Solar Energetic Particles and Cosmic-Ray Effects at Earth and Planets

R. Vainio

Department of Physics, University of Helsinki, Finland

Abstract: The paper presents an overview of about half of the solar and heliospheric sessions of the 32nd International Cosmic Ray Conference (ICRC), Beijing, 2011. It covers the topics of solar energetic particle (SEP) acceleration and transport at the Sun and the interplanetary medium as well as the effects of SEPs and galactic cosmic rays on Earth and planetary environments. The paper is written from a personal perspective, emphasizing those results that the author found most interesting. The debate of the SEP origin in flares and coronal mass ejections (CMEs) is still partly undecided. The focus of the debate is presently on the acceleration mechanisms responsible for the generation of particles at the highest energies (deka-MeV and beyond) during the early phases of large gradual energetic particle events. Several papers addressing the roles of flares and CMEs in the acceleration process were presented. Results on electromagnetic emissions during the timing of particle release were presented, revealing that timing alone cannot distinguish between flare and CME-shock related acceleration. Observations on charge states showed a large variety of possible sources and/or seed populations during SEP events. Theoretical/numerical studies revealed that particles acceleration at shocks can produce a variety of particle spectra when time-dependent effects are included showing that the common expectation that shocks produce featureless power-law spectra does not apply to particle observations far from the source. SEP transport modeling in the interplanetary medium is entering a new era, as models implementing the full three-dimensional transport in space within the focused transport theory are becoming available. Several new modeling results on SEP events highlight the new effects that the inclusion of perpendicular diffusion brings to the theory. While this paper will focus on the SEP acceleration and transport, it will cover some interesting highlights of the results on space weather predictions using SEP and GCR fluxes, atmospheric particle acceleration, ionization, and cosmogenic isotopes. Also, a few of the numerous papers presenting new experiments and observational techniques are covered by the review.

Key words: Solar Particle Emission, Solar Flares, Coronal Mass Ejections, Shock Waves, Diffusion, Space Weather

1 Introduction

Solar energetic particles (SEPs) and galactic cosmic rays (GCRs) constitute two high-energy charged-particle populations in the interplanetary medium with different observational characteristics [1]. Nevertheless, the physics of their transport and, at least partly, their acceleration is the same [1]. Both populations are also important from the point of view of the space radiation environment [2], which is one of the most important components of space weather — the physical and phenomenological state of natural space environments [3]. GCRs and the high-energy SEP component affect also the terrestrial and planetary atmospheres. These topics were covered by the SH sessions of the 32nd International Cosmic Ray Conference (ICRC) held in Beijing in August 2011. In the following, we will review the results of the following sessions:

SH1: Sun and solar emissions
SH2.1: Interplanetary transport of solar energetic particles

SH4: Cosmic rays at Earth and in planetary environments.

The paper is organized as follows: in section 2, we present the results on solar energetic particles discussing both the origin and transport of SEPs; in section 3, we discuss the effects of cosmic rays at Earth and planetary environments; in section 4 we highlight some of the experimental work presented; and in section 4 we summarize the results.

2 Solar energetic particles

2.1 Origin of Solar Energetic Particles

The origin of SEPs is a matter that has been debated for decades. Prior to the detection of CMEs in the early 1970s, solar flares were the only perceivable source of energetic particle emissions from the Sun. In the early 1980s it became clear that while flares are the source of impulsive \(^{3}\)He-rich SEP events, CMEs are main cause of large gradual energetic particle events [1]. Thus, the pendulum swung to the other extreme, pushing flares from the focus of discussion of the large gradual events almost entirely. After the excellent measurements from several space missions during the 23rd solar cycle, however, the matter is no longer clear concerning the origin of the SEPs at the highest energies (beyond some tens of MeVs).

Experimental knowledge on SEP origin can be obtained (at least) through the analysis of

- timing of SEP event onset;
- energetic neutral emissions (neutrons and photons) associated with the SEP event; and
- composition of SEPs, i.e., their abundances and charge states.

All these experimental tools were utilized in the papers presented in the SH1 sessions. In addition, several papers were presented addressing these observational issues using numerical models of particle acceleration at/near the Sun. We will consider each of these in turn.

2.1.1 Timing of SEP event onset

Several authors [4–6] performed observational analysis of the onset of large SEP events and compared the inferred solar release times with electromagnetic emissions from the Sun. When using the onset analysis to infer the origin of relativistic protons, the main electromagnetic emissions considered are X-rays and gamma-rays from flares and type II radio emission from shock waves driven by CMEs.

