Satellite Impacts of Solar Energetic Particles and Galactic Cosmic Rays

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ABSTRACT

Both solar energetic particles (SEPs) and galactic cosmic rays (GCRs) present radiation hazards to satellites and astronauts. However, their sources and solar cycle dependences are very different. SEPs are associated with activity on the Sun, specifically violent expulsions of material called coronal mass ejections. They dominate the radiation hazards near the peak of the solar cycle when solar activity is maximized, however have been known to occur during periods of lower activity leading up to or declining from solar maximum. In contrast, GCRs originate outside our solar system and while fairly ubiquitous in interstellar space, their access to the inner heliosphere near Earth is strongly reduced by high levels of solar activity. This paper describes the origins of these radiation sources, their variability in time and characteristics, and the current efforts to predict them.

1. INTRODUCTION

Space weather is a broad term encompassing a number of different phenomena, including solar flares, coronal mass ejections (CMEs), energetic particles, and geomagnetic storms. Here we focus on the energetic particle portion. Although particles are energized through a number of different processes, it is convenient to divide them into three categories that roughly relate to their origin: solar energetic particles (SEPs), galactic cosmic rays (GCRs), and radiation belt particles. All three are space weather concerns, and much work has been done on each (see e.g., the review by [1] which also catalogs a number of space weather resources); this paper provides a brief overview of SEPs and GCRs, leaving radiation belt particles to another paper.

Figure 1 shows the 21 MeV/nuc C intensity as a function of time as measured by the Solar Isotope Spectrometer (SIS [2]) on the Advanced Composition Explorer (ACE [3]; launched in 1997). This illustrates one of the key differences between SEPs and GCRs; SEP events are the large, short duration spikes that appear superimposed on the slower time-varying background of GCRs. As will be discussed more below, SEP events are episodic, last for a few days, and dominate energies typically below ~100 MeV/nuc; in contrast, GCRs are always present, vary less in their peak intensities, and have a maximum intensity occurring at energies typically in the few hundreds of MeV/nuc.

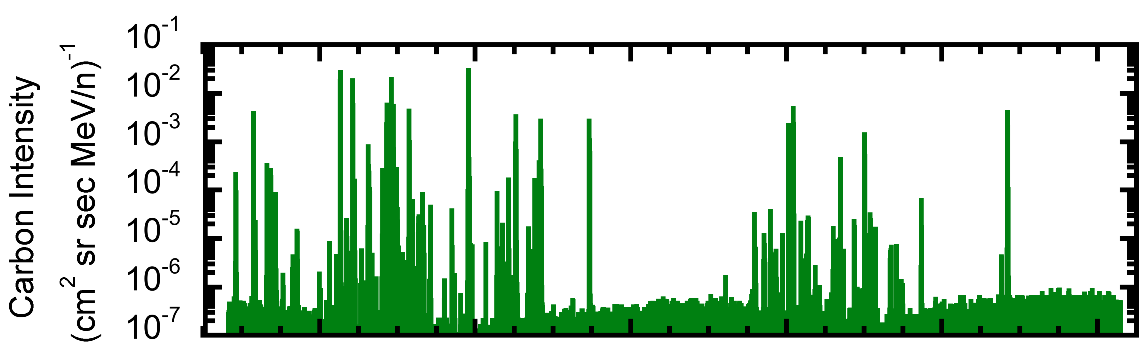

Figure 1. Daily averaged intensities of 21 MeV/nuc carbon as a function of time (measured by ACE/SIS). The high-intensity spikes are SEP events, while the slowly modulated background is due to GCRs.

Both SEPs and GCRs present a significant radiation hazard for astronauts and spaced-based instrumentation. To some degree, they can also affect airline crews of polar-routed flights. Details regarding the increases in cancer rates, effects of high doses to blood-forming organs, as well as impacts to brain activity and eye cataracts due to energetic particles can be found in [4] and references therein. The effects on instrumentation and spacecraft range from degradation of solar panels and sensors to single event upsets (which can cause 'phantom' commands and corrupt memory) to spacecraft charging on surfaces and internally (see reviews by [5] and [6]). Certain protective procedures can be invoked to minimize these damaging effects, e.g., astronauts sheltering in a shielded location, spacecraft and instrumentation put into safe modes, etc; however, this requires some advanced warning of the increased hazard as well as the relevant characteristics (e.g., the duration and peak intensity of an ensuing SEP event). Such a predictive capability relies on our accurate understanding of the generation and variation of GCRs and SEPs.

