Helios Solar Storm Scenario

3 November 2016

Introduction to Space Weather & The Ground Effects of Extreme Events

Centre for
Risk Studies

UNIVERSITY OF CAMBRIDGE
Judge Business School

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What is Space Weather?

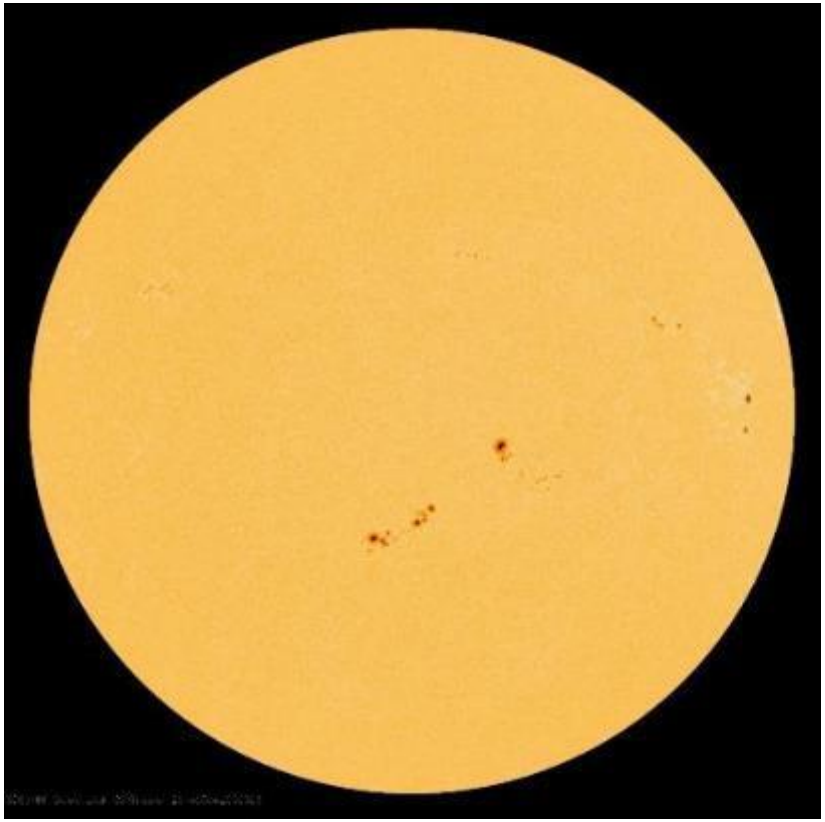
"Space Weather" is a generic term for how the changing space environment impacts our technological systems, and most commonly how processes which
start on the Sun drive activity in and around the Earth which can pose a
hazard to such systems.

There are multiple ways that different systems can be affected, through a variety of physical processes.

(Source: Professor Craig Rodger, University of Otago, New Zealand)

