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Acceleration of Solar Cosmic Rays in a Flare Current Sheet and Their Propagation in Interplanetary Space

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Abstract—Analyses of GOES spacecraft data show that the prompt component of high-energy protons arrive at the Earth after a time corresponding to their generation in flares in the western part of the solar disk, while the delayed component is detected several hours later. All protons in flares are accelerated by a single mechanism. The particles of the prompt component propagate along magnetic lines of the Archimedean spiral connectng the flare with the Earth. The prompt component generated by flares in the eastern part of the solar disk is not observed at the Earth, since particles accelerated by these flares do not intersect magnetic-field lines connecting the flare with the Earth. These particles arrive at the Earth via their motion across the interplanetary magnetic field. These particles are trapped by the magnetic field and transported by the solar wind, since the interplanetary magnetic field is frozen in the wind plasma, and these particles also diffuse across the field. The duration of the delay reaches several days.

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1. INTRODUCTION

In powerful solar flares, an energy of $\sim 10^{32}$ erg is released in the corona over 10–20 min, accompanied by a number of physical phenomena. Impulses of thermal and hard X ray beams, coronal masses ejections with masses $\sim 10^{15}$ g having supersonic velocities, broadband electromagnetic emission, etc. are observed. Some large flares are accompanied by solar cosmic rays, i.e., relativistic protons [1, 2]. Each flare exhibits its own individual features. Some processes can dominate while others may be virtually absent. Flares usually display maximum thermal X ray energies of 12–15 keV. The X ray emission of typical flares increases rapidly (over 1–2 min), reaches a sharp peak, and then decreases. The decrease in X rays can take from 10 min to several hours. Each X ray impulse has its own form.

The proton fluxes of proton events are even more individual. Among proton flares detected over the last 10 years, it is difficult to find two proton fluxes with the same time behavior. The difference between proton flares occurring in the western and eastern parts of the solar disk can be traced clearly against the background of this variety. Our aim in this study is to identify these differences and their origins. We consider GOES measurements for protons with energies of 10–100 MeV and discuss data from neutron monitors for energies of 1–10 GeV. Both theory and experimental data indicate that the magnetic fields of current sheets formed above preflare active regions are the source of the flare energy.

The shapes of flare γ lines indicates the time scales for the generation of proton fluxes. The durations of the proton fluxes detected at the Earth's orbit significantly exceed the durations of X ray impulses; at the same time, the duration of the 2.22 MeV γ impulse associated with the radiative capture of neutrons by protons, resulting in the formation of deuterons, does not exceed the duration of X ray impulses [1, 2]. This indicates the formation of proton fluxes that can be detected over a long time traveling in the interplanetary medium.

Numerical MHD simulations [3, 4] whose initial and boundary conditions are specified by measurements carried out for preflare states of active regions show that the energy required for flares accumulates in the magnetic fields of current sheets. The locations of the calculated current sheets coincide with the sources of observed thermal X rays [5]. Current sheets form several dozen hours before their associated flares. The decay of current sheets heats the plasma contained in the sheet.

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Heating the plasma in the current sheets and accelerating the protons to relativistic energies should be observed during the dissipation of the magnetic energy accumulated in the magnetic fields of preflare current sheets. The explosive dissipation of this magnetic energy occurs in the transition of the sheet to an unstable state [6]. Decays of current sheets are nonadiabatic processes. An increase in the rate of magnetic reconnection $\mathbf{V}_{in}$ during the decay of current sheets results in the generation of strong Lorentz electric fields $-\mathbf{V}_{in} \times \mathbf{B}/c$ directed along X-type singular (in particular, zero) wagnetic-field lines; calculations made using the test-particle method have shown that this field can accelerate particles to gigantic energies [7]. Such acceleration is observed in laboratory experiments on the fast compression of a plasma column by magnetic fields due to rapidly increasing currents of electric discharges (the pinch effect). Particles are accelerated by the Lorentz electric field directed along the axis of the gaseous discharge [8, 9].

Measurements carried out on the worldwide network of neutron monitors show that some powerful flares are accompanied by fluxes of relativistic protons. About 30 monitors located at various stations throughout the world are used for analyses of such measurements [7, 10–12]. Each monitor detects protons arriving along specific trajectories in the Earth's magnetic field, which depend on the proton energy. Each particle energy interval ΔW detected by an individual monitor corresponds to a narrow interval of the solid angle containing the velocity vector of the particles arriving at the Earth's magnetosphere. Reduction of the data from this magnetometer network enables determination of the dynamics of the energy spectra of the flare protons and the angular distribution of their velocity vectors. For proton flares occurring in the western part of the solar disk, some monitors detect the maximum flux after a time interval corresponding to the transit time for particles moving along a magnetic-field line of the Archimedean spiral. The duration of this prompt flux has an exponential spectrum reaching 10–30 min. The prompt component is strongly anisotropic; i.e., the particle velocity vectors are directed along the Archimedean spiral.

Other monitors detect proton fluxes generated by the same flares but with delays of more than an hour; these fluxes slowly increase and then decay over tens of hours. These delayed fluxes have power-law spectra $dn/dW \sim W^{-k}$ (where $k \sim 4$) and isotropic angular distributions for their velocity vectors.