Yushkov et al. [4] considered the historical record of Ground Level Enhancements (GLEs), which represent the most energetic SEP events detected. They analyzed 42 GLEs observed since 1972 for which solar X-ray and gamma-ray observations are available. Using the soft X-ray flux as a proxy of the total energy deposited in the flare volume, the authors determined the time of the main energy release of the flare, \(T_{\nu}\). This time is then compared with the observed relativistic proton onset time from neutron monitor (NM) observations. The study indicates that the time of maximum flare energy release always precedes the onset time of relativistic proton flux, typically by less than 10 minutes, but also considerably longer (up to 50 minutes) in some cases (see Figures. 3 and 4 in [4]). This is interpreted by the authors as support for the flare origin of these particles. They note, however, that the onset time of the type II radio burst related to the same event is typically very close (within 10 minutes) to the time of maximum energy release of the flare. Thus, from this correlation alone it is impossible to draw a definite conclusion about the origin, flare or coronal shock, of the relativistic protons. The authors, however, point out that when high-energy gamma-rays (from pion decay) are observed from the flare, their onset time is in close correlation with the main energy release of the flare [7]. This leads them to support the flare origin of the relativistic protons. (See also [5].)

Gopalswamy et al. [6] analyzed the 16 GLEs of the 23rd solar cycle in great detail with the aim of finding out how the release of relativistic protons compares with the times and heights of shock formation in the solar corona. The basic measurements they use are the CME height-time profiles, type II radio burst onset times, the onset times of X-ray flares and the onset times of GLEs. These authors also demonstrate, using new EUV observations from AIA/SDO, that the onset of the metric type II burst really corresponds to the generation of the CME-driven shock wave in the low corona. Through a careful analysis of the CME height-time evolution, the authors derive the coronal shock heights at the time of the relativistic proton release. These heights vary between 1.74 and 7.98 solar radii, the mean value being 3.6 solar radii. The shocks themselves form at low altitudes, indicated by the CME heights at the start times of the type II radio bursts that average around 1.4 solar radii. For well-connected GLEs/CMEs (i.e., those occurring close to the footpoint of the nominal Parker spiral), the
average shock height at the time of solar proton release is 2.6 solar radii, which is consistent with an average particle acceleration from shock formation to relativistic proton release of 6 minutes.

The onset times of particle fluxes given by Yushkov et al. [4] and Gopalswamy et al. [6] are slightly different, being typically later in [6]. This may be due to the fact that some of the GLEs have small precursors that show increases of only a few sigma above the background, followed by the main increase some minutes later. As an example, Figure 1 of [4] shows the South Pole NM counting rates for the 15 April 2001 GLE, which show a small precursor at the quoted onset time of 13:48, whereas the main increase occurs at 13:59, closer to the time quoted in [6] (13:57). This indicates that the times deduced by Yushkov et al. [4] would be consistent with a source operating earlier, and in some cases coinciding with the type II onset, which leaves very little time for acceleration at the shock. Furthermore, the presence of pion-decay gamma rays during the flare energy release is a clear indication of proton acceleration. Thus, it seems that in some GLEs there is a contribution to the fluxes from the flare. However, the main phase of the GLE seems consistent, timing-wise, with the shock source in all cases considered in [6].

It should also be kept in mind that the onset time of a charged-particle flux at 1 AU is always compromised by interplanetary transport processes [8, 9], which may lead to uncertainties of the order of several minutes of the solar release time of relativistic protons [10]. This adds to the uncertainty of the conclusions so it is fair to say that both flares and CME-driven shocks are still candidates for the acceleration of GLEs.

2.1.2 Energetic neutral emissions

Preliminary Fermi-LAT observations of a very long duration gamma-ray flare were presented in the conference [11]. The solar event on 7-8 March 2011 showed a peculiar time-intensity profile of pion-decay gamma rays. The light curve at \(E_\gamma > 100\) MeV showed a maximum around 3:00 UT on 8 March, i.e., 7 hours after the maximum of the preceding M3.7 X-ray flare. No corresponding long-lasting flux increases in hard or soft X-rays or at radio frequencies was observed. However, GOES detected a moderate solar energetic proton event at 1 AU concurrently with the gamma-ray event. There was a fast CME (with a speed of 2200 km s\(^{-1}\)) related to the flare. There were no neutron capture or de-excitation lines observed by RHESSI during the event, but that was calculated to be consistent with the sensitivities of the two instruments. The same event was also reported as a possible source of high-energy neutrons [12], but these were observed only in close connection with the soft X-ray flare.

Long-duration high-energy gamma-ray events have been observed before, but this event was a very peculiar one because of its very late peaking. Two possible scenarios were considered: stochastic acceleration of a trapped proton population in a closed loop or continuous acceleration by the CME-driven shock. Both scenarios meet obvious problems: the loop scenario would require turbulence to be maintained for 12 hours after the main energy release of the flare, while no strong additional energy releases were observed. The shock scenario, on the other, should somehow explain the propagation of particles back to the Sun. The approximate location of the gamma-ray source is consistent with the footpoints of the field lines connected to the shock, but the protons accelerated by the shock should propagate against the CME flow back to the corona from distances that are a large fraction of an AU. At present, this event remains a puzzle, but demonstrates the capabilities of Fermi-LAT as a solar-gamma-ray observatory. Thus, more interesting results on long-duration gamma-ray events from the Sun may be expected in future, as the solar activity picks up. At the same time, also the capabilities of detecting high-energy solar neutrons will significantly increase [13, 14] through the introduction of the SciCR telescope at Mt. Sierra Negra in Mexico.

