Helio2050: Observations for Improving SEP Forecasts and Warnings

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Why Forecasting Solar Energetic Particles is Important

Solar energetic particles (SEPs) are accelerated to relativistic speeds at flare sites and at shocks driven by Coronal Mass Ejections (CMEs) (Lin 1970, Kahler et al 1978, Cane et al. 1988). They pose a direct threat to astronauts, high latitude/altitude aircraft crews, satellites, and 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 transport and acceleration involve fundamental physical processes including magnetic reconnection, collisionless shocks, and turbulence, though details are still unclear. While advances have been made in SEP forecasting, improvements are needed. Much of our understanding of SEP production has been made using archival datasets, but utilizing many of these for near- and real-time forecasting is unsuitable as they are not accessible in near-real-time or are no longer available. Only limited sets of measurements are available in near-real-time from operational space- (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 outlines the benefits of including near-real-time low corona CME observations, 0.05 to 0.4 nm solar flare emission, low frequency radio emissions and relativistic electron intensities in SEP forecast systems. These data can increase warning times and improve SEP predictions while providing insights into SEP formation and complementing new and existing heliophysics missions.

Value of monitoring CME properties near onset leading to shock formation

CMEs associated with large SEP events have above-average acceleration, width and brightness (i.e. higher line-of-sight density) (Kahler and Vourlidas 2005, Gopalswamy 2006, Kahler 2013). The largest kinetic energy (~>10^{32} ergs) CMEs are strongly correlated with Ground Level Enhancements (GLEs), extreme SEP events that extend to high (GeV) energies and produce energetic secondaries recorded on the ground (Mewaldt et al. 2008). CMEs producing 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 most forming at ≤ 2 solar radii, below the LASCO field-of-view. This points to rapid acceleration of these CMEs near onset. 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) confirm that fast CMEs have *significantly* larger accelerations in the low corona (see also Majumdar et al. 2020). CME width can also increase significantly below 3 solar radii (Cremades et al. 2020). ***These results emphasize the value of low corona observations in assessing CME widths and accelerations connected to SEP intensity and spectrum.*** SDO AIA Extreme Ultraviolet (EUV) 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 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 ground and estimated that the ***low corona data provided a warning of potential SEPs at least 19 minutes earlier than LASCO data alone.*** They proposed requirements for low corona WL SEP forecasting. ***Ground-based or near Earth observations can detect CMEs with the largest and fastest-arriving SEPs*** as they tend to come from the western-hemisphere at > 45^{o} longitude where the spiral interplanetary magnetic field is best connected to Earth; CMEs originating behind the west limb can also be detected. A field of view down to 1.2 solar radii with one-minute cadence is needed to record rapid acceleration of fast CMEs. ***Data processing and availability must be swift (<=2 minutes of acquisition).*** The system must include an automated CME detection algorithm that provides rapid, accurate estimates of CME location, width, acceleration and speed, and alerts the NOAA Space Weather Prediction Center. Such a system is discussed by Thompson et al. 2017 and is in use as part of the near real-time WL coronagraph system at Mauna Loa.

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 X-ray 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 X-ray 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 fluxes and found that for western hemisphere sources the ***GOES peak-flux ratios are statistically lower for SEP fluences > 10 pfu 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 data they continue to go unused in SEP forecasting. ***We recommend the GOES 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 to produce a yes/no forecast or a probabilistic event determination and can improve performance of multiple component forecasts. SEP probability tables are used for the PROTONS forecast model (Balch 2008)***. 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

Decades of observations have shown that slowly-drifting, low frequency radio bursts (Type II) are likely evidence of shock waves in the low corona. Space-based measurements revealed that solar radio emissions were seen to extend to extremely low frequencies (km) in interplanetary space. Cane *et al.* (2002) proposed that fast-drift, low frequency radio bursts (Type III-l) are evidence of open magnetic field lines near the Sun allowing electron beams, likely associated with SEP events, to escape. Laurenza et al. (2009) described a short-term SEP warning technique (ESPERTA) based on Wind/WAVES measurements of Type III emissions at 1 MHz with soft X-ray flares that exceeded intensities ≥M2. Statistics from the technique were reported by Laurenza et al. (2018). Radio bursts at these extremely low frequencies do not penetrate Earth's ionosphere; observations must be made from space-based platforms. Currently, only the STEREO-A beacon provides some near-real-time coverage from the SWAVES instrument. ***Reliable, long-term, near-real-time low frequency radio emissions are needed.***

Benefit of near-real-time relativistic electron intensities

Posner (2007) exploited an observation by Van Hollebeke *et al.* (1975) that relativistic electrons are the first *in situ* sign of an impending SEP event. Using archival 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 with > 30 min warning before the onset of 30–50 MeV protons*** with an average warning time of 63 min. The technique was rebranded as Relativistic Electron Alert System for

Exploration (REleASE) and predictions are available online (*e.g.*, http://iswa.gsfc.nasa.gov) whenever SOHO COSTEP data are available in near real time (Posner *et al.*, 2009). Unfortunately, SOHO is 25 years old and has little priority in near-real-time telemetry. ACE/EPAM data are available but ACE is 27 years old and neither DSCOVR nor the Space Weather Follow-On monitor relativistic electrons. ***Long-term near-real-time relativistic electron intensities are needed.*** The REleASE technique and the low corona WL data are perhaps the only schemes that provide any reliable SEP forecasts for eruptions that occur behind the West limb of the Sun, yet still impact Earth. This is an important gap for modeling techniques that are driven by soft X-ray light curves, since those may be occulted by the solar limb. An alternative means for addressing this problem is discussed in another white paper submission (Posner *et al.*).

Summary

Solar Energetic Particles are a key cause of space weather impacts, and are a top forecasting priority. It has been demonstrated that near-real-time measurements of CME acceleration in the low corona, 0.04 to 0.5 nm X-rays, low frequency radio emissions and relativistic electron intensities are valuable SEP forecasting tools that should be incorporated into SEP warning systems. Low coronal observations, achievable from the ground, should be recognized as a Space Weather asset. These observations should be in place to support astronaut flights to the Moon and Mars in the mid-2020s to 2030s. They are also complementary to current and 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. We support the closely-related white papers submitted to this call by Vourlidas et al. ("Exploring the critical coronal transition region), and Posner et al. ('Focused space weather strategy for securing Earth, and human exploration of the Moon and Mars').

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