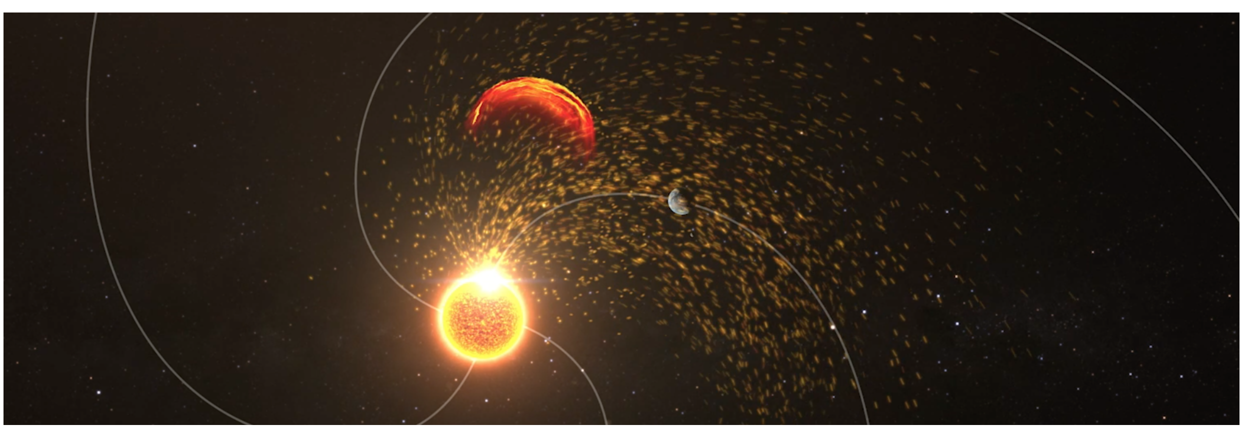
Cover Page

Advancing Solar Energetic Particle Forecasting

See attached author list.

Synopsis

With growing interest from the aviation and satellite industries, and for NASA's upcoming Artemis lunar missions, the need for improved scientific understanding and accurate forecasting of solar energetic particle events has never been stronger. In this paper we discuss the observational, validation and model transition support required to achieve these goals. Well-calibrated, high-quality energetic electron, proton, and ion measurements are essential. Expansions to the fields of view offered by current X-ray, extreme ultraviolet and coronagraph instruments, to obtain increased coverage of the solar corona and heliosphere, from vantage points off the Sun-Earth line, are desired for model input. New observations of suprathermal particles are needed to characterize seed particle distributions and low latency space-based observations of solar radio emissions are also desired. Together, this observational suite should offer high cadence, low latency, reliable and accurate space weather data streams. Consistent, extensive and quantitative model validation is required to assess scientific advancements and pave the way for models transitioning to real-time forecast operations. Model performance and skill should be compared to observations and to current operational forecasting baselines. Finally resources are required to support the significant effort of transitioning mature models into forecast operations.



Visualization of CME and SEPs. Image Credit: NASA's Goddard Space Flight Center Conceptual Image Lab

Advancing Solar Energetic Particle Forecasting

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The text of this paper has been largely adapted from Whitman et al. (2022), *Review of Solar Energetic Particle Models*.

Introduction

Solar Energetic Particle (SEP) events are transient injections into the heliosphere of protons, electrons, and higher mass charged particles with a wide range of energies (typically MeVs to GeVs), spectra, composition, and intensities. They follow energetic solar eruptions that are generally associated with flares and Coronal Mass Ejections (CME). They are accelerated by processes associated with flares, such as wave-particle interactions and reconnection, as well as by acceleration at CME-driven shocks. The most prompt and most intense SEP events measured at Earth, and hence the most important to forecast, are usually associated with strong flares and fast CMEs at western longitudes that are well-connected to Earth by the spiral interplanetary magnetic field. Magnetic connectivity to the particle source (flare/CME shock) strongly influences the development and intensity of an SEP event.

As has long been recognized since at least the Apollo era (Hilberg, 1969), SEP events are hazardous to electronics and humans in space. As humans pursue space exploration outside of low Earth orbit, the understanding, monitoring, and forecasting of SEP events becomes increasingly important. SEPs are also hazardous to aircraft crews and passengers, in particular on polar routes, and to modern technological systems in space. Plans for the NASA Artemis missions to send astronauts back to the Moon in the mid-2020s make it a critical need to improve SEP forecasting in the coming decade.