2.1.3 Modeling of emission from shocks and flares

Several papers were also presented on modeling of solar energetic particle acceleration in shock waves and flares [15–21]. Berezhko and Taneev [15] presented a model, where particle transport is treated using the Parker equation with a diffusion tensor of form \( \kappa = \kappa \vec{\mathbf{r}} \vec{\mathbf{r}} \) and \( \kappa \) determined from the intensities of self-generated Alfvén waves that are computed concurrently with the particle distribution using quasilinear approximation. They consider a model of the ambient Alfvén wave intensity that uses as boundary conditions the observed turbulent magnetic fluctuation intensity at 1 AU and a coronal Alfvén wave energy flux of \(10^9\) erg cm\(^{-2}\) s\(^{-1}\). The spectral form used is consistent with Kolmogorov turbulence at high frequencies. This results in an ambient wave intensity scaling as \(r^{-4.3}\), which means that the turbulence is relatively strong in the corona as the background magnetic field scales like \(r^{-2}\).

The model of Berezhko and Taneev [15] shows that protons can be accelerated in coronal shocks to
very large energies, exceeding 10 GeV. The spectrum of shock-accelerated protons and alphas compares well with the observations during the largest GLEs. The background turbulence in the model is very intensive, enough to produce \( \sim 1 \) GeV protons even in the linear approximation (excluding wave growth) already for shock speeds of 1000 km s\(^{-1}\) within 5 solar radii. This indicates that the background turbulence in the model is exceedingly large, since typical SEP events with 1000 km s\(^{-1}\) CMEs are far from generating GLE energies. Nevertheless, the modeling shows that in principle shocks have no problems in generating GLEs within a couple of solar radii from the surface, so the observational constraints from the work of Gopalswamy et al. [6] are satisfied.

Another self-consistent shock acceleration model was presented by Battarbee et al. [16]. They considered a similar radial magnetic field geometry and wave growth model as in [15], but including the WKB effects on the wave transport equation and computing the particle distribution under the focused transport assumption, using a Monte Carlo simulation. The model normalizes the background wave intensities by fixing the ambient particle mean free path at 1 AU to a value consistent with observations. As Berezhko and Taneev [15], Battarbee et al. [16] used a seed particle population that scales with the ambient coronal ion density, but they used a re-scaling of the density by a factor of 0.01 to limit the wave growth and maximum proton energies achievable during the event to values well below those observed in GLEs. In addition protons, they consider also heavy ions including He isotopes, oxygen and iron. They show that the maximum energies per nucleon for heavy ions scale less steeply with charge-to-mass ratio than proposed previously based on theoretical estimates [17], i.e., approximately as \( E_c/A \propto (Q/A)^{1.5} \), compared to \( E_c/A \propto (Q/A)^{2} \) obtained from simple theory. The simulated value of the scaling exponent agrees well with observations during many events. The spectral indices of different ion species in the upstream region behave differently as a function of time, which is also a result that cannot be obtained from simple theoretical estimates.

A third shock acceleration model was presented by Kocharov et al. [18]. In this model, turbulence was assumed to be of ambient type (linear approximation) but the magnetic geometry of the system corresponded to a shock propagating in a closed loop with leakage of ions from the loop-top area assumed to have a Y-type neutral point in the vicinity. The model is designed for MHD input and solves the Parker equation using the Monte Carlo method in a coordinate system that is Eulerian along the magnetic field direction and Lagrangian in the perpendicular directions. This has the advantage that the MHD input can be given on a single field line, only, if perpendicular diffusion is neglected. The model also includes stochastic re-acceleration of particles in the downstream region of the shock. The first results of the model indicate that the first tens of minutes of major SEP events, often showing high-energy bump-in-tail-like distribution even after the removal of velocity dispersion, could be explained assuming acceleration in closed loops followed by rigidity-dependent escape from the top of the loop. It is important to understand that shock acceleration is not a model that categorically produces power laws with or without exponential cutoffs. This is important also in the interpretation of spectra the highest energies that are becoming available from careful analyses of GLE data (e.g., [22]).

Also models appropriate for flares were presented. Kartavykh et al. [19] considered a model with stochastic acceleration in external Alfvenic turbulence and Coulomb losses, applied to the calculation of the enrichment of heavy and ultra-heavy ions in SEP events. The authors found the enrichment to be sensitive to the turbulence spectral index, \( S \), and reported systematic increase of heavy-ion acceleration efficiency for spectral indices \( S \geq 2 \), and average enrichment factors of 200 for ultra-heavy ions for \( S = 2.5 \), in agreement with observations from impulsive flares.

