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On the Correlation between Spectra of Solar Microwave Bursts and Proton Fluxes near the Earth

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Abstract—Studies of the extreme solar proton event of January 20, 2005 intensified the contest over of a long-standing problem: are solar cosmic rays arriving at the Earth accelerated by solar flares or by shocks preceding rapidly moving coronal mass ejections? Among the most important questions is the relationship between the energy spectra of the solar cosmic rays and the frequency spectra of flare microwave bursts. Some studies of previous solar-activity cycles have shown that such a relationship does exist, in particular, for protons with energies of tens of MeV. The present work analyzes this relation using data for 1987–2008. For flare events observed in the western half of the disk, there is a significant correlation between the index δ, which is equivalent to the power-law index of the integrated energy spectrum of 10–100 MeV protons detected near the Earth's orbit, and radio burst parameters such as a ratio of peak fluxes S at two frequencies (for example, at 9 and 15 GHz) and a microwave peak frequency f_m. Proton fluxes with hard (flat) energy spectra ($\delta \leq 1.5$) correspond to hard microwave frequency spectra ($S_9/S_{15} \leq 1$ and $f_m \geq 15$ GHz), while flares with soft radio spectra ($S_9/S_{15} \geq 1.5$ and $f_m \leq 5$ GHz) result in proton fluxes with soft (steep) energy spectra ($\delta \geq 1.5$–2). It is also shown that powerful high-frequency bursts with the hardest radio spectra ($f_m \approx 30$ GHz) can point at acceleration of significant proton fluxes in flares occurring in strong magnetic fields. These results argue that solar cosmic rays (or at least their initial impulses) are mainly accelerated in flares associated with impulsive and post-eruptive energy release, rather than in shocks driven by coronal mass ejections.

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1. INTRODUCTION

The acceleration of solar cosmic rays (SCRs) is among the most important and widely discussed questions whose answer remains unclear. There are two extreme points of view. In one, protons arriving at the Earth are accelerated directly in flares during the primary impulsive energy-release process at low altitudes above sunspots, and also during the prolonged post-eruptive energy release that occurs at high altitudes in the corona (see, for example, [1–7]). In the other point of view, SCR protons are accelerated in shocks moving ahead of rapidly moving coronal mass ejections (CMEs) [8–11]. There are a number of experimental and theoretical arguments supporting both these points of view [12–15].

Discussions on the origin of SCRs have intensified in recent years in connection with the extreme solar-proton event observed on January 20, 2005 (see, for example, the articles listed at http://creme96.nrl.navy.mil/20Jan05/, as well as [6, 16]). In particular, Grechnev et al. [6], based on the detailed analysis of various data, received essential arguments in favor of that protons of the main pulse of the SCR ground-level enhancement (GLE) were accelerated in the flare rather than in the CME-driven shock. They show that, rather than any parameters of the CME, the extreme features of this event appear to be related to some characteristics of the flare occurring in strong magnetic fields above sunspots, including a powerful, hard microwave burst with peak fluxes at 17 and 35 GHz $S > 80\,000$ sfu[1] and the peak frequency of the spectrum being $f_m \approx 30$ GHz. In addition, the temporal profile of the first powerful anisotropic GLE impulse corresponds in time and is similar in form to the profile of the high-energy (photon energies >60 MeV) pion gamma-ray emission excited by protons accelerated to energies >300 MeV in the flare (see also [17]).

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[1] 1 sfu (solar flux unit) = 10^{-22} W m^{-2} Hz^{-1}.

For proton events associated with flares occurring in the western half of the solar disk, numerous works have revealed sufficiently high correlations between proton fluxes of various energies detected near the Earth and the intensity of the flare emission in various ranges, in particular, such parameters as the peak and integrated fluxes of microwave bursts [18–21], soft X-ray fluxes [22, 23], and fluences of gamma-ray line emission at 4–7 MeV [24, 25]. However, the conclusion that these correlations indicate to the acceleration of solar cosmic rays in flares was questioned by Kahler [26]. He argued that the correlations mentioned above could be explained by the so-called "big flare syndrome." The latter means that any parameters (including those with no physical relations between them) reflecting the flare energetisc will correlate well. In the concept of SCR acceleration in shocks, it assumes that stronger flares are accompanied by more massive and rapid CMEs, and thus by stronger shocks that are able to accelerate greater numbers of particles to high energies. Correlations between finer quantitative parameters, such as those describing the spectra of the flare emission, and the energy spectra of SCRs may support a flare origin for SCRs. Close relations between parameters of this sort can hardly be explained by the "big flare syndrome."

A number of studies [25, 27–29] indicate correlations between parameters of the frequency spectra of microwave bursts, which reflect the energy spectra of the electrons accelerated in flares, and parameters of the energy spectra of protons with energy of tens MeV detected near the Earth. In particular, the western events of 1966–1986, i.e., of the 20th and 21st solar cycles, were examined in [28, 29]. In this case, the ratios of the peak fluxes of microwave bursts at near 9 and 15 GHz (S_9/S_{15}) and the peak frequency f_m were adopted as parameters of the radio spectrum, while the proton fluxes were characterized by the index δ of the power-law integrated energy spectrum, $J_E \propto E^{-\delta}$. As was expected for a flare origin of the SCRs, flares with hard radio spectra (i.e., with $S_9/S_{15} < 1$ and/or $f_m \geq 15$ GHz) were accompanied by proton fluxes with hard energy spectra ($\delta \leq 1.0$–1.5), whereas the proton fluxes with the softest energy spectra ($\delta \geq 2$) were associated with flares displaying soft microwave-burst spectra ($S_9/S_{15} > 1.5$ and/or $f_m \leq 5$ GHz).

The purpose of our present study is to verify these important correlations and relationships using new data obtained in 1987–2008, during the 22nd and 23rd solar-activity cycles. Our analysis supports a statistical relation between the spectra of solar microwave bursts and of protons detected near the Earth. In addition to the correlation between these spectra, we also analyze the relation between powerful high-frequency radio bursts at $f \approx 35$ GHz and the strongest proton events.

