Everyday Solar Storms . . . and Their Everyday Impacts[1]

JUDITH L. LEAN
Senior Scientist for Sun-Earth System Research
Space Science Division
Naval Research Laboratory

Our Home in Space

> "*Look again at that dot. That's here. That's home. That's us . . . a mote of dust suspended in a sunbeam. The Earth is a very small stage in a vast cosmic arena*." – Carl Sagan (1934–1996)

The view of Earth from a distance of 7.2 billion km (4 billion miles), shown in Figure 1,[2] indeed underscores Earth's tiny cosmic presence—and hints at its susceptibility to the Sun's vagaries. In our orbit of radius 149.6 million km around the Sun, we depend entirely on, and are potential victims of, its energetic output.

Solar electromagnetic radiation makes Earth habitable. As Figure 2 shows, solar energy, in the form of photons, travels directly to Earth from the Sun's surface and atmosphere, reaching us in just 8 minutes. It is the balance of this incoming radiative energy (primarily at visible wavelengths) with outgoing thermal energy (at near-infrared wavelengths), which the solar-warmed Earth radiates back to space, that establishes the temperature of Earth's surface and atmosphere. The Sun's visible radiation varies only minimally, by a tenth of a percent or so over decades (Lean 2010).

Electromagnetic radiation is not the only form of energy that the Sun sends to Earth. Figure 3 depicts how the Sun and Earth are also intimately connected in a quite different way—by a solar wind of magnetic fields and plasma that blows by Earth. Magnetic fields from the Sun's surface extend through its outer atmosphere—the *corona*—and pervade the space environment between the Sun and the Earth—the *heliosphere*. They deform Earth's intrinsic magnetic field forming a magnetospheric

1 Read 14 November 2015, as part of the symposium on the 1859 (Carrington) solar storm.
2 All Figures appear in the Appendix at the end of this paper.

bubble that, to a large extent, protects Earth's underlying atmosphere and surface—and our societal infrastructure—from energetic particles in the solar wind plasma and magnetosphere.

Unruly Sun: Driver of Space Weather

The Sun's magnetic fields are in constant motion. Convective, diffusive, and meridional flows continually jostle the field line footprints, which are anchored beneath the Sun's visible surface. When magnetic fields interact, they can abruptly reconfigure, producing eruptions that perturb the outflow of both electromagnetic and plasma energy. Frequently—but not always—enhanced electromagnetic radiation is evident at this time from the region of the Sun where the fields distort and reconnect. The flares are observed primarily as enhanced radiation at extreme ultraviolet and X-ray wavelengths. An ejection of mass from the outer solar atmosphere often results. *Coronal mass ejections* (CMEs) spew outward from the Sun into the surrounding heliosphere as a cloud of plasma and magnetic fields producing shocks that propagate through the solar wind (Vita-Finzi 2015; current issue). Figure 4 depicts the morphology of an eruptive solar event whose origin on the Sun is such that the Earth, in its transit around the Sun, is in the path of the CME.

Eruptive events perturb the heliosphere initially in the vicinity of the location of the event on the Sun and increasingly over a wider volume of the solar system as the Sun's rotation generates a spiraling of the outward-spreading magnetic fields and plasma. The original location of the CME on the Sun and its subsequent transit through the heliosphere determine the extent of its interaction with objects in the solar system, including the Earth. Because of its miniscule cosmic footprint (Figure 1), Earth mainly avoids significant disruption of its local space environment by the Sun's eruptions. The magnetosphere (with an up-wind diameter of ~128,000 km) encompasses only about 0.013% of the circumference of Earth's orbit around the Sun (940 million km).

Figure 5 shows, on the left, an image of an eruptive solar event on 15 March 2015, observed by dual instruments on the twin spacecraft of NASA's Solar Stereo Observatory (STERO). On the right are simulations using the WSA-ENLIL model that the National Oceanic and Atmospheric Administration's (NOAA's) Space Weather Prediction Center (http://www.swpc.noaa.gov/products/wsa-enlil-solar-wind-prediction) made of the density (upper right) and velocity (lower right) of the heliosphere as the 15 March 2015 eruption transited. The simulations indicated that the magnetic cloud from the solar eruption would interact only tangentially with the Earth, delivering a "glancing blow" rather than colliding directly; the initial forecast for 17 March 2015

was minor—if any—impacts, a G1 level on the SWPC scale. It was eventually reclassified as a G4 event, much stronger than expected.

The most obvious manifestation of a solar storm's impact on the Earth is the occurrence of an aurora. On St. Patrick's Day, 17 March 2015, there were "incredible auroral displays at mid to high latitudes" (http://www.solarham.net/march2015storm/index.htm), such as that shown in Figure 6. Aurorae occur primarily in polar regions because this is where Earth's intrinsic magnetic field connects most directly with magnetic fields in the heliosphere (Figure 3). Energetic particles in the solar wind and those in the ambient magnetosphere perturbed by the impact of the CME (Figure 4) can flow down field lines into Earth's upper atmosphere—the *thermosphere*. There, the energetic particles excite atmospheric gases, which subsequently radiate visible (and other spectral region) emissions at wavelengths corresponding to their atomic properties: green and red are oxygen emissions (wavelengths of 557.7 nm and 630.0 nm), and blue and purple are nitrogen emissions.

Aurorae have been observed for centuries, in different strengths, with different colors, and extending over varying degrees of latitude. The Carrington Event in September 1859, arguably the largest solar storm yet to impact the Earth in modern times, produced aurorae that were seen widely across the United States (Cliver and Svalgaard 2004, Giegengack 2015; current issue), including in the South, and likely inspired Church's 1865 painting *Aurora Borealis* (Figure 7), possibly as a tribute to the end of the Civil War (Love 2014; https://eos.org/features/aurora-painting-pays-tribute-to-civil-wars-end).