We will mainly focus on this issue today

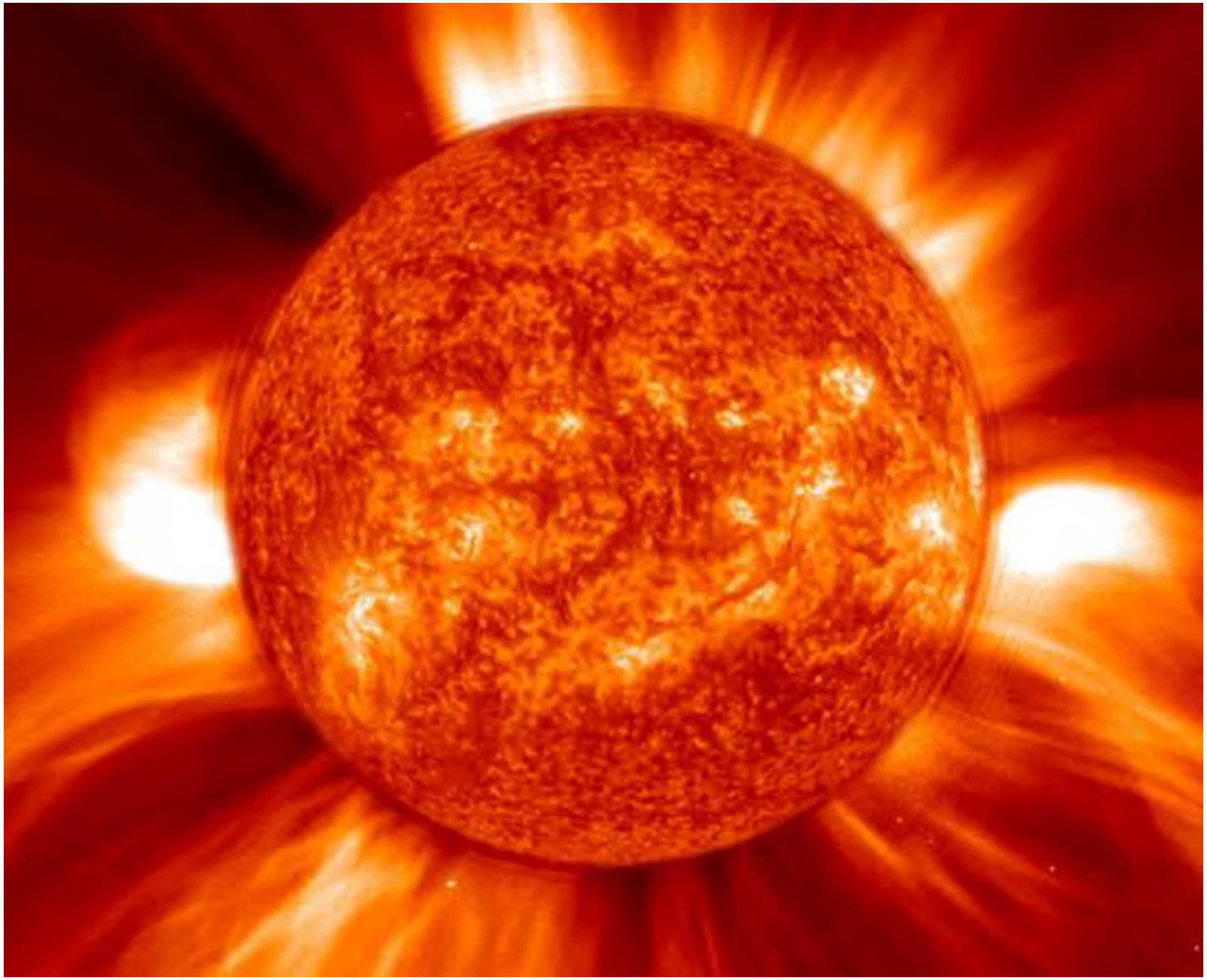
The Source of Space Weather



(Source: NASA Earth Observatory, earthobservatory.nasa.gov/)

We normally view the Sun as being unchanging with a constant output. And as far as Sun light, warming the surface of the Earth, this is very close to being accurate.

The Source of Space Weather



(Source: NASA Solar and Heliospheric Observatory, https://sohowww.nascom.nasa.gov/)

However, viewed at different wavelengths the Sun is shown to be dynamic and complex.

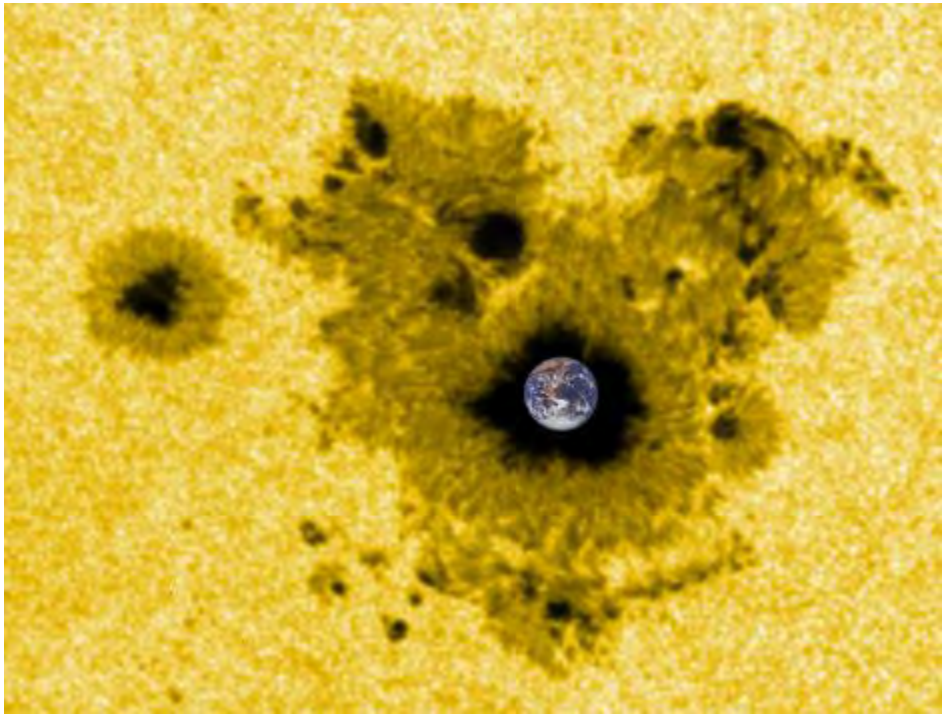
The Source of Space Weather

Solar Storms arise from eruptions occurring in the outer layers of the Sun.

There are 3 main types:

- **Solar flares** which involve the rapid release of electromagnetic energy, radio to x-ray wavelengths.
- **Coronal Mass Ejections** (CME) which involve billions of tonnes of charged particles being ejected into space
- **Solar Proton Events** (SPE) which involve the release of very energetic particles

A close up of a sunspot region, with the Earth for scale.



(Source: NASA Transition Region and Coronal Explorer)

