# **Observations for Improving SEP Forecasts and Warnings**

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# **Synopsis**

Solar energetic particles (SEPs) consist of electrons, protons, and higher mass charged nuclei that are accelerated to near-relativistic speeds at flare sites and at shocks driven by Coronal Mass Ejections (CMEs). They pose a direct threat to human exploration beyond low Earth orbit, astronauts, high latitude/altitude aircraft crews, and satellites. This paper demonstrates the importance of including the following data in SEP forecasts: 1) near-real-time low corona CME observations; 2) 0.05 to 0.4 nm solar flare emission; 3) low frequency radio emissions, 4) relativistic electron intensities from the L4 Lagrangian point; and 5) high-quality energetic proton measurements from Sun-Earth line (SEL) and the L4 point. The availability of these data in near-real-time can increase SEP warning times and improve SEP predictions that address radiation hazard concerns to astronauts and critical technological infrastructure, while providing insights into SEP formation and complementing new and existing heliophysics missions.

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#### The Problem:

- 1. There are no available white light observations of the low corona that provide high duty cycle, and low latency tracking of CMEs.
- 2. The short channel GOES X-ray data continue to go unused in SEP forecasting, despite their demonstrated value.
- 3. Reliable, long-term, observations of near-real-time low frequency solar radio emissions, important for SEP forecasting, are not available.
- **4.** Observations of near-relativistic particles and solar X-Rays emanating from behind the west limb of the Sun are not available.
- **5.** High-quality, high energy proton observations are not available. Current high intensity proton measurements suffer from cross-talk leading to poorly calibrated or contaminated measurements.

#### The Solution:

- 1. Create a ground-based network of white light coronagraphs (e.g. ngGONG K-Cor) that provide the high duty cycle, low latency, near real-time CME alerts needed for SEP forecasting.
- 2. Upgrade SEP forecasts to include the integration of the short channel GOES X-ray data outlined by Kahler and Ling (2018).
- 3. Deploy space-based instruments that provide reliable, low latency, low-frequency radio emissions to improve SEP forecasting models.
- 4. Deploy an L4 Mission that includes near-relativistic electron and high-quality, high intensity proton measurements and X-rays, needed by multiple SEP forecasting models.
- 5. Deploy instrumentation along the Sun-Earth line the provides high-quality, high intensity proton observations needed to improve SEP forecasts.

## Why Forecasting Solar Energetic Particles is Important

Solar energetic particles (SEPs) are accelerated to near- relativistic speeds at flare sites and at shocks driven by Coronal Mass Ejections (CMEs) (see: Lin 1970, Kahler et al 1978, Cane et al.

1988, Desai and Giacalone 2016). They pose a direct threat to astronauts, high latitude/altitude aircraft crews and satellites, and they can disrupt communications. Understanding the physical mechanisms responsible for the acceleration and transport of SEPs, and forecasting their occurrence and impact on geospace, spacecraft, astronauts and future crewed missions beyond Earth's orbit, are primary goals of NASA, NSF, NOAA, and other Federal agencies. SEP acceleration and transport involve fundamental physical processes including magnetic reconnection, collisionless shocks, and turbulence though details are still unclear (Desai and Giacalone, 2016). While advances have been made in SEP forecasting (Bain et al 2021), improvements are needed. Much of our understanding of SEP production, and the development and validation of SEP forecasting models (Whitman et al., 2022), has been made using archival datasets, but utilizing many of these for near- and real-time forecasting is challenging as the data may not be accessible in real time or are no longer available. Limited sets of measurements are available in near-real-time from operational space-based missions (e.g. NOAA's GOES, DSCOVR) and ground-based assets (e.g. GONG, SOON, RSTN), or at times from NASA research platforms (e.g. ACE, SOHO, SDO, STEREO beacons). This paper highlights the benefits of providing a set of near-real-time observations that can increase warning times of SEP events, improve SEP predictions, address radiation hazard concerns to astronauts and technological infrastructure, provide insights into SEP formation, and complement observations from new and existing heliophysics missions.

