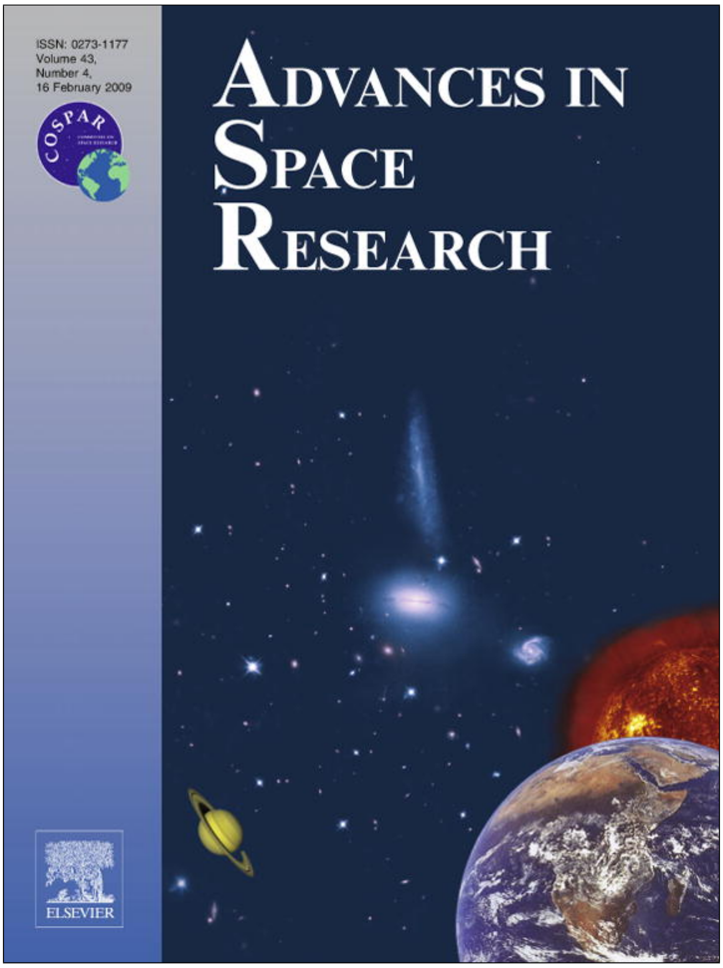
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On the early phase of relativistic solar particle events: Are there signatures of acceleration mechanism?

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Abstract

Many physical processes precede and accompany the solar energetic particles (SEP) occurrence on the Earth's orbit. Explosive energy release on the Sun gives rise to a flare and a coronal mass ejection (CME). X-ray and gamma emissions are believed to be connected with flares. Radio emission is signature of disturbances traveling through the corona and interplanetary space. Particles can gain energy both in the flare and the accompanying wave processes. The beginning of the SEP events has the advantage of being the phase most close to the time of acceleration. Influence of interplanetary transport is minimal in the case of first arriving relativistic solar protons recorded by ground based neutron monitors in so called ground-level enhancements (GLE). The early phase of the SEP events attracts attention of many scientists searching for the understanding of particle acceleration. However, they come to the opposite conclusions. While some authors find arguments for coronal mass ejections as a sole accelerator of SEPs, others prove a flare to be the SEP origin. Here, the circumstances of SEP generation for several GLEs of the 23rd solar cycle are considered. Timing of X-ray, CME, and radio emissions shows a great variety from event to event. However, the time of particle ejection from the Sun is closer to maximum of X-ray emission than to any other phenomena considered. No correlation is found between the particle fluxes and the CME characteristics.

Keywords: Acceleration of particles; Ground-level enhancement; Relativistic solar particles; Flare; Shock; Coronal mass ejection; Solar radio emission

1. Introduction

The relative role of flares and shocks in the solar energetic particles (SEP) acceleration is one of the central problems in the solar-heliospheric aspect of the cosmic ray physics. Up to now, there is no generally accepted opinion about the place and dominant mechanism of acceleration. Since the powerful SEP events always occur after big solar flares the SEP origin seemed to be clear until the early 1990s. However, flare identification often met significant difficulties. That led to revision of the existed paradigm, and during some recent decades many researchers hold the opinion that two separate SEP classes exist owing to different source where acceleration took place (Gosling, 1993; Kahler, 2005; Reames, 1999; Tylka, 2001). Particles are accelerated in the flare processes in the impulsive rather small events. Acceleration occurs on the shocks driven by a coronal mass ejection (CME) in the corona and in the interplanetary space in large gradual events.

