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How open data and interdisciplinary collaboration improve our understanding of space weather: A risk and resiliency perspective

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Space weather refers to conditions around a star, like our Sun, and its interplanetary space that may affect space- and ground-based assets as well as human life. Space weather can manifest as many different phenomena, often simultaneously, and can create complex and sometimes dangerous conditions. The study of space weather is inherently trans-disciplinary, including subfields of solar, magnetospheric, ionospheric, and atmospheric research communities, but benefiting from collaborations with policymakers, industry, astrophysics, software engineering, and many more. Effective communication is required between scientists, the end-user community, and government organizations to ensure that we are prepared for any adverse space weather effects. With the rapid growth of the field in recent years, the upcoming Solar Cycle 25 maximum, and the evolution of research-ready technologies, we believe that space weather deserves a reexamination in terms of a “risk and resiliency” framework. By utilizing open data science, cross-disciplinary collaborations, information systems, and citizen science, we can forge stronger partnerships between science and industry and improve our readiness as a society to mitigate space weather impacts. The objective of this manuscript is to raise awareness of these concepts as we approach a solar maximum that coincides with an increasingly technology-dependent society, and introduce a unique way of approaching space weather through the lens of a risk and resiliency framework that can be used to further assess areas of improvement in the field.

KEYWORDS

space weather, risk and resiliency, solar activity, solar storms, geospace, Sun and society, open data, open science

1 Introduction

Space weather is the physical and phenomenological state of space environments. The associated discipline aims through observation, monitoring, analysis, and modeling to understand and predict the state of the Sun, the interplanetary and planetary environments, and the solar and non-solar driven perturbations that affect them, as well as to forecast and nowcast the potential impacts on biological and technological systems (from COST Action 724, 2009[1], and in line with Temmer, 2021). As our understanding of space weather increases, so does the realization that answering the field's most complex questions requires a new scientific approach that values convergence: The merging of innovative ideas, approaches, and technologies from a diverse range of sectors and expertise. In this article, we reflect on the current state of space weather research and discuss the next steps to advance the field during the next decade and beyond, specifically by formulating space weather in a risk and resiliency framework.

The grand challenges in heliophysics and space weather, especially those that involve complexity precluding uni-disciplinary analyses, may require new frameworks to further understand the multi-disciplinary knowledge necessary to make significant progress. A risk and resiliency framework (Scheffer et al., 2001; de Bruijn et al., 2017; Angeler et al., 2018, see **Figure 1**) provides a solid foundation for the evolution of our sciences beyond the next decade. Within this framework, a system is treated as a complex entity that can be defined by whether or not it can accommodate changes and reorganize itself while maintaining its unique characteristics (Scheffer et al., 2001). The framework is built on two important principles: 1) Consideration of the holistic Sun-to-society system, and 2) Quantification of the uncertainty that arises from coarse-graining and statistical simplification (McGranaghan, 2022). If space weather is approached through the lens of risk and resiliency, the domain could share a common framework with other risks such as terrestrial weather (e.g., hurricanes). This would allow researchers to conduct trans-disciplinary research into the convolved and compounding effects of space weather.

Space weather currently affects four main industry domains: ground infrastructure, high-frequency (HF) communications, near-Earth space assets and services, and aviation. Our nearest star creates five main space weather disturbances discussed in this article:

1. Coronal mass ejections (CMEs; e.g., Webb and Howard, 2012) are large-scale eruptions that carry huge quantities of plasma and magnetic fields into interplanetary space, occasionally in the direction of Earth. The fastest CMEs are usually the most geoeffective.
2. Solar flares (e.g., Benz, 2017) are sudden intense bursts of electromagnetic radiation from the solar atmosphere, and are associated with the impulsive release of magnetic energy via reconnection.
3. Solar energetic particle (SEP; e.g., Reames, 2013) events are associated with CMEs and flares. They cause large fluxes of high-energy relativistic protons and electrons to travel with the solar wind along the interplanetary magnetic field.
4. (Coronal-hole) high-speed streams (HSSs; e.g., Cranmer et al., 2017) are flows of fast solar wind that originate from open magnetic field lines in the Sun's corona.

1 https://swe.ssa.esa.int/what-is-space-weather.