# Benefit of near real-time measurements of CME properties near onset leading to shock formation

Studies have shown that SEP-rich CMEs are faster, wider, and brighter (i.e. higher line-of-sight density) than average CMEs (Kahler and Vourlidas 2005, Gopalswamy 2006, Kahler 2013). CMEs with the largest kinetic energies (~>10<sup>32</sup> ergs) are strongly correlated with Ground Level Enhancements (GLEs), extreme SEP events that extend to high (GeV) energies and produce energetic secondary particles recorded on the ground (Mewaldt et al. 2008). CMEs producing

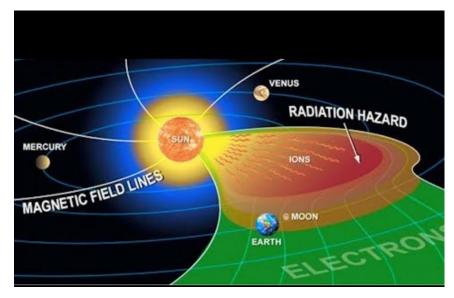


Figure 1. A cartoon depicting the extent of near-relativistic electrons and ions that pose radiation hazards

large SEP events drive shocks that form in the low corona (Ciaravella et al. 2005, Reames 2009, Gopalswamy et al. 2013, Mäkelä et al. 2015), with the majority forming at =< 2 solar radii, below the LASCO field-of-view. Identifying large, rapid CME expansion during CME onset in the low corona may be a key factor in assessing the probability of CMEs producing SEP events (Balmaceda et al. 2022). Gopalswamy et al. (2016) found that the highest CME accelerations were associated with hard spectra GLEs. Comparisons of CME acceleration with height (St. Cyr et al. 1999, Yashiro et al. 2004, Zhang et al. 2006) confirm that fast CMEs have significantly larger acceleration in the low corona. These results emphasize the value of low corona observations in assessing CME acceleration and expansion connected to SEP intensity and spectrum. EUV low corona images from SDO AIA are used with LASCO white light (WL) to detect CMEs, but EUV has a limited off-disk field-of-view due to the sharp falloff in emission with height and cannot track CMEs to the heights accessible by WL. It is also easier to track CMEs from the low to middle corona using WL images rather than a combination of EUV and WL. St. Cyr et al. (2017) examined a SEP-producing CME using low corona WL data from the COronal Solar Magnetism Observatory (COSMO) K-Coronagraph (K-Cor) at the Mauna Loa Solar Observatory (MLSO) in Hawaii and estimated that the low corona data provided warning of potential SEPs at least 19 minutes earlier than LASCO data alone. They proposed requirements for low corona WL SEP forecasting that include a field-of-view (FOV) down to 1.2 solar radii with one-minute cadence needed to record the rapid acceleration of fast CMEs. K-Cor has a FOV down to 1.05 solar radii and a cadence of 15 sec, exceeding these requirements. Furthermore, St. Cyr et al. emphasized that data availability must be swift (within 2 minutes of acquisition). The system must include an automated CME detection algorithm that provides rapid alerts with accurate estimates of CME location, speed and acceleration. Such a CME detection system is discussed by Thompson et al. 2017 and is now in use as part of the near real-time K-Cor automated data processing at MLSO. The MLSO 'raw' K-Cor images from the telescope are fully processed and calibrated, and analyzed by the CME detection code within 2 minutes of data acquisition. Examination of six CMEs with elevated proton fluxes showed that CME alerts were issued from 5 to 20 minutes **before** the CME entered the LASCO FOV. Accounting for LASCO data latency times of > 30 min, the *K-Cor alerts provide at least 35 to 55* minutes advance warning of an ongoing CME. A network (ngGONG) that includes a K-Cor coronagraph will greatly improve duty-cycle and forecasting impact (see white paper by Alexei Pevstov). MLSO CME-alerts have been integrated into the NASA Coordinated Community Modeling Center (CCMC) SEP probability scoreboard. Examination of This CME alert system will also be available from COSMO (see white paper by Steven Tomczyk). A near-real-time CME prediction system using SOHO and STEREO WL data has been operational for more than a decade at George Mason University (http://spaceweather.gmu.edu/seeds/realtime.php) (Olmedo et al. 2007). It is also important to note that coronal observations along the Sun-Earth line can detect CMEs with the largest and fastest-arriving SEPs as these events tend to originate from the western-hemisphere > 45° longitudes where the Parker-spiral interplanetary magnetic field is best connected to Earth. CMEs originating behind the west limb can also be detected. This is important because around 25% of the SEP events detected at Earth originate on the far side of the Sun (e.g., Richardson et al., 2014) so their source signatures such as solar flares are not visible from Earth.