Kinetic modeling studies of shock structure [20] and radio emission from shocks [21] were also presented. Ganse et al. [21] addressed the generation of type II radio bursts using a Particle-in-Cell (PiC) simulation model. They initialized the simulation with an electron distribution function that had two counter-streaming beams on top of a quasi-thermal main component. The motivation for the study was that in order to understand the narrow-band nature of type II radio emission from global CME-driven shocks, some sort of special conditions need to be met. One option is that the emission comes from a quasi-perpendicular rippled shock that contains regions where counter-streaming shock-accelerated electron beams can collide. The study revealed efficient generation of electrostatic beam-driven waves and electromagnetic emission at plasma frequency and its first harmonic. However, the results are not completely clear since the electromagnetic modes have also a continuum component, probably directly driven by the...
statistical fluctuations in the simulation. The study, however, indicates that kinetic simulations on radio emission are a promising way forward in trying to understand the solar radio emissions related to SEP events.

2.1.4 Composition

Elemental, isotopic and charge-state composition of energetic particle populations can be used to deduce the properties and origin of the seed population being accelerated during the event. Thus, it is one of the most important tools to solve the remaining puzzles of SEP origin. Several interesting contributions on SEP composition were presented in the conference [23–26].

Charge states of accelerated heavy ions are determined by the temperature of the source plasma and the product of the source density and acceleration time, which determine the additional stripping during the acceleration. Thus, when studying the charge states as a function of energy, we can infer a lot of information on the acceleration process and the acceleration site. Klecker et al. [23] and Popecki et al. [24] studied the iron charge-state distributions and the evolution of mean charge in five large gradual SEP events using observations from ACE/SEPICA. They obtained large variability in event characteristics: one event out of five had an iron charge state distribution consistent with a single 1-MK source combined with an average ionic charge that showed no temporal variations over the event. The event showed a classical intensity-time profile of a low-energy SEP event accelerated by an interplanetary shock that passed the spacecraft on Day 160, 2000. Four events were consistent with a 1-MK source plus another source with higher charge state. In two of these events, the higher-Q source was consistent with the charge state distribution obtained as an average from impulsive flares, but in the other two, the high-Q component charge distribution could not be fitted with the impulsive-flare-like distribution. Interestingly, in the cases where the impulsive-like material was observed, it could be observed after the passage of the related interplanetary shock in a solar-wind stream with high iron charge states, indicating that it could be transported there by the ejecta of the eruption or accelerated out of the solar wind. The other two events that could not be fitted with the impulsive-flare-like charge distribution, showed the high-Q component during the onset of the event. Thus, the authors speculated that this source could be related to shock acceleration in the dense low corona with stripping during the acceleration.

The high charge states of low-energy iron ions have typically been taken as an indication of high source plasma temperature. Guo et al. [25] reported on four gradual SEP events that show high iron charge states ($Q > 14$) around $\sim$0.1 MeV/nuc, as observed by ACE/SEPICA. In order to study the source region of these events, they determined the helium charge states during the events and found that a significant amount of singly charged helium was present at these energies. This indicates that the source region is in the solar wind, where interstellar pick-up helium can explain the observation. The high iron charge state is probably due to the presence of remnant material from impulsive events that is accelerated locally by the interplanetary shock and does not reflect the local temperature of the source region.

Elemental abundance ratios of ions accelerated in interplanetary shocks were used by Desai et al. [26] to study the acceleration mechanisms at work in these shocks. The authors studied 74 CME-driven shocks observed by ACE and Wind during solar cycle 23. Besides composition, Desai et al. [26] also used observations of the power spectrum of magnetic fluctuations around the shock to search for indications of turbulence generated by the accelerated ions. They searched for events showing clear signatures of diffusive shock acceleration (DSA) or shock drift acceleration (SDA) in the temporal evolution of the particle events around the shock passage. Only 10 cases were clearly classifiable in either category, whereas 64 events showed mixed signatures. Out of the ten events, four quasi-perpendicular shocks were classified as SDA events and six oblique and quasi-parallel shocks as DSA events. The SDA events showed no significant increase in the wave activity and no significant change in the spectral index of the ions during the shock passage. These events also showed that their Fe/CNO ratio was preserved from the seed population. The DSA cases, on the other hand, showed strong amplification of proton-resonant waves in the upstream plasma and strong softening of the spectrum as the shock approaches the spacecraft, as expected from the theory. Also, the Fe/CNO ratio shows $Q/A$-dependent fractionation in these events. This, in fact, was also present in the heavy-ion simulations of coronal shocks with self-generated turbulence presented by Battarbee et al. [16].

