

# Once again about origin of the solar cosmic rays

**G A Bazilevskaya**

Lebedev Physical Institute, Leninsky prospect, 53, Moscow, 119991, Russia

E-mail: [bazilevs@sci.lebedev.ru](mailto:bazilevs@sci.lebedev.ru)

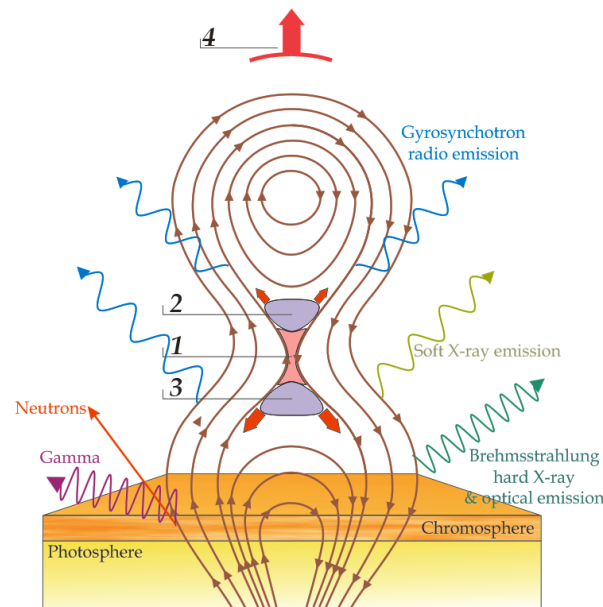
**Abstract.** Discussion about sources of energetic particles - solar cosmic rays (SCRs), or solar energetic particles (SEPs) - emerging in the interplanetary space after an explosive energy release on the Sun lasts during more than 20 years. The main candidates for the SEP sources are a solar flare and a coronal mass ejection (CME). This paper briefly outlines the main observational results related to the problem of the SEP origin. Main focus is directed to the recently discovered manifestations of the sudden energy release on the Sun - long lasting high-energy solar gamma emission, new information on solar neutrons and THz radio emission. Actually, description of particle acceleration on the Sun appears to be even more complicated than it was believed earlier.

## 1. Introduction

During more than half of a century, the observers residing at the Earth try to understand the origin of high-energy particles connected with explosion-like releases of energy on the Sun. These particles were named "the solar cosmic rays (SCRs)" because enhancement of particle intensity against the background of galactic cosmic rays was observed after powerful solar flares occurred. Nowadays, the customary name is "the solar energetic particles (SEPs)", or "the solar protons" since more than 90% of SEPs are protons. The lower energy limit of SEPs is not strictly determined being at least less than  $\approx 100$  keV/n. The higher energy limit of SEPs is certainly above 10 GeV/n, however, particles with energies below 100 MeV/n are detected during majority of SEP events. Electrons comprise  $< 1$  % of SEPs. A flare was considered as a main source of SEPs since the SEP discovery in 1942 [1].

A flare is a bright manifestation of an explosive energy release on the Sun. Figure 1 demonstrates a schematic of a solar flare without a real spatial scaling. It is thought that energy is accumulated via dynamics of solar magnetic field thereby condition for reconnection arises. Magnetic field reconnection is a primary energy release. There are at least three sites in the flare region where acceleration takes place, designated by 1, 2 and 3 in figure 1. Inside the reconnection region 1 the electric field is produced which can accelerate charge particles, e.g., [3]. At the explosion the matter is expelled upwards and downwards of reconnection region (2 and 3 in figure 1) where shocks are produced [4]. In addition, turbulence enhances so, that condition develops for the diffusive shock acceleration and stochastic acceleration, e.g., [5, 6]. The upward moving hadrons have possibilities to escape into the space along the open magnetic field lines or to be trapped in the closed magnetic field on the Sun, the downward directed hadrons interact with the ambient solar atmosphere giving rise to gamma emission and neutrons. If the open magnetic field exists near the flare region the upward moving electrons excite the plasma waves in the corona which are recorded as the type III radio emission. The downward propagating





**Figure 1.** Schematic of solar flare. 1 - reconnection region of particle acceleration by the electric field, 2 and 3 - regions of acceleration by the diffusion and stochastic mechanisms above and below of reconnection region, correspondingly, 4 - a CME front. The figure is modified from [2].

electrons interact with the higher density solar atmosphere to produce hard X-ray emission via bremsstrahlung and, in energetic events, gamma-ray emission. Concomitant heating leads to enhanced emission in soft X rays and  $H_\alpha$  brightening [4].