2. GALACTIC COSMIC RAYS

Galactic cosmic rays are particles accelerated by supernova shocks to high energies which impinge upon the heliosphere as they move through the galaxy. As the particles are typically highly ionized, they are affected by the heliospheric magnetic field and its variations [7]. These magnetic structures, generally from CMEs and the interactions of high-speed and low-speed solar wind, modulate the incoming GCRs by scattering the lower energy particles and depressing their intensity as measured at 1 AU. Since there are more CMEs and general structure to the solar wind during solar maximum (for which the solar sunspot number is a proxy), the GCR intensity measured near Earth is anticorrelated with the sunspot number, with the amount of GCR modulation being lower at solar minimum and higher at solar minimum. This is illustrated in Figure 2 which shows the history of the sunspot number over six solar cycles (~1960-2010) (top panel) and the GCR intensity as measured by spacecraft (middle panel) and high altitude balloon-borne instruments (bottom panel).

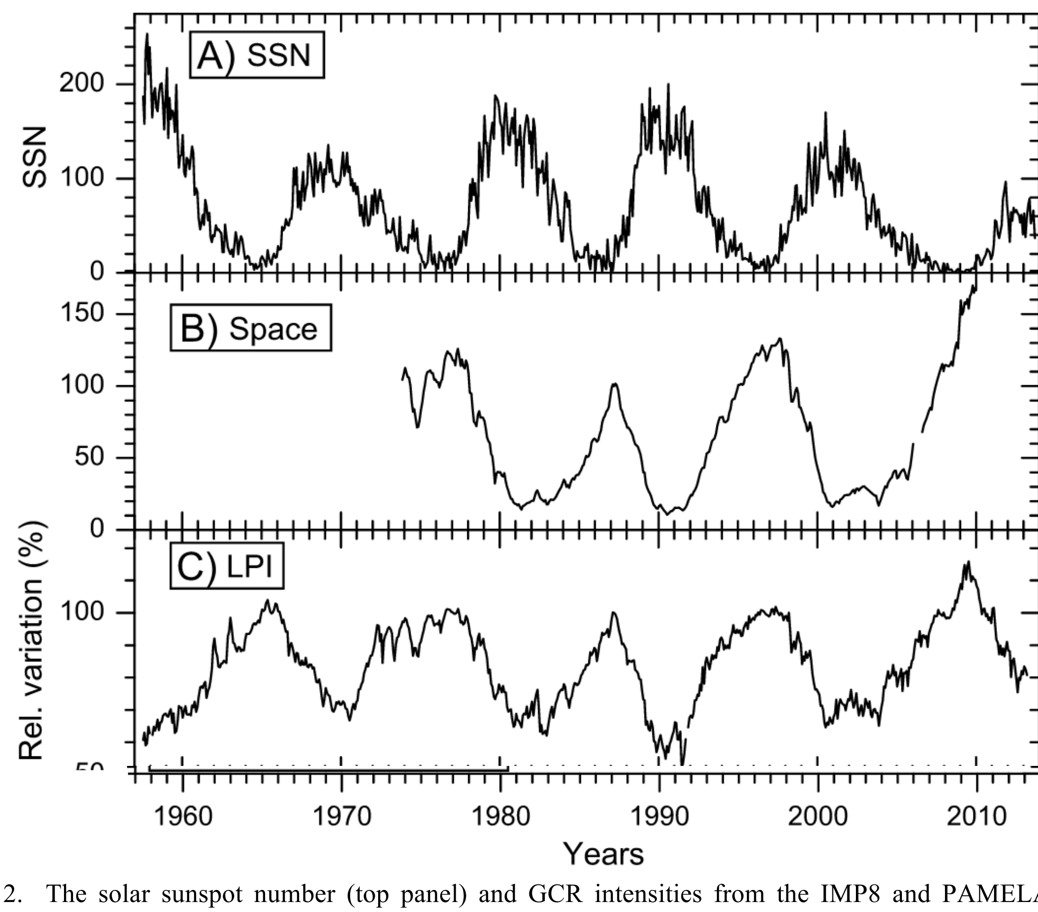

Figure 2. The solar sunspot number (top panel) and GCR intensities from the IMP8 and PAMELA spacecraft (middle panel) and relative intensities from high altitude balloon-borne instruments of the Lebedev Physical Institute (bottom panel) as a function of time. The GCR intensity is anticorrelated with the solar activity (as indicated by the sunspot number). Adapted from [7].