Yet the commonalty of their beautiful aurorae belies significant differences in the characteristics of the 2015 St. Patrick's Day and 1859 Carrington events. The St. Patrick's Day event took 57 hours to transit the heliosphere; the 1859 Carrington Event reached Earth in just 17.6 hours. One measure of the impact of a solar eruption when it arrives at Earth is the *ap* index, derived from ground-based magnetometers. Figure 8 shows 3-hourly values of the *ap* index since the 1930s. By comparison with the "super" Carrington event, for which *ap* likely exceeded 400 (Cliver and Svalgaard 2004), the St. Patrick's Day event was modest, with *ap* of 179. As Figure 8 shows, it was weaker than hundreds of events with greater *ap* values in the last 60 years, many of which did not produce such dramatic aurorae.

In reality, solar eruptions, CMEs, and their impacts on the Earth involve multiple interacting processes, vary widely in character, and are extremely difficult to forecast; the St. Patrick's Day event, for example, arrived at Earth 15 hours sooner than predicted. Not all flares are accompanied by CMEs and vice versa. Not all solar eruptions on the Sun produce geomagnetic activity—and hence large values of *ap*—at

Earth. Furthermore, although the fastest CMEs are considered the most likely to impact Earth, geoeffective CMEs have been found to have speeds that range from many hundreds to a few thousand kilometers per second (Wood et al. 2016).

Solar flares and CMEs are aspects—albeit dramatic and potentially consequential ones—of the Sun's activity. A sub-surface dynamo alters the amount of magnetic flux that emerges from beneath the solar surface into the solar atmosphere in cycles of approximately 11 years. The cycling of the Sun's energy output is pronounced in electromagnetic radiation and in the number of sunspots on the disk, but less so in the plasma and magnetic fields that compose and perturb the solar wind. Compared in Figure 8 with the *ap* index of geomagnetic activity is the sunspot number, a common indicator of general solar activity; the correlation of the daily values of the *ap* index and the sunspot number is only 0.14. The St. Patrick's Day event was the largest thus far in our present solar cycle 24, which commenced in 2008. Cycle 24 is of modest strength historically, weaker than all prior cycles in the twentieth century, and more similar to cycles in the late nineteenth century.

Were solar eruptions correlated tightly with solar activity such as indicated by sunspot numbers, the cyclicity of their occurrence might enable some predictive capability. Although there is a tendency for more geomagnetic activity during times of higher solar activity, the occurrence of eruptive solar events and their terrestrial impacts does not depend in a straightforward way on solar activity (Figure 8). This lack of robust correlation underscores the unpredictability and complexity of solar-heliospheric processes and presents a significant challenge for forecasting the occurrence of an eruption of the Sun and the extent of its subsequent impacts on Earth. Moreover, extreme events such as the Carrington Event are relatively rare in recent solar-terrestrial records, and forecasting their occurrence with uncertainties sufficiently small for meaningful utilization is essentially impossible. Such events are thought to occur once every few centuries. Riley (2012) boldly suggests that the chance that a Carrington-strength event will impact the Earth in the next decade is about 12%; alternatively, Love (2012) predicts the likelihood is half this.

More certain, by far, is the knowledge that solar eruptions occur continually, as do their impacts on Earth. And although modest "everyday" solar storms may not produce such serious consequences as evidenced in 1859 and envisioned as the consequence of a future Carrington event, they nevertheless disrupt and perturb the space environment near Earth in ways that often affect the everyday activities of our technological society (Skone et al. 2004).

Space Weather Impacts on Everyday Activities

CMEs can impact Earth's environment and our society less benignly than the production of visually appealing aurorae because today the engineered systems and infrastructure that enable and support many societal activities reside in, traverse, or are otherwise susceptible to conditions in the extended environment, well beyond that at Earth's surface (Royal Academy of Engineering 2013). Solar eruptions—even modest ones—produce "weather" in space by distorting and disrupting the ambient near-Earth space environment; this space weather, like meteorological weather, can affect our everyday activities.

Space is not empty. Near the Earth it contains primarily low densities of oxygen and nitrogen molecules and atoms, along with a small amount of ionospheric plasma. Also resident in the region of space from a few hundred to many thousands of kilometers above the Earth's surface are more than 1,300 active Earth-orbiting spacecraft and more than 20,000 space "debris" objects, a number that is increasing at five per day. Figure 9 depicts these objects, detected by a radar "fence" that the U.S. Space Command uses to continually monitor the orbits of space objects. Although the density of the thermosphere at 500 km is 13 orders of magnitude less than at Earth's surface, it is nevertheless sufficient to produce atmospheric drag that alters the motions of Earth-orbiting objects. The impact of a CME is to abruptly alter the density and temperature of the thermosphere over time scales of days. The resultant orbital disruptions cause loss of object tracking, opening the possibility of unexpected collisions and "unknown"—and possibly misidentified adversarial—objects (National Research Council [NRC] 2012).

Space contains not only neutral but also charged particles (i.e., electrons and ions). Solar electromagnetic radiation at extreme ultraviolet wavelengths ionizes neutral oxygen and nitrogen in the upper atmosphere, producing the ionosphere at altitudes from 60 to 1,000 km—layers of electrons and ions embedded within the neutral thermosphere. Figure 3 depicts the plasmasphere, extending to several Earth radii. The ionosphere diffracts, reflects, distorts, and at times completely absorbs radio signals that propagate through it. The effects are approximately proportional to the total (integrated along the slant path) electron content in the ionosphere and inversely proportional to the frequency squared of the radio wave (Skone et al. 2014). Ham radio operators, who utilize the ionosphere to reflect radio waves so they can communicate over long distances, are familiar with this phenomenon (http://www.eham.net/newham/propagation). Communications among Earth-orbiting spacecraft and Earth, including those that facilitate autonomous

geospatial positioning using Global Navigation Satellite Systems (GNSS), similarly communicate with radio waves at a range of frequencies.

Figure 10 depicts the constellation of U.S. Global Positioning System (GPS) spacecraft that orbit Earth at 20,300 km and the ionosphere and plasmasphere that pervade the space between them. Changes in the composition, temperature, and morphology of this plasma can disrupt—or even prevent—radio communications. The use of Ultra High Frequencies (in the megahertz range) for space-based communication systems generally minimizes their susceptibility to ionospheric disruptions. Approximate location precision of the GPS averages about 1 meter, but this precision can degrade to tens of meters during geomagnetic storms (Skone et al. 2014).

