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Interplanetary Space Weather: A New Paradigm

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In September 1859, Earth was hit by a solar storm so powerful that it set telegraph offices on fire and sparked northern lights in the South Pacific. Historians call it the "Carrington Event," after English astronomer Richard Carrington, who witnessed the instigating solar flare on a projecting screen with his unaided eyes. Many consider this to be the birth of space weather.

"Space weather" refers to the magnetic disturbances and high radiation levels that result from solar activity. Auroras, power outages, and radio blackouts are some of the manifestations of space weather that we experience on Earth. In space, high-velocity solar energetic particles strewn from the Sun can cause satellite damage, and space radiation is a hazard to astronaut health.

For nearly 40 years the space-based efforts of NASA, the National Oceanic and Atmospheric Administration (NOAA), and the U.S. Department of Defense, as well as space agencies in other countries, have focused on monitoring and forecasting space weather events likely to affect Earth. NASA in particular has been very focused on space weather. A look at NASA's emphasis on space weather research shows that the field is rapidly evolving to keep up with technological advances and space exploration ambitions.

The 2012 St. Patrick's Day Solar Storms

Since the Carrington Event, interest in space weather has naturally focused on our own planet. This is beginning to change, however, as NASA and other space agencies expand their research into the solar system. Probes are now orbiting or en route to Mercury, Venus, the Moon, Mars, Ceres, Saturn, and Pluto—and it is only a matter of time before astronauts are out there too. Each mission has a unique need to know when a solar storm will pass through its corner of space.

An intense episode of solar activity in March 2012 drove this point home. It began on 2 March with the emergence of sunspot AR1429. For the next 2 weeks, the angry-looking active region rotated across the solar disk and fired off more than 50 flares, 3 of which were X-class flares, the most powerful type of flare. The Sun's rotation carried AR1429 around to the far side of the Sun, where the explosions continued. By the time the sunspot finally decayed in April 2012, it had done a 360-degree pirouette in heliographic longitude, hitting every spacecraft and planet in the solar system at least once with either a coronal mass ejection (CME; a cloud of magnetized plasma) or a burst of radiation (Figure 1). This extraordinary series of solar storms, referred to as the "St. Patrick's Day storms" because of their proximity to 17 March, caused reboots and data outages on as many as 15 NASA spacecraft (Y. Zheng and NASA mission operators, private communication, 2012).

A New Paradigm

Until recently, operators of distant missions generally had no clue when a solar storm was about to engulf their spacecraft. Forecasters could barely predict space weather in the vicinity of Earth; forecasts for other parts of the solar system were even more challenging. This is not the case anymore. During the St. Patrick's Day storms, most mission operators knew the storms were coming and had opportunities to take protective action.

This signals a new paradigm in space weather forecasting: The discipline is now becoming interplanetary. There is a simple reason for this: NASA and other agencies have surrounded the Sun. It began in 2006 with NASA's launch of the twin Solar Terrestrial Relations Observatory (STEREO) [*Kaiser et al.*, 2008] spacecraft, followed in 2010 by the Solar Dynamics Observatory (SDO). Together with the Solar and Heliospheric Observatory (SOHO), a joint European Space Agency (ESA) and NASA mission, these spacecraft can see nearly every square inch of the stellar surface. No matter where a flare erupts or which way a solar storm travels, the STEREO-SDO-SOHO fleet can track it. These spacecraft form part