General scenario of the CME-driven shock acceleration includes formation of a wide shock in front of a CME where particles are subject to the first order Fermi acceleration. It is important that particles themselves generate the turbulence in vicinity of the shock by amplifying the preexisting Alfvén waves. Evolution of the moving accelerating region leads to the complicated dynamics in the observed SEP characteristics, for example, to peculiar temporal changes in the SEP composition, streaming-limited intensities, and flattening of energy spectra in the low-energy range. These features were confirmed by both modeling and observations and became a crucial argument for the shock origin of SEPs (Tylka, 2001). However the observations did not relate to the relativistic solar particles (RSP)

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which are the main signature of the most powerful SEP events recorded by the ground-level neutron monitors, so called Ground Level Enhancements (GLEs).

The GLEs refer to the gradual class, and therefore they are believed to originate from the CME-driven shocks. Indeed, Bieber et al. (2004, 2005), Gopalswamy et al. (2005), and Kahler (2005) adhere to such point of view. However, a number of observational facts argue against such a conclusion, for example, the attribution of virtually all GLEs to the flares at the western solar hemisphere (Bazilevskaya et al., 2003), strong connection with the flare gamma emission (Kuznetsov et al., 2005, 2007) and with most powerful solar X-ray bursts (Bazilevskaya et al., 2006). The flare origin of RSPs is supported by analysis made by Vashenyuk et al. (2006, 2007). It seems more properly to admit the contribution to SEP in gradual events of both the flare and the shock sources (Cane et al., 2006; Li and Zank, 2005; McCracken and Moraal, 2007). Still the relative role of a flare and a CME-driven shock is of great interest. Concerning the GLEs, fast CMEs and flares always occur together, which makes it difficult to identify the actual source of SEP events detected near Earth orbit.

The observed SEPs are influenced by many processes of multiple and/or prolonged acceleration and propagation in the corona and interplanetary space. Therefore, it is difficult to distinguish signatures of acceleration mechanisms from particle observations. However, the early phase of the SEP events is most close to the time of acceleration, and the role of interplanetary transport is minimal for the first arriving particles. Extreme events provide the best opportunity for study of the early phase because of high signal to noise ratio. Relativistic solar protons are the most proper candidates for approaching to the problem of particle acceleration. In this work, the early phase of several powerful GLEs of the 23rd solar cycle is studied together with concomitant phenomena on the Sun with the aim to find the existence of closest relations. Recently similar work was fulfilled by Kahler et al., (2003) and the pioneer paper belongs to Cliver et al. (1982).

2. Data selection

The 23rd solar cycle was chosen for analysis because continual information on some important phenomena accompanying the SEP generation became available only recently. All the GLEs of the cycle 23 were examined (http://www.wdcb.ru/stp/data/cosmic.ray), and those with the amplitude of enhancement greater than 10 % at any polar neutron monitor were selected for further analysis. This provided a good signal to noise ratio. Nine GLEs were selected. Concomitant solar parameters were chosen as follows. Powerful solar flares are always preceding the RSP occurrence. Information on the solar flares was taken from (ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SOLAR_FLARES/XRAY_FLARES/) Hard X-ray emission is one of most energetic demonstrations of the flare process. The data of RHESSI on the hard X-rays (http://www.mssl.ucl.ac.uk/www_solar/surfindex.html) are available for the events beginning from 2002. Radio emission of the type II is believed to be an indicator of shock formation in the corona, and that of the type III means existence of the magnetic field lines connecting the flare area with the interplanetary space (Cane et al., 2002). The data on the solar radio emission were taken from http://www.ngdc.noaa.Gov/stp/SOLAR/ftpsolarradio.html#fixedbursts. CMEs are considered to be the main alternative to flares as the sources of RSPs. Information on CMEs is available on (http://cdaw.gsfc.nasa.gov/CME_list/). All CMEs related to the chosen GLEs were of the halo type.