People never denied existence of shocks connected with a sudden solar energy release. A coronal shock was involved as a possible additional accelerator and a factor allowing particles to escape from the Sun. A signature of interplanetary shock are energetic storm particles (ESP) seen at the intensity-time profile of SEP events close to the shock front arrival. The ESP energy is usually below 100 MeV. By the late 1980s the evidence was accumulated that shocks may play a significant role in the SEP acceleration up to GeV energy (see for detail [8]). In 1993 J.T. Gosling summarized arguments against a flare as a main SEP accelerator [7]. A collisionless shock wave driven by a coronal mass ejection (CME) in the corona and interplanetary space was introduced instead of a flare as a source of most energetic so called gradual SEP events. Upstream of the shock the accelerated protons excite high intensity cyclotron-resonant waves. Downstream of the shock the high intensity waves are generated due to compression. The waves are transmitted through the shock to create a turbulent sheath on both sides of the shock [8]. Thus, favorite conditions for the diffusive and stochastic mechanisms of acceleration are created.

It is worth noting that additional acceleration can take place due to reconnection and turbulence arising in magnetic restructuring in the corona after the coronal mass ejection passage [9].

In [10], it is believed that only minor part of the flare originated particles escapes into the space and produces the less energetic so called impulsive SEP events. Particles accelerated in the flare site are mainly trapped in the closed magnetic loops in the Sun's lower corona. These particles interact with the ambient solar matter and generate secondary emission, such as hard X-rays, gamma-rays, and neutrons which are detected after some solar flares. The main differences of the impulsive and gradual SEP events stem from different conditions in the region of acceleration: temperature  $T = 10^7$  K and  $\approx 2 \times 10^6$  K, density  $n = 10^{11}$ – $10^{12}$  cm $^{-3}$ , and

$10^9\text{--}10^{11}\text{ cm}^{-3}$ , height  $< 10^4\text{ km}$  and  $10^5\text{ km}$ , respectively. Consequently, the ion charges in the impulsive events are higher: for Fe  $\langle Q \rangle \approx 20$  against  $\langle Q \rangle \approx 14$  in the gradual events. Also, the impulsive SEPs are enriched by the heavy elements and by  $^3\text{He}$  [10].

This paper outlines main observational results which addresses the problem of the SEP origin. The focus is directed to the recently discovered manifestations of the sudden energy release on the Sun (sections 4-6). Actually, description of particle acceleration on the Sun appears to be more complicated than it was believed earlier.

## 2. Flare versus CME acceleration: correlation between SEPs, Flares and CMEs; energy spectrum and abundances

During the last decade, a lot of works examined correlations between the characteristics of SEPs and flares or CMEs, e.g., [11–16]. A general conclusion was that contributions of flares and CMEs are roughly equal, but the high energy SEPs are more affected by flares than the low energy ones.

Investigation of relative timing of the first SEP arrival versus a flare and a CME features does not result in a decisive conclusion, e.g. [17–20]. One cause is lack of accuracy in the determination of the particle release time, especially uncertainty in the interplanetary condition of particle propagation. Another cause is that times of a flare impulsive phase and of a shock development are rather close to each other.

Tylka et al., 2013 [21] examined the Fe/O enhancement in the initial phase of two large gradual SEP events. Since the observed Fe/O  $\approx 1$  ratio was typical for impulsive events this could be naturally interpreted as indication of contribution of the flare material in the seed population. However, the authors preferred to explain their results as a transport effect.

