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Multiple Acceleration of Protons on the Sun and Their Free Propagation to the Earth on January 20, 2005

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Abstract—We analyze the observations of solar protons with energies >80 MeV near the Earth and the January 20, 2005, solar flare in various ranges of the electromagnetic spectrum. Within approximately the first 30 min after their escape into interplanetary space, the solar protons with energies above 80 MeV propagated without scattering to the Earth and their time profiles were determined only by the time profile of the source on the Sun and its energy spectrum. The 80–165 MeV proton injection function was nonzero beginning at 06:43:80 UT and can be represented as the product of the temporal part, the ACS (Anticoincidence System) SPI (Spectrometer on INTEGRAL) count rate, and the energy part, a power-law proton spectrum $\sim E^{-4.7\pm 0.1}$. Protons with energies above 165 MeV and relativistic electrons were injected, respectively, 4 and 9 min later than this time. The close correlation between high-energy solar electromagnetic emission and solar proton fluxes near the Earth is evidence for prolonged and multiple proton acceleration in solar flares. The formation of a posteruptive loop system was most likely accompanied by successive energy releases and acceleration of charged particles with various energies. Our results are in conflict with the ideas of cosmic-ray acceleration in gradual solar particle events at the shock wave driven by a coronal mass ejection.

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INTRODUCTION

The prolonged solar gamma-ray emission detected in June 1991 with the Gamma-1 and CGRO astrophysical satellites was an amazing and unexpected experimental result of the observations in solar cycle 22. Peculiar conditions in the region of acceleration and/or proton confinement after the impulsive phase of a solar flare are required for the generation of this emission (Ramaty and Mandzhavidze 1999). No unequivocal theoretical explanation has been given for this result as yet, nor has it been confirmed by direct observations in other solar particle events (see the review by Ryan (2000) and references therein). These observations initiated a number of works that related the parameters of solar protons and neutrons near the Earth to the prolonged solar gamma-ray emission.

Thus, for example, the similarity of the time profiles for the gamma-ray and microwave emissions served as a basis for the model neutron injection function in the June 4, 1991 (Struminsky et al. 1994), and June 15, 1991 (Kovaltsov et al. 1995), events, when in both cases it was necessary to assume prolonged neutron generation in the impulsive and posteruptive phases of the solar flare. According to the estimations by Kocharov et al. (1994) and Akimov et al. (1996), the protons with energies <150 MeV were injected into interplanetary space on June 15, 1991, earlier than the relativistic protons responsible for the ground level enhancement (GLE) of cosmic rays observed by the neutron monitor (NM) network. These authors argued that the relativistic protons were accelerated for a long time in the posteruptive phase rather than were trapped.

Based on the diffusion model of proton propagation and their prolonged injection into interplanetary space, we previously estimated the number of protons with an energy of 100 MeV in the source on the Sun at various times in large solar proton events of solar cycles 22 (Struminsky 2003a) and 23 (Struminsky 2003b). For the June 11, 1991, and June 15,

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Parameters of the solar flares under discussion

Date	Coordinates	Importance	X-ray	Beginning, UT	Maximum, UT	End, UT
Oct. 28, 2003	S16E08	4B	X17.2	09:51	11:10	11:24
Jan. 20, 2005	N12W58	2B	X7.1	06:36	06:43	08:54
Sep. 7, 2005	S06E89	3B	>X17	17:17	17:40	18:03

1991, events, we obtained, respectively, qualitative and quantitative agreement with the number of protons required for the generation of the observed gamma-ray emission (as estimated by Kocharov et al. (1998)). This suggests that the generation of prolonged gamma-ray emission was also quite possible in other events, when similar numbers of protons could be trapped near the Sun for several hours. However, at this time, such observations were just not performed or were performed, but the measurement accuracy was definitely not enough. These conclusions need to be confirmed or refuted in other events of solar cycle 23.

The processes of multiple and prolonged acceleration of charged particles in the posteruptive phase of solar flares are an alternative to the current paradigm for the origin of solar energetic particles. According to this paradigm, the shock wave driven by a coronal mass ejection (CME) in gradual events (the soft X-ray emission lasts for more than 30 min) accelerates particles high in the corona and supplies them into interplanetary space (Reams 1999), while the processes in the lower and middle corona that generate gamma-ray emission on the Sun give no significant contribution to the fluxes of interplanetary particles.

To all appearances, the solar particle events that occurred before January 20, 2005, created conditions in the heliosphere for the propagation of protons with energies >80 MeV almost without scattering. This allowed the source's effects to be directly observed on Earth within the first 20–30 min after the GLE onset. The objective of this paper is to show this quantitatively and to calculate the time profiles for 80–165 and 165–500 MeV protons near the Earth using solar gamma-ray observations. The mean free paths of such protons in interplanetary space typically lie within the range 0.06–0.3 AU (Bieber et al. 1994), which masks the effect of the source on the solar cosmic-ray fluxes observed near the Earth.