3. Relative timing of the first RSP ejection and the concomitant phenomena on the Sun

Because of strong anisotropy in the first arriving RSP fluxes (e.g., Vashenyuk et al., 2006) the first RSPs come to different places not simultaneously. The station with the earliest RSP arrival time was found for each GLE. In order to infer the solar time of a RSP ejection it is necessary to know the time of particle flight from the Sun to the Earth

$$t = L/(c\beta\cos\theta),$$

where L is the length of the field line of interplanetary magnetic field, c is the speed of light, $c\beta$ is the particle velocity and θ is the pitch angle. It was suggested that $\cos\theta = 1$ for the first arriving RSPs. The effective particle velocity depends on the energy spectrum of the first arriving RSPs and could be estimated for 7 GLEs of 9 selected using the spectra of Vashenyuk et al. (2007) and the yield functions for the neutron monitors of Lockwood et al. (1974). The mean effective energy of the first arriving RSPs for the chosen GLEs was 1.5 GeV, which corresponds to $\beta = 0.923$. The path length along the field line of interplanetary magnetic field depends on the solar wind velocity, the hourly data being available at (ftp://nssdcftp.gsfc.nasa.gov/spacecraft_data/omni/). The solar wind velocity for the time of RSP arrival was obtained by interpolation between the neighboring hourly values. The accuracy of the inferred RSP ejection time was estimated by Bazilevskaya and Svirzhevskaya (2008) as ± 1 min with possible systematic shift by 1.5 min, since RSPs might actually leave the Sun earlier because the mean pitch angle for the first arriving particles could actually be not zero (Klein and Posner, 2005). Table 1 summarizes the data on the chosen GLEs, corresponding flares, time of earliest RSP arrival, neutron monitors recorded the earliest RSP arrival, interpolated solar wind velocity, and the time of RSP flight from the Sun to the Earth.

For each GLE, the distance of the leading edge of concomitant CME from the center of the Sun versus solar time was plotted as it is shown in Fig. 1. A parabolic extrapolation of a CME trajectory outside the observation limit was

Table 1
GLEs selected for analysis (with international event number), corresponding flares, the earliest time of particle arrival, the neutron monitor recorded it, solar wind velocity and time of flight of a proton with energy 1.5 GeV from the Sun to the Earth

GLE number	Date	Flare		Time of the earliest arrival, UT	Neutron monitor	Solar wind velocity, km/s	Time of flight, s
55	06.11.1997	S18 W63	2B/X9.4	12:17	South Pole	349.66	10.94
59	14.07.2000	N22 W07	3B/X5.7	10:32.5	Oulu	593.47	9.76
60	15.04.2001	S20 W87	2B/X14.4	13:57	South Pole	498.85	10.04
61	18.04.2001	S20 W120	.../C2.2	2:33	South Pole	490.15	10.07
65	28.10.2003	S16 E08	4B/X17.2	11:13.5	Moscow	774.26	9.47
66	29.10.2003	S19 W09	2B/X10	20:58	South Pole	No data	11.00
67	02.11.2003	S14 W56	2B/X8.3	17:21	Lomnitsky Stit	525.97	9.95
69	20.01.2005	N12 W58	2B/X7.1	06:48.5	South Pole	855.40	9.39
70	13.12.2006	S06 W23	4B/X3.4	02:47.5	Oulu	641.36	9.66