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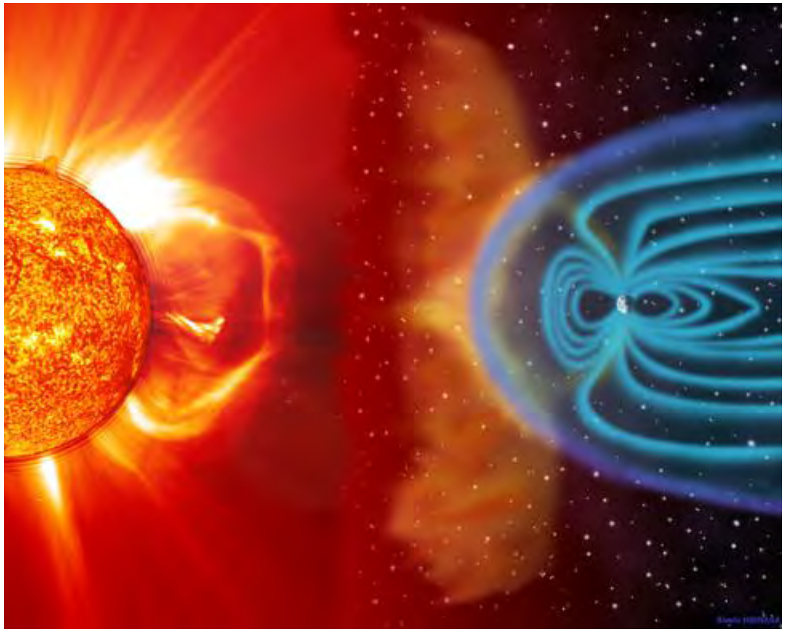
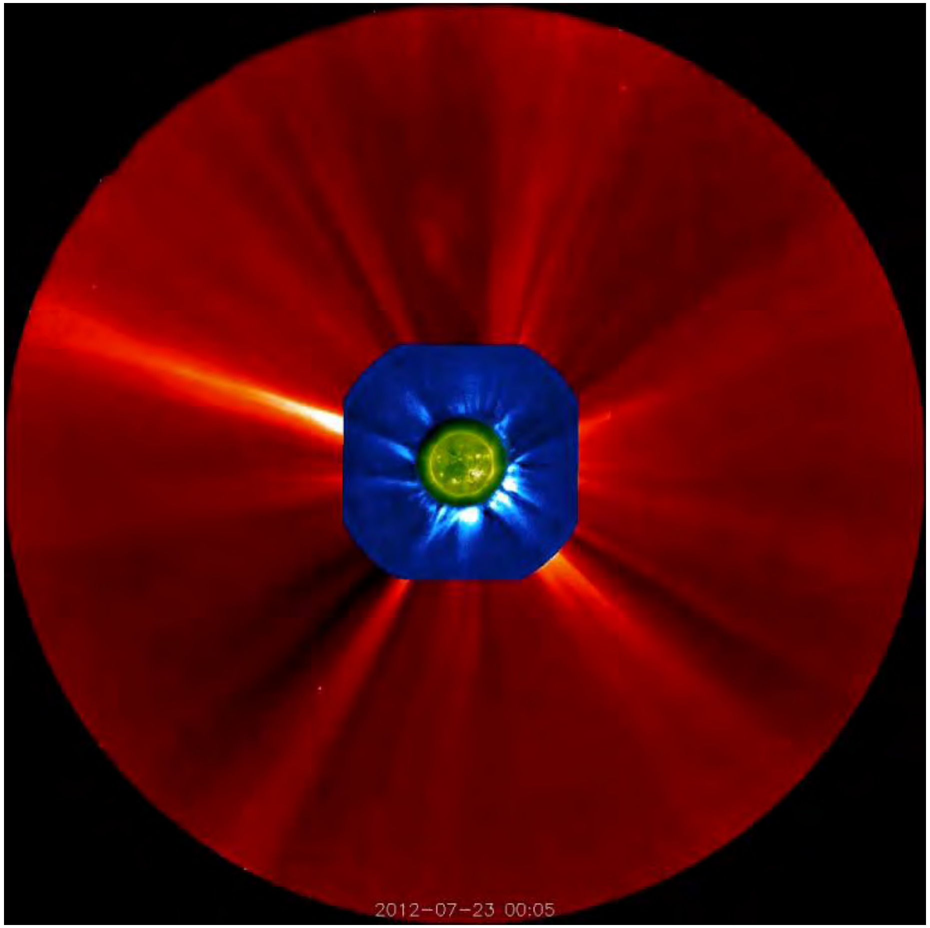
The Source of Space Weather

CMEs erupt from the Sun and sometimes hit the Earth, which is partially protected by its Magnetic field





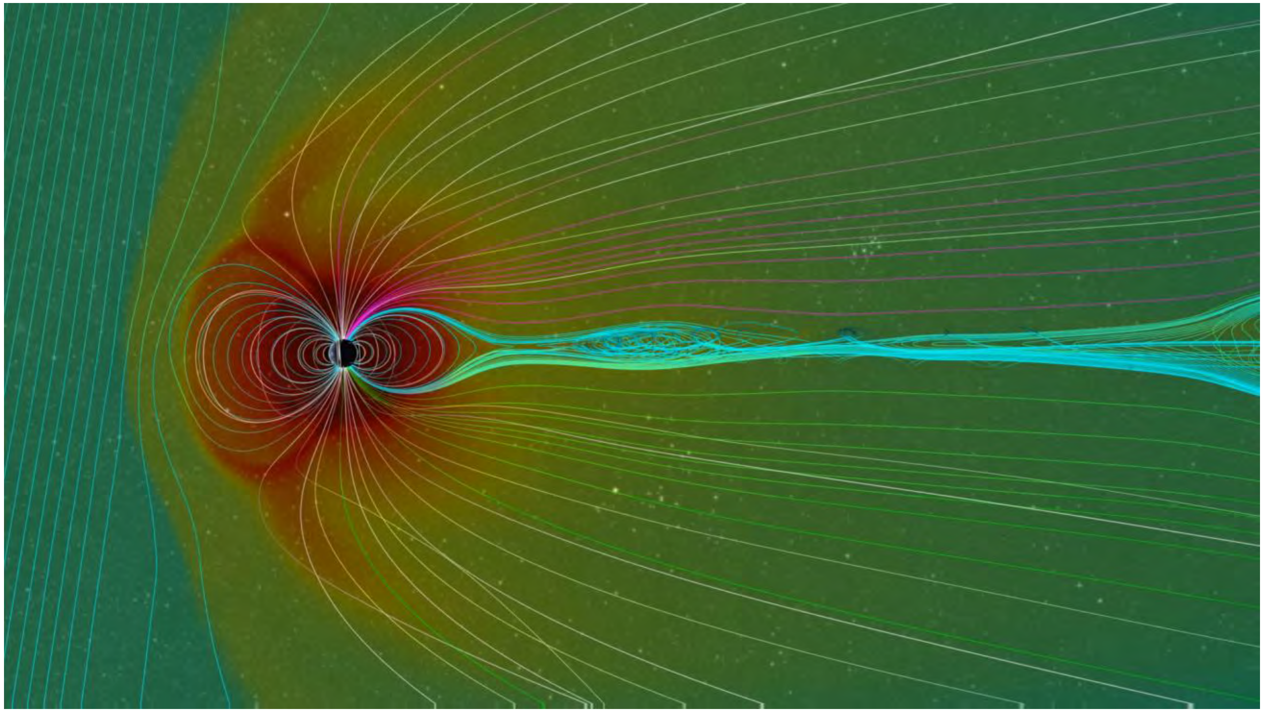
(Source: NASA Solar Terrestrial Relations Observatory, https://stereo.gsfc.nasa.gov)

View of the stream of solar wind coming from the Sun.
This movie is from 23 July 2012, and shows a Coronal Mass Ejection associated with an active region (AR 1520).