AN OVERVIEW OF THE RESULTS OF OBSERVATIONS

The January 20, 2005, solar particle event occurred in the active region AR 10720. Table 1 presents some of the parameters for this event. They are compared with the parameters of the October 28, 2003, and September 7, 2005, solar flares, which are also considered here. Below, while talking about the proton processes on the Sun, we discuss the observations of electromagnetic (EM) emission on Earth; therefore, all times are given relative to the Universal Time (UT) of arrival of the EM emission at the Earth (~8 min must be subtracted from UT to pass to the solar time).

Hard X-ray and gamma-ray emissions from this flare were detected onboard RHESSI, CORONAS-F, and INTEGRAL. Figure 1 shows a black-and-white version of the four visualization frames (http://svs.gsfc.nasa.gov/vis/a000000/a003100/a003162/) for the times marked by the arrows in Fig. 2a. This visualization was constructed using (RHESSI) gamma-ray and X-ray images superimposed on a (TRACE) ultraviolet image of the flare. We clearly see a white two-ribbon structure of the flare with dark (blue in the original) spots of gamma-ray emission at the loop footpoints and a gray (red in the original) cloud of X-ray emission of the highest loop. Note that a frame-by-frame watching of this movie shows that the emission at the loop footpoints disappeared at 06:50:10, 07:00:00, and 07:05:20 UT.

The first CME was observed beginning at 06:54 UT (there may have been the second CME at 07:12 UT), which corresponds to its detachment from the solar surface at 06:40 UT (Simnett 2006). The type-II radio emission, which is generally associated with the emission of electrons near a shock, began at 06:44 UT. Thus, the times beginning at 06:44 UT correspond to the posteruptive phase of the flare.

The Australian Learmonth Observatory was at the most favorable position for the observation of radio emission from the January 20, 2005, solar flare. Figure 2a shows the time profiles of 8.8-GHz radio emission and the ACS (Anti Coincidence System) SPI (Spectrometer on INTEGRAL) count rate. The microwave emission is a prolonged and powerful spike that is evidence of prolonged (including posteruptive) energy release (Chertok 2005, private communication). The second peak of 8.8-GHz emission was observed approximately at 07:12 UT.

