Cosmic Research, Vol. 43, No. 3, 2005, pp. 165–178. Translated from Kosmicheskie Issledovaniya, Vol. 43, No. 3, 2005, pp. 171–185.

Proton Events and X-ray Flares in the Last Three Solar Cycles

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Received August 12, 2004

Abstract—A database joining the available information about proton enhancements near the Earth and their possible solar sources is organized on the basis of proton measurements of the *GOES* and *IMP-8* satellites, the data of neutron monitors, and *GOES* X-ray measurements. One thousand one hundred and forty-four proton events with energy > 10 MeV have been selected in the period from 1975 to 2003. More than a half of these events can be reliably related to X-ray solar flares. A statistical analysis shows the probability of observing solar protons near the Earth and their maximum flux value to be strongly dependent on the importance of a flare and its heliolongitude. Proton events are recorded after all suitably located (western) flares with X-ray importance > X5. The heliolongitude of a flare predetermines the character of the time profile of proton events in many respects. The relationship of proton events with the other characteristics of flares is established. The flares associated with proton enhancements are characterized by longer duration, slower rise to the X-ray maximum, smaller temperature, and larger length of the X-ray loops.

1. INTRODUCTION

Long ago first observers noticed the relation between proton events and solar flares. This relation is quite obvious for ground-level enhancements of solar cosmic rays [1, 2] which are usually observed simultaneously with very strong flares or immediately after them. In those cases, when no evident data about a strong flare on the visible part of the Sun are available, there is convincing indirect evidence that such a flare took place behind the solar limb. Proton enhancements and solar flares used to be observed and discussed together. This was the case for many years before the famous paper *Solar flare myth* by J. Gosling [3] and the works by D. Reames (for example, [4]), and this is still the case after these publications. One can see this tendency in some papers (for example, [5–7]) and, which is more important, in everyday practice.

At the moment we understand that coronal mass ejections (CME), and coronal and interplanetary shock waves can have a substantial effect on acceleration of charged particles, and they can be even more important for the conditions of escape and propagation of these particles [8–14]. The characteristics of a proton enhancement observed near the Earth and on the ground, and even the very possibility of such an observation, can be determined by the properties of ejections and shock waves [15–19]. However, our recognition of the role played by CME should not prevent us from studying the links between proton events and flares, and the importance of such studies should not be underestimated.

Even those researchers who deny the flares' involvement in acceleration processes cannot but admit that the relation of flare characteristics to the properties of proton events does exist and can be used for predictions of radiation danger. For those who believe (as we do) that acceleration of charged particles is a part of flare mechanism the joint analysis of characteristics of solar flares and proton events is natural and logical.

Investigations of this type were undertaken many times. For example, Van Hollebeke et al. [20] have found 125 proton events in the data of *IMP-4* and *IMP-5* and have studied their correlation with solar flares. Theoretically, any sporadic manifestations of solar activity can be useful for probabilistic models of proton enhancements [21–23, etc.], but generally they are based precisely on the characteristics of flares. One can only say welcome to the complex approach that was demonstrated by creation of the database http://cdaw.gsfc.nasa.gov/LWS/data/event_list.html which had joined a variety of data for the periods of proton enhancements. Unfortunately, such an approach is fully applicable only to the last solar cycle and to a limited number of events.

We believe that X-ray flares can be used as a best basis for long-term studies and comparison with a large number of proton events. Sufficiently long (already 29 years) and homogeneous series of data almost without gaps are available for them. These data include qualitative characteristics of various types, and this facilitates classification procedures. X-ray observations are less dependent on flare longitudes than optical

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observations, and they allow one to detect close events behind the limb. The last circumstance is very important for us, since frequently such events are a source of proton enhancements. The main drawback of X-ray observations are as follows: no data are available before 1975, and up to the recent time (until *GOES-12* epoch) it was impossible to localize an event on the Sun. The use of optical observations together with X-ray data, as it is done by the *GOES* group, allows one to eliminate this last drawback.

In this paper we make an attempt to isolate all proton enhancements in the last three cycles of solar activity (1975–2003), to find the most probable solar sources of these enhancements, to join the characteristics of proton enhancements and solar flares associated with them in a single database, and to carry out the statistical analysis using a larger body of data than that used in our earlier studies [24–32].

2. DATA

Protons

We use the integral fluxes of protons measured onboard *IMP-8* and a series of *GOES* satellites (from *GOES-5* to *GOES-12*). The *IMP-8* data for energies >10, > 30, and > 60 MeV are taken from the OMNI database (http://nssdc.gsfc.nasa.gov/omniweb/ow.html). The fluxes of protons and nuclei with energy >106 MeV were supplemented to them (http://ulysses.sr.unh.edu/WWW/Simpson/imp8.html). As for *GOES* data, we mainly used integral channels for protons with energies >10, >30, >50, >60, and >100 MeV (http://spidr.ngdc.noaa.gov/spidr/). The protons of lower energies are subject to strong influence of interplanetary disturbances, and variations of their fluxes have poorer correlations with solar events.

The *IMP-8* data were represented by mean hourly values, while for *GOES* measurements we used different time resolutions from 1 min up to an hour. Half-hour averaging was usually taken for numerical estimates. The difference in time resolution had no essential effect on the results, since the typical characteristic time of enhancement development significantly exceeds one hour even for protons with energies >100 MeV, and to determine the exact time of proton enhancement commencement was not our aim. There are other differences between the *IMP-8* and *GOES* data, but as we made ourselves certain, they should not prevent us from using these data and getting the reliable results.

For the earlier period (1975–1986) we used only the *IMP-8* data, and for the period after 2002 only the data of *GOES* satellites were at our disposal. Even in 1987–2001, when all measurements were available, due to the gaps in data we had sometimes to use the measurements of a single spacecraft. In those cases, when there were all types of measurements, the agreement between them was usually reasonable.

Solar Observations

We use the database of X-ray flares created in IZMIRAN on the basis of observations and catalogs of *GOES*, which was already used as a tool for several investigations [33–34]. In addition, we have widely used the catalogs of optical flares, in some cases correcting and refining optical references made by the *GOES* group. The information about flares was supplemented by the data on radio bursts and observations of CME made by the *SMM* [35] and *SOHO* (http://lasco-www.nrl.navy.mil/cmelist.html) missions.

In order to estimate possible influence of interplanetary disturbances on the proton fluxes measured near the Earth we use the catalogs of storms with sudden commencements (SSC) (which coincide with arrivals of interplanetary shock waves to the Earth) and the database of solar wind disturbances [36].

3. SELECTION OF PROTON EVENTS AND THEIR SOLAR SOURCES

Selection of Events

We endeavored to select all proton enhancements which were discernible in observations of protons with energies > 10 and > 100 MeV and could be associated with acceleration processes on the Sun. When compiling a catalog of solar proton events (SPEs) we had in mind that our main task was to study the relationships between SPEs and their solar sources; therefore, we tried to separate the effects from different sources. In this respect our catalog is distinct from the NOAA catalog [37, 38], where the entire period, in which the flux of protons > 10 MeV persisted to be higher than the threshold of 10 pfu, was considered as a single event, independent of the number of possible solar (and interplanetary) sources. We defined our proton event as an effect associated with a single source. Such an approach was also used earlier in papers [20, 39–42]. It makes the selection of events more difficult and less accessible to formalization. The difference in formation of the catalogs is demonstrated by Fig. 1 with well-known events of October 1989.

In this period one can easily select at least four proton events marked in Fig. 1 by arrows (three of them are accompanied by large ground-level enhancements). However, since beginning from October 19 to the end of month the flux of > 10 MeV protons did not drop below 10 pfu, this entire period is a single proton event for the NOAA catalog.