Impact of a CME on the Earth's magnetic field

A large CME can: have great mass (10^{12} kg), and travel at >500 km/s.

The blasts typically arrive at the Earth within a few days, and cause large deformations of our protective magnetic field.

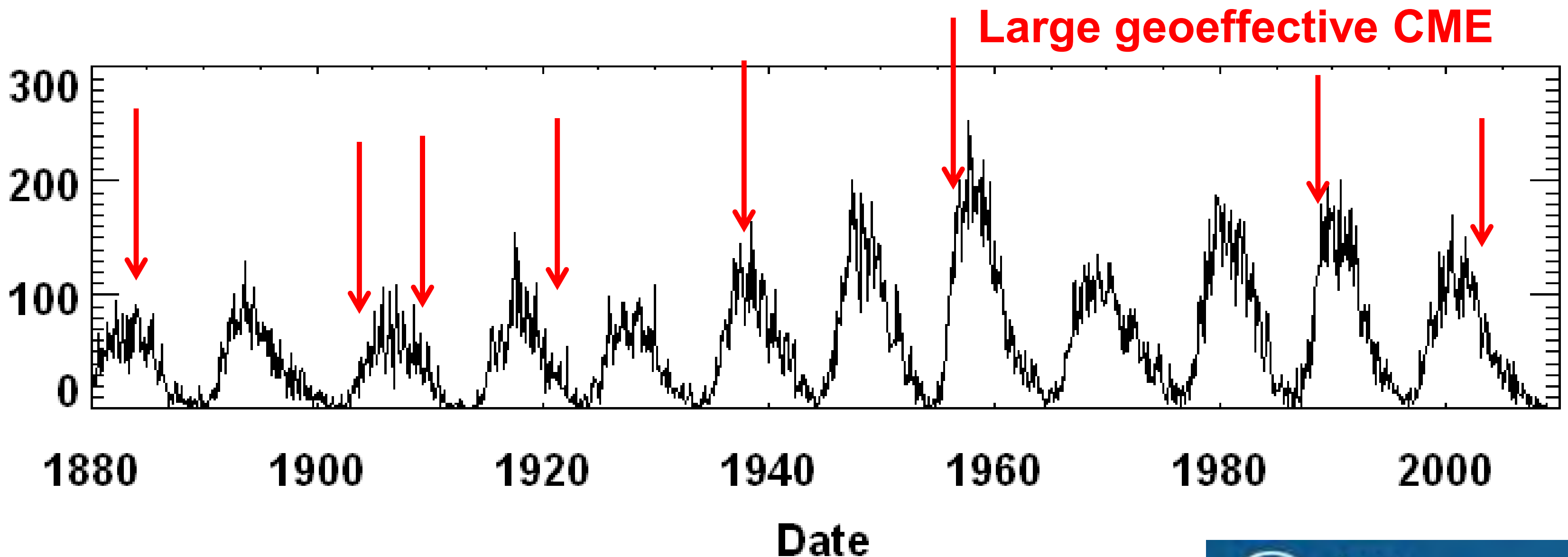


MHD simulation of Carrington-Class CME

(Source: NASA)

So what do we know about CME?

- Large eruptive events on the Sun
- Associated with complex magnetic field configurations on the Sun – sunspots
- Associated with the quasi-11 year solar cycle of sunspots
- Their sources rotate with the period of the Sun -25-30 days
- Sometimes they hit, but often they miss the Earth



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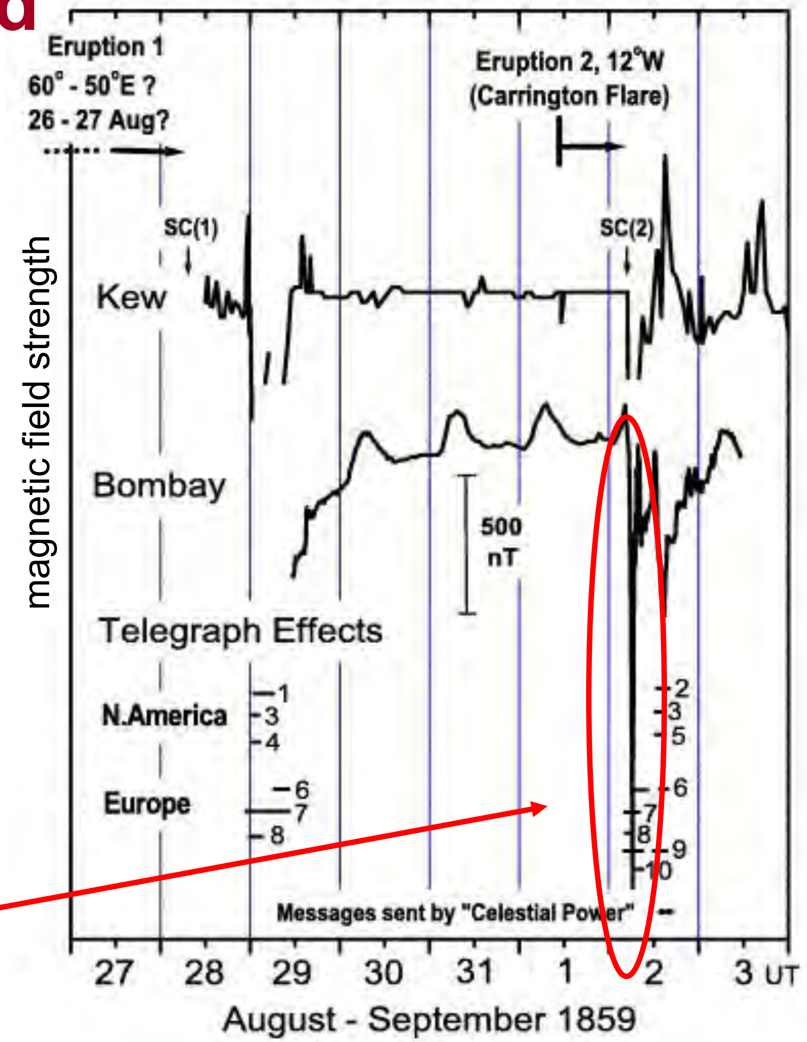
We can measure the magnetic field variations on the ground