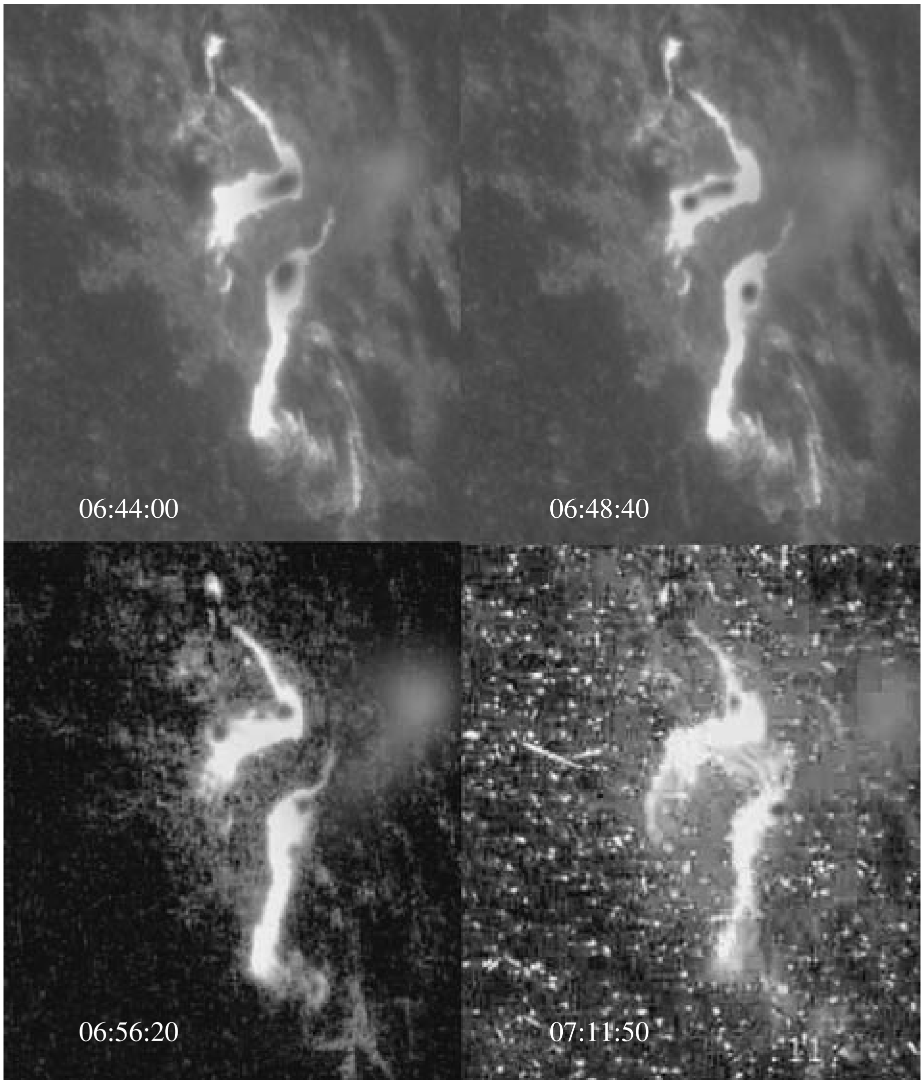

Fig. 1. Visualization frames of the January 20, 2005 flare in the X-ray, gamma-ray (RHESSI), and ultraviolet (TRACE) ranges at various times.

According to the first RHESSI spectroscopic data, the power-law spectral index of protons at low energies obtained from gamma-ray observations is 2.3 ± 0.3 and is almost equal to the spectral index measured near 1 AU (2.1 ± 0.1). This suggests that the protons propagating in interplanetary space were accelerated in the flare and not necessarily by shock waves (Krucker et al. 2005). The calculations by Murphy et al. (2005) point to a chemical composition of the solar ions characteristic of acceleration in flares with a ratio $\alpha/p > 0.1$ rather than by shock waves. The RHESSI X-ray and gamma-ray time profiles are presented on the Internet (see http://hesperia.gsfc.nasa.gov/rhessidatacenter/).

The high-energy part of the gamma-ray spectrum in the January 20, 2005, event was measured by the SONG instrument onboard the *CORONAS-F* spacecraft (Kuznetsov et al. 2005). No gamma rays from pion decay were detected up until 06:45:30 UT. On the other hand, the gamma-ray spectrum recorded in the time interval from 06:46:58 to 06:50:28 UT is indicative of the interaction of protons with energies above 300 MeV in the solar atmosphere.

The cosmic-ray GLE detected by the neutron monitor network on January 20, 2005, was the record in the entire history of 50-year-long observations (Belov et al. 2005; Bieber et al. 2005; Vashenyuk et al. 2005; Moraal et al. 2005; Simnett 2006). The anisotropic arrival of solar protons with energies >450 MeV was observed more than 30 min after the GLE onset. The South Pole (SOPO) and McMurdo (MCMD) neutron monitors, which are located in Antarctica and showed the maximum GLE at approximately $06{:}54 \pm 1$ min UT, were at the most favorable position for observations. At the time of