In general terms, SEP models have been motivated either by research aimed at understanding the physical processes related to SEPs or by operational forecasting needs. Models built with a forecasting focus attempt to produce a rapid forecast with high levels of skill and reliability in a statistical sense. The model inputs are restricted to data streams that are available in real time, and typically, forecasts are made using only information that is accessible before or at the start of an SEP event. *Forecast accuracy is impacted by any limitations in the observations, including lack of coverage, availability, and quality of measurements.*

Observations Typically used as Model Inputs

Observations used by the models as inputs include: solar magnetograms, optical imaging, extreme ultraviolet (EUV) imaging, Soft X-Ray (SXR) measurements, coronagraph imaging of CMEs from single or multiple vantage points, ground and space-based radio observations in the wavelengths that measure Type II, III, and IV radio bursts, in situ energetic proton and electron observations, and in situ measurements of solar wind density, temperature, velocity, and magnetic field. Table 1 shows model inputs used by 36 SEP models developed in the scientific community.

Model	Magnetograms	Optical Imaging	EUV Imaging	Soft X-ray Intensity	Ground-based Radio	Space-based Radio	Coronagraph	Solar Wind (n,T,p,v)	Suprathermal Particles	Energetic Protons	Energetic Electrons	Neutron Monitors
ADEPT										x		
AFRL PPS		x		x	x							
Aminalragia-Giamini model			x	x								
AMPS	x		x				x					
Boubrahimi model				x						x		
COMESEP SEPForecast			x	x			x					x
EPREM	x		x				x		x			
ESPERTA			x	x		x				x		
FORSPEF	x	x		x		x	x					
GSU	x											
iPATH	x		x				x	x	x			
Lavasa Model		x		x			x					
MAG4	x	x		x								
MagPy	x	x		x								
MEMPSEP	x		x	x		x	x	x	x	x	x	
M-FLAMPA	x		x				x					
PARADISE	x		x				x					
PCA model				x			x					
PHSVM				x						x		
PROTONS				x	x							
REleASE											x	
Sadykov's Model	x			x	x					x		
SAWS-ASPECS	x	x		x			x			x	x	x
SEPCaster	x		x				x	x				
SEPMOD	x		x				x					
SEPSTER			x				x	x				
SEPSTER2D			x				x	x				
SMARP Model	x											
SOLPENCO			x				x					
SOLPENCO(2)			x				x	x		x		
South African model			x	x			x					
SPARX			x	x								
SPREAdFAST	x		x				x		x	x		
SPRINTS	x		x	x						x		
STAT	x		x				x		x			
UMASEP				x	x					x		
Zhang model	x		x				x	x				
Total	19	6	21	19	4	3	21	7	5	11	3	2

Table 1: The observational inputs used by 36 SEP models developed in the research and operations communities (Whitman et al. 2022).

Need for Improved Availability of Observations for Forecasting

It is critical that continuous near real-time high-cadence, reliable and accurate space weather data streams for all phenomena relevant to SEP production are publicly available for research, deployment, and development of forecasting models, and operations.

Increased coverage of the solar surface with X-ray and EUV imaging will improve the detection of solar eruptions that produce SEP events. Flare parameters are widely used by SEP forecasting models as solar X-ray time series are continually monitored and available in near-real time, for example from GOES. The flare source location on the solar disk may be identified using X-ray imagers or in EUV observations**.** However, the current 180 degree view of the front side of the Sun is a limiting factor as SEP events detected at Earth can originate on the far side of the Sun, in particular behind the west limb [e.g., ~ 25% of the SEP events discussed by Richardson et al. (2014)]. *Extending X-ray monitoring and EUV imaging to cover more or all of the solar surface, particularly from the L4 vantage point, will ensure that all source eruptions of SEPs can be readily identified for forecasting purposes.*

Low latency, high cadence coronagraph imagery from multiple vantage points are critical for the accurate measurement of CMEs. Table 1 shows that several SEP models use information derived from CME imaging extensively for forecasting because if a CME is accompanied by an SEP event (most are not), then the CME's properties can be predictive of the characteristics of the SEPs. Currently, images from coronagraphs on scientific spacecraft such as SOHO/LASCO and STEREO/SECCHI are not available sufficiently rapidly for real-time forecasting. Delays in receiving and analyzing these images to obtain CME parameters may range from hours to even days. Thus, currently models using CME parameters as input are not suitable for predicting the onsets of prompt SEP events. The accuracy of CME parameters improves significantly on the availability of multiple vantage points. However, at present, the STEREO A spacecraft is approaching Earth and will not be able to provide a view that is substantially different from that of Earth. *It is critical to implement near-real time white light coronagraph observations, such as the Compact Coronagraph (CCOR) on NOAA's Space Weather Follow On - Lagrange 1 (SWFO-L1) spacecraft scheduled to launch in 2025, for SEP prediction. Additional coronagraphs with similar capabilities must be placed in other vantage points, such as at L4 or L5.*