An example of space-based infrastructure that informs everyday activities in the United States is the Wide Area Augmentation System (WAAS) that the Federal Aviation Administration operates for precision navigation of flight paths of commercial aviation (http://www.nstb.tc.faa.gov). As Figure 11 shows schematically, WAAS combines multiple space-based transmitters and ground-based receivers to achieve nominally 100% coverage of the Continental United States (CONUS), Alaska, and Canada. Supplementary aircraft guidance is needed during times of impaired coverage, during which airline efficiency is reduced, flights are delayed, and safety is decreased.

Even modest "everyday" solar eruptions can reduce WAAS coverage if they perturb the space environment sufficiently. The solar eruption on 15 March 2015 was such an event. Its strength, indicated by an *ap* value of 179, was modest compared with major solar geomagnetic storms in the past 60 years and the Carrington Event, for which *ap* values were in excess of 400 (Figure 8). Although the St. Patrick's Day storm imparted only a glancing blow to the Earth with (initially) low expected impact, it nevertheless produced the most dramatic and visible aurorae thus far in solar cycle 24 (Figure 6). It arrived at Earth 15 hours earlier than forecast because it traveled through the heliosphere considerably faster than model simulations (Figure 5) predicted. However, the transit still took 52 hours, and its speed was much slower than the 1859 Carrington Event, which reached Earth in just 17.6 hours.

The St. Patrick's Day solar storm reduced WAAS coverage significantly for a few hours. The upper row of Figure 12 compares the CONUS WAAS >99% coverage on 16 March 2015, the day before the storm arrived at Earth, and on the following day during the storm when coverage declined to 73%. Another solar storm in October 2011, even more modest in strength (*ap* of 154) and traveling more slowly (transit time 61 hours) than the St. Patrick's Day event, caused even greater reduction (to 64%) in WAAS coverage on 24 October 2011,

also shown in Figure 12. For a time on October 25 when coverage was reduced to 0%, this "everyday" storm eliminated CONUS coverage entirely (Datta-Barua et al. 2014).

The FAA's WAAS is just one example of the many and varied applications of high precision navigation that support the day-to-day workings of our technological society—not just in the sky but also on land and in the ocean. Commercial, national, and Department of Defense (DoD) security endeavors rely on high precision geolocation and timing. It is crucial for deep sea drilling and surveying, mining, farming, and oil industry operations. In the Gulf of Mexico, for example, where the pipeline infrastructure is dense and complex (Figure 13), operations are prioritized for times when no solar storms are forecast. The foundation of command, control, and communication capabilities that underlie DoD and national security activities is precision navigation and timing (Filler et al. 2004), and thus knowledge of ionospheric variability and space weather is crucial (Cannon 2009).

Solar eruptions can impact activities on Earth in other ways too. Induced currents can stress power plants and transmission lines, to which the electrical infrastructure is especially susceptible (National Science and Technology Council, Space Weather Operations, Research and Mitigation [SWORM] Task Force 2015). The energetic particles that often accompany CMEs—*solar cosmic rays*—are sources of radiation that can damage space-based electrical systems and are also biologically harmful. Their relatively easy access to the Earth's lower atmosphere—down to altitudes of 10 km or so, where aircraft fly—is a significant concern for polar flight paths. Polar routes from the United States to Asia, such as the United flight paths shown in Figure 14, are expanding with the economic growth of China and India, facilitated by the availability of modern aircraft with extended range. Traversing the North Pole reduces flight time from 1 to 3 hours, and there is an absence of turbulence and convection prevalent at mid latitudes—where storm tracks primarily manifest. But polar aviation risks exposing passengers to energetic particle radiation exposure in the event of a geomagnetic storm (http://www.bbc.com/future/story/20131113-the-supernova-inside-your-plane?ocid=ww.social.link.email), and aircrew are routinely equipped with radiation badges; reliable timely forecasts of such events help minimize costly disruptions and alternative routes and maximize the safety and efficiency of these routes.

In the United States, the NOAA's Space Weather Prediction Center (SWPC; http://www.swpc.noaa.gov) and the Air Force Weather Agency (http://science.dodlive.mil/tag/air-force-weather-agencys-space-weather-operations-center/) alert users 24/7 about the likelihood of solar eruptions and their potential space environment impacts. In

excess of 45,000 users include aviation, electric power, emergency management, position, and navigation and satellite operations among federal, commercial, international, and popular stakeholders. Other countries operate analogous space weather capabilities, and organizations that provide space weather services collaborate within the International Space Environment Service (ISES; http://www.spaceweather.org).

Watching the Weather from Space

As with meteorological weather, for which the NOAA employs multiple spacecraft in geostationary, polar, and-low Earth orbits (Figure 15), so too are space-based products crucial for space weather specification and forecasting. Currently, many such products are derived from research activities that are not formally operational. The recent launch of the NOAA's DSCOVR and its operation at L1 (one of the Lagrangian points where a spacecraft can be stably "parked"), shown in Figure 16, is a new capability for operationally monitoring solar wind and space environment conditions up-wind of Earth; this capability provides a 1-hour warning of impending disturbances at Earth. Envisioned—and necessary—for the future is a fleet of spacecraft strategically located to track and forecast solar eruptions, CMEs, geomagnetic storms, and associated perturbations of the magnetosphere, plasmasphere, thermosphere and ionosphere, analogous to the meteorological weather satellites that track hurricanes, floods, earthquakes, volcanoes, and tsunamis. Figure 17 illustrates such a concept, conceived by the NRC 2013 decadal survey of *Solar and Space Physics: A Science for a Technological Society*.