2. DATA AND PARAMETERS ANALYZED

There are fairly complete data on solar flares, radio bursts associated with flares, and the corresponding proton fluxes detected near the Earth for 1987–2008. Our analysis mainly considers the proton events contained in the 1987–1996 catalog of [30] and the NOAA list encompassing the entire period up to 2008 (see http://umbra.nascom.nasa.gov/SEP/seps.html). We also used time profiles of proton fluxes regularly detected near the Earth by the geostationary GOES satellites at energies of $E > 10$, 50, and 100 MeV (graphical files of these profiles for every three days can be found at http://www.swpc.noaa.gov/ftpmenu/warehouse.html). These data together with some additional information reveal distinct SCR enhancements exceeding $J_{10} \approx 5$ pfu[2] for the proton flux in the $E > 10$ MeV channel and detectable enhancements to $J_{100} \geq 0.03 - 0.05$ pfu above the background in the $E > 100$ MeV channel. In cases when distinct enhancements were detected in both the 10 MeV and 100 MeV channels, we examined some weaker events as well. All the peak proton fluxes considered were analyzed using the five-minute GOES data.

For further study, we chose proton events originating from flares occurring in the western half of the solar disk, within heliolongitudes W00–W90. It is well known that proton enhancements associated with such events and their relation to the flare radiation are not distorted strongly by heliolongitude effects of the SCR propagation. Among western near-limb events (W≈ 90°) we analysed only those events that did not display any explicit screening of the microwave emission. As an exception, we also included three strong GLEs originating with flares located slightly to the east of the central meridian,observed on October 19, 1989 (heliolongitude E10), August 24, 1998 (E07), and October 28, 2003 (E08).

Comparing the radio and proton spectra, we must minimize effects exerted on the SCR energy spectrum by the escape of particles from the acceleration region and their propagation in interplanetary space. Therefore, in addition to the limits imposed on the heliolongitudes, for more suitable comparison with spectra of particles accelerated in flares, we accepted the spectrum of the initial, almost freely propagating and frequently anisotropic proton impulse. In the time profiles of the western proton enhancements, this

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[2] The unit for measured proton fluxes is 1 pfu = 1 proton cm^{-2} s^{-1} sterad^{-1}.

impulse corresponds to either a rapid maximum (for $E > 10$ MeV, the time delay is within several hours relative to a flare), or fairly distinct steps with weak dispersions in the three energy channels $E > 10$, 50, and 100 MeV. We excluded very extended peaks in the profiles of the proton enhancements, as well as maxima that obviously coincided with the sudden commencements of geomagnetic storms, i.e., with interplanetary shocks arriving at the Earth. In these cases, the proton flux, in particular, the flux at 10–50 MeV, was significantly increased due to particles captured in the interplanetary disturbance. In addition, the geomagnetic storms that frequently follow such sudden commencements considerably change the measurement conditions for space and ground detectors of energetic particles. For these reasons, we excluded events that directly coincided with one or two sudden commencements, such as those of November 26, 2000; November 9–10, 2002; and May 29, 2003.

By analogy with [5], for each event, we determined the parameter $\log(J_{10}/J_{100})$, which characterizes the proton energy spectrum, where J_{10} and J_{100} are the peak proton fluxes at $E > 10$ and 100 MeV, respectively. It is obvious that this parameter is nearly equivalent to the index δ of the power-law integrated energy spectrum, $J_E \propto E^{-\delta}$, and we shall use δ to denote this parameter. We note again that this is by no means an instantaneous energy spectrum simultaneously detected in the various channels, but instead the spectrum of the peak proton fluxes, taking into account the spread in the arrival times of particles of various energies at the Earth.

To determine the parameters of the frequency spectra of microwave bursts associated with the the selected proton flares, we used in first instance the round-the-clock data of the RSTN world network of radio observatories at 1.4, 2.7, 5.0, 8.8 and 15.4 GHz, published in Solar-Geophysical Data (http://sgd.ngdc.noaa.gov/sgd/jsp/solarindex.jsp) and also available at ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SOLAR_RADIO/BURSTS/. Information on bursts at the higher frequencies 17, 35, and 80 GHz was obtained from corrected measurements by the Nobeyama radio polarimeter (see http://solar.nro.nao.ac.jp/norp/), which are not round-the-clock. We thoroughly examined the records for the selected events and refined the excess fluxes relative to the pre-flare levels that were automatically calculated by the software controlling the radio polarimeters. The 80 GHz fluxes measured from June 1999 to June 2005 were corrected, since they were progressively underestimated due to equipment degradation. In several extreme events recorded in the Nobeyama radio polarimeter data at 35 GHz, there are intervals spoiled by overloads due to extremely high fluxes. Each spoiled interval was replaced with the square root of the product of the time profiles at 17 and 80 GHz, while the scaling coefficients were found by joining the recovered curves with the starting and ending intervals recorded at 35 GHz without overloads.

There are two mechanisms responsible for microwave bursts: gyro-synchrotron emission of electrons accelerated in the flare and thermal bremsstrahlung of the flare plasma [31]. The flux density of thermal radiation rarely exceeds 100 sfu, and its spectrum is flat in the optically thin region (which is most probably relevant at 9 GHz and above). Thermal radiation is appreciable in weak radio bursts associated with large X-ray flares, whereas gyro-synchrotron radiation from accelerated electrons dominates in powerful microwave bursts. Therefore, the slope of the radio spectrum in the optically thin region (to the right of the spectral maximum f_m) is a relevant parameter describing the spectrum of accelerated electrons [31]. However, the statistical analysis of [19] shows that $f_m \approx 9 - 15$ GHz in most microwave bursts (in some cases, this can be attributed to the predominance of radiation from the tops of flare loops at frequencies below 15 GHz). Consequently, round-the-clock measurements carried out at 8.8 and 15.4 GHz frequently do not correspond to the optically thin region of the radio spectrum. The Nobeyama radio-polarimeter observations at 17, 35, and 80 GHz do not clarify the situation, since these observations are not round-the-clock and the f_m value or large-scale proton events can shift to higher frequencies, reaching 35 GHz and above (see also [6, 18]). Therefore, as was the case for the earlier studies [28, 29], we compare the energy spectrum of proton fluxes detected near the Earth with some other parameters of the microwave-burst spectrum, namely, the ratio of the peak flux densities S at $f = 8.8$ and 15.4 GHz, S_9/S_{15}, and the frequency f_m of the maximum flux density of the microwave radio emission. For the events observed at Nobeyama, we also used a third parameter: the ratio of the peak flux densities at $f = 17$ and 35 GHz, S_{17}/S_{35}.