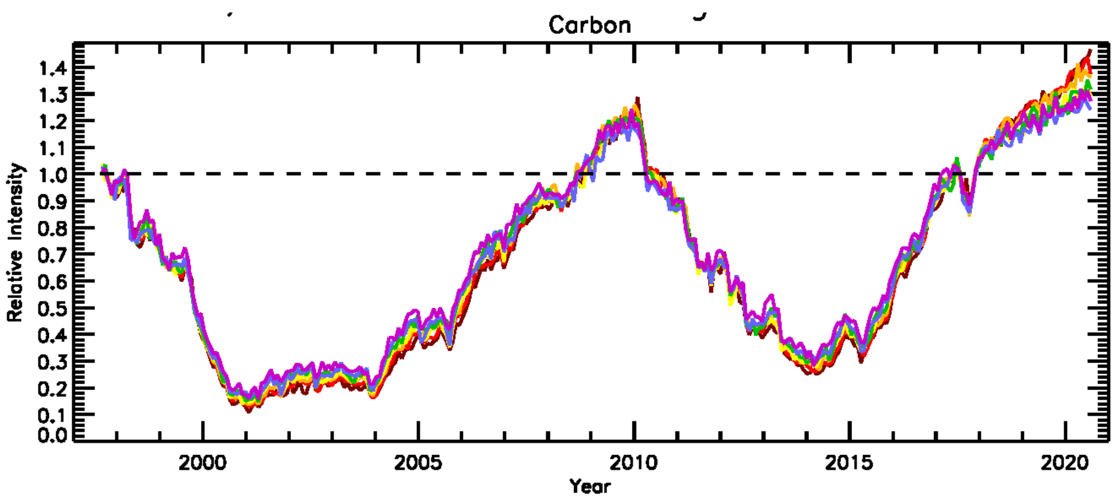

Figure 3. Carbon intensities at several energies ranging from ~70 to ~200 MeV/nuc vs time as measured by ACE/CRIS from launch to the present. All energies (different colored traces) are normalized to values observed at launch in August 1997 [10]. Relative to that value, intensities were ~20% higher in 2009 and are currently 30-40% higher.

Although the short-term variability (i.e., days to months) of the GCR intensity is low, there is some cycle-to-cycle variation. As can be seen from Figure 2, the deep solar minimum around 2009 resulted in extremely high GCR intensities at 1 AU and is discussed in detail in [8]. The following weak solar cycle 23 (peaking around 2014) led to less modulation of the GCRs and thus higher intensities than were seen at the peak of cycle 22 (~2001), evident in Figure 3. Shown are the carbon intensities measured by the Cosmic Ray Isotope Spectrometer (CRIS [9]) on ACE at several different energies from ~70 to ~200 MeV/nuc, all normalized to the observed values at launch in August 1997. In addition to the 2009-2010 record setting values, one can also see that the current GCR intensities are even higher [10]. Some predictions of the GCR intensities for the upcoming solar cycles have been made by comparing the last two cycles to historic cycles of low sunspot numbers [11] and suggest that the intensities will be high in cycles 24-25. If so, this will shorten the time astronauts can be in space before exceeding their permissible exposure limits, a prime concern for future long-duration manned space missions.

3. SOLAR ENERGETIC PARTICLES

In the large SEP events that are the primary space weather concern, the particles are accelerated by shocks driven by fast and wide CMEs [12 and references therein]. Turbulence ahead and behind the shock causes local suprathermal particles to scatter back and forth across the shock, gaining energy until they can no longer be effectively trapped in the shock region. Particles can be accelerated to hundreds of MeV/nuc, often forming a power-law distribution with an index that depends on the shock strength. As the shock moves away from the Sun, it decreases in strength and the maximum particle energy reached also decreases. When integrated over the duration of the SEP event, the particle spectra often exhibit a softening of the spectra with increasing energy, typically well described either by a broken power law or a power law multiplied by an exponential [13]. Thus, the shock parameters and the environmental conditions in which it propagates (including the properties of the suprathermal particle seed population) dictate the SEP event characteristics.

Most observations of SEP events are from near Earth and illustrate a wide variability in SEP characteristics. Figure 4 presents oxygen intensities at several energy bands as measured by ACE/SIS during a series of SEP events in October-November 2003 [14]. Even over such a relatively short time period, there are orders of magnitude variation in the intensities of the events. Additionally, some events, such as #4, have prompt onsets while others, e.g., #3, have slower onsets. Some events, e.g., #2 and #4, exhibit strong increases in the intensities of the lower energy particles when the shock arrives at the spacecraft (as indicated by the vertical lines), while others, #1 and #5, do not.

