The Carrington Coronal Mass Ejection of 1859[1]

ROBERT GIEGENGACK
Professor Emeritus, Earth and Environmental Science
University of Pennsylvania

Introduction

The single major coronal mass ejection (CME) known to have struck Earth occurred in 1859, at a time when civilization had not yet developed the extensive system of energy-distribution and communication networks that drives and regulates our modern society.

We don't know the frequency of major CME impacts on Earth. Prior to the modern electronic-communication industry, even a major CME would have gone unnoticed by most people, except for the spectacular auroras it would have generated. No historical record of such observations has yet been presented.

Apart from the controversial features in Antarctic ice mentioned by Claudio Vita-Finzi (2015; current issue), scientists have not identified a definitive signature, in any geological or archeological archive, that would serve as a stratigraphic marker for CMEs in recent Earth history.

Thus, the 1859 CME event, the effects of which were witnessed by some well-placed observers in a world just entering the earliest stages of electronic communication, offers the closest approximation of the effects that such an event would have on the modern world. The extent of those projected effects elevates the repetition of the 1859 CME to the stature of one of the more severe environmental risks that modern society faces.

The 1859 "Carrington Event"

Richard Carrington was a respected nineteenth-century British amateur astronomer, who in 1852–53 built a state-of-the-art observatory attached to his house at Redhill. His work centered on a systematic and precise documentation of the number, size, and location of sunspots

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

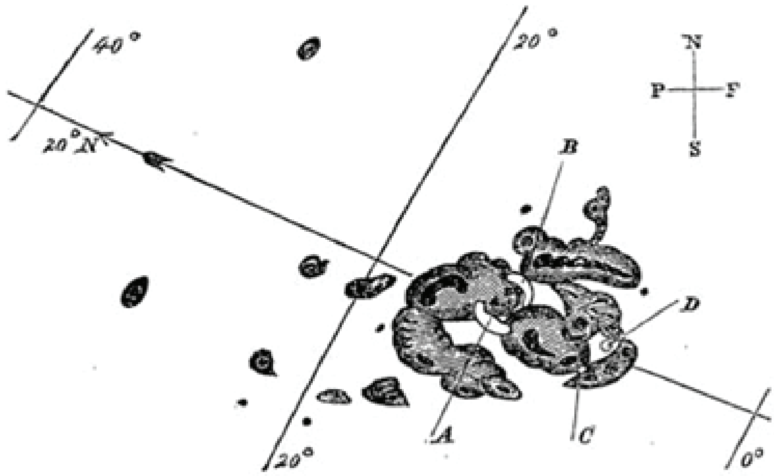

Figure 1. Richard Carrington's sketch of the solar phenomenon he observed on 1 September 1859 (Carrington 1859).

and the influence of the number of sunspots on Earth's magnetic field, both subjects of intense interest among contemporary solar astronomers, despite Lord Kelvin's dismissal of any connection between the two phenomena.

Carrington was in his observatory on 1 September 1859, observing a magnified image of the Sun projected through his telescope onto a screen shielded from other sources of light. He was studying an unusually large and well-developed sunspot when he noticed, at 11:23 AM, that two intensely bright points of light suddenly appeared within that sunspot. Carrington at first thought that his apparatus had developed a light leak; when he determined that his apparatus was intact, he outlined the two bright spots, points A and B on his sketch (Figure 1). Carrington then rushed from the observatory to find a witness, as he feared that such a phenomenon, if it should be reported by a single observer, might be attributed to some idiosyncrasy of that observer. Carrington returned to his observatory with a witness (whom he did not identify in his subsequent publications), who corroborated the existence of the two bright spots, which by then had diminished in intensity and had moved across the sunspot to points C and D on the sketch. Carrington assumed that point A had migrated to point C and that point B had migrated to point D. He determined that each of the two bright spots had been about the size of the Earth, and he calculated that the spots had moved across the sunspot at a velocity of 420,000 miles/hour.

In the days after the event, Carrington learned that Richard Hodgson, another British Solar astronomer, had observed the same anomaly. At

Kew Observatory, a continuous photographic recording of the strength, polarity, and declination of the Earth's magnetic field had been established in early 1859. That record shows significant perturbation of both intensity and declination, beginning on August 27, a few days before Carrington's observation, and extending through September 5.