It is clear that the ratios of the peak fluxes observed at these pairs of frequencies somehow characterize the same peak frequency f_m of the microwave bursts. The parameter S_9/S_{15} is attractive, since it can be easily determined using openly available data for most events and it describes well both the hard frequency spectrum ($S_9/S_{15} < 1$, $f_m \geq 15$ GHz) and the comparatively soft radio spectrum ($S_9/S_{15} > 1$, $f_m \leq 5$–9 GHz). This also is true to a lesser extent of S_{17}/S_{35}. Note that the peak frequency f_m depends on both the energy spectral index of the radiating

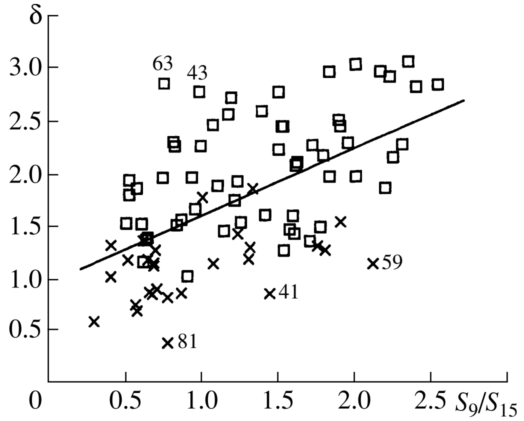

Fig. 1. Correlation between the ratio of the peak fluxes of the flare microwave bursts at 8.8 and 15.4 GHz (S_9/S_{15}) and the spectral index of solar proton fluxes ($\delta = \log(J_{10}/J_{100})$) determined near the Earth at $E > 10$ and 100 MeV. The plot includes proton events associated with flares observed in the western half of the disk during 1986–2008. The straight line corresponds to a linear regression fit. The events with ground-level enhancements (GLEs) of high-energetic particles are distinguished by crosses. The numbers indicate the following events (according to the Main Table): 41—July 14, 2000; 43—September 12, 2000; 59—December 26, 2001; 63—July 15, 2002; and 81—January 20, 2005.

electrons and other parameters, such as the magnetic field in the source, the number of electrons accelerated in the flare, and the angle between the magnetic field and the line of sight [31]. To a considerable degree, this explains the spread in the correlation between the indicated radio parameters and the proton energy-spectral index detected near the Earth. When different RSTN observatories gave different fluxes for a given frequency, we used the averaged flux for S. As a rule, we adopted one of the observed frequencies indicated above as f_m without any interpolation. Due to the lack of the data for 15.4 GHz, we did not analyze the western events observed January 2–3, 1988; November 8, 1988; June 18, 1989; and October 19, 1994.

Our main table of proton events, i.e., the SCR enhancements and corresponding flares whose spectra we compare, is presented at http://helios.izmiran.troitsk.ru/lars/Chertok/SEPs_radio/index.html, and is referred to further as the Main Table. Some additional illustrations omitted here can be found at this site. For each event, the Main Table indicates the number of an event; the date and time of the peak proton flux used to measure the fluxes in the $E > 10$ and 100 MeV channels and the energy-spectrum parameter $\log(J_{10}/J_{100})$; the maximum percentage of ground SCR enhancements [32] for GLE-accompanied events; the time of the microwave-burst maximum, and the class and coordinates of the flare that was the source of the proton event; the maximum sfu fluxes of microwave bursts detected at 8.8 and 15.4 GHz, and the ratio of these fluxes, S_9/S_{15}; the analogous Nobeyama data for 17 and 35 GHz; and, finally, the peak frequency of the microwave bursts f_m. The Main Table indicates the frequency f_m determined from the Nobeyama radio polarimeter multi-frequency records in parentheses. This frequency is determined as the vertex of a parabola passing through three points near the maximum of the radio spectrum detected at each time in $\log f - \log S$ coordinates (the table takes the highest f_m over the entire burst). It is impossible to calculate such refined f_m values for all the events in the Main Table, since the RSTN observations are limited to 15.4 GHz, and records accessible by Internet are available only for events observed after 2000. To keep the technique uniform, we did not attempt to derive f_m values via interpolation.

Note that the strong proton enhancement following the western flare of March 17, 1989 (time of maximum 17:35 UT, magnitude 2B/X6.5, and coordinates N33 W61) was exceptional, and it was excluded from the Main Table and our the further analysis. This enhancement displays an extremely soft proton-energy spectrum at tens of MeV: during the step in the growth phase and at the first maximum of $J_{10} \approx 170$–300 pfu, the proton flux at >100 MeV exceeds the background by not more than $J_{100} \approx 0.003$ pfu. This corresponds to a proton spectral index $\delta \geq 4.75$, which substantially exceeds the proton indices $\delta \approx 3.2$ for the softest western events. The most probable reason for this is that the event occurred in the decay phase of an extremely powerful geomagnetic storm with its minimum index $D_{\rm st} \approx -589$ nT observed on March 14, 1989.