Availability of space-based radio observations in real time is required for the improvement of SEP forecasting accuracy. Both type II and type III radio emissions observed by spacecraft are found to be strongly correlated with the occurrence of SEP events (e.g., Cane et al., 2002; Cliver et al., 2004; Laurenza et al., 2009; Richardson et al., 2018). Spacecraft instruments cover emissions produced in the high corona and solar wind out to the distance of the observing spacecraft. Solar radio emissions at frequencies above the ionospheric cutoff at about 10 MHz are monitored in real time from the ground by a world-wide network of observatories. However, observations below ~ 20 MHz are difficult due to the ionospheric cut-off, terrestrial interference, and emission from lightning. Observations from space-based satellite radio science instruments such as those on Wind, STEREO, Parker Solar Probe (PSP) and Solar Orbiter (SolO) can extend to lower frequencies. Unfortunately, although data from these science instruments have demonstrated the value of incorporating radio observations into SEP forecasting, they are not generally available in real time since they were not designed to be operational instruments and since these instruments were not designed to provide support for operations often have very limited telemetry. *A reliable stream of space-based radio observations are necessary for improved forecasting accuracy and could be immediately used by existing SEP forecasting models.*

Reliable, real time measurements of energetic electrons (hundreds of keV to few MeV) and energetic protons (~ten to hundreds of MeV) are necessary for space weather monitoring and forecasting. Near-relativistic/relativistic SEP electrons may arrive at Earth tens of minutes earlier than, and provide a warning of the impending arrival of, protons with energies of tens of MeV that are of space weather interest (Posner, 2007; Malandraki et al., 2020). The initial rise of the SEP proton intensity is also used in existing forecasting approaches as an early predictor that the intensity may cross a specific threshold of concern (Núñez, 2011). Therefore, the capability to make these electron and proton observations with minimal data gaps should be maintained.

Table 1 clearly demonstrates the heavy current utilization of magnetograms, EUV imaging, coronagraph observations and energetic particle observations for SEP prediction. ***Therefore, we emphasize that such data streams must be supported to ensure that SEP models can be further developed and used for research and operational forecasting – this includes the continuity of existing data streams and development of new ones to enhance or replace them.***

See the white paper by Burkepile et al. (2022) titled *Observations for Improving SEP Forecasts and Warnings* for more perspectives on this topic.

Need for New Observations

SEP forecasting will benefit from new types of measurements to fill knowledge gaps and measurements from multiple locations to fill blind spots.

Measurements of suprathermal particles (few to hundreds of keV) near the Sun, both in time and longitude, are needed to understand the wide variability of SEP event characteristics. Suprathermal "seed" particles are swept up by shocks and accelerated to higher SEP energies. It is thought that the availability of these particles in the solar corona influences the intensity and spectral characteristics of SEP events at Earth. Currently, measurements of suprathermal particles are made in situ at 1 AU or sporadically near to the Sun by PSP and SolO. Increased near-Sun measurements could lead to improved scientific understanding of their role in SEP event variability.

A space weather observatory at L4 would fill critical gaps in space weather forecasting for the Earth, Moon, and even missions to Mars. Observations of the type that are most widely utilized for SEP prediction along the Sun-Earth line would have greatly enhanced value if obtained from the L4 Lagrange point, where the observed central meridian lies at W60° (Posner et al., 2021). Magnetograms, X-ray and EUV imagery from this vantage point would cover locations on the Sun with the highest degree of magnetic connectivity to the Earth-Moon system and points along minimum-energy transfer (Hohmann) orbits to Mars. SEP events from these well-connected source locations have the highest potential impact, thus posing the largest risk for human radiation and space hardware concerns. This includes locations that are beyond the Earth-Sun west limb that our present set of observatories do not cover, therefore limiting our ability to produce a complete forecast. See the white paper by Posner et al. (2022) titled *Sun Chaser A Mission to the Earth-Sun Lagrangian Point 4* for extended details.