The maximum increase above the background of the proton flux averaged over 15–60 min was used as a main quantitative characteristic of the enhancement value. The use of fluences for such investigations is less convenient, since no fluence is measured directly, and to calculate it for separate events is difficult in some cases. Under quiet conditions one can isolate sufficiently reliably the enhancements with amplitudes of 0.1 pfu, thus reducing the threshold accepted by the

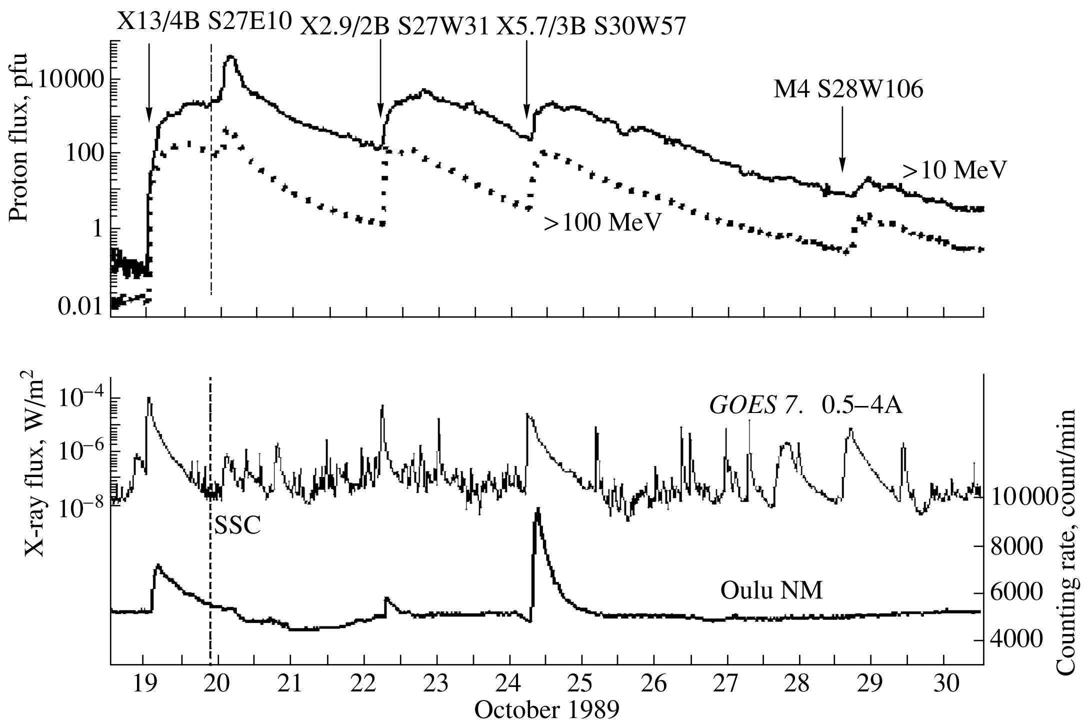

Fig. 1. An example of a series of proton events associated with the active region 5747.
X-ray and proton measurements of *GOES-7* and 15-min data of the Oulu neutron monitor are presented.

NOAA catalog by a factor of 100. In the cases when proton enhancements follow one after another their isolation becomes considerably more different, and sometimes it is impossible altogether. First of all this is valid for the smallest enhancements, but there are cases when on the decline phase of giant proton events it is difficult to isolate a new enhancement even with a value of 100 pfu. For example, it is not easy matter to decide whether proton event was associated with the flare M8.7/2N on October 25, 1989 because of a high background (about 1000 pfu) of protons from the preceding event.

Modulation effects in cosmic rays (due to shock waves and other disturbances of the solar wind) also prevent one from isolating proton events reliably. In some cases two (more rarely, three) maximums are observed in a single event. This occurs more frequently for protons > 10 MeV, and considerably less frequent such events are for > 100 MeV (one example gives the event on October 19, 1989 in Fig. 1). If two maximums were well pronounced, the second one being larger in its value than the first one, we included both these values in our database, while only the first maximum value was used in the analysis.

For the most part we analyzed in this paper the enhancements for protons > 10 MeV and > 100 MeV, as well as ground-level enhancements (GLEs). If an enhancement selected from the *IMP-8* data was discernible in the channel > 106 MeV, we considered that this enhancement took place also for > 100 MeV protons. The amplitude of this enhancement was determined by interpolation between the channels > 60 and > 106 MeV. The amplitudes of ground-level enhancements were not used in the analysis.

Reference to Solar Sources

Our aim was to produce a catalog of solar sources of accelerated protons rather than mere catalog of proton events. Therefore, the reference of a proton enhancement to a certain solar event (we sought for it primarily among solar flares) was important and in many respects crucial part of our study. It is this part of such investigations that often leads to doubts and debates. We have also not avoided some problems, though they turned out to be even less numerous than one could expect. In most cases one could find a flare immediately before the proton enhancement, and this flare was clearly distinguishable among other flares of the period, which made our choice sufficiently simple. Rather often this choice was difficult because of the presence of two or more almost equivalent candidates for the role of associated flare. The cases when no real candidates were found upon the first glance on the situation were no less frequent. Mainly, these were the cases when the source of accelerated particles was located behind the western limb of the Sun. Sometimes, we have observed direct evidence of this fact: ejections of solar mass on the invisible side of the Sun, limb processes, and radio bursts not associated with any visible activity. As a rule, before such events the active region went behind the

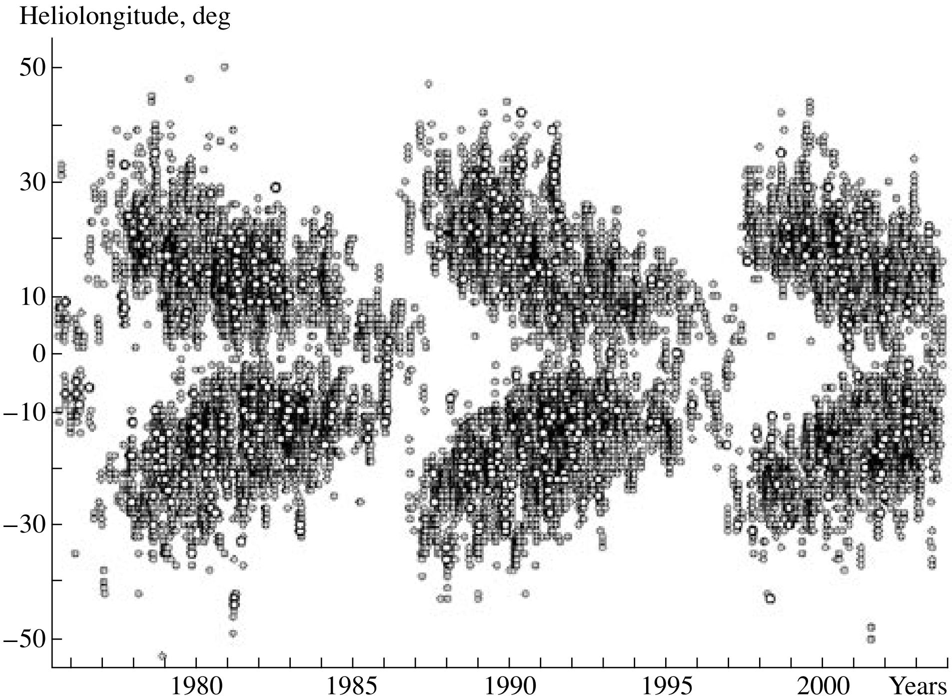

Fig. 2. The Maunder's butterfly diagrams for all X-ray flares identified with H_α flares (gray circles) and for flares associated with proton enhancements (empty circles).

limb, which had already generated considerable bursts and become a source of other proton enhancements. In some cases we had all grounds to believe that a small X-ray flare without optical reference is only the upper part of a considerably stronger behind-the-limb flare. Though in this case the optical flare was not observed, we were able to localize it reliably enough. It is clear that there were events when no reasons for localization of sources were found, and one could only suspect their behind-the-limb origin.

We fully aware that it was impossible to avoid errors while referencing the events. In order to express quantitatively the quality of reference, i.e., the degree of our confidence in it, we assigned to each event the index of quality q_a with five grades. Index 5 means that we are sure in our reference, index 4 corresponds to some doubts in it, index 3 stands for serious doubts, index 2 means that the reference is very doubtful, while at index 1 we are almost sure that it is wrong. In what follows we use the events with $q_a = 5$ or 4 in all types of comparison. All others are used only at some cases, when characteristics of solar flares are not very important.

4. DATABASE

We have selected and included in our catalog 1144 proton (> 10 MeV) enhancements for approximately 28 years. This is a sufficiently large number. It is less than the number of Forbush effects and magnetic storms at the same period, but only by a factor of 2–3. It is possible that some of the smallest SPEs included in our database will not be confirmed in the future. On the other side, the probability of addition of new events which turned out to be missed due to various reasons is no less. One should not forget gaps and interruptions in data series, as well as objective difficulties in selecting the proton enhancements. In some cases a considerable modulation of the cosmic ray background could prevent an event from being selected, in other cases the enhancements from differing sources turned out to be so close in time that it was impossible to separate them. Notice that such a number of proton enhancements approximately corresponds to the number of flares with importance ≥M4 (1152 in the period under consideration). Among the selected events 547 were also accompanied by enhancements of protons > 100 MeV (with a flux of > 0.02 pfu), and 38 events were accompanied by proton ground-level enhancements (GLEs).

We have succeeded in referencing more than a half of 617 selected proton events to certain flares with sufficient reliability ($q_a = 4$–5), more exactly, a source of protons was localized in space and time for these events. These flares are shown by empty circles in Fig. 2 against the background of all X-ray flares in 1975–2003. One can see that proton events are inherent in virtually all phases of the solar cycle. They are frequently associated both with high-latitude active region of the cycle beginning and with low-latitude groups of sunspots on the decline phase of solar activity.