Carrington presented his observations and the sketch he had made in his observatory to the Royal Astronomical Society on 1 September 1859 (Carrington 1859). His paper was followed by a report from Hodgson, whose sketch had been less detailed than Carrington's and was not included in the published account of the meeting.

Observed Effects of the 1859 CME

An unprecedented effect of the Carrington CME was the numerous reports of spectacular displays of the Aurora Borealis at many sites in North America and Europe where the aurora had not previously been observed. These reports came from as far south as Cuba (lat 22° N), Hawaii (lat 21° N), and El Salvador (lat 13°18' N), and from many ships at sea near-equatorial latitudes, where displays of Aurora Borealis had not previously been observed. Fewer observations were recorded from the Southern hemisphere, only sparsely inhabited in 1859.

In addition, the Carrington CME effectively closed down the nascent telegraph system, which in 1859 consisted of ~200,000 km of telegraph lines, of which ~40,000 km were in North America. The telegraph had only become a commercial possibility in 1837. The first lines followed newly constructed railroad lines to help regulate train traffic but were soon utilized to send other commercial and personal messages (Lloyd 1867).

Elias Loomis, a mathematician at New York University, compiled many reports of disruptions of the telegraph network in the days immediately before and after the 1859 CME (Clark 2007). The currents induced in those lines were sufficient to overload batteries and transformers at nodes in the system; many of those components failed. Telegraph operators at several stations in North America, when they realized that currents much stronger than the lines were designed to carry were flowing along those lines, disconnected power supplies to protect the electronic components. At some sites, the operators then observed that the induced current was sufficient to allow the transmission of telegraph messages, even though they had turned off the power supplies, and they used the induced current to send messages. At a handful of sites, sparks generated by the anomalous current flowing to ground within the transmission stations started fires, and

several operators were burned in those fires and/or shocked by the current. No serious injuries were reported.

Estimates at the time asserted that the total cost to the telegraph system, in equipment damage, salaries paid to operators when they couldn't use the apparatus, and the resending of messages when service had been restored, was $200,000 to $300,000.

The World in 1859

The world in 1859 supported ~1.4 billion people, most of them rural subsistence farmers. Few people had access to any equipment that today we would recognize as electronic. There were no generating stations, no electric transmission grid, no incandescent light bulbs, no telephones. Power to drive industry was provided by water power and steam engines, driven by fuel-wood or coal. Sputnik was launched into orbit 98 years after the Carrington CME!

Thus, the 1859 CME, except for the unusual display of auroras and damage to the nascent telegraph system, largely escaped notice.

In 1859 there were five cities on Earth of 1 million people, four of them in China. London reached a population of 1 million in 1825. Today, there are more than 500 cities in the world with over 1 million inhabitants.

CMEs After 1859

In the years since 1859, a number of CMEs less powerful than the Carrington CME have been documented.

In 1989, a CME disabled much of the Hydro-Quebec power-distribution network in the province of Quebec, denying 6 million subscribers electric power for 9 hours. The Hydro-Quebec grid sustained substantial damage; power was restored to subscribers by shunting electricity from other parts of the interconnected grid while extensive repairs were undertaken. The Quebec CME was also characterized by spectacular displays of Aurora Borealis as far south as central Florida

During the period 9 October through 7 November 2003, 80 CMEs erupted from within three sunspot groups. Energetic particles from the so-called Halloween event did not strike Earth directly but were observed from spacecraft and recorded at SOHO and other satellites. Much of the Global Positioning Satellite (GPS) network that serves North America was temporarily disabled on October 29.

The World in 2015

Today, 156 years after the Carrington CME, the world supports 7.3 billion people. One half of those people live in cities. The United Nations now projects that the global human population will swell to 9.7 billion by 2050, and to 11.2 billion by 2100. All of that net growth will be in cities (Fischetti 2014; UN News Centre 2015).

Today, there are no commercial telegraph services in operation; the last official telegram on Earth was sent in India in July 2013.

Today's complex civilization is supported by an extensive, complex, multi-component network of energy-distribution and communication facilities.