On Earth, a growing population is more reliant than ever on technology delivered by increasingly sophisticated networks of ground—and space—based engineered systems that are susceptible to space weather. The need to protect these systems, specifically the electrical power grid, from severe space weather is a primary motivation of the SWORM Task Force 2015. The near-space environment itself is also becoming crowded. The ever-increasing number of objects increases the probability of collisions, which atmospheric disruptions by geomagnetic activity further exacerbate.

Demand for improved performance and reliability of Earth's technological infrastructure is likely to increase; for example, future needs for precision geolocations are perhaps centimeters, an order of magnitude improved over current capability of meters. Collision avoidance of the growing number of space objects requires higher precision satellite geolocation than is possible today. Achieving these

requirements will require continuous specification and forecasting of space weather and ionospheric and thermospheric conditions with unprecedented accuracy—not just for managing high-risk extreme events but also ongoing fluctuations 24/7.

Recognition is growing that our home in space extends well beyond the surface where we live and encompasses the space environment that enables and supports our engineered societal infrastructure. It is expected that the specification and forecasting of space weather will ultimately blend seamlessly with that of meteorological weather. Toward this end, space weather is now an integral part of the NOAA National Weather Service in the United States and the United Kingdom Met Office (http://www.metoffice.gov.uk/publicsector/emergencies/space-weather). As everyday encounters sharpen our alertness and advance forecast skill, so too does our capacity increase to counter the problems of a future Carrington Event.

Acknowledgments

The Chief of Naval Research supported this work. The Space Science Division of the Naval Research Laboratory undertakes research to specify, understand, and forecast the extended operational environment. Acknowledged and appreciated are ongoing collaborations with these scientists. C. Vita-Finzi, R. Giegengack, and R. Meier provided valuable comments on the manuscript. A number of the figures include images from Google Images.

References

Cannon, P. S. 2009. "Mitigation and Exploitation of the Ionosphere: A Military Perspective." *Radio Science* 44 (1). doi:10.1029/2008RS004021

Cliver, E. W., and L. Svalgaard. 2004. "The 1859 Solar-Terrestrial Disturbance and the Current Limits of Extreme Space Weather Activity." *Solar Physics* 224: 407–22.

Datta-Barua, S., T. Walter, G. S. Bust, and W. Wanner. 2014. "Effects of Solar Cycle 24 Activity on WAAS Navigation." *Space Weather* 12 (1): 46–63, doi:10.1002/2013SW000982.

Filler, R., et al. 2004. *Positioning, Navigation and Timing: The Foundation of Command and Control*. United States Army Command and Control Directorate (C2D). Fort Monmouth, N.J.

Giegengack, R. 2015. "The Carrington Coronal Mass Ejection of 1859." *Proceedings of the American Philosophical Society* 159 (4): 421–33.

Lean, J. L. 2010. "Cycles and Trends in Solar Irradiance and Climate." *Wiley Interdisciplinary Reviews: Climate Change* 1 (1): 111–22.

Love, J. J. 2012. "Credible Occurrence Probabilities for Extreme Geophysical Events: Earthquakes, Volcanic Eruptions, Magnetic Storms." *Geophysical Research Letters*. 39 (10). doi:10.1029/2012GL051431

Love, J. J. 2014. "Auroral Omens of the American Civil War." *Weatherwise* 67 (5): 34–41, doi:10.1080/00431672.2014.939912

National Research Council. 2012. *Continuing Kepler's Quest: Assessing Air Force Space Command's Astrodynamics Standards*. Committee for the Assessment of the U.S. Air Force's Astrodynamic Standards.

National Research Council. 2013. *Solar and Space Physics: A Science for a Technological Society*.

National Science and Technology Council, Space Weather Operations, Research and Mitigation (SWORM) Task Force. 2015. *National Space Weather Strategy*. Washington, DC.

Riley, P. 2012. "On the Probability of Occurrence of Extreme Space Weather Events." *Space Weather* 10 (2). doi:10.1029/2011SW000734

Royal Academy of Engineering. 2013. *Extreme Space Weather: Impacts on Engineered Systems and Infrastructure*.

Skone, S., R. Yousuf, and A. Coster. 2004. "Combating the Perfect Storm: Improving Marine Differential GPS Accuracy with a Wide-Area Network." *GPS World*, October.

Vita-Finzi, C. 2015. "The Perfect Solar Storm." *Proceedings of the American Philosophical Society* 159 (4): 415–20.

Wood, B. E., J. L. Lean, S. E. McDonald, and Y.-M. Wang. 2016. "Comparative Solar Origins and Ionospheric Impacts of Nine Strong Geomagnetic Storms in 2010–2015." *Journal of Geophysical Research*, submitted.

Appendix

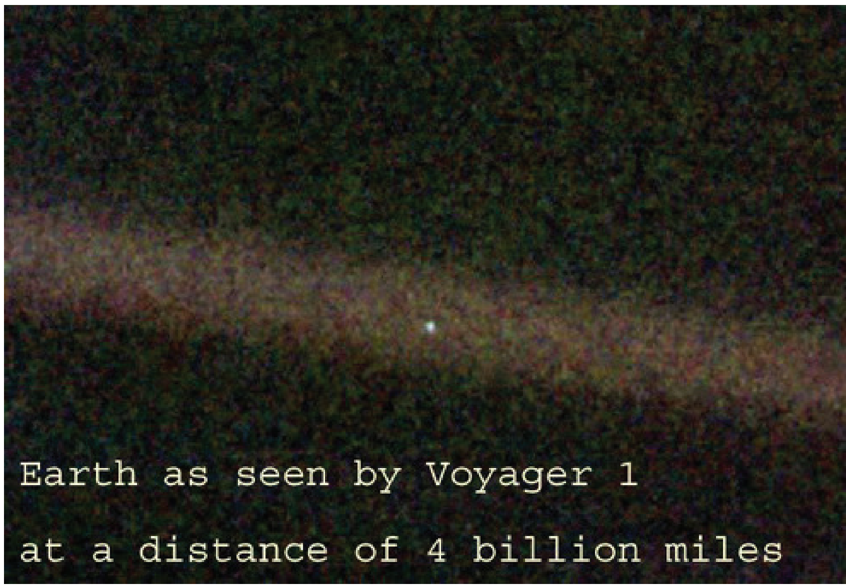

Figure 1. Our home in space—a pale blue dot suspended in a sunbeam.