The number of events for which localization failed or was made without certainty ($q_a < 3$) is 151. A part of references with index 3 or, possibly, even 4 should be added to this number. However, it is not to be supposed that all events without reference or at least their major part are not associated with flares. A certain fraction of flares was missed due to gaps in observations, a more significant part of flares turned out to be accessible for proton observations and inaccessible for observations in all other radiations, since these flares occurred on the invisible side of the Sun sufficiently far from the limb. The fraction of such flares should be no less than 20%. It must be also taken into account that sometimes no reference is possible because appropriate flares are too abundant rather than absent: it is difficult to choose between several candidates.

Generally, rapidly developing enhancements with a sharp commencement can be referenced more easily than gradual events with a slow development. Everybody who studied GLEs can recall that usually for the strongest proton events their reference to a solar source is no problem.

Proton Events and Active Regions

Rather often proton events are observed in series, when a single active region generates several proton events one after another. For example, in November 1989 the group of sunspots 5793 occurred to be associated with proton events nine times in a week. Surprisingly, in none of them were detected protons with energy > 100 MeV. More frequently serial proton flares were accompanied by acceleration to high energies. For example, in May 1990 the group 6063 gave five proton flares, all of them with protons > 100 MeV, and four out of five were accompanied by GLEs (the only exception was the eastern E38 flare, the first in the series). The group 6659 in June 1991 also gave five enhancements for the energy > 100 MeV in five proton flares. Finally, six proton enhancements were associated in April 2001 with the group 9415, five of them with energies > 100 MeV and two with GLEs. The only exception (no particles with the energy > 100 MeV) again was the first and most eastern (E31) flare. Apparently, the recent active region 10486 turned out to be still more productive (three GLEs and no less than ten proton enhancements in the end of October – beginning of November 2003 which so far are not included in our database).

There is an impression that the capability to generate accelerated particles is inherent for active regions to a variable degree. Some of them can accelerate particles to ultra-relativistic energies and repeatedly demonstrate this, while others are capable to accelerate only up to energies of tens of MeV.

One can find large groups of sunspots without production of accelerated particle, but usually they are also not productive with respect to strong flares. Quite rarely the region with serial strong flares turns out to be unrelated to proton events, for example, the group of sunspots 5047 in June 1988.

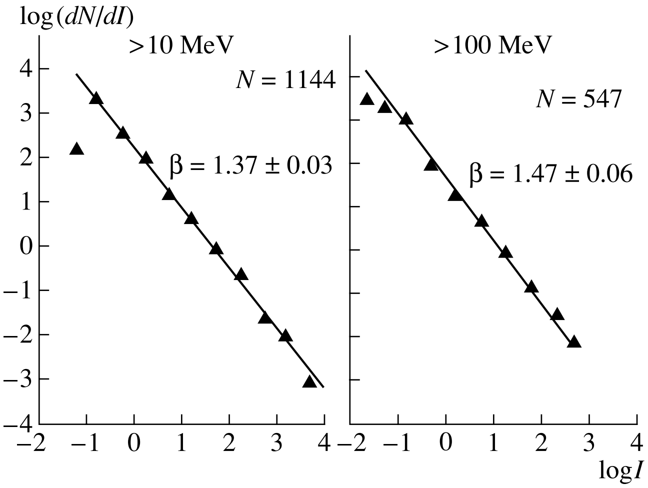

Fig. 3. Intensity distributions of proton enhancements for energies > 10 MeV and > 100 MeV. Straight lines correspond to power law fits of weighted data.

5. GENERAL CHARACTERISTICS OF PROTON EVENTS AND THEIR RELATION TO INTENSITY AND LONGITUDE OF FLARES

Let us first discuss some properties of proton events and the relationship between X-ray and proton characteristics which do not depend on identification of solar sources.

Distribution of Proton Enhancements in Their Flux Value

We have found the function of differential distribution of all proton events in their flux value in the form $\Psi(I) = dN(I)/dI$, where dN is the number of events with the flux value within the limits between I and $I + dI$ (Fig. 3).

This distribution is sufficiently well approximated by a power law function with indices 1.37 ± 0.03 and 1.47 ± 0.06 for energies > 10 and > 100 MeV, respectively. Various indices of this dependence were obtained in earlier papers [14, 42–47] with smaller statistics, within the limits 1.15 to 1.5. We can see that the agreement with the power law function do exist, and in a wider range of fluxes (10^{-1}–5×10^3 pfu) than it has been possible to obtain previously.

Time Dependence

We have calculated a correlation between the monthly mean number of flares with importance ≥M1, ≥M2, …, and so on up to ≥X3 and the number of all proton enhancements. The correlation coefficient ρ turned out to be maximal for flares ≥M5, and it is equal

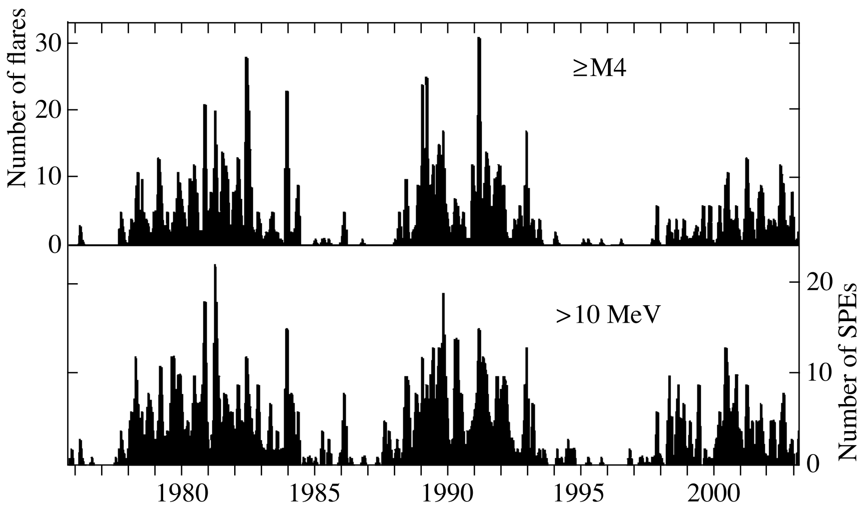

Fig. 4. Time variations of monthly mean monthly numbers of flares with importance ≥M4 and solar proton events (> 10 MeV) in the period 1975–2003.

to 0.743. The value of corresponding coefficient for correlation with the sunspot number is substantially less (ρ = 0.65). The similarity in the behavior of the numbers of major (≥M5) flares and proton events is well seen in Fig. 4.

For year averaged values the correlation coefficients are higher [32]. The best linear correlation (with coefficient ρ = 0.933) takes place here for ≥M4 flares (Fig. 5). One can see that the linear regression is sufficiently good only for periods with a large number of flares. In reality, the following power law function $N_{SPE} = (0.79 \pm 0.07) N_{\geq M5}^{0.82 \pm 0.06}$ better fits the data (ρ = 0.947).

Thus, the study of the long-term time behavior shows that the number of X-ray flares with importance

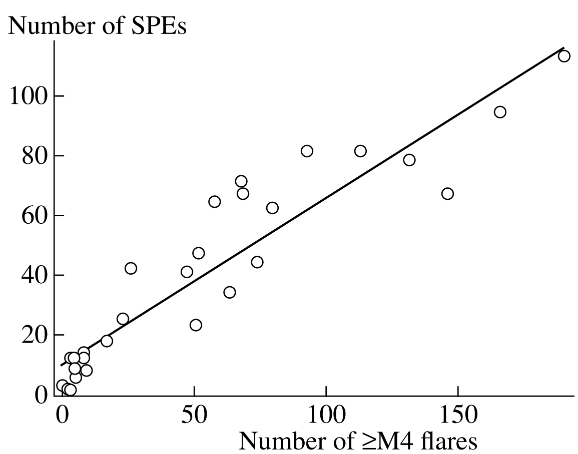

Fig. 5. The relationship of year averaged numbers of solar proton events and X-ray flares with importance ≥M4 in the period 1976–2002. The straight line corresponds to linear regression.

≥M4–M5 can be used as an index of solar activity that determines the proton productivity of the Sun [30, 32].

Averaged Behavior of Proton Fluxes after Flares

Using the method of superposed epoch analysis we have averaged the time profiles of proton fluxes measured onboard the *IMP-8* (Fig. 6) for several samples of flares. The hour of the beginning of the X-ray flare was taken as a zero hour. Events were selected according to flare characteristics. The only restriction was imposed on cosmic ray data: no gaps in data series. The upper panel presents 42 averaged periods of western (W0–W90) flares ≥M5. Immediately after these flares a rapid growth of the proton flux begins, up to ≈400 pfu and ≈80 pfu for energies >10 MeV and > 100 MeV, respectively. For the middle panel of the figure we have chosen also western but much weaker flares in the range C1–M1 (939 events). Here the effect is much less pronounced: variations of the averaged flux become observable only in three hours after a flare, and they do not exceed 10 pfu and 1.5 pfu for energies > 10 MeV and > 100 MeV, respectively. The third sample (the bottom panel) consists of 19 strong (≥M5) eastern flares (E0–E70). There are no clear variations in the averaged flux behavior for energies > 100 MeV, while the flux of > 10 MeV protons increases gradually and rather insignificantly (by less than 2 pfu).