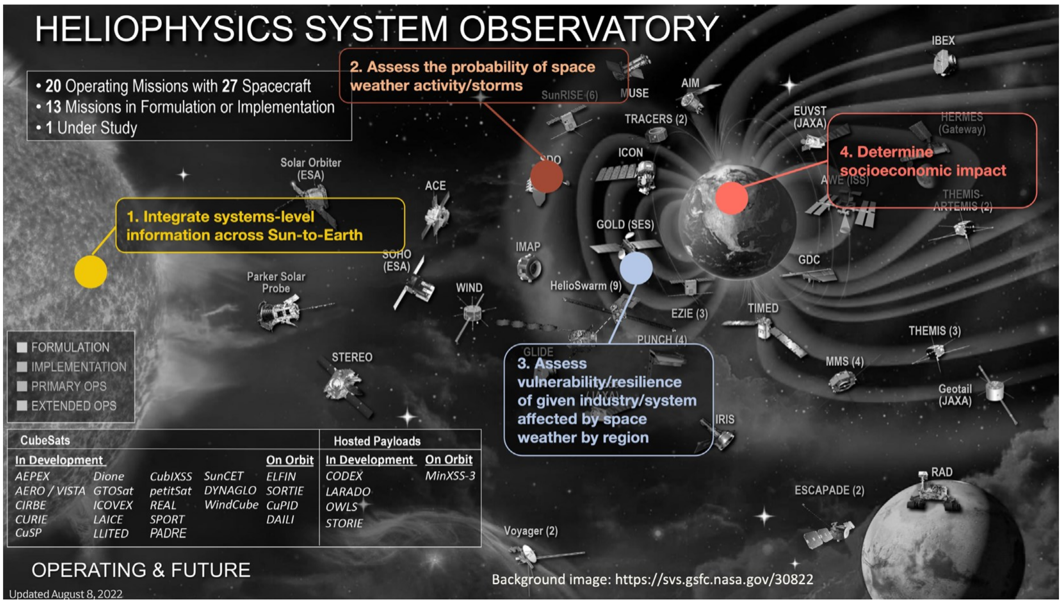

FIGURE 1
Overview of the Space Weather Risk and Resiliency Framework. Adapted from https://svs.gsfc.nasa.gov/30822 (original credit: NASA).

5. (Co-rotating) stream interaction regions (SIRs; e.g., Richardson, 2018) occur when HSSs overtake slower solar wind, producing regions of enhanced density and magnetic field strength.

In **Section 2** of this article we provide a background of space weather and highlight areas of improvement in science and forecasting. We also share possible solutions (**Section 3**) using the concepts of open data and data science (**Section 3.1**), cross-disciplinary science and information systems (**Section 3.2**), as well as citizen science (**Section 3.3**). Concluding thoughts are summarized in **Section 4**.

2 Space weather's impacts on industries

The disturbances from the Sun mentioned in the Introduction can manifest into three main categories of space weather effects at Earth: Geomagnetic storms and substorms, radiation storms, and radio blackouts[2]. On Earth, space weather can lead to damaging effects with varying time scales and spatial footprints (see Eastwood et al., 2017; Hapgood et al., 2021). So-called "Carrington-scale events" refer to extreme space weather events that cause widespread infrastructure damage (Tsurutani et al., 2003; Baker et al., 2013; Riley et al., 2018; Cliver et al., 2022; Hayakawa et al., 2022). For industries, Carrington-scale events often present a "worst-case scenario."

Although there are many affected sectors of society, within this article we will discuss space weather impacts in five industry domains, outlined below.

2.1 High-frequency communications

During radio blackouts and radiation storms, increased ionization in the atmosphere and ionosphere impacts high-frequency (HF) radio communication, which relies on ionospheric propagation for signal transmission and integrity. Signals either become degraded from distortion and scintillation or completely absorbed by the ionosphere (Kintner et al., 2007). HF radio communication is used by the aviation industry, the shipping industry, emergency responders, the amateur radio operator ("ham") community (Frissell et al., 2022, 2019), and the military (Balch et al., 2004; Kelly et al., 2014). Mobile phone networks and global navigation satellite system (GNSS) timing services can also be affected and debilitated by solar flare radio noise (Kintner et al., 2009; Cannon et al., 2013). During minor-to-moderate space weather events, regional and global gaps in HF radio bands occur, but most critical infrastructure is designed to be resilient, i.e., capable of using multiple bands of communication or operating under expected noise. However,

2 https://www.swpc.noaa.gov/noaa-scales-explanation.

some infrastructure is not resilient enough: Even minor radio blackouts have caused airplanes to lose contact with ground controllers, especially over the North Atlantic (Fiori et al., 2022). Carrington-scale events may cause degraded HF communication performance for several days due to intense and prolonged radio blackouts caused by severe space weather (Cannon et al., 2013; Frissell et al., 2019).