Energy spectrum is the most important property of the SEPs. Historically, the spectrum in the maximum of the intensity-time profile (the TOM spectrum) is a characteristic of a given event [22], but a physical meaning of such spectrum is questionable in view of the recent paradigm. Nowadays the fluence spectrum is generally used in analysis. However, it accumulates signatures of particle acceleration and propagation on the Sun and in the interplanetary space during all the time of event observation, therefore information on primary acceleration is shadowed. Various mechanisms of particle acceleration yield rather similar energy spectrum forms. In reality, spectrum depends on particular condition for particle trapping and escaping. Recent works use for fitting of spectra a power-law with a rollover [23] or a double power-law [24, 25]. Fitting parameters should be used for interpretation with precaution because they depend on the energy range of approximation [26]. Nevertheless important information on the SEP source was obtained by Desai et al., 2016 [27]. Analysis of the spectra in the 15–21 MeV/n band showed that the Fe/O ratio of more energetic events corresponded to larger contribution of flare material in the seed particle population. Also, the more energetic events demonstrated larger enhancement in the  $^3\text{He}/^4\text{He}$  ratio indicative of the flare origin.

In summary, there is consensus that particles are accelerated both at in a flare region and at a CME driven shock. However a flare or a shock can dominate in different events and even in different energy ranges. From the study of 4 April 2000 event, Laurenza et al., 2012 [28] found that the most probable sources of 0.1–1 MeV, 1–30 MeV and 30–100 MeV protons were an interplanetary shock, a coronal shock, and a flare, respectively.

## 3. The role of coronal waves

One of the properties that distinguish the impulse of the gradual SEP events, is a broad distribution of the parent flares of the gradual events over the heliolongitude [10]<sup>1</sup>. This

<sup>1</sup> By the way, the parent flares of the most powerful gradual ground level enhancements (GLEs) have a narrow longitudinal distribution, similar to the impulsive SEP events [29].

distribution is naturally explained by the extended accelerating shock front, but meets difficulties in the case of the flare as an accelerator. Since mean free path of a charged particle along the magnetic field line in the interplanetary space is much larger than a perpendicular path, particles should propagate in the corona from the flare to the base of the spiral field line connecting the Sun with an observer. Such an opportunity gives a coronal wave [30] that can act as an accelerator or as a trigger that opens the closed solar magnetic field and releases the SEPs into the space. Coronal waves are visible in the EUV band and are often referred to as the EIT waves after the name of the Imaging EUV instrument on the SOHO spacecraft. Rouillard et al., 2012 [31] found that in the event of 21 March 2011 the delay between the SEP releases as retrieved from the observations of the SOHO and STEREO spacecraft was consistent with the time ( $\approx 30$  min) required for the coronal wave front to propagate between the locations connected to the corresponding spacecraft magnetic line. In this case the EIT wave acted as a SEP release trigger. It is worth mentioning that in the event of 3 November 2011 the SEPs were observed to propagate around the Sun along the solar surface with a speed of 1070 km/s [32]. Fast coronal propagation can explain a broad heliolongitudinal distribution of the parent flares of the gradual events without the involvement of the extended accelerating shock front.

Miteva et al., 2014 [33] examined a role of the EIT wave in the SEP acceleration for 179 events during 1997 - 2006, 87% of the events being accompanied by EIT waves. From the timing analysis of the SEP release and the EIT wave intercept of the spacecraft-connected interplanetary magnetic-field line, the authors of [33] concluded that the acceleration scenario is consistent with observations of the SEP protons and not consistent with observations of the electrons.

Thus, the role of the coronal wave in the SEP release was confirmed but the role in the SEP acceleration is not clear as yet.