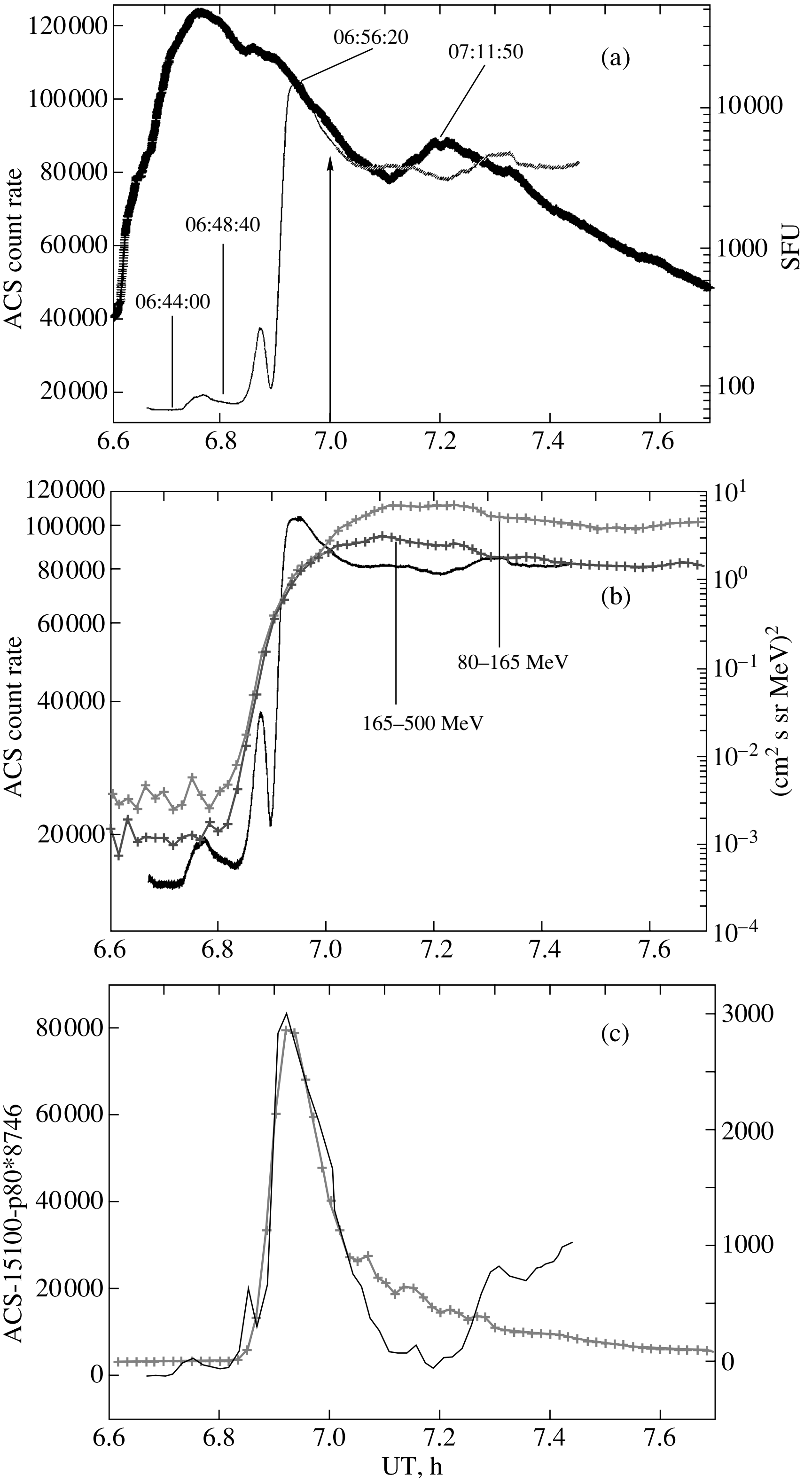

Fig. 2. Comparison of various time profiles for the January 20, 2005, event: (a) radio emission at 8.8 GHz (Learmonth Observatory) and the ACS count rate; (b) GOES 80–165 and 165–500 MeV protons and the ACS count rate; (c) ACS count rate (minus the background and the possible contribution from 80–165 MeV protons) and the McMurdo (MCMD) NM variations.

the anisotropic NM GLE, the index of the proton rigidity spectrum near the Earth was −5 (Bieber et al. 2005). To interpret the NM data, Saiz et al. (2005) assumed the injection of relativistic protons into interplanetary space beginning at 06:49 ± 1 UT (the injection maximum at 06:52 ± 2 min UT). Mean free paths of 0.9 ± 0.1 AU at the anisotropic phase and 0.6 ± 0.1 AU later were used in their model of proton propagation to the Earth.

According to the GOES data (http//spidr.ngdc.noaa.gov), the 80–165 and 165–500 MeV solar protons showed a very rapid and almost simultaneous onset of the enhancement above the background (Fig. 2b). The proton spectrum was unusually hard (a positive spectral index) and pointed to velocity dispersion effects. The temporal variations in the spectrum suggested a possible additional proton injection at approximately 07:21 UT (Struminsky 2005b).

INTERPRETATION OF THE ACS SPI DATA

ACS SPI records primary and secondary gamma rays with energies >150 keV. At the time of the January 20, 2005, solar flare, the ACS count rate was above the background and had three distinct peaks that correlated with microwave features (Fig. 2a). The background of secondary gamma rays produced by previous events exceeded the typical background values approximately by a factor of 3 (Figs. 3a and 3b). This makes it difficult to analyze in detail the characteristics of the gamma-ray emission in this event (Gross 2005, private communication).

Comparison of the ACS count rate with the proton intensity in the 80–165 and 165–500 MeV channels (Fig. 2b) shows that a contribution from the secondary particles generated by solar protons inside the detector is possible after the onset of a proton enhancement. Note that the ACS count rate is virtually constant at constant and high GOES proton intensity, i.e., it is predominantly the result of secondary particles. A proton intensity of 1 $(\mathrm{cm}^2\ \mathrm{s\ sr\ MeV})^{-1}$ in the 80–165 MeV channel will correspond to the generation of ∼8746 pulses. Clearly, primary solar gamma rays produced the first enhancement above the background, while the role of the relative contribution from primary and secondary gamma rays at the times of the second and third ACS peaks requires a further study.

Figure 2c compares the ACS count rate minus the initial background (∼15 100 pulses) and the possible contribution from 80–165 MeV protons with the relative enhancement of a solar origin observed with the McMurdo NM. We see that, in this case, the second ACS peak is ahead of the arrival of relativistic protons, while the third peak coincides almost exactly with the anisotropic McMurdo NM enhancement. Clear evidence for the existence of a fourth enhancement related to the second peak of radio emission and the second CME also appeared. The third and largest ACS peak was produced both by the secondary gamma rays formed through the interaction of relativistic solar protons with the detector and by the primary solar gamma rays.