2.2 Geomagnetically-induced currents

During geomagnetic storms, substorms, and sudden impulse events, geomagnetically induced currents (GICs) in the ground may damage infrastructure, particularly power transformers, ofline certain power surge protection and fault-detection systems (Tsurutani et al., 2003; Cannon et al., 2013). These effects are most intense in the vicinity of the auroral ovals that surround Earth's magnetic poles, but have also been observed at mid and low latitudes due to the effects of ionospheric (Pulkkinen et al., 2012; Ngwira et al., 2013; Carter et al., 2015) and magnetospheric (Russell et al., 1992; Shinbori et al., 2009) current systems. Consequently, GIC power grid impacts are widespread and have been observed in the United Kingdom (Erinmez et al., 2002; Thomson et al., 2005), Finland (Juusola et al., 2015), Sweden (Pulkkinen et al., 2005), Spain (Torta et al., 2012), the United States and Canada (Bolduc, 2002), South Africa (Lotz and Cilliers, 2015; Matandirotya et al., 2015), Japan (Watari, 2015), China (Wang et al., 2015), Australia (Marshall et al., 2011), New Zealand (Oliveira et al., 2018), and Brazil (Trivedi et al.,2007).

2.3 Satellite infrastructure

During geomagnetic storms, the thermosphere often expands and changes the neutral density of low-Earth-orbit altitudes (Danilov and Laštovička, 2002; Prölss, 2011; Oliveira et al., 2020). Satellites flying at these heights experience increased drag, causing a deceleration in the orbital direction and loss of altitude. Manual intervention often must be taken to ensure the nominal orbit of the spacecraft is maintained (Capon et al., 2019; Smith et al., 2019). A notable recent example of this phenomenon was in February 2022, when 38 SpaceX Starlink satellites re-entered Earth's atmosphere after a space weather event (Dang et al., 2022; Hapgood et al., 2022). During geomagnetic storms and substorms, energetic electrons become trapped in Earth's radiation belts, causing electrostatic charging and discharging on spacecraft, which can damage sensitive electronic equipment (Koons et al., 1998; Wrenn et al., 2002; Hapgood, 2004; Choi et al., 2011; Loto'aniu et al., 2015). Alongside short-term effects, a satellite's performance may also degrade over time due to radiation events. Many satellite providers use our current understanding of the climatology of the radiation environments to determine the expected total dose over their satellite's lifetime and include a safety margin to ensure resiliency. As a consequence, complete satellite losses are rare.

2.4 Humans working in the atmosphere and in space

Earth is constantly bombarded by high-energy charged particles either from the Sun (i.e., SEPs) or from interstellar space (known as galactic cosmic rays or GCRs). During strong radiation storms, SEPs can be accelerated to relativistic energies (thus penetrating Earth's magnetosphere) and secondary or particles can be detected even on the ground by neutron monitors, a phenomenon known as a ground level enhancement (GLE; e.g., Nitta et al., 2012). Due to open magnetic field lines at Earth's poles, particle fluxes and the resulting background radiation environment are highest at high latitudes (Compton, 1933; O'Brien et al., 1996; Mertens et al., 2010). This ionizing radiation can have biological impacts on aircrew (Dyer and Truscott, 1999; Lindborg et al., 2004). While unlikely, during severe space weather events crew radiation dose limits may be reached and airlines may choose to reroute high-risk flights (Jones et al., 2005). In geospace, humans lose radiation protection from the atmosphere, receive higher overall dose rates (Dachev et al., 2017), and are greatly affected by radiation storms (Berrilli et al., 2014), potentially leading to adverse health effects over time (Cucinotta, 2014). In interplanetary space and on the Moon, humans lose all magnetic or atmospheric shielding and are exposed to even higher radiation levels (Reitz et al., 2012). On Mars, due to the planet's thinner atmosphere and weaker magnetic field, dose rates are much higher than on Earth (Guo et al., 2021). The space radiation environment will present challenges to upcoming crewed lunar and martian missions.

2.5 Single event upsets

Single event upsets (SEUs) occur when ionizing radiation changes the internal voltages in electronics, leading to the corruption of stored or transmitted data (Dodd and Massengill, 2003; Oates, 2015). During radiation storms, highly energetic particles cause increased rates of SEUs in electronics (Campbell et al., 2002; Lohmeyer and Cahoy, 2013). SEUs affect all electronics, regardless of altitude. During the 2003 Halloween storms, about 10% (47 out of 450) of satellites experienced anomalies, one scientific satellite was lost, and 10 satellites were non-operational for over 1 day (Balch et al., 2004). Effects from these events were observed even at Mars, the most dramatic outcome being the loss of a radiation monitor aboard the 2001

Mars Odyssey satellite (Zeitlin et al., 2010). SEUs also affect avionics instruments (Taber and Normand, 1993), although almost all commercial aircraft contain mitigation techniques to limit disruptions[3], and ground electronics, although critical electronics have error-correcting mechanisms in most cases (Normand, 1996).

