20:46 | X9.3 | 59 | 3 | 1B | 33 | 78 | 96 | 25 | 20 | GLE |
| Mar. 22, 1991 | 22:43 | X9.4 | 34 | 2 | 3B | −26 | −28 | 10000 | 866 | 257 | |
| June 4, 1991 | 3:37 | X12.0 | 233 | 15 | 3B | 30 | −70 | 43 | 4.96 | 3.522 | |
| June 6, 1991 | 0:54 | X12.0 | 81 | 18 | 4B | 33 | −44 | 150 | 25.2 | 4.78 | |
| June 9, 1991 | 1:37 | X10.0 | 167 | 3 | 3B | 34 | −4 | 30 | 5.1 | 1.94 | |
| June 11, 1991 | 2:09 | X12.0 | 71 | 20 | 3B | 31 | 17 | 2300 | 317 | 95.2 | GLE |
| June 15, 1991 | 6:33 | X12.0 | 284 | 118 | 3B | 33 | 69 | 950 | 124 | 116 | GLE |
| Nov. 2, 1992 | 2:31 | X9.0 | 57 | 37 | 2B | −23 | 90 | 630 | 108 | 24.1 | GLE |
| Nov. 6, 1997 | 11:49 | X9.4 | 12 | 6 | 2B | −18 | 63 | 490 | 109 | 78.1 | GLE |
| July 14, 2000 | 10:03 | X5.7 | 40 | 21 | 3B | 22 | 7 | 7000 | 1200 | 623 | GLE |
| Nov. 8, 2000 | 22:42 | M7.4 | 83 | 46 | 3F | 10 | 77 | 14800 | 1580 | 451 | halo NW |
| Apr. 15, 2001 | 13:19 | X14.4 | 36 | 31 | 2B | −20 | 85 | 951 | 223 | 250 | GLE |
| Sept. 24, 2001 | 9:32 | X2.6 | 97 | 66 | 2B | −16 | −23 | 12900 | 100 | 20 | |
| Nov. 4, 2001 | 16:03 | X1.0 | 54 | 17 | 3B | 6 | 18 | 31700 | 200 | 220 | GLE |

often coincides with the impulsive phase of the flare and particle acceleration, was missed in this case, all the indirect evidence discussed in [13] indicates that there was no efficient acceleration of particles before the Yohkoh observations. This satellite detected two maxima at hard X-ray energies, 100–300 keV, in the delayed and prompt $\gamma$-ray lines. The lines associated with electron–positron annihilation and the capture of a neutron by a proton, as well as the rapid unresolved lines due to the excitation of oxygen and nitrogen nuclei, reached their maximum intensity on July 14, 2000, at 10:21:05 UT. A second, more powerful maximum in these lines was reached at ≈10:27 UT [14, Fig. 1].

The observations unambiguously fixed the time of powerful particle acceleration in the flare of July 14,

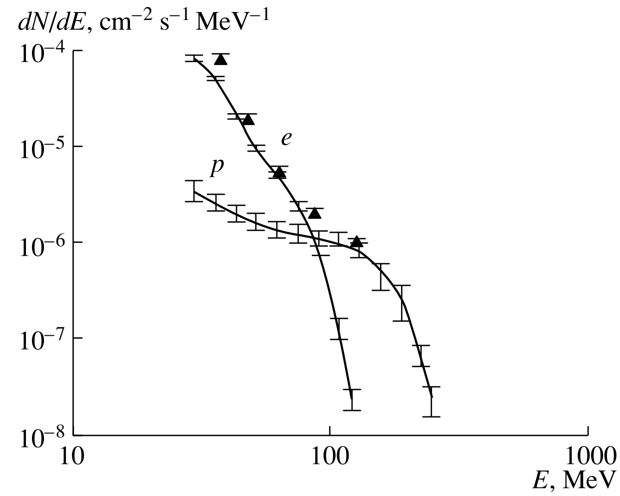


**Fig. 2.** Differential photon spectrum emitted by the flare of March 26, 1991 (near the disk center), at an angle below 25° from the radial direction. The calculated contributions from electrons and protons are plotted by the solid curve [11, 12]. The observed values are presented by triangles.

2000. Electron bremsstrahlung, hard radiation due to $\pi^0$-meson decays, and the onset of emission in the 0.511 keV and 2.22 MeV lines were synchronous in the second act of acceleration. In this case, the simultaneous acceleration of relativistic electrons and protons was confirmed directly by observations.

Thus, the most efficient acceleration of relativistic particles in this flare took place in a time interval that coincided with the hard $\gamma$-ray burst, from 10:19 to 10:30 UT, and the process seems to be separated into two stages. This heliophysical information can be compared with other observational data on the flare and the arrival time of the accelerated particles at the Earth.

In their analysis of GLEs of solar cosmic rays, Belov *et al.* [15] concluded that all or most of the energetic particles arriving at the Earth were accelerated between 10:19 and 10:29 UT, probably before 10:27 UT. Based on ground-based observations, Bieber *et al.* [16] calculated the characteristics of the solar source of accelerated particles using two different models for the propagation of the charged particles in interplanetary space. They obtained good agreement between the model calculations and the fluxes observed near the Earth under the assumption that the main emission by the charged particles was relatively brief ($<5$ min) and possessed a maximum at 10:26–10:27 UT.