The October 28, 2003, flare is the first solar event to be investigated in detail by INTEGRAL instruments (see Kiener et al. 2006). The ACS increase on October 28, 2003, contained information about the nuclear processes on the Sun and was used to model the solar neutron event (Struminsky et al. 2005a). It coincides in duration and intensity with the first ACS peak on January 20, 2005 (Fig. 3a). The September 7, 2005, event is interesting in that it occurred near the eastern solar limb. The solar protons arrived with a long delay, providing ideal conditions for the observation of solar gamma rays at a late stage of the flare.

The time profiles in Fig. 3b are shown relative to the onset of X-ray flares (see the table); we see that the third ACS peak on January 20, 2005, might well include an event like the September 7 one.

Below, we use the ACS count rate to model the solar proton enhancement.

CALCULATIONS AND DISCUSSION

The Model of Free Solar Proton Propagation

Observations of the solar flare and the solar proton event give grounds for considering the following model of proton escape and propagation in interplanetary space: the proton injection function is the product of the ACS count rate (the temporal part) and a power-law proton spectrum (the energy part); the protons propagate without scattering and traverse a distance of ∼1.2 AU to the Earth.

This model is used to calculate the solar proton intensity that must be observed in the energy ranges 80–165 and 165–500 MeV on the GOES satellite within approximately the first half an hour after the onset of increase (corresponds to the anisotropic phase of GLE on NM). We find the index of the proton energy spectrum near the Sun through fitting with a step of 0.05 by taking −5 as the zeroth iteration.

Figure 4 shows the results of this modeling. The 80–165 MeV protons (Fig. 4a) began to escape into interplanetary space at 06:43:80 UT with a differential energy spectrum $\sim E^{-4.8}$. At approximately 06:50:12 UT, a change in the power-law spectral index must be assumed (the spectrum became harder $\sim E^{-4.6}$) for the best agreement with experimental data. This corresponds to acceleration at the time of the second ACS peak. The 165–500 MeV protons (Fig. 4b) began to escape into interplanetary space

