

Space Weather: Risks, Challenges and Solutions



Dr. Jonathan Eastwood discusses the risk of space weather, the evolving challenges it poses, and what is being done to meet those challenges. He explains what is meant by space weather and describes some of its main risk pathways and potential impact on human activity and technology both in space and on the ground. He then assesses the magnitude of the problem and concludes by highlighting some future trends around ensuring that the future of space is safe, secure and sustainable.

Space weather represents a significant threat to modern critical infrastructure and is an important socio-economic risk that has become increasingly prominent in the past two decades in the UK. It is arguably uniquely challenging, because although high-impact events are known to occur, their frequency is relatively low, meaning that society has not experienced a major space weather event in the modern technological era (e.g. the last 20 years). During this time, ever more complex technologies have transformed daily life, and we rely on space-based services in ever more intricate, and surprising, ways.

What causes space weather?

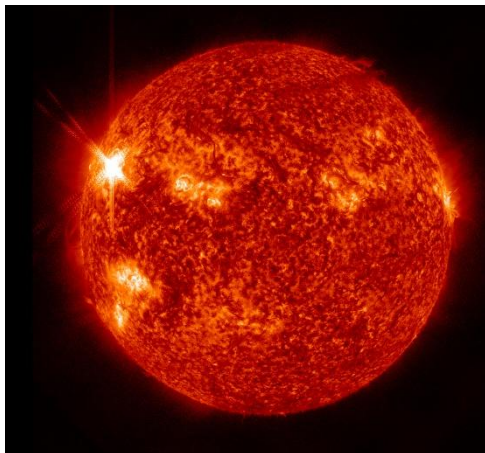
In the past 20 years, space weather has risen from being well known in the space science community to a subject that has caught the attention of the wider world to very high political levels [1]. In the UK specifically, space weather is listed on the national risk register [2], cited in the national space strategy [3] and is the subject of a dedicated policy paper on severe space weather preparedness [4].

Broadly speaking, the study of space weather is concerned with understanding how natural phenomena in space can have real and tangible impacts on human activity and technology both in space and on the ground. It is intimately related to the more general study of solar-terrestrial physics, which in itself is part of the field of heliophysics (The NASA Heliophysics Division [5] notes that it 'studies the nature of the Sun, and how it influences the very nature of space – and, in turn, the atmospheres of planets and the technology that exists there.')

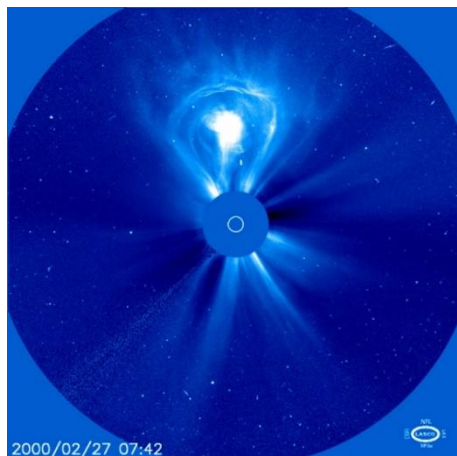
The space weather phenomenon that most people are familiar with is probably the aurora, as illustrated on the previous page by a photograph taken in Alaska. Auroras are seen near the northern and southern poles, and have intrigued and inspired observers for thousands of years.

On occasion, tremendous auroral displays can occur, with vivid and bright features filling the sky. We now understand that these are caused by the Sun. Whilst the Sun appears somewhat featureless and uninteresting when seen at sunrise or sunset, in fact it is an incredibly active and dynamic object, with two main phenomena that interest us here: *solar flares* and *coronal mass ejections* (CMEs).

A solar flare is essentially a flash of light with emission across the electromagnetic spectrum, that lasts of the order of minutes. The image on the right was taken by NASA's Solar Dynamics Observatory and is a false-colour ultraviolet image of the Sun, designed to show the lowest layers of the solar atmosphere. The brighter regions are called *active regions*, which tend to be associated with more variability and stronger magnetic fields in sunspots. The flare is visible on the left-hand side, north of the equator. *Radio blackouts* are primarily caused by solar flares increasing ionisation of the upper atmosphere and distorting/disrupting signals.