#### 4. Long-term gamma-ray emission from the solar flares

Ions and electrons accelerated in the flare region can precipitate into the solar atmosphere and interact with the ambient matter. Gamma-ray lines, arising in the neutron capture by a proton (2.223 MeV), in prompt nuclear deexcitation (4–6 MeV) and in pion-decay radiation (above 70–100 MeV) are generated by the accelerated ions precipitating into the solar atmosphere, while the accelerated precipitating electrons generate in the solar atmosphere the bremsstrahlung continuum. These emissions have been traditionally considered as signatures of the particle acceleration in the flare region [34–36]. In majority of events gamma-ray emission lasted not longer than the impulsive phase of a flare, however, in several events of 1991 the GAMMA1 and CGRO spacecraft detected the high-energy gamma-emission for several hours after the flares [37–39]. The energy of the gamma radiation was above  $\approx 50$  MeV and up to several GeV, the time profile demonstrated a double component structure with the fast decay corresponding to the impulsive phase of a flare and the slow decay sometimes up to the several hours. The pion emission was detected only during the slow phase. Therefore, it was concluded that the processes taking place during the extended phase differ from those during the impulsive phase. Two main scenarios of gamma-ray generation were suggested: the first one is based on continuous acceleration [40, 41], the second one is connected with injection of the flare accelerated particles into a coronal loop, trapping and subsequent precipitation of particles into the photosphere [38, 42].

The regular monitoring of the high-energy gamma emission from the solar flares started in 2008 with the launch of the Fermi Gamma Ray Space Telescope, but such events resumed only in 2010 at the ascending phase of the solar cycle 24. During 2010–2012 the Fermi LAT instrument recorded 18 episodes of the flare gamma-ray  $> 30$  MeV emission, almost all of them with  $> 100$  MeV and a few up to several GeV radiation [43, 44]. Majority of events had an extended gamma-ray emission lasting more than an hour. The events localized in the flare solar active regions. The rate of the  $> 100$  MeV gamma-ray events appeared to be much higher than it was previously

thought and, surprisingly, they were mostly connected with the moderate M-class flares rather than with the X-class flares. Majority of events demonstrated an impulsive phase lasting for  $\approx 10$ – $100$  s similar to that of the HXRs, but  $> 100$  keV bursts were not found during the long-term phase of the gamma-ray events [45]. It should be mentioned that the total emitted energy in the  $> 100$  MeV gamma radiation integrated over the long-term phase composed only a small fraction of energy in the SXR range ( $\approx 10^{22}$ – $10^{23}$  erg against  $10^{25}$  erg). All the events were accompanied by the fast CMEs.

Analysis of the distinguish events of 7 March and 7 June 2011 was performed in [43] and that of 7 March 2012 in [44]. The event of 7 March 2011 lasted  $\approx 14$  hours and the highest recorded energy of gamma-rays was  $\approx 1$  GeV. This requires the protons of energies  $\approx 5$  GeV in the case of the  $\pi^0$  decay origin and electrons with energy above 1 GeV in the case of the electron bremsstrahlung. The event of 7 March 2012 yielded the most energetic photons up to 5 GeV and lasted during  $\approx 20$  hours. The gamma-ray spectra modeling showed better agreement with the pion-decay rather than bremsstrahlung emission, the power-law index of protons being  $\approx -4.5$  [43]. Analysis of the energy gain versus energy loss and temporal behavior of the gamma-ray spectrum showed that trapping of particles was not a likely scenario and the more realistic was continuous stochastic acceleration at the corona [44].

Relation between the interplanetary SEPs and the protons generating the prolonged high-energy gamma-ray emission is ambiguous. From August 2010 to August 2012, 18 episodes of the high-energy solar gamma-emission were recorded by the Fermi LAT, while around 40 SEP events with the flux of  $> 10$  MeV protons  $\geq 1 \text{ cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$  was recorded by the GOES [46]. Only 50% of SEP events with  $> 100$  MeV protons coincided with the Fermi LAT events. According to estimation by [44] protons producing gamma rays in the event of 7 March 2012 carried significantly less energy than SEP protons observed by GOES.

In 2013–2014 the  $> 100$  MeV solar gamma-rays were observed from the behind-the-limb solar flares on 11 October 2013, 06 January 2014, and 01 September 2014, at the heliolongitudes of E106, W110 and E126, respectively [47, 48]. Localization of the flares was confirmed by the STEREO observations of the extreme ultraviolet intensity. All events were accompanied by the CMEs with the speed above 1200 km/s. Gamma-ray emission from these flares could not originate from the flare site because of high optical depth. Generation of photons by the particles trapped in the coronal loops needed rather unrealistic condition. Therefore, the authors suggested that gamma-ray emission was caused by protons accelerated at the CME-driven shock and precipitated to the solar disk.

