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Solar energetic particles in the inner heliosphere: status and open questions

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Solar energetic particle (SEP) events are related to both solar flares and coronal mass ejections (CMEs) and they present energy spectra that span from a few keV up to several GeV. A wealth of observations from widely distributed spacecraft have revealed that SEPs fill very broad regions of the heliosphere, often all around the Sun. High-energy SEPs can sometimes be energetic enough to penetrate all the way down to the surface of the Earth and thus be recorded on the ground as ground level enhancements (GLEs). The conditions of the radiation environment are currently unpredictable due to an as-yet incomplete understanding of solar eruptions and their corresponding relation to SEP events. This is because the complex nature and the interplay of the injection, acceleration and transport processes undergone by the SEPs in the solar corona and the interplanetary space prevent us from establishing an accurate understanding (based on observations and modelling). In this work, we review the current status of knowledge on SEPs, focusing on GLEs and multi-spacecraft events. We extensively discuss the forecasting and nowcasting efforts of SEPs, dividing these into three categories.

Finally, we report on the current open questions and the possible direction of future research efforts.

This article is part of the theme issue 'Solar eruptions and their space weather impact'.

1. Introduction

Solar energetic particle (SEP) events are observable enhancements of electrons, protons and heavy ion fluxes at energies well above the average thermal energy of the solar wind population that occur as a consequence of transient solar activity [1–3]. These SEP events result from solar flares and coronal mass ejections (CMEs). Processes of magnetic reconnection in solar flares and of particle acceleration at shocks, driven by fast CMEs, are believed to be the origin of SEP events [4]. However, the relative role of flares and CME-driven shocks in the processes of particle energization is still under debate. This is mainly due to the fact that SEP events appear in connection with both solar flares and CMEs, while the transport conditions of SEPs in interplanetary (IP) space blur direct cause/effect association [5,6]. Critical information on the acceleration mechanisms of SEPs can be derived from the remote sensing observations of the solar corona during solar eruptive phenomena (e.g. solar flares, CMEs) [7,8]. At the Sun, both X-ray and γ-ray emissions are produced by accelerated particles during solar flares. In particular, accelerated electrons produce X-rays as they collide with ambient ions (bremsstrahlung emission), while streams of accelerated ions produce gamma-rays as they hit the dense layers above the solar surface (nuclear collisions). Hence, X-ray and γ-ray observations yield direct information on ion and electron acceleration at the solar corona and further provide diagnostics of accelerated particles as they hit the Sun. Therefore, they give complementary diagnostics to the escaping energetic particles seen in *in situ* as SEPs. Moreover, the radio emission at wavelengths from centimetre (cm–) to decametre (dm–) waves includes a large variety of emission processes particularly from non-thermal electron distributions and enhanced levels of various kinds of plasma waves and plasma phenomena [9,10].

Since the 1980s and 1990s, SEP events have been divided into two basic classes: *impulsive* and *gradual* ones [11]. The two-class scenario was originally related to the duration of the soft X-ray emission of the associated flare [12]. Specifically, impulsive SEP events were related to short duration (less than 1 h) solar flares. Such SEP events are observed over narrow longitudinal extents, associated with type III radio bursts and tended to be of brief duration. But, gradual SEP events were related to long duration SXR flares observed over broad longitudinal extent, lasting from a few hours to several days and tended to be associated with CMEs and type II radio bursts [13]. However, the rapidly growing fleet of spacecraft that provide valuable *in situ* particle measurements, as well as remote sensing observations of the solar eruptive phenomena provides observational evidence that such a clear-cut distinction does not apply across the bulk of the recorded SEP events [14,15]. In order to explain the variable behaviour of Fe and O, intensity time profiles during SEP events [16] proposed the dependence of the relative contributions from solar flares and CME-driven shocks arguing for a *direct flare contribution*. Contrary to this plausible explanation, it was suggested [17] that the behaviour of Fe and O in SEP events could potentially occur due to the preferential injection of flare suprathermals at quasi-perpendicular shocks with respect to solar wind thermal particles in quasi-parallel shocks. Both SEP intensities and ion compositional signatures of the SEP events can also be due to the presence of a pre-event suprathermal population generated in prior solar flares and CME-driven shocks that fill the inner heliosphere and act as seed population to be re-accelerated by a subsequent CME-driven shock [18]. Additionally, building on the effect of CMEs to SEP events, interactions of multiple CMEs have been proposed as an efficient accelerator of energetic particles [19–21]. Finally, it should be noted that the energy of SEPs can reach up to several GeV in some (rare) events, which in turn are sometimes energetic enough to penetrate through the Earth's magnetic field and atmosphere and thus reach the ground. Thereby, these large SEP events are termed as ground level enhancements (GLEs) [22].