3. CORRELATION BETWEEN S_9/S_{15} AND δ

Figure 1 presents the correlation between the parameters of the 10–100 MeV proton-energy spectrum detected near the Earth $\delta = \log(J_{10}/J_{100})$ and of the microwave-burst spectrum S_9/S_{15} determined for 86 events observed during 1987–2008. The GLE-accompanied cases, i.e., events displaying significant fluxes of high-energy protons with $E \approx 1$ GeV, are distinguished by crosses. Though the spread is large, there is a significant positive correlation between the parameters of the radio and proton spectra, with correlation coefficient $r \approx 0.55$. When the radio spectrum changes from hard to soft (S_9/S_{15} increases from 0.3 to 2.5), the proton spectrum near the Earth also displays a tendency to change from hard to soft (δ increases from 1.2 to 2.6, on average). Among the 34 proton events with the hardest energy spectra ($\delta \leq 1.5$), 24 events, or about 71%, are associated with flares of comparatively hard microwave-burst spectra ($S_9/S_{15} < 1.5$). On the other hand, 20 of the 28 proton events with the softest energy spectra ($\delta > 2$), also about 71%, correspond to soft microwave-burst spectra ($S_9/S_{15} \geq 1.5$). For the flare events, 26 of the 36 total (72%) microwave bursts with the hardest radio spectra ($S_9/S_{15} < 1$) were accompanied by proton fluxes with fairly hard spectra ($\delta < 1.75$), while 19 of 30 (63%) flares with soft radio microwave-burst spectra ($S_9/S_{15} \geq 1.5$) resulted in proton events with soft energy spectra ($\delta \geq 2$).

There are numerous reasons for the large spread in the events shown in the correlation diagram of Fig. 1. For microwave bursts, these include the properties of gyrosynchrotron microwave-burst emission discussed in Section 2, in particular, the dependence of the frequency spectra on the spectra of the radiating electrons, as well as other parameters, such as the magnetic field in the radiation region. In addition, there are some discrepancies between the peak radio flux measurements carried out by different observatories. The spread in the proton fluxes is probably determined primarily by conditions of the particle escape from the acceleration region and their subsequent propagation in the corona and interplanetary space.

Enhancements in proton fluxes detected near the Earth can be associated with both flares occurring in active regions and flare-like processes occurring during filament eruptions outside active regions. It is well known that such events are accompanied by proton fluxes with softer energy spectra and by comparatively weak microwave emission. For such radio bursts, the bremsstrahlung contribution can be significant.

Let us now consider several exceptional events, marked by numbers in Fig. 1. In the events of September 12, 2000 (43) and July 15, 2002 (63), very soft proton spectra ($\delta \approx 2.82$ and 2.9) were combined with fairly hard radio spectra ($S_9/S_{15} \approx 0.98$ and 0.75). The main reason for the soft proton spectrum (and the weakness of the microwave emission) in the event of September 12, 2000 is that this event is right associated with the eruption of a large filament outside an active region; the hardness of the radio spectrum has been caused by a significant thermal contribution. In addition, the source of this event was located at heliolongitude W09, fairly far from the optimum region launching open magnetic field lines arriving at the Earth. The effect of the heliolongitude softening of the proton spectra is apparently even more pronounced in the event of July 15, 2002, resulting from a flare at W01. The extended temporal profile of the proton flux, which is similar to those typical for eastern flares, supports this hypothesis. Nonmetering of these two exceptional events increases the correlation coefficient to $r \approx 0.60$.

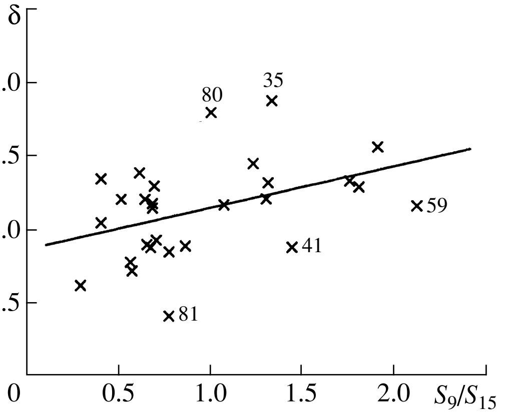

Fig. 2. Same as Fig. 1 for the GLE cases only. The numbers indicate the events: 35—May 6, 1998; 41—July 14, 2000; 59— December 26, 2001; 80—January 17, 2005; and 81—January 20, 2005.

Among proton enhancements with hard energy spectra under comparatively soft radio spectra, we first consider the GLE case observed on December 26, 2001 (59), which has $S_9/S_{15} \approx 2.11$ but small $\delta \approx 1.17$ at the ten of MeV range. According to [32], this GLE event was associated with the weakest soft X-ray burst (M7.1) over the three last solar-activity cycles. The microwave emission of this event was also quite moderate ($S_9 \approx 3800$ sfu and $S_{15} \approx 1800$ sfu), and had a comparatively low peak frequency $f_m \approx$ 7 GHz. This indicates that the microwaves were generated in comparatively weak magnetic fields. The well known Bastille Day event observed on July 14, 2000 (41) displayed a fairly hard proton spectrum ($\delta \approx 0.89$) under a comparatively soft radio spectrum ($S_9/S_{15} \approx 1.44$). This radio spectrum was probably associated with a pronounced post-eruptive energy release that appeared, in particular, through one of the most extended flare arcades in soft X-rays and the extreme ultraviolet [33]. The extreme GLE event on January 20, 2005 (81) displayed the hardest proton spectrum at tens of MeV, though the radio spectrum in the region 8.8–15.4 GHz was only moderately hard ($S_9/S_{15} \approx 0.77$); however, as was already mentioned, an extreme radio burst occurred at higher frequencies [6]. The reason for this discrepancy is the saturation of the RSTN radiometer at 15.4 GHz. According to the Nobeyama radio polarimeter data, $S_{9.4}/S_{17}$ reaches 0.54, and a recalculation to the RSTN frequencies yields $S_9/S_{15} = 0.52$.