2.6 The current state of space weather

Space weather simultaneously affects these five domains and creates complex and challenging situations for forecasters and industry managers. Our scientific understanding of these industry-specific risks to space weather is growing, but there are still gaps in knowledge. Several international efforts are underway to identify and reduce these gaps, as well as to explore ways to improve our readiness for harmful space weather impacts (e.g., Schrijver et al., 2015; Opgenoorth et al., 2019; Tsurutani et al., 2020; Lilensten et al., 2021), but are we fully prepared for a Carrington-scale event (Riley and Love, 2017)? The answer to this question depends on who is being asked, and information regarding the ways in which industries respond to space weather is not readily publicly available. As we prepare for the next decade of space weather, including the Solar Cycle 25 maximum, there are a multitude of avenues by which we can improve forecasting and research to achieve clearer scientific understanding and well-integrated inter-disciplinary collaboration.

3 Open-data and cross-disciplinary efforts in space weather

Adopting a new systems-science approach for space weather, utilizing, e.g., open data and citizen science, will cultivate cross-disciplinary collaborations that help solve challenging problems in unique ways.

3.1 Open-data and data science

As the amount of space weather data increases, data science projects and principles will enable new scientific discoveries via open access and collaboration.

As the number of models, data, and model–data fusion products increases with the growth of the space weather field, so does our recognition that powerful new opportunities for scientific discovery are made possible by utilizing data science optimized for large data volumes. Data science in regards to space weather refers to scalable architectural approaches, techniques, software, and algorithms that alter the paradigm by which data are collected, managed, analyzed, and communicated (McGranaghan et al., 2017).

Data science-driven transformations in related fields such as Earth science (Yue et al., 2016) and climate research (Carleton and Hsiang, 2016) are a testament to the immense potential of leveraging these new ideas, and similar efforts are beginning to take root in space weather.

The NSF EarthCube project, Assimilative Mapping of Geospace Observations (AMGeO[4]; Matsuo et al., 2021) demonstrates the potential of implementing data science best practices. The project deploys a collaborative data science platform to investigate the constantly changing conditions of high-latitude ionospheric electrodynamics. AMGeO connects geospace observational datasets from NSF-funded facility programs (e.g., SuperDARN, AMPERE, and SuperMAG) to form a coherent specification of ionospheric electrodynamics. AMGeO does this through open-source Python software and an online interface that facilitates data acquisition and pre-processing. The project streamlines data access, collection, and integration, and its software is designed to be transparent, expandable, and interoperable to encourage collaboration and engagement within the geospace community. The newly-formed "near-Earth space data infrastructure for e-science" (ESPAS; Belehaki et al., 2016) is a similar project with a special emphasis of standardized vocabulary and expandability to improve long-term sustainability. The Python in Heliophysics Community (PhYC[5]) effort promotes open data through a knowledge base for performing heliophysics research in Python.

Given the breadth of the space weather field—spanning from solar physics to geology—inter-disciplinary science connecting phenomena from the Sun to Earth may require datasets from many organizations, instruments, and agencies. Making observations and data open source reduces the barrier to starting research and can help accelerate needed discoveries—the "democratization" of science. While the needs of specific industries may vary from country to country, these specific perspectives help scientists understand why these regional variations exist. Making these data available, translatable, and accessible to a worldwide audience will help foster international collaboration, a critical step in reacting to and developing technology for the regional and global nature of space weather phenomena.

3 https://www.faa.gov/aircraft/air_cert/design_approvals/air_software/media/TC-15-62.pdf.

4 https://amgeo.colorado.edu.

5 https://heliopython.org/.

3.2 Cross-disciplinary science and information systems

Understanding space weather from a broad perspective is important for industries to communicate their needs to scientists, and vice-versa. Common scientific understanding improves the utility of discovery and unifies efforts.