Therefore, we know the time for efficient particle acceleration on the Sun and can analyze the processes occurring there during this period.

The flare began at approximately 10:03 UT in the western part of an active region. The ordinary impulsive phase at 10:04–10:06 UT was weak, and it was impossible to predict that it would grow into a powerful event. Next, an ordinary flare with somewhat complex ribbons began to develop in the central part of the group. This is illustrated in the 195 Å TRACE satellite picture obtained at 10:14:24 (Fig. 3a). The situation changed dramatically at approximately 10:19 UT, when one of the ribbons of the flare, which formed at 10:12 UT and was immediately adjacent to the large spot, began to develop, and luminous plasma crossed the spot from west to east. This process was observed most clearly by the TRACE satellite in the continuum near 1600 Å (Fig. 4a) and in the line emission near 171 Å, i.e., in the emission by plasma with a lower temperature than the emission at 195 Å.

Along with the first bright point, which corresponded to the first maximum at 10:19 UT, another region to the east of the main spot is visible in subsequent pictures at 195 Å (Figs. 3b and 3c). Starting from 10:25 UT, the emission at 195 Å began to propagate to the northeast part of the group.

Note that, during 10:24–10:26 UT, the brightening at 171 Å propagated along a broken line that seems to correspond to a boundary of cells of the chromospheric network in the active region; further, it continued along a straight line, and emission in other feet of the loops of the flare arcade appeared on the opposite side of the neutral line. Next, this arcade covered the region of the former two-ribbon event; the top part of the arcade was heated over several hours, followed by the gradual ascent of the loops. The development of the first and then the second, more powerful, type-II radio outburst [17] began just at 10:19 UT; these are probably associated with several plasma ejections.

Thus, the flare process on July 14, 2000, reached the large spot at 10:19 UT; after 10:24 UT, the emission propagated toward the northeast; and the hard X-ray and $\gamma$-ray radiation reached their maxima at 10:27 UT (Fig. 3d). Although the flare continued to develop after 10:27 UT, the rate of acceleration seemed to drop sharply, and nonthermal processes gradually diminished. This can be seen in the rapid decay of the gamma-ray burst. Posteruptive heating of the plasma began near the top of the helmet structure just near this time (10:27 UT), and only at 10:38 UT did this structure decay into individual high loops. This marked the end of the formation of the arcade, which encompassed the eastern and western flare ribbons (Fig. 4c, 10:48 UT).

Let us now consider in more detail the specific features of this flare as a source of photons and energetic