Particles of the prompt component moving along lines of the interplanetary magnetic field undergo no scattering. These particles carry information about the acceleration mechanism. The prompt component has an exponential spectrum, $dn/dW \sim \exp(-W/W_0)$. A technique for calculating the spectra of protons accelerated in current sheets was proposed in [7, 12]; according to MHD numerical simulations, such current sheets are formed before flares [3–5]. The initial and boundary conditions used in the numerical simulations of flare current sheets are usually specified using preflare measurements of magnetic fields in active regions. The acceleration of the relativistic protons is due to the Lorentz electric field, $\mathbf{E} = -\mathbf{V}_{in} \times \mathbf{B}_{cs}/c$, and occurs along X-type singular lines. Here, $\mathbf{V}_{in}$ is the velocity of the reconnection of magnetic-field lines and $\mathbf{B}_{cs}$ the magnetic field in the current sheet. The numerical simulations show that the exponential spectrum of the detected prompt component of the relativistic protons, $\exp(-W/W_0)$ ($W_0 \sim 1.3$ GeV), coincides with the calculated spectrum for a reconnection velocity $\mathbf{V}_{in} = 2 \times 10^7$ cm/s.

A number of authors [13, 14] have suggested that two independent mechanisms generate the prompt and delayed components of the solar cosmic rays. Independent mechanisms considered include the flare acceleration of the protons arriving at the corresponding transit time and the acceleration of the other particles in interplanetary space, for example, in shocks generated in the interplanetary plasma by supersonic coronal ejections.

The delayed proton fluxes are explained in [12] as corresponding to the arrival of particles that were accelerated in the current sheet like the prompt component, but did not intersect field lines connecting the flare and the Earth's magnetosphere. Such particles would be trapped by the magnetic field frozen in the solar-wind (SW) plasma, and so must drift across magnetic-field lines with the solar-wind velocity. In the drift approximation, these protons move in crossed fields: the magnetic field $\mathbf{B}$ of the interplanetary medium and the Lorentz electric field $\mathbf{E} = -\mathbf{V}_{SW} \times \mathbf{B}/c$ generated by the flow of the solar-wind plasma. Here, $\mathbf{V}_{SW}$ is the velocity of the solar wind. Cross-field diffusion due to scattering on inhomogeneities of the magnetic field is also possible. This scattering could result in some changes in the spectrum of the solar cosmic rays. The similar energy ranges of particles detected and similar fluxes of the two components, with these properties being independent of the power of the proton events, support the idea that a single mechanism generates the prompt and delayed components of the high-energy protons.

Here, we analyze 34 proton events observed by the GOES spacecraft. In contrast to neutron monitors, these measurements were carried out by wide-angle detectors, with the total isotropic and anisotropic proton fluxes being detected at each time. The regularities found were clearly manifest in significant fluxes of protons ($\Phi > 1$ cm^{-2} s^{-1} sr^{-1}). Weak proton fluxes do not always display relations to flares observed on the day side of the solar disk. Flares occurring on the far side of the Sun are presumably responsible for unidentified proton events.

2. DIFFERENCES BETWEEN THE FLUXES OF PROTONS ACCELERATED BY WESTERN AND EASTERN FLARES

Figure 1 shows proton fluxes detected in three energy ranges (10, 50, and 100 MeV) typical for flares observed in the western part of the solar disk. Here, we present X ray and proton measurements carried out by the GOES11 spacecraft with a temporal resolution of 5 min. The X8.3 flare responsible for the proton fluxes was observed on November 2, 2003, and was the first and largest of three X-class flares observed during a day. The flare occurred near the western limb (S19 W59), when the weak proton flux originating from an X10 flare preceding the event by three days was still arrived at the Earth. The proton flux generated by the flare observed on November 2, 2003 grew steeply soon after the arrival of the X ray impulse. The time lag between the arrival of the proton front and the onset of the flare (the arrival of the X ray front) was about 15 min. The two subsequent X-class flares generated no accelerated protons. The flux of protons with high energies ($W >$ 100 MeV) displayed the steepest increase, which took place over ~10 min. The maximum of the flare flux of high-energy protons occurred after ~2 h, and the maximum of the flux with $W > 10$ MeV after ~6 h. The less steep front of the latter flux results from the larger interval of velocities involved (starting from $V \sim 2 \times 10^9$ cm/s).

After reaching their maxima, the proton fluxes decrease over tens of hours, though the duration of the flare 2.22 MeV γ line characterizing the generation time for the high-energy protons never exceeds tens of minutes. The delayed particles arriving at the Earth several tens of hours after the flare cannot represent any direct flux traveling from the flare along the Archimedean spiral. Such a delay in the proton flux arrival should be observed in two cases.

