The Perfect Solar Storm[1]

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The phrase *perfect storm* has become familiar thanks to the title of Sebastian Junger's book about the 1991 Halloween Nor'easter that struck the East Coast of the United States. The symposium held at the American Philosophical Society (APS) in November 2015 adopted the phrase in reference to a solar storm observed in 1859, whose strength has not been exceeded since then (Riley 2014), because it too resulted from the unusual conjunction of two events, in this case a large mass ejection associated with a dramatic flare and the location of the Earth in its path.

Why commemorate this solar storm 156 years after the event rather than, say, 150 or 200 years? The need to assess the risks to our society by a repetition of the 1859 event—a coronal mass ejection (CME) associated with a large white-light solar flare—was underscored by the impact of a solar storm of similar magnitude in July 2012, which missed the Earth (Figure) but demonstrated its potential to impact our technology by colliding with the orbiting STEREO-A spacecraft (Baker et al. 2013). Bruce Mainwaring, a long-term student of space physics, accordingly felt that the time was ripe for an interdisciplinary meeting to review recent progress in the study of solar storms. Coincidentally, the *Wall Street Journal* (on 30 July 2015) warned that an electromagnetic pulse (EMP) attack powered "most probably from a nuclear weapon in space" launched by North Korea or another U.S. adversary could cause millions of deaths from starvation and societal chaos resulting from the destruction of the nation's electric grid and the dependent infrastructure. At about the same time, the Pentagon was reportedly moving the headquarters of the North American Aerospace Defense Command (NORAD) back into the Cheyenne Mountain site near Colorado Springs, a decade after vacating it at the end of the Cold War, to safeguard its communication systems in the event of such a nuclear attack.

1 Read 14 November 2015, as part of the symposium on the 1859 (Carrington) solar storm.

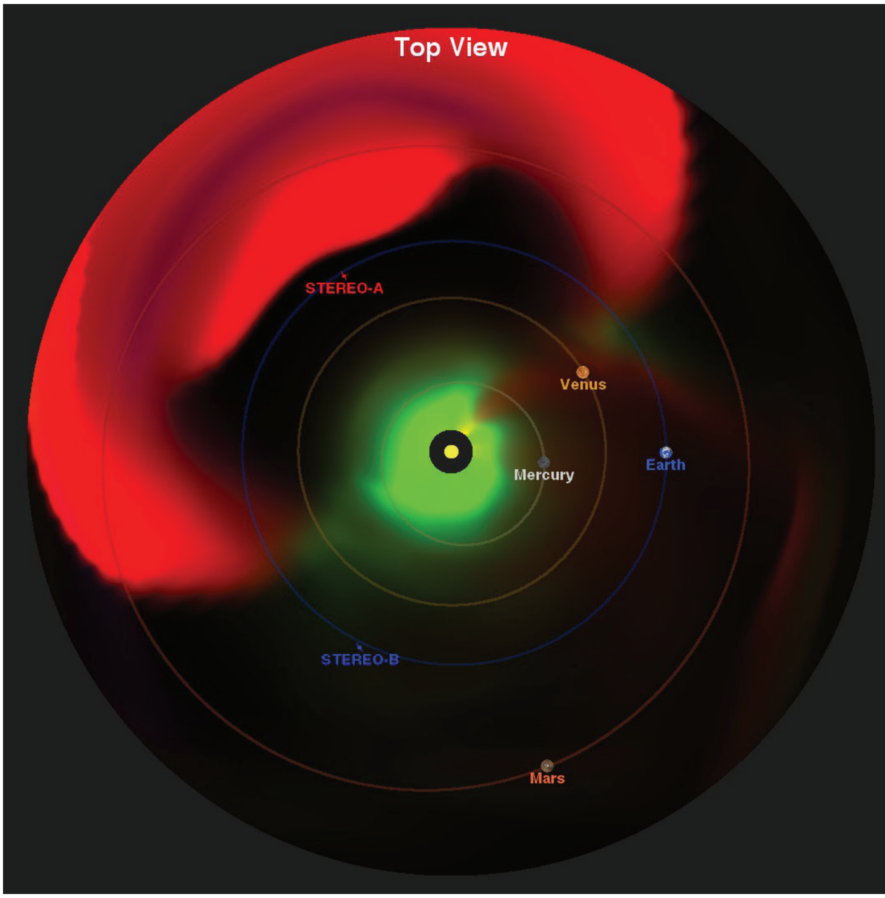

Figure. False color plan view from NASA video of 23 July 2012 CME based on ELIL space weather model. Red represents particles at high temperatures. Note the position of Earth (center right). The CME has just swept radially over STEREO-A (top left). Image courtesy of NASA. Accessed at https://svs.gsfc.nasa.gov/

The Hazard

A CME consists of up to 10 billion tons of plasma, or ionized gas, which incorporates magnetic field and travels at speeds from a few hundred to a few thousand kilometers per second. It thus takes 1 to 3 days to reach the Earth. CMEs are often preceded by a solar flare whose photons travel at the speed of light and therefore reach the Earth in 8 minutes. Flares represent an explosive increase in the emission of X-rays and ultraviolet radiation from regions measuring a few hundred million square kilometers on the Sun where sunspots already indicate enhanced activity; they are triggered by the sudden reconnection of magnetic field lines and may cause auroral displays and geomagnetic storms on Earth. CMEs are

commonly discharged during the early “flash phase” of large flares, to the potential benefit of attempts at forecasting.