A CME is an expulsion of material from the solar atmosphere travelling out through space at speeds of the order of 1000 km/s. The image below was taken by the ESA/NASA SoHO satellite and is a white light image of the solar atmosphere (the corona). The central blue circle blocks direct light from the Sun (outlined as a white circle), allowing the structure of the corona to be seen directly.



The Sun is the source of the solar wind, which is a supersonic stream of material (plasma) that is constantly emitted from the corona at speeds of hundreds of kilometres/second and fills the solar system.

The CME is the lightbulb shaped object at the top of the image, and a time-lapse movie created from many similar images can be used to trace the motion of the CME away from the Sun as part of the solar wind.

Whereas the light travel time to Earth is 8 minutes, and so flares are seen 'immediately', CMEs can take 2-3 days depending on their speed to reach the limit of Earth's orbit. CMEs travel radially from the Sun (more-or-less), and so establishing if a CME is Earth-directed is of critical importance for understanding the space weather risk.

If a CME arrives at Earth, and directly interacts with the Earth's magnetic field in space (the magnetosphere), it can drive a *geomagnetic storm* where energy and material circulates from the CME and solar wind into the magnetosphere. Through a chain of processes best described in terms of plasma physics, energy is stored in the magnetic field and explosively released, accelerating particles into the auroral regions and the Van Allen radiation belts. This causes the bright auroral displays referred to earlier. Of crucial importance is the magnetic structure of the CME. For certain magnetic field orientations, the interaction can be very weak, and little activity arises, but for others, a very strong interaction can occur. CME magnetic field structure can only be diagnosed by in situ measurements made by satellites just upstream of the Earth such as DSCOVR and ACE [6]. Thus, ground truth about whether a CME will cause a significant impact can only be ascertained shortly before they arrive at Earth. Whilst CMEs are the major source of storms, they can also be driven by structure in the background solar wind.

Finally, both solar flares and CMEs are also sources of so-called *Solar Energetic Particles* (SEPs), highly accelerated particles that represent a space weather risk in their own right, being the main source of *solar radiation storms*.

The impact of space weather

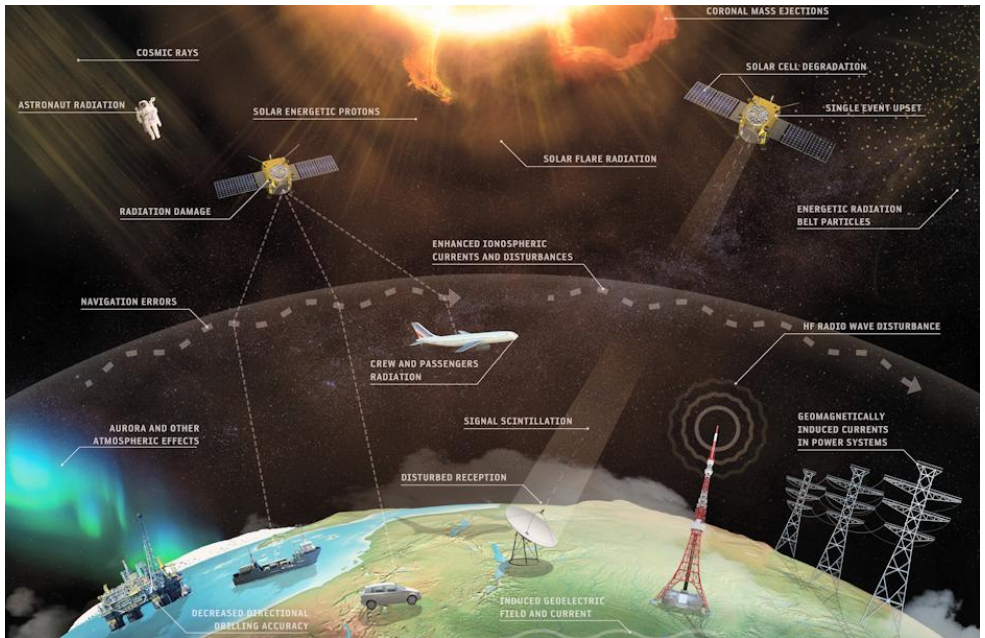
The following figure, produced by the European Space Agency, describes the wide variety of impacts that can arise as a consequence of space weather.