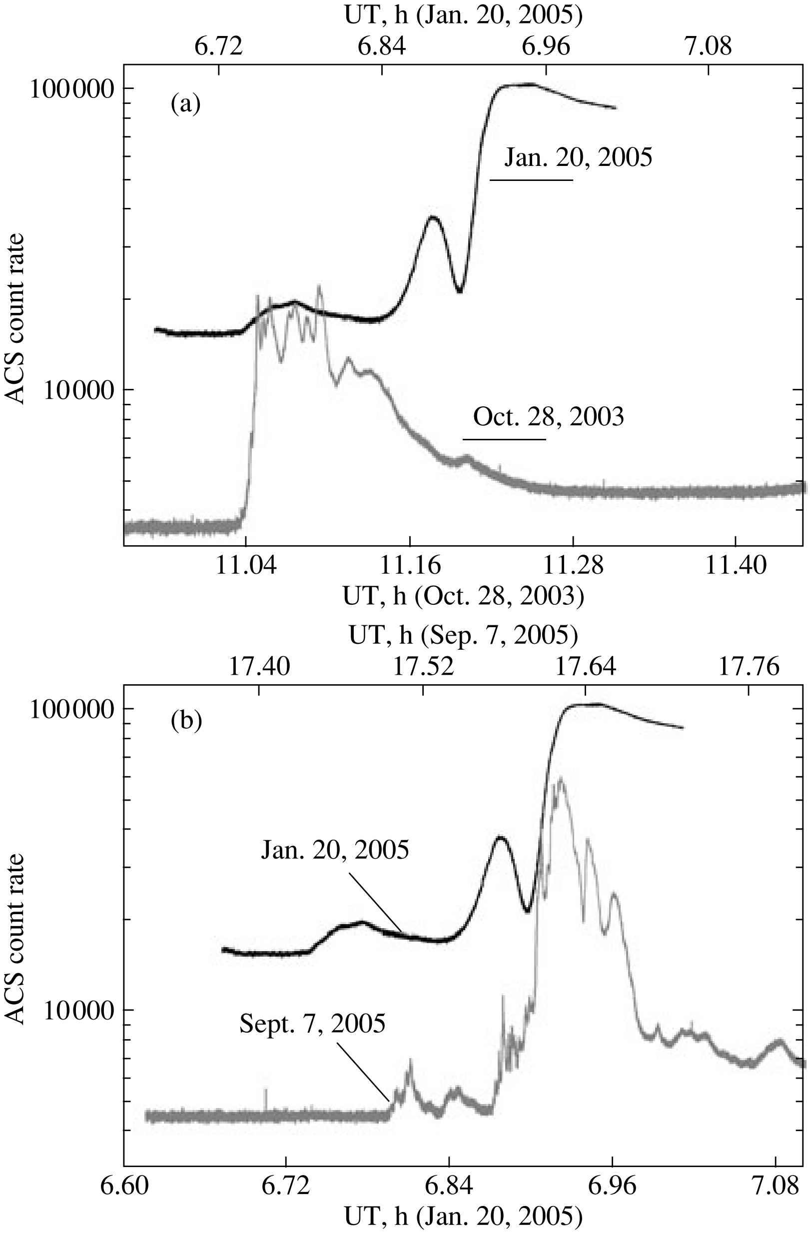

Fig. 3. Comparison of the ACS count rates in the following events: (a) October 28, 2003, and January 20, 2005; (b) January 20 and September 7, 2005.

at 06:47:30 UT with similar variations of the energy spectrum. The maximum of relativistic proton injection on the Sun (Saiz et al. 2005) corresponds to the second ACS peak. According to Simnett (2006), the relativistic electrons escaped into interplanetary space 5 min later than the relativistic protons.

Since the normalization factor of the power-law spectrum was constant as the spectral index varied, the ratio of the number of protons escaped into interplanetary space and the ACS count rate increased by a factor of 2–3, implying that the proton escape or gamma-ray generation conditions on the Sun changed.

If the third ACS peak is used as an extension of the temporal part of the source function, then there is a discrepancy by a factor of ~2 between model and experiment for both 80–165 and 165–500 MeV protons (Figs. 4a and 4b).

Note that the maximum ACS count rate on January 20, 2005, is approximately twice that observed in the September 7, 2005 event (Fig. 3b). Let us modify the injection function and use the data for the September 7, 2005, event indicated by the gray