In a companion paper [4], the relationship between flares, CMEs and SEPs has been discussed and an extensive review of the present status of likely acceleration mechanisms is presented. In this paper, we focus on the high-energy SEP events (i.e. GLEs) (§1a), multi-spacecraft SEP events (§1b) and the forecasting and nowcasting of SEP events (§2). We finally conclude with several open issues, organized around what is still unknown, the need for new missions and the future of SEP event prediction (§3).

(a) Ground level enhancements

GLEs comprise the highest energy SEP events and constitute a class of events in which ions are accelerated to relativistic energies, causing a significant sudden increase of solar cosmic rays at ground level, as detected by e.g. neutron monitors (NMs) [23,24] (figure 1*a*). In particular, by definition a GLE requires a clear intensity enhancement registered by at least two differently located NMs [25]. These high-energy SEP events are also recorded by spacecraft in the IP space covering a wide energy range (from tens of MeV up to a few GeV) [26]. From 1942 up to 2018, 72 GLEs[1] have been recorded [22]. The onsets of these events are closely related to the processes of particle acceleration at the Sun, and the role of IP transport is considered to be minimal (scatter-free propagation). Therefore GLEs are excellent candidates to unfold long-standing issues on the particle acceleration at the Sun and to pinpoint their parent solar drivers. As a result, detailed case studies have been conducted on a number of individual GLEs, mostly using NM and near Earth space measurements [24,27–37]. However, the conditions and processes that are responsible for these extreme SEP events are not yet fully understood [29,38,39].

GLEs are rare (approx. 1 per year), unlike the most abundant regular SEP events that typically reach lower energies (see, for example, the statistics of greater than 25 MeV proton events collected over five solar cycles by Richardson *et al.* [40]). At the same time, GLEs last from tens of minutes to hours, whereas large gradual SEPs can last for several days. Relativistic particle events are usually accompanied by both strong solar flares and fast and wide CMEs. Therefore, the identification of the origin of GLEs is still an open issue. However, the unusual morphology of GLEs suggests two components: a *prompt* (PC) one (associated with solar flare signatures), which is highly beamed followed by a *delayed* component DC (which is composed of shock/CME accelerated particles) [32,33]. In particular, these studies concluded that the spectra of the PC and DC components approximated exponentials and power laws in energy, respectively. Furthermore, they showed that the PC was accelerated in electric fields associated with magnetic reconnection in the solar corona [38] and the DC due to stochastic acceleration in turbulent solar plasma in the outward expanding CME [33]. Thereby, signatures of both major accelerators have been identified in the measurements of GLEs by NMs. Once the first arriving particles (at GeV energies) recorded at NMs give rise to a GLE event, the bulk of the MeV protons follow (figure 1*b*). However, spacecraft measurements extend up to a few hundreds of MeV, while NMs respond to higher energy particles ($E \geq 433$ MeV), creating a *critical gap* between both energy ranges. Detectors like the Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (PAMELA) [41,42] and the Alpha Magnetic Spectrometer (AMS02) [43] have bridged this gap quite recently, providing a representative spectrum of high-energy SEP events [44]. Such instruments and their corresponding measurements provide—for the first time—good accuracy for the identification of spectral features at moderate (approx. 80 MeV) and high energies (a few GeV), giving ground to important constraints for current SEP models. Additionally, such observations allow the relationship between low- and high-energy particles to be investigated, enabling a clearer view of the SEP origin [42]. Over the past few years, a large number (greater than 25) of greater than or equal to 500 MeV SEP events have been recorded by spacecraft (e.g. the Electron Proton and Helium Instrument (EPHIN) onboard the Solar and Heliospheric Observatory (SOHO)

[1] http://gle.oulu.fi/.

