British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Geomagnetic Storms and the UK Power Grid

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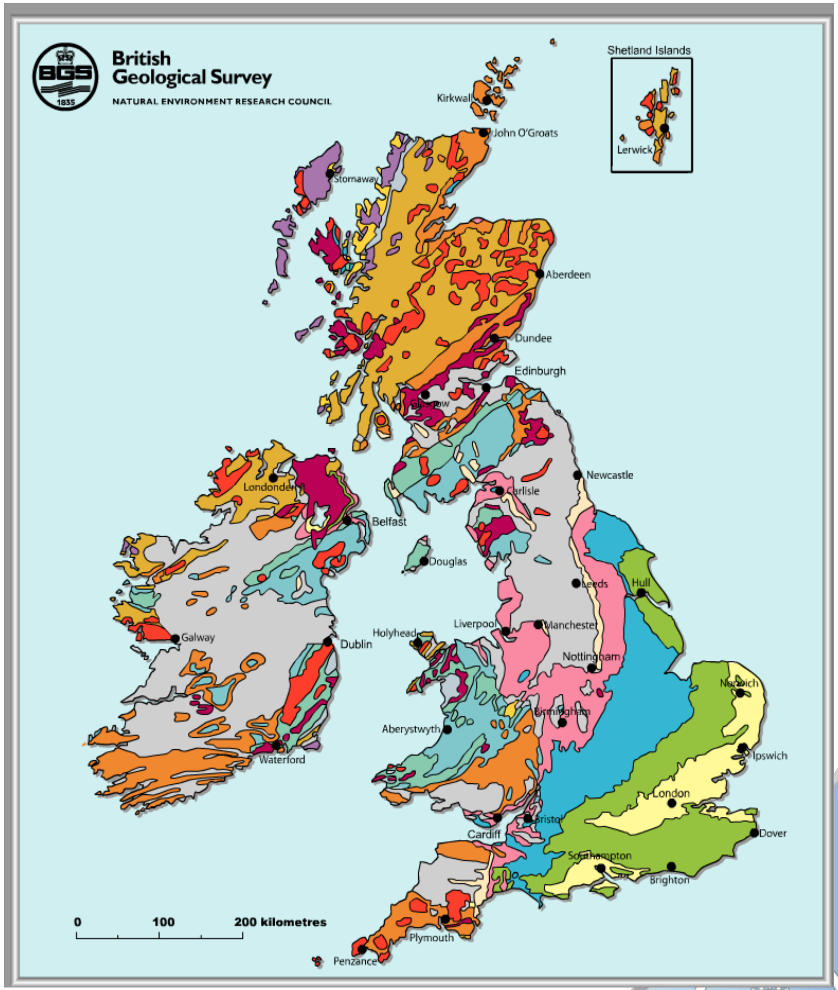
www.geomag.bgs.ac.uk

British Geological Survey

- The UK ‘Earth Sciences’ national research institute:
  - Employs about 680 staff around the UK
  - Budget of ~ £40M per year (>40% external funding)
  - Geological mapping, seismology, hydrology, building materials, natural hazards (e.g. volcanoes), geological storage of waste geochemistry, international consulting ...
  - ... and Geomagnetism



Geology of Britain and Ireland

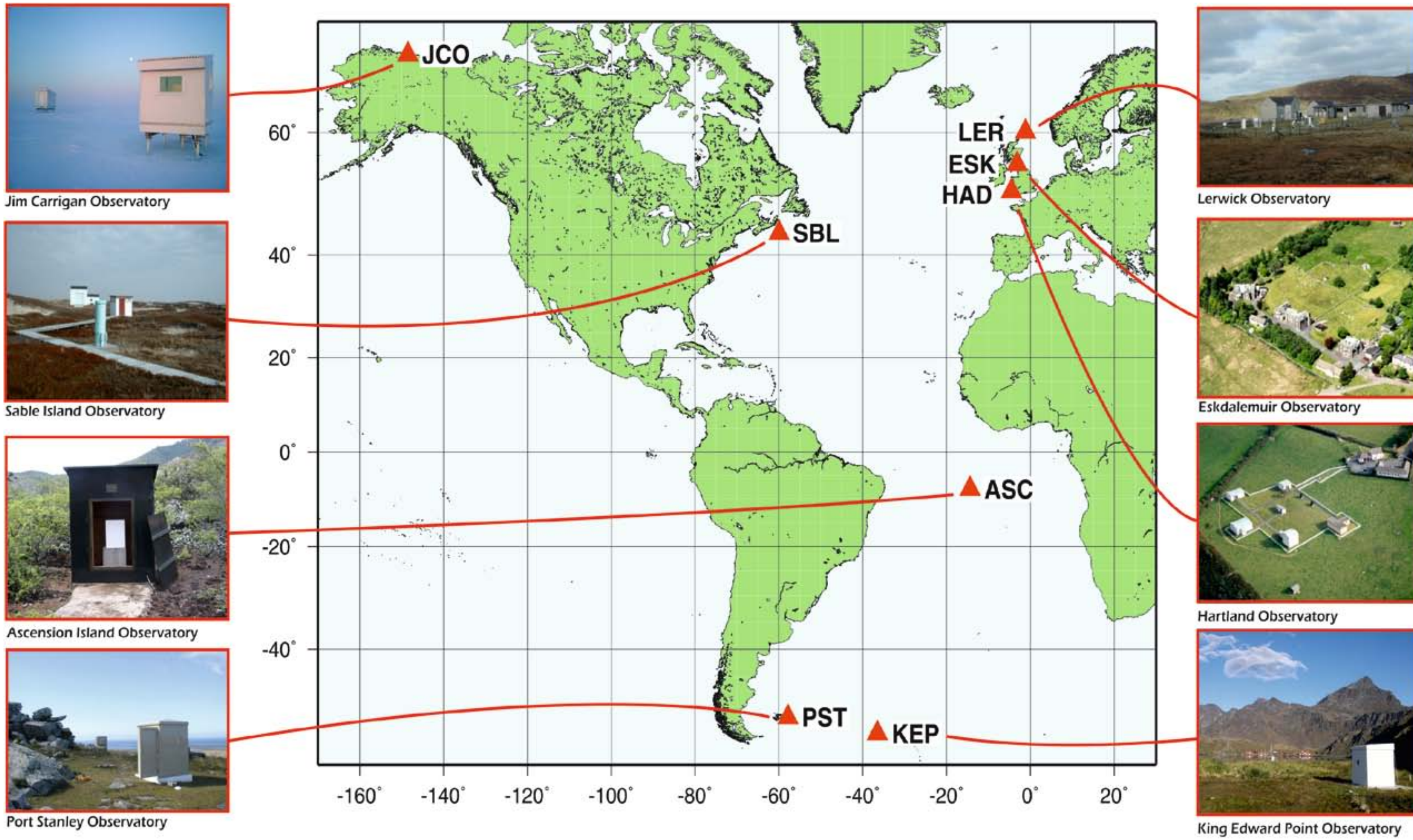
Geomagnetism at the BGS

- Based in Edinburgh (+ Eskdalemuir & Hartland)
- Over 20 full and part-time staff including:
  - Mathematicians
  - Geophysicists
  - Engineers
  - Observatory staff

- Income from National Capability (NERC) and external contracts (oil/gas directional drilling, Ordnance Survey, European Space Agency)

- World-class geomagnetic research – academic papers & reports etc

UK & Overseas Observatories

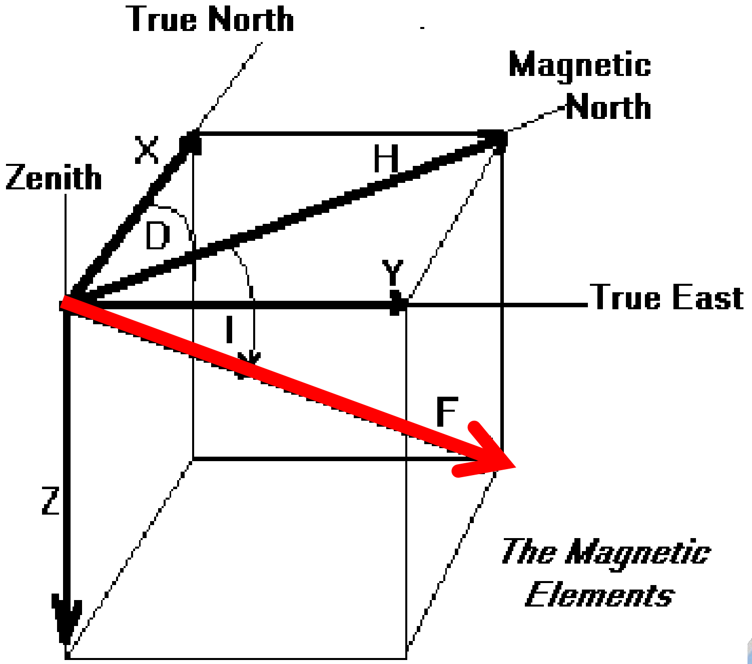


Observatories measure magnetic fields

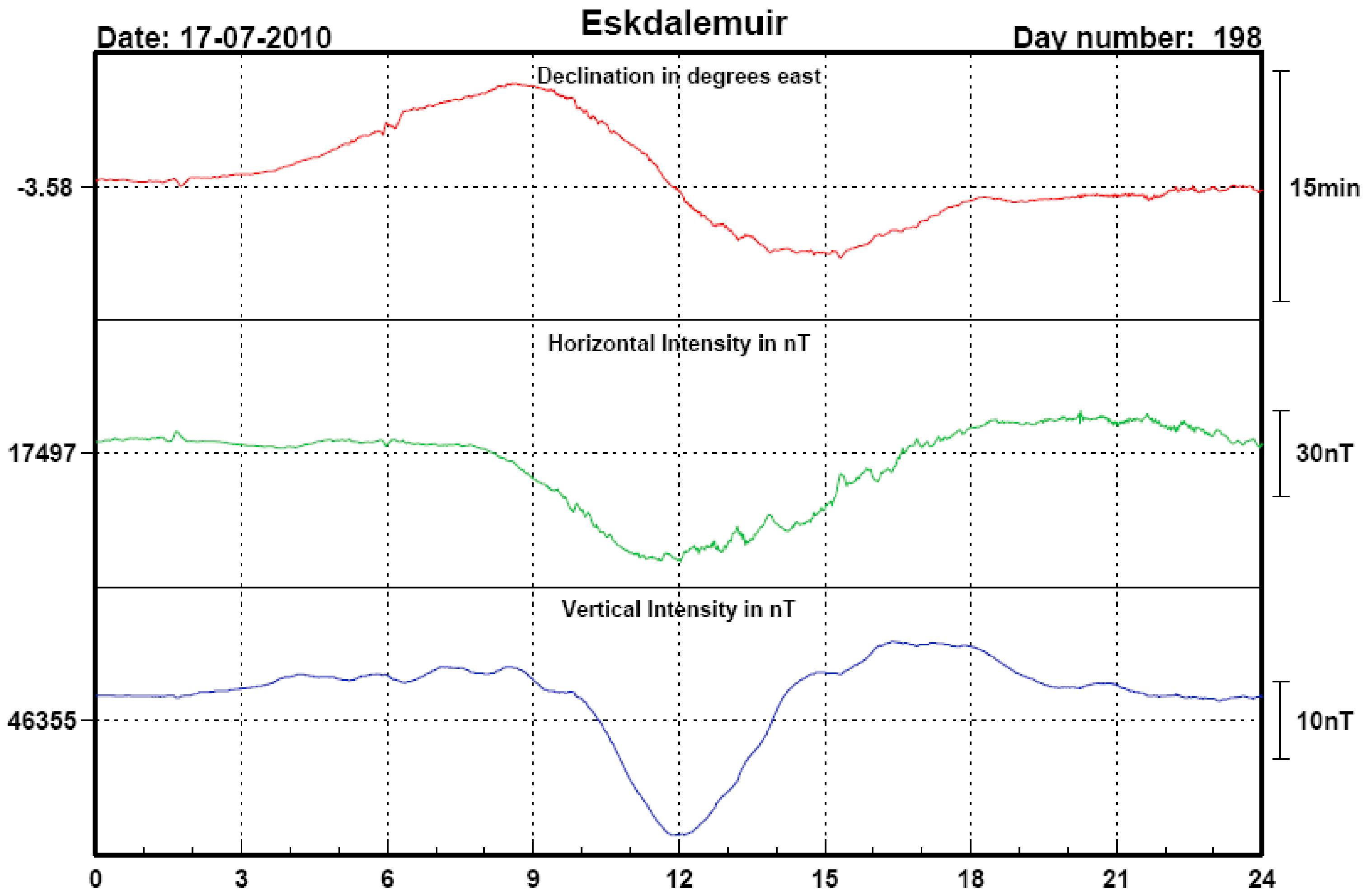
Suspended triaxial fluxgate magnetometer

Fluxgate theodolite

Proton precession magnetometer



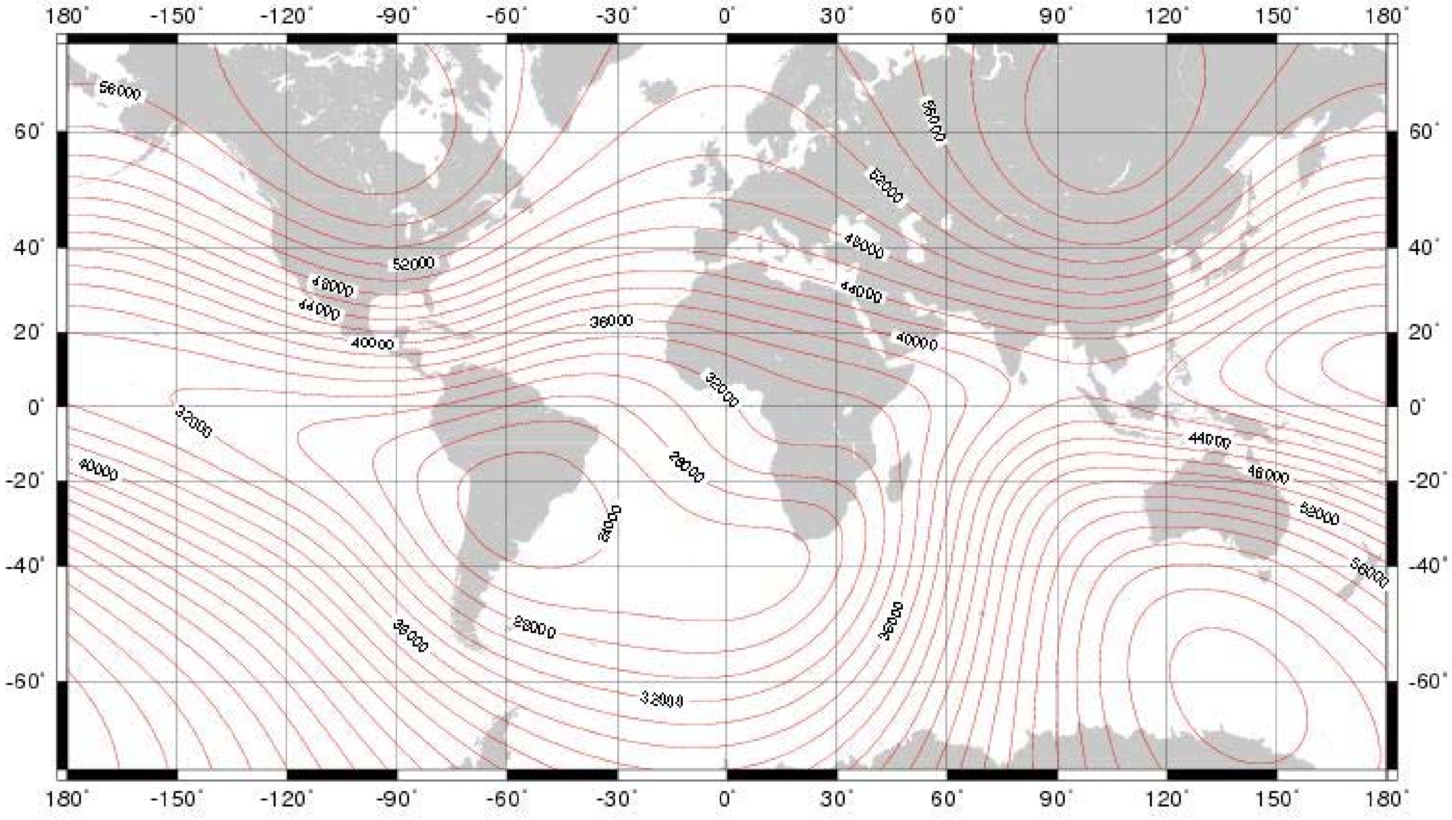
Magnetogram



Teslas

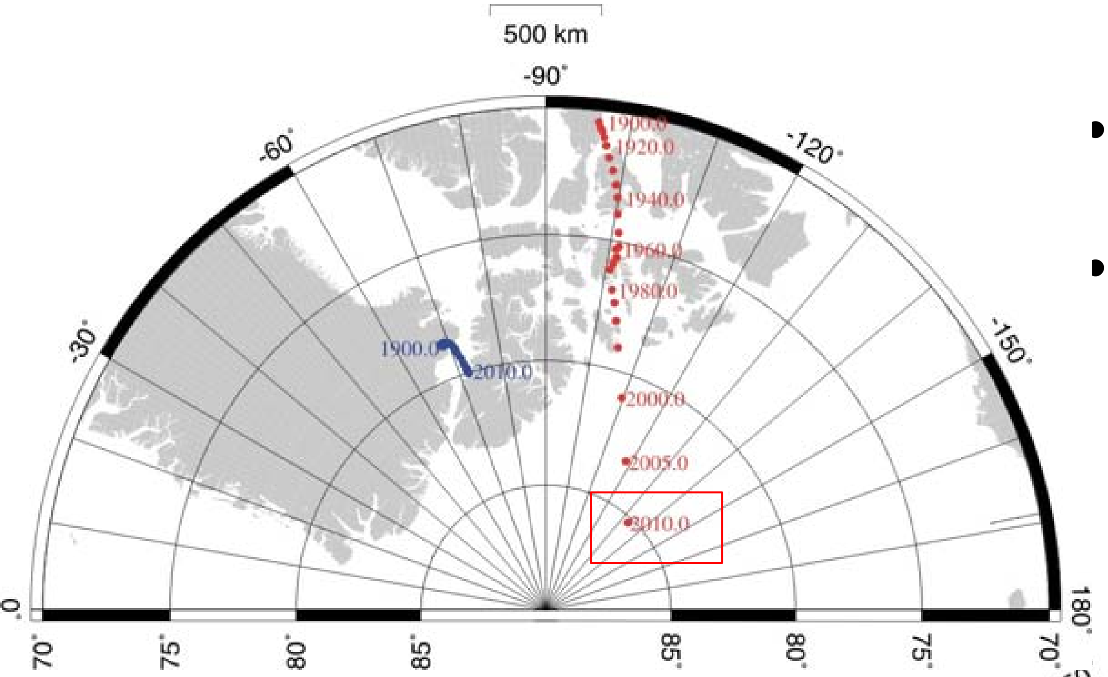
Unit	Strength	Example
nanotesla	0.1 nT to 10 nT (10×10^{-9} T)	Magnetic field from 'quiet time' ionospheric currents
microtesla	24,000nT (24×10^{-6} T)	Strength of magnetic tape
	31 µT	Strength of Earth's magnetic field at the equator
	58 µT	Strength of Earth's magnetic field at 50° latitude
millitesla	500,000nT (0.5×10^{-3} T)	Suggested exposure limit for cardiac pacemakers
	5 mT	Strength of a typical fridge magnet
tesla	1 T to 2.4 T	coil gap of a typical loudspeaker magnet
	1.25 T	Strength of a modern neodymium-boron-iron magnet
	1.5 T to 3 T	Strength of medical MRI systems in practice
	16 T	Strength used to levitate a frog (unharmed)