Figure 1 shows that almost all the GLE cases (25 of 28, or 89%) displayed fairly hard proton spectra ($\delta < 1.5$) in the range of tens of MeV. It is especially important that, if we consider only GLE events as those with hardest proton spectra, there is also a correlation between the hardness of the microwave-burst spectrum and the hardness of the proton-energy

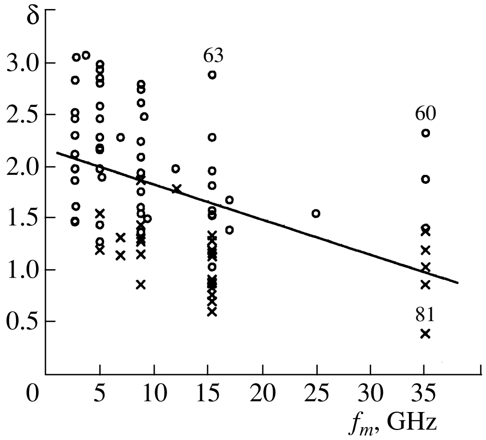

Fig. 3. Correlation between the peak frequency of microwave bursts f_m and the proton-spectrum parameter $\delta = \log(J_{10}/J_{100})$. The notations are the same as in Fig. 1. The numbers indicate the events: 60—February 20, 2002; 63—July 15, 2002; and 81—January 20, 2005.

spectrum detected near the Earth (see Fig. 2). However, this correlation for the GLE events is not as strong as the correlation for the proton events as a whole, since the parameter δ at tens of MeV varies over a smaller range for the GLE cases ($\delta \approx 0.4 - 1.9$) than for the proton events as a whole ($\delta \approx 0.4$ (Fig. 1)). For the GLE cases, the correlation coefficient between δ and S_9/S_{15} is $r \approx 0.41$. When S_9/S_{15} increases from 0.25 to 2, δ increases from 0.95 to 1.4, on average. Among the 17 GLE cases with the hardest radio spectra $S_9/S_{15} < 0.9$, the proton spectrum parameter was $\delta < 1.2$ in 13 cases (76%), while among eight GLE cases with comparatively soft radio spectra ($S_9/S_{15} > 1.25$), six events displayed proton fluxes with comparatively soft spectra $\delta \geq 1.2$ at tens of MeV.

The two GLEs with the softest proton spectra in the range of tens of MeV are distinguished in Fig. 2. The event of May 6, 1998 (35) had $\delta \approx 1.89$ at $S_9/S_{15} \approx 1.33$, while the event of January 17, 2005 (80) had $\delta \approx 1.81$ at $S_9/S_{15} \approx 1$. The ground SCR enhancements were among the weakest for these events (4 and 3.5%, respectively [32]), that probably excluded them from the total GLE ensemble. Figure 1 clearly shows that these combinations of S_9/S_{15} and δ correspond well to the mean relationship between such parameters for the entire ensemble of events considered, but differ from larger GLEs by softer proton spectra in the range of tens of MeV.

4. CORRELATION BETWEEN f_m AND δ

Following the earlier works [25, 27–29], we next analyze the relationship between the proton spectral index δ and the peak frequency of the microwave bursts f_m, which also specifies the energy spectrum of particles accelerated in flares [31]. Figure 3 presents the results of such an analysis for the considered ensemble of western proton events observed in 1987–2008, with GLE cases again marked by special symbols. We can again see a statistical correspondence between the hardness (softness) of the radio spectra and the hardness (softness) of the proton energy spectra detected near the Earth. When f_m increases from 3 to 35 GHz, the proton spectral index δ decreases nearly from 2.1 to 1.0, on average. The correlation coefficient between f_m and δ is $r \approx 0.46$. The spread of the points in Fig. 3 is mainly due to the same effects as those discussed in the preceding section. In addition, the available observations of many events provide no data for frequencies above 15.4 GHz, with this frequency thus representing a lower boundary for the peak frequency.

Among 31 events with soft radio spectra ($f_m \leq 5$ GHz), 21 (71%) displayed fairly soft proton-energy spectra ($\delta \geq 2$). At the same time, 20 of 30 (67%) events with hard radio spectra ($f_m \geq 15$ GHz) were accompanied by proton fluxes with hard energy spectra ($\delta < 1.5$). The event of July 15, 2002 (63) at a flare heliolatitude of W01 is again exceptional, combining a hard radio spectrum ($f_m \approx 15.4$ GHz) with one of the softest proton spectra ($\delta \approx 2.9$). We indicated possible reasons for this seeming inconsistency in the preceding section. Another exception is provided by the weak-intensity proton event of February 20, 2002 (60), which combines a hard radio spectrum ($f_m \approx 35$ GHz) and a fairly soft proton spectrum ($\delta \approx 2.34$) associated with a short-term impulsive flare. Such flares occurring at low altitudes in the corona are most often combined with hard radio spectra, but are accompanied by weak proton fluxes near the Earth. Neglecting these two exceptional events raises the correlation coefficient between f_m and δ to $r \approx 0.53$.

The GLE cases considered separately also demonstrate a correspondence between their radio and proton spectra. Among 28 events, only two flares displayed soft radio spectra ($f_m \leq 5$ GHz), nine events displayed medium-hard radio spectra ($f_m \approx 7 - 12$ GHz), and 17 events ($\approx 61\%$) displayed hard radio spectra ($f_m \geq 15$ GHz). Among 11 events with soft and moderate radio spectra ($f_m \leq 9$–12 GHz), the proton spectra at energies of tens of MeV were also comparatively soft ($\delta \geq 1.3$) in seven cases. Among 17 cases of GLEs with hard radio spectra ($f_m \geq 15$ GHz), only two events displayed comparatively soft proton spectra ($\delta > 1.3$), while nine had harder spectra, with $\delta < 1.0$. Thus, the f_m values for the GLEs also show a statistical correspondence between the radio and proton spectra.

5. CORRELATION BETWEEN S_{17}/S_{35} AND δ

Thirty-one of the 86 events considered are provided with the radio data at frequencies ≥ 35 GHz, mainly by the Nobeyama observations (and Bern data for event No. 29). This enables us to compare the proton spectral index δ with the ratio of the peak radio fluxes at 17 and 35 GHz (S_{17}/S_{35}). Figure 4 presents the results obtained, and again shows a statistical correspondence between the hardnesses of the proton spectra near the Earth and the radio-burst spectra. When the radio parameter S_{17}/S_{35} increases from 0.25 to 4, the proton spectral index δ increases from 1.4 to 2.4, on average. However, this tendency is more weakly expressed than the analogus relation between δ and the ratio of the peak fluxes at 8.8 and 15.4 GHz (S_9/S_{15}, see Section 3). The correlation coefficient between S_{17}/S_{35} and δ is $r \approx 0.35$. The significant spread of the points in Fig. 4 is due to the effects noted above and the comparatively low number of events considered. Another possible reason for the spread is that the spectral maxima of radio sources located near the bases of loops and closely related to the parameters of the radiating electrons could be located between 17 and 35 GHz.[3] The relationship between the radio intensity and the parameters of accelerated electrons are different on either side of the spectral maximum. On the other hand, as a rule, radio emission at 9 and 15 GHz radiated by sources at the bases of loops is optically thick, and S_9/S_{15} indirectly indicates the peak frequency of the microwave spectrum in most cases.