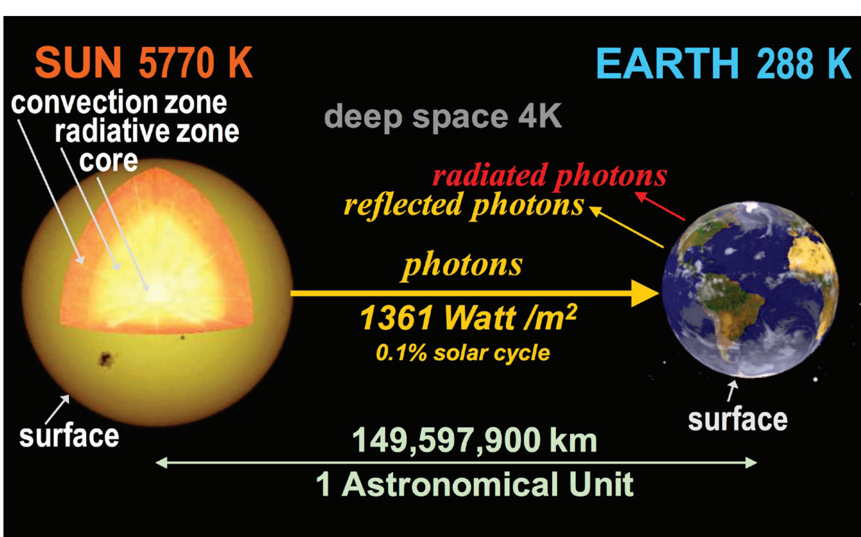

Figure 2. The Sun provides energy in the form of electromagnetic radiation that makes Earth habitable.

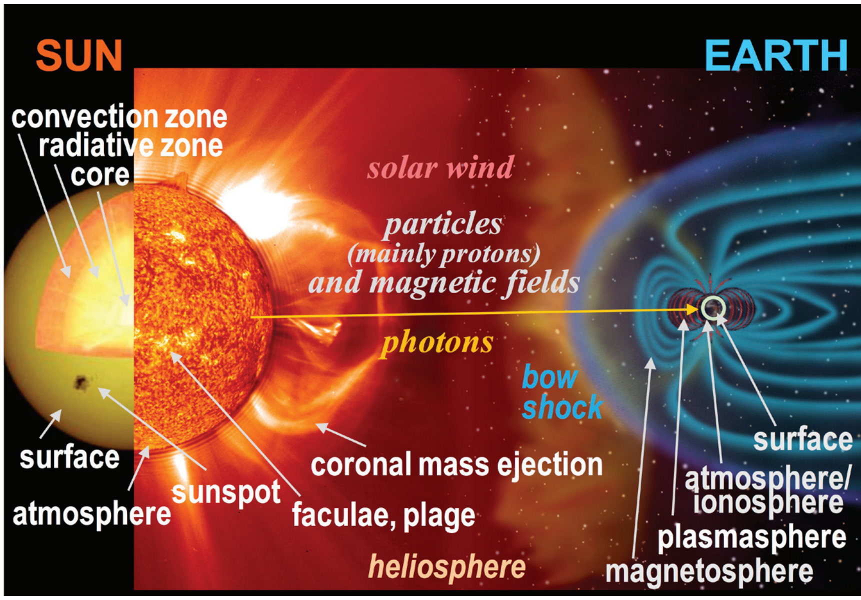

FIGURE 3. The solar wind—streaming plasma from the Sun's outer atmosphere—flows into the heliosphere and deforms Earth's intrinsic magnetic field, forming a protective magnetosphere that envelops and protects Earth's atmosphere and surface.

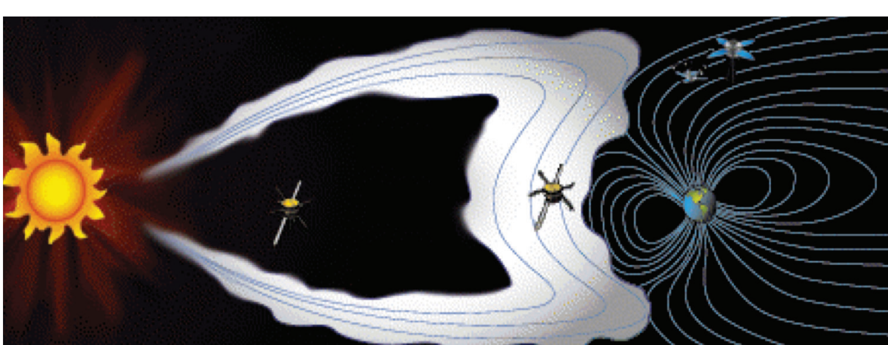

FIGURE 4. Depiction of a coronal mass ejection pervading the heliosphere and distorting Earth's magnetosphere.