Earth's Main Field

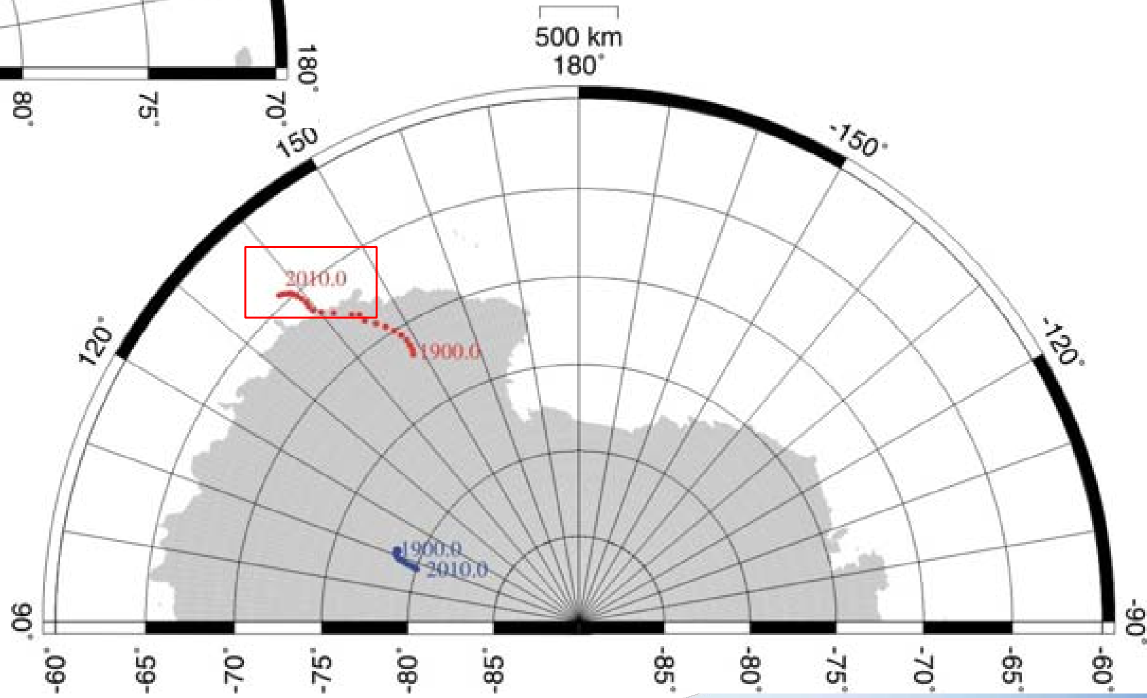


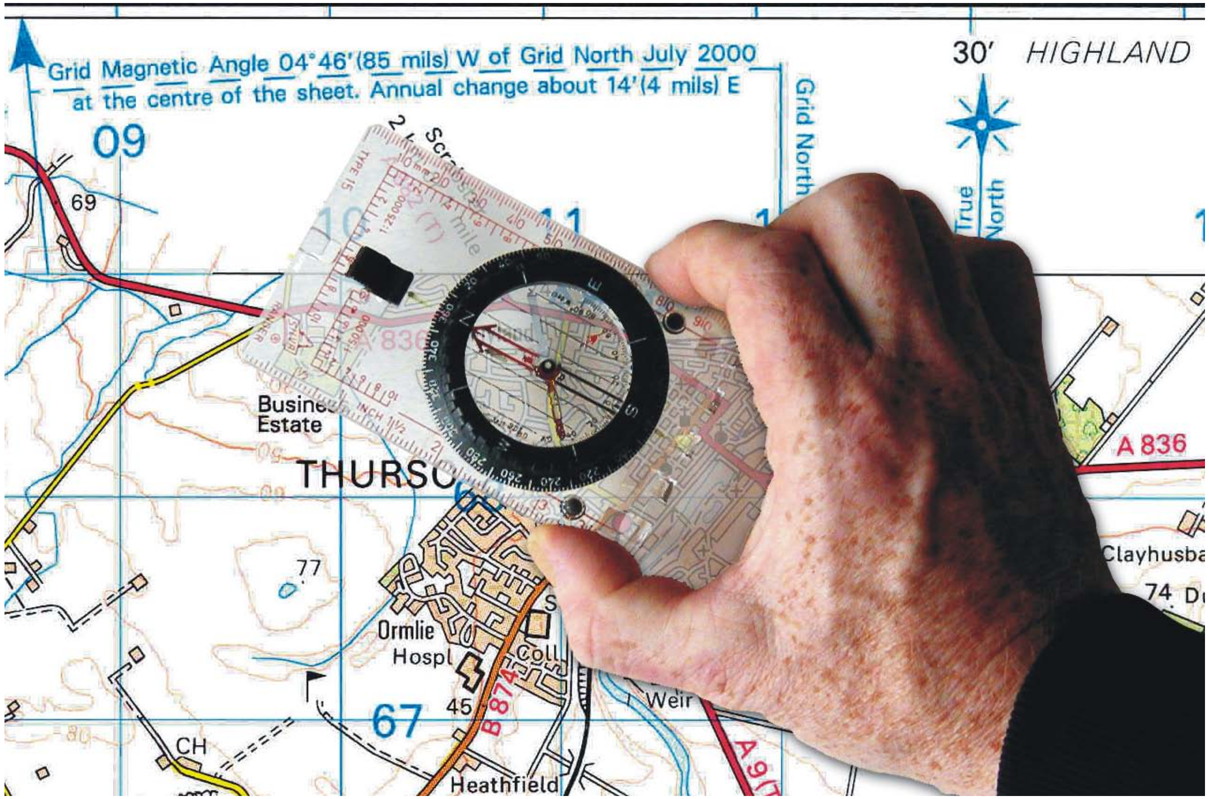
Total intensity (*F*) at 2010.0 from the World Magnetic Model (WMM2010). Contour interval is 2000 nT and projection is Mercator. This is an example of an isodynamic chart. Credit: British Geological Survey (Natural Environment Research Council).

Change of the Main Field: Poles Apart



- Geomagnetic Pole
  - global best fit dipole
- Magnetic 'Dip' Pole
  - where inclination is 90°
  - actually a diffuse region





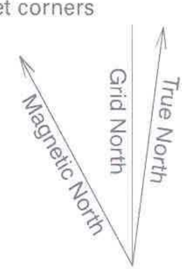
Technical Information

NORTH POINTS

Difference of true north from grid north at sheet corners

NW corner 1°35′(28 mils) E	NE corner 1°00′(18 mils) E
SW corner 1°34′(28 mils) E	SE corner 0°59′(18 mils) E

To plot the average direction of magnetic north join the point circled on the south edge of the sheet to the point on the protractor scale on the north edge at the angle estimated for the current year

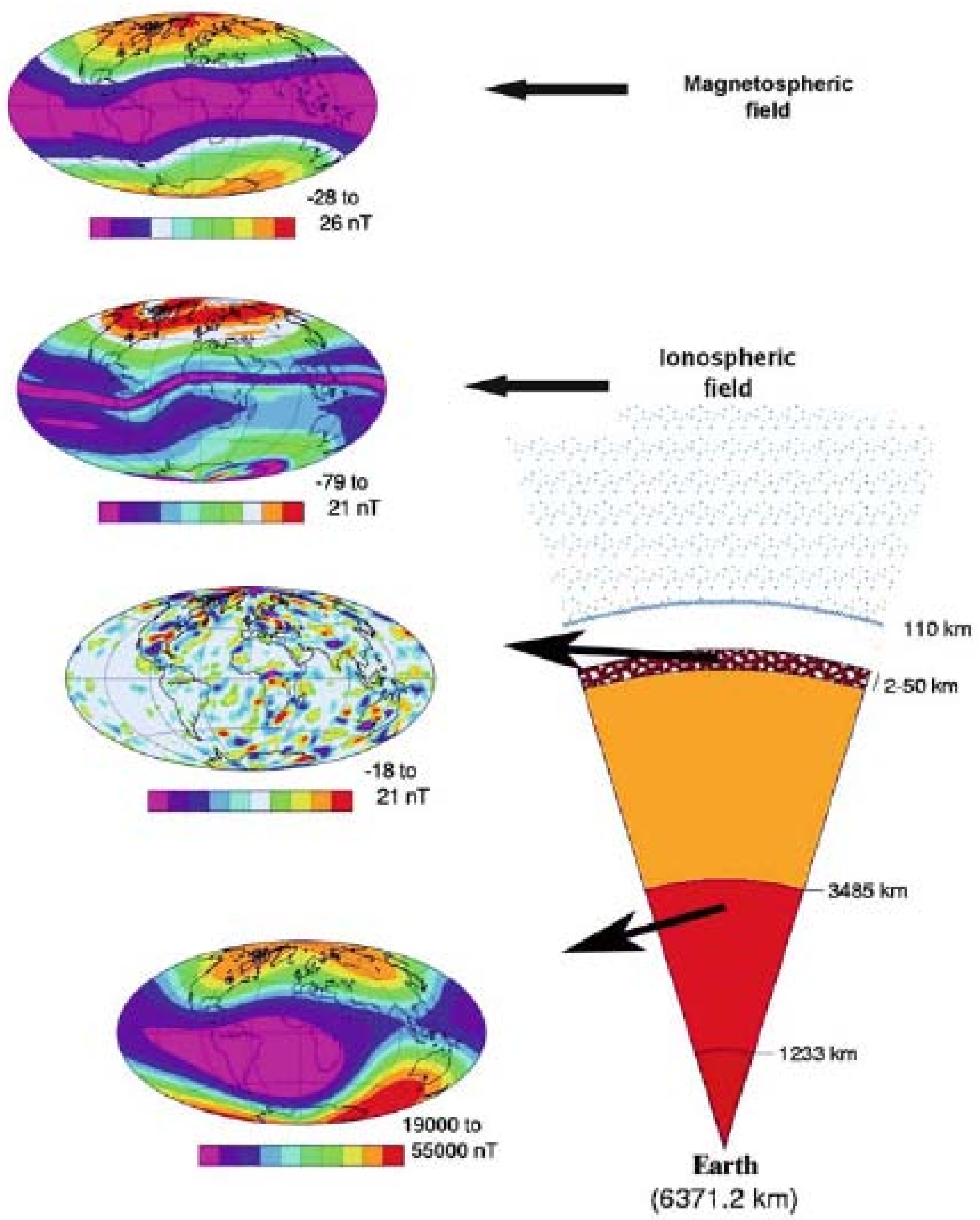


Diagrammatic only

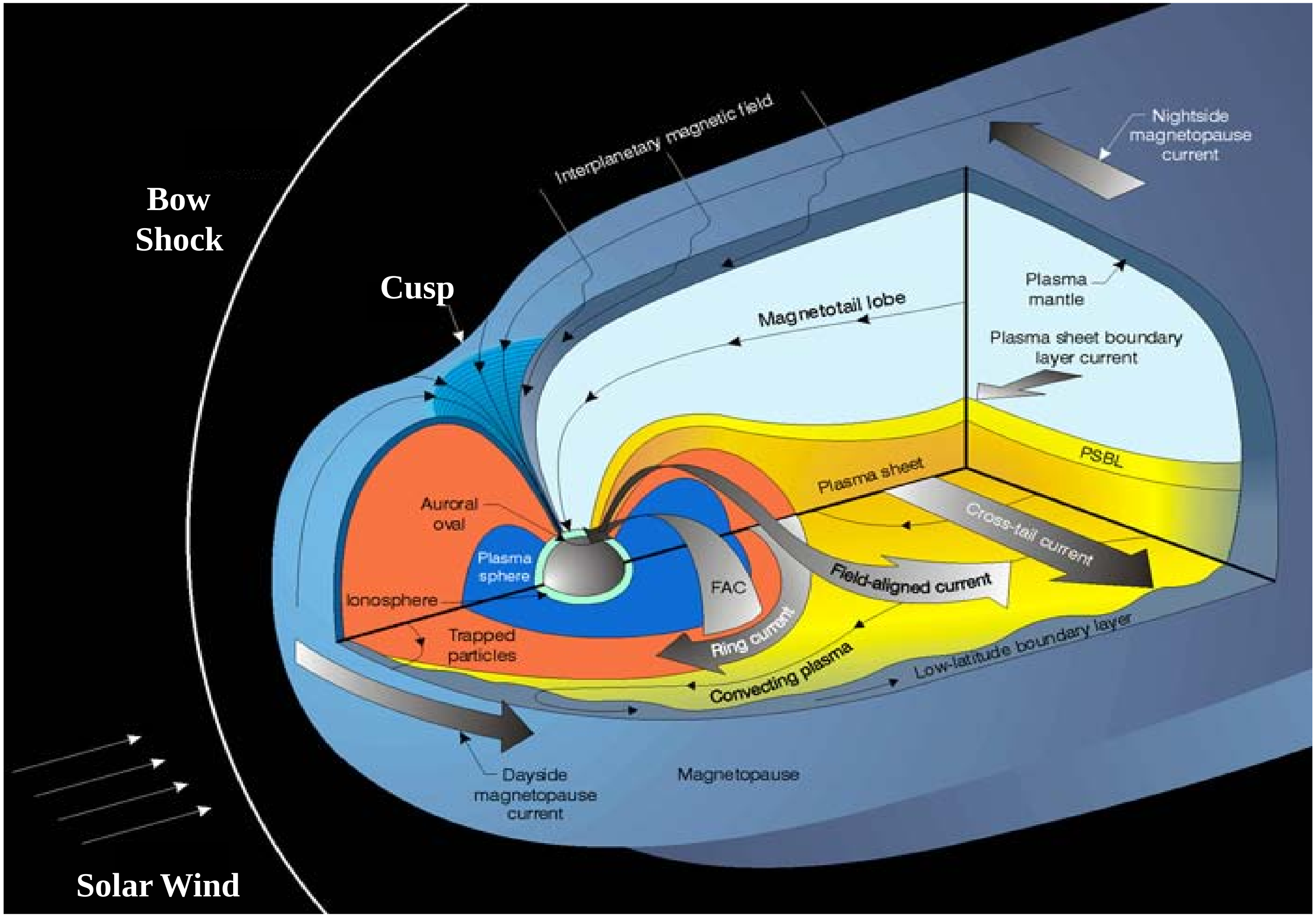
Magnetic north varies with place and time. The direction for the centre of the sheet is estimated at 4° 46′ (85 mils) west of grid north for July 2000.
Annual change is about 14′ (4 mils) east

Magnetic data supplied by the British Geological Survey

Base map constructed on Transverse Mercator Projection, Airy Spheroid, OSGB (1936) Datum. Vertical datum mean sea level (Newlyn)



Magnetospheric field
-28 to 26 nT
Ionospheric field
-79 to 21 nT
110 km
2-50 km
-18 to 21 nT
3485 km
1233 km
19000 to 55000 nT
Earth (6371.2 km)



Bow Shock
Cusp
Solar Wind
Interplanetary magnetic field
Nightside magnetopause current
Plasma mantle
Magnetotail lobe
Plasma sheet boundary layer current
PSBL
Plasma sheet
Cross-tail current
Field-aligned current
Auroral oval
Plasma sphere
FAC
Ionosphere
Trapped particles
Ring current
Convecting plasma
Low-latitude boundary layer
Dayside magnetopause current
Magnetopause

Geomagnetic Storms? Space Weather?