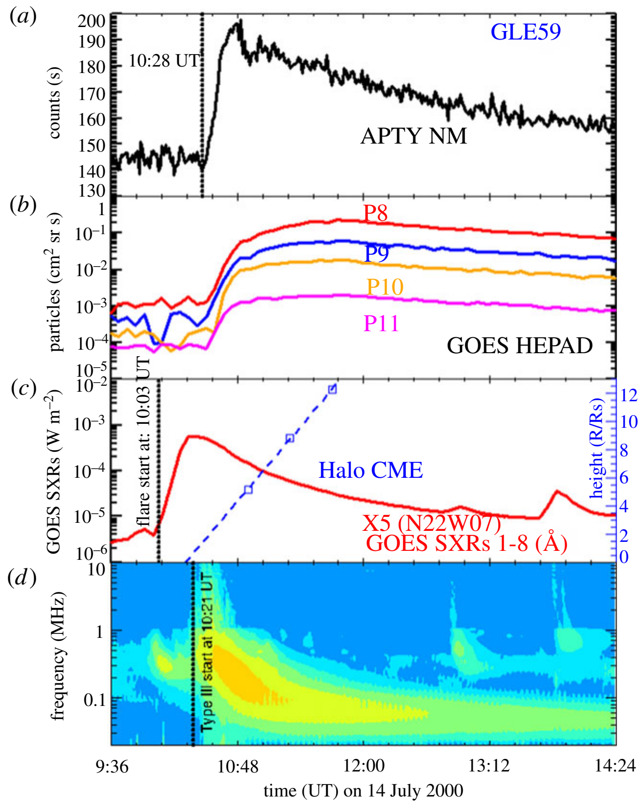

Figure 1. The large SEP/GLE59 on 14 July 2000. From (*a*) to (*d*): The counting rate of the Apatity (APTY) NM. The black dashed vertical line corresponds to the onset time for this event; the GOES/ High Energy Proton and Alpha Detector (HEPAD) proton flux at P8 (330–420 MeV), P9 (420–510 MeV), P10 (510–700 MeV) and P11 (greater than 700 MeV) (red, blue, orange and magenta lines, respectively). The SXRs flux observed by GOES, denoting an X5 solar flare at N22W07 (red curve; left axis). The black dashed vertical line corresponds to the start time of the solar flare. The dashed blue line provides the height-time plot of the CME leading edge observed by SOHO/LASCO (blue line; right axis), extrapolated back to the surface of the Sun. The radio flux observed by Wind/WAVES. The dashed black line corresponds to the start time of the identified type III burst.

and the High Energy Proton and Alpha Detector (HEPAD) onboard Geostationary Operational Environmental Satellites (GOES)) [45,46] without a clear trace at NM recordings, apart from a few cases that were spotted by NMs situated at high-latitude polar locations [47]. Virtually all GLEs are accompanied by major SEP events at lower energies; therefore, such events have the advantage of providing identifications over a large energy span (from a few MeV up to a few GeV). This means, on the one hand, we record typical GLEs, and on the other hand we measure mildly relativistic SEP events, that are often named sub-GLEs [25] or small-GLEs [48,49]. These high-energy SEP events constitute a new addition to the puzzle of particle acceleration for high-energy SEP events, but at the same time offer new opportunities for a potential breakthrough in our understanding of energetic particle acceleration.[2]

In order to shed light on the particle acceleration mechanisms that take place during GLEs and to consider the new addition to this puzzle, i.e. sub-GLEs, it is highly important to use all observational evidence at hand. These processes include: (1) bringing together measurements of low-energy particles from spacecraft together with NM, PAMELA and AMS recordings [44], (2) connecting these particle measurements to their parent solar events [23,50], (3) applying comprehensive timing analysis [51,52] and (4) invoking modelling efforts [53–55] and critical

[2] http://www.issibern.ch/teams/heroic/.

understanding of the IP conditions and structures that affected the transport of these high-energy particles [56] to associate the processes of particle acceleration at the shock with the space and ground-base observations. This said, NMs provide vital, continuous context for space-based missions, leading to a better understanding of GLEs and providing the ability to compare with spectra derived from PAMELA, AMS, HEPAD and low-energy SEPs.

(b) Multi-spacecraft observations of solar energetic particle events

Studies of the IP medium began in the 1960s and missions usually included energetic particle detectors. Earlier, widely separated observations of SEPs from the Earth were made by Pioneers 6 and 7 during the late 1960s, providing evidence of the efficient longitudinal spreading of SEPs able to uniformly fill the inner heliosphere during the decay of intense SEP events [57]. The first landmark mission was the twin Helios A and B spacecraft in the 1970s and early 1980s that provided evidence for the efficiency of the CME shock acceleration in large SEP events [58,59]. Additionally, ^{3}He-rich measurements of impulsive solar particle events, originating from wave particle interactions during impulsive solar flares came into view [60,61]. Multi-spacecraft observations of SEPs by the two Helios and near-Earth spacecraft allowed us to investigate the radial and longitudinal dependences of particle intensities and intensity time profiles of the SEP events [62,63]. Later, the Ulysses mission provided the opportunity to detect SEP events at high heliographic latitudes and thus gave rise to observations of the three-dimensional heliopshere, inside ≈5 AU. The direct comparison of *in situ* SEP measurements near the ecliptic plane to the relevant observations of Ulysses at high latitudes, showed that regardless of the longitudinal, latitudinal and radial separation of the spacecraft, clear enhancements were present at both sites [64–67]. Furthermore, using multi-spacecraft measurements it has been shown that particle intensities measured in the decay phase of large SEP events by widely separated spacecraft evolve similarly in time [57], suggesting that in these periods the inner heliosphere is acting as a 'reservoir' [68]. One possible explanation of the formation of the reservoir is based on the trapping of particles behind the CME where spectra are uniform in space and decrease adiabatically in time as the magnetic bottle that contains them slowly expands [3]. However, the Ulysses observations revealed the three-dimensional nature of the reservoir effects in the heliosphere [66,69] and Dalla *et al.* [66] concluded that the presence of a shock is not necessary for creating the near-equality observed at Ulysses and near Earth decay phases, but that these observations are better explained by diffusion across the interplanetary magnetic field (IMF). Additionally, testing the 'reservoir' effect using multi-spacecraft measurements from ACE and Ulysses, Lario [69] concluded that cross-field diffusion and/or re-distribution of particles from beyond the spacecraft location may be the cause of the formation of particle reservoirs.