- **Space:** Astronaut radiation, satellite radiation damage, satellite solar cell degradation, satellite single event upset
- **Atmosphere:** Aircraft crew and passengers' radiation, HF radio wave disturbance, signal scintillation
- **Ground:** Decreased directional drilling accuracy, induced geoelectric field and current, geometrically induced currents in power systems

Of primary concern is the *loss of power*. Strong fluctuating currents in the ionosphere (essentially associated with the aurora) induce potential differences and electric fields in the Earth's surface, which can then couple into conducting infrastructure on the ground such as powerlines, pipelines and rail networks.

Of particular note here are the relatively famous events of 13 March 1989 in Quebec, where blackouts and transformer damage occurred as a result of a geomagnetic storm. The 2012 Royal Academy of Engineering report [7] suggests that 6 super grid transformers in England and Wales, and a further 7 in Scotland could be damaged and taken out of service as a consequence of severe space weather.

More recently, the Space Environment Impacts Expert Group's (SEIEG) 2022 Reasonable Worst Case Scenario [8] envisages that premature aging, and damage of transformers could occur, but also that transmission system voltage instability and voltage sag could occur, with tripping of safety systems potentially leading to cascade failure of the transmission network and/or regional outages.



Another important area of impact is in Global Navigation Satellite Systems (GNSS) and position, navigation and timing (PNT) services (eg. GPS). GNSS can be disrupted by distortion to signals as a consequence of ionospheric disturbances driven by space weather. Outages could occur unpredictably and intermittently for several days during a major event, and the impact of this is still not well understood, particularly given the ever-increasing use of PNT services for a variety of downstream services.

Satellite anomalies have been extensively observed as a result of space weather. During what is arguably the last major period of space weather in October/November 2003, 33 Earth orbiting satellite anomalies were reported. Space weather can cause surface and deep dielectric charging, surface damage and solar panel degradation, background counts in sensors, and satellite drag and changes to orbit.

These issues are thrown into stark relief by the rise of mega-constellations. With the aim of providing high-speed internet access anywhere on Earth, companies such as Starlink, One Web, Amazon Kuiper, Telesat and others offer the potential to transform daily life for billions of people. Starlink has already launched more than 2000 satellites into orbit, and if all planned mega-constellations come to fruition, tens of thousands of satellites will orbit the Earth in the next 10-20 years. Mega-constellations have already been impacted by space weather. In February 2022, a batch of Starlink satellites re-entered after launch because of increased atmospheric drag. In this case, a small geomagnetic storm heated the upper layers of the atmosphere, causing it to expand and increasing the (small) atmospheric density at the initial satellite orbit. This increased the drag on the satellites, slowing them down, and ultimately causing them to re-enter.

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Finally I note that air travel is also subject to space weather considerations. For example, polar flights have been required to divert, because HF radio communications near the poles were disrupted by space weather. ICAO regulations now require space weather advisory information to be provided to the international aviation community.

Understanding, addressing and mitigating space weather risks

Space weather is a very difficult problem to assess. Firstly, the historical record shows that very severe events can happen, but they have not really happened in the modern era. A major event, such as experienced in 1859 (the so-called Carrington event) and with a return period of approximately 100 years, is expected to have a very significant impact on a wide variety of technological systems. Smaller events happen more frequently, and power-law behaviour is a feature of probability distributions describing various space weather phenomena.

It is highly likely that system failures will interact with each other to cause cascading failure modes that are fundamentally difficult to predict, and this is an area of research that has not received a great deal of attention

Secondly, each interval of severe space weather is unique, because it is ultimately driven by solar activity and so different combinations of flares, CMEs and solar energetic particles may occur depending on the underlying solar drivers.