In the first, the particles of the delayed flux are accelerated in processes occurring several tens of hours after the flare, for example, in shocks generated by supersonic coronal ejections. In the second, the appearance of delayed fluxes of energetic protons can be explained by the arrival of particles that have not intersected magnetic-field lines connecting the flare region with the Earth's magnetosphere. These particles can be transported by the solar wind or can diffuse across the magnetic-field lines. The flux of particles with lower energies drops more slowly, i.e. the slower propagation is explained by the slower diffusion in the interplanetary magnetic field. This behavior of the proton fluxes is typical for flares occurring in the eastern part of the solar disk. The dynamics of the proton fluxes shown in Fig. 1 for flares observed in the western part of the disk is sometimes disrupted if a flare follows strong perturbations in the interplanetary medium induced by preceding flare events and coronal ejections.

No sharp variations in the proton fluxes or other properties indicating the arrival of particles accelerated by two different mechanisms are observed in the dependence of the particle flux on time. Figure 1 does not show any flux changes indicating the end of the arrival of the prompt component and the onset of the arrival of the delayed particles. The increase in the isotropy of the fluxes of relativistic protons observed simultaneously with spectral changes in the relativistic part of the proton spectra [7, 10–12] does not provide evidence for the action of two different acceleration mechanisms, due to the gradual character of these changes.

The behavior of the proton fluxes presented in Fig. 1 is sometimes disrupted if the flares follow strong perturbations induced in the interplanetary medium by preceding flare events and coronal ejections. Figure 2 presents data for the unusual event observed on November 5, 2003. An X18 flare occurred on the western limb, while the proton flux resulted from the previous proton event was still continuing. A series of large flares, including three X-class and three M-class flares, accompanied by coronal ejections and proton fluxes was observed over the day preceding this event. These flares and coronal ejections probably distorted the shape of the field lines of the Archimedean spiral, apparently making it impossible for direct fluxes with steep fronts to travel from the flare to the Earth. Instead of a steep, 10 min front of arriving protons, a slow (~10 h) linear increase in the proton fluxes was observed for this event in all three energy ranges.

The absence of a slow solar cosmic-ray component for two X1.5 flares observed in the active region AR 10314 near the western limb (see Fig. 3) suggests a single mechanism generated both the prompt and delayed components of the solar cosmic rays produced during a flare. Both flares generated large coronal ejections. Nevertheless, these two powerful flares generated only very weak prompt proton fluxes (<1 cm^{-2} s^{-1} sr^{-1}) and no delayed fluxes, in spite of the fact that powerful injections of coronal plasma were observed. The coronal ejections did not generate any delayed solar cosmic rays. The absence of delayed protons following these flares indicates that it is the generation of accelerated protons directly in