Most of the energy that we use to drive every aspect of modern society is extracted from geologic contexts that lie, in most cases, far from the greatest demand for energy. The coal, oil, natural gas, and uranium on which modern society depends is extracted from sites where it had been concentrated by geologic processes; transported to refineries, factories, and other manufacturing facilities; delivered to electric-generating stations; converted to other products, including electricity; and re-distributed to users. This system requires a multi-level distribution network that has grown, helter-skelter, in response to demand. With few exceptions, demand lies far from the sites from which the energy resources have been extracted.

The energy-distribution network is paralleled by a communications network that operates independently of the energy-distribution network, except for the fact that it derives its energy from connections to the "grid." This network now delivers conventional land-line telephone service, cell-phone service via ~200,000 cell-phone towers (in the United States), and the ubiquitous Internet. As of 2015, 1 billion Internet hosts had been registered (Zakon 2015).

The Energy Information Administration (EIA) of the U.S. Department of Energy (DOE) maintains an interactive website (https://www.eia.gov/state/maps.cfm), on which the user can access up-to-date maps of railroads, pipelines, generating stations, electric-distribution grids, communication networks, cell-phone towers, etc. These maps are frequently updated and show in graphic form the enormous reach and complexity of the energy-distribution and communications networks in the United States. Much of that system is vulnerable to failure in a repetition of a CME of the scale of the 1859 Carrington Event. The ground-based communications network is now supplemented, and some day may be fully replaced, by satellites, some in geostationary orbits.

As of 31 August 2015, a total of 1,305 operational satellites circle the Earth, and are used to map features on the Earth's surface; provide

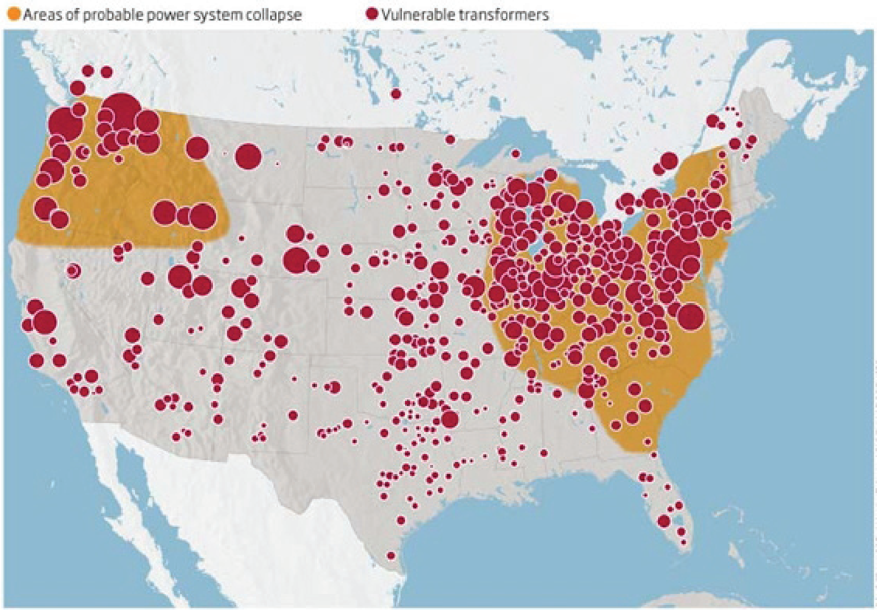

FIGURE 2. Regions of the U.S. electric-distribution system most vulnerable to failure in a major CME (National Research Council 2008).

geopositional control for many applications; receive, transmit, and relay messages, conversations, and data; and carry on international espionage (UCS). Depending on the intensity and duration of a CME, many of those satellites would be disabled, either temporarily or permanently.

In a powerful CME that sends a huge volume of ionized gases (plasma) and energetic particles to bathe the Earth, large electric potentials would be set up along artificial conductors (e.g., wires, pipelines). Currents that will flow in those conductors in response to those potentials will exceed the design capacities of the wires, transformers, and switching equipment constructed at nodes in the network. Currents will run along pipelines that were not designed to transmit electricity.

Some of the electric potential will be discharged through the Earth itself, particularly in locations where bedrock is an effective conductor, as in water-saturated sedimentary basins. At other sites, such as the Northeastern United States and the Pacific Northwest, bedrock is predominantly relatively dry crystalline rock; in those regions, the electric potential will be discharged by current flowing through the network of artificial conductors lying on the Earth's surface (Figure 2).