The Sun's rotation period means that from the point of view of the Earth, an active region will take about two weeks to transit across the solar disk, and in a severe space weather period, one may expect a two-week interval of elevated risk, during which time several different types of phenomena could occur in unknown order, severity, etc. It is highly likely that system failures will interact with each other to cause cascading failure modes that are fundamentally difficult to predict, and this is an area of research that has not received a great deal of attention, in part because of the complexity involved.

A third challenge to understanding space weather is that it is very much impact-led and driven by a desire to reduce the socio-economic footprint. Therefore, the appropriate response is a calculation that is fundamentally risk based, considering the exposure, vulnerability and hazards. This calculation is also dynamic, in the sense that as some risk is retired (for example through engineering and design choice), new risks can be introduced (such as the dramatic increase in the use of PNT services, and the wider interest in e.g. driverless cars).

This is related to the question of space weather impacts on internal organisational activity and business resilience. Many organisations are not aware of their reliance on space infrastructure, or internal exposure to space weather issues. Similarly, organisations may not be aware of how their products and services may be exposed to space weather impacts. This exposure could arise at many points and could be of particular importance where certain levels of service are guaranteed.

Here, it is typically necessary for the analysis to be client-led, where the specific organisation enlists the help of expert groups or space weather service providers to understand what

risks might be in play. It is important to recognise that space weather may well turn out not to be a major issue, but it is still necessary to investigate the possibilities as the unique nature of the space weather hazard means that surprising impacts may be identified.

The Future

At the national and international level, considerable efforts have been made to improve our ability to monitor and forecast space weather. In the UK, the Met Office is the 'owner' of the space weather risk, and operates the Met Office Space Weather Operations Centre (MOSWOC) [9] that provides 24/7 space weather forecasting. In the US, NOAA's Space Weather Prediction Center plays a similar role, and ESA's Space Safety office enables comparable space weather service provision.

Space weather forecasting relies on data and modelling, and whilst there are several satellites monitoring the Sun and the near-Earth space environment, there are plans to develop a new generation of observers, such as ESA's Vigil [10] space weather mission, that will provide new capabilities improving forecast quality and reliability. New generations of space weather models are being produced, in the UK the Space weather innovation, measurement, modelling and risk (SWIMMR) programme [11] funded by UK Research and Innovation is delivering new capabilities from the academic community into operational use at the Met Office.

Finally, space is a critical national infrastructure, and space weather is part of a wider drive to ensure the future use of space is safe, secure and sustainable. Work by the Space Lab network of excellence at Imperial College London has identified 5 key areas in this regard [12] – the terrestrial environmental impacts of space activities, space debris, planetary defence, space weather and space traffic management.

In particular, the impact of mega-constellations cannot be ignored, as they bring multiple issues about space safety, security and sustainability into sharp relief, raising many questions about policy and regulation.

Summary

Looking to the future, our use of space is transforming rapidly, and the benefits it brings has already changed many aspects of daily life. As organisations become ever more aware of how space technology is inextricably woven into the fabric of everyday life, the demand for knowledge about space weather is only likely to grow; where this touches on safety-critical systems, this may be particularly important. I hope this article will help raise awareness in the wider safety community about the risks of space weather, the challenges it poses, and what is being done to meet those challenges.

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Image Attribution

Northern lights over the Poker Flat Research Range, Alaska USA 16/02/17 [Credit: NASA/Terry Zaperach](#)

Solar flare observed by NASA's Solar Dynamics Observatory 03/11/11 [Credit: NASA](#)

Coronal mass ejection observed by the LASCO coronagraph on ESA's SoHO [Credit: SOHO ESA & NASA](#)

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Dr. Jonathan P. Eastwood, Reader in Space Physics, Imperial College London

Dr Jonathan Eastwood is a Reader in Space Physics in the Department of Physics' Space and Atmospheric Physics group at Imperial College London. His research interests include space weather, space plasma physics, and developing novel miniaturised instrumentation for space weather monitoring. He also serves as Director of the Space Lab Network of Excellence, which brings together all of Imperial's space capabilities under one network.