- Magnetometer networks have been operated since ~1850. They measure the deflection of the Earth's magnetic field in nT (nano Tesla).
- A very large CME in 1859 (the Carrington Event) produced huge changes in magnetic field intensity (1000's nT).
- Rapid changes were recorded at the onset of the event, i.e., 1000's nT/min

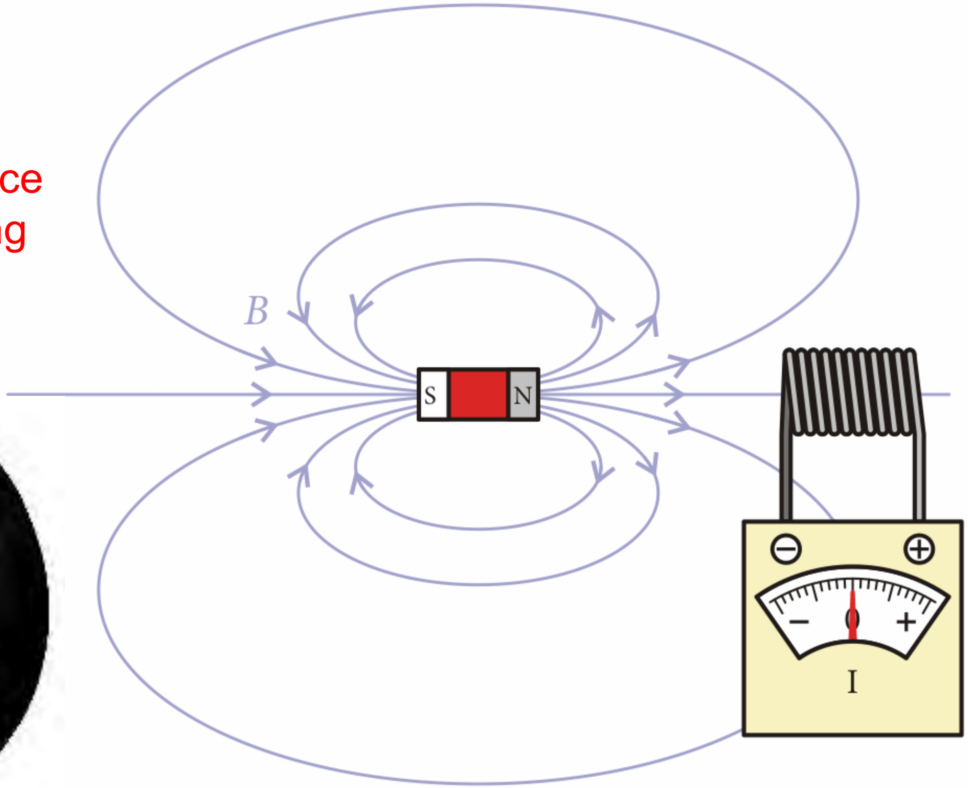


(Source: D. Boteler, 2006, British Geological Survey, Natural Environment Research Council)

Ground effects of Extreme Space Weather

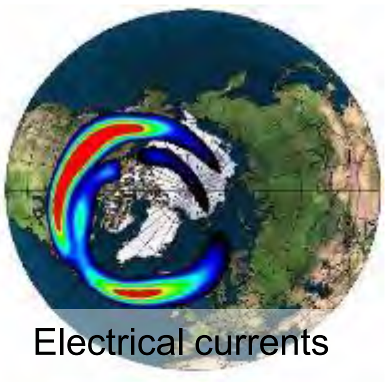
Credit:
Prof C Rodger, Univ Otago, NZ

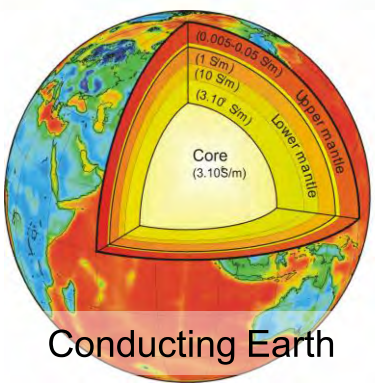
A moving magnet will produce a changing magnetic field.