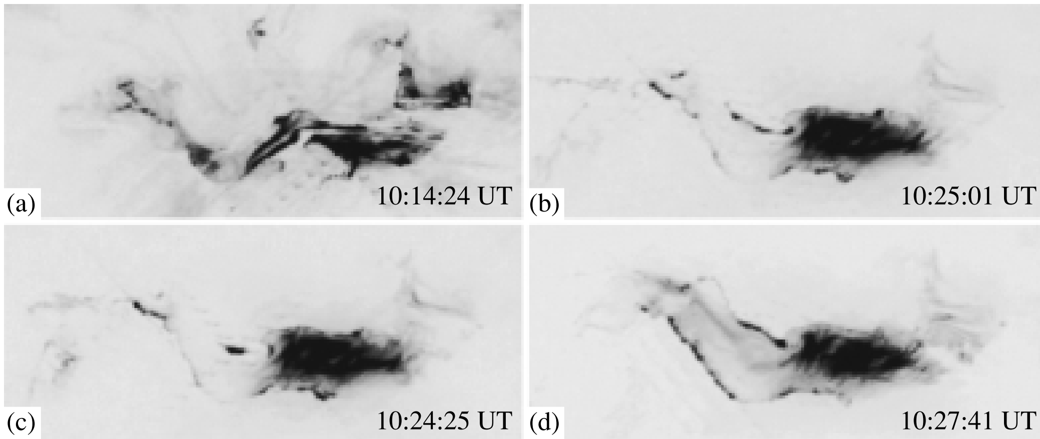


**Fig. 3.** Pictures of the flare of July 14, 2000, obtained by the TRACE satellite at 195 Å.

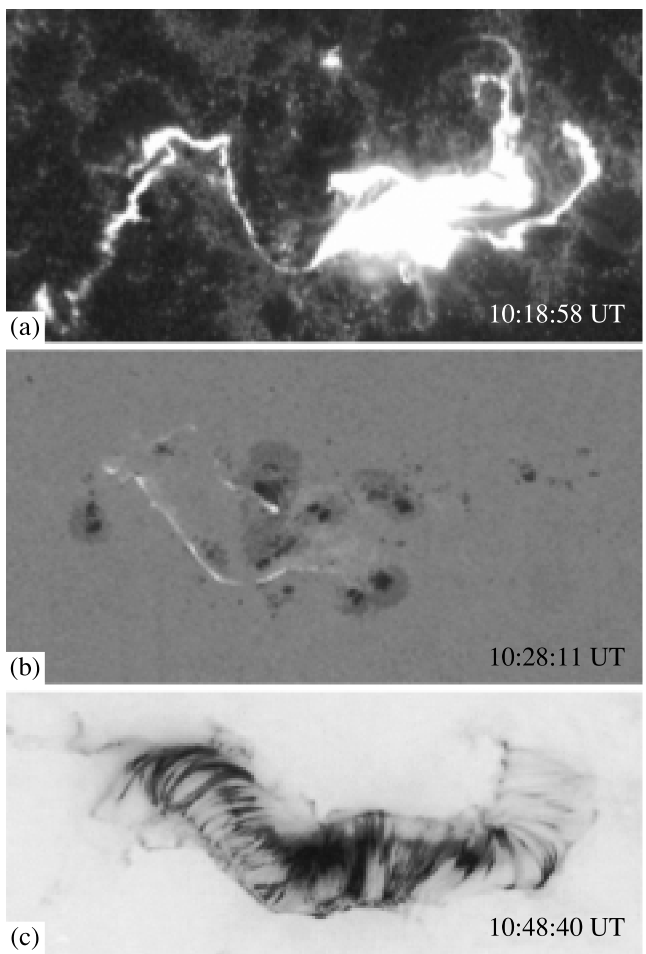


**Fig. 4.** Pictures of the flare of July 14, 2000, obtained by the TRACE satellite (a) at 1600 Å (with a short exposure of 30.4 s), where one can see an arm approaching the large spot from the west; (b) in white light; and (c) at 195 Å. The scales for pictures and the field of view were not accurately matched to each other.

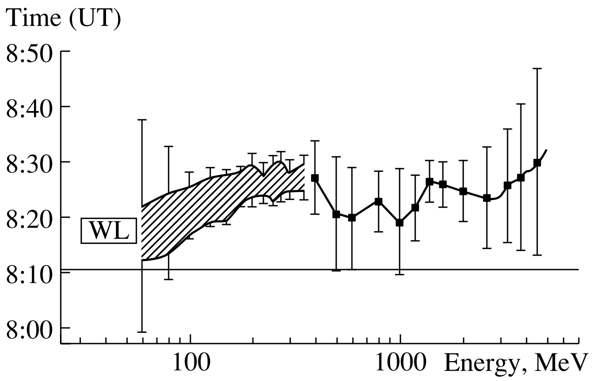


**Fig. 5.** Time interval in which particles of various energies left the solar corona during the flare of June 15, 1991 [21]. Only one time of escape was determined for the particles with energies above 350 MeV. The rms error in these times is plotted. The rectangle shows the lifetime of the white-light (WL) flare derived from ground-based observations.

particles. In most flares, nonthermal processes are characteristic of impulsive or explosive phases, which are close to the onset of the entire phenomenon. This phase is characterized by the maximum increase in the soft X-ray emission (at 1–8 Å). In some flares (especially, powerful ones), high-energy phenomena are manifest after a delay of up to tens of minutes rather than at the very beginning of the event. As a rule, this occurs when the flare process approaches large spots. The importance of this factor was discussed, in particular, by Ishkov [18] (this paper also contains references to earlier works by this author). The flare of July 14, 2000, is an example of a flare in which the "spot component" of the overall nonstationary process is clearly manifest beginning from 10:19 UT, 15 min after the onset of the flare and 10 min after the time of the maximum rate of increase in the soft X-ray radiation.

After 10:19 UT, the phenomenon develops, as do powerful impulsive events, in the immediate vicinity of strong magnetic fields and field gradients, but it is not absolutely identical to such impulsive events. Usually, the flare ribbons arise from a single center in a spot penumbra and then ignite bright points along a neutral line of the photospheric magnetic field, with their merging and subsequent evolution finally resulting in a set of high coronal loops. This first, ordinary, stage of development of the nonthermal process is followed by a more intensive one (stages *b* and *c* of the development of a $\gamma$-ray burst in Fig. 1 from [14]; see also [19, 20]). There are grounds to suppose that extremely efficient particle acceleration takes place in a structure between points on the opposite sides of the spot. Several such field lines (a loop?) at time 10:28:06 UT are shown in Fig. 5 in [22]; they connect two bright points located inside the main hard source in the 171 Å picture (HXR/M2, 10:27:00 UT). We emphasize that, according to this same work [22], the height of the top of this loop exceeds $20''$—a factor of two to three higher than in typical impulsive nonthermal sources. Another, weaker part of the hard source was localized in the ribbon on the opposite side of the neutral line.

One characteristic observable manifestation of the development of efficient nonthermal processes for the July 14, 2000, flare was the propagation of emission (a jet) in the TRACE picture obtained at 10:24:25 UT (Fig. 3b). This jet was subsequently transformed into a thin line, almost parallel to the neutral line but shifted significantly to the east (Fig. 3c). Later, this line formed the feet of loops in the regions of north polarity of the longitudinal field, and another ribbon appeared on the opposite side of the neutral line.