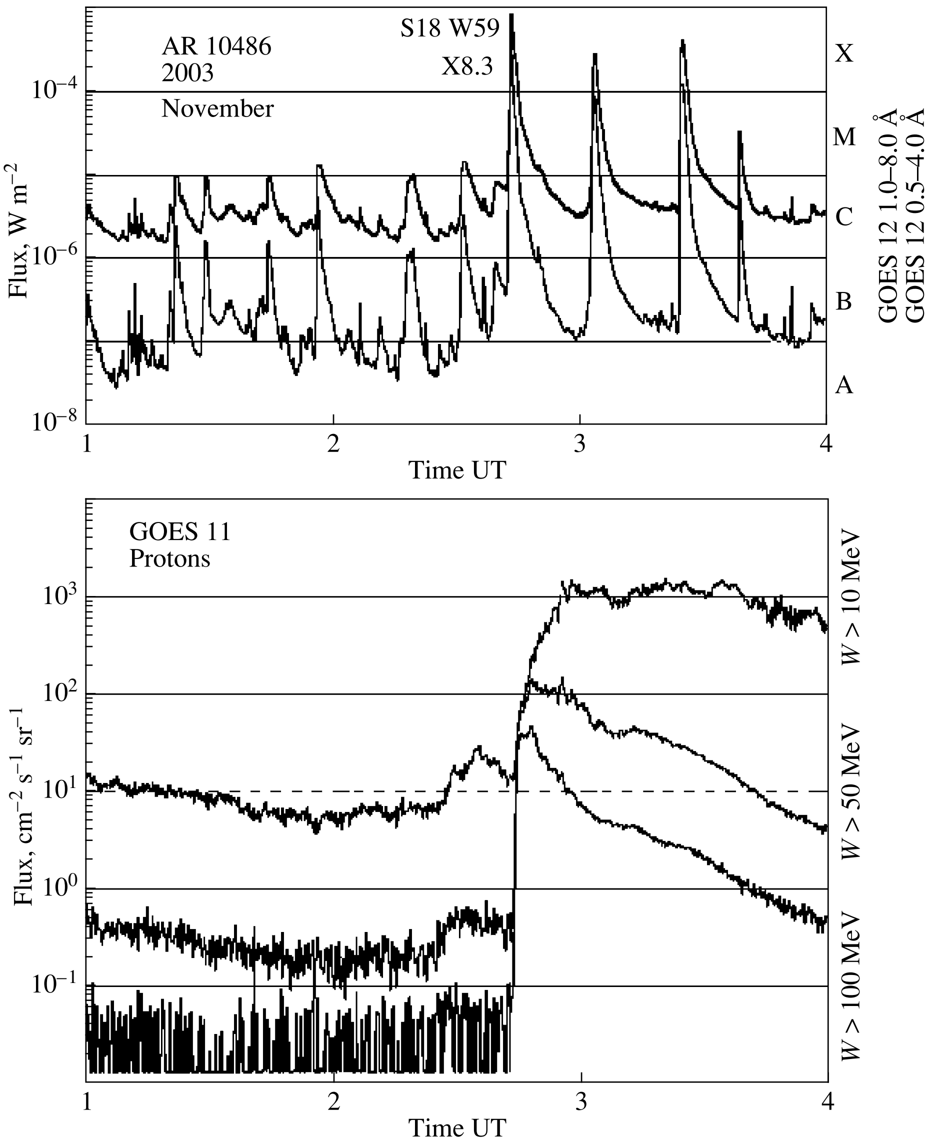

Fig. 1. Top: X ray flare emission generated near the western limb of the solar disk. Bottom: proton fluxes detected in three energy ranges.

the flares, not a coronal ejection, that is the necessary condition for the appearance of the delayed component. Some protons accelerated in western flares arrive at the Earth along magnetic lines of the Archimedean spiral connecting the flare region with the Earth's magnetosphere in accordance with the expected travel time. These protons form the prompt component, while other protons are transported by the solar-wind plasma and diffuse in the interplanetary magnetic field. These particles have isotropic velocity distributions. They arrive at the Earth with an additional delay, with the isotropic velocity distributions detected by neutron monitors. Thus, we can argue that the acceleration of the delayed protons also occurs directly in the flares.

If delayed protons generated by flares observed in the east of the solar disk arrive at the Earth traveling across the magnetic field, while the prompt protons generated by flares observed in the west arrive along the field lines of the Archimedean spiral, prompt proton fluxes generated by eastern flares are virtually impossible. There are no magnetic-field lines connecting eastern flares with near-Earth space. Figure 4 presents a proton event typical for eastern flares. In all three energy ranges, the protons were detected ∼5 h after the arrival of the X ray impulse, i.e., there is no prompt component. In contrast to typical western

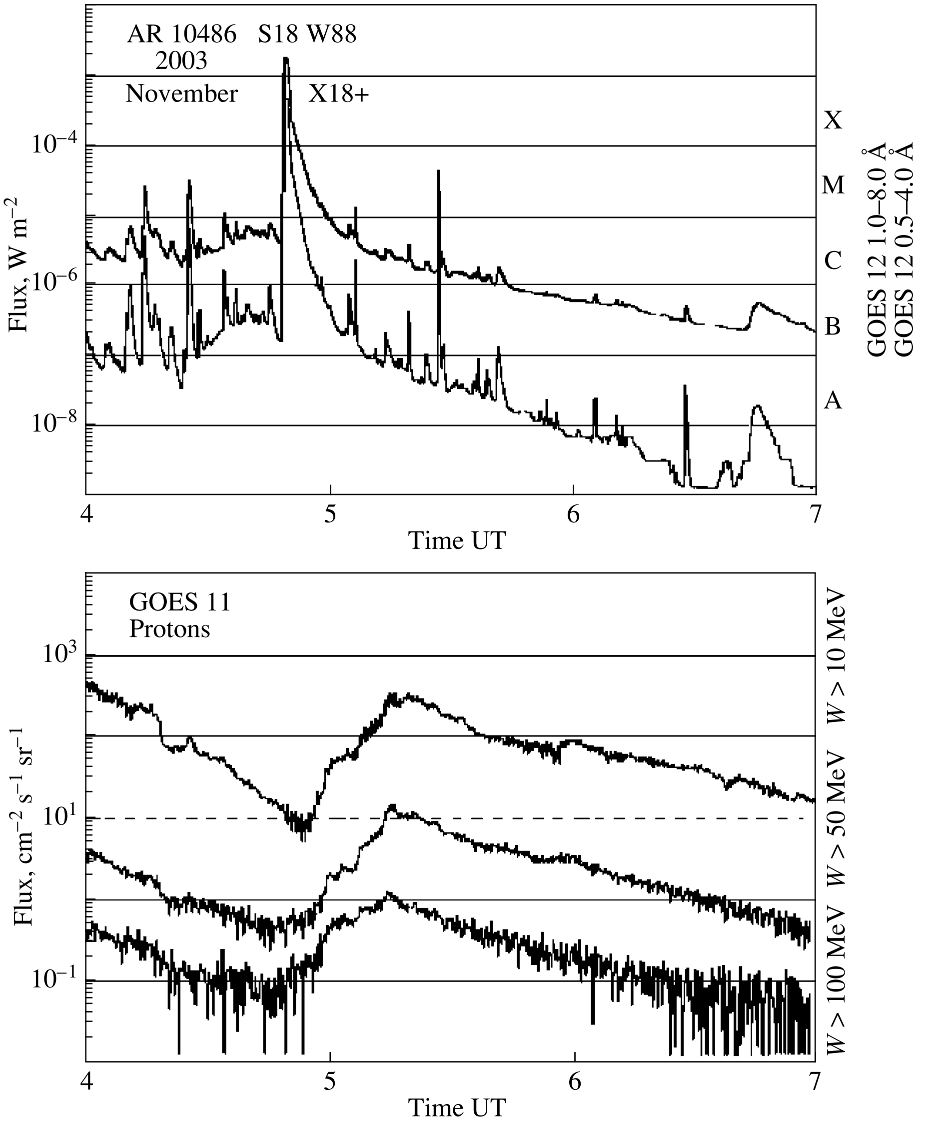

Fig. 2. A proton event generated on the western limb after perturbations induced in the interplanetary magnetic field by previous flares and ejections of coronal plasma. The uppe panel shows the X rays and the lower panel the proton fluxes.