The Solar Terrestrial Relations Observatory (STEREO) mission (launched in late 2006) allows the multi-spacecraft detection of SEPs from different longitudes. figure 2 presents a multi-spacecraft event observed at L1 and by the two STEREO s/c in 11 October 2013 (DOY 284). The 'reservoir' effect is quite notable after 15 October 2013 (DOY 288), when particle intensities at the 3 s/c reached uniformity that lasted for approximately 8 days. Using the valuable datasets offered from STEREO, [70,71] confirmed that the shock formation and the connection of the observer's footpoint to its flanks was linking the observed delays in the onset times and the shape of the intensity time profiles as previously observed [72,73] and modelled [74]. Consequently, the estimated solar release time (SRT) at each observation point within the heliosphere can be linked to the evolution of the CME-driven shock [53,75–77]. Moreover, cross-field diffusion processes in the solar corona and/or IP space [4] that allow particles injected from a narrow solar region to spread over a wide range of heliolongitudes can also be invoked to explain the longitudinal spread of SEPs [78,79]. At the same time, it was also shown that particles may undergo types of longitudinal transport such as corotation of flux tubes and longitudinal excursions of field lines that may explain the wide longitudinal extent of ^{3}He-rich events [80,81]. Lateral expansions of CME-driven shocks in the low corona have been invoked as a mechanism to inject particles onto a broad range of heliolongitudes [82]; however, the extent of the extreme ultraviolet (EUV)

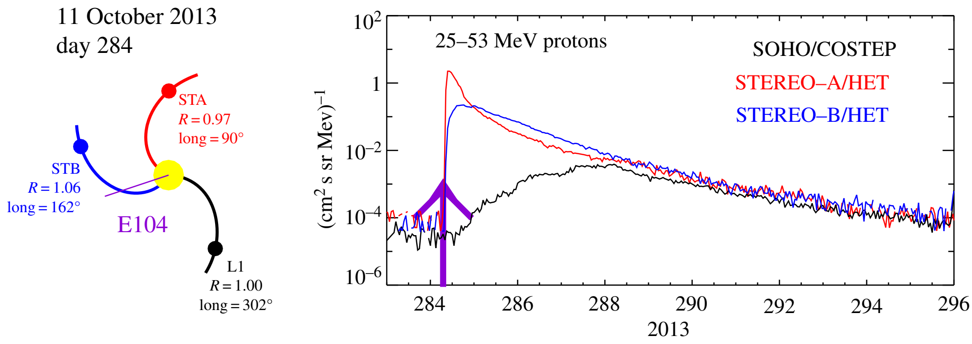

Figure 2. The right-hand side panel shows the intensity time-profiles for 25–53 MeV protons in the 11 October 2013 (DOY 284) event at SOHO (black), STEREO-A (red) and STEREO-B (blue). The 'reservoir' can be seen in the similarity of the time-profiles from 15 October 2013 (DOY 288) onwards. The left-hand side panel depicts the view from the north ecliptic pole showing the locations of STEREO-A (STA; red symbol), near-Earth spacecraft (L1; black symbol) and STEREO-B (STB; blue symbol). The heliocentric inertial longitude (Long) of each location is indicated in the figure. Also shown are nominal IMF lines connecting each spacecraft with the Sun (yellow circle at the centre, not to scale) considering the solar wind measured at the onset of the SEP event. The purple line indicates the longitude of the parent active region (E104 as seen from Earth).

waves in the corona (initially driven by the lateral expansion of CMEs) cannot be used as a proxy of the longitudinal extent of the SEP events in the inner heliosphere [75]. It should be noted that one of the major advances in the recent studies of multi-spacecraft events is the systematic usage of remote sensing and *in situ* measurements from L1 (SOHO), STEREO, ACE, Ulysses and Wind; but also MESSENGER [76], INTEGRAL and Rosetta [83], combined with the state-of-the-art modelling and ground-based measurements at Earth and/or Mars [84], all of which have provided new insights into the spatial distributions of SEP events.

2. Solar energetic particle events short- and long-term forecasting

High-energy particles both from the Sun and from outside the heliosphere (i.e. galactic cosmic rays) are a radiation hazard [85]. It is important to be able to predict the additional fluxes driven by solar eruptive events that are superimposed on the ever present cosmic ray background [86]. As stated in §1, the majority of SEPs are protons which reach energies up to the GeV range (i.e. GLEs) only on occasion. Thereby, although all GLEs are accompanied by major SEP events at lower energy, a considerable number of SEP events which can lead to a serious radiation risk are not accompanied by a GLE [87]. This highlights the fact that in the future an integration of the available forecasting tools from low-energy SEPs to relativistic GLEs should be made possible. Moreover, multi-spacecraft observations of SEPs, combined with the growing need for human exploration in space,[3] gave ground to efforts for the accurate quantification and prediction of the radiation environment in other planets (e.g. Mars) [84], and within the IP space, in general [88]. In order to be able to achieve an early warning and to take mitigating actions against solar radiation storms, two basic questions should be addressed:

(i) Will a solar eruptive event lead to an SEP event on the Earth or elsewhere in the heliosphere?
(ii) Which characteristics of the parent solar event(s) can be used for the prediction of the properties of the SEP event in specific locations?