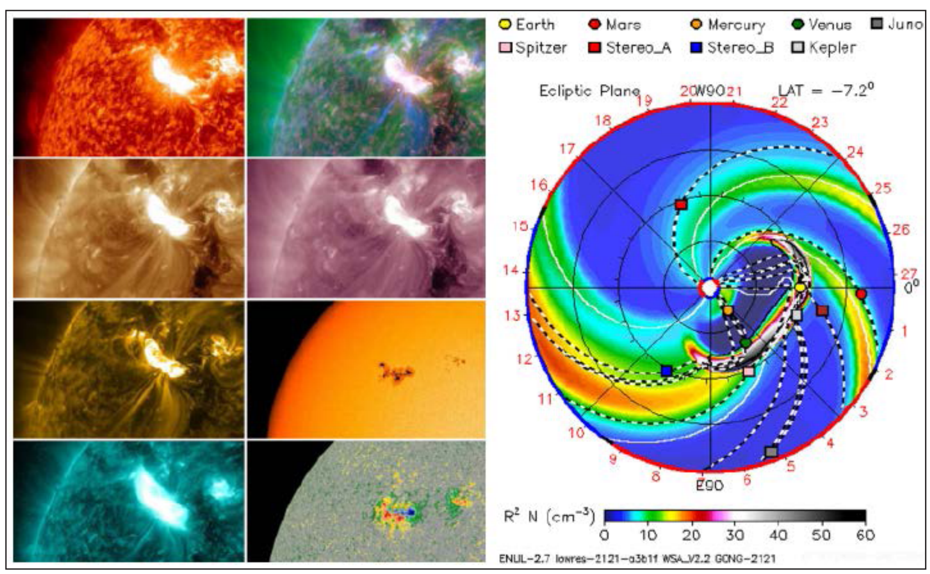

Fig. 1. Sunspot AR1429 unleashed a powerful X5-class solar flare on 7 March 2012, commencing the "St. Patrick's Day storms" of 2012. The blast also propelled a massive coronal mass ejection (CME) toward Earth. (left) NASA's Solar Dynamics Observatory recorded the flare at multiple extreme ultraviolet wavelengths. (right) A three-dimensional CME model run from the Community Coordinated Modeling Center Integrated Space Weather Analysis System shows how the CME would have propagated through the inner solar system.

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of NASA's distributed heliophysics fleet, which comprises a number of spacecraft in strategic locations between the Sun and the Earth. Other key observatories include the Advanced Composition Explorer, which provides upstream warnings of solar wind heading toward Earth. In the recent past, other agencies have launched Sun-observing spacecraft. For example, the Japanese Aerospace Exploration Agency, ESA, and NOAA have launched the Hinode, Proba-2, and Geostationary Operational Environmental Satellite (GOES) satellites, respectively.

Space Weather Models Contribute to Forecasting

Developments in modeling are also important. Around the time STEREO was launched, researchers supported by NASA's Living With a Star program [*Antiochos and Guhathakurta*, 2007] and others began to install physics-based models of the heliosphere on a bank of supercomputers at the Community Coordinated Modeling Center (CCMC), an interagency facility located at NASA Goddard Space Flight Center. NASA also established the Integrated Space Weather Analysis System (iSWA) to fetch space weather information from a wide array of spacecraft and sensors. Together, these programs can take data from NASA's heliophysics fleet and produce meaningful forecasts for any point in the solar system.

Currently, the most commonly used CCMC/iSWA data product is the three-dimensional (3-D) CME model (WSA/ENLIL cone model [*Odstrcil and Pizzo*, 1999; *Odstrcil et al.*, 2004]). The supercomputers combine observations from space-based STEREO, SDO, and SOHO and ground-based magnetographs to produce 3-D models of CME propagation. These models are akin to hurricane forecast tracks produced by the National Weather Service (NWS). Analysts at Goddard use them to predict when storms will hit Mercury, Venus, Mars, and a variety of NASA spacecraft. E-mail alerts notify mission subscribers when their spacecraft or planet of interest is about to experience a space weather event. For Earth, the Space Weather Prediction Center of the NWS provides forecasts for the world.

Space Weather Forecasting for Human Safety

NASA's need for interplanetary space weather forecasting may be divided into three pressing areas: human safety, spacecraft operations, and science opportunities.

Human safety is paramount. At the moment, humans are confined to low-Earth orbit, where the planetary magnetic field and the body of Earth itself provide substantial protection against solar storms. Eventually, though, astronauts will travel to distant places where natural shielding is considerably less.

Radiation health experts stress that accurate forecasting is urgently needed to support extravehicular activities [*Balcerak*, 2011]. Astronauts need to know when it is safe to leave their spacecraft or habitats. Mission controllers would love to receive "all clear" alerts—notices that tell them when space weather will be quiet long enough for astronauts to go outside and safely do their work.

It is commonly assumed that these kinds of forecasts would be critical only to astronauts. This is not so. Earth itself experiences space weather, even at ground level. During the Carrington Event of 1859, buildings caught fire when extreme geomagnetic storms sent currents flowing down telegraph lines, heating wires until they were too hot to touch. Similar currents damaged multiton transformers in Quebec, New Jersey, and Britain during the Great Quebec Blackout of 1989. According to *National Research Council* (*NRC*) [2008], similar storms today could cause lasting damage to modern smart power grids, irreparably damaging transformers and knocking out power for months in areas hundreds to thousands of miles wide. Clean water supplies, financial services, telecommunications, and even some aspects of medical care could be crippled by such an event.

Space Weather Needs for Spacecraft Operations

Satellites in Earth orbit and elsewhere are vulnerable as well. For instance, the upcoming James Webb Space Telescope mission, which will be located well outside Earth's protective magnetosphere, will be vulnerable to interplanetary space weather. There are already many examples of space weather interfering with spacecraft operations. The most ironic is that of the Martian Radiation Experiment (MARIE) on Mars Odyssey. Designed to measure space radiation near Mars, the sensor was disabled by solar protons during the Halloween storms of 2003. Turning MARIE off during the storm might have saved it, but no one knew the protons were coming. Controllers of future missions such as the Mars Atmosphere and Volatile Evolution Mission (MAVEN) and Mars Express could use Mars-specific warnings to help them safeguard their hardware.