Fifty percent of the world's 7.3 billion people now live in cities. Figure 3 is taken from an interactive website operated by *The Economist* that shows the growth of world cities since 1950 (http://www.economist.com/node/21642053). The number of people living in

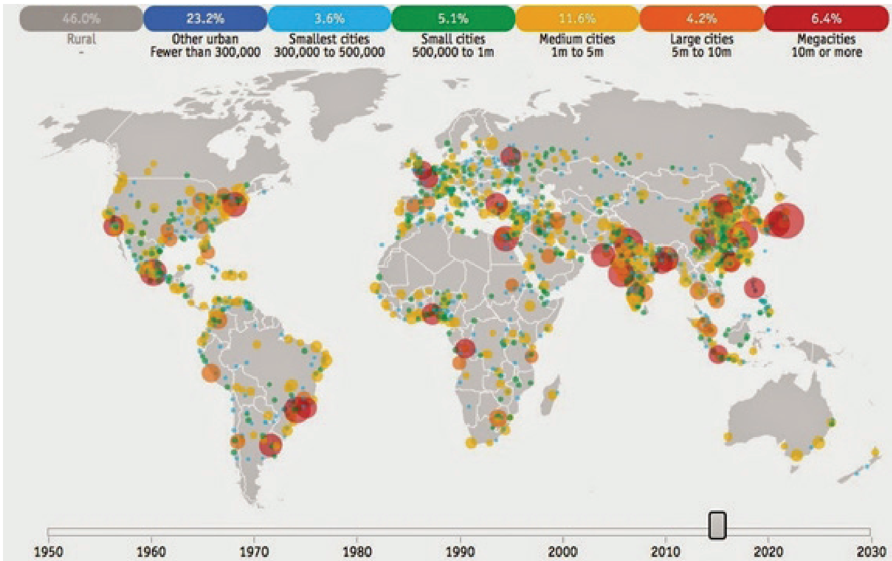

FIGURE 3. Distribution of large cities in the world in 2015 (*The Economist* 2015).

cities today, ~3.65 billion, exceeds the total global population of 1859. Today there are at least 500 cities worldwide that support 1 million or more people; 160 of those cities are in China, and 53 are in India.

Megacities emerged only after technology became available to provide inhabitants of those cities with the necessities of life. Thus, modern cities require large amounts of energy, which today is provided primarily by combustion of fossil hydrocarbons. That energy is used to transport water to private and commercial users, deliver food to the interior of cities before that food spoils, and power refrigeration to preserve the food within those cities until it is used. Few modern cities can store enough food to supply their inhabitants for longer than a week or two.

A consequence of a repetition of the Carrington CME would be the wholesale failure of networks that provide energy, water, and food to the ~3.65 billion people who now live in large cities. Furthermore, the transportation network that would be used by utility workers to report to sites that require repair of the CME-induced damage would not be functional, even if those technicians chose to attempt to repair the damage rather than flee the urban wasteland with their families.

Comparative Risk Analysis

The international insurance industry has long arrayed risk in terms of frequency versus consequence, or probability versus impact (Figure 4).

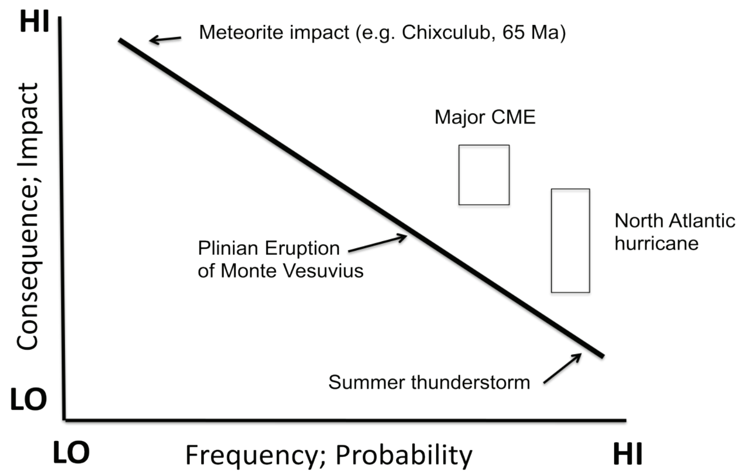

FIGURE 4. Comparison of the frequency and consequences of selected natural events.