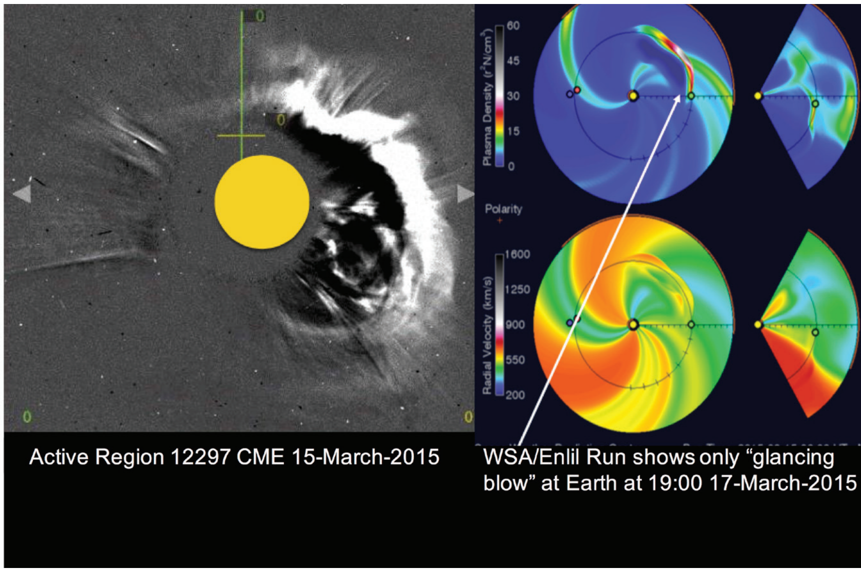

FIGURE 5. An eruptive event on the Sun on 15 March 2015 produced a coronal mass ejection imaged, on the left, by NASA's STERO spacecraft. A model of the propagation of the coronal mass ejection in the solar wind, on the right (in plan view and in partial cross section; Earth is the small circle to the center right), shows how the magnetic fields and plasma in the coronal mass ejection expand to fill the heliosphere as the coronal source region of the ejected mass rotates with the Sun. The model predicts that the coronal mass ejection delivers only a glancing blow to Earth. Figure courtesy of Dr. T. Berger, Director, NOAA Space Weather Prediction Center.

FIGURE 6. Aurorae are a visible indication of the Sun's activity impacting Earth's thermosphere. "A geomagnetic storm sparks an incredible show of the Aurora Borealis over Iceland Tuesday, 17 March 2015." Photo credit: Juan Carlos Casado, SLOOH/IAC Expedition.

FIGURE 7. *Aurora Borealis* paining by Frederic Edwin Church in 1865, possibly inspired by sightings of aurorae produced by the 1859 Carrington Event (Love 2014).

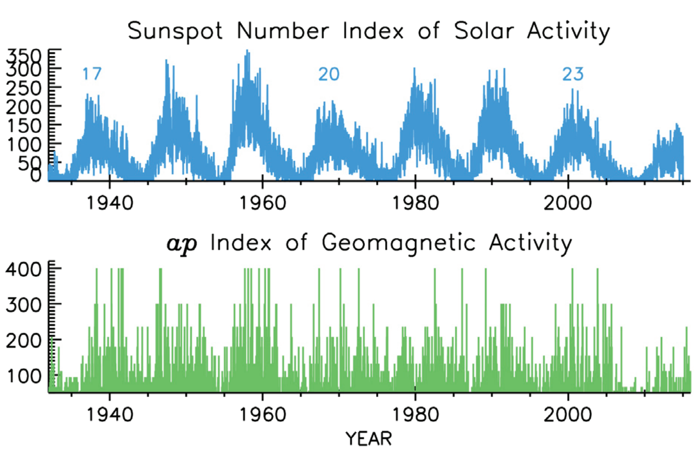

FIGURE 8. The *ap* index (lower plot) is a measure of geomagnetic activity—the relative strength of the impact on the Earth of a solar eruption. Its 3-hour variations are shown from the 1930s to the present, including the solar storm on 17 March 2015 at the very end of the record. Sunspot numbers (upper plot), included for comparison, are a generic indicator of overall solar activity. The numbering of the 11-year cycles in sunspot number, as shown, dates from the first cycle that commenced in 1755.

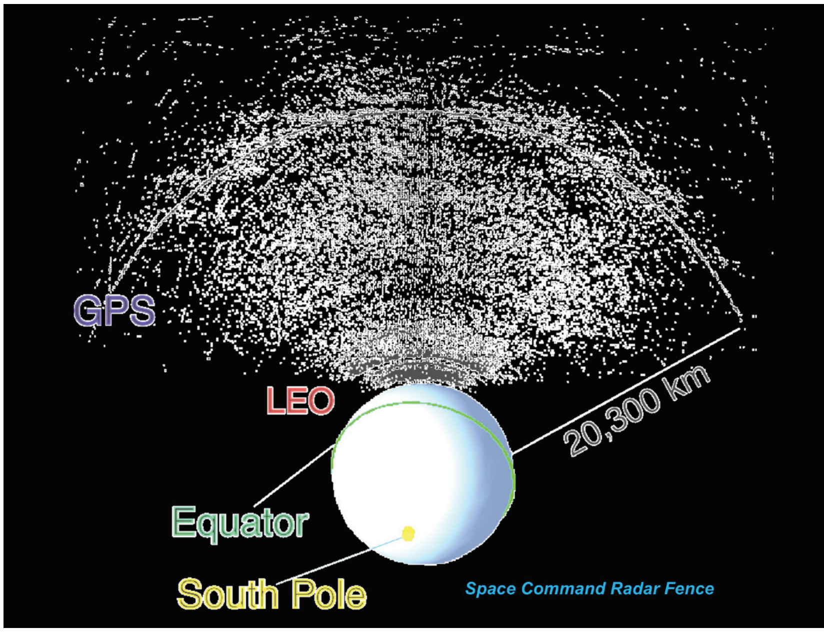

FIGURE 9. Radar scan depicting objects in the space environment at altitudes from Low Earth Orbit (LEO) to the 20,300 km orbit of Global Positioning System spacecraft.

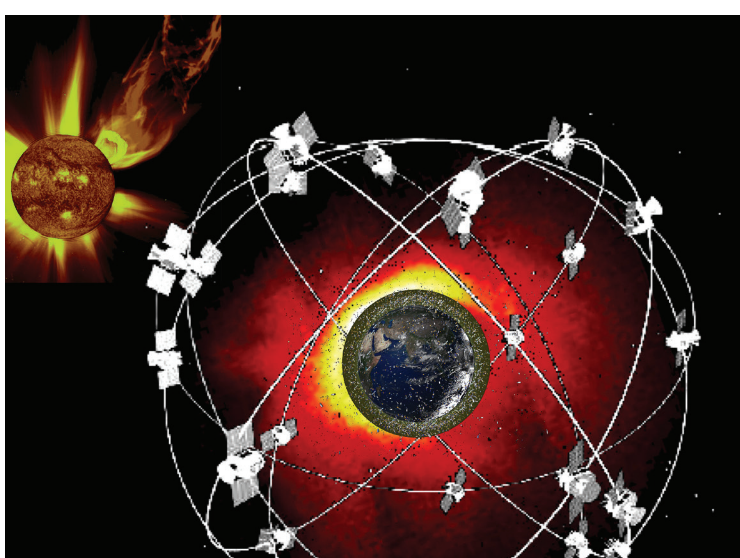

FIGURE 10. The Global Positioning System constellation of Earth-orbiting spacecraft. Fluctuations in the ionosphere and plasmasphere (depicted by the yellow and red colors, respectively) that intervene between the spacecraft and the earth can disrupt radio frequency communication.