The ratio of the peak radio fluxes at 17 and 35 GHz may be a good indicator of the hardest radio spectra. When $S_{17}/S_{35} \leq 1$, the peak frequency of the corresponding microwave bursts is $f_m \geq 24$ GHz. It is not surprising that most such events (see Fig. 4) have proton fluxes with fairly hard energy spectra: seven of nine events with $S_{17}/S_{35} < 1$ display $\delta < 1.6$, including five cases of GLEs. One of the two remaining events with $S_{17}/S_{35} < 1$ but comparatively soft proton spectra is the event of February 20, 2002 (60), which we have already discussed in the preceding section as an example of a short-term impulsive flare accompanied by a weak proton flux near the Earth. The proton spectrum of the other event, which was observed on April 2, 2001 (49) and had $\delta \approx 1.9$, was moderate rather than soft. Some softening of the proton spectrum in this case could be associated with the decay phase of a very strong geomagnetic storm with $D_{\mathrm{st}} = -387$ nT, observed on March 31.

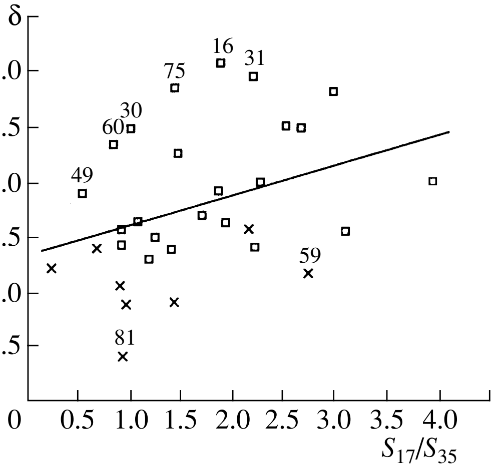

Fig. 4. Correlation between the ratio of the peak fluxes of the flare microwave events at 17 and 35 GHz (S_{17}/S_{35}) and the proton spectral index $\delta = \log(J_{10}/J_{100})$. The notations are the same as in Fig. 1. The numbers indicate the events: 16—June 12, 1990; 30—February 20, 1994; 31—October 20, 1995; 49—April 2, 2001; 59—December 26, 2001; 60— February 20, 2002; 75—April 11, 2004; and 81—January 20, 2005.

If the peak frequency is below 24 GHz, $S_{17}/S_{35} \geq 1$ for both harder and softer spectra. This can distort the correlation between S_{17}/S_{35} and the character of the proton spectra when $S_{17}/S_{35} \geq 1$, even the cases demonstrating a correspondence between the proton and radio spectra as revealed by other radio parameters. For example, the event of February 20, 1994 (30) had $S_{17}/S_{35} = 1$, because the peak radio fluxes were about 100 sfu at both frequencies due to the contribution of thermal bremsstrahlung. However, the peak frequency was $f_m \approx 2.7$ GHz, that corresponds to the observed soft proton spectrum with $\delta \approx 2.48$. The three other events with the softest proton spectra, observed on June 12, 1990 (16), October 20, 1995 (31), and April 11, 2004 (75) (see Fig. 4) had essentially similar combinations of parameters, with the ratio S_{17}/S_{35} being decreased due to a significant contribution of the flat thermal spectrum.

The results presented here and in preceding sections show that the ratio of the peak fluxes at 8.8 and 15.4 GHz and the peak frequency are the preferred radio parameters for revealing correlations between the microwave-burst and near-Earth proton spectra. The ratio of the radio fluxes at 17 and 35 GHz describes well the hardest proton spectra at tens of MeV, including those for numerous GLEs. The next section shows that both the spectrum and the intensity of radio bursts at and above 35 GHz are indicators of considerable proton fluxes following solar flares.

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[3] The estimates of f_m obtained for the 16 most powerful events presented below in the table yield frequencies from 11 to 47 GHz, with a mean $f_m = 33$ GHz.

Events with powerful 35 GHz radio bursts ($S_{35} > 10\,000$ sfu) observed at Nobeyama (upper portion) and proton enhancements without powerful radio bursts (lower portion, see text). The frequencies f_m were obtained from the time profiles

No.	Date	Time, UT	Flare		Radio burst		Protons	GLE,
			class	coordinates	S_{35}, sfu	f_m, GHz	J_{100}, pfu	%
A1	1990-04-15	02:59	2B/X1.4	N32 E54	19 600	11	<0.1	–
13	1990-05-21	22:15	2B/X5.5	N34 W37	37 800	47	18	24
A2	1991-03-22	22:44	3B/X9.4	S26 E28	142 000	35	55	–
A3	1991-03-29	06:45	3B/X2.4	S28 W60	10 800	30	<0.1	–
A4	1991-05-18	05:13	2N/X2.8	N32 W87	20 300	26	<0.1	–
A5	1991-06-04	03:41	3B/X12	N30 E60	230 000	44	2	–
A6	1991-06-06	01:09	3B/X12.5	N33 E44	245 000	46	4.8	–
A7	1991-06-09	01:39	3B/X10	N34 E04	73 000	36	1.2	–
21	1991-06-11	02:06	3B/X12.5	N32 W15	45 000	30	12	12
A8	1991-10-24	02:38	3B/X2.1	S15 E60	31 500	35	<0.1	–
26	1992-11-02	02:54	2B/X9	S23 W90	41 000	35	70	6.5
49	2001-04-02	21:48	X17.1	N18 W82	24 580	35	4.8	–
A9	2002-07-23	00:31	2B/X4.8	S13 E72	14 500	35	<0.1	–
66	2002-08-24	01:00	1F/X3.1	S02 W81	11 200	18	27	14
81	2005-01-20	06:46	2B/X7.1	N12 W58	87 500	28	680	5400
85	2006-12-13	02:21	4B/X3.4	S06 W24	13 000	40	90	92
B1	1990-05-28	04:30	C1.4	N36 W120	100	1.4	43	6
44	2000-11-08	23:28	1N/M7.8	N10 W75	140	2.8	320	–
B2	2001-04-18	02:15	C2.2	S20 W115	–	–	12	26
B3	2001-08-15	23:50	–	W>120		–	27	–
59	2001-12-26	05:06	1B/M7.1	N08 W54	740	6.9	47	13
62	2002-04-21	01:15	1F/X1.5	S14 W84	330	5	20	–