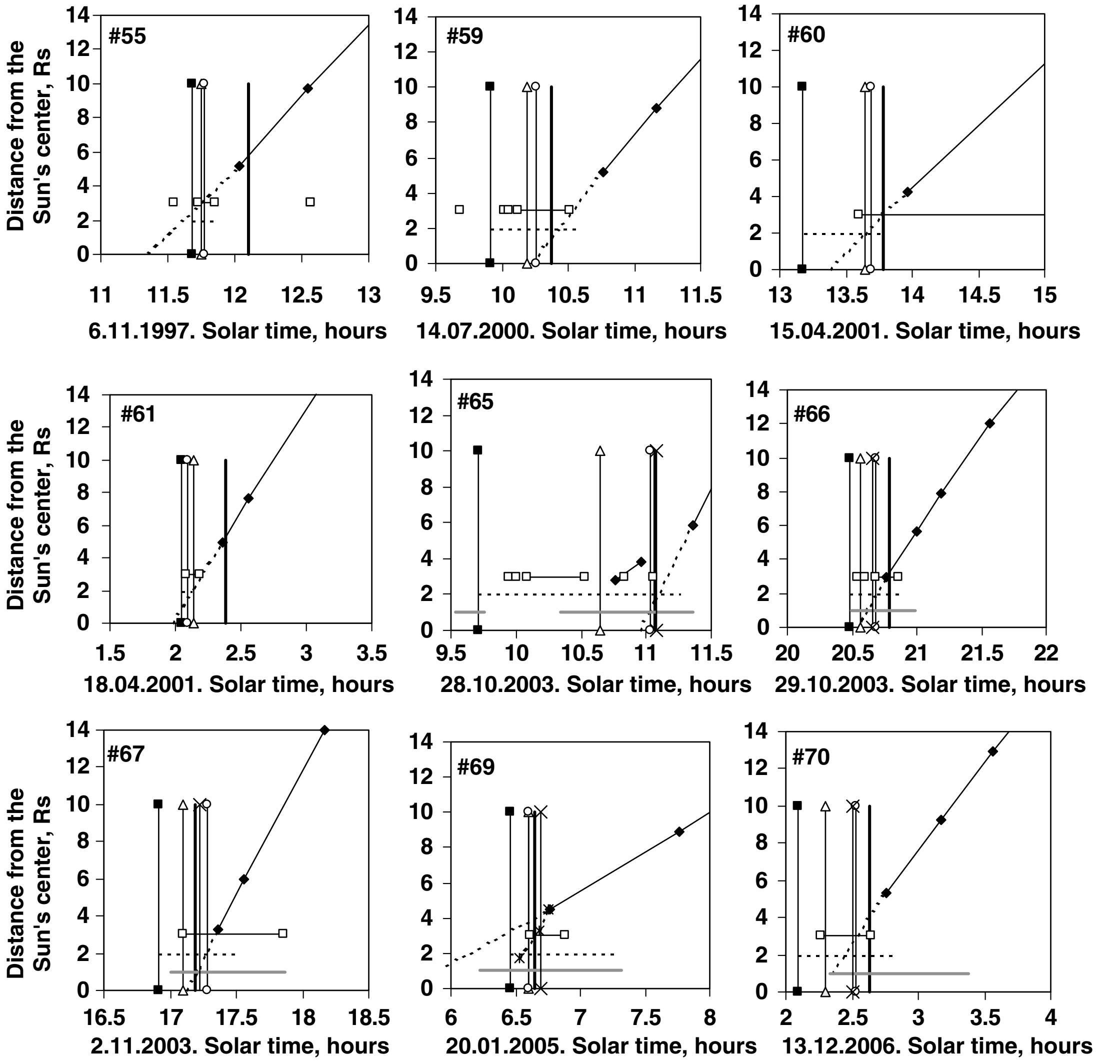

Fig. 1. Timing of the GLE-related phenomena on the Sun. The GLE number is given in the left upper part of each panel. Oblique line shows height of the leading edge of a CME versus time (solid line is the observed height, dashed line is parabolic extrapolation). Vertical bars do not refer to the height but indicate the time of various phenomena on the Sun: RSP injection (thick black bar without symbols), start of the soft X-ray (SX) emission (a bar with black squares), maximum of SX emission (a bar with white circles), maximum of the hard X-ray (HX) emission (a bar with crosses), start of type II radio emission (a bar with white triangles). Horizontal bars denote duration of the HX emission (thick grey), SX emission (dashed), radio emission of type III (a bar with white squares).

taken from (http://cdaw.gsfc.nasa.gov/CME_list/). In the event # 65, there were 2 CMEs in the corona but only the second one starting in around 1.3 h after the flare was powerful enough. For the event # 69, the CME suggested by Gopalswamy et al. (2005) is added, but it is not included in the catalogue (http://cdaw.gsfc.nasa.gov/CME_list/). It is possible to get roughly the time of the CME start at the trajectory crossing with the height of 1 solar radius, even if such extrapolation is not quite correct. The solar times of the RSP ejection, start and maximum of the soft X-ray (SX) burst, maximum of the hard X-ray (HX) burst, and start of type II radio emission are shown in Fig. 1 by vertical bars. Their crossing with a CME trajectory indicates the height of the latter at that time. In addition, the horizontal bars give the duration of the HX emission, SX emission, and radio emission of type III.