In view of new findings the observations of long-term high-energy gamma-ray emission from the solar flares are not a strong argument in favor of the particle acceleration in the flare site.

## 5. Recent results on the solar neutrons

Neutrons are generated in the solar chromosphere via nuclear interactions of accelerated protons and alpha particles. They can be revealed from the 2.223 MeV gamma-ray line caused by a neutron capture on protons and in the direct measurements by spacecraft detectors and ground-based neutron monitors. Since neutrons decay on their route from the Sun with a lifetime of  $\approx 885$  s only a  $\approx 30\%$  fraction of 100 MeV escaped neutrons can reach the Earth. For 10 MeV neutrons this fraction is  $\approx 2\%$ . It is possible to detect solar neutrons by measuring the decay protons and electrons but only a few such events have been observed up to now [49].

Discovery of solar neutrons was predicted in 1951 [50] and the first observation refers to 1982 [51], however the solar neutron events were seldom observed before late 2000s when the dedicated instrument was installed onboard ISS [52]. Observation of solar neutrons with the ground-based detectors is a difficult problem because of neutron absorption in the atmosphere. That is why a special network of neutron detectors (solar neutron telescopes (SNTs) and neutron monitors) was developed. All these detectors, sensitive to the  $> 100$  MeV solar neutrons, are

situated at the mountains at low latitudes and are spread more or less uniform over the Earth's longitude (see details in [53]). In 1990–2005 a bulk of the solar neutron events (in total, 12) were recorded with neutron monitors and the SNT network. From 2009, the SEDA instrument onboard ISS enables to retrieve the energy spectrum of solar neutrons in the band of 40–150 MeV. At present, circa 15 events were recorded, leading the authors [54] to conclusion that they were mostly produced by the moderate M class solar flares rather than by impulsive phase associated with the X class flares as previously observed. Note that previously observations mostly referred to the  $> 100$  MeV neutrons. Close connection with the long lasting Fermi LAT gamma-ray event was found.

Special interest presents the event of 8 July 2014 which was recorded both by two mountain solar detectors and by the SEDA instrument [55]. Two enhancements in the solar neutron intensity-time profile were recorded by the ground-based stations during  $\approx 50$  min. The first one presumably related to the protons accelerated by the electric field at the magnetic reconnection of two loops observed by the Solar Dynamical Observatory (SDO). The second enhancement lasting for  $\approx 25$  min was not accompanied by any signs of reconnection at the SDO. Moreover, the hard X-ray emission according to Fermi GBM spectrometer was recorded only at the time of the first solar neutron enhancement. To explain the second enhancement the authors [55] suggested a scenario where particles may be accelerated at the front shock of the CME, trapped in the CME magnetic loop and fall down to the solar surface, where they produce high-energy neutrons.

Thus, new observations indicate that of the solar neutrons can be generated not only by the protons accelerated in the flare region during the impulsive phase but also by the protons accelerated by the CME driven shock.

## 6. Sub TeraHertz and TeraHertz solar radio emission

Several patterns of radio emission connected to the flare activity are generally observed, such as type II, type III, type IV, and microwave emission. The electrons with energies of a few tens of keV moving upward from the flare site along the open magnetic field lines produce plasma waves which are recorded as the type III radio emission. Since the plasma wave frequency is directly related to the ambient density, which decreases with a distance from the solar surface, fast frequency drift is observed from hundreds of 100 MHz toward lower frequency band. Therefore the type III radio emission is indicative of open magnetic field in the flare region. Majority of type III bursts occur at the beginning of flare events, in the impulsive phase.

Type II bursts are assumed to be caused by shocks because their drift rates indicate speeds of about 1000 km/s. The disturbance excites plasma waves at the local plasma frequency. Relation of the type II bursts to CMEs is ambiguous. They may be CME driven or associated with mass motion, such as flare ejecta or chromospheric evaporation flows. Or they may be due to freely propagating blast waves caused by flare explosions. Nevertheless, start of the type II emission is considered as a signature of a shock occurrence in the corona.