Fluence spectra obtained by integrating over events also show dramatic variability. The proton fluence spectra of several SEP events which were of space weather concern are shown in Figure 5; one can see that which events to worry about depends on energy. At 15 MeV, the energy that can penetrate a spacesuit, events like October 1989 and

August 1972 are concerning but those similar to January 2005 and February 1956 are not. However, above 100-200 MeV, energies that can reach polar-routed airplanes, the case is reversed.

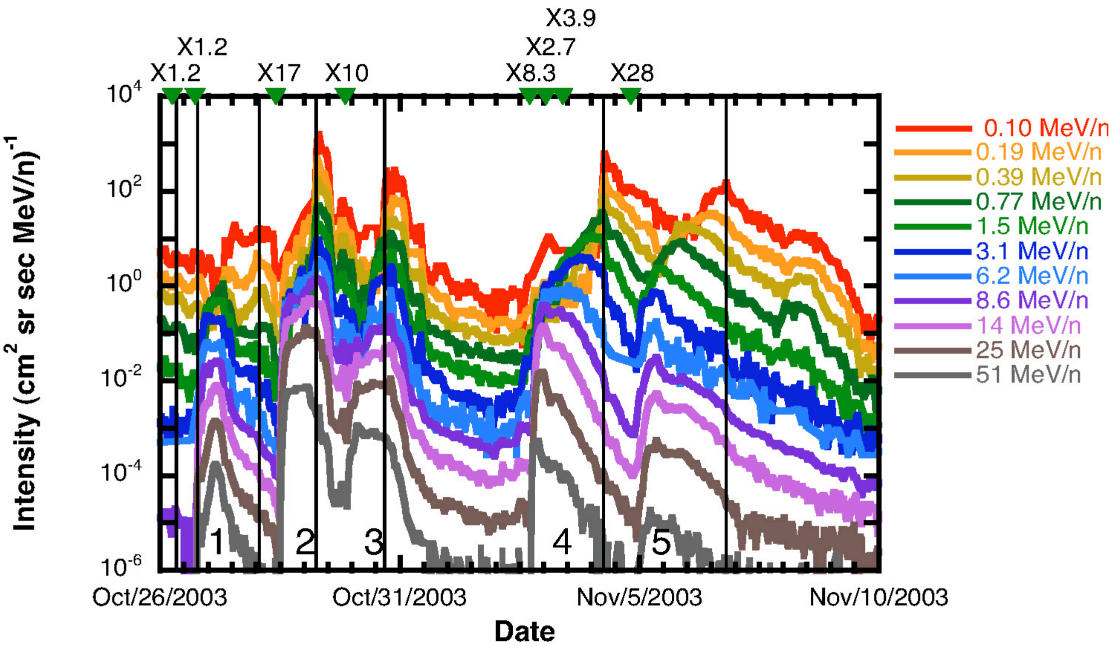

Figure 4. Oxygen intensities at energies from 0.1 to 51 MeV/nuc during several SEP events observed by ACE/SIS in October-November 2003. Inverted green triangles along the top axis indicate the timing of observed X-class soft x-ray flares; vertical lines indicate the arrival times of interplanetary shocks. Five separate SEP events are identified with numbers in the lower portion of the plot. From [14].

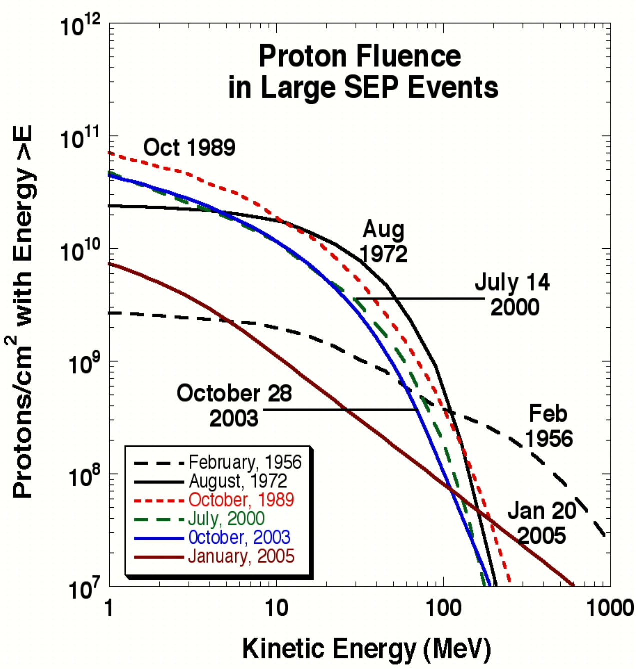

Figure 5. Proton fluence spectra for several space weather concerning, large SEP events showing a wide variation in shape and fluence. Events like October 1989 and August 1972 pose threats at energies <100 MeV, while ones like February 1956 and January 2005 are more worrisome at energies >200 MeV. From [15].