flares with steep fronts (∼10 min), the flux fronts of the eastern flare extend over 10 hours in all three energy ranges, and the lag between the observation of protons and the onset of the X ray impulse reaches ∼5 h. The mean velocity of the first protons arriving at the Earth did not exceed 10^9 cm/s. These protons apparently diffused across the magnetic field for some portion of their path to the Earth, then moved toward the Earth along field lines.

Figure 5 presents a case when two proton events occurred in different solar regions with an interval of less than two days. The first event was observed at 7 : 30 UT January 6, 2014, after a very weak C2.1 X ray impulse. Such a weak flare never generates significant neutron fluxes. According to the RHESSI data, the C2.1 flare was generated by the active region AR 11936, which the monitor data indicate was observed on the limb (S15 W89). Apparently, the X rays were mainly generated on the far side of the Sun. The X rays detected on the Earth were able to arrive along a tangent to the solar surface, but a significant portion of the X rays was blocked by the Sun, so that the C2.1 magnitude of the flare was significantly underestimated. Protons were detected ∼20 min after the onset of this flare, and displayed the steep front typical for large western flares. The proton flux could arrive at the Earth along magnetic-field lines of the Archimedean spiral starting on the far side of the Sun. The second proton event was generated by a X1.2 flare observed near the disk center (S12 W08). This