- Used to be called Solar Terrestrial Physics (STP)
  - Renamed as 'Space Weather' about 10 years ago

- *"Conditions on the Sun and in the solar wind, magnetosphere, ionosphere and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life or health."   - NASA*

- Covers everything from:
  - Satellite operations / anomalies
  - GPS / Navigation
  - Astronaut health
  - Aeroplane passengers
  - UHF radio disruption
  - etc.

In the news online ...

16 February 2011 Last updated at 15:36

Sun unleashes huge solar flare towards Earth

By Paul Rincon
Science reporter, BBC News

Time lapse image of the solar flare as seen by Nasa's Solar Dynamics Observatory

The Sun has unleashed its strongest flare in four years, observers say.

The eruption is a so-called X-flare, the strongest type; such flares can affect communications on Earth.

Nasa's Solar Dynamics Observatory (SDO) spacecraft **recorded an intense flash** of extreme ultraviolet radiation emanating from a sunspot.

The British Geological Survey (BGS) has issued a geomagnetic storm

Related Stories

Satellites sit either side of Sun

Are solar flares a real threat?

Plans for solar 'close encounter'

In Government ...

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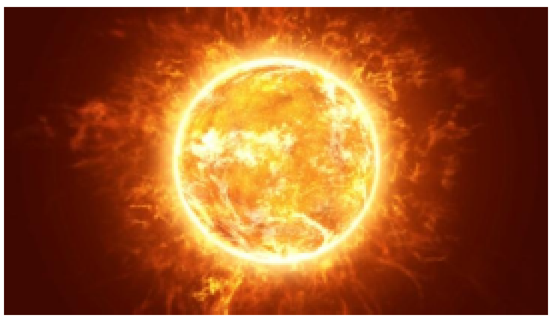
POSTNOTE

Number 361 July 2010

Space Weather



Overview

Space weather can affect space- and ground-based technological systems and cause harm to human health. Monitoring space weather is crucial in order to understand and mitigate its impacts. International collaboration, stimulated by the approaching peak in solar activity, has a key role to play in this area given the global nature of space weather.

Background

"Space weather" means changes in the near-Earth space environment. It is caused by varying conditions within the Sun's atmosphere. The Sun emits a continuous stream of particles, some highly energetic, and radiation of varying intensity. Solar activity changes according to an approximately 11-year cycle and the current consensus is that the next peak will occur in 2012-13.[1] Within the solar cycle, solar storms can occur. A solar flare (a rapid outburst of radiation and energetic particles) is one type of solar storm. Another is a coronal mass ejection or CME – a larger scale, violent ejection of material into space. If directed towards the Earth, CMEs can reach it within a few days, and cause disruptions of the Earth's magnetic field known as

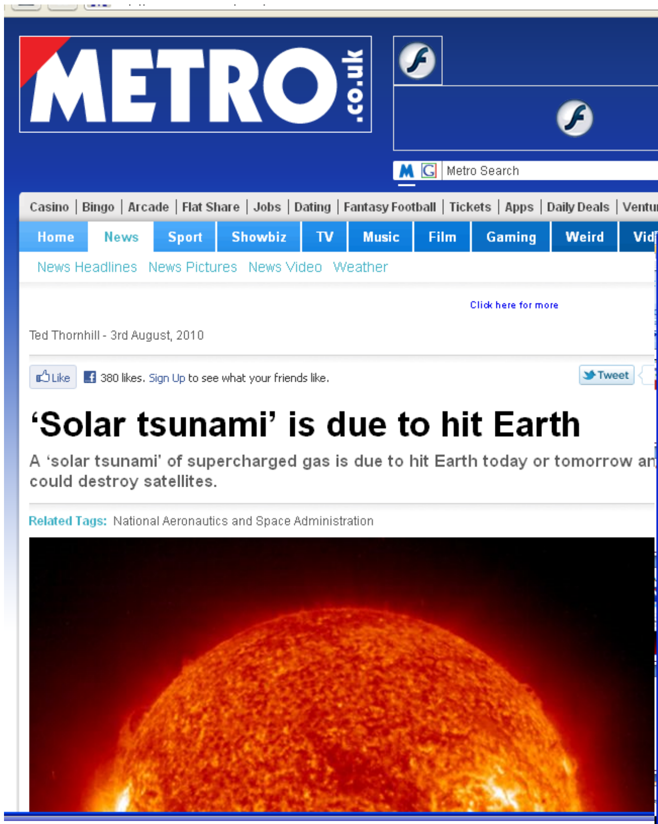
increased friction (atmospheric drag) slows down some satellites, which can drop to lower altitudes and sometimes be lost. Active satellites need to use up costly fuel to maintain orbit.

- Space weather disturbs the ionosphere (one of the upper layers of the atmosphere) which may temporarily degrade or disrupt communication and navigation signals. This can affect satellite-provided broadband and TV and satellite navigation (SatNav), on which society increasingly depends. For example, stock exchanges use GPS timing signals to record transactions accurately.

Box 1. Examples of Space Weather Effects

Quebec Blackout Storm of March 1989

And the papers ...



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Ted Thornhill - 3rd August, 2010

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‘Solar tsunami’ is due to hit Earth

A ‘solar tsunami’ of supercharged gas is due to hit Earth today or tomorrow an could destroy satellites.

Related Tags: National Aeronautics and Space Administration

Solar flare 'could paralyse Earth in 2013' | Mail Online - Mozilla Firefox

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http://www.dailymail.co.uk/sciencetech/article-1313858/Solar-flare-paralyse-Earth-2013.html

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Massive solar flare 'could paralyse Earth in 2013'

By DAILY MAIL REPORTER

Last updated at 8:38 PM on 21st September 2010

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A massive solar flare could cause global chaos in 2013, causing blackouts and wrecking satellite communications, a conference heard yesterday.

Nasa has warned that a peak in the sun's magnetic energy cycle and the number of sun spots or flares around 2013 could generate huge radiation levels.

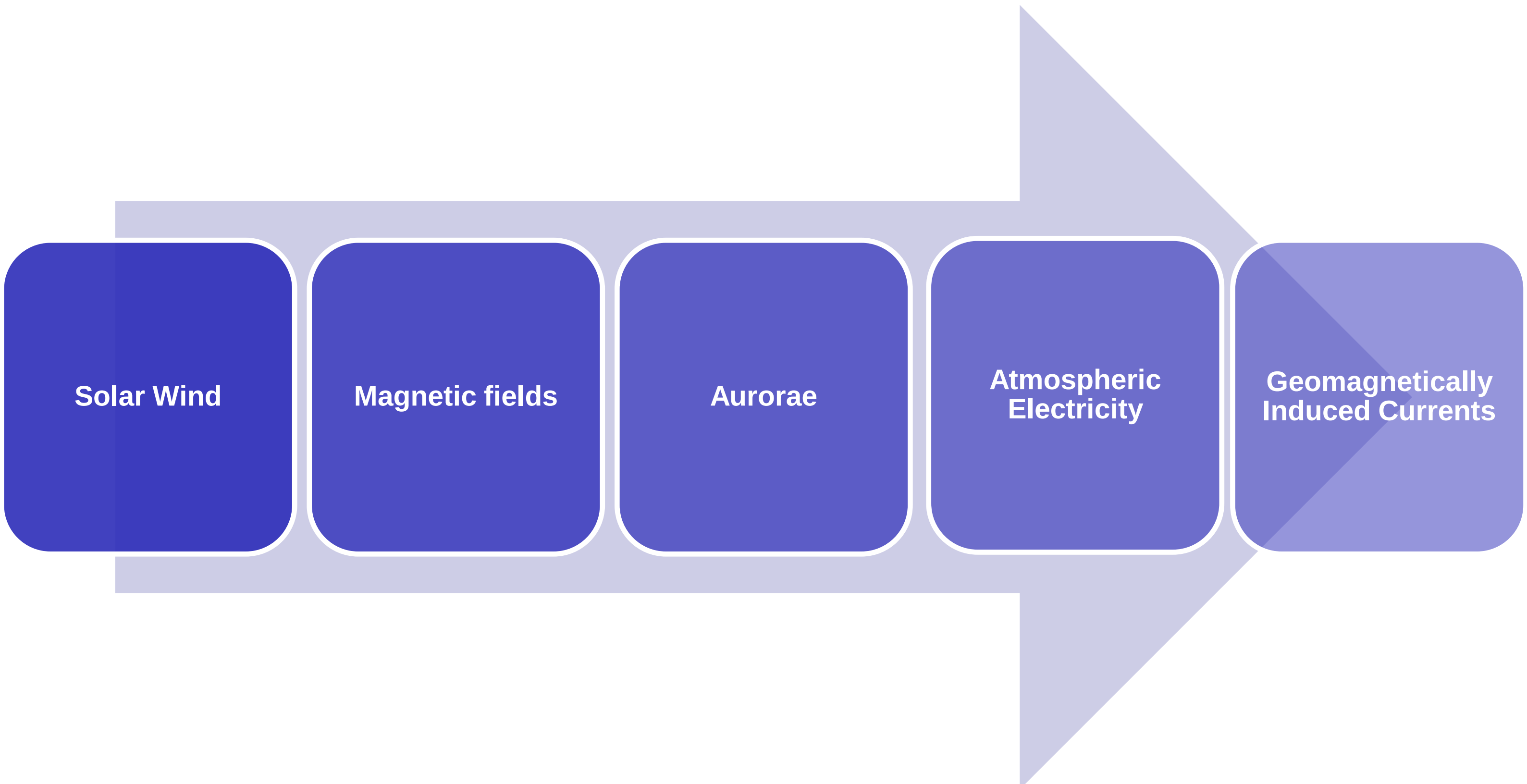
The resulting solar storm could cause a geomagnetic storm on Earth, knocking out electricity grids around the world for hours, days, or even months, bringing much of normal life grinding to a halt.

Defence Secretary Liam Fox, who delivered the keynote address at an international conference on the vulnerability of electricity grids around the world, warned that modern societies' dependence on technology leaves them vulnerable to such events.

Headlines | Most Read

- 'Earliest' Bronze Age battle site containing 100 bodies found on German river bank
- The curse of being too popular: Apple Macs now seen as a 'soft target' for spreading viruses
- Cosmic spectacle: Nasa pictures reveal the breathtaking eruptions on Jupiter's volcanic moon
- A new dimension: Astronaut takes the first 3D images in space
- Now that IS fast! Scientists transfer 700 DVDs of data down a single fibre-optic cable in ONE SECOND
- Dial M for music: How Parisians used their phones for entertainment 100 years before mobiles
- The science of sex: Secret online dating tips revealed by Harvard math majors (in graph form, of course)

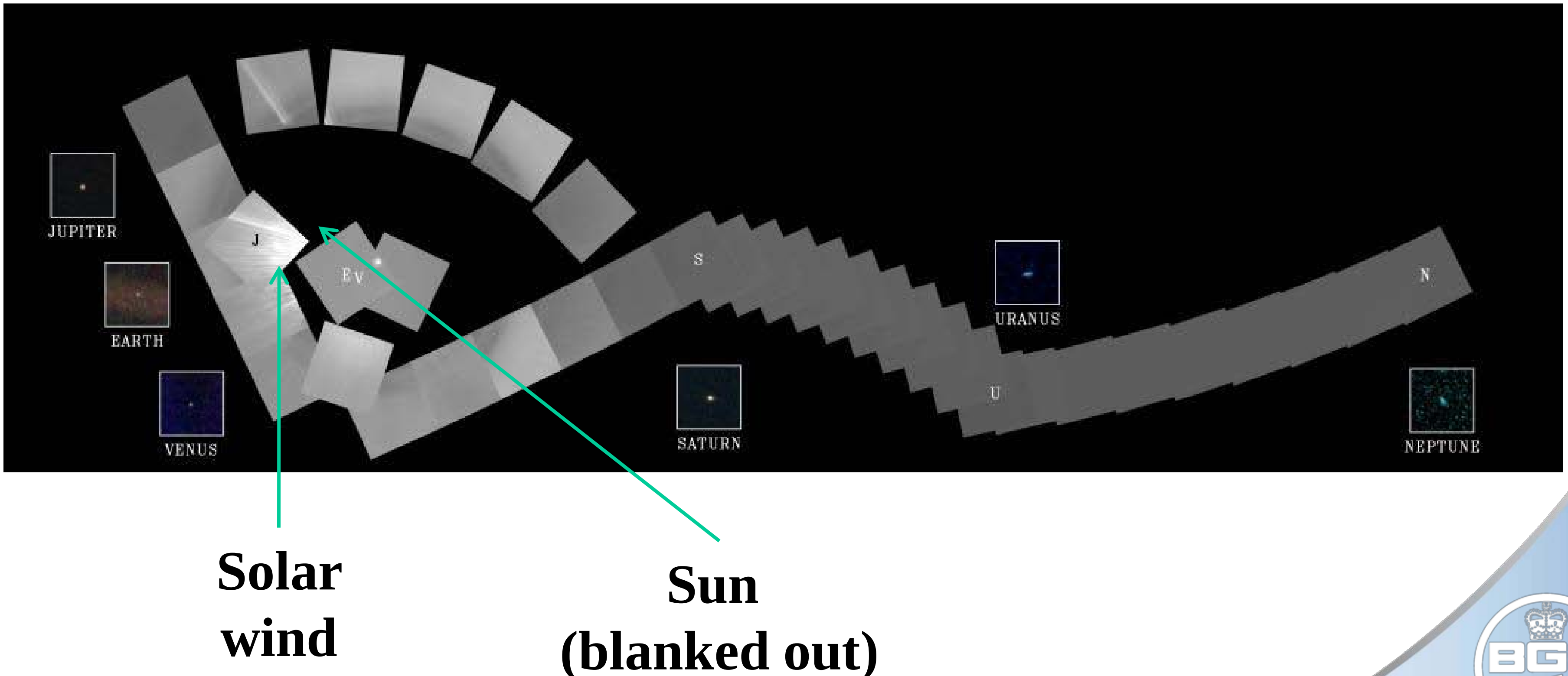
So ... what is going on?



An Overview: the Solar System

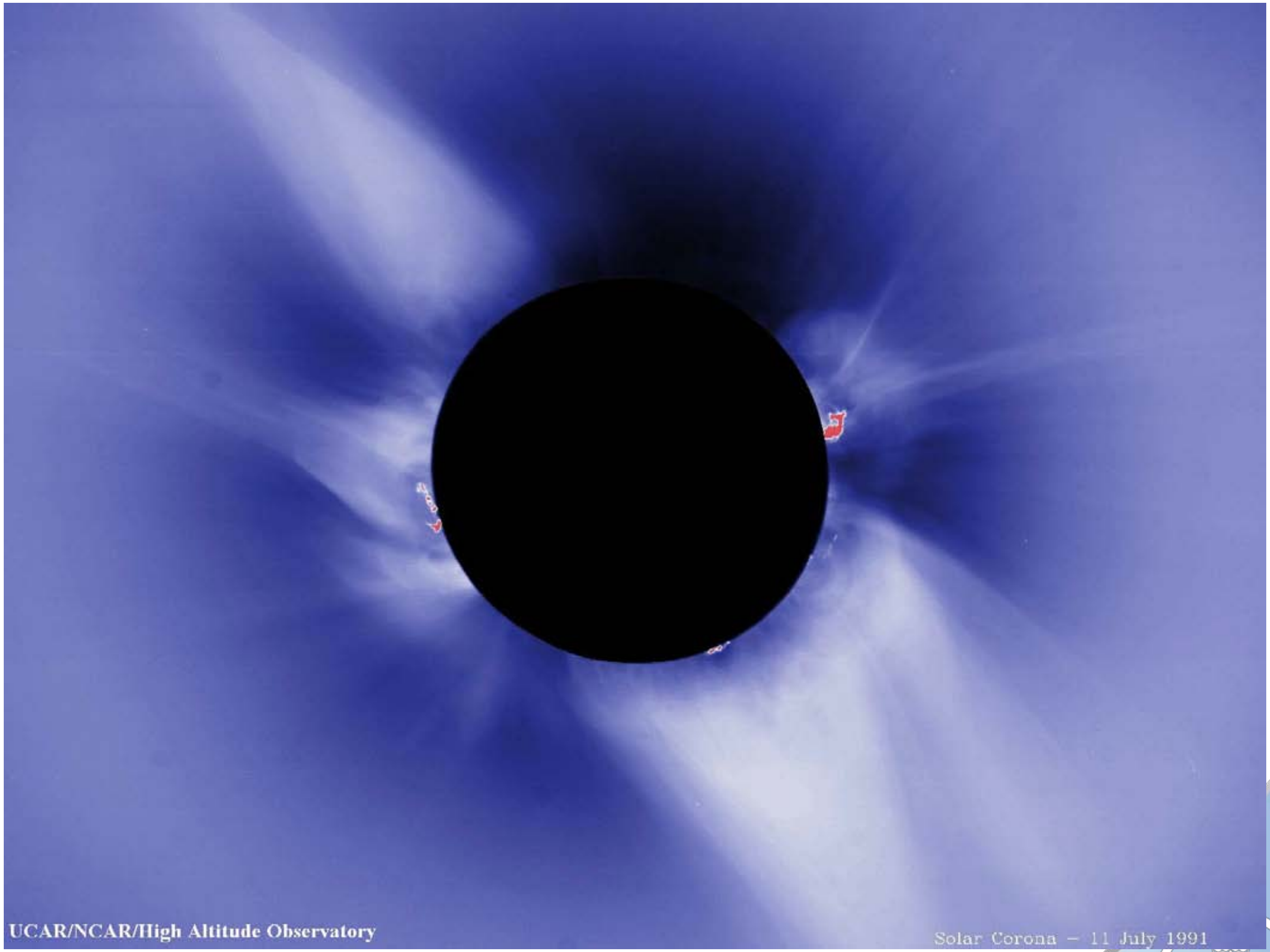
As seen by Voyager1 spacecraft:

- still going after 24 years
- ~9 billion miles out
- due to leave the Solar System in 3-5 years' times



Evidence for a complex solar atmosphere

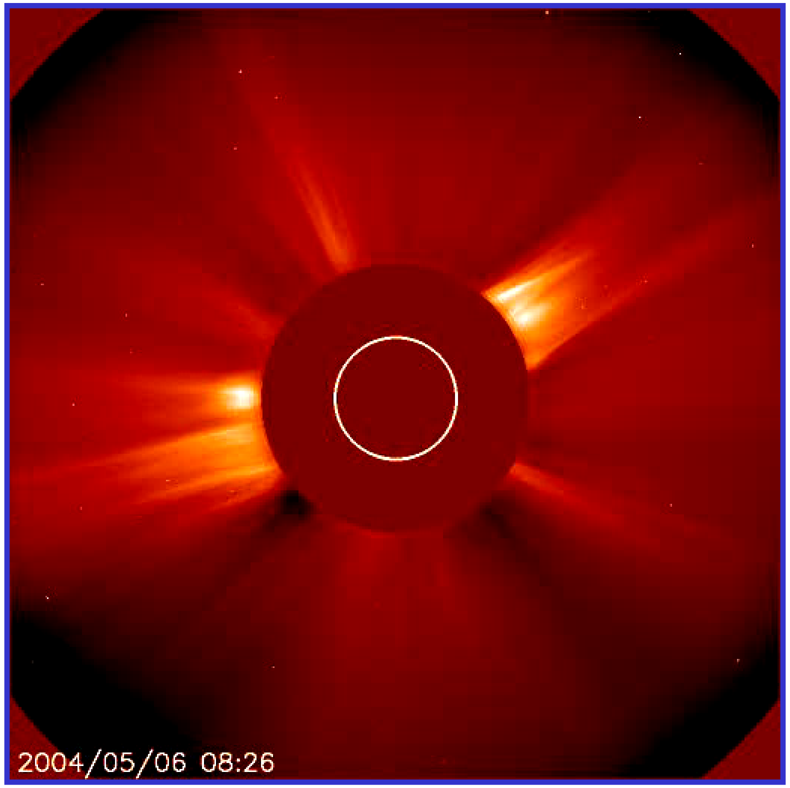
- Solar atmosphere
- Visible briefly during eclipses
- Continuous outpouring of matter and magnetic fields from the Sun



Evidence of a constant ‘wind’ - comets

What is the solar ‘wind’?

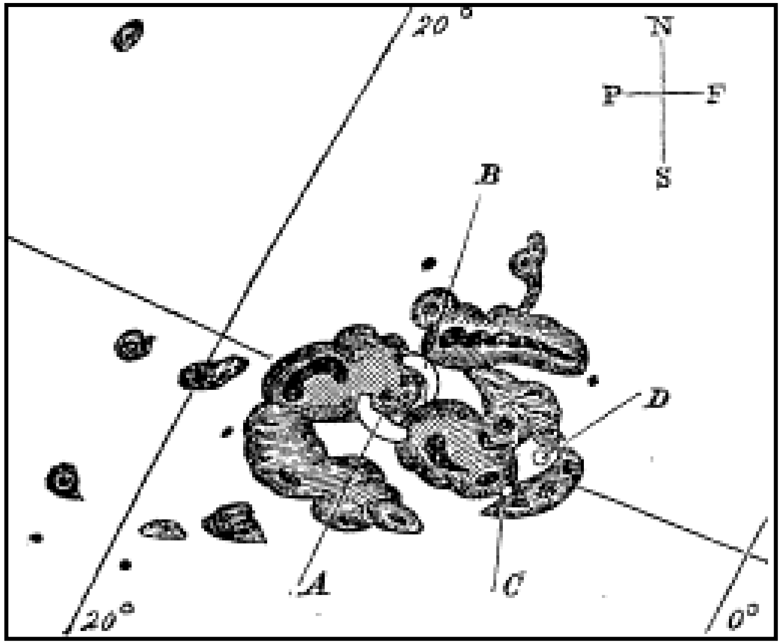
- Collisionless, magnetised ***plasma***
- Electrically neutral on average
  - mainly H^+, e^-
- Continual, but variable, outflow from Sun’s corona
- Carries waves and turbulence from corona



- **Hot**: >10^5 K
- **Rarefied**: few particles per cm^3 at Earth
- **Complex** due to solar variability, solar rotation, and in situ processes
- **Variable** on all measured scales, from sub-second → centuries

First evidence for interaction with the Sun

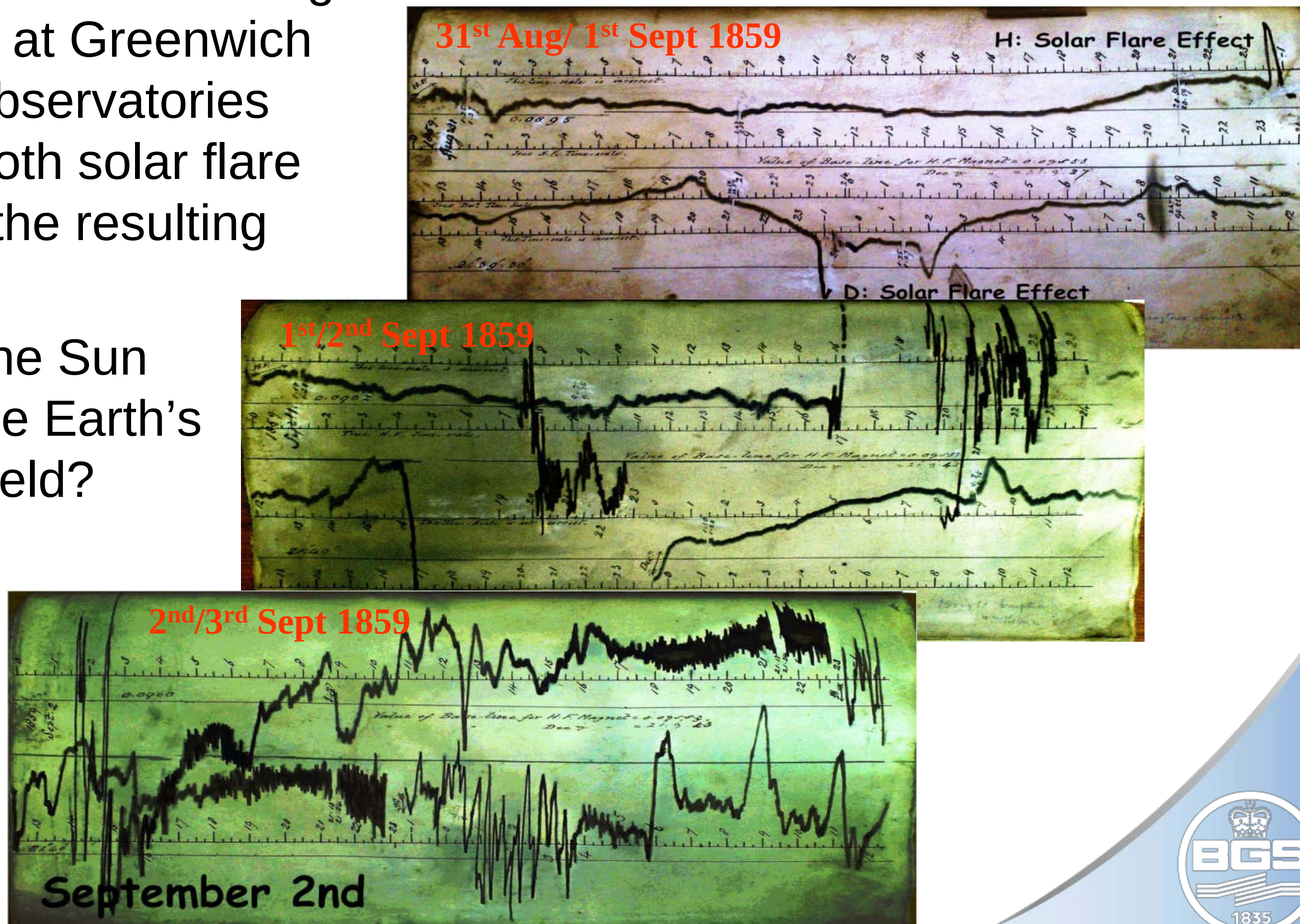
- 11:18am, 1 September 1859, Richard Carrington: observed two very bright and mobile regions on the Sun (sketch)
- Next day (~17hrs later): auroras down to very low latitudes (Cuba, Hawaii)
- Telegraph systems disrupted (*operators get electric shocks*); newspapers readable at night
- Evidence for particles from the Sun, travelling at ~2000 km/s to the Earth
- A link between the Earth and the Sun was considered *preposterous* at the time!



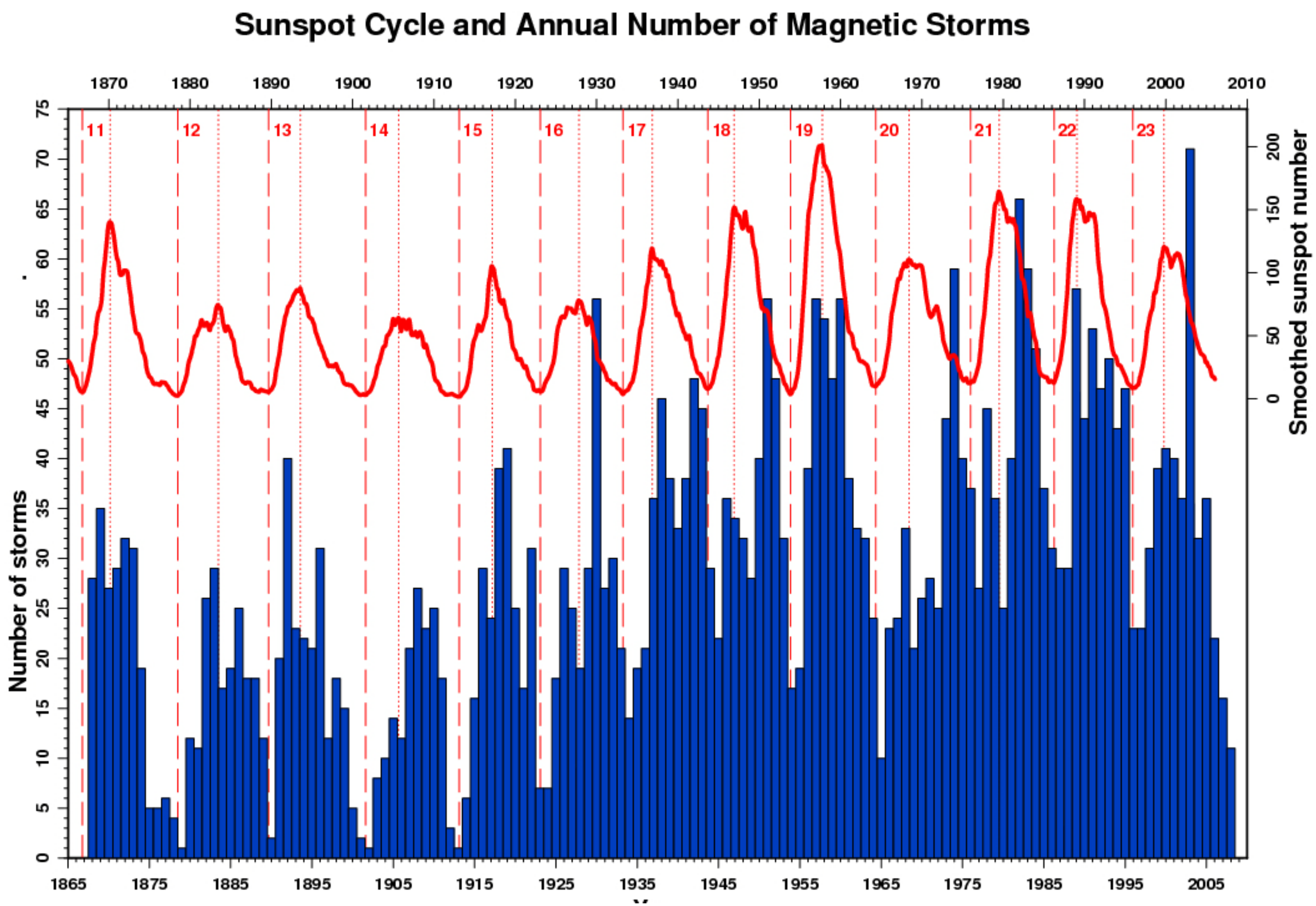
From Carrington's report to the Royal Society (1860)

Archive Magnetograms from 1859 (at BGS)

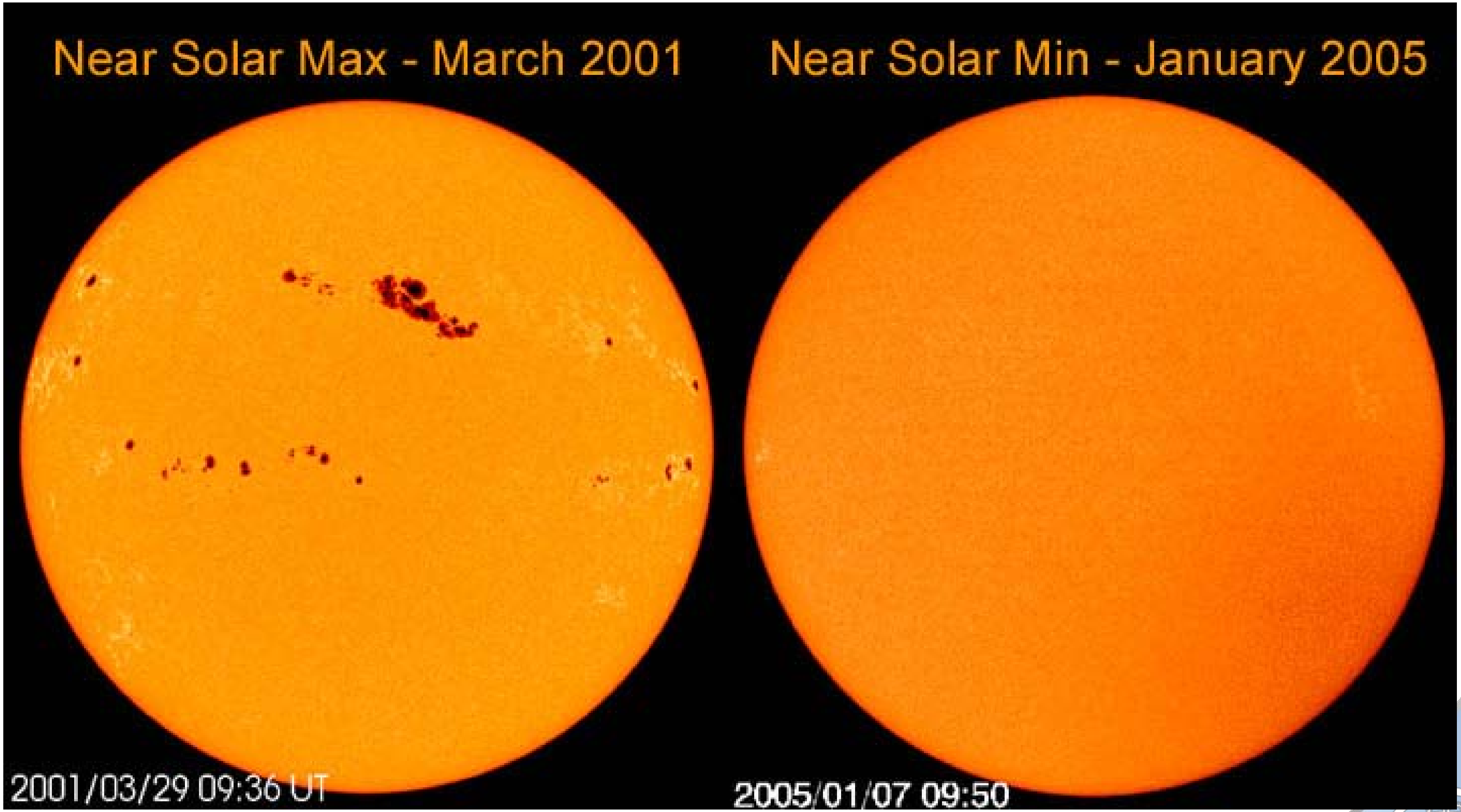
- New automated recording technology at Greenwich and Kew observatories captured both solar flare effect and the resulting ‘storm’
- How was the Sun affecting the Earth’s magnetic field?