A series of concepts and structured efforts that aim at forecasting and/or nowcasting (i.e. short-term forecasting) SEP events has been put forward by the scientific community [3].

[3]https://www.nasa.gov/directorates/heo/index.html.

Such efforts, described in the next subsections, are roughly categorized as: (a) empirical or semi-empirical, (b) physics based and (c) other.

(a) Empirical or semi-empirical

Based on observational evidence and the understanding of the solar-terrestrial environment, empirical relations point to the underlying physical processes of the generation, injection, acceleration and propagation of SEPs. It is currently established that SEP events are typically routed to the Earth from a direction of 45° west of the direction of the Sun following the nominal Parker spiral IMF lines, pointing to the magnetic connection of the observer at the Earth to the site of particle release [6,89]. At the same time, halo and fast CMEs are usually the drivers of strong shocks that accelerate particles to higher energies [15,19,90]. Additionally, type III radio bursts indicate the release of particles into open magnetic field lines [91] and type II bursts are the tracers of shocks propagating in the IP medium [19]. Hence, using these critical observations several different concepts have been proposed and implemented by the scientific community to predict the occurrence and properties of SEP events.

The PROTONS algorithm is based on precursor information of Hα flare location, time-integrated soft X-ray flux, peak of the soft X-ray flux and time of maximum, occurrence of type II and/or IV radio bursts. The output of PROTONS is a probability of the SEP occurrence and an estimation of the maximum proton flux at $E > 10$ MeV as well as the expected time of this peak intensity. This model is currently in use by the Space Weather Prediction Center (SWPC) at the National Oceanic Atmospheric Administration (NOAA) [92,93]. The Proton Prediction System (PPS), developed at the Air Force Research Laboratory (AFRL), uses signatures of solar flares such as the SXR intensity and location, a fixed time parameter (0.25 h after the flare's onset) for the injection of particles into the IP medium and a time-invariant longitudinal SEP intensity gradient of a factor of ≈10/radian from the position of the parent solar flare [94,95]. This gradient attenuates the maximum particle intensity as the angular distance from the site of the flare increases [94]. Recent multi-spacecraft studies verified the fact that the largest SEP intensities are observed from spacecraft that are well connected to the parent solar event and that there is a longitudinal gradient that on average falls in approximately 45° [79,96]. PPS provides predictions of the probability of SEP occurrence, as well as time-intensity profiles of SEPs observed at 1 AU for a number of user adjustable energy ranges [95,97]. Based on the association of properties of hard and soft X-ray flares with subsequent SEP events, concepts that use either the relation between gradual hard X-ray flares and SEP events [98] or the ratio of the soft X-ray fluxes of the two X-ray wavebands in solar flare events, which yield the flare plasma temperature and emission measure, assuming a single temperature source [89,99], have been proposed [100]. It was recently shown that the ratio of the soft X-ray solar flare fluxes [99] constitutes a viable SEP event forecasting parameter [100]. A technique to provide short-term forecasting of SEPs based on flare location, flare size and evidence of particle acceleration/escape as parametrized by flare longitude, time-integrated soft X-ray intensity and time-integrated intensity of type III radio emission at ≈1 MHz, respectively, was proposed by Laurenza *et al*. [101]. This concept was recently re-validated and termed as: Empirical model for Solar Proton Events Real Time Alert (ESPERTA) [102], while it was further extended to the prediction of greater than or equal to S2 radiation storms [103].

At this point, one should note that the aforementioned concepts are built on the dominant idea of the 1970s and the 1980s that solar flares are the single drivers of SEP events (figure 3). Thereby, the usage of CME characteristics (velocity and width) as input parameters in SEP event short-term forecasting concepts is not yet completely exploitable. This is also due to the fact that when the CME is—especially—well connected to the SEP-observer, particles could be arriving at 1 AU, while the coronagraph observations required to estimate the CME parameters are still being accumulated (as evidenced e.g. by the snowstorm effect in SOHO/LASCO images due to particle impacts). However, since the peak particle intensity may only be reached several hours later [105], a timely prediction of the peak intensity may still be possible if a reliable CME speed can be determined from the available coronagraph images [106]. However, taking