The character of the white-light flare of July 14, 2000, was appreciably different from most similar phenomena (Fig. 4b). The optical continuum emission usually makes up two or more bright points located in the penumbra or just near the spots. However, in this case, another component dominated after 10:19 UT: the ribbon emission, which is usually very weak even in the most powerful impulsive events. We should make the following qualification here: white-light emission was detected in this event only by the TRACE satellite. There are grounds to suppose that the TRACE spectral band is more sensitive to the blue part of the spectrum (the flares detected at the Earth in green and red light are not identical to those detected by TRACE), so that it includes the contribution of numerous lines formed in the lowest layers of the chromosphere. Nevertheless, the absence of well-defined bright points in the corresponding TRACE pictures probably points toward the specific nature of the particle propagation in the loop (the source of acceleration); namely, most of the particles (especially, the relativistic particles) did not disappear into the feet, but instead filled the entire large-scale coronal structure. The influence of the accelerated electrons and considerable heat fluxes on the dense chromospheric layers near the feet of the coronal loops resulted in the white-light emission of the ribbons.

Therefore, the extensive observational data for the flare of July 14, 2000, enable us to localize the source of acceleration of the relativistic particles. There is clear evidence that its height exceeded the heights of loops in typical sources of accelerated electrons in ordinary impulsive events. We will briefly discuss a possible scheme for the development of such a nonthermal process below.

## 4. COMPARATIVE ANALYSIS OF PARTICLE ACCELERATION IN POWERFUL FLARES

It has recently become possible to carry out a statistical study of proton events. The IZMIRAN database contains 1143 proton enhancements detected over approximately 28 years of observations of particles in near-Earth space. The fact that 1152 flares stronger than M4 took place during this period suggests that the proton acceleration is associated with events of such power. Over half of these proton enhancements (618) were firmly identified with solar flares. The other events correspond to phenomena that occurred behind the limb (at least 20%), as well as to cases when individual flares are superposed in periods of very high activity and to gaps in the X-ray observations in 1975–1985.

We will discuss here only a few results, which are considered in detail in [23]. It is clear that the more powerful the flare, the higher the probability that it is a proton flare. We compared the characteristics of all 409 reliably localized proton flares at longitudes from 20° E to 90° W with a group of control flares that occurred in the same longitude range and had the same mean power (M6 and brighter) but did not display enhanced proton fluxes. We found that the duration $dt$ of the proton events was $80 \pm 4$ min, while that for the control group was $57 \pm 4$ min.

Therefore, the relation between the total number of protons accelerated to $E \geq 10$ MeV and the overall energetics or X-ray magnitude of the flare is the most clearly expressed. The duration of the entire event probably also has some influence, but this is expressed weakly and cannot be used as a serious argument in support of the posteruptive acceleration of particles in a vertical current sheet or by a shock.

By considering 110 proton flares more powerful than X1, we were able to reveal the following tendency [24]: large fluxes of protons with energies of about 10 MeV "feel" the development of giant arcs after CMEs, while the relative number of relativistic particles (or the 10–100 MeV spectrum in the acceleration region) is related more closely to the general development of nonthermal processes during or near the impulsive phase. The posteruptive phase is identified both via direct observations of giant loop systems and from an analysis of the temperature behavior derived from the ratio of the signals from the two channels of the GOES satellites [25]. On the other hand, impulsive events are characterized, first and foremost, by the fluence of nonthermal emission with $E \geq 30$ keV.

These general conclusions for X flares are valid as well for the data compiled in the table, which represent events with the most efficient acceleration of relativistic protons. Of course, all the tabulated flares in the western and central parts of the disk were included among the above proton X flares and were simply the events with the greatest fluxes of relativistic protons. In a few cases, the events in the table were preceded by flares with approximately the same efficiency of relativistic-particle generation, but the fluxes in the second event were enhanced due to the interaction of a CME in interplanetary space (between the two shocks in the process of "cannibalizing" the CME), as took place on August 4, 1972.

Returning to the effect of the flare duration on the acceleration, we note that the table contains only a few short-lived, compact flares, on March 22, 1991, May 24, 1990, and November 6, 1997, whereas the total durations of the soft X-ray emission in other events exceed one hour. However, in most cases, the impulsive phase was clearly expressed, although in the powerful events under consideration it may not occur at the onset of the phenomenon. Thus, we believe that the role of the duration of the events in the generation of relativistic particles was overestimated in previous studies, and the most efficient acceleration is associated with the powerful, impulsive episodes of large flares.

It has been shown using a database of over 55 000 X-ray flares that even powerful, impulsive events on the Sun are usually not followed by an appreciable flux of accelerated protons. This is due to the fact that the source of the acceleration is localized in loops of a closed magnetic configuration near the chromosphere. In this case, the hard X-ray and $\gamma$-ray radiation is maximum, but it is very difficult for accelerated particles to escape. In the rare cases when a powerful short flare results in the formation of even a small region where the magnetic field lines extend outwards to the sphere of solar-wind source, the accelerated particles escape into interplanetary space. One such example is the event of May 24, 1990, for which the flux of solar neutrons detected at the Earth was maximum.