## Benefits of short channel X-ray observations in a SEP warning system

X-ray observations of flares have long been used in SEP-related studies and forecasting. The Xray flare rise time is close to the time of CME impulsive acceleration for fast CMEs (Zhang et al. 2001). Nunez et al. (2019) use the GOES long channel (0.1 to 0.8 nm) X-rays in the UMASEP scheme to forecast SEP occurrence and intensity. Kiplinger (1995) used data from the HXRBS on SMM to show that 22 of 23 flares for which the spectral slope hardened with time were associated with SEP events, whereas only 8 of 708 flares without spectral hardening had SEP events. Garcia (2004) and Kahler and Ling (2018) demonstrated that the GOES X-ray short channel (0.05 to 0.4 nm) data are a successful SEP forecasting tool. Kahler and Ling (2018) used the ratio of GOES short to long channel peak flux and found that for western hemisphere sources, the GOES peak-flux ratios are statistically lower for SEP proton fluences > 10 pfu at >10 MeV than for non-SEP events and are even lower for large (>300 pfu) SEP events, providing a testable metric for SEP production. Despite the demonstrated value of the short channel X-ray data they continue to go unused in SEP forecasting. We recommend the GOES Xray data be used as suggested by Kahler and Ling (2018). The GOES peak-flux short-to-long channel ratios can be quickly calculated (~1 minute latency) shortly after the long channel peak flux is observed. The flare longitude can be used in a SEP event probability table (similar to those used for the PROTONS forecast model (Balch 2008)) to produce a yes/no forecast or a probabilistic event determination and can improve performance of multiple component forecasts. . Near real-time available imaging (e.g. GOES SUVI, X-ray or gamma ray) can locate flares during solar maximum activity conditions when multiple flares occur simultaneously, as well as provide physical insights into flare physics. An L4 location would provide views beyond the west limb.

## Benefit of near-real-time low frequency radio emissions

It has been known for decades that slowly-drifting, low frequency radio bursts (Type II) are likely evidence of shock waves in the low corona (Wild, 1950). With the advent of space-based measurements, these emissions were seen to extend to extremely low frequencies (km wavelengths) in association with shocks (that also may accelerate particles) moving out from the corona into interplanetary space (e.g., Cane and Stone, 1984). Furthermore, Cane et al. (2002) showed that fast-drift, low frequency radio bursts (Type III-I) accompany major SEP events, proving that magnetic field lines near the Sun were opened, allowing the escape of electron beams that generated these bursts. In 2009 Laurenza et al. reported a short-term SEP warning technique based on Wind/WAVES measurements of Type III emissions at 1 MHz for soft X-ray flares that exceeded certain intensities (>M2). Statistics from the technique (known as ESPERTA) were reported recently (Laurenza et al., 2018). In addition, Richardson et al. (2014) discussed how the presence or absence of low frequency type II or type III radio bursts may be used to differentiate between CMEs with or without SEP events, reducing the rate of false predictions for a CME-triggered SEP prediction model. Radio bursts at these extremely low frequencies do not penetrate Earth's ionosphere, so these observations must be made from space-based platforms. Though Wind/WAVES data have been widely used for such studies, they are not available in real time. Only the beacon on the single remaining STEREO-A

provides some near-real-time coverage from the SWAVES instrument. Whitman et al. (2022) note in their conclusions that "the limited use of space-based radio emissions reflects the fact that such observations are not currently available in near-real time, notwithstanding their demonstrated strong association with historical SEP events". *Therefore, reliable,long-term, observations of near-real-time low frequency solar radio emissions are needed. This gap was also highlighted in the recent NASA Space Weather Gap Analysis.* 