Spectral shape, time profiles, and peak intensities are not the only variable characteristics observed in SEP events. Composition, particularly in the abundance ratios of heavy ions such as Fe/O, can vary by orders of magnitude. Figure 6 shows the Si fluence as a function the Fe/O abundance ratio measured in more than 100 SEP events (each point is a separate SEP event). Large events often have Fe/O ratios similar to that deduced for the corona (vertical line, from [16]), but many mid-sized events have enhancements in Fe which can be a greater concern for the occurrence of single event upsets in space-based instrumentation.

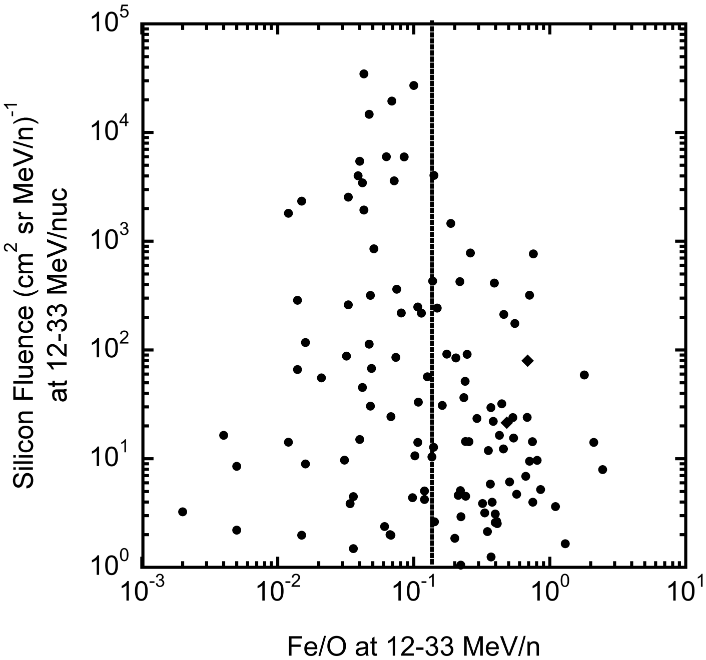

Figure 6. Silicon fluence vs Fe/O abundance ratio for >100 SEP events as measured by ACE/SIS. The vertical line indicates the Fe/O abundance ratio deduced for the corona by [16]. Many mid-sized SEP events have substantial enhancements in Fe/O, a concern for single event upsets in spaceflight electronics.

4. PREDICTIVE CAPABILITY

As mentioned previously, short-term forecasting of GCRs is not difficult due to their slow variation. Longer term forecasting is largely dependent on predictions of the upcoming solar cycle(s). As was done for cycle 24, the Space Weather Prediction Center (SWPC) at NOAA convened a panel of international experts to review various predictions for the next solar cycle. Their finding was released in December 2019 and stated that cycle 25 will be similar in size to cycle 24 [17]. These predictions can generally be categorized as using one of three methods: precursor, model-based, or extrapolation. Many of the current prediction models are reviewed in detail by [18] along with an evaluation of their past performance. They find that, in general, precursor methods tend to yield more reliable predictions.

Unlike GCRs, the extreme variability of multiple characteristics of SEP events makes it particularly difficult to predict the associated radiation hazard. Additionally, there is limited information upon which to derive such forecasts. While remote observations are available for several 'steps' in the chain of events leading up to an SEP event (Figure 7), there are difficulties in predicting each successive step. Routine monitoring of sunspots allows identification of large and complex regions as they develop, however, not all such regions produce large x-ray flares and CMEs. When a sunspot does erupt, realtime observations of the flare are available, but not of the accompanying CME (although this will change with the launch of GOES-U, scheduled for 2024, which will host a coronagraph). Complicating predictions is the fact that not all large flares are accompanied by fast and wide CMEs. Although the cadence is generally too slow to be suitable for realtime operations, the Large Angle and Spectroscopic Coronagraph (LASCO) on the Solar and Heliospheric Observatory (SOHO) provides observations on CMEs and some indications of the presence of associated shocks. However, while the speed of the CME can be determined from these observations, it is subject to projection effects (which are unfortunately the worst for CMEs directed towards Earth)