Notice that in all samples the selected enhancements develop on a substantially increased proton background created by preceding proton events. The fact that strong flares and proton enhancements occur in series is a serious problem when the method of superposed epoch analysis is used and such plots are constructed. It is because of this that we cannot use the periods with gaps (even short) in the proton data.

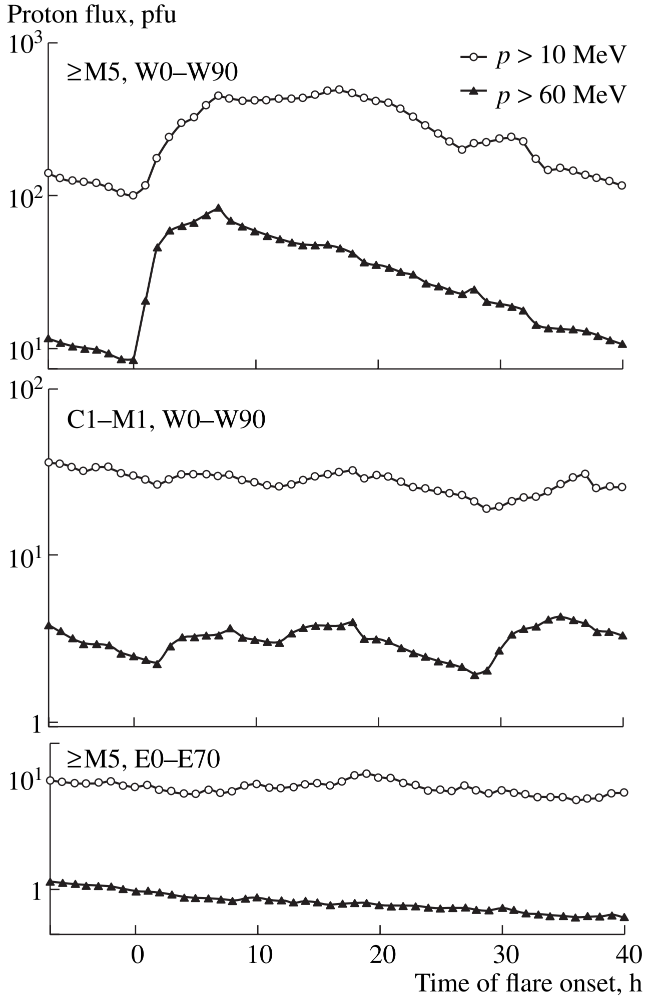

Fig. 6. Time characteristics of the fluxes of protons with energy >10 MeV and > 100 MeV averaged by the superposed epoch method after X-ray flares of various types.

Thus, we see that the averaged increase of the proton flux after an arbitrary strong flare is very large and considerably exceeds the threshold of a radiation storm of the second class according to classification of NOAA/SEC. The effect after weak and/or eastern flares is substantially (at least by a factor of 10) less.

Intensity and Heliolongitude of Associated Flares

The figures presented above show the characteristics of a proton event to be dependent both on intensity and on heliolongitude of its solar source. The heliolongitude dependence is well known for GLEs (for example, [48]), but it also exists for lower energies, in particular, for > 10 MeV protons [16, 30, 49]. We see in Fig. 7 that proton events (determined here for the energy > 10 MeV) are rare for the most eastern flares, and they are completely absent in the left lower corner of the figure. On the contrary, for sufficiently strong western flares the accompanying protons are a standard situation. For the

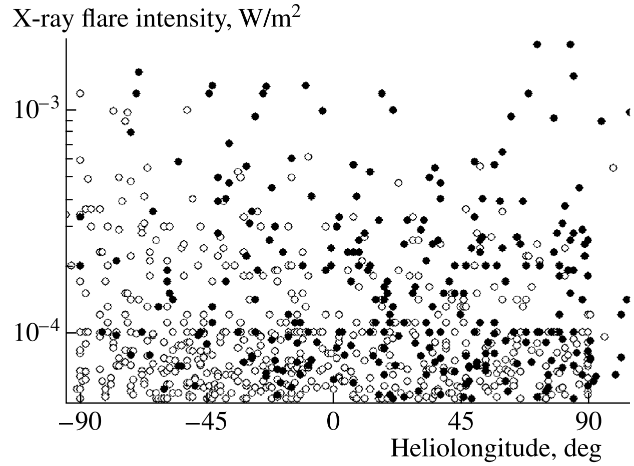

Fig. 7. Power and longitude distributions of the flares of importance ≥M5 with protons (solid circles) and without protons (empty circles).

strongest flares this can be applied to central flares too, since all ≥X7 flares with heliolongitude from E45 to the western limb and further are accompanied by proton enhancements.

Flare Intensity and the Probability of a Proton Event

Here and in the further analysis we use the data about associated flares for those 617 events whose reference seems to be sufficiently reliable for us. We have calculated the fraction of flares related to proton enhancements for the flares with an X-ray importance exceeding a given threshold (Fig. 8). Only western and central (more western than E20) flares were used.

An arbitrary X-ray flare has small chances (< 0.4%) to be accompanied by protons. Though, it is worthwhile to note that the true probability most likely would appear higher, if we were able to increase the number of reliable identifications. The fraction of proton flares becomes substantial beginning from the interval C3–M1. Every fourth flare with importance ≥M3 gives protons (and, if one does not take care of reference quality, even every third flare). Beginning from flares ≥X1, the probability of ground-level enhancements becomes significant. All eight suitably located flares with importance ≥X10 were accompanied by proton enhancements not only for energies > 10 MeV, but for > 100 MeV as well, and most of them turned out to be GLEs. Only for two of these eight flares the maximum flux of protons with energies > 10 MeV was lower than 100 pfu (the minimum value equaled 30 pfu), in all other cases it was about 1000 pfu or > 1000 pfu.

Additional analysis shows that all 14 flares ≥X6.5 with more western location than E20 gave a large amount of protons (≥30 pfu), nine of them were accompanied by GLEs. If one goes from the strongest flares to weaker flares, the first exception appears at the level of X6.2. It is the eastern (N16E09) flare on December 13,

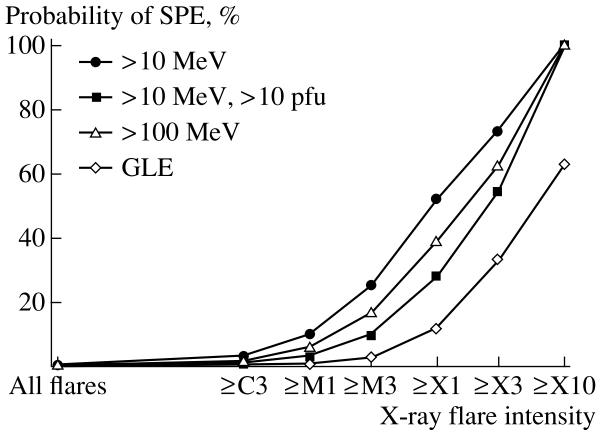

Fig. 8. The probability to detect proton events of different types versus the power of associated X-ray flares.

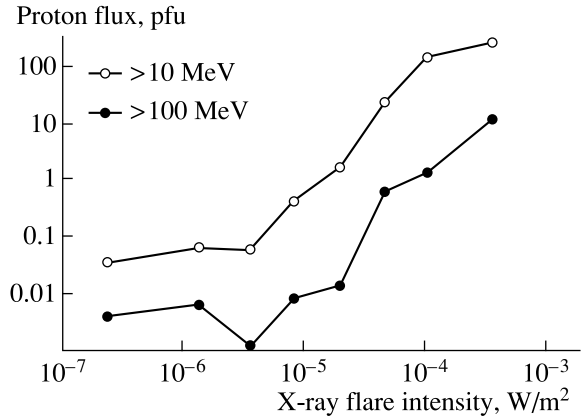

Fig. 9. The mean intensity of a proton enhancement which can be observed after an arbitrary flare of a given power.

2001. Among 24 flares with importance >X5 all but four flares were proton flares. There are grounds to believe that in these few exceptional events protons were accelerated, but did not reach the Earth due to various reasons.

Flare Intensity and SPE Values

We divided all flares according to their maximum intensity in logarithmically equal intervals, and the mean value of proton enhancement was calculated for each interval (Fig. 9). In this case, no previous filtering was made for flares, and we used all flares together (proton and non-proton flares, western, eastern, and flares without optical reference). Nevertheless, averaged fluxes of protons turned out to be sufficiently high. After any flare with importance of about M5 we observed, on the average, a radiation storm, and a radiation storm of the second class (according to NOAA classification) after a flare ≥X1.