In our previous paper [26], we analyzed data on the detection of neutrons by the FEBUS apparatus on the GRANAT satellite [9]. We used a simple kinematic model to determine the duration of neutron generation, $\delta t = 230 \pm 15$ s; the exponent of the power-law spectrum, $\gamma = -1.94 \pm 0.08$; and the total number of particles escaping into interplanetary space, about $2 \times 10^{28}$ neutrons with energies $E > 100$ MeV. The theoretical results of [27] indicate that $N_p(E > 30\,\mathrm{MeV}) = 2 \times 10^{33}$ protons are necessary to generate this number of neutrons; this is typical for other solar CRs. The $\gamma$-ray burst profile [28] enables one to refine the adopted approximation for the observed flux of solar neutrons during the registration of a large flux of hard photons. The resulting estimate for the duration of the interval of relativistic-neutron generation is less than 100 s. Therefore, the required fluxes of relativistic particles are generated on the Sun within a few minutes, so that the duration of the flare as a whole is not a determining factor.

Let us now consider the long-lived powerful flares presented in the table. One typical case is the event of June 15, 1991. This magnitude-X12.5 flare began at 8:10 UT, had coordinates 36° N and 70° W, and was characterized by a powerful impulse and the subsequent development of a set of giant loops, which existed until the end of that day. Powerful optical continuum emission was observed at 8:15–8:23 UT in compact arcs about $10''$ in size [29]. The development of bright points near spots is characteristic of white-light flares. One characteristic feature of this particular white-light flare is the presence of a neutral-carbon absorption line, demonstrating that the electron beam penetrated into fairly deep layers of the photosphere.

The enhancement of the flux of energetic protons was almost isotropic, probably due to the extremely perturbed state of interplanetary space at this time. Under such conditions, we can use the diffusive model for propagation of the particles [30], modified for the case of prolonged injection. This model describes the observed temporal profiles of the event fairly well, including the very beginning of the enhancement, which is usually not possible when analyzing solar cosmic rays. The observed profiles and the diffusive approximation for them can be used to derive the integrated fluxes and fluences of particles with various energies and to estimate the total number of accelerated protons in near-Earth orbit. The integrated fluence for energies over 30 MeV was $(4 \pm 2) \times 10^8$ cm$^{-2}$, and the total number of particles was $N_{tot}(\geq 30 \text{ MeV}) = (1.7 \pm 0.9) \times 10^{33}$.

The injection time is determined fairly accurately for energies of 80–350 MeV. The results for the exit of the proton flux are presented in Fig. 5. Models with instantaneous and continuous injection are compared in [21]. It was found that protons with energies of 175–350 MeV began to leave the Sun at $8{:}23 \pm 0{:}01$ UT, with their emission continuing for $6 \pm 1$ min. This time coincides with the end of the impulsive microwave burst—the end of the impulsive phase, when the H$\alpha$ ribbons deviate sharply from each other. In previous studies, this was called the flash phase. The acceleration of protons with higher energies of 1.3–4 GeV takes place at almost the same time, $8{:}25 \pm 0{:}03$ UT, and continues for an even shorter time.

Therefore, the acceleration of relativistic protons with a wide range of energies begins just after the impulsive phase of the flare of June 15, 1991, and continues for several minutes.

Thus, for all the events listed in the table, there are grounds to suspect an additional acceleration of relativistic particles, whose localization and duration are close to those of the impulsive acceleration. Detailed gamma-ray measurements were carried out for some of the flares in the table. They indicate that the durations of the main relativistic-particle acceleration were no longer than a few minutes. This was confirmed for some events from an analysis of data on protons and neutrons detected at the Earth and in interplanetary space.

Recall that we consider here the acceleration of the largest fraction of the relativistic particles. The observation of photons with energies from 30 MeV to a few GeV by the GAMMA-1 telescope beginning on June 15, 1991, after 8:37 UT demonstrated the existence of energetic solar particles at the beginning of the posteruptive energy release. The high level of $\gamma$-ray emission within about 10 min after the impulse was a general characteristic of all the powerful flares of June 1991. In their analysis of the GAMMA-1 data for the flare of June 15, 1991, Akimov *et al.* [31] suggested that the second maximum of the microwave burst (at ≈8:30 UT) corresponded to an additional particle-acceleration event rather than particles being confined in a magnetic trap.

It stands to reason that not all of the cases presented in the table had impulses as powerful as that of June 15, 1991. Moreover, the impulsive energy release and the hard burst occur in powerful flares within tens of minutes after their onset, as in the flare of July 14, 2000, and the similar event of November 4, 2001. The character of the white-light flare also varies slightly: instead of ordinary bright points in the penumbra of a spot (or spots), 1600 Å continuum emission by ribbons was observed in the events of July 14, 2000, and November 4, 2001. Such emission in the lower chromosphere could be due to the filling of high coronal loops with relativistic particles and their disappearance in the feet of the arc system.

Concluding this section about powerful flares, we note that, in most cases, it is not necessary to assume that the most efficient acceleration of relativistic particles occurs in more than one process. On August 4, 1991, there were two successive energetic events, as follows from observations of two maxima of the intensity of the 2.22 MeV line [32] and of the continuum emission formed by the decay of neutral $\pi^0$ mesons; however, such cases seem to be the exception rather than the rule.