6. EVENTS WITH POWERFUL BURSTS AT 35 GHz

It is well known [18] that western flares with powerful non-impulsive radio bursts at high frequencies are usually accompanied by appreciable enhancements in the proton fluxes detected near the Earth, and the most intense of them reach the GLE level. We demonstrated above a general correspondence between the proton spectra at tens of MeV and the spectra of radio bursts. We can illustrate these relationships using the collected microwave/millimeter bursts detected at the Nobeyama Observatory since 35 and 80 GHz observations began in 1990.

The upper portion of the table presents data on 16 events in 1990–2008 and selected according to a strict criterion, including only events with maximum 35 GHz burst fluxes $S_{35} > 10\,000$ sfu. Seven of these events are the western proton enhancements considered above; these are listed in the table under the same numbers as in the Main Table. New events presented in the table are indicated by numbers with the letter "A." Analysis of the data on flares and accompanying proton fluxes reveals the following. All the events have hard radio spectra, with thirteen being extremely hard, with peak frequencies $f_m \geq 35$ GHz. These include the well known events of June 1991, the two strongest recent proton enhancements, observed on January 20, 2005 (81) and December 13, 2006 (85), etc. As one could expect, in 4 cases (A1, A5, A8, A9), the near-Earth proton fluxes were considerably weakened due to the high eastern longitudes of the flares (E $> 50°$). Among the remaining 12 western and moderately eastern events, 10 events displayed proton fluxes at $E > 100$ MeV $J_{100} = 1.2 - 680$ pfu, with seven of these being especially large, $J_{100} > 10$ pfu, and with six cases of GLEs. In the last two cases (A3 and A4), the near-Earth proton fluxes were fairly weak, though the microwave bursts were powerful, the locations of the flares favorable (W60 and W90), and type II and type IV meter-wavelength bursts were observed. The A3 microwave burst was short, and proton fluxes associated with impulsive flares are known to usually be fairly weak. The event A4 was a powerful, prolonged X-ray flare near the western limb, and could be a proton event according to a number of features. It is possible that the magnetic connection between the event and the Earth was unfavorable in this case for unknown reasons.

To consider proton events that are missed by the criterion $S_{35} > 10\,000$ sfu, the lower portion of the table contains data on six additional SCR events (under numbers used in the Main Table with the added letter"B") with significant near-Earth proton fluxes, $J_{100} \geq 10$ pfu, corresponding to flares observed from 21–22 UT to 07–08 UT by the Nobeyama polarimeters. One can see that three events associated with flares occurring far behind the western limb (B1, B2, and B3) and, consequently, any microwave bursts could not be detected at the Earth. Of the three remaining events, two (59, 62) had high intensities at 9.4 GHz (4190 and 2480 sfu, respectively) and soft frequency spectra with low intensity at high frequencies. In particular, event 62 displayed a significant radio flux (15 000 sfu) at $f \approx 1$ GHz, in the decimeter-wavelength range, which corresponds to a fairly soft SCR energy spectrum. There Several other proton events for earlier years are known, which were not preceded by any flares with powerful radio bursts [23].

Summarizing the data analyzed, we conclude that most flares with powerful high-frequency bursts ($S_{35} > 10\,000$ sfu) and extremely hard radio spectra ($f_m \geq 35$ GHz) are accompanied by significant proton fluxes near the Earth with $J_{100} > 1$–10 pfu. It is important that this is true for both western and moderately eastern flares. The latter can also result in strong SCR enhancements when their 35 GHz fluxes are extremely high. On the other hand, among flares that were not hidden behind the limb, there were only a few proton events with $J_{100} > 10$ pfu, which were not accompanied by powerful hard bursts at 35 GHz. On the whole, we conclude that powerful high-frequency microwave radio bursts are informative indicators of the acceleration of significant proton fluxes in flares occurring in strong magnetic fields [6].

This conclusion finds additional support if we examine the largest radio bursts and proton events contained in the Main Table that are associated with flares with no Nobeyama radio polarimeter data at 35 GHz. In this case, we must limit high frequencies considered to 15.4 GHz. Of 14 such events with powerful ($S_{15} > 5000$ sfu) and hard ($f_m \geq 15.4$ GHz) radio bursts, 11 displayed significant near-Earth proton fluxes, $J_{100} \geq 1$ pfu, with $J_{100} \geq 45$ pfu in seven cases. On the other hand, among 19 proton enhancements with $J_{100} \geq 1$ pfu, 17 events occurred after powerful microwave bursts ($S_{15} > 5000$ sfu), while 11 displayed fairly hard radio spectra with $f_m \geq$ 15.4 GHz. Almost all recent outstanding proton enhancements, including the events of October 29, 2003 (71), November 2, 2003 (72), and November 4, 2003 (73), as well as the eastern event of September 7, 2005, which falls outside our consideration, correspond to this type of event. Note that the well known Bastille Day event observed on July 14, 2000 (41) is not an event of this type, since its powerful flux ($S_{15} \approx 6100$ sfu) displays a moderate rather than a hard spectrum, with $f_m \approx 8.8$ GHz. In the event of the October 2003 series observed on October 28, 2003 (70), a powerful burst saturated the detectors at the levels $S_9 \approx 70\,000$ sfu and $S_{15} \approx 57\,000$ sfu; according to its duration, the flux at 15.4 GHz was higher than at 8.8 GHz, indicating $f_m > 15.4$ GHz.