Let us consider now similar relationship only for the proton flares which are reliably identified. In order to reduce the possible influence of heliolongitude of a source (which will be discussed below), we took for Fig. 10 only flares in a relatively narrow interval of longitudes W15–W75. In the first approximation the intensity of an X-ray flare is related to the values of associated proton enhancement by power law functions. We obtained for these functions $I_p(>10\ \mathrm{MeV}) = (4.8 \pm 1.3) \times 10^7 I_x^{1.14 \pm 0.14}$ and $I_p(>100\ \mathrm{MeV}) = (2.6 \pm 1.1) \times 10^6 I_x^{1.19 \pm 0.22}$, where the X-ray flux I_x and proton flux I_p are measured in W/m^2 and pfu, respectively.

Heliolongitude Dependence

Figure 11 presents the longitude distribution of proton flares, the number of which was calculated for each 15-degree interval of heliolongitudes and for three energy ranges. All well referenced proton events were used for the energy > 10 MeV, all GLEs and all events with a flux of > 0.1 pfu for the energy > 100 MeV were taken. In the most western interval all behind-the-limb sources are collected. For the majority of these events (they turned out to be rather numerous) heliolongitude was unknown. We assumed for this interval that the number of events $n(\varphi)$ decreases linearly with longitude from the maximum value at 90° W (equal to the number of events in the interval W75–W90) down to zero at the limiting longitude φ_u. The longitude φ_u was defined so that the integral $\int_{90}^{\varphi_u} n(\varphi)d\varphi$ would be equal to the total number of behind-the-limb proton sources.

The dependence of the number of events on the heliolongitude of sources is observed in all energy ranges. For ground-level proton enhancements the longitude E30 is limiting, not a single more eastern GLE source

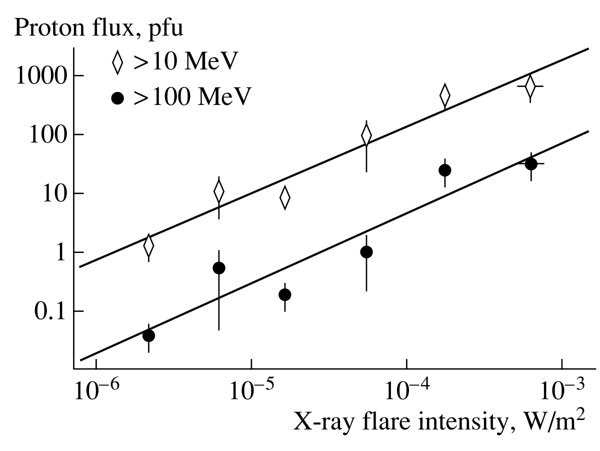

Fig. 10. The intensity of a proton enhancement versus the power of an associated X-ray flare. Straight lines correspond to power law fits.

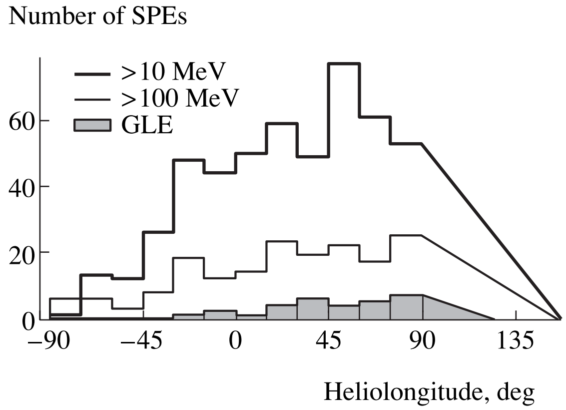

Fig. 11. Heliolongitude distribution of the flares associated with proton events of various types.

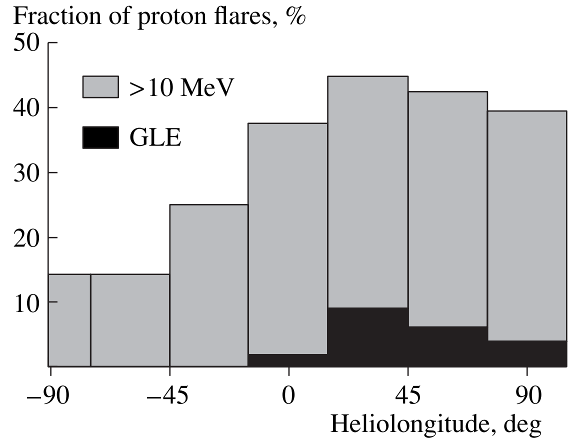

Fig. 12. Heliolongitude distribution of the fraction of proton flares among the flares with X-ray importance M8–X3.

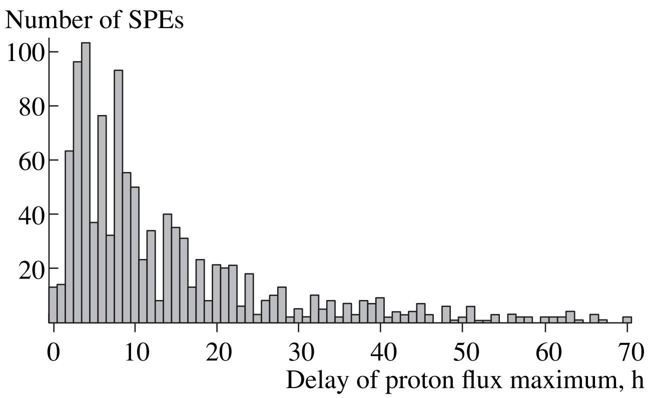

Fig. 13. Distribution of time delays of the maximum of proton (> 10 MeV) enhancement relative to the time of onset of an associated X-ray flare.

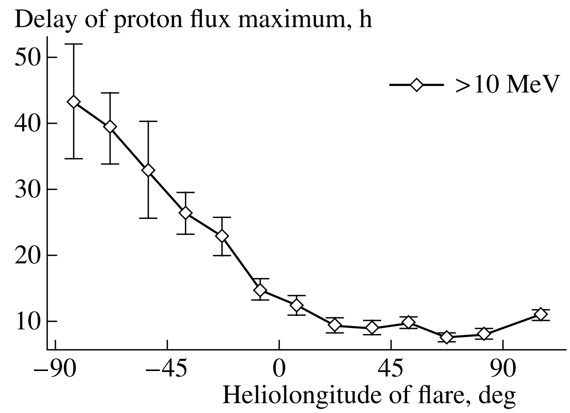

Fig. 14. Time delay of the maximum of a proton enhancement versus the longitude of an associated flare.

was observed. In the ranges > 100 MeV and > 10 MeV such sources were repeatedly observed, but the longitude E30 is singular for them too. The numbers of sources to the east and to the west of this boundary are essentially different. The interval of longitudes E30–W120 contains the bulk of all proton flares (97% for GLEs, 96% for > 100 MeV, and 94% for > 10 MeV). Inside this interval of longitudes the changes of $n(\varphi)$ are not so large, though its values are higher for longitudes W30–W105 than for more eastern longitudes. This is especially clearly seen for GLEs, though it is apparently not by chance that the maximum of $n(\varphi)$ distribution for > 10 MeV is located in the interval W45–W60, i.e., exactly at the place from which the field line of the interplanetary magnetic field connecting the Sun and the Earth goes out in the quiet solar wind. If one takes into account the real scatter of the solar wind velocities, this line can go out from a wide range of longitudes W25–W75, which covers the largest part of the range of longitudes of the solar proton sources contributing to Fig. 9. Naturally, protons can be transferred to the terrestrial field lines from adjacent longitude intervals, especially from the more western ones.

Let us try to estimate the dependence of the probability of a proton event on the source heliolongitude. In order to reduce the flare intensity effect, we take not all flares, but only those in the range M8–X3, and for each 30-degree interval we calculate, what fraction of these flares was accompanied by proton enhancements (Fig. 12). After a western flare we have much more considerable chances to detect protons near the Earth. This is valid both for relativistic and for relatively low-energy (> 10 MeV) protons, however, in the latter case the longitude distribution of sources is much wider than for GLEs.

Table

Flare characteristic	Flares associated with proton events	Flares ≥ M6 without protons
Number	409	162
Power, W m^{-2}	$(1.16 \pm 0.11) \times 10^{-4}$	$(1.16 \pm 0.06) \times 10^{-4}$
Duration, min	80 ± 4	57 ± 4
Duration of the phase of growth, min	21.5 ± 1.4	15.0 ± 1.9
Heliolongitude, deg	37.5 ± 1.5	29.7 ± 2.4
Difference $\Delta\lambda$ of the Earth and flare, deg	17.5 ± 0.4	19.4 ± 0.7
Temperature, 10^6 K	17.7 ± 0.4	19.9 ± 0.3
Loop length, 10^3 km	37.9 ± 2.0	22.9 ± 1.4
Impulsiveness, 10^6 W m^{-2} min^{-1}	13.7 ± 1.7	19.2 ± 2.2

The Delay of a Proton Enhancement with Respect to a Flare

Figure 13 presents the distribution of the time t_{10} of delay of the proton enhancement (> 10 MeV) maximum relative to the flare instant.