Space Weather Science Throughout the Solar System

Finally, scientific research could be the greatest beneficiary of interplanetary space weather forecasting. What happens to asteroids, comets, planetary rings, and planets themselves when they are hit by solar storms? Finding out often requires looking at precisely the right moment.

The most ferocious space weather in the solar system is felt on Mercury, the closest planet to the Sun. Researchers are anxious to observe a CME impact there. Even garden-variety CMEs may be strong enough to overwhelm Mercury's weak magnetic field and strip atoms right off the planet's surface. Mercury's comet-like tail of sulfur is likely populated by this process. The Mercury Surface, Space Environment, Geochemistry and Ranging (MESSENGER) probe orbiting Mercury has a front-row seat for such events. If controllers know when a CME is coming, they might be able to make special preparations, e.g., instructing their sensors to collect data at the highest rates during CME passages.

Mars is another place where science stands to gain. Mars has a unique response to solar storms shaped by the planet's strange magnetic topology [*Brain*, 2007]. Instead of a global magnetic field like that of Earth, Mars is patchily covered by dozens of magnetic "umbrellas." When Mars gets hit by a CME, the resulting magnetic storms take place not at the planet's poles but rather in the umbrellas. Circumstantial evidence collected by the Mars Global Surveyor suggests that the tops of the umbrellas sometimes light up with bright ultraviolet auroras. Because the umbrellas are distributed around the planet, Martian auroras can appear even at the equator.

Magnetic umbrellas are at the heart of one of Mars's greatest mysteries: What happened to the atmosphere? Billions of years ago, the air on Mars was thick enough to protect vast expanses of water. Now, however, the atmosphere is 100 times thinner than Earth's, and the planet's surface is bone dry. NASA's upcoming MAVEN mission will address some of these questions. A growing body of research suggests that magnetic umbrellas are involved. When solar wind buffets the umbrellas, magnetic storms could pinch off parcels of air trapped in their canopies and propel air-filled magnetic bubbles into space. Spacecraft or rovers could study the process if they know when to look.

As the scope of space weather forecasting expands to other planets, it is also expanding in directions traditionally connected to climate research. Climate refers to changes in planetary atmospheres and surfaces that unfold much more slowly than individual storms. There is no question that solar activity is pertinent to climate time scales. The radiative output of the Sun, the size and polarity of the Sun's magnetic field, the number of sunspots, and the shielding power of the Sun's magnetosphere against cosmic rays all change over decades, centuries, and millennia.

The Sun-climate connection is a matter of cutting-edge research on Earth as described in *NRC* [2012a]. The new paradigm of interplanetary space weather sets the stage for it to be cutting-edge research on other planets, too. How do magnetic storms affect the density of the Martian atmosphere? How do cosmic rays influence cloud cover on Titan? How do long-term changes in total solar irradiance alter surface temperatures of any rocky planet? These are questions that can be answered as scientists learn more about space weather throughout the solar system. Moreover, comparative climatology shows that these questions must be answered to get to the bottom of what is happening on Earth [*Mackwell et al.*, 2013].

Moving Forward With New Instruments and Interdisciplinary Research

Currently, NASA's heliophysics fleet provides data crucial to space weather forecasting. Ultimately, the fleet will need to expand, replacing older spacecraft with newer ones and distributing "space buoys" to distant corners of the solar system. As suggested in *NRC* [2012b], scientists need to develop instruments to measure solar photons, particles, and magnetic fields on spacecraft at various Sun-Earth Lagrange points (Lagrange points are gravitational balance points where spacecraft can "park"; they are good places for space-based observatories) [*NRC*, 2012b] and other strategic locations throughout the solar system. NASA's Solar Probe Plus and ESA and NASA's Solar Orbiter missions, slated for launch near the end of this decade, will be essential new components of the heliophysics interplanetary space weather fleet. Other space agencies around the world also have plans for notional missions that could be launched into this interplanetary environment in the coming decades (http://ilwsonline.org/ilws_missions.htm).

To capitalize on the science that will naturally emerge from the growth and modernization of the heliophysics fleet, researchers from many different fields will have to work together. Interplanetary space weather forecasting is essentially interdisciplinary. Progress requires expertise in plasma physics, solar physics, weather forecasting, planetary atmospheres, and more. In the past, NASA has assembled such teams under the umbrella of virtual institutes, where widely dispersed researchers confer from a distance using the Internet and other forms of telecollaboration. Interplanetary space weather might call for a similar approach. One thing is certain: The Sun is not waiting, and the stakes are as big as the solar system itself.

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