The National Research Council (NRC; 2008) estimates that a repetition of the 1859 event could cost $1 to $2 trillion in the first year, as satellites, surface pipelines, power grids, and transport systems would be severely damaged. The radiation from both CMEs and manmade EMPs strips electrons from atmospheric nitrogen and oxygen, and they interact with the Earth’s magnetic field to induce powerful electrical currents in susceptible systems, such as spacecraft circuits and networks of power lines and pipelines, leading to serious damage requiring 4 to 10 years for full recovery. STEREO-A survived to monitor the storm because it was outside the Earth’s magnetosphere and was thus spared the powerful electric currents that would have been induced by the magnetic field within the CME itself.

The need for precautionary measures to protect the nation, whether from natural or military strikes, has long been recognized. In a report sponsored by the U.S. Department of Homeland Security, the MITRE Corporation (2011) made a number of recommendations for protecting the electric grid from the threat of solar storms. It proposed various steps to improve the monitoring of space weather by means of satellites, the coordination of pertinent observation by civilian and military agencies, and continuing research into operational prediction of CMEs.

Various other bodies have recently recognized the need for improved monitoring and preparedness. In the United States, the Space Weather Program Council published a report on space weather observing systems in 2013 (Office of Science and Technology Policy 2013), and a Space Weather Operations, Research, and Mitigation (SWORM) task force was asked in 2014 to develop a national strategy to enhance preparedness for space weather hazards (National Science and Technology Council 2015). A submission by Richard Garwin (2015) to a congressional hearing on protecting the electric grid from potential threats of high-altitude EMPs as well as solar storms reviewed various protective measures that called for urgent implementation. In 2013, the UK Royal Academy of Engineering (RAE) published a report on extreme space weather impacts on engineered systems and infrastructure (RAE 2013), and in 2014, the UK Meteorological Office set up a Space Weather Operations Centre.

As the report by the MITRE Corporation (2011) emphasizes, the need remains for coordination among the various agencies and enhanced solar monitoring from space. What is already under way in understanding and forecasting solar eruptive events capable of causing geomagnetic storms was one of the themes discussed at the APS meeting

by Judith Lean (2015, current issue). The aim is to maximize the benefits of the potential for early warning provided by direct observation of a major flare, or at best the onset of the CME, whereupon the locations of the satellites in question need to be addressed. Four research satellites gather the most important space weather data: SOHO (launched in 1995), ACE (1997), and STEREO-A and -B (2006). All are aging and were designed for research rather than operational forecasting. ACE (the Advanced Composition Explorer) alone carries a magnetometer that indicates the orientation of the CME's magnetic field, and its propellant should last until only 2024. The MITRE report documents the minimum requirements for effective monitoring; they include additional as well as replacement satellites at strategic locations in space. The very recent launch of the National Oceanic and Atmospheric Administration's DSCOVR operational spacecraft upwind of Earth is an important step in this direction. The NRC (2013) outlines what else is required.

Besides the benefits of short-term forecasting for protecting sensitive installations and preparing for emergency activation of power supplies and navigational systems, the need is for two further approaches: (1) long-term analysis of CMEs in context of the solar history as a whole and (2) continued observational and modeling studies of pertinent aspects of solar physics.

Pre-Instrumental CMEs

A somewhat facile assumption persists that CMEs, like much else about the Sun, are linked to the ~11-year Schwabe (sunspot) cycle. To be sure, CMEs are more numerous near solar maximum than near solar minimum (Webb and Howard 1994), with an average of about 15 to 20 per week compared to one per week, and their frequent association with flares endorses the link, as monthly large- and medium-sized flares (X and M, respectively) are strongly correlated with the International Sunspot Number up to ISN ~100 (Hathaway 2010). But as CMEs were not discovered until the early 1970s, and have been routinely monitored from space since only 1980, their record is insignificant when compared with the 400 year or so of sunspot data, let alone the 4.6 billion years of the Sun's evolution (Vita-Finzi 2013).

The events of 13 March 1859, discussed by Robert Giegengack (2015, current issue), remain the standard against which flares and associated CMEs are measured, and they have been analyzed from various scientific and applied viewpoints (*Advances in Space Research*

2006). However, many unanswered questions remain regarding the links between flares, CMEs and precursor events on the Sun, for which the Solar Dynamics Observatory and other dedicated satellites may provide answers. But the brief instrumental and historical evidence is unlikely to reveal changes in the Sun with ages measured in thousands, if not millions, of years.

The lunar record reportedly embodies evidence of variations in solar flare incidence, including a significant surge about 20,000 years ago (Zook 1980), and solar proton events driven by the impact of CMEs on the Earth's atmosphere have been identified in ice cores drilled in Greenland and the Antarctic (Mekhaldi et al. 2015). If confirmed—and there has been some dispute over earlier such reports because the Carrington event was not represented in several ice cores (Wolff et al. 2012)—there is the prospect of extending the CME record throughout the 800,000 years of ice-core stratigraphy already available. Moreover, one of the solar proton events dated to AD 774–5 was found to be at least five times stronger than any solar event that has been recorded instrumentally (Mekhaldi et al. 2015), and it coincides with an increase in radiocarbon (^{14}C) from tree rings of that date (Usoskin 2013; Zhou et al 2014; but see Richard Stephenson 2014), which would rank it as the strongest in the last 11,400 years. The Carrington Event is at risk of losing its perfect status and we our complacency.

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