The plots in Fig. 1 show a great variety of phenomena sequence and its duration. An order of phenomena accompanying the RSP ejection may be different. In the events # 55, 61, and 69 the extrapolated time of the CME start was earlier than or equal to the moment of the SX flare start, and in event # 65 it was coincident with the RSP ejection. The RSP ejection occurs in the late part of the sequence; it happened slightly earlier than the SX and HX bursts maxima in the event # 67, and before the HX burst maximum in events # 65 and 69. Type III radio emission was observed simultaneously with the RSP ejection excluding # 55 and 61 events. Type III bursts were observed earlier in those events. That means presence of open field lines connecting the flare region with the interplanetary space (Cane et al., 2002).

Fig. 2 summarizes the timing of selected solar events. Each panel demonstrates distribution of the time shifts of a given parameter relative to the RSP ejection moment taken as a zero time and marked by a vertical dashed line.

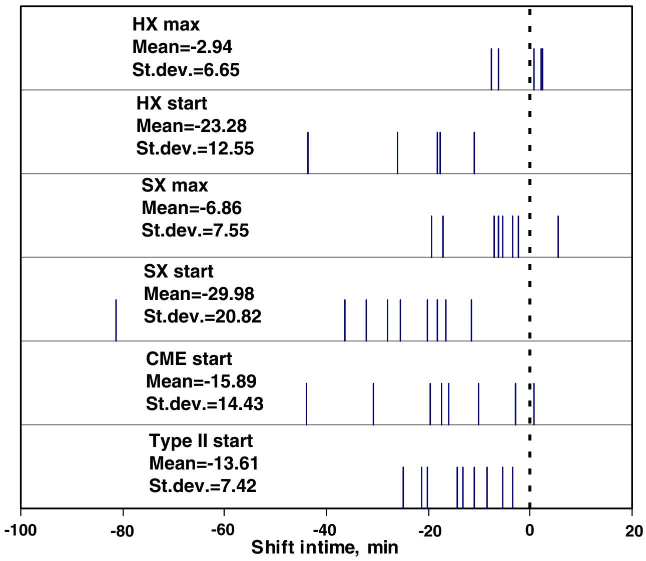

Fig. 2. Time shift between the RSP ejection (zero time and a vertical dashed black line) and various phenomena on the Sun. Each panel presents the timing of one phenomenon as indicated. Vertical bars mark the time of given phenomenon relative to RSP ejection for different GLEs. Negative shift means that a phenomenon occurred before RSP ejection. Mean shift and standard deviation (min) for each phenomenon are also given.

The mean value of the time shift and the standard deviation are given in each panel. It is clearly seen that the RSP ejection is most closely connected with the representatives of the flare processes. Relation to the HX maximum was available only for five events supported by the RHESSI observations however it is remarkable as can be seen in Fig. 2. However the scatter and diversity of the time shifts for all the parameters argue against the conclusion that they have simple connection to the RSP ejection.

It is seen in Fig. 2 that the CME start time relative RSP ejection varies greatly from event to event. The same is correct for the CME heights at the moment of RSP ejection. Fig. 3 presents the CME velocity (in parabolic approximation) versus its height at the moment of RSP ejection. The correlation coefficient is -0.35 indicating no significant relation between these two parameters.

The Alfvén velocity in the corona $V_A = B/(4\pi\rho)^{0.5}$ (here B is magnetic field induction, ρ is the plasma density) was calculated in order to find if a shock was developed. The model of the solar corona from (Mann et al., 1999) was used for getting the plasma concentration

$$n(R) = n_s \exp(A/\mathrm{Rs}(\mathrm{Rs}/R - 1)),$$

where R is the distance from the Sun's center, Rs is the solar radius, $n_s = n(R = \mathrm{Rs}) = 5.14\ 10^9\mathrm{cm}^{-3}$, $A/\mathrm{Rs} = 13.83$. The coronal magnetic field was taken from Vainio and Khan (2004) as

$$B = 1.7(\mathrm{Rs}/R)^3 + 1.3(\mathrm{Rs}/R)^2.$$

The Alfvén velocity in the corona is also shown in Fig. 3. The Mach number $M = V_{\mathrm{CME}}/V_A$ is big enough with exception for one event (# 69). However, it is possible that another faster CME was present during this event (Gopalswamy et al., 2005), see Fig. 1.