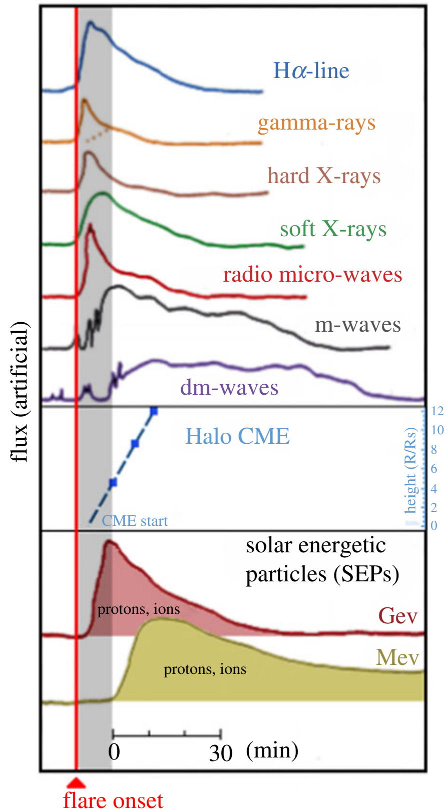

Figure 3. Timing of solar energetic particle (SEP) fluxes ranging from MeV to GeV energies (bottom panel), in context to the signatures of electromagnetic emissions across the spectrum, from gamma-rays to radio waves (top panel). The middle panel presents a corresponding artificial Halo CME though its height-time plot (with the relative *y*-axis on the right-hand side of the panel). The onset of the solar flare is indicated with a vertical red line and a corresponding triangle under the abscissa, which in turn depicts the time evolution. The ordinate provides the artificial flux of the EM emissions and resulting protons. The grey shaded area depicts the Δt between the start time of the SEP event at MeV energies and the onset of the solar flare. Figure adapted by Miroshnichenko [104] and modified.

into account both flare and CME characteristics (e.g. as a function of longitude and magnitude of the flare for halo CMEs), the COMESEP SEPForecast Tool[4] incorporates the outputs of a detailed statistical analysis [107] utilizing CME inputs. Recently, [108] proposed a concept using CME characteristics alone, constructing 2D probabilities for the SEP occurrence and linear regressions for the expected SEP characteristics for a set of different energies.[5] Richardson *et al.* [106] proposed a scheme for the prediction of the expected intensity of an SEP event at any location at a heliocentric distance of 1 AU, based on CME speed and width and the observation of related solar events. Finally, [109] showed that it is possible to build an operational SEP forecasting system using near-real time measurements from coronagraphs. Although this is a very promising possibility, it remains unexplored for a large number of events. It would potentially use ground-based coronagraph observations, timely enough to provide accurate SEP nowcasting.

Apart from the signatures of the parent solar eruptive events of SEP events, it has been shown that the *in situ* particle fluxes can be used for prognosis of forthcoming proton events. Posner [110]

[4]http://comesep.aeronomy.be/alert/.

[5]This was further used under the FORSPEF Tool (http://tromos.space.noa.gr/forspef/).

demonstrated the successful usage of near relativistic electron fluxes for the short-term forecasting of 30–50 MeV protons. The Relativistic Electron Alert System for Exploration (REleASE) concept is based on a matrix that maps the registered electron intensity to the expected intensity of the protons and thus provides a deterministic nowcasting of the expected proton flux at each moment of time [110]. Concepts are also built based on the arrival of relativistic protons ($E \geq 433$ MeV) at the Earth leading to GLEs providing consequent nowcasting of the arrival of lower energy particles in the IP space [87,111].

Methods that use the lag-correlation of the solar flare electromagnetic flux (soft X-rays) with the particle (differential and/or integral) flux recorded *in situ* near the Earth have been proposed (such concepts use the grey shaded area depicted in figure 3). In particular, a new method was proposed in [112] for the prediction of SEP events at $E > 10$ MeV, introducing the UMASEP concept. This scheme was further adapted to the prediction of SEP events at higher energies ($E > 100$ MeV [113] and $E > 500$ MeV [114]), while it has recently been used for the prediction of well-connected SEP events using the time lag between soft X-rays and near-relativistic electrons [115].

Finally, an additional number of concepts and schemes have been proposed by the scientific community focusing on the prediction of the expected SEP time-profile using simple fits [116] and exploring the possibility to establish an empirical algorithm for the SEP probability of occurrence taking into account the time delays from the peak time of the soft X-rays to the onset time of the SEP event [117]. Once a solar flare occurs on the solar disc, electromagnetic radiation is emitted virtually across the electromagnetic spectrum (see figure 3 for a simplified example). In more detail, during the early impulsive phase, electrons are accelerated to high energies and speeds resulting in radio bursts and hard X-rays. At the same time, the sequential gradual phase is clearly identified with soft X-rays. Thereby, most of the flare signatures have been used in several more concepts apart from those mentioned here above. In particular, Zucca *et al.* [118] presented the use of the UMASEP scheme, incorporating radio bursts instead of soft X-rays. Furthermore, Chertok *et al.* [119] proposed a relationship between the hardness of the proton spectrum and the microwave spectrum. However, this hypothesis was recently tested and its applicability is under debate.[6]

(b) Physics based

Approaches that fall under this category aim to model the acceleration and transport processes of SEP events. Broadly speaking, these approaches are based on the solution of an SEP transport equation for the distribution function of the energetic particles accelerated and injected at CME-driven shocks.