## 5. CONCLUSIONS

We have carried out a morphological study of the proposed source of relativistic-particle acceleration. This has become feasible due to the availability of

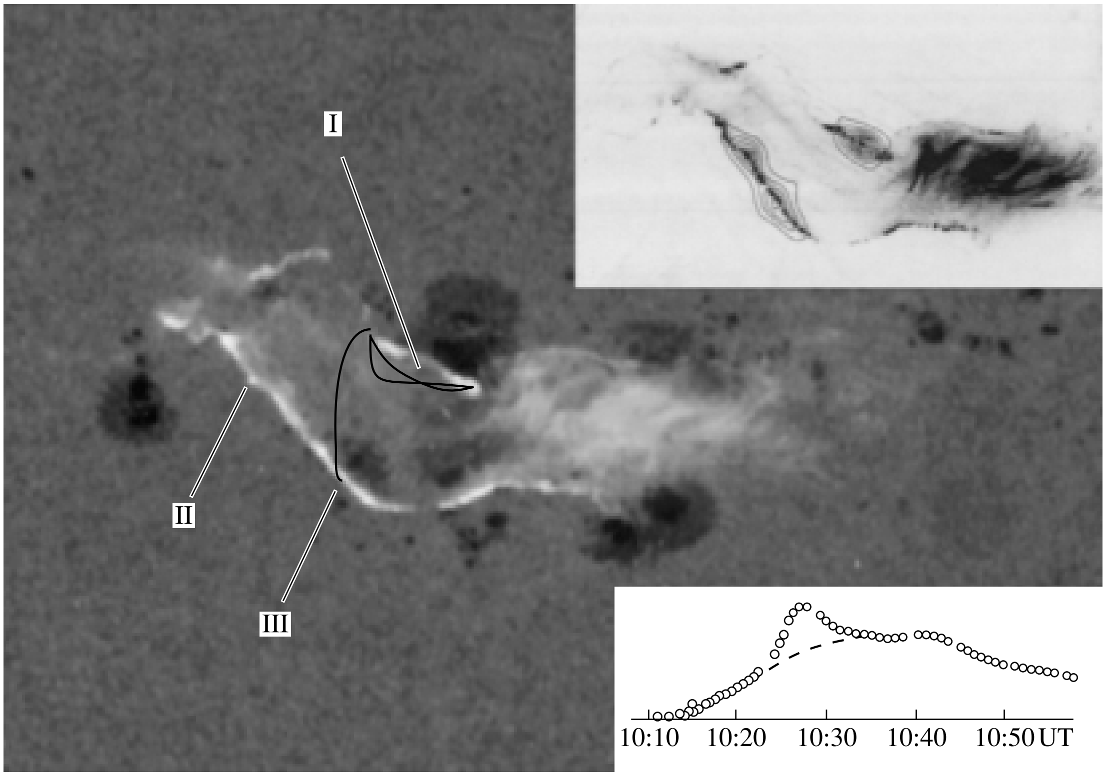


**Fig. 6.** Schematic comparison of effects near the maximum of the $\gamma$-ray burst of July 14, 2000. The ribbons of the flare are superimposed onto the picture of the spots (at 195 Å, and with the brightness of the western part reduced). The positions of sources of hard X-ray emission are marked by the Roman numbers I, II, and III; contours of equal brightness are presented in the top right corner (in accordance with Fig. 8 in [19]). The position of the loops satisfying the calculations [22] of the behavior of the magnetic field lines in the region of hard emission is shown schematically. The brightness variations at 171 Å above the entire flare region are presented in the bottom right corner, in accordance with [20]; the dashed curve denotes the brightness of the same region without the area covered by the hard source I.

observations of hard electromagnetic radiation from nonstationary processes on the Sun with very high temporal and spatial resolution, as well as the direct detection of accelerated particles in interplanetary space and at the Earth. We have presented arguments in support of the idea that, in approximately 30 powerful events occurring over the last three solar cycles, there was an additional source accelerating particles to relativistic energies much more efficiently than the acceleration that occurs in purely impulsive flares and in the posteruptive phase of powerful events.

Modern observations make it possible to localize the source of this efficient acceleration using the fact that the relativistic electrons and protons are accelerated simultaneously. As an example, we discussed the flare of July 14, 2000, in detail in Section 3. The result of this analysis is very simple: the location of the acceleration coincides with the source of the emission at $h\nu = 33$–$53$ keV at the time of the maximum of the $\gamma$-ray burst. To within an accuracy of $3''$, the same location is associated with the emission of an excess number of photons in short-wavelength lines of ions with ionization temperatures of 1.2–1.5 MK. This is illustrated in Fig. 6, which shows that the position of the brightest source I in the M2 band of the HXT hard X-ray telescope touches the eastern edge of the largest spot of the group. This schematic also shows the positions of loops calculated in [20] for both the loop located inside the source I and the higher loop, which connects the source with another flare ribbon (II and III). The relative brightness of source I at 171 Å shows that extra emission appears during the acceleration [20] (see also [19] for 195 Å). This probably implies that a source of intense hard emission is localized at a higher height than the sources of small, impulsive flares, i.e., above the chromospheric H$\alpha$ bulge over this zone of spots. As follows from the calculated magnetic fields and observations of large active regions at the limb at 171 and 195 Å, this height can be estimated to be $15 \pm 5$ thousand kilometers. This corresponds to a mean scale between the characteristic sizes of the chromospheric and coronal loops. Therefore, the acceleration really can be more efficient in a more extended source that remains in a region of strong magnetic fields and field gradients.