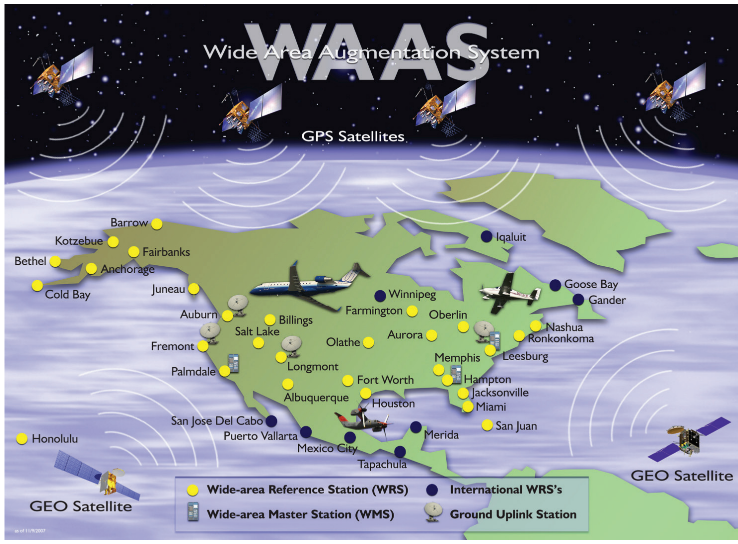

FIGURE 11. The FAA's Wide Area Augmentation System combines space-based and ground-based assets to precisely navigate efficient and safe flight paths in the USA.

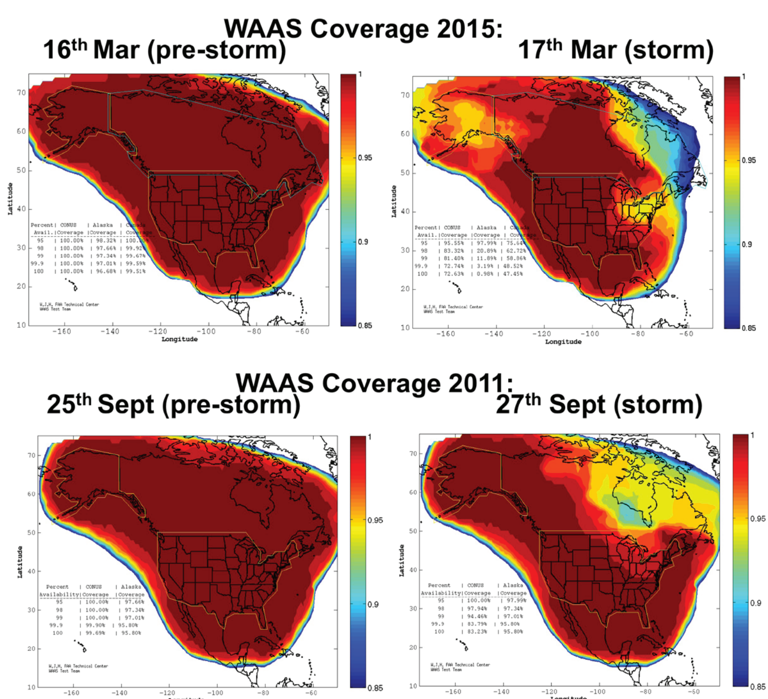

FIGURE 12. Examples of Wide Area Augmentation System CONUS coverage before and during two recent modest solar storms. Images from http://www.nstb.tc.faa.gov. Maroon shading indicates total coverage.

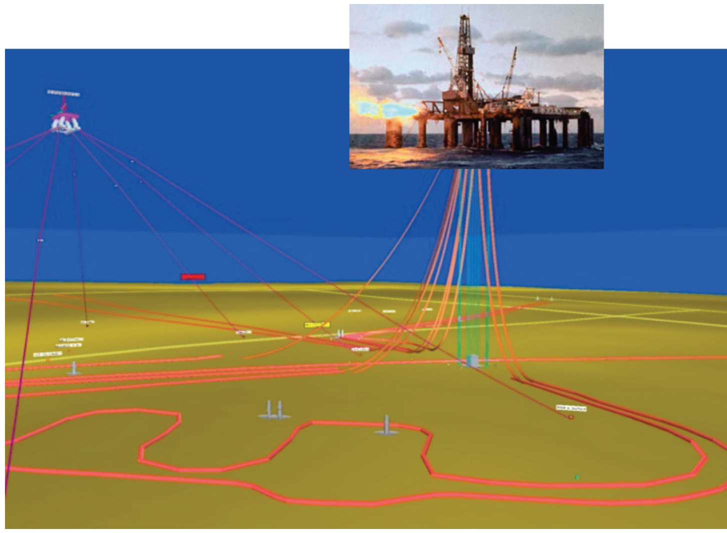

FIGURE 13. Gulf of Mexico sea floor. Image courtesy of Richard Barker, Fugro Chance Inc. Presented at the Space Weather Enterprise Forum, Washington DC, 2007.