2.2 Solar Energetic Particle Transport

2.2.1 Three-dimensional focused transport modeling

Focused transport model [27] has been work horse
of SEP transport in the interplanetary medium for decades. There, one considers particle transport along the heliospheric magnetic field lines under the influence of focusing caused by the decrease of the magnetic field strength outwards and pitch-angle scattering caused by magnetic fluctuations. The model evolved in the 1990s with the inclusion of solar-wind effects [28, 29]. The properties of classical focused transport are quite well understood up to 1 AU distances from the Sun, and the model has been commonly accepted as the standard model to use in the outer heliosphere, while in the inner heliosphere, the standard transport model is Parker’s equation. (See, however, [30].)

Most recently, the focused transport model has been appended with perpendicular diffusion [31, 32], which allows for three-dimensional transport modeling in the interplanetary medium. Several groups presented new models and analyzed their results and predictions [33, 34]. Many key observations, like the homogeneity of intensities downstream interplanetary shocks, can be explained by including perpendicular diffusion to the focused transport scenario. Some SEP events have shown anisotropies towards the Sun in their initial phases, which can be explained by three-dimensional propagation, where the connection of the observer to the source is poor and particles reach observer’s field line first beyond 1 AU [32, 33]. A poorly connected observer close to the Sun, who only detects particles that have diffused across the magnetic field, will typically also see a more diffuse/smear intensity-time profile than a more distant observer. Thus, in a three-dimensional transport scenario a poorly connected observer has a better vantage point to make observations further out than close to the Sun. (See Figures. 6 and 7 in [34].) This has implications on our expectations on future missions like Solar Orbiter and Solar Probe Plus [35], that are going to observe the events closer to the Sun than before.

2.2.2 Multi-spacecraft observations

Since the end of 2006, STEREO spacecraft have returned the SEP research community to the era of multi-spacecraft observations. Unfortunately, the Sun was very inactive during the first years of the mission, which means that SEP transport studies with a spacecraft separation angles of some tens of degrees are not possible due to the lack of SEP events. Since 2010, however, some events have been observed with STEREO spacecraft separated by close to ninety degrees from the Earth, where SOHO, ACE and Wind can be used to offer a third vantage point [36, 37].

One of the most puzzling events was the $^3$He-rich event on 7 Feb 2010, observed by STEREO-A, ACE and STEREO-B, analyzed by Wiedenbeck et al. [38]. The three spacecraft had a separation of 136 degrees and still the event was observed by all three spacecraft. The best connected one, STEREO-B, observed the event as a typical impulsive event with a fast rise to the maximum followed by an exponential decay. ACE, about 70 degrees away, observed a much weaker event, still with an impulsive-type intensity-time profile, but delayed by several hours from the onset at STEREO-B. Finally, STEREO-A observed a very weak event with low statistics making it impossible to analyze the shape of the intensity-time profile in detail, but with an onset time delayed from STEREO-B by about 18 hours (see Figure 2 of [38]).

Based on the so-called flux drop-outs observed during impulsive events [39], Wiedenbeck et al. [38] reject perpendicular transport as a plausible explanation of the observed longitudinal extent of the event. However, one should take into account that perpendicular diffusion consists of two components: field-line random walk and particles crossing actual field lines. Obviously, flux drop-outs imply that the latter mechanism is quite inefficient as fluxes on neighboring field lines can vary by orders of magnitude. However, depending on the actual geometry of turbulence, perpendicular transport by field-line meandering could still be an efficient way to transport particle fluxes over large longitudinal distances. First-principles computations of particle orbits in synthetic or MHD-simulated fields (see, e.g., [40]) should be performed to bring more understanding on the subject.

2.2.3 Particle transport in special magnetic geometries

Focused transport equation can be applied to many types of magnetic geometries, and not only the Parker spiral interplanetary magnetic field. Sun et al. [41] applied the model to Wind/3DP observations of electrons upstream the Earth’s bow shock. The authors applied a model, where the magnetic field line of the observer was partially immersed in the magnetosheath with an enhanced magnetic field strength and turbulence intensity relative to solar wind. The model reproduces observations of electron pitch-angle distributions quite well using a magnetic-field compression ratio at the bow shock of $B_2/B_1 = 3$ and a very short mean free path of 2 Earth radii in the magnetosheath.

Particle transport under very turbulent conditions in the magnetosheath can be contrasted with
almost scatter-free particle propagation in special category of interplanetary CMEs, i.e., magnetic clouds. Leske et al. [42] analyzed STEREO-A observations of 18 August 2010 event, which showed very large bi-directional anisotropies for the first 18 h of the event, when the spacecraft was inside a magnetic cloud. The authors compare the event with previous observations by SOHO/ERNE [43] of the 2 May 1998 event, which showed a parallel proton mean free path reaching 10 AU. Bi-directional anisotropies inside magnetic clouds are typically explained in terms of mirroring, as particles propagate from one leg of the closed loop-like structure to the other. Kubo and Shimazu [44], however, present an interesting calculation showing that bi-directional fluxes could be achieved also inside a cylindrical magnetic cloud simply a result of cloud expansion.