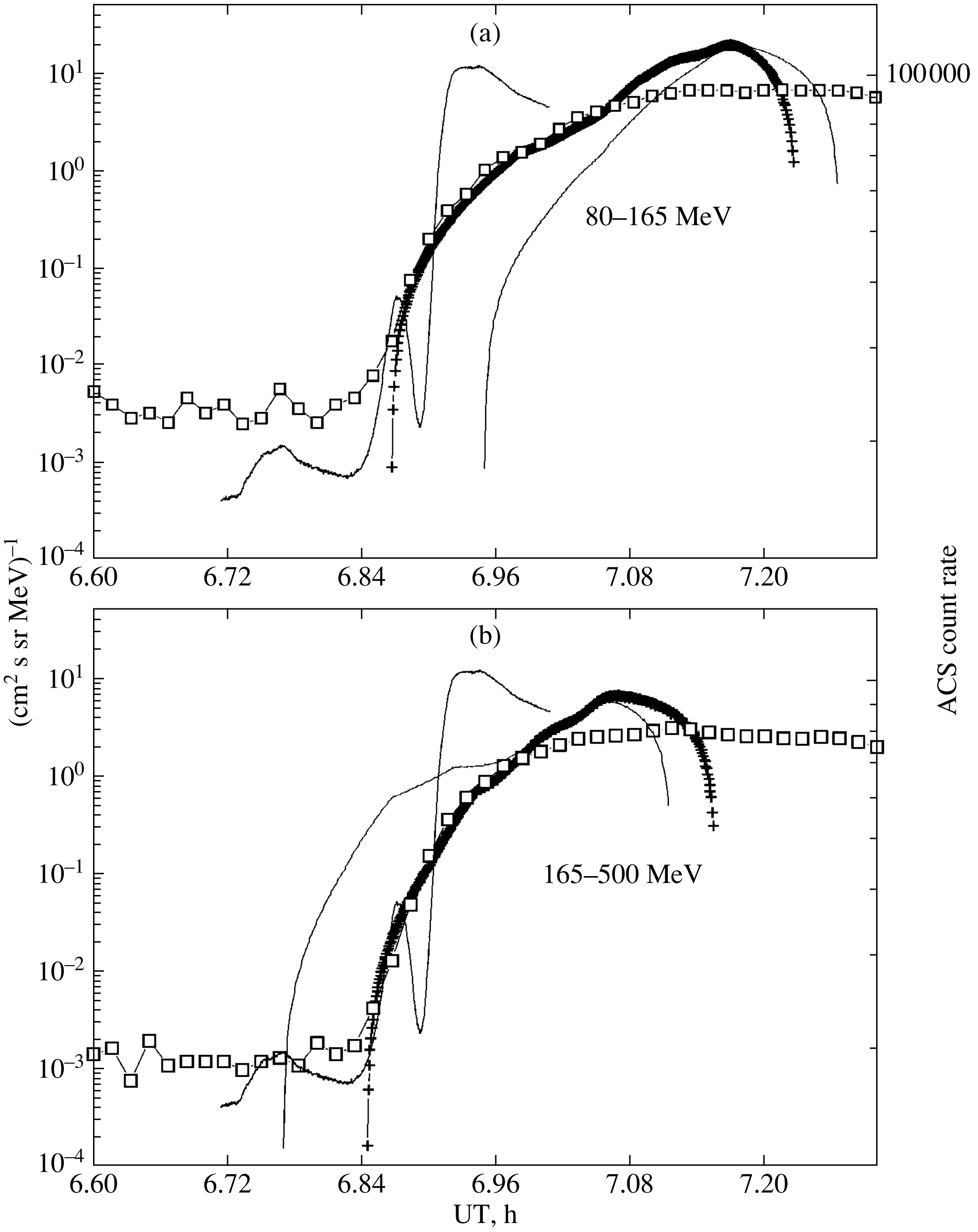

Fig. 4. Comparison of the (a) 80–165 and (b) 165–500 MeV solar proton intensities in the model of free propagation (crosses) with GOES observations (1-min averages, open squares). The ACS count rate that defines the time dependence of the injection function is shown. The black lines correspond to later (earlier) injection of 80–165 MeV (165–500 MeV) protons.

curve in Fig. 5 beginning at 06:53:52 UT. We see that the results of our calculations with the modified injection function agree with the experimental data for another ∼10 min (Fig. 5). Given the proton intensity in the 80–165 MeV channel and the maximum ACS count rate in the model, respectively, 0.131 (cm^2 s sr MeV)$^{-1}$ and 60 000 pulses at the time of the third peak, the contribution of the secondary gamma rays from relativistic protons can be estimated. In this case, the record GLE is most likely associated with the unique conditions for the escape and propagation of protons in interplanetary space.

To describe the time profile of 80–165 MeV protons, we must assume at least three episodes of proton escape into interplanetary space that are related to high-energy processes in the solar atmosphere. These episodes differ in absolute intensity, spectrum, maximum energy, and ratio of the numbers of protons and electrons escaped into interplanetary space. They are not related to the confinement of the same group of particles in a trap, since the particle energy and

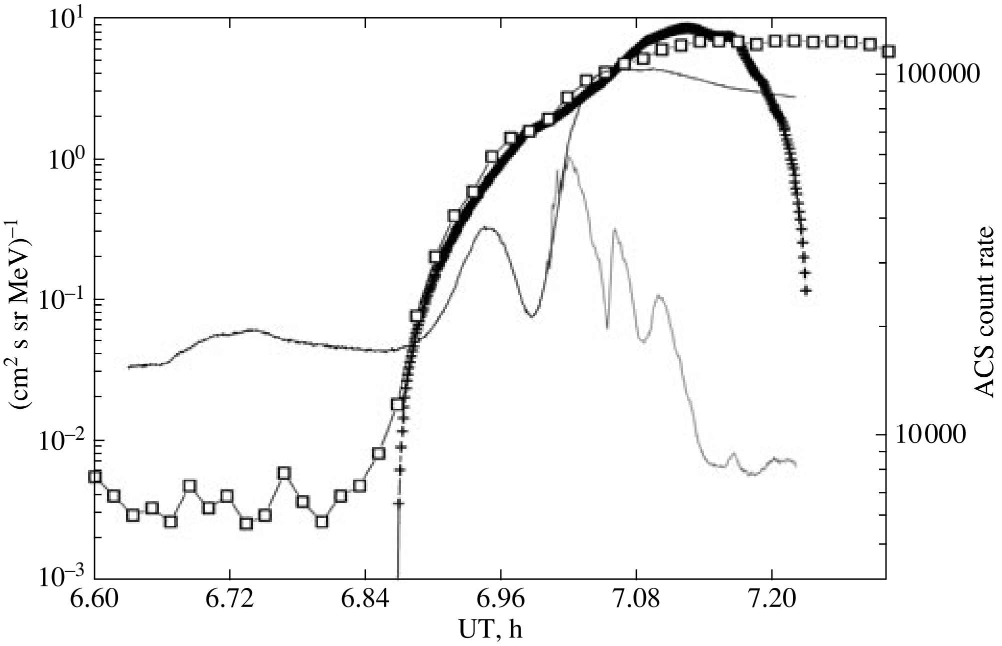

Fig. 5. Comparison of the 80–165 MeV proton intensity in the model of free propagation (crosses) with observations (1-min averages, open squares) for the modified injection function. The September 7, 2005, ACS data (gray curve) are used after 06:53:42 UT.

intensity rose with time. The realization of several acceleration stages that differ in intensity by several factors at one CME-driven shock propagating away from the Sun also seems unlikely. Thus, we are dealing with several particle acceleration episodes in one solar flare.