The main maximum of this distribution is observed at a delay of 3–4 h, but other groups of events with substantially longer times of delay are also seen. The wide distribution of t_{10} is caused primarily by different heliolongitude location of solar sources, as is demonstrated by Fig. 14 for which the values of t_{10} were averaged over different longitude intervals.

Protons from the zone W60–W90 arrive first. Here, the longitude W105 is assigned arbitrarily to all behind-the-limb flares, and they have approximately the same delay as in the zone W0–W60. The rapid increase of delay is observed for eastern flares when one goes from the central meridian. For almost a half (48.3%) of eastern flares the delay exceeded 20 h, while for all western flares (W0–W90) the fraction of such delays was < 8%. But even among the proton enhancements associated with the most suitable longitudes there is a small part of events with long delays.

Let us consider the heliolongitude zone W35–W85 corresponding to the shortest averaged time of delay. We exclude the events with gaps in proton data near the maximum. Among the remaining 72 events in this zone only five events had delays of > 16 h. In addition to the longitude of a source, its heliolatitude λ could also influence the time delay. More exactly, the effect should depend on the difference between latitudes of the source and the Earth (λ_E), i.e., on the quantity $\Delta\lambda = abs(\lambda - \lambda_E)$. Indeed, all five events with long delays in this longitude zone corresponded to $\Delta\lambda > 20°$. Not a single long delay was observed in 38 events with $\Delta\lambda < 20°$. Apparently, in most cases (at least for western flares) it may be said that the time delay of the maximum flux corresponds to a certain effective diffusion coefficient that characterizes propagation of particles from the Sun to the Earth. In the case of small time t_{10} this diffusion proceeds preferentially along the field, while in case of large time delays the role played by diffusion across the filed is considerable. In those rare cases when neither longitude nor latitude distances of a source can explain long delays, it is appropriate to hypothesize some unusual interplanetary conditions near the Earth or between the Earth and the Sun.

6. DEPENDENCE OF PROTON EVENTS ON OTHER CHARACTERISTICS OF FLARES

We have already established that the stronger flare the higher probability for it to be a proton flare, and almost all sufficiently strong flares are proton flares. In addition, the probability and time behavior of a proton enhancement strongly depend on the source longitude. Let us now examine other characteristics of X-ray flares. Some of them (for example, the flare duration dt_X and the duration of the growth phase of X-ray flux) are given in catalogs of the *GOES* group. The maximum temperature and the length of X-ray loops were calculated for a great number of events (about 1500) in papers [27, 28]. We have also calculated for each flare its impulsiveness (maximum power of X-ray emission divided by the growth phase duration), the characteristic introduced in [50]. The group of proton flares included 409 reliably identified flares in the range of longitudes from E20 to W90. Their mean importance turned out to be ≥X1.2. As a control group we take the flares in the same longitude belt and of approximately the same intensity, but unrelated to proton enhancements. Such flares turned out to be flares ≥M6. The mean characteristics of the basic and control groups are given in Table.

It is obvious that the distinctions between flares with and without protons are essential, and they are far beyond the limits of statistical errors. We see that proton flares are longer and reach their maximums in longer time. They are less impulsive, less remote from our field line both in longitude and latitude, and they have considerably longer and colder X-ray loops.

Flare Duration and the Probability of a Proton Event

On the average, a proton flare has the duration dt_X of 1 h 19 min, which is by 40% longer than an average flare in the control non-proton group. In order to see more clearly the relationship between a proton event probability and the X-ray flare duration, we restricted ourselves to the flares with heliolatitudes between E20 and W90, dividing them in three groups with different intensity (< M6, from M6 to X3, and ≥X3). Inside each of these groups we calculated the fraction of proton flares among the flares with varying duration: ≤30 min, 31–60 min, 61–90 min, and > 90 min. The results (mean probabilities with statistical errors) are presented in Fig. 15.

For the group of the weakest flares the statistical error turned out to be small (it is less than the points' sizes in the figure). In this group (< M6) and in the group (M6–X3) one can clearly trace the dependence on the flare duration: the probability of a proton event quickly increases with increasing duration. This dependence is especially strong for the group of the weakest flares, where the probability increases almost by a factor of 20. On the contrary, for the strongest flares (>X3) the probability (not given in the figure) turned out to be high in all intervals of dt_X and at the first glance to be independent of it. Admittedly, one should make here a couple of remarks. First, for this (least numerous) group of flares the statistical accuracy is not sufficient; and, second, the strong flares often last much longer than the formally determined time dt_X (the time of drop down to 1/4 of maximum).

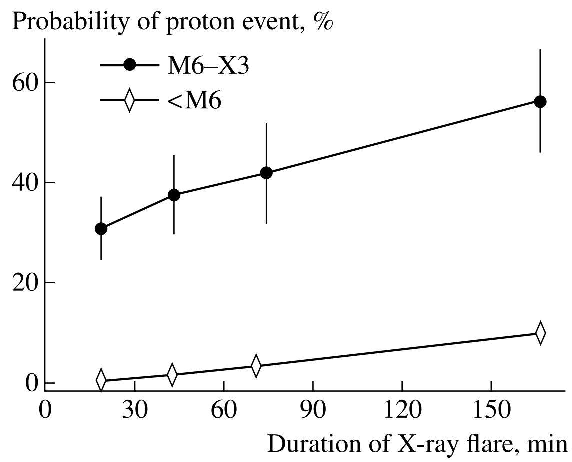

Fig. 15. The fraction of proton (> 10 MeV) flares among the flares of various powers versus the X-ray flare duration.

Temperature and the Length of X-Ray Loop.

In order to understand better the relationship between the probability of a proton enhancement with a flare temperature T_m and the X-ray loop length L, we considered the same groups of flares (< M6, from M6 to X3, and ≥X3 for longitudes E20–W90), as in the previous paragraph. Since the quantities T_m and L do not almost correlate with each other [28], one can assume them to be independent parameters and study the relationship with them simultaneously. The group ≥X3 happened to include only 24 events with calculated values of T_m and L. Since almost all of them were proton events, we did not study the group in detail. Two other groups with less powerful flares we divided into subgroups in accordance with the values of T_m and L so that each group would include approximately equal numbers of flares. For the flares from M6 to X3 we isolated 9 subgroups, while the flares < M6 with which much lower number of proton events was associated were divided in 4 subgroups.

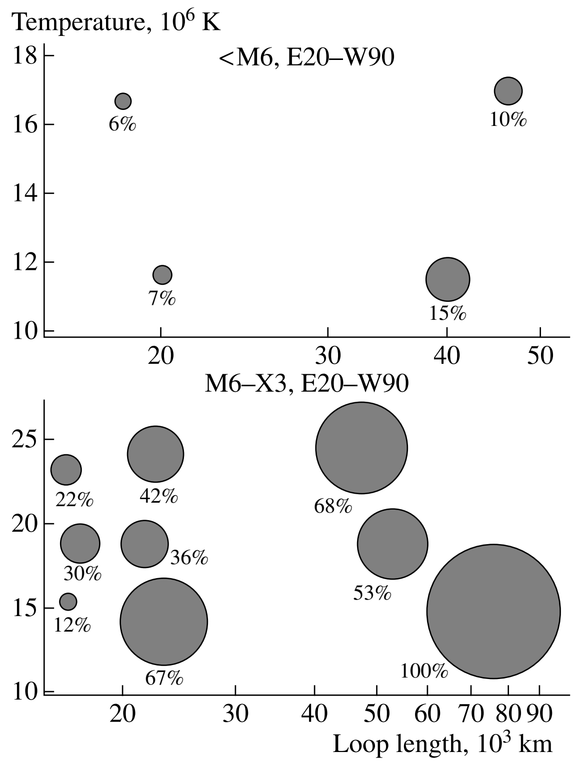

Fig. 16. The probability of proton events after flares with different maximum temperatures and the X-ray loop lengths. The size of circles corresponds to the fraction of proton flares among all flares with given properties.