3 Cosmic rays at Earth and Planets

3.1 Space Weather

Space weather can be defined as the physical and phenomenological state of natural space environments. The associated research discipline aims at predicting the state of the near-Earth space environments. Space storms can be divided in three categories [45]:

(a) solar radiation storms;
(b) radio blackouts; and
(c) geomagnetic storms.

SEP s and GCRs have a role in each of these, SEPs being the direct cause of (a) and contributing strongly to (b), and both providing predictive tools for (c).

SEP events are the most important contribution to the total fluence (i.e., time-integrated intensity) over solar active periods at energies below about 100 MeV. Typically, in radiation effects modeling SEPs are treated using a probabilistic approach. The SEP effects models output the maximum fluence spectrum over a given time period given a user-specified (or fixed) confidence level as input. The models are typically constructed using experimental data, only. Adams et al. [46] present a new probabilistic SEP model that makes use of data on all SEP events from solar cycles 21–24. In the modeling, peak fluxes or fluences from individual SEP episodes (i.e., SEP events of successive events) are fitted as a function energy to a spectrum that captures the intensity and spectral form of the event. From those fits, the integral fluences/fluxes above a given energy can be computed and a distribution of these fluences/fluxes constructed (i.e., number of events per year exceeding a given threshold flux). Such distributions, constructed for a number of energies, can then be used to obtain a probabilistic model of SEP flux/fluence over a given mission time.

Large gradual SEP events and geomagnetic storms are linked together through their common cause, the CMEs. The propagation of a fast CME to Earth takes about two days, but SEP events commence much faster after the lift-off of a CME. Furthermore, SEP events including a passage of a strong (i.e., fast) interplanetary shock over the spacecraft typically contain an energetic storm particle (ESP) component, i.e., a flux enhancement by up to an order of magnitude of low-energy cosmic rays during the shock passage. Thus, it has been proposed (e.g., [47]) that SEP event flux profiles could provide warning of CMEs approaching the Earth hours ahead of the arrival of the CME to the Earth.

Le et al. [48] consider large gradual SEP events and divide them according to the of their intensity-time profiles in three classes: (1) events with only one maximum, soon after the flare; (2) events with two maxima, second one lower than the first one; (3) events with monotonous rise or two maxima, second one higher than the first one. They study the relationship of the events in the different classes with the occurrence rates of geomagnetic storms. Their results are: class (1) events show no intense storms and a few followed by minor or moderate storms; most of the class (2) events are followed by intense, some by moderate storms; and all class (3) events are followed by intense storms. Thus, one could use time-intensity profiles of events in classes (2) and (3) as predictors of moderate to intense storms and the method would have a very low false prediction rate. However, only 1/3 of the total amount of geomagnetic storms could be predicted by SEP events in the first place, so the method cannot be used as only means to provide storm forecasts.

Not only the particle fluxes in ESP events but also the magnetic fluctuations they generate (recall, [26]) can be used as means to provide ahead warnings of fast interplanetary disturbances approaching the observer. Starodubtsev et al. [49] devised a model that makes use of both particle fluxes and magnetic intensity fluctuations to provide ahead warnings of the geomagnetic storms. The first results of the model imply that the lead times of the warning system can be quite long, up to a day before the storm commen-
ment. Statistical results on the performance of the warning system are, however, still missing.

Atmospheric muon detectors with directional sensitivity have also been proposed as efficient detectors of interplanetary magnetic disturbances approaching the Earth. It can shown that there is a relationship with the CR anisotropy observed by muon telescopes [50] and magnetic disturbances driving geomagnetic activity but a quantitative relationship between these is still missing. Note that besides space weather, also atmospheric conditions can be probed with ground-based CR muon detectors [51, 52]. Atmospheric electromagnetic phenomena can also be detected by CR instruments as shown, e.g., by the usage of Pierre Auger Observatory as an elves detector [53].

3.2 Terrestrial Effects

Atmospheric particle acceleration was discussed in several papers of the session on terrestrial effects. Thunderstorm ground enhancements (TGEs) are the most energetic atmospheric particle acceleration events that can be observed by CR detectors [54]. In these events, increases of soft gamma-rays are observed during thunderstorms. The events are modeled using Geant4 by Vanyan and Chilingarian [55]. The studies show that small TGEs can be explained in terms of modulation of the spectrum of secondary CR electrons by the ground-to-cloud electric field (\(\sim 10 \text{ kV m}^{-1}\)). Large TGEs, however, are accelerated in much higher thundercloud fields producing electron-gamma avalanches, analogous to terrestrial gamma ray flashes observed from Earth orbit. Note that direct detection of charged particles accelerated in thunderstorms has also been reported [56].