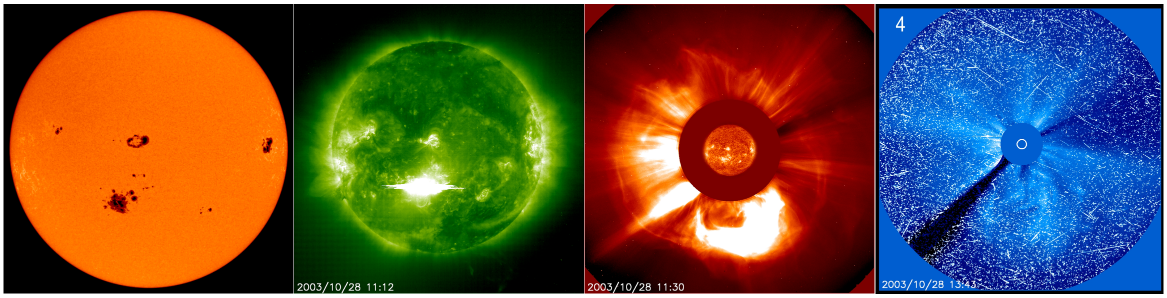

Figure 7. Remote sensing observations from instruments on SOHO during the 28 October 2003 SEP event. (left panel) Magnetogram showing active regions from MDI (Michelson Doppler Imager); (left-center panel) EUV emission from the flare from EUVI (Extreme Ultraviolet Imager); (right-center panel) a C2 coronagraph image of the coronal mass ejection from LASCO; (right panel) and the effect of SEPs impinging on the detector on the C3 coronagraph image from LASCO.

and it is not possible to determine the shock parameters (e.g., strength and orientation) important to SEP generation. SEP peak intensities are known to be correlated with observed CME speed, however, the four orders of magnitude spread in the intensities for a given speed is not conducive to accurate forecasting [19].

Currently SWPC provides probability forecasts of SEP events based on solar flare activity and sunspot observations [20]. However, this is only a prediction of occurrence, not of characteristics. Given the difficulty and necessity of predicting SEP event characteristics, over the last few years there has been significant effort made to create and improve forecasting tools. These include physics-based methods as well as using empirical associations, in some cases utilizing machine learning techniques. The SEP Scoreboard is a project spearheaded by the Community Coordinated Modeling Center (CCMC) at NASA/Goddard Space Flight Center which seeks to objectively evaluate the predictive capability of several tools currently in development [21]. Not all the SEP prediction models are currently capable of running in realtime, but the number that are actively running at the CCMC is increasing [22].

5. SPACE WEATHER BENCHMARKS

Space weather has been recognized as a national priority and in 2015 the National Space Weather Strategy and Action Plan sought to coordinate efforts to improve predictive capabilities and mitigation strategies. As part of this plan, the Space Weather Operations Research and Mitigation subcommittee was formed and used several working groups to conduct a rapid analysis of five key space weather phenomena: induced geo-electric fields, ionizing radiation, ionospheric disturbances, solar radio bursts, and upper atmospheric expansion. As a phase 1 effort, the working groups identified initial benchmarks within each area for once in 100 years occurrences and theoretical maxima [23]. The ultimate goal is to create a set of benchmarks that can be used to drive engineering requirements and risk assessments, as well as in evaluating the current vulnerabilities and mitigation efforts.

Leading into phase 2, which will entail a more detailed evaluation of the current state of knowledge and available data to establish more rigorous benchmarks, was an effort led by IDA Science and Technology Policy Institute, supported by NSF and NASA, to critically evaluate the phase 1 benchmarks and make recommendations for the phase 2 working groups. This ‘Next Steps Space Weather Benchmarks’ activity was performed by a group of international space weather scientists and resulted in the 2019 report [24]. The report details a number of recommendations for refining and expanding the benchmarks (e.g., adding 1-in-N years benchmarks where N is <100 and identifying cases for which theoretical maxima are unknown), as well as suggesting short and long term scientific studies that would aid in the determination of more rigorous benchmarks.

6. ACKNOWLEDGMENTS

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