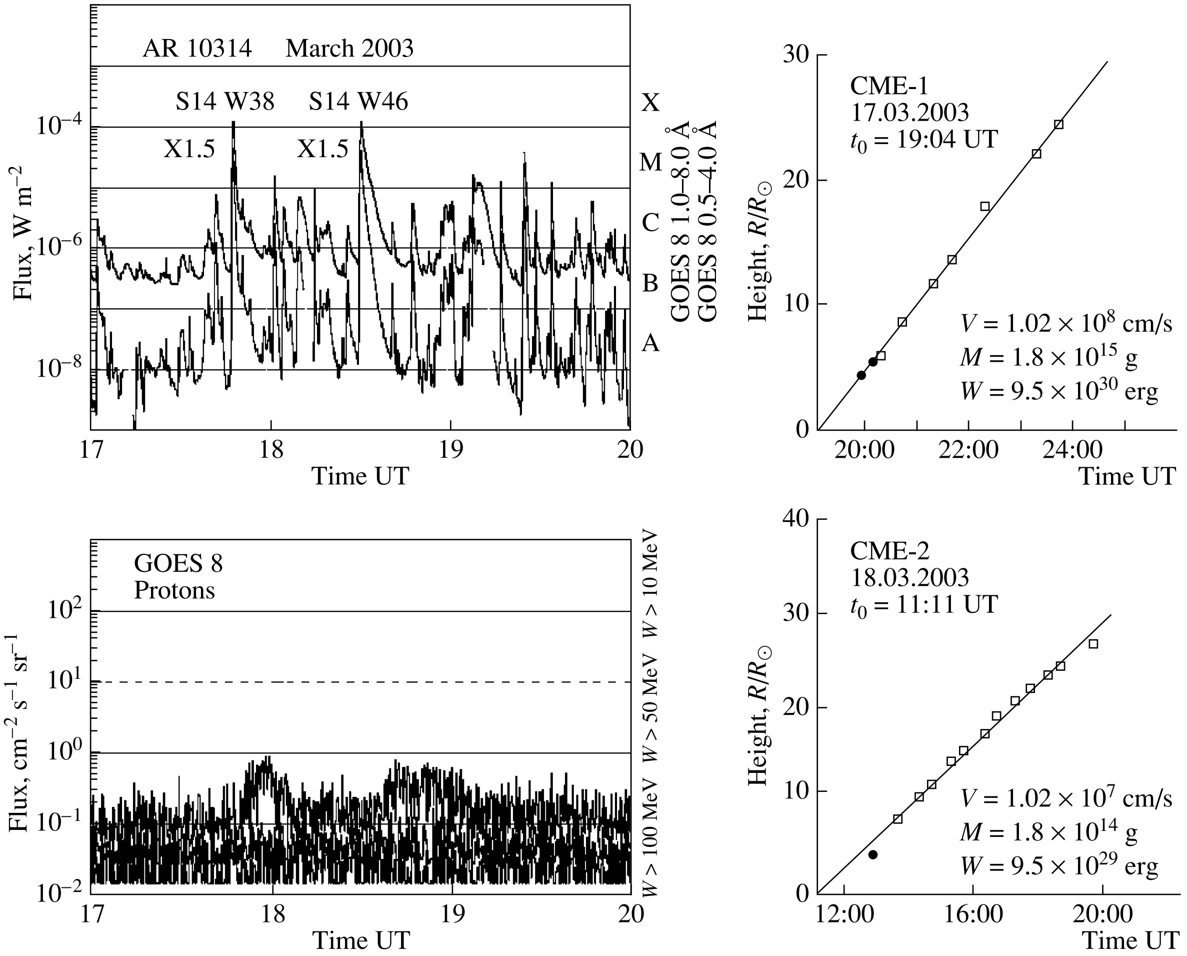

Fig. 3. Two large X-class flares that occurred on the western limb and generated no prompt accelerated protons. The slow cosmic-ray components are also absent, in spite of the occurrence of powerful coronal mass ejections. The upper left panel shows the X rays, and the lower left panel the proton fluxes. SOHO measurements of the coronal ejections are shown to the right.

proton flux was detected 2 h after the onset of the flare; in contrast to the steep front of the protons generated by the C2.1 limb flare, we see here a less steep front with a duration of about 5 h, which clearly exceeds the typical front durations for western flares. This proton event generated near the disk center demonstrates elements typical for both eastern and western solar flares.

3. DISCUSSION

The smooth variation of the spectrum of relativistic protons (a transition from an exponential to a power-law spectrum) occurs simultaneous with the isotropization of the particle velocity vectors relative to the magnetic field in the interplanetary medium [11, 12]. The absence of any appreciable changes in the proton fluxes as the spectrum varies provides direct evidence for a single mechanism accelerating the prompt and delayed components of the accelerated protons. The prompt component is formed by a particle flux traveling along lines of the interplanetary magnetic field, corresponding to the motion of protons accelerated in western flares and tied to field lines connecting the flare with the Earth's magnetosphere. These magnetic-field lines are part of the Archimedean spiral starting from the western part of the Sun. Particles that do not intersect these field lines can arrive at the Earth's magnetosphere only by diffusing across the magnetic field or being transported with the magnetized solar-wind plasma. This diffusion leads to changes in the particle spectra: the exponential spectra of the relativistic particles are transformed in power-law spectra [11, 12]. We currently have no information about the diffusion mechanism; the diffusion could arise from scattering on fluctuations of the magnetic field. The problem of

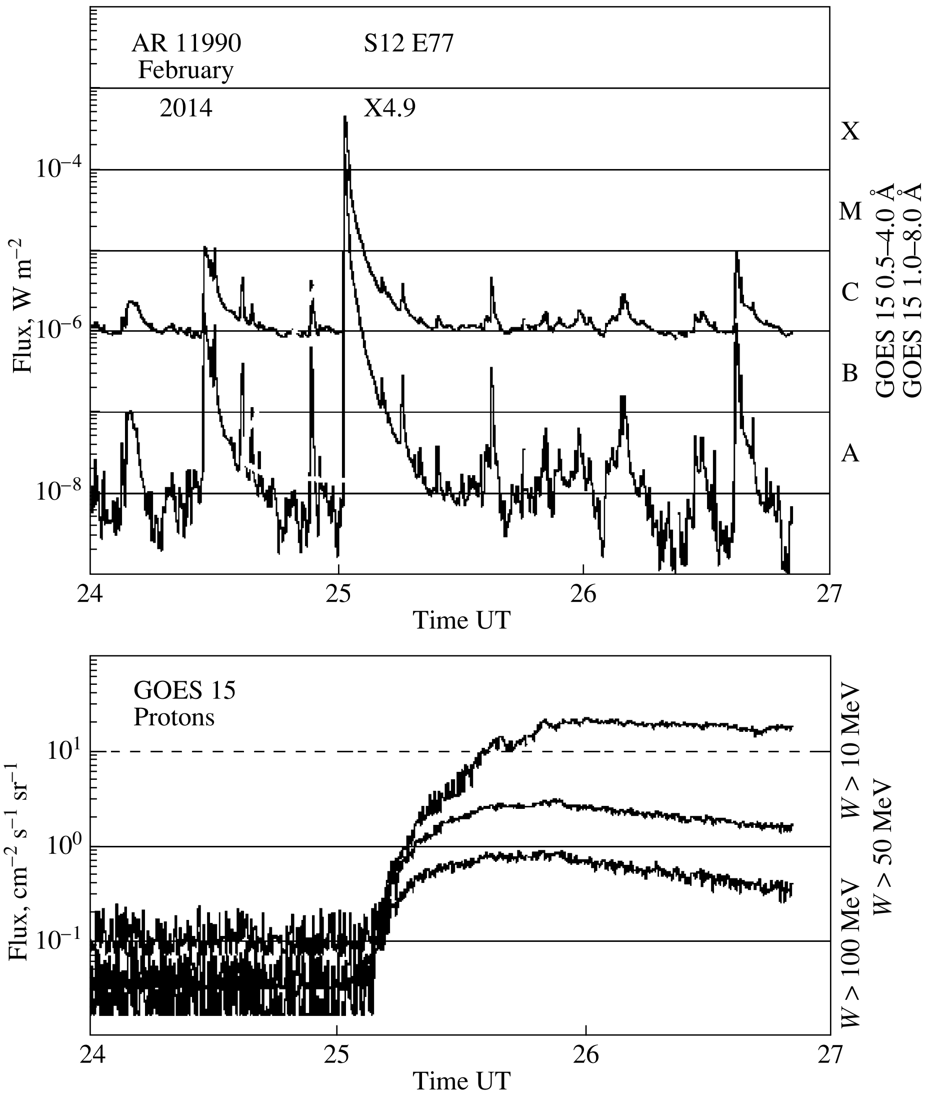

Fig. 4. A typical proton event induced by a flare observed in the eastern part of the solar disk. The upper panel shows the X rays, and the lower panel the proton fluxes.

