Severe space weather: solar storms[1]

Electromagnetic and particle radiation emitted by the sun are the primary causes of space weather affecting the Earth. Radiation carried by solar flares (caused by sudden releases of magnetic energy from the sun's corona) and coronal mass ejections (CMEs) (large-scale, high-mass eruptions of plasma from the sun's corona) can be harmful to biological systems and cause disruptive currents in the Earth's ionosphere and magnetosphere, resulting in geo-magnetic storms.

The frequency and intensity of solar flares and CMEs peak and trough according to the eleven-year solar activity cycle (i.e. there are, on average, eleven years between solar maxima, when the sun is most active in producing flares and CMEs). At a solar maximum (the next one is predicted by NASA to occur in April/May 2013) a CME reaches Earth's orbit about once every five days and an average of 12 CME-induced geo-magnetic storms can be expected annually on Earth [Jansen et al., 2000]. History tells us that very large storms are low probability events – the largest storm on record, the 'Carrington event' of 1859, was caused by a massive CME and a storm of this magnitude is probably a once-in-500-years event. Storms of half this intensity can be expected every 50 years or so [Odenwald and Green, 2008]. Severe solar storms are therefore low probability, high impact events.

These space weather events are a natural source of risk and are nothing new – such events have been observed for as long as humankind has been watching the skies. However, while it may not be possible to classify the *risk* as emerging, it is certainly the case that human societies (mainly in the sense of built infrastructures and economies) exhibit emerging *vulnerabilities* to space weather.

Where radiation hazards are concerned, although the Earth's atmosphere shields people on the ground from harmful doses of radiation, the advent of the 'space age' and the increased frequency of space missions and of commercial flights means that more people are now at risk of exposure to higher doses of radiation. Major airlines already reroute flights away from the poles during solar storms (high northern latitudes entail higher radiation exposure) and NASA takes precautions to protect astronauts in space [NOAA, 2006].

The greatest vulnerabilities, however, and the ones with the potential to have the largest adverse impacts on society, are related to technologies that are sensitive to disruptions in the Earth's ionosphere and magnetosphere. Over the course of the last hundred years, ***technological advances*** have steadily increased the importance of communication technologies, transport networks, and the power and interconnectedness of electricity grids (not to mention their interdependence with other infrastructures). Such progress has "inadvertently and unknowingly escalated the risks from geomagnetic storms" [Brooks, 2009].

These vulnerabilities stem from the fact that charged particles from the sun can:

- cause physical damage to orbiting satellites and spacecraft by damaging microchips, solar cells, accelerating orbital decay, etc;
- disturb electromagnetic interactions in the ionosphere and thus severely interfere with GPS navigation signals and the propagation of radio waves; and
- cause variations in Earth's geomagnetic field that can induce currents – known as geo-magnetically induced currents (GICs) – to flow between conductors on the ground (for example, between transformers in a power transmission network or along buried pipelines).

GICs in particular pose important risks to modern society because of the wide range of essential infrastructures that could be affected. Voltage fluctuations in deep-sea cables could

[1] This paper aims to illustrate some of the contributing factors to the emergence of risks described in the IRGC report "The Emergence of Risks: Contributing Factors". This report is part of phase 1of IRGC's project on Emerging Risks. More information can be found online at http://irgc.org/Project-Overview,219.html

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disturb telecommunications networks; transformers in electric power systems may be saturated by GICs, causing emergency shutdowns; oil and gas pipelines can suffer corrosion; and, rail signalling systems can be disturbed.

Although vulnerabilities to space weather do not receive a lot of press coverage, there is precedent (confirmed or strongly suspected) for all of the above-mentioned occurrences [Jansen et al., 2000]. To take one example, in March 1989, a solar storm caused a GIC that resulted in the failure (within 90 seconds) of the entire Quebec-Hydro power grid in Canada, leaving six million people without electricity for up to 9 hours. In the event of a bigger solar storm – say, as big as the Carrington event of 1859 – it would not be hard to imagine that widespread electric power blackouts could occur as electricity transformers overheat and fail. As damaged transformers cannot be repaired in the field and must be replaced with new units, which have manufacturing lead times of twelve months or more, long-term blackouts and chronic shortages may persist for some time. Transportation, banking and finance systems, communications and government services would cease operation or be severely disrupted. Drinking water and fuel supplies would soon run dry as pumps from water reservoirs or underground tanks at fuelling stations stopped working. Back-up generators would assure power to pivotal sites such as hospitals, but only for a few days. And, perishable foods and medications would soon spoil, creating shortages of vital supplies.

Extreme as it may sound, this is the kind of scenario imagined in a recent study by the US National Research Council [NRC, 2008]. This study estimated that a severe solar storm could lead to societal and economic costs for the United States of USD 1-2 trillion in the first year alone, and that complete recovery may take from four to ten years.

Of course, there are many factors that can act to amplify or attenuate a society's vulnerability to space weather events… although not all of them are necessarily controllable.