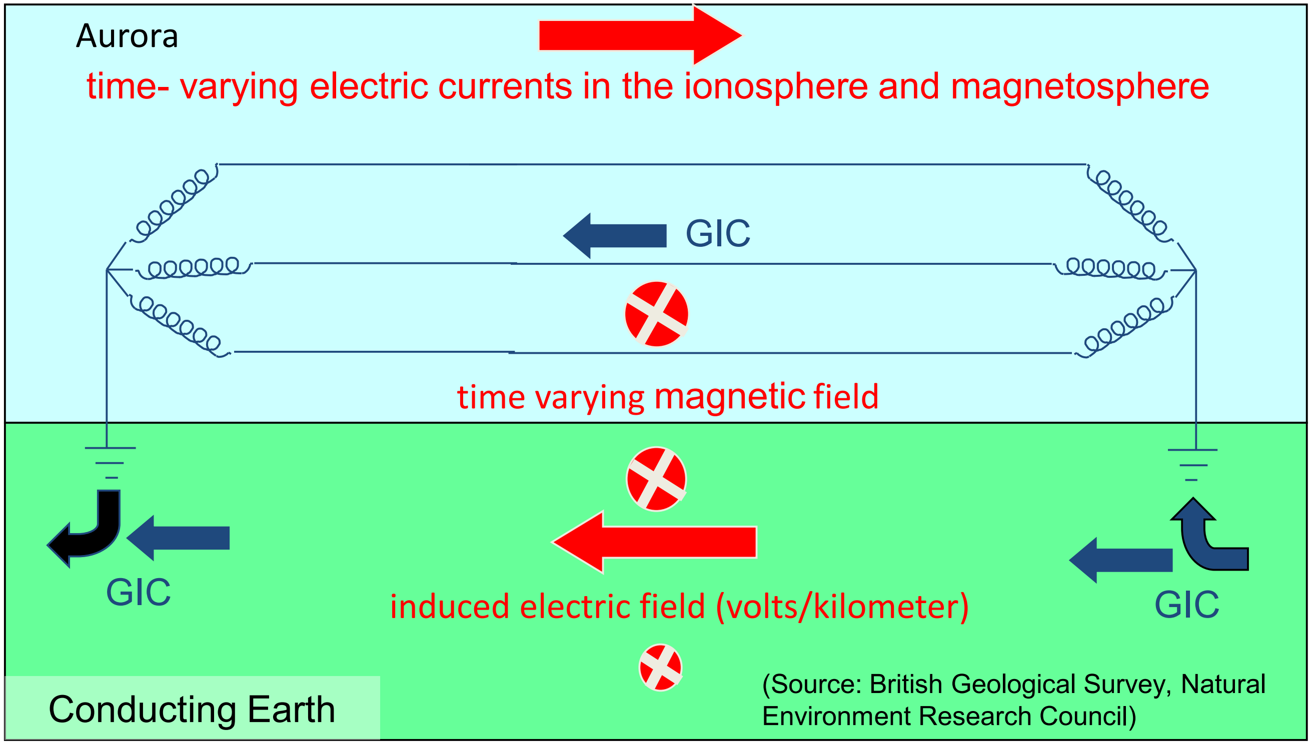


Famous physicist Michael Faraday demonstrated the law of induction, where a **changing magnetic field induces a current** in a conductor (like a wire, or the ground).

Why Does Space Weather Cause Grid Problems?







- Geomagnetically induced currents (GIC) cause
  - Half-cycle saturation of transformers, voltage harmonics, overheating, increased reactive power demand, and/or drop in system voltage.
  - Leading to transformer burn-out (in rare big storms) or shortened transformer lifetimes (due to many smaller storms).

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The pathway to damage

- There are multiple factors that influence transformer susceptibility to GIC-induced damage:
  - **Severity** of the storm.
  - **Design** of transformer.
  - **Position** within the grid (including proximity to coast line).
  - **Age** of the transformer.
  - **Surface conductivity** under the network.
  - **Orientation** of the transmission lines.
  - **Exposure** of the transformers to previous GIC.

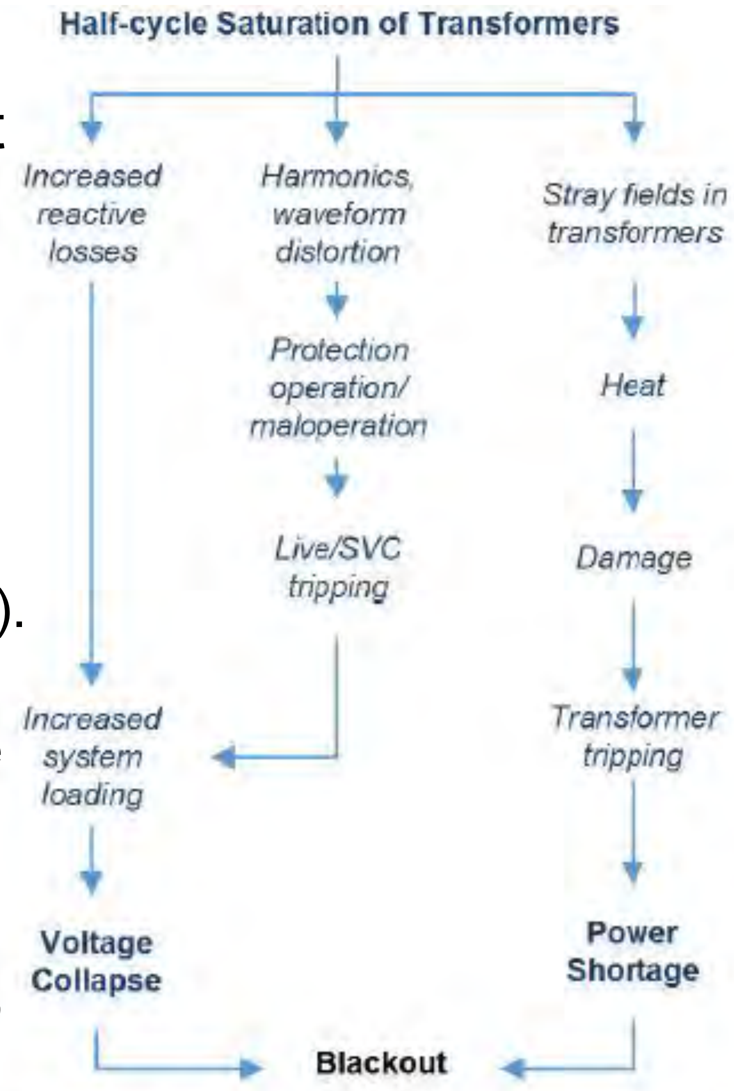

Figure 6: Pathway to damage (adapted from Boteler, 2015 and Samuelsson, 2013)

Effects of GIC on power systems - local scale

These can be local to a specific transformer in a given substation, potentially destroying a transformer.

New Jersey, March 1989.