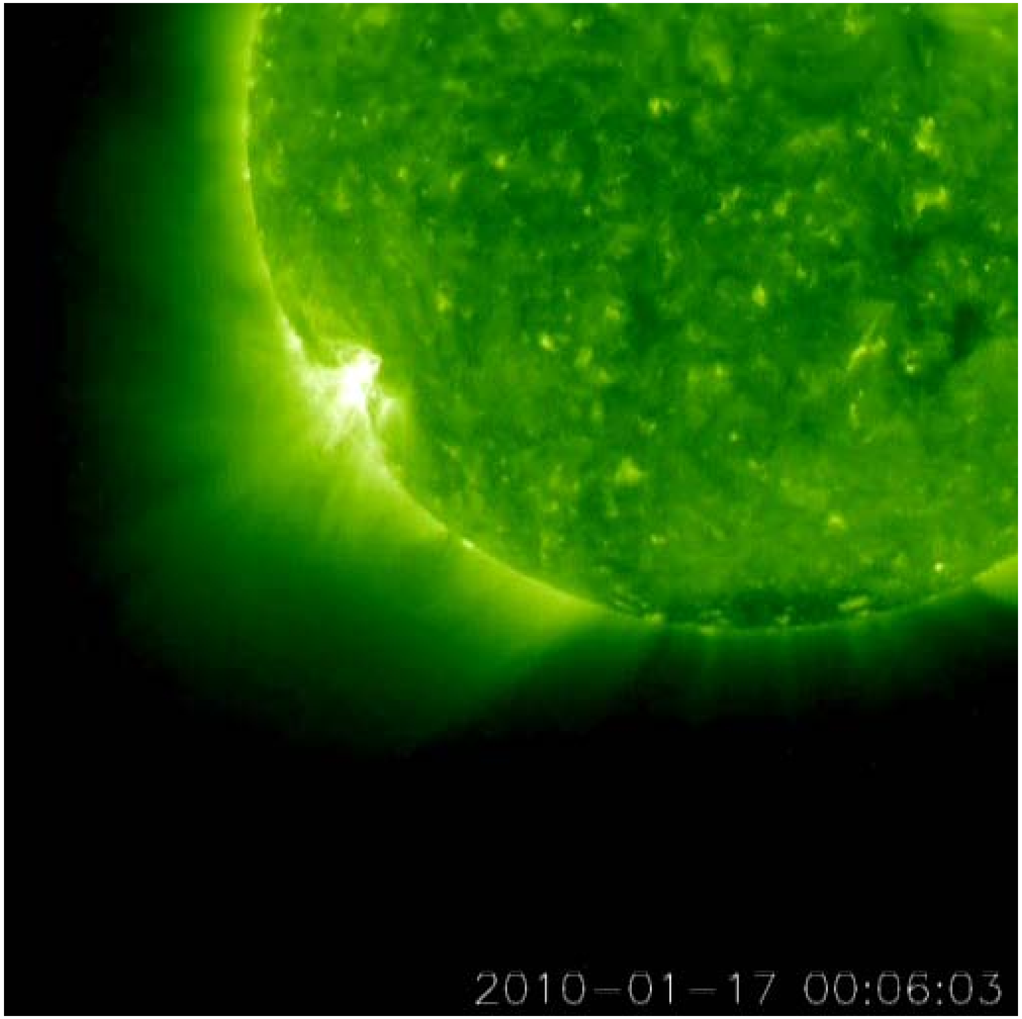
Solar storms tend to come in cycles



Sunspot cycle

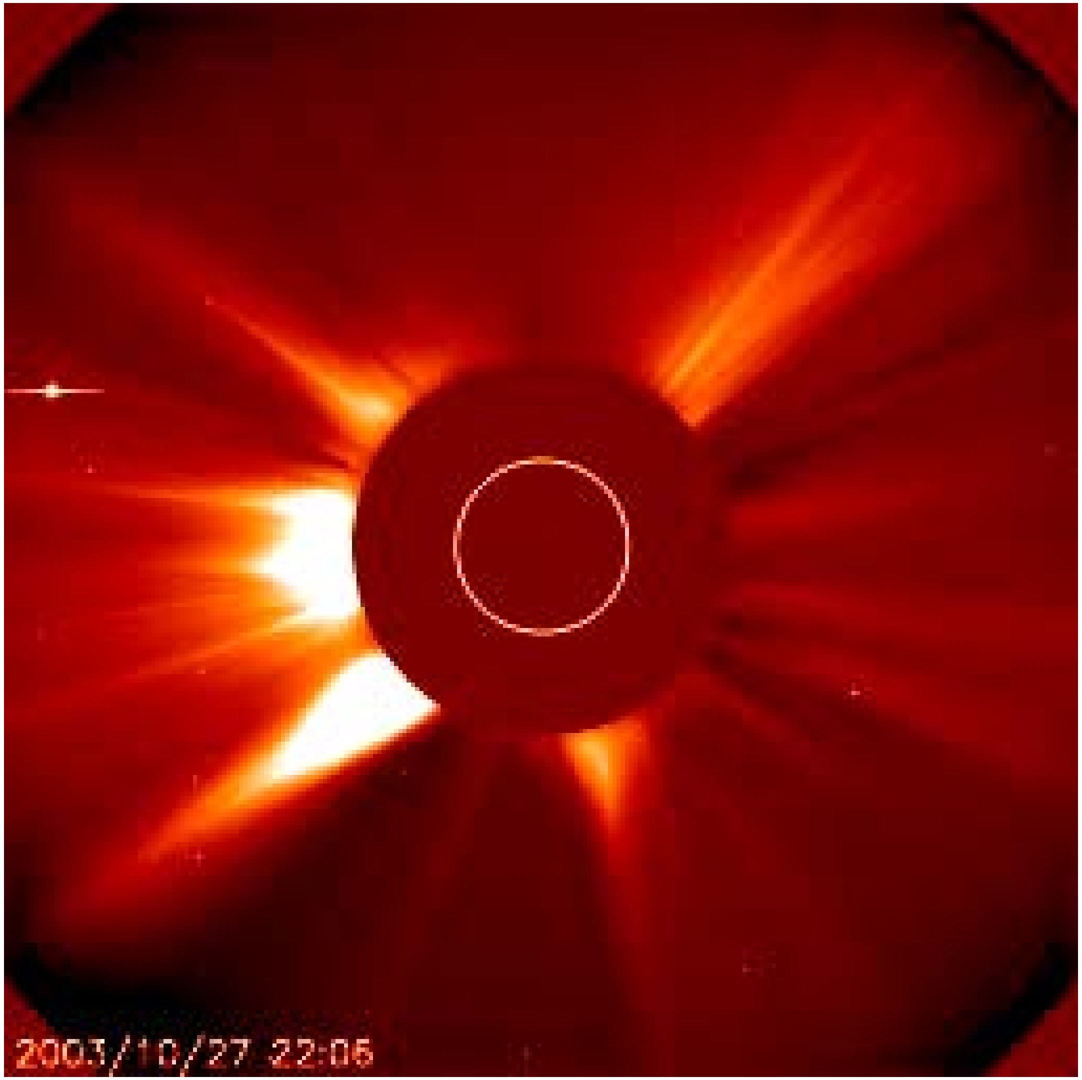


Solar Flares



UV Image: Solar Dynamic Observatory (NASA)

Coronal Mass Ejections



From SOlar and Heliospheric Observatory (SOHO) mission [NASA and ESA]

The Magnetosphere

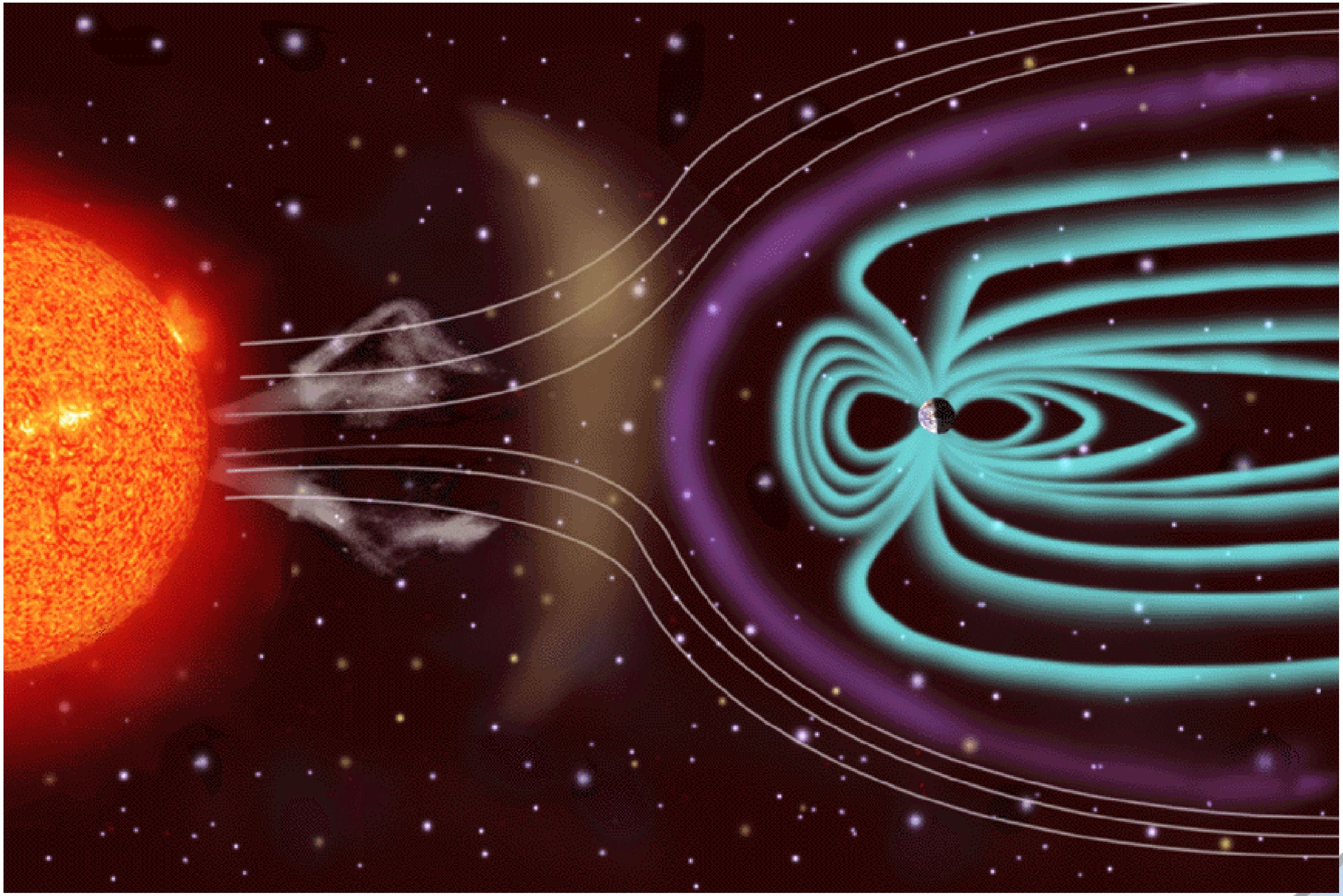
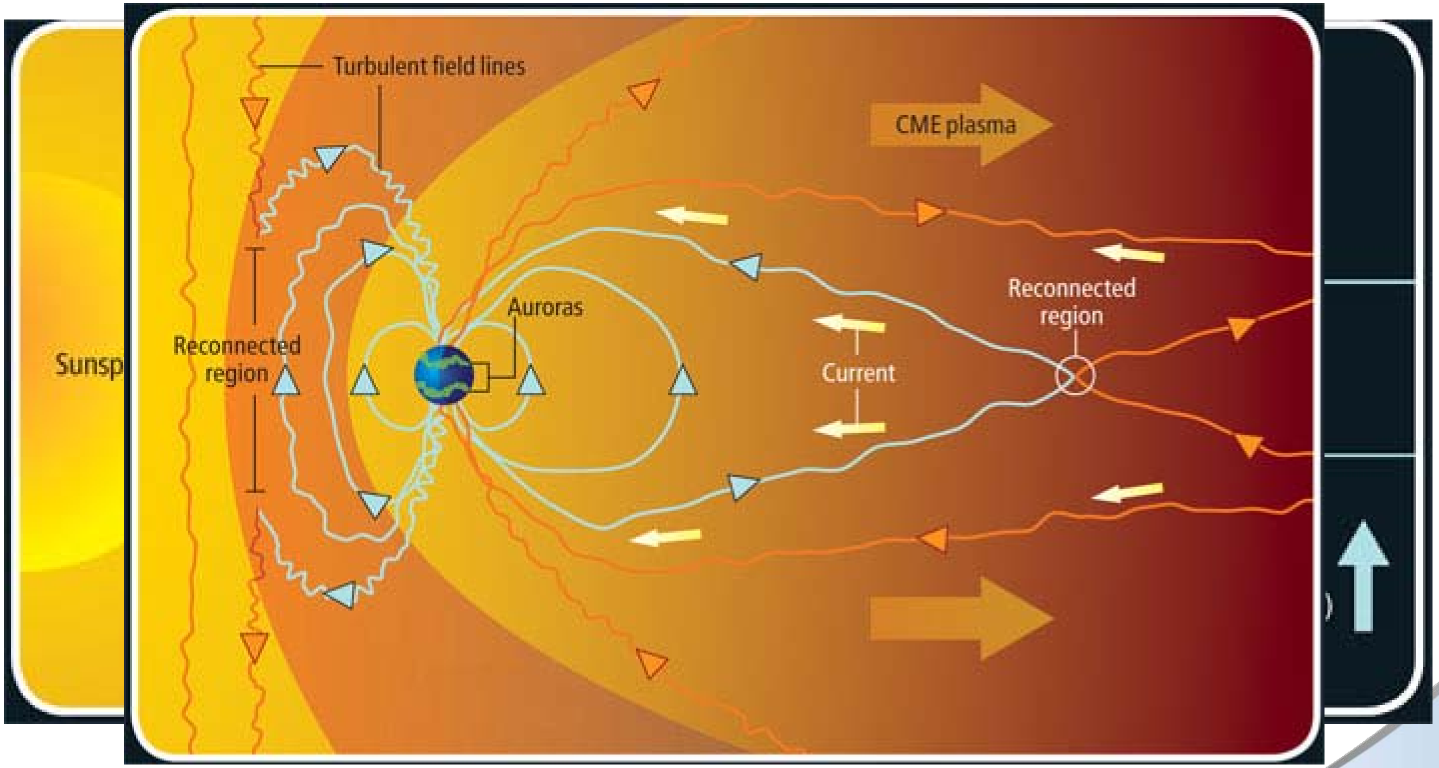


Image: NASA

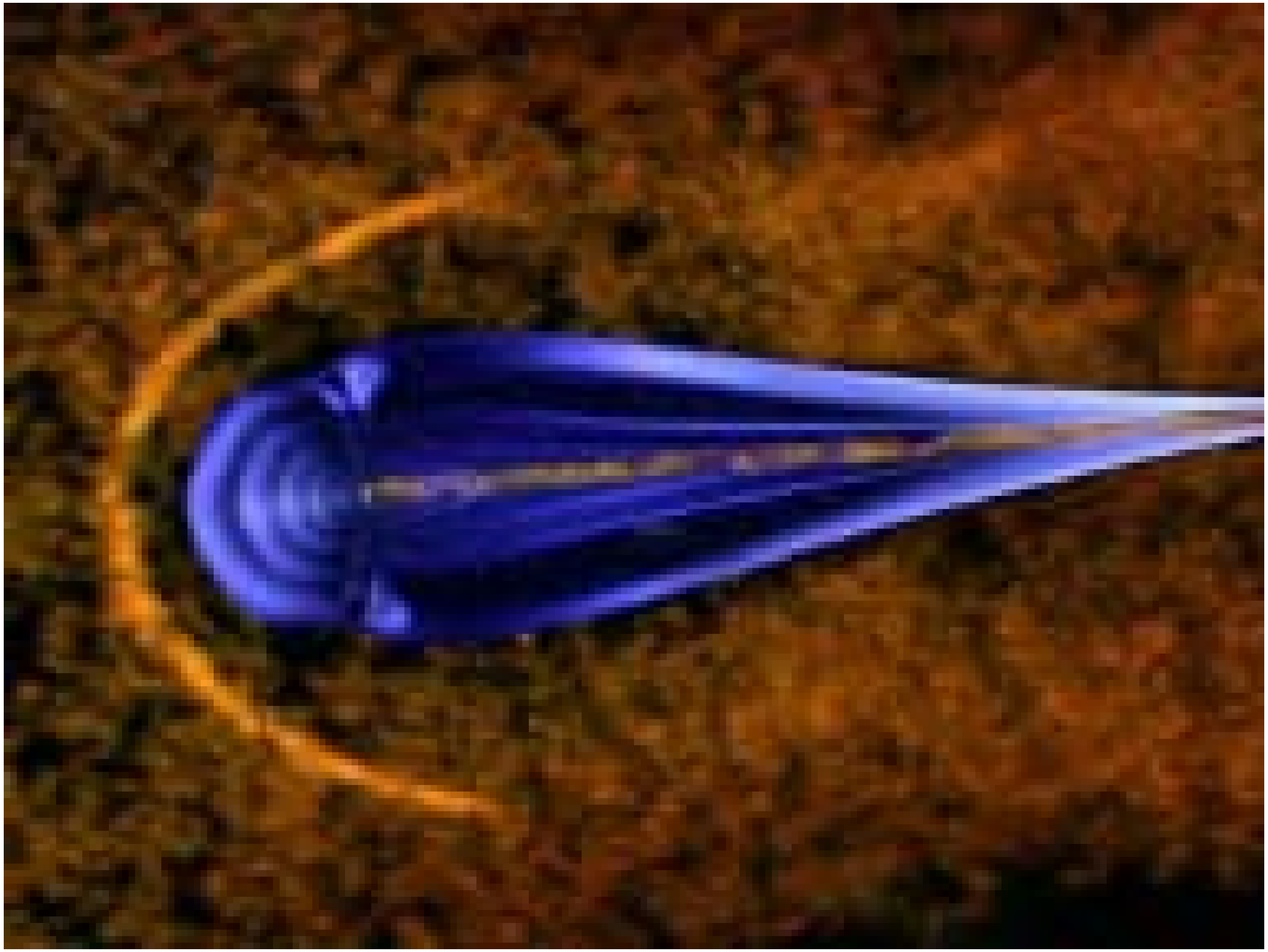
Eruption in space

Effects of CME at Earth

- Large pulse of North or South directed magnetic fields
- Reconnection with Earth's magnetic field
  - Large amounts of energy pumped into the magnetotail and the field aligned currents (FAC)