In addition, the escape of the accelerated particles and filling of the coronal loops are facilitated by the higher location of the source. This probably initiated the development of the powerful posteruptive phase in the flare of July 14, 2000. The entire sequence of events after 10:24 UT shows that the propagation and drift of the accelerated particle in the magnetic field must be included in flare models. In this particular case, the first brightenings at 195 Å appeared at opposite ends of the northern ribbon, separated by a distance of over 200 000 km, within less than one second. Consequently, the speeds involved must be comparable to the speed of light. Heating near the top of the arcade began within a few seconds, but the arcade decayed into the postflare X-ray loops only approximately 10 min after the large-scale ejection and particle acceleration. Note also that the large-scale disturbance that occurs in some flares is perpendicular to both the field (i.e., the field lines) and the height gradient, i.e., along the drift velocity in the nonuniform magnetic field.

Our analysis demonstrates that there was an additional source of acceleration of energetic particles in all the events listed in the table (except for the event of November 8, 2000), as well as in the powerful flares of February 23, 1956, and August 4, 9, 11, and 15, 1972. At least one characteristic feature of these events seems to be clearly demonstrated: the process took place in groups of spots covering a small area and, for recent flares, just near the penumbra. One dominant acceleration process seems to be sufficient for most prominent proton enhancements in which protons with energies of 1 GeV and large fluxes of protons with energies over 100 MeV were observed. The peculiarities of the observed temporal profiles of the particles can be reasonably explained by the conditions for the subsequent evolution of the beams in the corona and in interplanetary space.

The entire set of accumulated data on proton events makes it possible to outline the basic features of the acceleration process producing large fluxes of relativistic protons. The effective acceleration should take place in a fairly strong magnetic field, which can trap the charged particles during the acceleration. On the other hand, this field must not be extremely strong, so that the accelerated particles can leave after they are generated. The height of the acceleration region cannot be small, since a large density of matter at a small height would be unfavorable for particle acceleration. On the other hand, a height that is too large would also be unfavorable, since the solar magnetic fields become increasingly simple and weak with increasing height.

The solar relativistic "accelerator" operates rarely and only for short periods, during the impulsive phases of the most powerful flares. The duration of the acceleration (or its most efficient phase) does not exceed a few minutes. In other words, the Sun works as a relativistic accelerator only $10^{-6}$ of the time. This provides evidence that efficient acceleration is associated with some type of rapid changes in the solar magnetic fields, which can be considered catastrophic. The time when the solar accelerator operates coincides with the onset of a powerful ejection of plasma (eruption). The eruptive reconstruction of the solar magnetic field simultaneously accelerates the particles and facilitates their escape from the generation region.

Of course, not every eruption results in the efficient generation of solar cosmic rays. When this takes place, acceleration to relativistic energies occurs only within a small fraction of the extensive eruption zone, namely, in the region where strong magnetic fields with large gradients initially existed. Such conditions are satisfied near spots, i.e., precisely where the discussed flare episode was observed.

Therefore, the generation of energetic particles on the Sun is associated with both CMEs and flares. There is no reason to think CMEs produce the relativistic particles, but we believe that CMEs and energetic solar CRs are formed by the same complex of interconnected sporadic solar phenomena. The relation to flares is even closer than that to CMEs. The acceleration of charged particles is a natural part of a flare, and the accelerated relativistic particles facilitate a faster spatial expansion of the flare process. We believe that our general conclusions are valid not only for the largest but also for ordinary proton events, in which the flux of protons with energies over 100 MeV is small or absent. Of course, the relative contributions of impulsive acceleration, the additional (eruptive) acceleration discussed here, and posteruptive acceleration may be different.

We especially emphasize that the coincidence between the region of acceleration of relativistic particles and the source of hard photons found for the flare of July 14, 2000, seems to occur frequently but not always. An alternative is the situation when another foot of the coronal loop is brighter and more extended in the hard X-ray and $\gamma$-ray radiation (in Fig. 6, this corresponds to a larger flux from sources II and III compared to source I). This situation was detected for the first time in a stellar flare observed by the ASTRON satellite, where the response to the action by the accelerated particles on the chromosphere was most powerful after 40 s rather than at the onset of the flare, probably in another foot of the loop. In other words, the conditions for the propagation of the accelerated particles downward, to dense layers just under the source of the acceleration, may be less favorable, so that hard bremsstrahlung photons will be formed here over less area than in another foot of the loop. If intense emission appears in the foot opposite to the acceleration region, then the propagation of accelerated particles with various energies can lead to some difference in the positions of the photon sources.

A discussion of the theoretical problems related to flares and the acceleration of particles is beyond the scope of this paper. Nevertheless, we emphasize that the crucial point for the theory is whether the additional acceleration takes place along moderate-scale loops or in a strong current flowing along the separatrix. Unfortunately, the calculations of [22] indicate only the possible presence of loops in the hard source I; however, this was not confirmed by observations and cannot be considered to be an established fact. Thus, this problem requires more careful study.