One can see in Fig. 16 how the probability of proton events depends on temperature and the loop length. For both groups and all ranges of temperature the fraction of proton flares increases with increasing length of an X-ray loop. Each of 21 flares >M6 in the interval E20–W90 with a loop length of > 60000 km was accompanied by a proton enhancement. The situation with the temperature dependence is more complicated (at least in the group M6–X3). Here, both the highest and the lowest probabilities of proton events are associated with low temperatures of flares. At the temperature $<17 \times 10^6$ K and the loop length < 19000 km it is only

12%, while for the temperature > 21×10^6 K and the loop length > 28000 km it equals 100% (all 13 flares in this subgroup turned out to be proton flares). At the same time, if the loops are sufficiently long and the flares are sufficiently strong, the fraction of proton events is large even for high temperatures.

Gamma-Flares and Proton Enhancements

The solar flares in which gamma rays are observed together with X-ray emission are especially important for studying the proton events. In these cases we have a direct proof that protons accelerated to considerably high energies were present on the Sun. There is no necessity to substantiate the proton character of such flares, and one can immediately pass to comparison of their features with characteristics of proton events. Unfortunately, the measurements of gamma-rays were carried out only for a small number of flares. There are only 67 events with gamma-ray lines in our database [51], 37 of them were accompanied by proton enhancements. If one does not consider the most eastern flares, then, according to near-Earth observations, 26 out of 37 flares in the longitude range E20–W90 turned out to be proton flares, and in 6 more cases protons were observed, but we were not sure to associate them with precisely these flares. Only in 5 cases there were no protons near the Earth. We compared mean characteristics of these five events with characteristics of 26 proton gamma-ray flares and found them to be substantially inferior in intensity (1.7 ± 0.6 versus $4.0 \pm 0.9 \times 10^{-4}$ W m^{-2}) and still more inferior in duration (42 ± 9 min instead of 125 ± 25 min). In addition, they had mainly more eastern position, being located around the central meridian. The greatest surprise is the flare X3.5/3B, the strongest among these 5 flares. Having occurred on August 14, 1989, it was accompanied by significant emission in gamma-ray lines, in addition, it had a favorable location at W60. It well may be that the absence of protons in this case is caused by two interplanetary shock waves which reached the Earth in first six hours after the flare. These shock waves and subsequent amplification of the IMF strength up to 32 nT could shield the Earth from the proton source. In all 16 cases, when the flux in gamma-ray lines exceeded 10 photons cm^{-2} s^{-1}, protons were observed near the Earth after gamma-flares.

Effect of Interplanetary Propagation

So far we almost did not touch the issues concerning the escape of particles into the interplanetary space and their propagation there. This was the case not because these issues were considered as having small importance. On the contrary, we are sure that the peculiarities of interplanetary propagation of solar particles have a substantial effect on proton flux observed near the Earth and sometimes even can make such observations impossible. Interplanetary propagation of solar particles in connection with characteristics of near-Earth proton events is a vast topic, and it requires a separate comprehensive consideration. Here we restrict ourselves to only one example. Let us take sufficiently strong western flares (≥M6, W0–W75). Immediately after such flares (within the next 10 h) in 17 cases the shock waves arrived at the Earth (naturally, related to some preceding flares rather than to these events). Only for two of these 17 events (<12%) proton enhancements were detected near the Earth with a maximum delayed by less than 10 h after the flare. In 234 events, when no shock waves arrived at the Earth in the next 15 h after flares, proton enhancements rapidly reaching their maximums were recorded 67 times (about 29%). One can assume that interplanetary shock waves (and, more generally, any IMF disturbances) moving to the Earth at the same time when accelerated charged particles propagate from the Sun prevent proton events from rapid developing, and sometimes (as we could see in the example of a gamma-ray flare in August 1989) they even impede the very detection of events. It is clear that the effect of the interplanetary medium state on characteristics of proton enhancements is much more diverse than it follows from the example given above, but in any case this effect makes serious troubles when studying the relationship between proton events and parameters of their solar sources. We believe that the major part of difficulties with which we encountered in this work could be caused by interplanetary factors and the problem of particle propagation.

7. CONCLUSIONS

We have succeeded in isolating > 1100 protons enhancements observed near the Earth (and sometimes on the Earth) for 28 years of X-ray observations of the Sun. These experimental data form a firm basis for studying possible relationships between proton events and solar flares. Even the simplest analysis shows that such relationships can be easily found both on the long-term scale for time-averaged characteristics and between separate events (solar and near-terrestrial).

There is a sufficiently close correlation between monthly and yearly averaged numbers of proton events and major (>M5) flares. In the fluxes of protons with energies > 10 MeV and > 100 MeV averaged by the superposed epoch method after strong flares one observes a substantial increase whose features essentially depend on the importance of an X-ray flare and its location on the Sun.

The most part of isolated proton events can be associated with particular X-ray flares. The analysis of such associated events shows that the probability of a proton event and its intensity strongly depend on the flare power and its heliolongitude. In the first place the duration and the time profile shape of a proton enhancement are longitude-dependent. We have found no facts contradicting to the hypothesis that acceleration of protons takes place at the same place and at the same time as the X-ray flare.

If one succeeds in some way to exclude the strong influence of power and heliolongitude, it is seen that the features of proton events are also related to other characteristics of X-ray flares. The probability of a proton event increases significantly with increasing duration of flares, which is especially true for the flares of relatively small importance. Proton enhancements are more probable after flares with lesser impulsiveness in which the X-ray maximum is reached later. A relationship emerges between the probability of a proton enhancement and temperature and the length of flares' X-ray loops. Other things being equal, protons appear more frequently after relatively cold flares with a large length of X-ray loops. There exist certain combinations of characteristics of a flare at which it is necessarily accompanied by a proton enhancement.

We believe that the regularities found above can be used for construction of prognostic models allowing one to calculate the probability of a proton event, its delay, and expected proton flux on the basis of observed characteristics of X-ray flares.

ACKNOWLEDGMENTS

The work is carried out as a part of the Russian–Greek research collaboration with a partial support of the Russian Foundation for Basic Research (project 04-02-16763) and the ENTER fund (2003 70/4/6890). We thank E.A. Eroshenko, M.A. Lifshits, and L.I. Miroshnichenko for their assistance in doing this research.

REFERENCES

1. Forbush, S.E., Three Unusual Cosmic-Ray Intensity Increases due to Charged Particles from the Sun, *Phys. Rev.*, 1946, vol. 70, pp. 771–772.
2. Shea, M.A. and Smart, D.F., A Summary of Major Solar Proton Events, *Solar Phys.*, 1990, vol. 127, pp. 297–320.
3. Gosling, J.T., The Solar Flare Myth, *J. Geophys. Res.*, 1993, vol. 98, no. A11, pp. 18937–18949.
4. Reames, D.V., Solar Energetic Particles: A Paradigm Shift, *Revs. Geophys. Suppl.,* 1995, vol. 33, pp. 585–589.
5. Hudson, H.S., Solar Flares: No "Myth", *EOS Transactions, AGU*, 1995, vol. 76, no. 41, pp. 405–406.
6. Hudson, H.S., Haisch, B.M., and Strong, K.T., Comment on "The Solar Flare Myth", *J. Geophys. Res.*, 1995, vol. 100, no. A3, pp. 3473–3477.
7. Simnett, G.M., A New Concept for Solar Flares, in *Solar Variability as an Input to the Earth's Environment. International Solar Cycle Studies (ISCS) Symposium*, Wilson, A., Ed., ESA SP-535, Noordwijk: ESA Publications Division, 2003, ISBN 92-9092-845-X, pp. 613–618.
8. Axford, W.L., Anisotropic Diffusion of Solar Cosmic Rays, *Planet. Space Sci.*, 1965, vol. 13, pp. 1301–1309.
9. Krimigis, S.M., Interplanetary Diffusion Model for the Time Behavior of Intensity in a Solar Cosmic Ray Event, *J. Geophys. Res.*, 1965, vol. 70, no. 13, pp. 2943–2960.
10. Burlaga, L., Anisotropic Diffusion of Solar Cosmic Rays, *J. Geophys. Res.*, 1967, vol. 72, no. 17, pp. 4449–4466.
11. Dorman, L.I. and Miroshnichenko, L.I., *Solnechnye kosmicheskie luchi* (Solar Cosmic Rays), Moscow: Fizmatgiz, 1968.
12. Jokipii, J.R., Propagation of Cosmic Rays in the Solar Wind, *Rev. Geophys. Space Phys.*, 1971, vol. 9, no. 1, pp. 27–87.
13. Gombosi, T.I. and Owens, A.J., Numerical Study of Solar Flare Particle Propagation in the Heliosphere, *Adv. Space Res.*, 1981, vol. 1, no. 3, pp. 115–119.
14. Ma Sung, L.S., van Hollebeke, M.A.I., and McDonald, F.B., Propagation Characteristics of Solar Flare Particles, *Proc. 14th ICRC*, 1975, vol. 5, pp. 1767–1772.
15. Richter, A.K., Verigin, M.I., Kurt, V.G., *et al.*, The 3 January 1978 Interplanetary Shock Event as Observed by Energetic Particle, Plasma, and Magnetic Field Devices on Board of *HELIOS-1, HELIOS-2*, and *PROGNOZ-6*, *J. Geophys. Res,* 1981, vol. 50, pp. 101–109.
16. Cane, H.V., Reames, D.V., and von Rosenvinge, T.T., The Role of Interplanetary Shocks in the Longitude Distribution of Solar Energetic Particles, *J. Geophys. Res.*, 1988, vol. 93, no. A9, pp. 9555–9567.
17. Ruffolo, D., Transport and Acceleration of Energetic Charged Particles Near an Oblique Shock, *Astrophys. J.*, 1999, vol. 515, no. 2, pp. 787–800.
18. Berezhko, E.G., Petukhov, S.I., and Taneev, S.N., Acceleration of Charged Particles by Shock Waves in the Solar Corona, *Izv. RAN, Ser. Fiz.*, 2001, vol. 64, no. 3, pp. 339–342.
19. Miroshnichenko, L.I., *Solar Cosmic Rays*, Kluwer Academic, 2001, p. 492.
20. Van Hollebeke, M.A., Wang, J.R., and McDonald, F.B., *A Catalogue of Solar Cosmic Ray Events*, NASA Goddard Space Flight Center, 1974, X-661-74-27.
21. Bazilevskaya, G.A., Sladkova, A.I., Fomichev, V.V., and Chertok, I.M., Possible Relationship between Fluxes of Solar Protons and Formation of Systems of After-Flare Coronal Loops, *Astron. Zh.*, 1990, vol. 67, no. 2, pp. 409–419.
22. Garcia, H.A., Greer, S., and Viereck, R., Predicting Solar Energetic Particle Events from Flare Temperatures, *Proc. of the 9th European Meeting on Solar Physics*, 1999, ESA SP-448, pp. 983–987.
23. Balch, C.C., Energy Analysis of Post Mass Ejection Solar Coronal X-Ray Loops, *PhD Thesis*, 1999, PB2002-101748; NCAR/CT-166.
24. Garcia, H.A., Temperature and Hard X-Ray Signatures for Energetic Proton Events, *Astrophys. J.*, 1994, vol. 420, pp. 422–432.
25. Garcia, H.A. and Kiplinger, A.L., Low-Temperature Soft X-Ray Flares, Spectrally Hardening Hard X-Ray Flares, and Energetic Interplanetary Protons, *Proc. of the 16th Intern. Workshop National Solar Obs. Sacramento Peak*, 1996, p. 91.
26. Garcia, H.A., Farnik, F., and Kiplinger, A.L., Hard X-Ray Spectroscopy for Proton Flare Prediction, *Proc. SPIE–Int. Soc. Opt. Eng.*, 1998, vol. 3442, pp. 210–216.
27. Garcia, H.A., Reconstructing the Thermal and Spatial Form of a Solar Flare from Scaling Laws and Soft X-Ray Measurements, *Astrophys. J.*, 1998, vol. 504, no. 1, pp. 1051–1066.