Type IV at frequency lower than  $\approx 300$  MHz is due to gyrosynchrotron emission of mildly relativistic electrons trapped in the coronal magnetic field. Radio emission in the  $> 1$  GHz band is commonly referred to as a microwave emission. It is a synchrotron radiation of the relativistic tail of the non-thermal flare electrons accelerated in the impulsive phase of a flare. The frequency spectrum has usually a maximum around  $\approx 3$ –30 GHz, for the powerful events up to  $\approx 100$  GHz. Then a microwave flux decreases with the frequency growth. Features of the microwave emission are rather closely related to the fluxes and spectra of SEPs and were successfully used as arguments in favor of a dominant flare contribution to the SEP acceleration [35, 56].

In early 2000s, new instruments capable measuring radio emission in the sub-THz range found that the microwave flux of some flares increased after a local minimum [57]. The enhanced emission was observed at 210–212 GHz and at 405 GHz, although it was not always a case.

Krucker et al., 2013 [58] presented 14 events with the data above 200 MHz, among them 50% demonstrated the "normal" microwave spectra. In all these events, SEPs were not detected that may partly be explained by the eastern heliolongitudinal position of 5 flares from 7. Actually, in the event of 25 August 2001, X5.3, S21E34, the orbital SONG spectrometer has recorded the pion decay gamma emission which proved presence of the  $> 300$  MeV protons, however no SEPs were detected. The timing analysis [59] showed significant correlation between the dynamics of the gamma-ray spectrum and the frequency spectrum of the radio-emission in the impulsive phase of the event.

The events where the sub-THz radio flux increases with frequency got name the terahertz events [58]. All but one events were associated with the X-class flares. The new component was observed in the impulsive phase of a flare and in general it showed noticeable relation with different hard X-ray and gamma-ray features. Close spatial position on the Sun of the THz and 2.223 MeV gamma-ray line sources enables [58] to suggest nuclear interactions to be possible origin of the THz component in the event of 28 October 2003. A noticeable feature of the THz component are rapid pulsations (at 1 s period or faster) which are superimposed on a more gradual flux-density variation. The onset of pulsation was found to be close to a CME occurrence therefore a relation may exist between sub-mm pulsations and a CME launch [60]. Possible mechanisms of the THz flare emission are overviewed by [58].

Further development of technique led to detecting of events with the higher flux at 30 THz, [61]. A real maximum is not possible to determine because of the poor frequency coverage. Three such events have been recorded up to now: 13 March 2012, 01 August and 27 October 2014, only the first one being a SEP event. All three events exhibited intense fluxes in the range of  $3 \times 10^4$  solar flux units (SFU), considerably larger than those measured for the same events at microwave and submillimeter wavelengths, which comprised  $< 10^3$  SFU. None of the 30 THz events coincide with the Fermi LAT Significant Event List. Analysis of the 01 August 2014 event performed by [62] showed complex spatial and temporal relationships between the 30 THz and other wavelength emissions coming from the chromosphere, transition region and corona. The timing analysis argues that origin of the 30 THz emission might be close to the loop footpoints, at a flaring site lower in the chromosphere. There are signatures of both thermal and nonthermal sources of the THz radiation.

Observational data are now too scarce and the THz emission needs further study.

## 7. Conclusion

It is now clear that the most energetic particle fraction of gradual SEP events, including relativistic protons responsible for the GLEs, can originate from the flare region. A broad distribution of the parent flares of the gradual events can be explained, at least partly, by the fast coronal propagation of the SEPs [32]. On the other hand, the contribution of the CME acceleration can be dominating in the less energetic SEPs.

Recent discoveries showed that processes of particle acceleration on the Sun appeared to be more complicated than it was believed. The intensity-time profiles of the long lasting gamma-ray emission do not correspond to the SEP time histories, probably, the fluxes of high-energy protons being too small and beyond the sensitivity of the recent particle detectors. The  $> 100$  MeV gamma-ray emission lasts for hours and is localized near the flare region [43, 44]. The long-lasting acceleration in the flare region is now not incorporated into the flare acceleration processes. New observations [47, 48, 55] showed that the particles generating the  $> 100$  MeV gamma rays and the solar neutrons can originate from a CME driven shock. That means that protons can be accelerated at a shock front in the corona up to relativistic energy during a short time, be trapped and precipitate downward [55].