#### Benefit of near-real-time relativistic electron intensities from L4

Posner (2007) exploited a Van Hollebeke et al. (1975) observation that relativistic electrons are the first in situ sign of an impending SEP event. Using archival electron data from SOHO COSTEP/EPHIN [Müller-Mellin et al., 1995], **Posner demonstrated that a reliable short-term** prediction of the resulting SEP proton intensity was available 30–60 min before the onset of **30–50 MeV protons**. The technique was rebranded as the "Relativistic Electron Alert System for Exploration" (REIeASE), and SEP predictions are provided online (e.g., at http://iswa.gsfc.nasa.gov) whenever the SOHO COSTEP data are available in near real time [Posner et al., 2009]. SOHO is nearly 27 years old and retrieving near-real-time telemetry is a low priority and the 25 year old ACE/EPAM electron data are available. The Interstellar Mapping and Acceleration Probe (IMAP) (McComas et al. 2018) and the Space Weather Follow-On Lagrange 1 (SWFO-L1) missions, scheduled for launch in 2024 and 2025 respectively, will provide relativistic electron measurements at the L1 point along the Sun-Earth Line. While needed, these new missions do not solve the problem of the lack of observations of particles produced from behind the west limb of the Sun, which are magnetically well-connected to Earth. Current forecasting models such as UMASEP and ESPERTA would directly benefit from such observations. The REleASE technique and the low corona WL data are perhaps the only schemes that currently provide any reliable forecast for eruptions that occur behind the West limb of the Sun, yet still impact Earth. This is a particularly important gap for modeling techniques that are driven by soft X-ray light curves, since those may be occulted by the solar limb. A mission to the Lagrangian Point 4 (L4) would provide relativistic electron measurements, as well as high energy protons, X-rays and other crucial observations (see Posner et al. 2021) would improve forecasting for human exploration to Mars.

### Benefit of high-quality energetic proton measurements

Energetic protons (10 MeV and above) are the most critical sources of space radiation effects for hardware and humans in space. SEP events experience a wide variability in proton intensities, spectral characteristics, time profiles, and longitudinal extent. In general, SEP spectra tend to have a rollover near 10 MeV and a second rollover between ~100 - 500 MeV or higher (Bruno et al., 2018). To capture the full range of SEP proton variability, it is necessary to employ high quality, well-calibrated detectors with low instrument backgrounds, minimized contamination from side-penetrating particles, and a large dynamic range in both energy and intensity. Currently available experiments are limited in one or more of these aspects. In particular, while the GOES series of satellites are able to measure high intensities, there is cross-talk between the energy channels that results in the reporting of unphysical SEP event

onsets in the lower energy channels (Posner 2007). In addition, the GOES high energy measurements up to hundreds of MeV typically have high backgrounds and coarse energy channels. The science-grade detectors on SOHO have low backgrounds and well-calibrated energy channels, but SOHO/EPHIN only extends to 50 MeV, while SOHO/ERNE experiences saturation during very intense events (Valtonen et al., 2009). SEP forecasting models are developed, triggered, and validated using available proton measurements. High background measurements reduce the number of observed SEP events that could be used in model training, already a problem for machine learning models that struggle with sparse data sets. Using poorly-calibrated or contaminated measurements for model development or validation poses the risk of influencing models to reproduce instrumental effects rather than true proton intensities, a particular problem for physics-based models that aim to disentangle the complex physical processes from the corona to the Earth and improve our understanding of the primary drivers of SEP events. High quality proton detectors covering the full range of SEP variability, i.e. multiple decades in intensity and energy, are essential for the accurate forecasting, validation, and understanding of SEP events. The addition of these observations from L4 would improve SEP forecasts at Earth and reduce risks to human ventures to Mars.

#### Recommendations

Solar Energetic Particles are a key cause of space weather impacts, and are a top forecasting priority. The benefits of near-real-time measurements of: 1) low coronal observations of CME acceleration and expansion in the low corona, 2) 0.04 to 0.5 nm X-rays, 3) low frequency radio emissions, 4) relativistic electron (and proton) intensities from an L4 vantage point, and 5) high quality energetic proton measurements from the SEL and the L4 point with a large dynamic range in both energy and intensity as valuable SEP forecasting tools have been amply demonstrated. *Therefore, these near-real-time observations, noted in the Solution section above, should be made readily available and incorporated into SEP warning systems*. These are needed to support astronaut flights to the Moon and Mars in the mid-2020s to 2030s. There is also a growing interest from the aviation industry for space weather radiation advisories. The new advisories for the International Civil Aviation Organization (ICAO) would benefit from accurate forecasts of SEP time profiles. In addition, the observations discussed here are also complementary and valuable to new research missions such as Parker Solar Probe, Solar Orbiter, DKIST, SunRISE, and PUNCH, that will shed light on some of the outstanding questions of the fundamental physical processes in SEP acceleration and transport.

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