Soft-gamma-ray increases are observed also during and after precipitation without thunderstorms. Such events were reported and analyzed in two contributions. Vashenyuk et al. [57] explain the events as being produced by the electric field (\(\sim 10 \text{ kV m}^{-1}\)) in low nimbostratus clouds by acceleration of cosmic-ray secondary electrons, which produce bremsstrahlung in the atmosphere. They use a numerical simulation of the acceleration and radiation process and obtain good fit to the observed gamma-ray spectrum. However, Salikhov et al. [58] report similar soft gamma-ray events and interpret them as being produced by increase of a short-lived (life time 1.5–2 h) component of natural radioactivity as a consequence of the precipitation. While the decay of the activity of rain-water samples analyzed by Salikhov et al. [58] was well explained by short-lived exponential decay, identifying a component in the natural radioactivity with such properties was not without problems.

Cosmic-ray induced ionization (CRII) in the atmosphere is one of the important links between Earth’s climate and space environment. The ionization in most parts of the atmosphere is governed by secondary particles produced in cosmic-ray atmospheric cascades (CRAC). Usoskin et al. [59] report on a new CRAC:CRII model that can be applied in the whole atmosphere to account for the ionization produced by GCRs and SEPs. They compare their models with historical and recent observations and find that the model is validated at all heights from the ground to the top of the atmosphere. (See, however, paper by Bazilevskaya et al. [60] for observations in near ground atmosphere that are not explained by typical CRAC:CRII models.) Typical variation in CRII over the solar cycle is a factor of two from solar maximum to solar minimum, because of the effect of solar modulation of GCR. The model has also been used to evaluate the effect of solar activity events, i.e., GLEs followed by Forbush decreases, on the CRII. (See also [61].) Typically, the latter overcompensate the effect of the former.

3.3 Cosmogenic Nuclides

Solar activity reconstructions for Maunder and Spörer minima were addressed by Muraki et al. [62] by measuring the width of tree-rings of Japanese cedar trees. The growth of the trees shows, quite surprisingly, 12-year periodicity during the Maunder minimum, but no strong signal was found after this period. Miyake et al. [63] reconstruct the solar activity in the 7th to 11th century using \(^{14}\text{C}\) content in tree-rings. The accuracy of the dating is quoted to be 2 years, which implies that individual solar cycles could be reconstructed from that long ago. The results of Miyake et al. [63] reveal 11 and 14 periodicities in the tree-ring data, but they seem not to be persistent in the dataset. This is attributed to the sensitivity of the applied wavelet analysis method to measurement errors.

3.4 Planetary environments

Laurenza et al. [64] studied the cosmic-ray cutoff rigidities in the magnetic field of Mercury in preparation for the up-coming BepiColombo mission, where the X-ray emission generated by fluxes of energetic particles on the surface of the planet will be measured. With the relatively weak internal dipole field of the planet, the entire surface can be reached by \(>2\) MeV protons. The magnetic latitude of 1 MV cutoff rigidity in the dipole approximation is 68 de-
grees. Thus, even relativistic solar electrons can reach the high-latitude regions of the planet and produce detectable X-ray emissions. The work of studying the cutoff with the PLANETOCOSMICS code, using a more complete model of the Hermean field, is in progress.

4 Selected Papers on Experiments

In the following, some personally selected experiment papers will be highlighted. The papers are chosen based on their perceived importance in the SEP research following the author’s personal judgement.

4.1 Space Missions

Solar probe plus [35] will carry instrumentation capable of measuring the SEP spectrum from \( \sim 1 \) to \( >100 \text{ MeV/nuc} \) for protons and heavy elements and \( \sim 0.5 \) to \( 6 \text{ MeV} \) for electrons. The orbit of the spacecraft has a perihelion distance of about ten solar radii, more than eight times closer than previous spacecraft. The mission is scheduled to be launched in 2018 and the closest distances to Sun will be achieved in 2024. The particle instrumentation will deliver the differential energy spectra at 1 s time resolution for protons and electrons and 1 min resolution for heavier ions. The mass resolution is adequate to discriminate between the helium isotopes when the abundance ratio is above 0.01. Anisotropies are detected with a 20-degree resolution for protons and with a coarse (front/back) resolution for electrons. The compact instrumentation is also capable of observing energetic neutral atoms and neutrons and gamma-rays with limited sensitivity.

It is hard to imagine a mission more promising for SEP science than Solar Probe Plus, especially, when its measurements in the corona will be combined with measurements of Solar Orbiter in the inner heliosphere and with several remote-sensing and in-situ instruments at 1 AU.

4.2 Ground Based Experiments

One of the puzzling effects witnessed over the decades has been the decay of certain high-latitude NM counting rates with respect to others. Especially the South Pole NM has shown anomalous behavior, and because this monitor has a unique location from the point of view of SEP research, its condition is important for the community.