On this plot, events that occur with high frequency (e.g., thunderstorms) are typically events of low consequence; human society has adapted to those frequent events. At the other end of the distribution, events of low frequency may produce catastrophic consequences; the impact of a 10-km-diameter meteorite at Chixculub, Yucatan, 65 million years ago, produced a global faunal extinction that eliminated, among other forms of life, the dinosaurs.

Monte Vesuvius has erupted ~37 times since 25,000 BP. Twelve of those eruptions have been explosive "Plinian" eruptions; ~25 have been more quiescent (De Vivo and Rolandi 2013). The term "Plinian" has been coined to describe the explosive events, one of which, in 79 AD, buried the towns and inhabitants of Pompeii and Herculaneum and was described by Pliny the Younger from the vantage point of a ship at anchor in the harbor of Naples. Thus, we can say that the frequency of "Plinian" eruptions of Vesuvius is once in ~2,000 years; lesser eruptions have occurred more frequently

Some common risks produce consequences that would not be predicted simply from their frequency because human society has placed itself and its investments in the way of those risks. For example, we know that Atlantic hurricanes occur with predictable frequency, yet we continue to build, and rebuild, enormous resort communities that lie directly in the path of those hurricanes. Thus, the consequences of Atlantic hurricanes have been far higher than would be predicted from their frequency.

A CME cannot be plotted on this graph with confidence because the frequency of such events is not well known. But we do know that society has built an enormous electronic edifice that is vulnerable to a CME, and we have built that edifice largely oblivious to that risk.

The National Research Council (NRC) convened a workshop in 2008 to assess the magnitude of the risk to modern civilization of a repetition of the Carrington Event (NRC 2009). The summary of that workshop presented the calculation that a repetition in 2010 of the Carrington Event would cost $1 to $2 trillion (US) in damage to the energy and information infrastructure and would require 2 to 10 years for full recovery. In that summary, the NRC did not hazard a guess as to the magnitude of human mortality that might result from such an event.

In 2015, the World Economic Forum (WEF) presented an assessment entitled *Global Risk 2015: 10th Edition* (WEF 2015). That document offered a comprehensive plot of impact versus probability, on which the risk of a repeat of the 1859 CME was buried within the category "Major Natural Catastrophes (e.g., earthquake, tsunami, volcanic eruption, geomagnetic storm)." The impact of a geomagnetic storm was plotted as less severe than water crises, failure of climate-change adaptation, or extreme weather events. *Global Risk 2015* was published shortly before the start of the Conference of the Parties 21, the Paris climate conference. In *Global Risk 2016: 11th Edition* (WEF 2016), the impact of "failure of climate change mitigation and adaptation" is plotted as greater than the impact of either water crises or geomagnetic storms.

What Can Modern Technological Society Do to Protect Itself from a Repetition of the Carrington Event?

Although we still lack an historic baseline of the frequency of major CMEs, the dynamics of occurrence of such events is such that we know, with confidence, that other Carrington-magnitude CMEs will strike the Earth. The Sun emits one such pulse per day at times of solar minimum, and four to five pulses per day at times of solar maximum; the CMEs are typically generated within large sunspots and are often associated with flares. A typical CME represents 10^{11} to 10^{12} kg of matter, and travels away from the Sun at 400 to 1,000 km/sec (Howard 2011). But neither the more or less predictable inventory of sunspots nor the association of flares with those sunspots enables us to predict which sunspot will launch a CME—and when.

The Earth is very small and lies very far away from the Sun. CMEs erupt from the solar surface and travel far beyond the Earth's orbit; most cross that orbit at sites and times when the Earth is not there.

The size of the CME as it intersects that sphere whose radius is defined by the distance between the Sun and the Earth is many times the diameter of the Earth disk. Typically, a CME subtends "several tens of degree of heliographic latitude"; the diameter of Earth represents 5×10^{-30} of heliographic latitude (Howard 2011). Thus, at the distance of Earth from the Sun, a CME is much larger than the Earth itself.