Perhaps the most obvious factor is ***scientific unknowns*** – the knowledge that we have of the natural systems involved (of solar chemistry or atmospheric physics) and of the nature and extent of where our vulnerabilities lie is incomplete While we know a lot about solar chemistry and understand the processes by which solar flares and CMEs are formed, there are still important unknowns due, in large part, to the complexity of the systems involved (complexity of solar chemistry, of the interplanetary environment between the earth and the sun, etc). Despite the fact that the eleven-year solar cycle helps predictability of space weather to some extent, modelling is still not accurate enough to give more than a few hours of qualitative warning of a solar event [Cole, 2003]. Although most flares and CMEs occur at solar maxima, large magnetic storms have also occurred at solar minima and, indeed, the largest flare in modern times occurred during a solar lull in 2006 [Turner, 2009]. Deep, structural uncertainty provides obstacles to accurate forecasting of solar events.

Vulnerabilities are hard to gauge with accuracy, for a number of reasons. First, because damaged satellites and other space electronics cannot be recovered, the true cause of failures cannot be established. Added to this there is sometimes the problem of ***information asymmetries*** between scientists and satellite owners, who are often unwilling to divulge the number and causes of failures they have suffered for reasons of security and competitiveness [Odenwald, 2001]. Second, many technologies on the ground have simply never been put to the test, as previous experiences of large solar storms occurred in a world that was less technology-dependent; and finally, it is hard to determine the effectiveness of any shielding measures, as "experts don't fully know what the sun is capable of spewing out" [Turner, 2009].

Another element that is vital in defining the *scope and scale* of risk from solar storms is to do with situational context and ***varying susceptibilities*** to the risks posed by solar storms – geography, geology, wealth and development all strongly influence a society's level of susceptibility. Because the effects of solar storms are centred on the Earth's magnetic poles, regions close to these poles are more at risk. In practice, North America is the most exposed region because it is close to the North magnetic pole (which tilts towards it). The South

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magnetic pole, by contrast, is far from inhabited land off the coast of Antarctica. Not only is North America close to the North magnetic pole, but it is also a wealthy and highly-developed region, heavily reliant on technology and with a dense power grid infrastructure. The geology of the region amplifies risks from solar storms, too, as much of the power grid is located in areas of igneous rock, which has a higher electrical resistance to GICs, thus making it more likely that the GICs will flow through power transmission lines above ground [Kappenman et al., 1997].

The complexity and high connectivity of infrastructure such as the North American power grid creates an important challenge for risk governance – many other systems rely on electricity, and so the consequences of a power black-out will have widespread effects on society. Thus, for each system or technology at risk, secondary effects in other areas must also be considered. Large networks with many interdependencies are obviously much harder and more expensive to protect from the effects of solar storms. Tight coupling and a resulting ***loss of safety margins*** in these networks can amplify the consequences of damage froma solar storm. Building resilience and redundancies that reduce the consequences of solar storm damage is one possible way to mitigate risk; however the potential gains (reduction of harmful effects) must be carefully weighed against the costs and difficulty of the task.

Whether or not building redundancies and resilience is the chosen governance alternative depends heavily on how risks are prioritised and how trade-offs are dealt with. The US National Oceanographic and Atmosphere Administration (NOAA), which has satellites in geosynchronous orbit to monitor the US, has an on-orbit spare in place (as well as spares in production) for its most critical satellites in case of damage from space weather [Turner, 2009]. As in this case, when national security could be endangered due to failures, the cost of creating redundancies may be judged worthwhile. However, in the case of a commercial power company, this solution might not be so appealing. Although resilience can be built by coupling the systems in a loose way such that cascading failures are stopped, rebuilding or reorganising an existing system may be complicated and expensive. And while it is possible to install devices to block the flow of GICs, such devices are also complicated and expensive to install across a large area. Given the low probability that a storm big enough to cause widespread damage will occur; companies may prefer to avoid such a costly (and potentially redundant) investment and instead rely on contingency procedures.

Contingency procedures – such as reducing system load or disconnecting system components of a power grid – are another method of reducing the harmful consequences of solar storms. However, there are ***temporal complications*** that may reduce the efficacy of these solutions, the problem being that implementing contingency procedures almost always requires early warning capabilities… with one hour notice, much can be done, but with five minutes notice, the possibilities are few. Current early warning systems, notably NASA's Advanced Composition Explorer (ACE), can provide between 15 minutes and one hour of warning for incoming solar storms, allowing power companies to prepare their systems and minimise damage. However, ACE is already operating beyond its planned lifespan and a very powerful solar flare would likely saturate its sensors. Building a back-up warning system would be sensible, but one huge problem is that "it is terribly difficult to inspire people to prepare for a potential crisis that has never happened before and may not happen for decades to come" [NRC, 2008: 90].

In conclusion, despite our generally good understanding of the physical processes that create solar storms and of how such extreme space weather will impact modern technologies, the systems involved are highly complex and thus a lot of uncertainty remains with regard to our ability to forecast space weather events and to analyse our future vulnerabilities. If current trends continue, it is likely that our vulnerability to solar storms will further increase. Safeguarding our technological infrastructures will require substantial investments from the public and private sectors, but it is difficult to know if, should we make the investment, it will be sufficient; or should we choose not to make the investment, how severe the societal and economic consequences will be.

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