(Source: Metatech Corporation)

South Africa, Oct 2003

Examples of transformer burn-out

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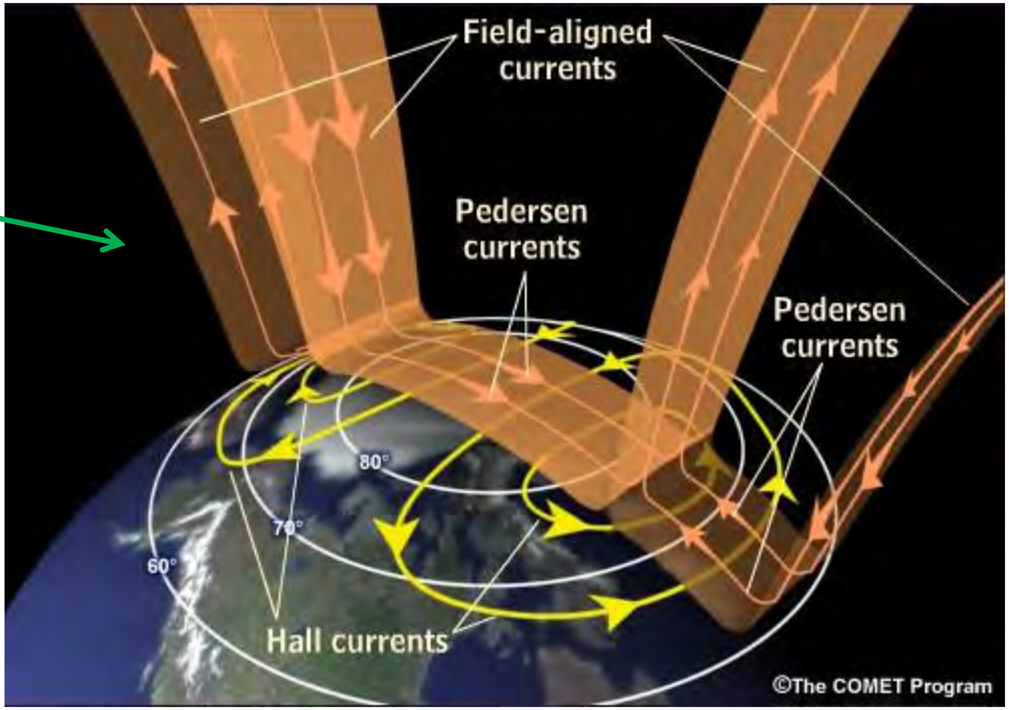
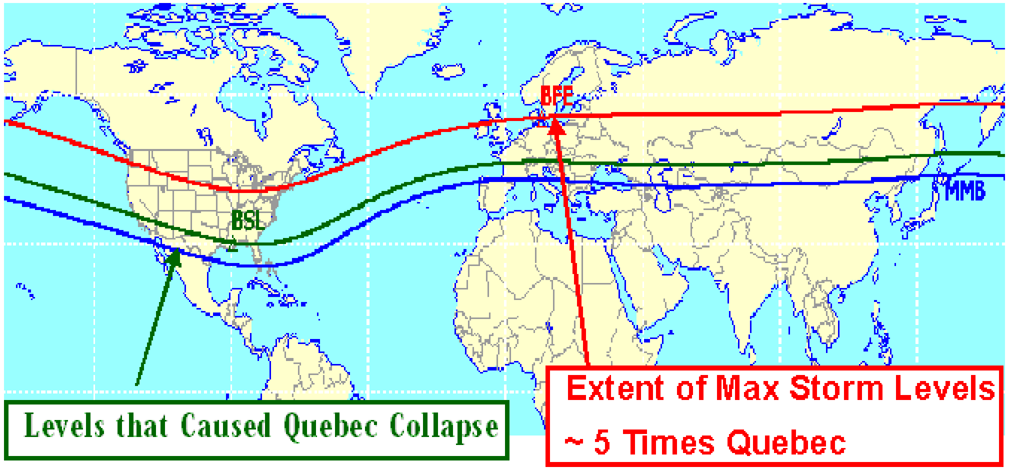
Where do the largest currents occur?

Currents flowing in the upper atmosphere (~120 km altitude) are driven by large-scale magnetic field-aligned currents generated throughout the Earth's magnetosphere.



They are associated with the **aurora**, and therefore occur predominately at high latitude, apart from during **big storms** when the region **expands equatorwards.**



(Source: Metatech Corporation)

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Where do the largest threats occur?