Charged particles interact with ionosphere

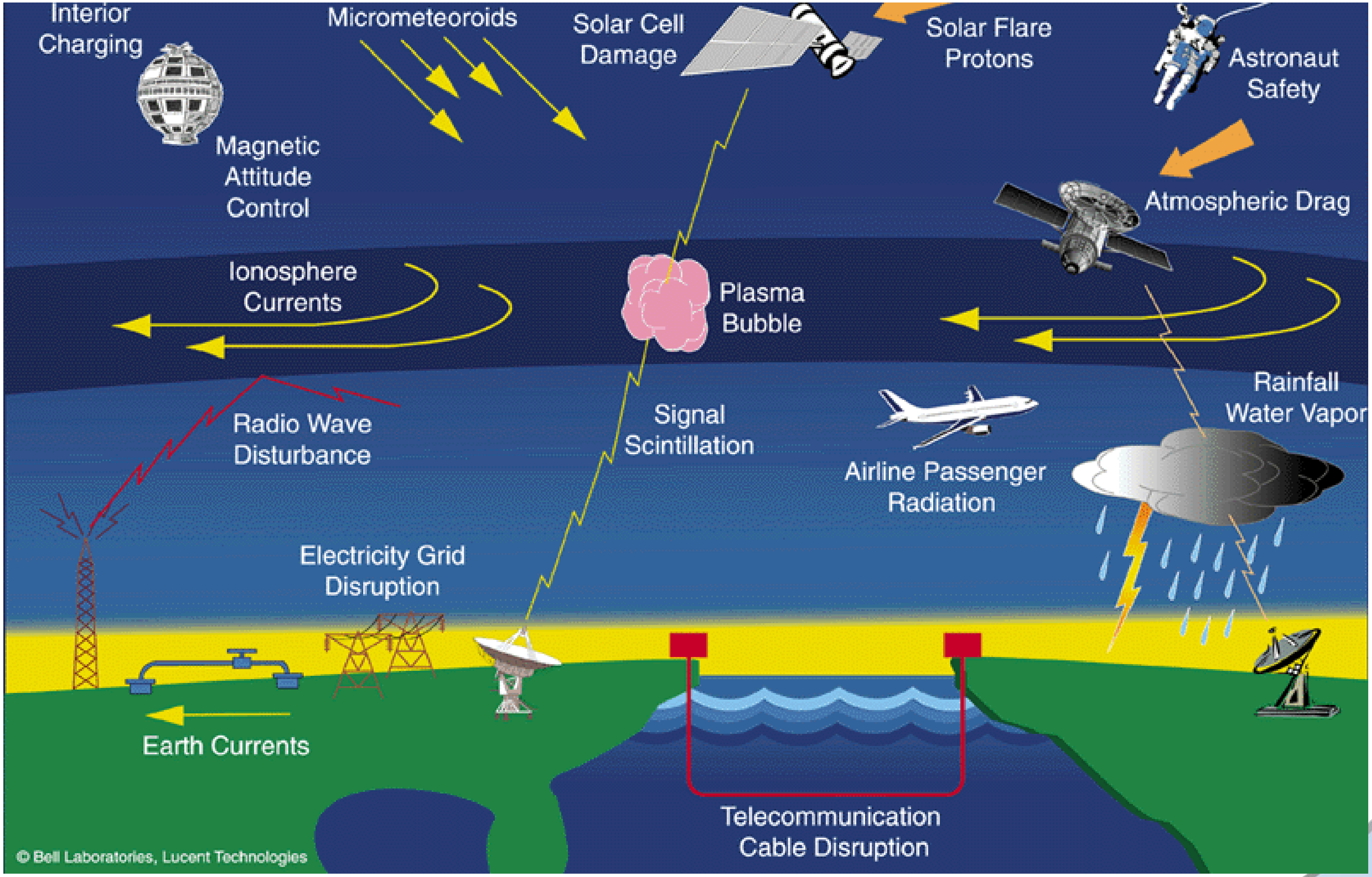


An Aurora over Edinburgh in October 2003

CME impacts

- Increased Total Electron Counts
  - Interferes with ionosphere and affects GPS speed of light travel-time models
- High Energy particles
  - Dangerous to high-altitude aeroplane passengers and crew
  - Space station inhabitants get a large radiation dose
- Atmospheric heating
  - ‘Puffed-up’ atmosphere increases ‘drag’ on low-orbit satellites
- Ionospheric Electrical currents
  - Induced magnetic fields threaten power grids
  - Radio-reflective layers (~100km altitude) are diminished

CME impacts



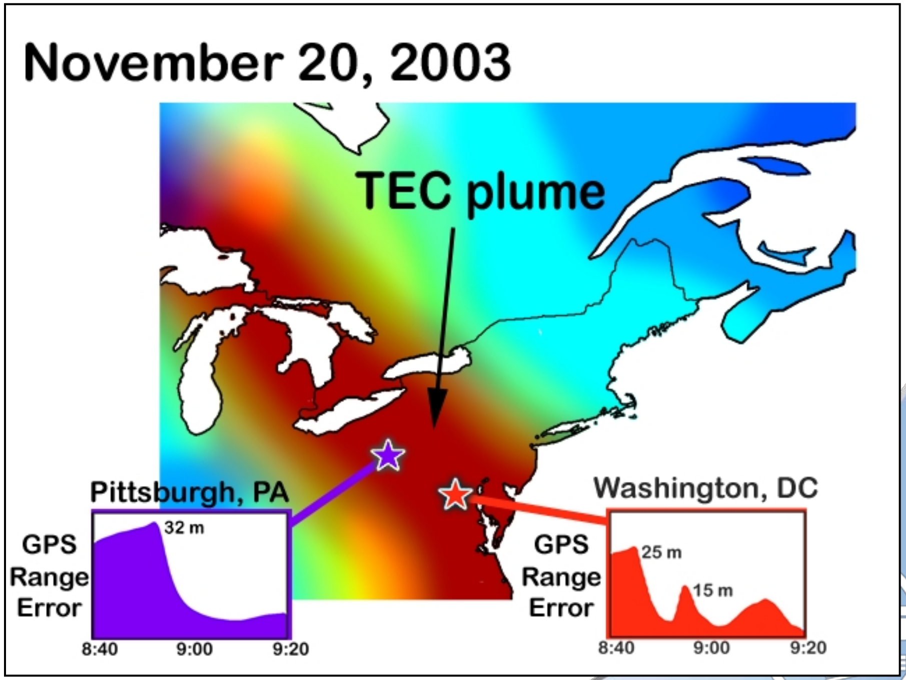
Interior Charging
Micrometeoroids
Solar Cell Damage
Solar Flare Protons
Astronaut Safety
Magnetic Attitude Control
Atmospheric Drag
Ionosphere Currents
Plasma Bubble
Rainfall Water Vapor
Radio Wave Disturbance
Signal Scintillation
Airline Passenger Radiation
Electricity Grid Disruption
Earth Currents
Telecommunication Cable Disruption
© Bell Laboratories, Lucent Technologies

Global Positioning Systems

- Navigation and timing errors increase:
  - Documented up to 90m instantaneous errors
  - Aircraft landing systems rely on GPS (as well as other systems)
  - E.g. Stock market transactions rely on microsecond synchronisation

Error Type	One-Sigma error (meters)	Segment
Ephemeris	2.0	Signal-In-Space
Clock	2.0	Signal-In-Space
Ionosphere	4.0	Atmosphere
Troposphere	0.7	Atmosphere
Multipath	1.4	Receiver
Receiver	0.5	Receiver
RSS Total	**5.17**	

Typical GPS error budget



Satellite electronic failures

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04/20/10 02:05 PM ET

Orbital Blames Galaxy 15 Failure on Solar Storm

By Peter B. de Selding

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PARIS — The in-orbit failure of the Orbital Sciences-built Intelsat Galaxy 15 telecommunications satellite April 5 was likely caused by unusually violent solar activity that week that damaged the spacecraft's ability to communicate with ground controllers, Orbital officials said April 20.

Galaxy 15 satellite. Credit: Orbital Sciences' photo

Enlarge Image

Similar events have occurred, if less severely, on other Orbital spacecraft over the years, and all of these satellites were returned to service. Company officials said they remain confident that once Galaxy 15's commercial traffic has been off-loaded to another Intelsat satellite and full testing of the stricken spacecraft begins, Galaxy 15 will recover its full operational status.

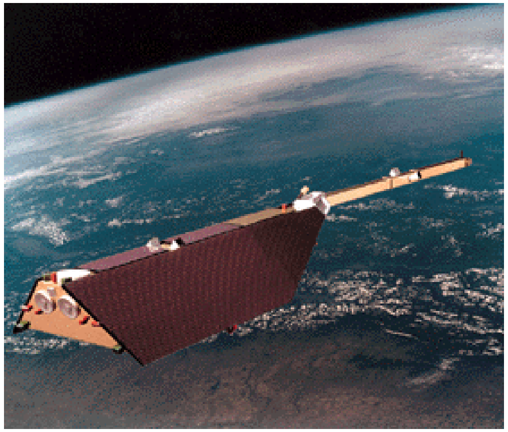
Dulles, Va.-based Orbital, in a conference call with investors, said a series of minor delays in development of the company's new Taurus 2 rocket and its Cygnus space station cargo transporter will push the inaugural Taurus 2/Cygnus launch into May or June 2011 instead of the March date earlier targeted.

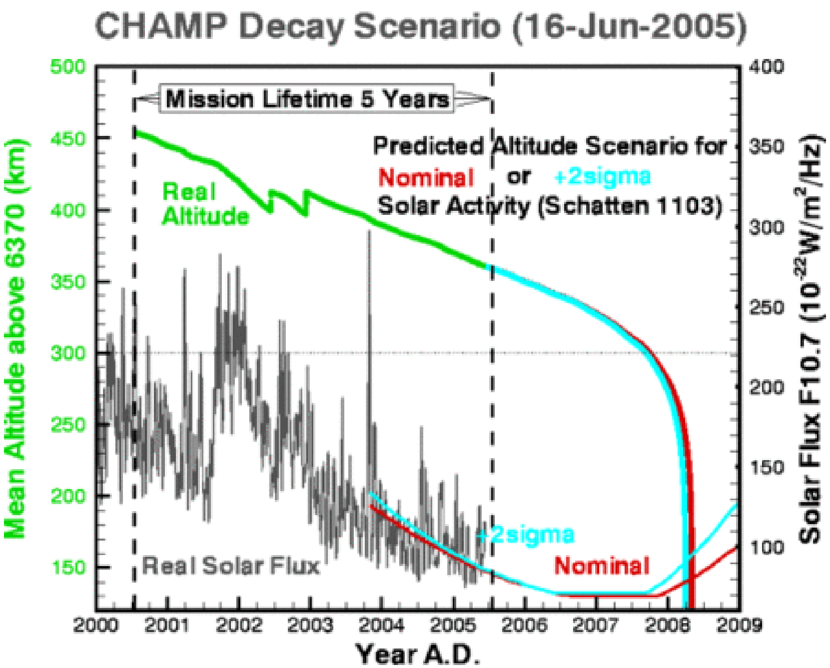
Sites of 'T ... **1000km.**

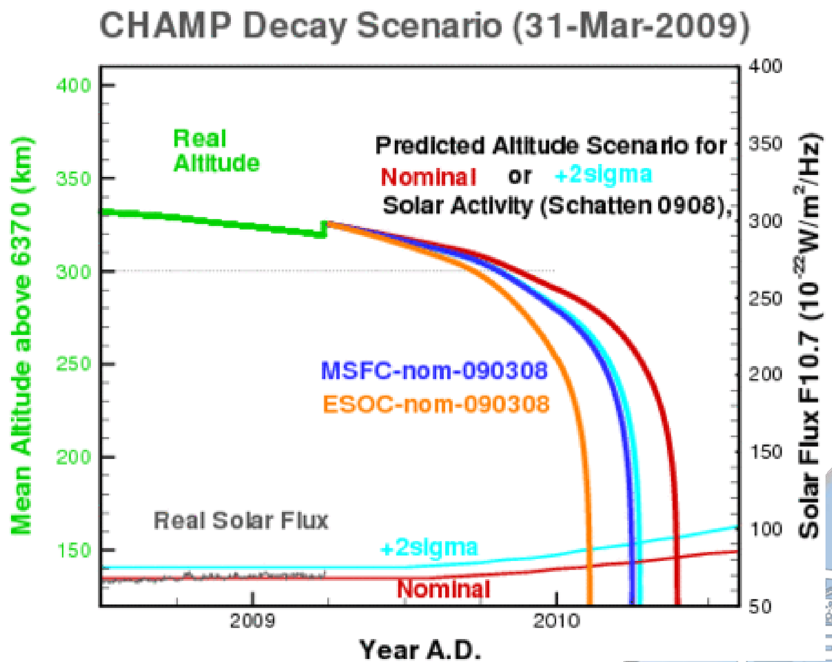
Red star is site of MODIS satellite failure.

Satellite atmospheric drag

- Satellites remain in orbit for longer
  - Upper atmosphere contracts
    during quiet period of the solar cycle







Human Health

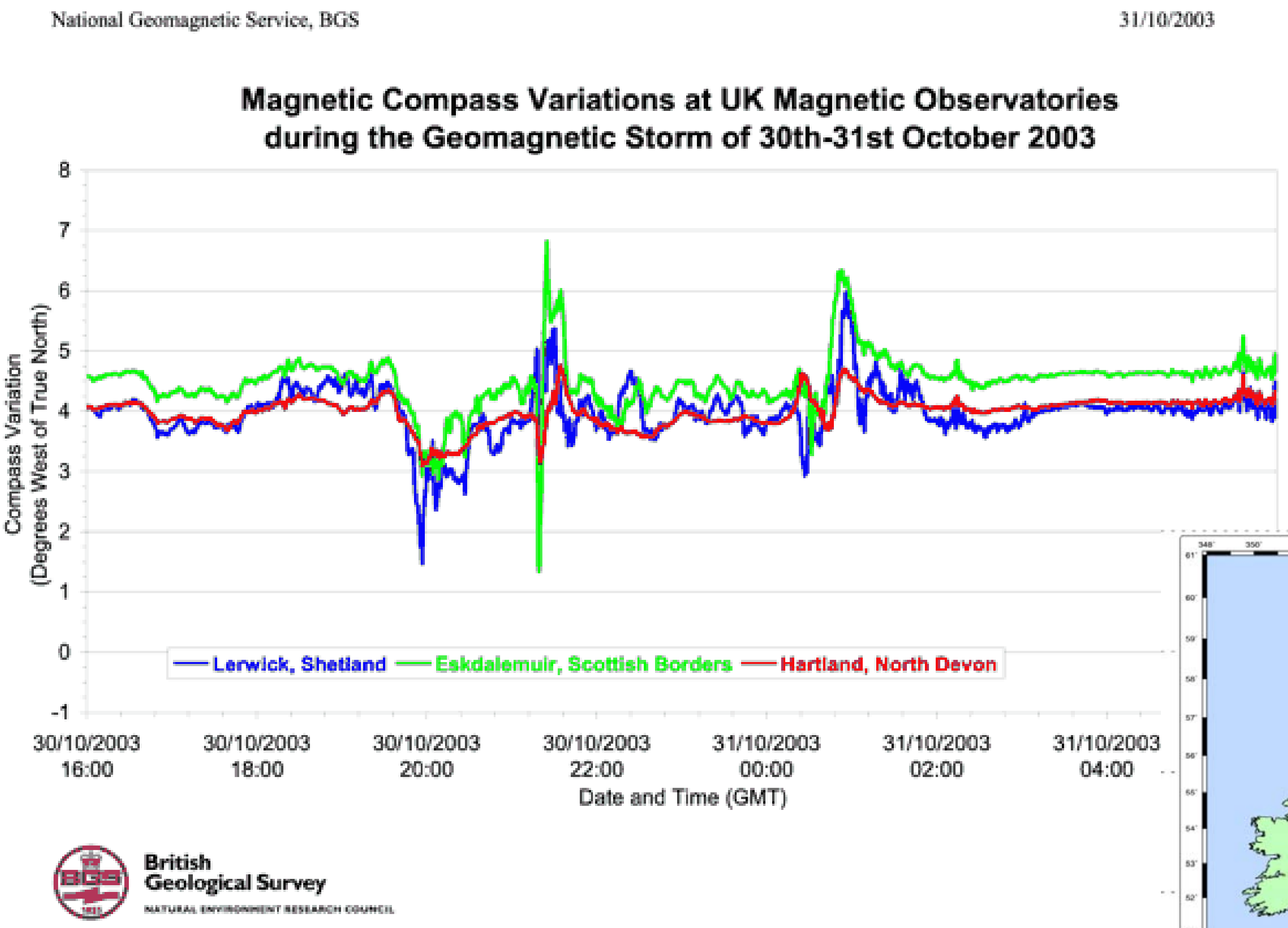
- Increased radiation doses on long-haul flights
  - Re-route aircraft around the poles?
- Astronauts exposed to high-energy particles on space missions
- Links to mental health admissions and other traumas (heart attack)
  - Much studied by Russian scientists
  - Possible link to Schumann resonance (i.e. frequency of lightning radiation)