the transport of the delayed component of the solar cosmic rays in interplanetary space remains topical.

In contrast to neutron monitors, with their narrow angular resolution, the GOES instruments have no angular resolution, and detect particles with a given energy and various pitch angles. The temporal resolution reaches 5 min. Steep, 10 minute increases in the fluxes observed at the fronts of the prompt proton components generated by western flares gradually flatten, so that flat maxima are detected 10–20 h later. After the maximum is reached, a slow decrease in the flux of solar cosmic rays occurs. The decrease in the flux of protons with energies ∼10 MeV occurs over two to three days, which corresponds to the time for the solar wind to travel from the Sun to the Earth. Fluxes of protons with higher energies decrease more rapidly. Short delays and steep fronts should be observed for proton fluxes only if some portion of the flare-accelerated particles reaches the Earth's orbit along magnetic-field lines and undergoes no scattering, with the delay being determined by the travel time. Accelerated protons that do not intersect the field lines of the Archimedean spiral connectng the flare with the magnetosphere become trapped by the magnetic field. These particles can reach the magnetosphere only by being transported by the solar wind or diffusing across the magnetic field. These protons form the delayed component of solar cosmic rays. The transition from the prompt to the delayed component is smooth in all energy ranges. It is difficult to find two independent acceleration mechanisms that al-