The speed of the shock connected with the type II radio emission can be derived from the observations and is given

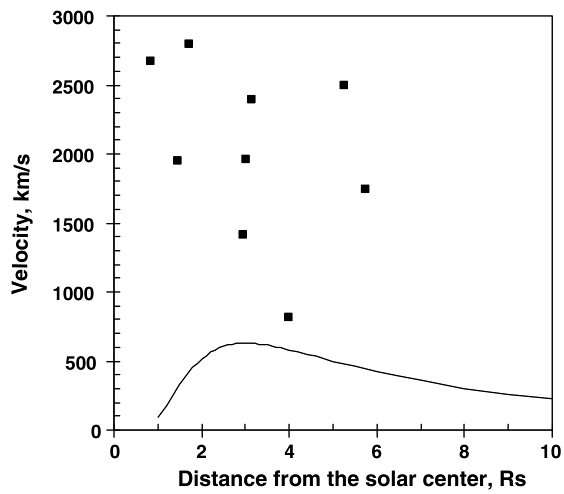

Fig. 3. Velocity versus distance from the Sun's center. Black squares are the CME velocity at the moment of RSP ejection for different GLEs. The curve is Alfvén velocity calculated using models of Mann et al. (1999) and Vainio and Khan (2004).

as Estimated Shock Speed (ESS) in (http://www.ngdc.noaa.Gov/stp/SOLAR/ftpsolarradio.html#fixedbursts). No correlation was found between ESS and the CME speed for the events under study (Bazilevskaya and Svirzhevskaya, 2008). It can be expected bearing in mind a rather complicated relation between the CMEs and the metric–decametric–hectometric type II bursts (Pohjolainen and Lehtinen, 2006).

4. Relation between the observed RSP characteristics and the parameters of the shocks in the corona

Vashenyuk et al. (2006, 2007) found the fluxes J of first arriving (prompt) RSPs for the recent GLEs from the analysis of the neutron monitor network data in the form

$$J(E) = J_0 \exp(-E/E_0),$$

where E is the particle energy. The values of J_0 and E_0 can be taken from Vashenyuk et al. (2006, 2007) for all the events under study with exception for # 61 and # 66. In the case of shock acceleration a correlation may exist between the observed RSP fluxes and the shock speed values. Also, it may be supposed that acceleration process started at the moment of coronal shock formation as indicated by the beginning of the type II radio emission and lasted until the RSP ejection. Then the correlation might exist between the observed prompt RSP fluxes and the supposed duration of acceleration. The expected relationships are presented in Fig. 4a and b. No significant correlation was found. A certain negative correlation can be seen in Fig. 4a between the CME speed and the first arriving RSP fluxes (correlation coefficient is −0.53). However, for the CME-accelerated particles the expected correlation is positive (Kahler, 2003).

Certain relationships are expected between energy spectra of particles and wave parameters in the case the particle acceleration occurs at the shock front. For the diffusive shock acceleration, the energy spectrum has a power law form with the spectral index

$$G = (\sigma + 2)/(\sigma - 1),$$

where σ is the compression ratio at the shock front,

$$\sigma = (\gamma + 1)M^2/((\gamma - 1)M^2 + 2),$$

$\gamma = 5/3$ is the adiabatic index for the fully ionized plasma, M is the Mach number (Berezhko et al., 1988). Therefore it is possible to estimate the expected value of the spectral in-