The discovery of the THz solar emission was not predicted. It requires high plasma density, strong magnetic field and a great number of energetic electrons. That poses a question about a

height of the energy release. At the moment, the observational data are not sufficient to propose a realistic scenario.

It is known that particle acceleration on the Sun is triggered by a sudden energy release usually concomitant of a flare and/or a CME. The electromagnetic emission from radio to gamma-rays and the SEPs in the interplanetary space can emerge as a result of a solar explosion. It was previously assumed that the more strong events generate more numerous and energetic SEPs, and gamma-ray emission and neutrons are signatures of the most powerful events. New observations showed that the long-lasting  $>100$  MeV gamma-ray emission and the neutron generation are often connected with moderate flares of the M-class. Moreover, there is neither close correspondence between the SEP events and the  $>100$  MeV gamma-ray events, nor between energies of the SEPs and the gamma-ray emission. Particles are accelerated on the Sun up to GeV energies much more often than it was earlier believed. The scenarios with prolonged acceleration and with trapping and precipitation are not developed enough as yet.

In any case, the new discovered manifestations of a sudden energy release are connected with particle acceleration, and often up to much higher energies than SEPs. New discovered manifestations have to be incorporated in the paradigm of the explosive energy release on the Sun. It is necessary to find out how energy of solar explosion is distributed among various channels of particle acceleration. Understanding of condition and processes resulting in occurrence of one or another type of manifestation may be achieved by further accumulation of observational data and profound modeling.

## Acknowledgments

This work is partly supported by the Russian Foundation for Basic Research Grants no. 14-02-00905, 16-02-00100. Thanks are due to my colleagues from the Lebedev Physical Institute for useful discussions.

## References

- [1] Forbush S E 1946 *Phys. Rev.* **70** 771
- [2] Hilton E 2008 <http://docslide.us/documents/2-physical-processes-in-solar-and-stellar-flares-eric-hilton-general-exam>
- [3] Li Y and Lin J 2012 *Solar Phys.* **279** 91-113
- [4] Raymond J C *et al.* 2012 *Space Sci. Rev.* **173** 197-221
- [5] Schure K M *et al.* 2012 *Space Sci. Rev.* **173** 491-519
- [6] Petrosian V 2012 *Space Sci. Rev.* **173** 535-56
- [7] Gosling J T 1993 *Geophys. Res.* **98** 18937-49
- [8] Lee M 2005 *ApJS* **158** 38-67
- [9] Klein K-L *et al.* 2014 *Astron. Astrophys.* **572** A4
- [10] Reames D V 1999 *Space Sci. Rev.* **90** 413
- [11] Kahler S W and Vourlidas A 2013 *Astrophys. J.* **769** 143
- [12] Miteva R *et al.* 2013 *Sol. Phys.* **282** 579-613
- [13] Richardson I G *et al.* 2014 *Sol. Phys.* **289** 3059-107
- [14] Dierckxsens M *et al.* 2015 *Sol. Phys.* **290** 841-74
- [15] Grechnev V V *et al.* 2015 *Sol. Phys.* **290** 2827-55
- [16] Salas-Matamoros C and Klein K-L 2015 *Sol. Phys.* **290**(5) 1337-53
- [17] Simnett G M 2006 *Astron. Astrophys* **445** 715-24
- [18] Bazilevskaya G A 2009 *Adv. Space Res.* **43** 530-6
- [19] Gopalswamy N *et al.* 2012 *Space Sci. Rev.* **171** 23-60
- [20] Thakur N *et al.* 2014 *Astrophys. J.* **790** L13
- [21] Tylka A J *et al.* 2013 *Sol. Phys.* **285** 251-67
- [22] Logachev Yu I *et al.* 2016 [http://www.wdcb.ru/stp/online\\_data.en.html#ref113](http://www.wdcb.ru/stp/online_data.en.html#ref113)
- [23] Ellison D C and Ramaty R 1985 *Astrophys. J.* **298** 400-8
- [24] Band D, Matteson J and Ford L 1993 *Astrophys. J.* **413** 281-92
- [25] Nymmik R A 2011 *Bulletin of the Russian Academy of Sci. Phys.* **75**(6) 761-3
- [26] Bruno A 2016 Private communication