The Diffusion Model of Solar Proton Propagation

No flux of relativistic protons is observed ~30 min after the GLE onset, and the model of free proton propagation for lower energies definitely does not work. Therefore, we use the diffusion propagation model (Struminsky 2003a) to investigate the event on long time scales (the second peak of 80–165 MeV protons) and the balance between the propagation conditions and the properties of the source.

The results of fitting the 5-min data of the 80–165 MeV channel in this approach are presented in Fig. 6. Assuming the mean free path to be 0.3 AU, 2.8×10^{32} protons with energies above 100 MeV must be injected almost instantaneously into interplanetary space at 06:42 UT ± 5 min. This model describes well the first peak and the prolonged intensity decrease, but not the dip between the first and second peaks (Fig. 6a). For a mean free path of 0.5 AU and injection of the same number of protons at 06:46 UT ± 5 min, the proton intensity decreases too fast (Fig. 6b). However, if we assume the second delta injection of 5.9×10^{31} protons at ~07:30 UT, which corresponds to the posteruptive phase after the second CME, then we can model both the two proton peaks and the prolonged decrease in proton intensity. Thus, in the event under consideration, $\sim 3.4 \times 10^{32}$ protons with energies >100 MeV escaped into

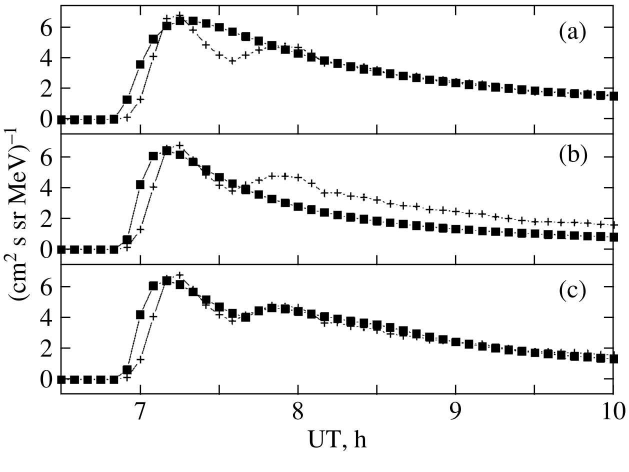

Fig. 6. Comparison of the calculated 80–165 MeV proton intensities in various diffusion propagation models (filled squares) with observations (5-min averages, crosses): (a) the model with one instantaneous injection and a mean free path of 0.3 AU; (b) the model with one instantaneous injection and a mean free path of 0.5 AU; and (c) the model with two instantaneous injections and a mean free path of 0.5 AU.

interplanetary space. This number is comparable to its estimates for the powerful solar proton events of September 29 and October 19, 1989 (Struminsky 2003a), and July 14 and November 8, 2000 (Struminsky 2003b), but it is not an outstanding one. In this case, only the unique proton propagation conditions in the interplanetary medium are most likely responsible for the record GLE.

In the diffusion propagation model with an uncertainty in the mean free path, we cannot distinguish the first three acceleration episodes. Saiz et al. (2005) modeled the prolonged decrease at high energies by changing the propagation conditions in the interplanetary medium without considering the possible contribution from prolonged injection. However, we have every reason to believe that there were also several injections at relativistic proton energies. According to the observations by Moraal et al. (2005) on the Sanae NM, there were three peaks (06:54, 07:07, 07:24 UT) that correlated in time with the suggested proton injection episodes. How will the conclusion reached by Saiz et al. (2005) about the proton propagation conditions in the interplanetary medium change if prolonged injection is used?

CONCLUSIONS

(1) A joint analysis of the TRACE and RHESSI images, the time profile of radio emission (Learmonth), and the ACS SPI count rates in the January 20, 2005, event shows that the formation of a posteruptive loop system was accompanied by successive energy releases and accelerations of charged particles with various energies. A set of such elementary events may form the entire variety of observed characteristics of solar energetic particle events.

(2) On January 20, 2005, conditions for free escape of protons from the acceleration region and their propagation to the Earth almost without scattering for the first 30 min of event development were created.

(3) The time profiles of solar protons with energies above 80 MeV near the Earth were determined by the time profile of the source on the Sun and its energy spectrum.

(4) Assuming that the 80–165-MeV proton injection function is nonzero beginning at 06:43:80 UT and is the product of the ACS SPI count rate (the temporal part) and a power-law proton spectrum $\sim E^{-4.7\pm0.1}$ (the energy part) and that the protons traverse a distance of ~1.2 AU to the Earth without scattering, we can achieve reasonable agreement between the model calculations and the GOES observations.

(5) Protons with energies 165–500 MeV were injected 4 min later at 06:48 UT with approximately the same energy spectrum.

(6) The ACS SPI count rate carries information about the solar protons that directly interact in the solar atmosphere. The creation of a database of INTEGRAL solar proton events and their detailed investigation are required.

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