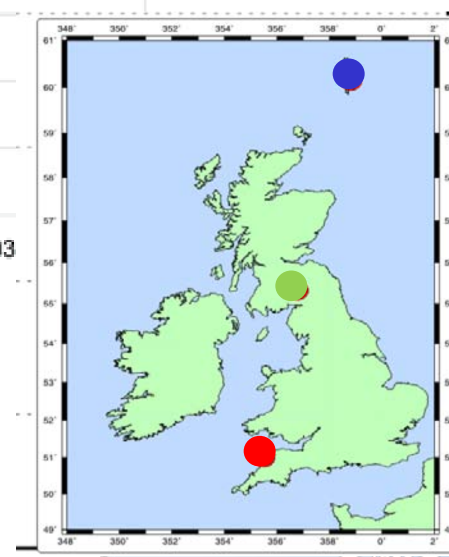
New York - Beijing

Sydney – Rio de Janeiro

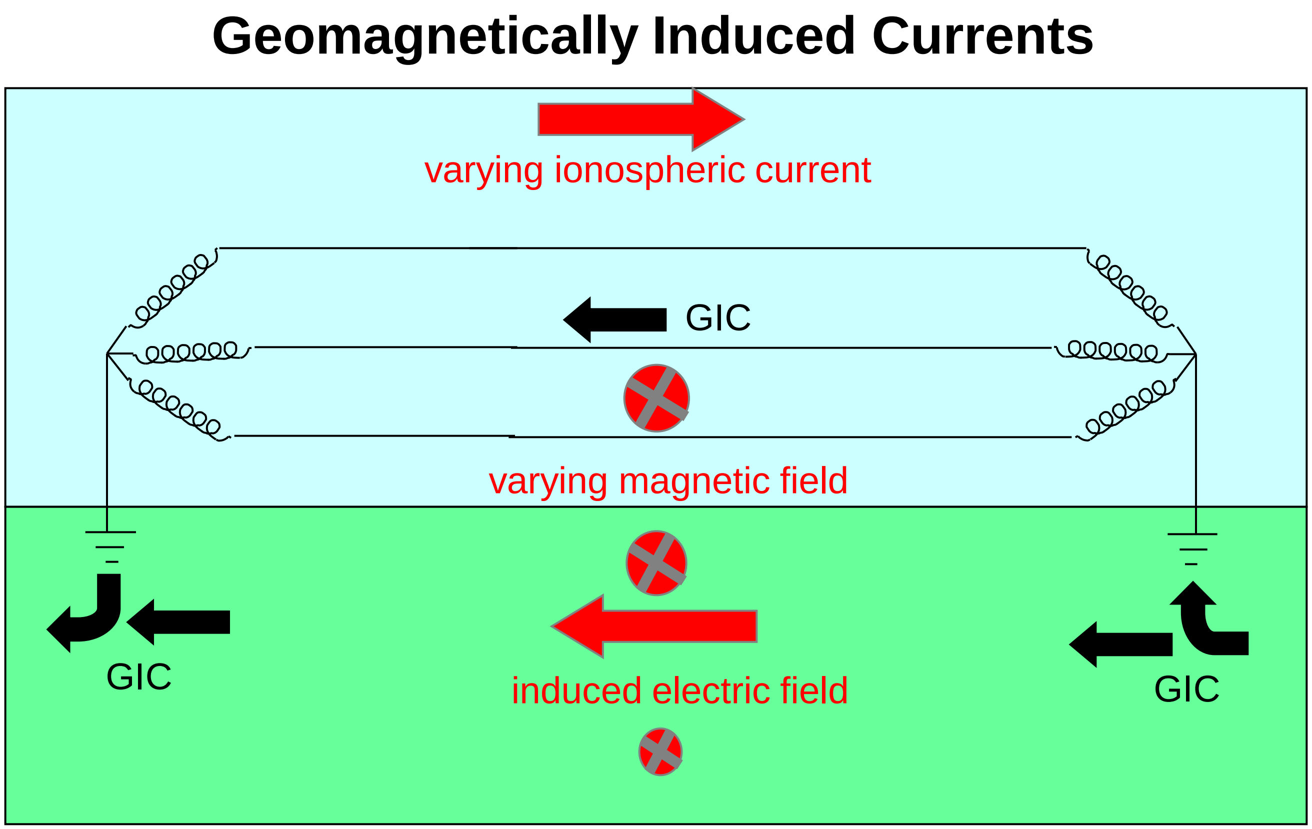
From http://www.gcmap.com/

Magnetic Field Variations





Geomagnetically Induced currents



GIC appear as near-DC currents which can saturate transformers, leading to harmonic generation, overheating, increased reactive power demand, and/or drop in system voltage.

Threat to electrical power grids

- High-latitude power grids are vulnerable to Ground Induced Currents (GIC) during geomagnetic storms

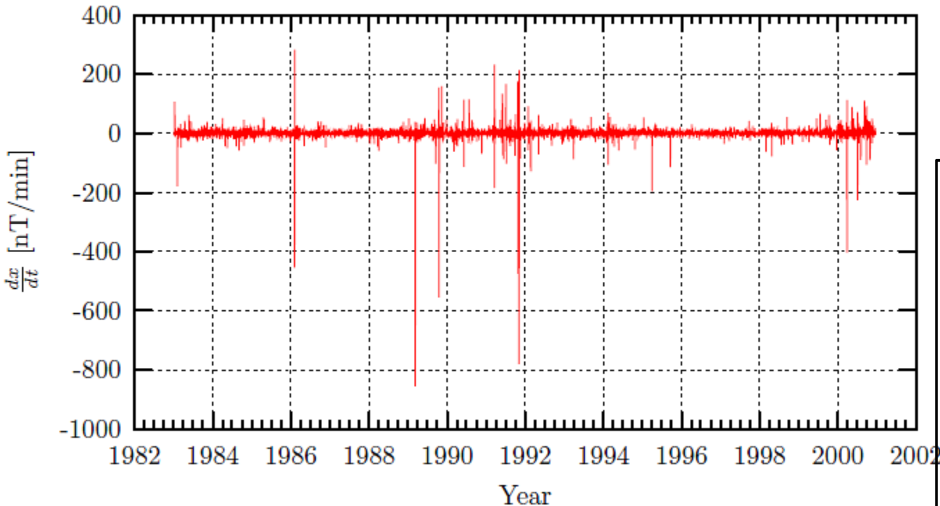
- Canada, USA, Sweden, South Africa, UK and Brazil have all suffered
  - damage to transformers and/or
  - power cuts due to geomagnetic storms

Damage in South African transformer

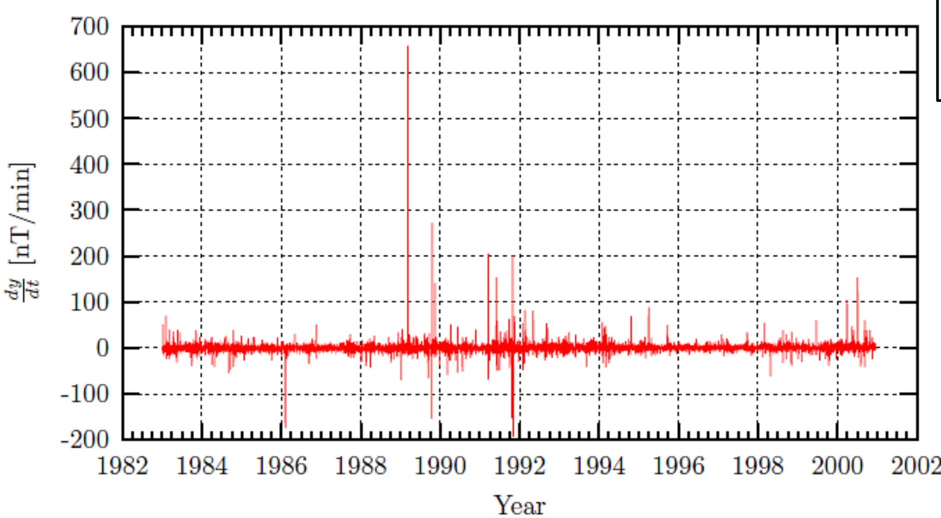
Northern Lights in Malmo, Sweden

UK Worst Cases?

Maximum dB/dt in Digital Age: 1983-2011



Eskdalemuir observatory data



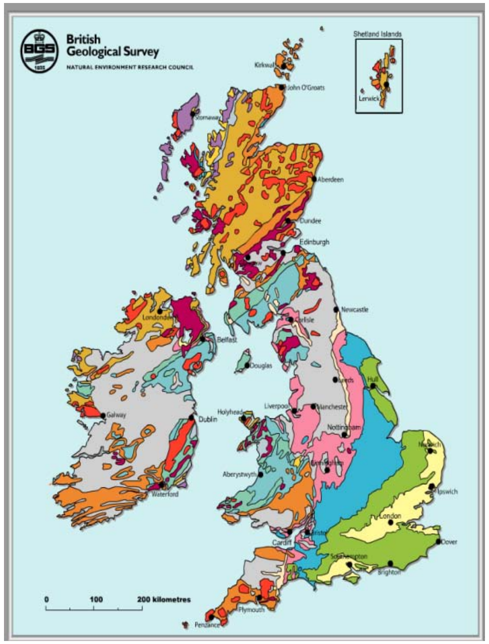
Top 6 Events Since 1983

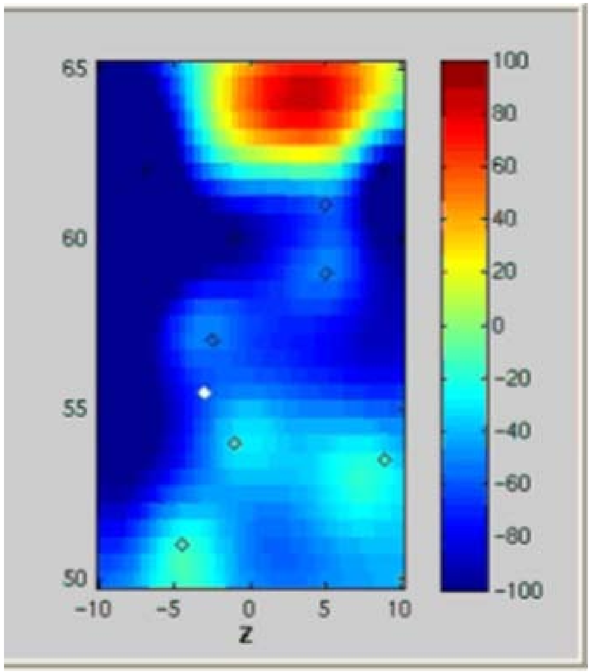
d*H*/dt	Date+Time	Date	GIC
1262 nT/min	**1991.8545890**	**8 Nov 1991**	**?**
934 nT/min	1989.1970015	13 Mar 1989	?
729 nT/min	1989.8048440	21 Oct 1989	?
628 nT/min	**2003.8298326**	**30 Oct 2003**	**42A**
500 nT/min	1991.8351846	1 Nov 1991	?
464 nT/min	1986.1033143	7 Feb 1986	?

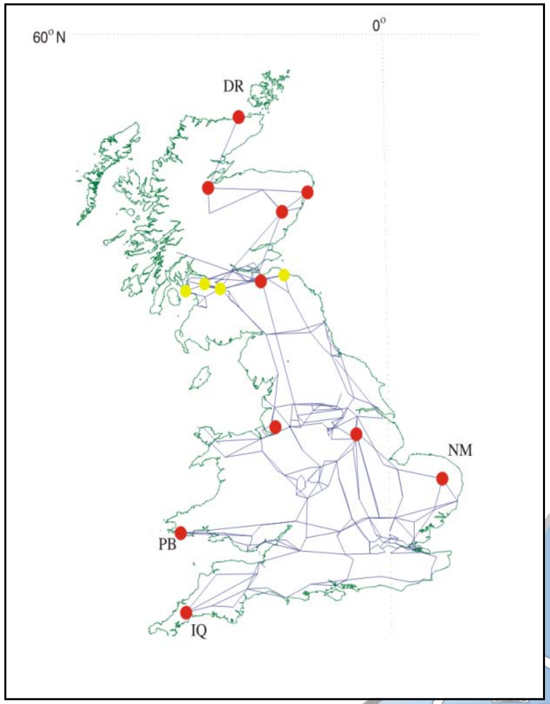
Events 1-3 were described as ‘causing problems’ by industry

Model and Predict?

- Three ‘ingredients’ required:
  - Geology and ground electrical conductivity
  - Ionospheric electrical currents from magnetic observatories
  - Model of the UK high-voltage grid connections and transformers