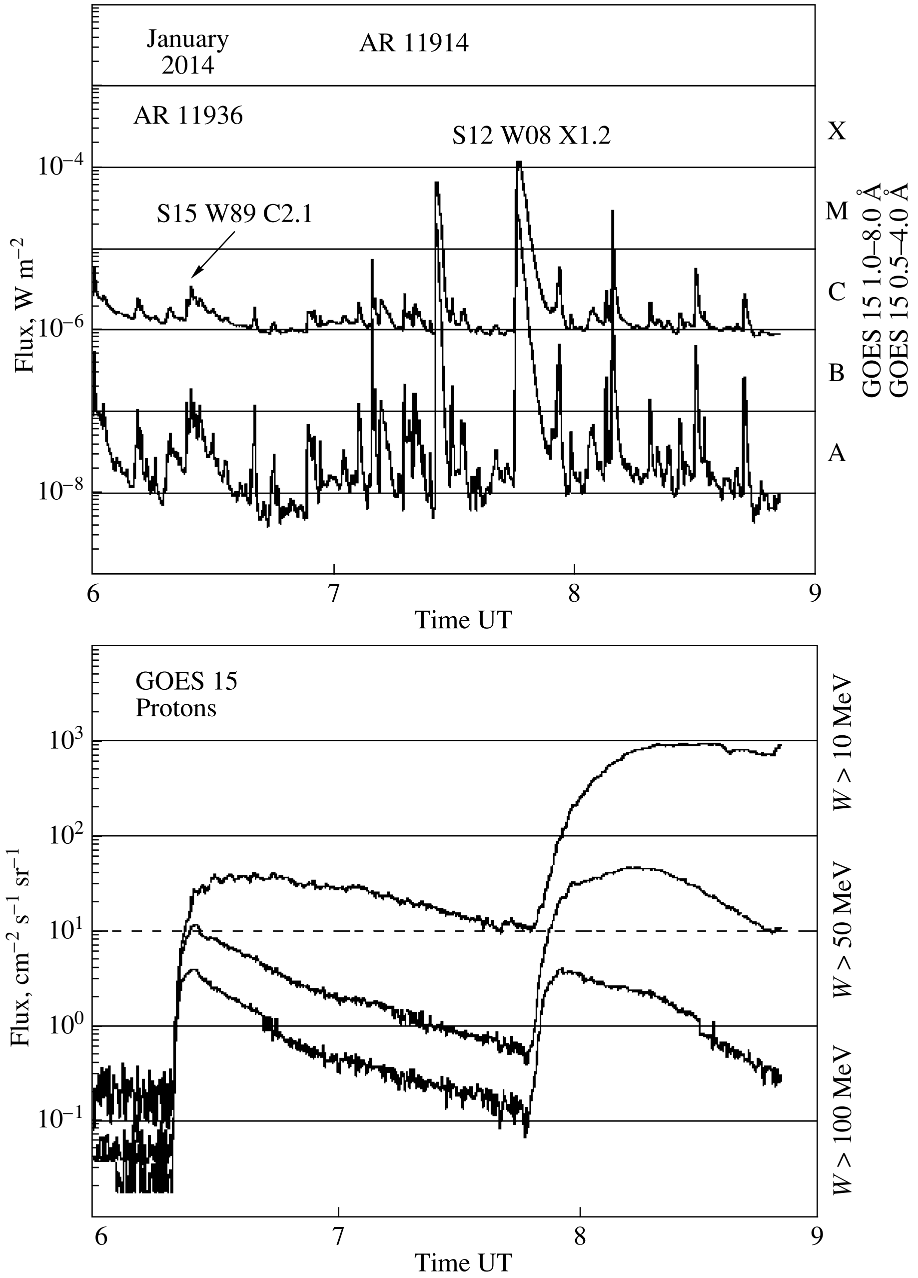

Fig. 5. X ray impulses and two proton events induced by flares separated by one day, generated above active regions observed by the GOES 15 spacecraft on the western limb and near the disk center. The upper panel shows the X rays, and the lower panel the proton fluxes.

ways give equivalent fluxes of accelerated particles in all the energy ranges observed.

Delayed fluxes are always present in proton flares. The delayed proton fluxes do not follow powerful flares when no proton fluxes arrive over the travel time (see Fig. 3). Thus, the generation of a prompt flare-proton component is a necessary condition for the appearance of a delayed component, and we have no reason to invoke shocks created by coronal ejections to explain the generation of the delayed protons.

Typical GOES observations of flare protons with energies of 10, 50, and 100 MeV are presented in Figs. 1 and 4. The prompt proton-flux component that arrives from western flares over the travel time is absent for flares observed in the eastern part of the solar disk. Typical delays for particles arriving from flares occurring in the eastern part of the solar disk reach several hours. Thus, the arrival delays for protons with energies 10–100 MeV generated by flares occurring on the eastern part of the limb exceed the arrival delays for the fronts of protons of the same energies resulting from flares on the western part of the limb by more than an order of magnitude. To intersect the magnetic-field lines of the Archimedean spiral connecting the Sun and the Earth, the particles accelerated by eastern flares must be transported across the field by drift or diffusion.

The usual dynamics of the proton fluxes is sometimes disrupted if flares follow strong perturbations of the interplanetary medium induced by preceding flare events; the X18 flare observed on the western limb on November 5, 2003 is one example (see Fig. 2). During the day preceding this proton event, there was a series of powerful flares accompanied by large coronal ejections. These coronal ejections apparently distorted the interplanetary magnetic-field lines, making a direct flow from the flare to the Earth impossible. The protons could arrive at the Earth only by crossing the magnetic field. Instead of steep fronts expected for the arrival of prompt protons, a gradual, linear increase was observed in all three energy ranges over $\sim$10 h.

Analyzing the fluxes of accelerated solar protons at energies of 10, 50, and 100 MeV, as well as data for energies 1–10 GeV taken from [7, 10–12], we have arrived at the following conclusions.

1. All significant proton events ($\Phi > 1$ cm^{-2} s^{-1} sr^{-1}) observed by the GOES spacecraft followed definite flares. Every proton event develops according to its own individual scenario.

2. Large individual proton events following flares observed on the western part of the limb start from a steep front detected after the time required for the particles to travel from the flare, with the particle velocities directed along lines of the interplanetary magnetic field [10–12]. The spectra of relativistic particles that arrive during the first 20–40 min (the prompt component) are exponential in form, $\exp(-W/W_0)$ [12]. The observed exponential spectra of the prompt component correspond to the results of numerical MHD simulations for a reconnection velocity of $\sim 2 \times 10^7$ cm/s. After 20–40 min, the relativistic-proton spectra are gradually transformed into power-law spectra, and the angular distributions of the protons become isotropic.

3. The GOES instruments observe the prompt proton component with energies below 100 MeV generated by large western flares. The prompt component can arrive at the Earth's magnetosphere only along magnetic lines of the Archimedean spiral. The proton-flux front generated by western flares arrive after the corresponding travel time. The delayed slow fluxes also generated by these flares and observed over tens of hours could be transported with the solar-wind plasma or by diffusion across magnetic-field lines.

4. The proton-flux fronts generated by eastern flares are never steep. For flares occurring in the eastern part of the solar disk, there are no field lines directly connecting the flare with the Earth; to intersect field lines extending toward the Earth, the accelerated protons must thus move across magnetic-field lines. This can be accomplished only via transport with the solar wind or diffusion across the field lines. Such particles are transported perpendicular to the magnetic-field lines with the motion of the plasma.

5. For protons originating in western flares, the smooth transition from the prompt to the delayed component and the observation of similar fluxes in all observed energy ranges during this transition, independent of the flare dynamics, argue against a picture in which different mechanisms generate the prompt and delayed components.

6. Proton events have no relation to the generation of powerful coronal ejections. Some flares accompanied by powerful coronal ejections do not result in any delayed component of the accelerated protons. These flares likewise do not generate any prompt component. The generation of prompt protons in a flare is apparently a necessary condition for the appearance of a delayed component in the solar cosmic rays. The time delays observed for the arrival of the delayed protons at the Earth are due to their propagation across lines of the interplanetary magnetic field.

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