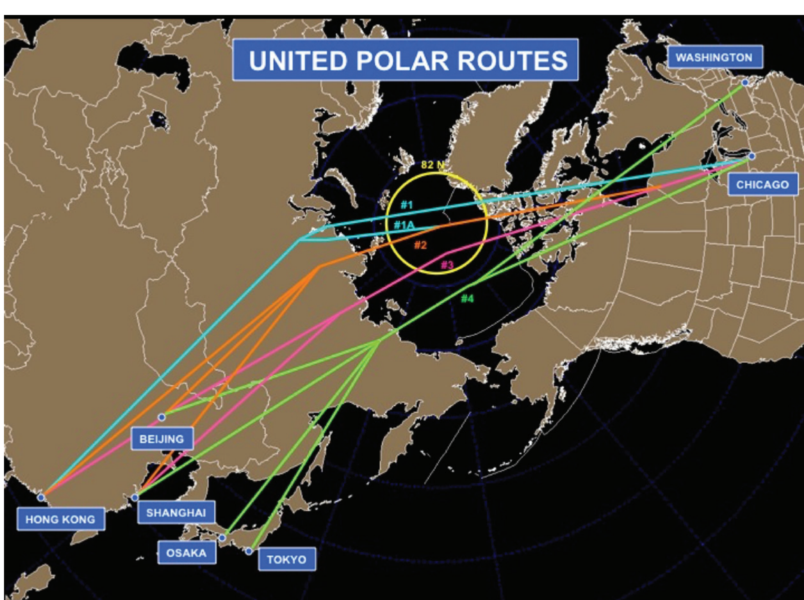

FIGURE 14. United Airlines Polar Routes. Image courtesy of Mike Stills, United Airlines. Presented at the Space Weather Enterprise Forum, Washington DC, 2007.

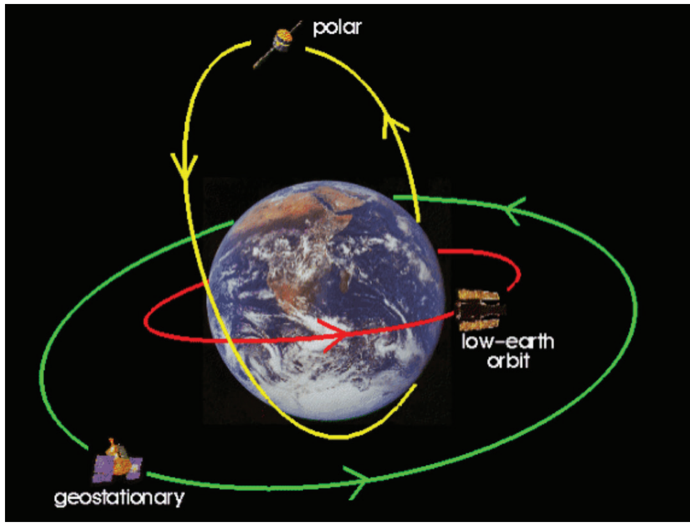

FIGURE 15. The U.S. National Weather Service uses geostationary, polar, and low-Earth orbiting spacecraft to track and forecast meteorological weather.

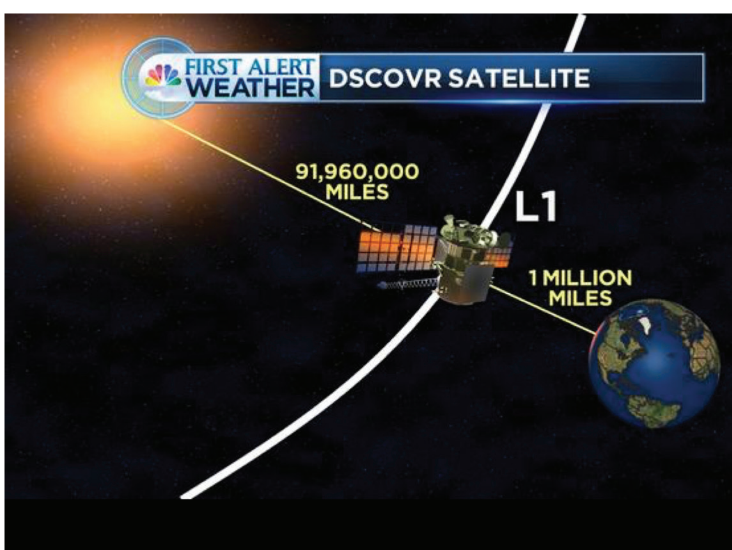

FIGURE 16. Recently added to the NOAA's fleet of operational spacecraft is the DSCOVR spacecraft, located at the L1 point upwind of Earth, for forecasting the weather in space.

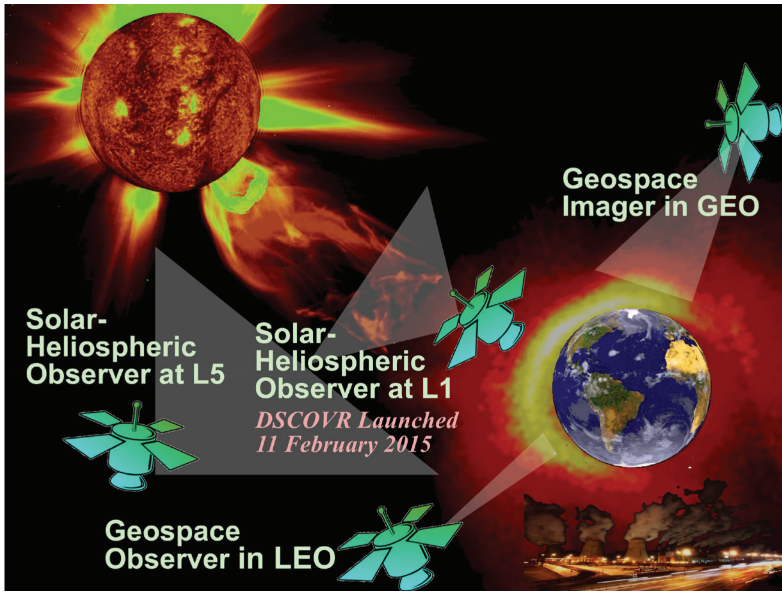

FIGURE 17. Envisioned—and needed—for future space weather monitoring and forecasting is a suite of strategically located spacecraft that observe the entire heliosphere from the Sun to Earth (NRC 2013).