In more detail, the SOLar Particle Engineering Code (SOLPENCO) [120–122] is an operational tool able to predict the flux and cumulative fluence profiles of gradual SEP events associated with IP shocks, originating from the solar western limb to far eastern locations as seen at two heliocentric distances (either 0.4 AU or 1 AU). Its core is a database that contains a large number of pre-calculated synthetic gradual proton events flux profiles for different solar-interplanetary scenarios. These scenarios are characterized by: (i) the heliocentric distance of the spacecraft, (ii) the initial speed of the shock at 18 solar radii, (iii) the heliolongitude of the corresponding parent solar event (any value between W90 and E75), (iv) the propagation conditions of shock-accelerated particles and (v) 10 proton energy channels. This model assumes that the injection of shock-accelerated particles takes place at the point of the shock front magnetically connected to the observer (also called ‘cobpoint’ [123]). An empirical relation between the injection rate of shock-accelerated particles, and the normalized downstream-to-upstream plasma velocity jump at the cobpoint, is used as a separate functional description of the injection of particles at the travelling shock.

[6]https://www.hesperia.astro.noa.gr/WP2/Hesperia_task_2-2.pdf.

The Earth-Moon-Mars Radiation Environment Module (EMMREM) provides a tool that describes time-dependent radiation exposure in the Earth–Moon–Mars and IP space environments [124]. Concerning SEP events, EMMREM incorporates the Energetic Particle Radiation Environment Module (EPREM) which is coupled with MHD models [125] and provides energetic particle distributions along a three-dimensional Lagrangian grid of nodes that propagate out with the solar wind [126].

Another approach on SEP modelling, SEPMOD, brings together heliospheric simulation results from the ENLIL model, coupled with the WSA model of the coronal sources of the solar wind and a cone model for CMEs [127,128]. Making a step further from the assumption of the particle propagation taking place only along the magnetic field, a full three-dimensional physics-based model for simulating SEP propagation, Solar Particle Radiation SWx (SPARX), was presented by Marsh et al. [129]. Finally, a promising effort that couples a time-dependent three-dimensional MHD model of the inner heliosphere (i.e. the EUropean heliospheric FORecasting Information Asset, EUFORIA) [130] to a newly developed numerical code that models the anisotropic three-dimensional propagation of SEPs in the IP space, was recently proposed [131, 132].

(c) Other

Several other techniques and concepts have been pursued by the scientific community, especially in the last couple of years, focusing on the automatic feature detection, using higher order regressions and machine-learning techniques. These include the usage of radio data through the identification of type II and III bursts applying a principal components analysis (PCA) [133]; the implementation of a concept to predict $E > 100$ MeV SEP events based on decision tree models that correlate the soft X-ray and proton flux measured *in situ* [134] and the creation of a promising index for the nowcasting of SEP events based on PCA and the application of logistic regression to a set of six (solar flare and CME characteristics) variables [135]. In addition, Engells *et al.* [136] presented the Space Radiation Intelligence System (SPRINTS) framework which incorporates several different expert-guided, statistical and machine-learned decision tree models; with the later one providing the most promising results in terms of SEP nowcasting.

Steps forward: Although many different concepts have been proposed by the scientific community, a common effort for standardization and inter-comparison was only recently put into effect by the NASA Community Coordinated Modeling Center (CCMC), under the SEP-scoreboard challenge.[7] This initiative brings together many different models from (a), (b) and (c) and tries to compare either between real-time (short-term) forecasts or for several historical events. At the same time, using categorical scores/metrics, the typical goal of any forecasting (nowcasting) system is to achieve as low as possible false alarm rate (FAR) and therefore achieving reliable and as high as possible probability of detection (POD) and thus discriminate between SEP events and non-SEP events. Therefore, it is important to compare different concepts in order to identify advantages and limitations and thus upgrade the forecasting capabilities [137]. Additionally, the need for larger warning times led the efforts to move SEP forecasting and nowcasting from past single predictors to integrated/ensemble approaches with inter-related modules. In this direction, the Forecasting Solar Particle Events and Flares (FORSPEF) Tool incorporates different modules for the forecasting (pre-event) mode [138] and the nowcasting (post-event) mode [139]. Furthermore, in the former mode, a coupling of solar flare forecasting proxies (B_{eff}[8]) to the establishment of the probability of SEP occurrence provides a forewarning up to 24 h in advance; while the latter mode includes modules for the prediction of SEP events based on solar flare and CME characteristics. In a similar direction, SPRINTS integrates pre-event data and forecasts from the MAG4 system [140] with post-event data in order to produce forecasts for solar-driven events [136].

[7]https://ccmc.gsfc.nasa.gov/challenges/sep.php.

[8]B_{eff} is the effective connected magnetic field strength [138,139].