28. Garcia, H., Thermal-Spatial Analysis of Medium and Large Solar Flares, 1976 to 1996, *Astrophys. J. Suppl. Series*, 2000, vol. 27, pp. 189–210.
29. Kurt, V.G., Electrons and X-Ray Emission from Solar Flares, in *Basic Plasma Processes on the Sun*, Priest, E.R. and Krishan, V., Eds., The Netherlands: Kluwer Academic, Symp. 142, 1990, pp. 409–413.
30. Belov, A., Kurt, V., Gerontidou, M., and Mavromichalaki, H., Statistical Analysis of Solar Proton Events in Different Energy Channels, *Proc. 27th ICRC*, 2001, vol. 7, pp. 3465–3468.
31. Kurt, V.G., Mavromichalaki, H., and Gerontidou, M., Energy Dependence of the Solar Proton Events at 1 AU, *Proc. SOLMAG Magnetic Coupling of the Solar Atmosphere Euroconference and IAU Colloquium*, 2002, pp. 473–476.
32. Kurt, V., Belov, A., Mavromichalaki, H., and Gerontidou, M., Statistical Analysis of Solar Proton Events, *Ann. Geophys.*, 2004.
33. Livshits, M.A., Badalyan, O.G., and Belov, A.V., Common Features of Development of Powerful Long X-ray Solar Flares, *Astron. Zh.*, 2000, vol. 79, pp. 597–610.
34. Osokin, A.R., Belov, A.V., and Livshits, M.A., Solar Flares of Different Types and Their Influence on Formation of Disturbances in Interplanetary Medium, *Astron. Vestn.*, 2003, vol. 37, no. 1, pp. 1–11.
35. Burkepile, J.T. and St. Cyr, O.C., A Revised and Expanded Catalogue of Mass Ejections Observed by the Solar Maximum Mission Coronograph, *NCAR Technical Note*, 1993. NCAR/TN-369+STR, Boulder, Co.
36. Belov, A.V., Eroshenko, E.A., Oleneva, V.A., and Yanke, V.G., Relation of the Forbush Effects to the Interplanetary and Geomagnetic Parameters, *Proc. 27th ICRC*, 2001, vol. 9, pp. 3552–3555.
37. NOAA SESC Solar Proton Events: January 1976 – December 1997, Preliminary List, *Solar-Geophysical Data*, NOAA, NGDC, Boulder, Co, 1998, V. 641, Part II, pp. 30–34.
38. NOAA SEC Solar Proton Events, *Solar Geophysical Data*, NOAA, Boulder, Co., 2003.
39. Bazilevskaya, G.A., Vashenyuk, E.V., Ishkov, V.N., *et al.*, *Solnechnye protonnye sobytiya, katalog 1970–1979 gg, Pod redaktsiei Yu.I. Logacheva* (Solar Proton Events: Catalog for 1970–1979, Logachev, Yu.I., Ed.), Moscow: IZMIRAN, 1986.
40. Bazilevskaya, G.A., Vashenyuk, E.V., Ishkov, V.N., *et al.*, *Solnechnye protonnye sobytiya, katalog 1980–1986 gg, Pod redaktsiei Yu.I. Logacheva* (Solar proton Events: Catalog for 1980–1986, Logachev, Yu.I., Ed.), Moscow: Mezhvedomstvennyi geofizicheskii komitet pri prezidiume AN SSSR, 1990.
41. Sladkova, A.I., Bazilevskaya, G.A., Ishkov, V.N., *et al.*, *Catalogue of Solar Proton Events 1987–1996,* Logachev, Yu.I., *Ed.*, Mosk. Gos. Univ., 1998.
42. Cliver, E.W., Reames, D.V., Kahler, S.W., and Cane, H.V., Size Distribution of Solar Energetic Particle Events, *Proc. 22nd ICRC*, 1991, vol. 3, pp. 25–28.
43. Van Hollebeke, M.A., Ma Sung, L.S., and McDonald, F., The Variations of Solar Proton Energy Spectra and Size Distribution with Heliolongitude, *Solar Phys.*, 1975, vol. 41, pp. 189–223.
44. Mendoza, B., Melendez, R., Miroschnichenko, L.I., and Perez-Enriquez, R., Frequency Distributions of Solar Proton Events, *Proc. 25th ICRC*, 1997, vol. 1, pp. 81–84.
45. Nymmik, R.A., SEP Event Distribution Function as Inferred from Spaceborne Measurements and Lunar Rock Isotopic Data, *Proc. 26th ICRC*, 1999, vol. 6, pp. 268–271.
46. Goswami, J.N., McGuire, R.E., and Reedy, R.C., Solar Flare Protons and Alpha Particles during the Last Three Solar Cycles, *J. Geophys. Res.*, 1988, vol. 93, no. A7, pp. 7195–7205.
47. Gerontidou, M., Vassilaki, A., Mavromichalaki, H., and Kurt, V., Frequency Distributions of Solar Proton Events, *Proc. JASTP*, 2002, vol. 64, p. 489.
48. Shea, M.A., Solar Cosmic Rays, 1960–1989, *Proc. 21st ICRC*, 1990, vol. 12, pp. 196–204.
49. Bazilevskaya, G.A. and Sladkova, A.I., Azimuth Distribution and Escape of Accelerated Particles from the Solar Corona, *Geomagn. Aeron.*, 1986, vol. 26, no. 2, pp. 187–190.
50. Pearson, D.H., Nelson, R., Kojoian, G., and Seal, J., Impulsiveness and Energetic on Solar Flares with and without Type II Radio Bursts: A Comparison of Hard X-rays Characteristics for over 2500 Solar Flares, *Astrophys. J.*, 1989, vol. 336, pp. 1050–1058.
51. Vestrand, W.T., Chare, G.H., and Murphy, R.J., The Solar Maximum Mission Atlas of Gamma-Ray Flares, *Ap. J. Suppl. Series*, 1999, vol. 120, pp. 409–467.