- [27] Desai M I *et al.* 2016 *Astrophys. J.* **816**(2) 68
- [28] Laurenza M *et al.* 2012 *Proc. AIP Conf.* **1539** 219-22
- [29] Bazilevskaya G A and Sladkova A I 1997 *Proc. 25th Int. Cosmic Ray Conf. (Durban, South Africa)* **7** 333-6
- [30] Warmuth A 2015 *Living Rev. Solar Phys.* 3-101
- [31] Rouillard P *et al.* 2012 *Astrophys. J.* **752** 44
- [32] Mewaldt R A *et al.* 2013 *AIP Conf. Proc.* **1539** 116
- [33] Miteva R *et al.* 2014 *Sol. Phys.* **289** 2601-631
- [34] Ryan J M, Lockwood J A and Debrunner H 2000 *Space Sci. Rev.* **93** 35
- [35] Grechnev V V. *et al.* 2008 *Sol. Phys.* **252** 149-77
- [36] Kurt V *et al.* 2013 *Advances in Astronomy* **2013** ID 690921
- [37] Akimov V V *et al.* 1991 *Proc. 22nd Int. Cosmic Ray Conf. (Dublin)* **3** 73-6
- [38] Kanbach G *et al.* 1993 *Astron. Astrophys. Suppl.* **97** 349
- [39] Rank J *et al.* 2001 *Astron. Astrophys.* **378** 1046
- [40] Akimov V V *et al.* 1996 *Sol. Phys.* **166**(1) 107-34
- [41] Ryan J M and Lee M A 1991 *Astrophys. J.* **368** 316-24
- [42] Mandzhavidze N and Ramaty R 1992 *Astrophys. J.* **396** L111-L114
- [43] Ackermann M *et al.* 2014 *Astrophys. J.* **787** 15
- [44] Ajello M *et al.* 2014 *Astrophys. J.* **789** 20
- [45] Struminsky A and Gan W 2015 *JPCS* **632** 012081
- [46] URL [http://satdat.ngdc.noaa.gov/sem/goes/data/new\\_avg/](http://satdat.ngdc.noaa.gov/sem/goes/data/new_avg/)
- [47] Pesce-Rollins M *et al.* 2015 *PoS(ICRC2015)* 128 *arXiv*: 1507.04303v2
- [48] Pesce-Rollins M *et al.* 2015 *Astrophys. J. Letters* **805** L15
- [49] Agueda N *et al.* 2011 *Astrophys. J.* **737** 53-60
- [50] Biermann L, Haxel O and Schluter A 1951 *Z. Naturforsch.* **6**(1) 47-8
- [51] Chupp E L *et al.* 1982 *Astrophys. J.* **263** L95
- [52] Muraki Y *et al.* 2012 *Advances in Astronomy* **2012** ID 379304
- [53] Valdes-Galicia J F *et al.* 2009 *Adv. Space Res.* **43** 565-72
- [54] Muraki Y *et al.* 2013 *arXiv*: 1307.5376v1
- [55] Muraki Y *et al.* 2016 *Sol. Phys.* published on line DOI 10.1007/s11207-016-0887-0
- [56] Chertok I M, Grechnev V V and Meshalkina N S 2009 *Astron. Rep.* **53**(11) 1059-69
- [57] Kaufmann P *et al.* 2004 *Astrophys. J.* **603** L121-4
- [58] Krucker S *et al.* 2013 *Astron. Astrophys. Rev.* **21** 58
- [59] Makhmutov V S *et al.* 2011 *Bulletin Russian Academy Sci. Phys.* **75**(6) 747-50
- [60] Kaufmann P *et al.* 2003 *J. Geophys. Res.* **108**(A7) 1280
- [61] Kaufmann P *et al.* 2015 *J. Geophys. Res. Space Phys.* **120** 4155-63
- [62] Miteva R *et al.* 2016 *Astron. Astrophys* **586** A91