3. Open questions

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The research on SEPs is still, after more than 70 years, at the forefront of the efforts of the Solar and the Heliospheric community. Although important progress has been achieved over the years, there are many parts of the puzzle that remain unsolved. In the coming years, new dedicated missions will certainly provide answers but will also create new questions. In the following, a list of the current open issues, together with the expectations from new missions and forecasting schemes, is presented.

— Challenges that still stand:

(a) How well can we identify the particle sources? and How well can we describe the magnetic connection between the particle sources and the spacecraft that is going to detect the SEP event? Impulsive particle events are generally understood to be accelerated in flares, whereas CME-driven shock waves seem to produce most of the large gradual proton events [3]. However, several studies have provided evidence of a shift from this dichotomous paradigm. Since solar flares and fast CMEs almost always occur together and the impulsive phase of the flare (i.e. the phase of the flare with the strongest particle acceleration) often occurs in relatively close temporal connection with the formation of the CME-driven shock in the low corona (as seen from Height-Time plots, see figure 3) it is important to distinguish both processes. Additionally, high-energy particle acceleration occurs in the low corona where CME-driven shock identification is challenging and conditions for particle acceleration are unknown (seed particle populations, injection processes, turbulence, shock properties, see [4]). Evidently, particle acceleration mechanisms early in the event are challenging to infer based on timing of the SEP event onsets at 1 AU and compared to the time histories of EM emissions from non-thermal particles interacting with the solar atmosphere [2,6].

(b) How do coronal and interplanetary transport processes modify the properties of the injected population? Energetic particles transported in the IP medium are affected by a number of processes which complicate the interpretation of their origin and history. The intensity time profiles and the energy spectra of an SEP event can, in principle, be representative of the source spectra. However, intervening IP structures, disturbed IP medium and magnetic turbulence are factors that affect the transport of SEPs [56,141]. In particular, magnetic turbulence facilitates the SEP transport perpendicular to the mean magnetic field by either transporting the magnetic field lines themselves or allowing particles to diffuse with respect to actual field lines through turbulent drifts and scattering processes [4].

(c) Where are the highest energy SEP protons accelerated? The number of fast CMEs, driving strong shock waves in the solar corona, is significantly larger than the number of relativistic particle events (i.e. GLEs) actually observed and it is presently an open question as to which properties of the shock or the ambient medium (if any) can make a fast CME efficient in accelerating particles to high energies. In addition, the acceleration of GeV particles in solar flares has been quantitatively diagnosed using hard X-ray (HXR)/γ-ray observations. In particular, when ions over a few hundred MeV/nuc are produced in a solar flare, nuclear interactions with the ambient medium produce secondary pions whose decay leads to a broadband continuum at photon energies above 10 MeV and also secondary neutrons [142–145]. Thereby, the γ-ray and neutron measurements can be used as probes of energetic ions accelerated in solar flares [146]. Moreover, several explanations have been proposed for the observed relativistic particle fluxes, e.g. (i) the dominant role of the magnetic connection that must be established between the observer and the relevant source region [34,42,53]—this is normally attributed to the longitude and the latitude of the source [34], as well as the CME-driven shock evolution [53]; (ii) the coronal shock geometry that may favour acceleration at different parts of the shock [53,147]; or (iii) the twin-CME scenario [148].

— Why do we need new missions and what should we expect in the near future?
From Helios to STEREO, multi-spacecraft measurements have provided unprecedented opportunities to understand the injection, acceleration and propagation of SEPs and to further enhance our knowledge on solar-terrestrial relations. Thereby, the exploration of the solar corona and the inner heliosphere with the state-of-the-art sensors on board missions such as parker solar probe, PSP (http://parkersolarprobe.jhuapl.edu/; [149]) which was launched on 12 August 2018 and Solar Orbiter, SolO (http://sci.esa.int/solar-orbiter/; [150]), which will be launched in the coming years, is expected to provide a closer connection between the SEP timing—due to the reduced distortion by the interplanetary transport—and the time profiles of the EM emissions. Hence, we will be able to shed light on several of the challenges that still stand.
— What is the future of SEP forecasting?
Most of the prediction schemes have been already used by the scientific community. An integrated system that mimics (different energies, thresholds, needs) terrestrial weather forecasting is the immediate future step. It was clearly demonstrated in this work that different predictors incorporate different concepts and thus have different advantages and limitations. Thereby, an integrated system that will combine in practice several different predictors ranging from Empirical (a), to Physics based (b) and Other higher order mathematical concepts (c) seems to be a realistic future step.[9]

Data accessibility. This article has no additional data.

Authors' contributions. A.A., A.P. and D.L. oversaw the writing of the manuscript. A.A. contributed to §1. D.L. and A.P. directly contributed to subsections 1-b and 1-a. A.P. led the writing of §2, in close collaboration with A.K., A.P., D.L., A.V., A.A. and A.K. contributed to §3. All authors have read and approved the manuscript.

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