An information system is a technology that provides the structure to collect, store, process, and integrate data. The Sun-to-industry information system is an important part of creating industries resilient to space weather, and coordinating collaboration across disciplines improves scientific knowledge. Specifically, information currently flows mainly in one direction: from space weather to industry, but this should not be the case. Bidirectional communication improves scientists' understanding of what industries need (e.g., real-time maps of GICs used by power grids). Communication also improves trust in space weather models, which helps clarify risk. Additionally, coordinating across scientific communities is an important step in developing a "systems science" approach to space weather. In order for the observation, forecasting, and modeling of space weather to improve, a knowledge commons shared between disciplines should be created. This sharing of information will standardize the glossary and semantics of space weather, fostering collaboration without current communication barriers, while also preventing the duplication of effort through the gathering and sharing of knowledge across groups. Optimizing the information flow "from Sun to mud" means that we can create more refined and polished plans for how industries prepare for and respond to space weather.

3.3 Citizen science

Citizen science is a field that connects scientists to the public, enabling discovery especially at disciplinary boundaries. Successful projects in heliophysics and related fields make citizen science capable of shedding light on some of the most challenging space weather mysteries.

Citizen science is a rapidly growing, recently formalized field that is fueled by the concept of cognitive surplus, i.e., that small amounts of volunteered time by many people can contribute to a larger scientific goal (Shirky, 2010). Projects that incorporate citizen science have the potential to engage and motivate broad, global audiences to drive new scientific discoveries, while still maintaining data quality. Citizen science also centers around creating open-data frameworks, making data accessible to the interested public. Citizen science projects are frequent and well-established in astronomy (e.g., Globe at Night), and within the past solar cycle, a number of projects have emerged to study space weather. One such project, Aurorasaurus (MacDonald et al., 2015), utilizes manual reports as well as aggregate Twitter sightings of aurora to develop a more accurate nowcast prediction of the auroral ovals. In some instances, citizen science reports map the aurora more realistically in real time than operational models (Case et al., 2016). The Aurorasaurus community has also contributed to discoveries relating to the STEVE (Strong Thermal Emission Velocity Enhancement) phenomenon, using citizen scientists' aurora photographs (Gallardo-Lacourt et al., 2018; MacDonald et al., 2018; Chu et al., 2020; Grandin, 2020; Hunnekuhl and MacDonald, 2020; Semeter et al., 2020). Other notable citizen science projects include Solar Stormwatch (Jones et al., 2017), Solar Jet Hunter (Musset et al., 2021), and NOAA's CrowdMAG (Nair et al., 2014), which has proven capable of detecting geomagnetic fields (Robinson et al., 2021). Citizen science works in tandem with initiatives focusing on systems science, open data, and international collaboration. Projects also serve educational purposes, helping to create a more well-informed public that is aware of space weather. MUSICS (Archer et al., 2018) and Space Weather UnderGround (Smith, 2022) are recent notable examples. In space weather, it enables novel ways to monitor conditions on the ground in real time, and contributes to scientific endeavors that require the analysis of large datasets. Together with developing data aggregates and knowledge commons, citizen science projects may be developed to leverage the large amount of data linking industry and science.

4 Conclusion

Adapting a risk and resiliency framework for space weather is crucial for tackling heliophysics challenges during the next decade and beyond. Utilizing open data and data science is one route to shape existing data products, tools, and software to be more easily accessible. The "democratization of science" will only happen if we promote existing projects and develop new efforts to converge information into a knowledge commons that can be accessed by scientists, industries, the public, and other end-users. Cross-disciplinary efforts will be crucial for advancing space weather. Specifically, adopting information systems where knowledge is shared between scientists, space weather forecasters, and affected industries will improve our readiness for space weather threats. Working towards this goal will require dedicated efforts to convene scientists, community members, and industry representatives (e.g., cross-disciplinary workshops and industry test-bed scenarios). Finally, citizen science takes these concepts and puts them into practice, by employing science–public partnerships, community-building, data sovereignty and accessibility, reciprocity efforts, and inter-disciplinary science to advance the field of space weather. Most importantly, citizen science projects are able to quickly evolve to answer emerging science questions. Agency-specific recommendations reflecting these sentiments can be found in the white paper of the same title submitted to the 2024–2033 Heliophysics Decadal Survey (Ledvina et al., 2022).

Over the next decade, the challenges of the next solar cycle maximum coinciding with an increasingly technology-dependent society will demand new technologies, collaborations, and innovative research methods to bridge knowledge gaps in science, operations, and industry responses to space weather. Creating a risk and resiliency framework for space weather will ensure that we can approach these problems prepared and adapt to create resilient and responsive systems.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding authors.

Author contributions

VEL led the organization of this article. All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

VEL, EP, EIM, and PR were employed by Predictive Science Inc. RMM was employed by Orion Space Solutions. JC was employed by 2i2c. JK was employed by Jufa Intermedia—Capture North.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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