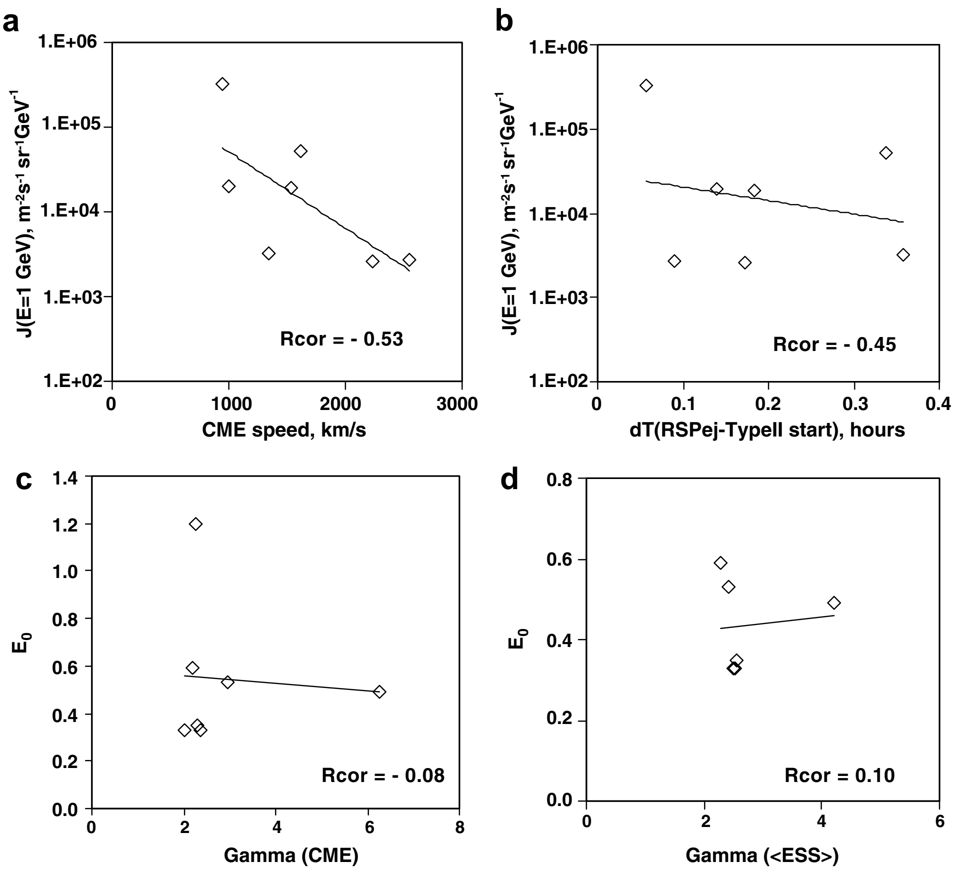

Fig. 4. Correlation between the features of the first arriving RSP as observed by Vashenyuk et al. (2006, 2007) and expected from the shock acceleration: prompt RSP flux at $E = 1$ GeV and CME speed (a), prompt RSP flux at $E = 1$ GeV and suggested time of acceleration (b), characteristic energy E_0 and a power law spectral index calculated for CME driven shocks (c) and those connected with the type II radio emission (d).The solid lines indicate the regression between the parameters.

dex G for given the CME (or ESS) and Alfvén velocities. A negative correlation might be expected between values of G and characteristic energy E_0 from observations. The expected G values were determined for both the CME-driven shocks and those connected with the type II radio emission (averaged values of ESS as found by different observatories were used). Virtually, no correlation was found between the parameters of the observed spectra and those expected from the shock acceleration (Fig. 4c and d). There is also almost no correlation between the observed RSP intensities and the height of CMEs at the moment of RSP ejection.

5. Conclusion

An attempt to find some relationship between the first arriving RSPs and the concomitant phenomena on the Sun, namely, a flare in SX and HX, CME speed and height at the moment of RSP ejection, and type II radio emission, showed that there is a great variety in the phenomena temporal sequence. Also the time period from the beginning of the flare in SX till the RSP ejection may be from around 20 min to more than 1 hour. To some extent, this can explain the controversial conclusions drawn by different authors analyzing various events. On the other hand, this is an indication that diverse scenarios may happen. Indeed, Bombardieri et al. (2007) suggest that the change in the spectrum form during the initial phase of the 2000 July 14 was indicative of the stochastic acceleration of RSPs occurred after the initial acceleration by the CME driven shock, but in the case of 2001 April 15 these authors argue for pure shock acceleration. The statistics should reveal general interrelations between the first RSP and different parameters but now there are few big events with good reporting on accompanying phenomena.

The results of this work favor a powerful flare as the necessary contributor to the first RSP population. The RSP injection time is closer to the maximum in the HX bursts and SX bursts than to any other phenomena considered. No GLEs were till now observed without a powerful flare situated on the western solar hemisphere or close to the central meridian. No correlation were found between the observed first RSP fluxes (Vashenyuk et al., 2006, 2007) and the CME-related parameters – speed, height of the leading edge at the moment of the RSP ejection, as well as between expected and observed spectral indices. However, the real speed and height of the halo CMEs are poorly determined from the present observations. It is hoped that the oncoming results of the 3D CME observations will allow a new understanding of CMEs and RSPs relation.

Given complexity of solar conditions concomitant of the RSP generation it is hardly possible to adhere to a single mechanism of particle acceleration, but rather the domination of one or another mechanism or the joint action are possible as it was claimed earlier by many authors. Nevertheless, first arriving relativistic particles can hardly be generated without a flare. A CME driven shock can contribute to the relativistic particle population later.

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