Evenson et al. [65] reported that the South Pole NM has been reactivated after a gap of four years. The authors considered the long term decline of the South Pole NM counting rate, trying to eliminate all possible experimental and environmental factors. Their conclusion was that the decline of the counting rate is caused by the solar modulation of cosmic rays or possibly by changes in the local galactic environment. Ahluwalia and Ygbuhay [66], however, point out that the median rigidity of the South Pole response function is not that different from other mountain site high- and medium-latitude monitors. For example, Calgary has a median response rigidity of 10 GV, whereas South Pole has 9 GV. Spacecraft measurements of the modulation (at a median rigidity of 3 GV) are not consistent with a decline of fluxes either. Thus, it seems that the NM in South Pole might suffer from an unidentified instrumental/environmental effect causing the decline. This highlights the importance of cross-calibration efforts on NMs [67].

5 Summary

This paper provides a brief summary of a selection of papers presented in the SH1, SH2.1 and SH4 sessions of the 32nd ICRC in Beijing in August 2011. I have concentrated mainly on SEP related results, although some other interesting topics (from a personal point of view) have been discussed as well. Based on the sessions, the main conclusions that can be drawn on the state-of-the-art of SEP research are the following:

- SEP events show more variability in their properties than a simple division to gradual shock-accelerated and impulsive flare-accelerated events allows.
  - New remote-sensing observations on coronal shock waves and their timing relative to the energetic particle release from the Sun, together with the modeling results obtained using codes with self-consistent turbulence generation, suggest that shocks can accelerate particles even to the highest energies in large SEP events.
  - The close connection of the proton release time with the main energy release phase of the associated flare suggests that at least some of the largest events may have contributions from flares.
  - Charge states of the low-energy ions accelerated in large gradual events show a great variability of characteristics as well. SEPs shock-accelerated in the solar wind, in the low corona, and possibly even in flares could be identified from the data.
Interplanetary shocks accelerate particles in a more complicated manner than a simple DSA or SDA model would suggest, as evidenced by the fact that only a minor fraction of shocks can be classified as being pure SDA or DSA events. This implies that models need to be able to account for both mechanisms.

- Particle transport from the source to the observer is governed by focused transport in the inner heliosphere. Perpendicular transport, however, seems quite important for many observational effects to be explained in the framework of focused transport, as evidenced by new multi-spacecraft observations. Another important factor to consider is realistic magnetic field geometry, as it largely determines particle transport in the interplanetary medium.

- Space weather warning systems using SEPs and the related fluctuations are emerging as tools to be used alongside with others in improving our forecasting abilities.

By the time of the next ICRC, the increased solar activity has resulted in much more events with multi-spacecraft observations from the STEREO mission as well as high-resolution and high-cadence remote-sensing observations of solar eruptions from, e.g., STEREO and SDO. These will allow us to make significant progress in SEP research within the next years.

6 Acknowledgements

The organizers of the 32nd ICRC are thanked for travel support and for an interesting and well-organized conference.

Apology. The author expresses his apology to experimenters for not being able to cover their work reported in the conference in any detail.

References

[18] L. Kocharov, 2011, ICRC, 10, 70
[33] H.-Q. He, 2011, ICRC, 10, 69
[34] Y. Kartavykh, 2011, ICRC, 10, 193
[38] M. Wiedenbeck, 2011, ICRC, 10, 205
[40] F. Spanier, 2011, ICRC, 10, 182
[41] L. Sun, 2011, ICRC, 10, 189
[54] X. Li, 2011, ICRC, 11, 252
<table>
<thead>
<tr>
<th>No.</th>
<th>Author</th>
<th>Year</th>
<th>Conference</th>
<th>Volume</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>G. Bazilevskaia</td>
<td>2011</td>
<td>ICRC</td>
<td>11</td>
<td>329</td>
</tr>
<tr>
<td>61</td>
<td>A. Mishev</td>
<td>2011</td>
<td>ICRC</td>
<td>11</td>
<td>317</td>
</tr>
<tr>
<td>62</td>
<td>Y. Muraki</td>
<td>2011</td>
<td>ICRC</td>
<td>11</td>
<td>422</td>
</tr>
<tr>
<td>63</td>
<td>F. Miyake</td>
<td>2011</td>
<td>ICRC</td>
<td>11</td>
<td>426</td>
</tr>
<tr>
<td>64</td>
<td>M. Laurenza</td>
<td>2011</td>
<td>ICRC</td>
<td>11</td>
<td>430</td>
</tr>
<tr>
<td>65</td>
<td>P. Evenson</td>
<td>2011</td>
<td>ICRC</td>
<td>11</td>
<td>454</td>
</tr>
<tr>
<td>66</td>
<td>H. S. Ahluwalia</td>
<td>2011</td>
<td>ICRC</td>
<td>10</td>
<td>162</td>
</tr>
<tr>
<td>67</td>
<td>H. Kruger</td>
<td>2011</td>
<td>ICRC</td>
<td>11</td>
<td>446</td>
</tr>
</tbody>
</table>