## ACKNOWLEDGMENTS

We are grateful to the researchers conducting observations with the TRACE, SOHO, and Yohkoh satellites (the solar images) and the GOES and IMP-8 satellites (data on the solar proton enhancements) who have provided free access to the corresponding results. We thank S.B. Rinchinov for permission to use a figure from his dissertation and I.M. Chertok, V.V. Grechnev, and V.G. Kurt for discussions of this study. This work was supported by the Russian Foundation for Basic Research (project nos. 02-02-17086, 03-07-90389, and 04-02-16763).

## REFERENCES

1. A. I. Sladkova, G. A. Bazilevskaya, V. A. Ishkov, *et al.*, *Catalogue of Solar Proton Events 1987–1996* (Univ. Press, Moscow, 1998), p. 246.
2. A. V. Belov and E. A. Eroshenko, Radiat. Meas. **26** (3), 461 (1996).
3. A. B. Struminskiĭ, Astron. Zh. **80**, 992 (2003) [Astron. Rep. **47**, 916 (2003)].
4. G. Rank, J. Ryan, H. Debrunner, *et al.*, Astron. Astrophys. **378**, 1046 (2001).
5. E. Rieger, *Solar and Stellar Flares*, Ed. by R. Haisch and M. Rodono (Kluwer, Dordrecht, 1989), p. 323.
6. E. V. Vashenyuk, Doctoral Dissertation in Mathematical Physics (Apatity, 2000).
7. M.-B. Kallenrode, in *Proceedings of the Solar Encounter: The First Solar Orbiter Workshop*, ESA **SP-493**, 23 (2001).
8. B. B. Akimov, N. G. Leikov, A. B. Belov, *et al.*, in *High Energy Solar Phenomena: New Era of Spacecraft Measurements*, AIP Conf. Proc. **294**, 130 (1994).
9. O. V. Terekhov, R. A. Syunyaev, A. V. Kuznetsov, *et al.*, Pis'ma Astron. Zh. **19**, 163 (1993) [Astron. Lett. **19**, 65 (1993)].
10. K. Watanabe, Y. Muraki, Y. Matsubara, *et al.*, astro-ph/0304067 (2003).
11. A. M. Gal'per, B. I. Luchkov, Yu. V. Ozerov, *et al.*, Astron. Zh. **77**, 447 (2000) [Astron. Rep. **44**, 389 (2000)].
12. S. B. Rinchinov, Candidate's Dissertation in Mathematical Physics (Moscow, 2003).
13. K.-L. Klein, G. Trottet, P. Lantos, and Delaboudiniere, Astron. Astrophys. **373**, 1073 (2001).
14. G. H. Share, R. J. Murfhy, A. J. Tylka, *et al.*, Solar Phys. **204**, 43 (2001).
15. A. B. Belov, J. W. Bieber, E. A. Eroshenko, *et al.*, in *Proceedeings of the 27th ICRC* (Copernicus Gesellschaft, Hamburg, 2001), Vol. 8, p. 3446.
16. J. W. Bieber, W. Dröge, P. A. Evenson, and R. Pyle, Astrophys. J. **567**, 622 (2002).
17. I. M. Chertok, V. V. Fomichev, A. A. Gnezdilov, *et al.*, Solar Phys. **204**, 141 (2001).
18. V. I. Ishkov, in *Contemporary Problems of Astrophysics*; Tr. Gos. Astron. Inst. Shternberga **67**, part 2, 264 (2001).
19. L. Fletcher and H. Hudson, Solar Phys. **204**, 71 (2001).
20. M. J. Ashwanden and D. Alexsander, Solar Phys. **204**, 93 (2001).
21. A. V. Belov, E. A. Eroshenko, and M. A. Livshits, in *Proceedings of the Eighth International Symposium on Solar Terrestrial Physics* (Japan, Sendai, 1994), p. 26.
22. Y. Yan, M. J. Ashwanden, S. Wang, and Y. Deng, Solar Phys. **204**, 29 (2001).
23. V. V. Akimov, H. Garcia, K. V. Getman, *et al.*, Astron. Lett. **25**, 42 (1999).
24. A. R. Osokin, A. V. Belov, and M. A. Livshits, Astron. Vestn. (2005, in press).
25. M. A. Livshits, O. G. Badalyan, and A. V. Belov, Astron. Zh. **79**, 659 (2002) [Astron. Rep. **46**, 597 (2002)].
26. A. V. Belov and M. A. Livshits, Pis'ma Astron. Zh. **21**, 42 (1995) [Astron. Lett. **21**, 37 (1995)].
27. R. Ramaty, in *Physics of the Sun*, Ed. by P. A. Sturrock *et al.* (Reidel, 1986), Vol. 2, p. 291.
28. N. Vilmer, A. N. Mac Kinnon, G. Trottet, and C. Barat, Astron. Astrophys. (2004, in press).
29. A. N. Babin and A. N. Koval', Pis'ma Astron. Zh. **18**, 727 (1992) [Sov. Astron. Lett. **18**, 294 (1992)].
30. S. M. Krimigis, J. Geophys. Res. **70**, 2943 (1965).
31. B. B. Akimov, P. Ambroz, A. B. Belov, *et al.*, Solar Phys. **166**, 107 (1996).
32. A. Struminsky, M. Matsuoka, and K. Takahashi, Astrophys. J. **429**, 400 (1994).

*Translated by Yu. Dumin*