7. CONCLUSIONS

Our analysis of proton events of 1987–2008 and associated with flares occurring in the western half of the solar disk supports the results of [28, 29], which were based on an analysis of similar events of 1966–1986. Thus, events observed during four solar-activity cycles support the existence of a statistical correspondence between the frequency spectra of microwave solar bursts and the energy spectra of near-Earth proton fluxes at energies of tens of MeV. We have found correlations between the ratio of the peak radio fluxes at 9 and 15 GHz (S_9/S_{15}) and the peak frequency of the microwave bursts f_m, on one hand, and the proton spectral index $\log(J_{10}/J_{100})$, on the other hand. The proton index is determined by the ratio of the peak proton fluxes in the $E > 10$ MeV and $E > 100$ MeV channels (J_{10} and J_{100}), and is equivalent to the power-law index δ of the integrated energy spectrum, $J_E \propto E^{-\delta}$. Flares with soft radio spectra ($S_9/S_{15} \geq 1.5$ and $f_m \leq 5$ GHz) are accompanied by proton fluxes with soft (steep) energy spectra ($\delta \geq$ 1.5–2), while proton fluxes with hard (flat) energy spectra ($\delta \leq 1.5$) correspond to flares with hard microwave radiation ($S_9/S_{15} \leq 1$ and $f_m \geq 15$ GHz).

The ratio of the peak burst fluxes at 17 and 35 GHz, S_{17}/S_{35}, also displays a statistical relation to the proton spectral index δ near the Earth. However, the correlation with the proton-energy spectrum is weaker for S_{17}/S_{35} than for S_9/S_{15} and f_m. This may indicate that 17 and 35 GHz are often located on different sides of the spectral maximum, that complicates the relationship between S_{17}/S_{35} and the parameters of the radiating electrons. In addition, S_{17}/S_{35} does not contain information on the peak frequency f_m when $S_{17}/S_{35} > 1$ ($f_m <$ 5–10 GHz). On the other hand, high-frequency microwave bursts that combine extremely hard frequency spectra ($S_{17}/S_{35} < 1$ and $f_m \geq 35$ GHz) with considerable radio fluxes ($S_{35} \geq 10\,000$ sfu) are typical for most large proton events ($J_{100} > 1$–10 pfu) with hard energy spectra, making it possible to identify extreme proton events of the last solar cycle. This can be understood if radio bursts with such characteristics act as indicators of the acceleration of large numbers of particles in flares occurring within strong magnetic fields [6].

Our results indicate that the microwave-burst frequency spectrum, which depends, in particular, on the energy spectrum of the radiating electrons, also represents the energy spectrum of protons detected near the Earth as SCRs. It is important that information on the accelerated-particle spectrum at tens of MeV is preserved, despite the complexities of the escape and propagation of protons and other effects. The correlation between the flare radio spectra and the proton-flux energy spectra cannot be explained by the "big flare syndrome" [26] mentioned above. It provides an important argument that, in most cases, the acceleration of protons arriving at the Earth (or at least their first impulsive acceleration) occurs directly in flares, not in shock associated with corresponding coronal mass ejections [6]. It is possible that protons are indeed accelerated by shocks in rare events, where significant proton fluxes are observed together with weak radio bursts, such as the event of November 9, 2000 (44). It is not unlikely that this may be true for the events of September 30, 1998 (37) and September 12, 2000 (43) as well. The few remaining events with weak radio bursts also display weak proton fluxes, and the seeming inconsistency between the soft proton spectra and, at first glance, hard radio spectra can be fully explained by the contribution of flat-spectrum thermal bremsstrahlung.

The high-energy acceleration of electrons and protons can occur in flares during both the primary impulsive energy release and the post-eruptive phase (see, for example, [34]). One modern model [35, 36] suggests that particle acceleration occurs in two stages: first, electrons and protons are accelerated within a high-temperature, turbulent current sheet in a region of magnetic reconnection, with subsequent acceleration occurring during the collapse of loop-like magnetic traps.

Our analysis significantly clarifies upon the results obtained in [5], which presents two important conclusions. The first is that the narrow Gaussian distribution of the proton spectral index δ, which has a pronounced maximum at $\delta \approx 1.5$, suggests the existence of a characteristic spectrum for particles accelerated in powerful flares. The second is that the ratio J_{10}/J_{100} increases by nearly an order of magnitude (the proton spectrum softens) from impulsive flares of moderate duration to events with prolonged soft X-ray radiation from post-eruptive loops. We have shown that the spectra of particles accelerated in flares vary widely, depending on the conditions (in particular, the magnetic-field strength) in the acceleration region, which affects both the microwave-burst frequency spectra and the proton-flux energy spectra detected near the Earth. It is important that this is true for both flares with soft spectra (with prolonged post-eruptive energy release), as was found in [5], and for flares with hard spectra (with predominant acceleration in impulsive phases occurring at low altitudes within strong magnetic fields above sunspots), including GLEs.

Our study demonstrates the relationship between the flare and SCR spectra indirectly, through the frequency spectra of microwave bursts generated by subrelativistic electrons. Meanwhile, for rare, most powerful flares, the energy spectrum of protons accelerated to energies >300 MeV can be directly estimated from the spectrum of the high-energy pion gamma-ray emission, whose maxima are typically located at photon energies of 70–100 MeV. In [37] evidences are presented that the SCR-proton energy spectrum reconstructed from ground-level enhancements are close to the spectrum of flare protons derived from the observed gamma-ray emission. This supports our conclusion that flare acceleration makes a significant contribution to the formation of the SCR spectra.

More and more data indicating that many SCR events must be considered as mixed cases combining both flare acceleration and acceleration in shocks preceding coronal mass ejections has become available in recent years [12–15]. Our results demonstrating a correlation between the flare-emission spectra and the near-Earth proton-flux energy spectra indicate that the characteristics of the initial SCR impulse are determined mainly by direct flare acceleration.

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