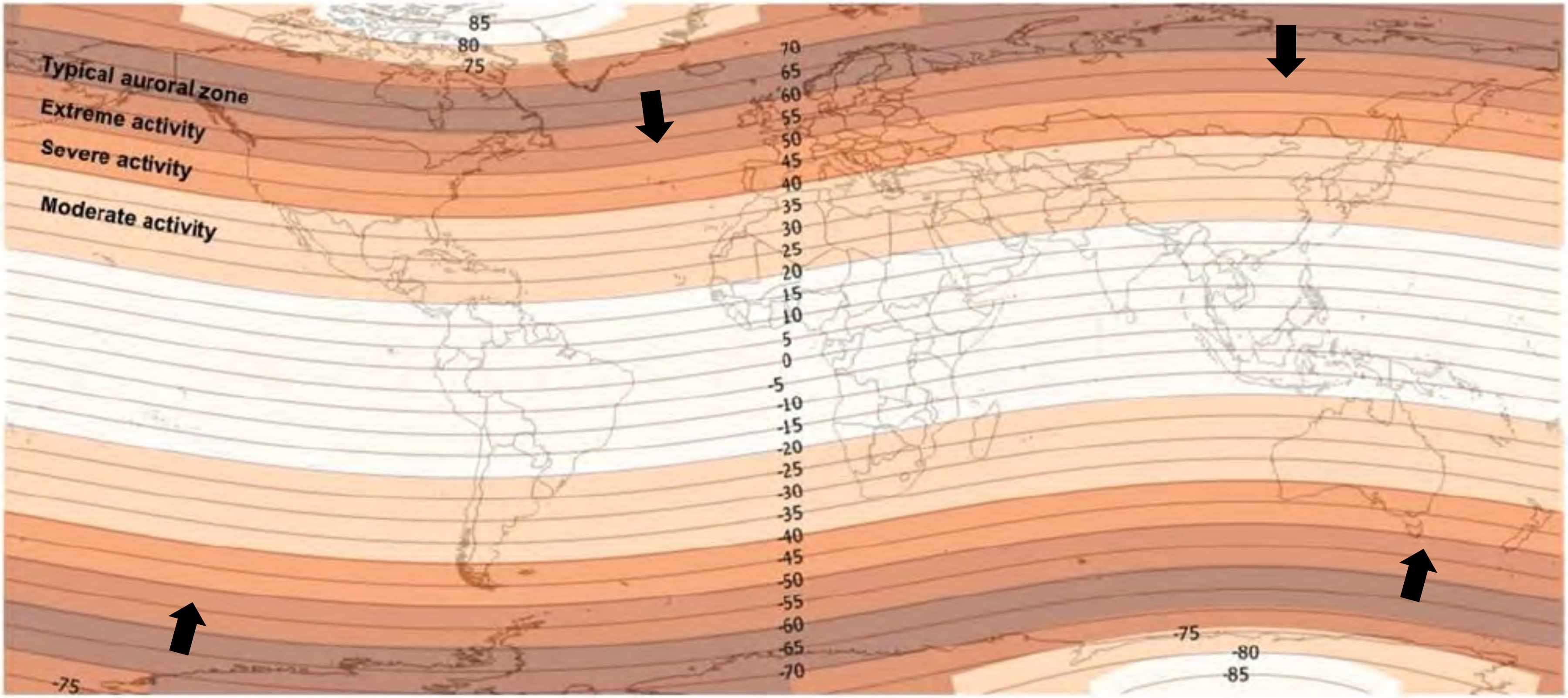


Figure 5: Geomagnetic latitude threat map following a shift in the auroral oval

The threat zones expand equatorwards with increasing severity of the solar storm.
The contours follow magnetic field latitudes, not geographic.

Historical extreme space weather events

1847,1859, 1882, 1903, 1909, 1921
All these events caused ‘anomalous’ currents on telegraph systems.

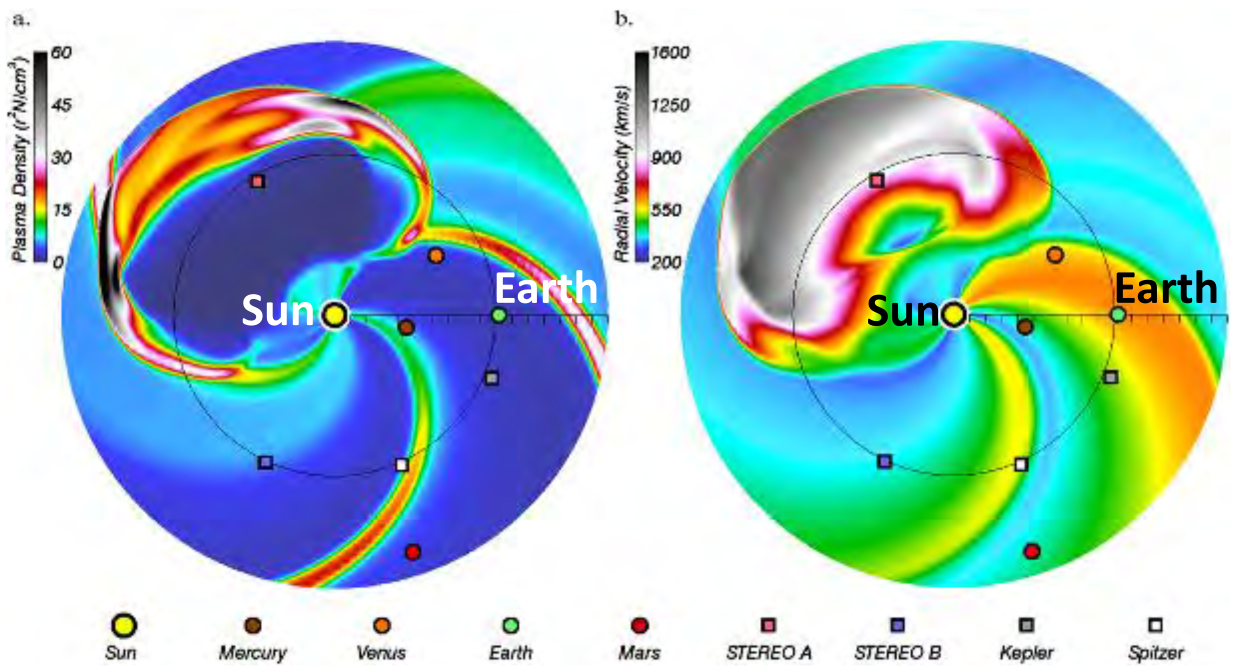
1859 – the Carrington Event, identified as the largest solar storm on record.

1938, 1940, 1958, 1989, 2003
All these events caused telephone, radio, transatlantic and GPS disruptions.

1989 – 90 seconds after the onset of the storm at Earth, the entire Quebec power grid collapsed. The power outage lasted 9 hours.

(Source: https://pixabay.com)

Finally, the one that got away…



(Source: Baker et all., 2013)

- On **23 July 2012**, a CME occurred that was well measured by spacecraft, but **missed the Earth**.
- Observations of the properties of the CME indicate that it was **larger than the most extreme event witnessed in the modern era**.
- The effect on the Earth's magnetic field would have been larger than the 1859 Carrington event, and significantly larger than the 1989 'Quebec' storm.
- Propagation speeds were ~2500 km/s, and the CME would have taken 19 hours to arrive in the vicinity of the Earth.