There is a need for well-calibrated, high-quality energetic electron, proton, and ion measurements with low instrument backgrounds and minimized contamination between energy channels and from side penetrating particles. The current spacecraft instruments that provide important SEP data sets have limitations that degrade their accuracy. In particular, the proton detectors on the operational GOES series of spacecraft have known problems with cross-talk between energy channels and contamination issues that impact the measurements, particularly during the onset of SEP events (Posner, 2007; Sandberg et al., 2014; Bruno, 2017). The SOHO experiment has two science-quality detectors, EPHIN , which only extends up to proton energies of 50 MeV, and ERNE, which extends up to higher energies, but saturates during the highest intensity SEP events (Valtonen et al., 2009). It would be extremely valuable to fly operationally supported proton detectors near the Earth and at other locations (e.g., L4) that can overcome the limitations of the current instruments. For a detector to appropriately characterize SEP events, Vourlidas et al. (2021) specify that energy coverage for protons should extend from 1 to 1000 MeV. Kühl et al. (2020) describe such a detector that would build on the design of SOHO/EPHIN, but use lessons learned to envision a more capable detector across extended energy ranges and intensity levels. See the white paper by Whitman et al. (2022) *Galactic Cosmic Rays and Solar Energetic Particles in Cis-Lunar Space* for more details on such an experiment.

The white paper by Raouafi et al. (2022) titled *Exploring the Heliosphere from the Solar Interior to the Solar Wind: Firefly* describes a mission that is highly relevant to the recommendations made here. Also see Collado-Vega et al. (2022) *Space Weather Operations and the need for Multiple Solar Observational Vantage Points*.

Need for Model Validation

Consistent, extensive, and quantitative validation of SEP forecasting models is needed to demonstrate forecasting accuracy. Models should be validated in an operational type of environment representative of the way they will be used by forecasters in real time.

All SEP models should pursue a quantitative comparison to observations. Validation of SEP models has been non-uniform across the community. Validation efforts have ranged from subjective comparisons between model and data “by eye” for a few selected events, to thorough efforts that assess a variety of metrics and skill scores for a statistical sample of events. This non-uniformity is generally a consequence of the different computational needs and level of automation of each model.

Steps can be taken to improve the quality, consistency, and ease of validation:

- The creation of a standard set of SEP event definitions and the identification of community-accepted metrics would facilitate consistent validation and cross-model comparison.
- Baseline performance metrics and skill scores for SEP forecasts made by operational centers (Bain et al. 2021), with and without a forecaster-in-the-loop should be kept current during the upcoming Solar Cycle. Details of how these scores were obtained should be clear and well communicated to allow modelers to carry out appropriate and actionable apples-to-apples validation studies.
- The curation of a shared data set of all observations required as input into the models (e.g., linked flare, CME, radio, and energetic electron measurements) and for comparison with model output (e.g., in situ particle data) would significantly reduce the workload for individual modelers and minimize duplicated efforts, and also remove disparities between model predictions that are due to the use of different input parameters.
- Lastly, a service with the ability to validate all types of SEP forecasts could be developed and made available to the community in a system such as CCMC’s Comprehensive Assessment of Models and Events using Library Tools (CAMEL) Framework (Rastätter et al., 2019).

- Validation performed with the intent to demonstrate operational performance should aim to reproduce real-time operational scenarios as closely as possible, such as through participation in CCMC's SEP Scoreboard.
- High quality proton measurements, as described above, will benefit validation efforts in the future, providing a more accurate assessment of SEP models.

Transition to Operations

Resources should be allocated to support the significant effort that is required to move a model from the development phase to running robustly in real time operations.

The worthwhile effort of R2O transitioning of SEP forecasting models will require support from the various institutions that hold stake in space weather forecasting. Significant effort is required on the part of model developers and the staff at the hosting institutions to onboard the models. This type of work does not typically fall within the scope of traditional funding opportunities, however it is necessary and important work for models that demonstrate benefit in the context of forecasting. At present, many model developers have expressed interest in working towards implementing their models in real time and are in the very early stages of this process.

Summary

New and improved observations are required to understand and forecast SEPs:

- Well-calibrated, high-quality, real-time energetic electron (hundreds to few MeV), proton, and ion (10 to hundreds of MeV) measurements with low instrument backgrounds and minimized contamination between energy channels and from side penetrating particles.
- Increased coverage of the solar surface with X-ray and EUV imaging.
- Low latency, high cadence coronagraph imagery from multiple vantage points.
- Availability of space-based radio observations in real time.
- Measurements of suprathermal particles (few to hundreds of keV) near the Sun, both in time and longitude.
- A space weather observatory at L4 to fill critical gaps in space weather forecasting for the Earth, Moon, and missions to Mars.

These data streams must be available in real-time to ensure use for forecasting.

All SEP models should pursue a quantitative comparison to observations and operational baselines. And finally, resources are required to support the significant effort of transitioning mature models into forecast operations.

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