The many variables that determine whether and when a destructive CME will strike Earth are as follows:

1. the frequency of occurrence of CMEs
2. the size, intensity, velocity, and trajectory of each CME
3. the location of the Earth on its orbit at the time a CME reaches that orbit

Major CMEs strike Earth at a lower frequency than summer thunderstorms, but they are not as rare as crater-producing, meteorite-impact events. If one were to estimate the frequency of a destructive CME based on information now available, it might be concluded that the recurrence interval of a CME is of the order of centuries, somewhat more often than destructive eruptions of Monte Vesuvius.

With better understanding of solar dynamics, we may be able to produce a better assessment of the frequency of destructive CME events, based on simple geometrical calculations from variables not now well understood. That frequency estimate will gain credibility if it can be correlated with a record of CME frequency from some geological archive.

What Can We Do?

The global resource-distribution and communications network has been designed and implemented largely without concern for the risk represented by a potential repetition of the 1859 CME. Now that the magnitude of the CME risk is being widely addressed, proposals are being offered to reduce the risk that components of that network will be disabled or destroyed by a major CME.

The U.S. government has studied the risk to communications infrastructure of a flood of plasma and energetic particles, either from a deliberately hostile electromagnetic pulse (EMP) attack or from a CME, at least since 1962, and many agencies, both domestic and international, have considered strategies to reduce that risk (Carafano et al. 2011).

In 2014, the U.S. Congress authorized a Space Weather Operations, Research, and Mitigation (SWORM 2014) task force to develop a national strategy to enhance preparedness for space weather hazards.

The initial report of that task force offers a blueprint whereby the complex risk of a CME might be productively addressed. These proposals focus on (1) retrofitting existing components of the network to survive a future CME, (2) designing future networks to survive a major CME, (3) placing satellites in orbit at locations that will provide 15 to 30 hours of warning before the arrival at the Earth's surface of a destructive CME, and (4) preparing and mobilizing a response to a CME that will restore the electronic infrastructure expeditiously.

During congressional testimony in 2015, Garwin (2015) offered some strategies to harden the network to survive a repetition of the Carrington CME.

A long-term strategy to reduce the damage of future CMEs will be a nationwide effort (paralleled globally) to reduce dependence on an antiquated energy-distribution grid. A component of that strategy will be to erect a distributed energy system, in which energy will be generated as close as possible to the sites where it will be used, thereby reducing the extent and importance of the grid.

Developing countries may be able to bypass the phase of energy distribution that led the West to construct a giant energy-distribution network by fueling further development via implementation of a distributed energy economy—specifically, solar installations at individual residences and/or businesses. An analogous trend is already under way in developing countries: telephone communication is leap-frogging the phase of construction of extensive land lines to transmit all communications via cell technology.

An economy built on the combustion of fossil hydrocarbons is a very recent development of human society. The first oil well was sunk in 1859, the same year that Carrington observed the first documented CME. Coal had been in commercial use for ~150 years. Prior to extraction of fossil hydrocarbons for use as fuel, all of human society had been powered by solar energy or its immediate derivatives. We will return to direct solar energy as the primary driver of human society, either by default when we have exhausted available reserves of fossil hydrocarbons or by planning for a more rational energy future.

In the process, we will reduce our vulnerability to EMP attacks, CMEs, and, perhaps, other solar excursions not yet identified.

Conclusion

The CME of August to September 1859 disabled a nascent telegraph system and produced spectacular displays of Aurora Borealis at near-equatorial latitudes where such displays had not previously been observed. At that time, human society had not developed the network

of energy-distribution and communication facilities that now drives every aspect of modern civilization in a rapidly urbanizing society that is many times larger and more vulnerable than was the society of 1859.

In recent years, government, military, and commercial organizations have grown aware of the potential of a repetition of the 1859 CME to impose wholesale destruction on the fabric of modern society. Efforts are under way to characterize the frequency of CMEs by physical modeling of solar dynamics and by seeking proxy evidence in various geological archives of CME events in recent Earth history.

At the same time, strategies are being developed to protect the elaborate network of energy-distribution and communications facilities from a repetition of the 1859 CME and to reconfigure those systems to be less vulnerable.

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