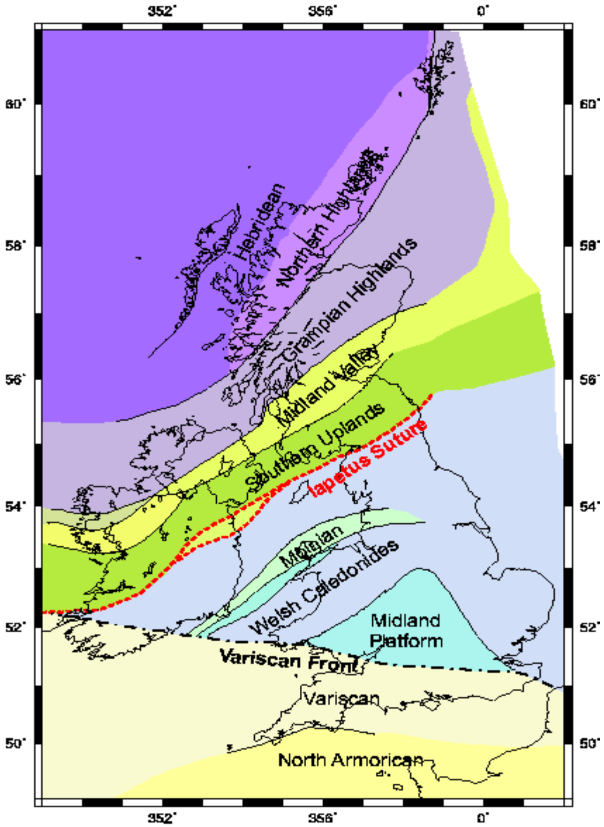


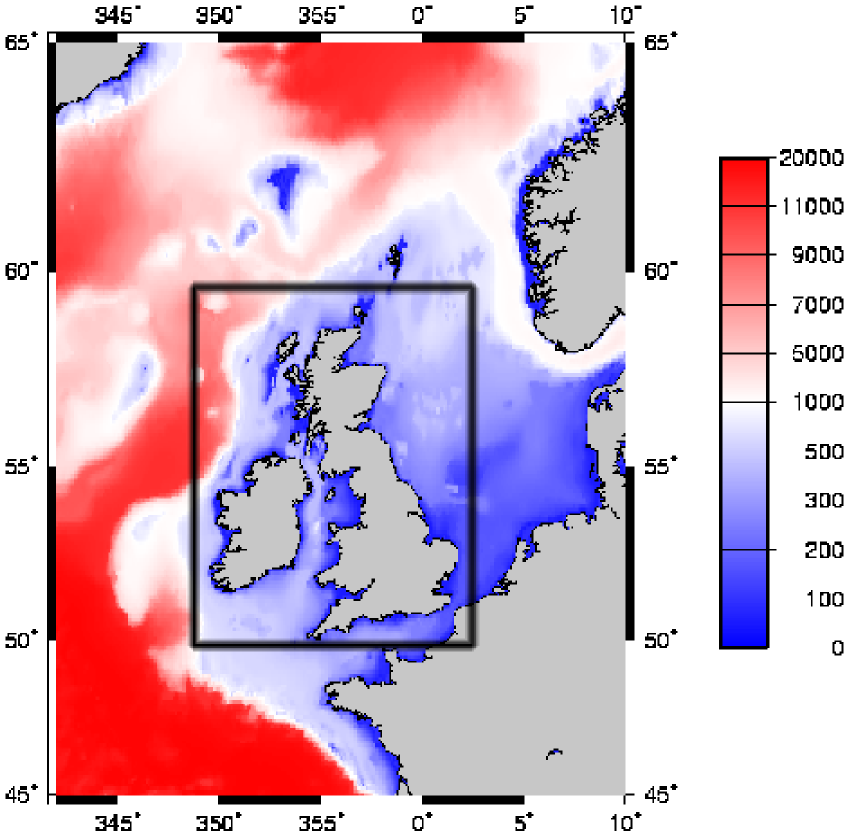




UK High-Voltage Network

Electric Field modelling





‘Thin Sheet’ Model

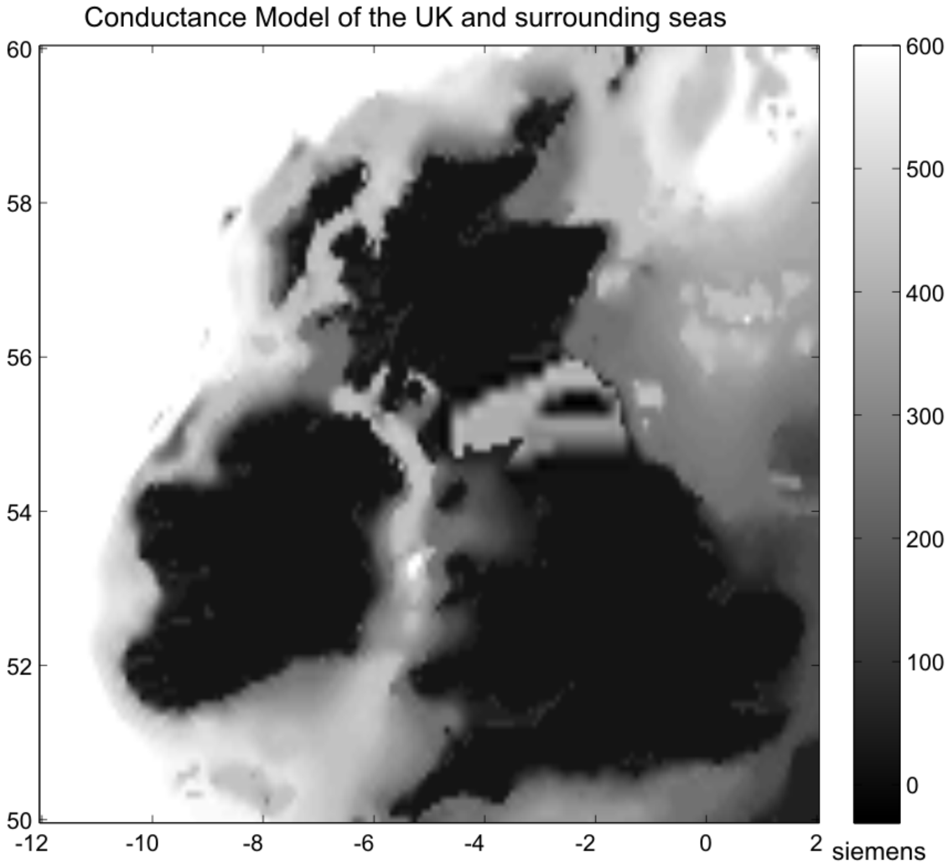
- appropriate for ‘low frequency’ GIC range of 100-1000s

- Horizontal field only required & Non-uniform source fields can be used

- Includes shelf seas & bathymetry

Resistive geology

- Resistive rocks make induced currents more likely to flow through ‘easy’ conduits
- Land-Sea coastal interaction generates largest voltage potential differences



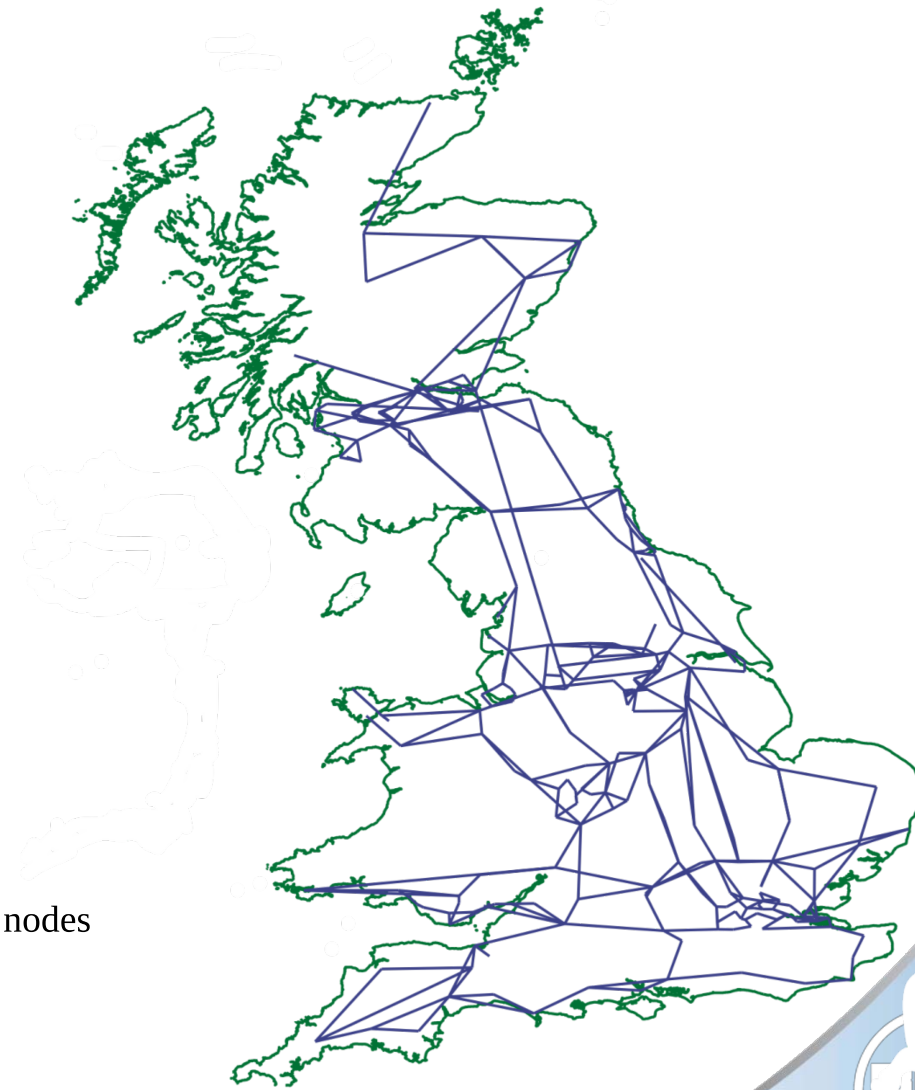
Simple model of 400 & 275kV networks

- Model of the National Grid SYS 2008 grid
  - 252 lines; 379 connections
  - Simple earthing resistances (0.1Ω) and transformer resistances (0.5Ω) used
  - Line resistance calculated through integration
- GIC: $I = (1+Y.Z)^{-1} \cdot J$

network admittance matrix

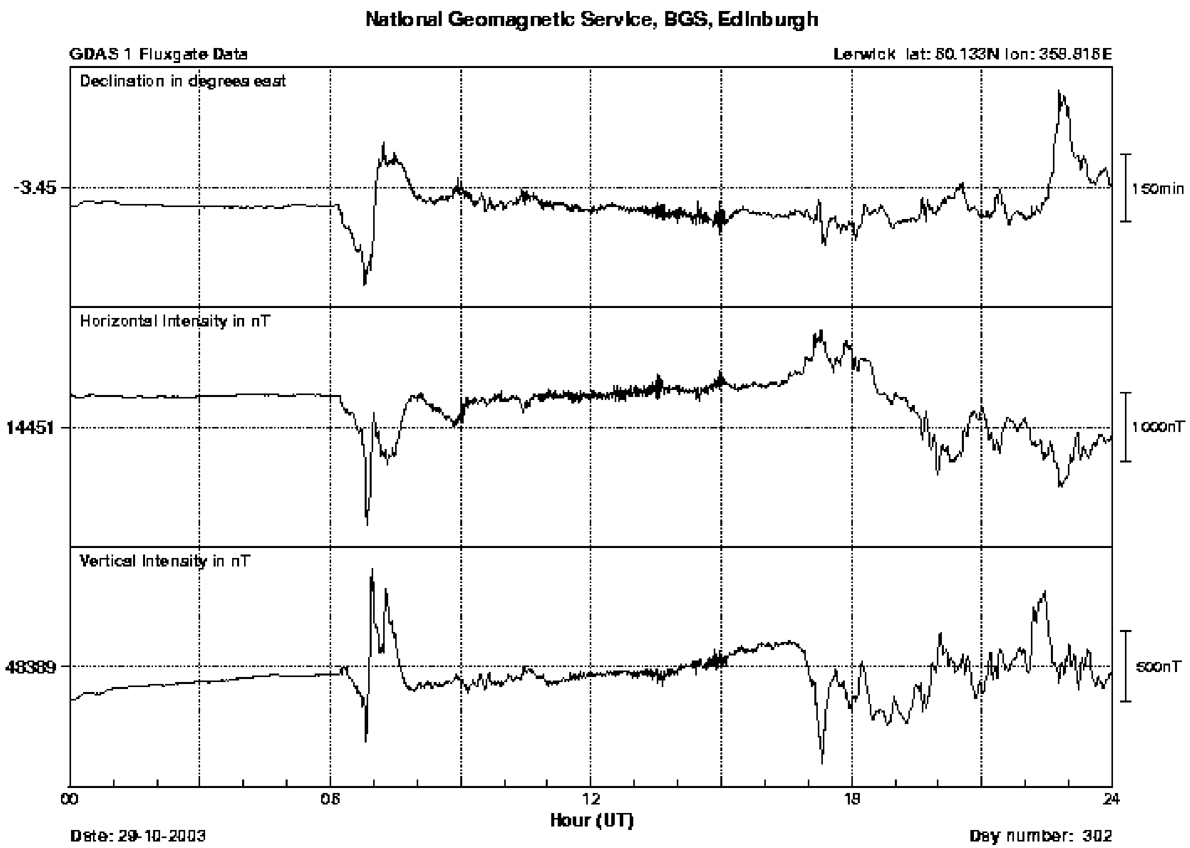
impedance matrix

geo-voltage between nodes



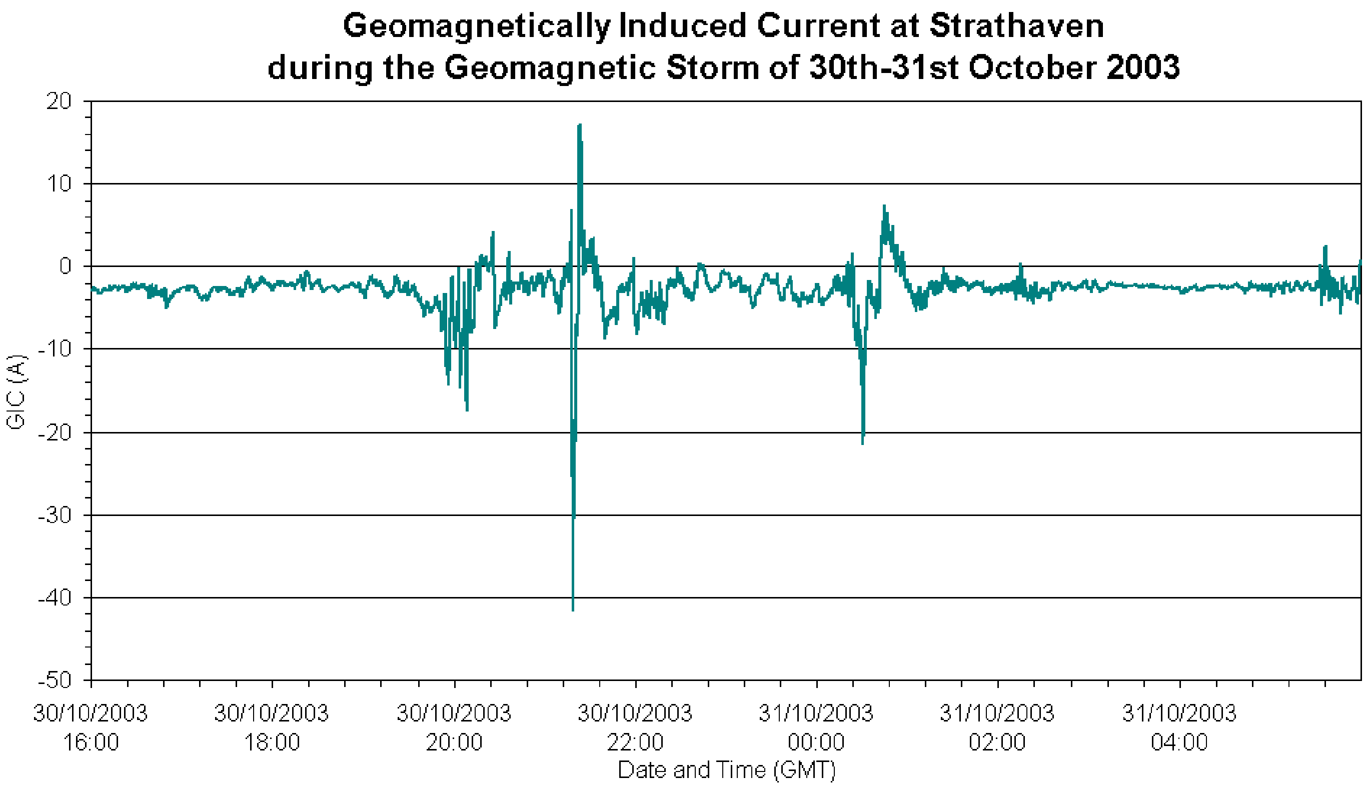
Geomagnetic Storm: Halloween 2003

- CME on the 28th October 2003
- Largest storm in ~20 years
- 6 degree compass swing at ESK in 5 minutes; 42A GIC in Scotland

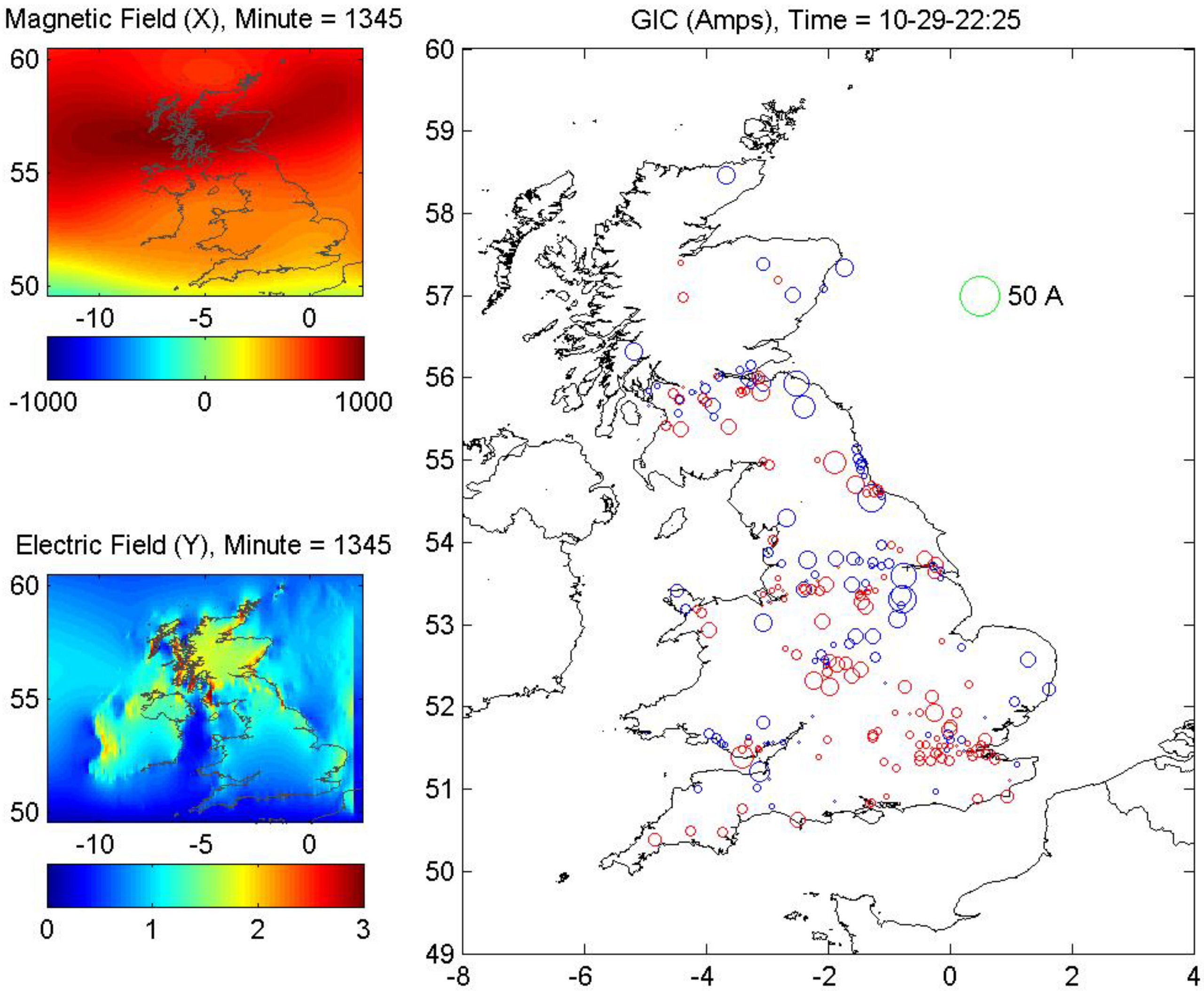


Measured GIC

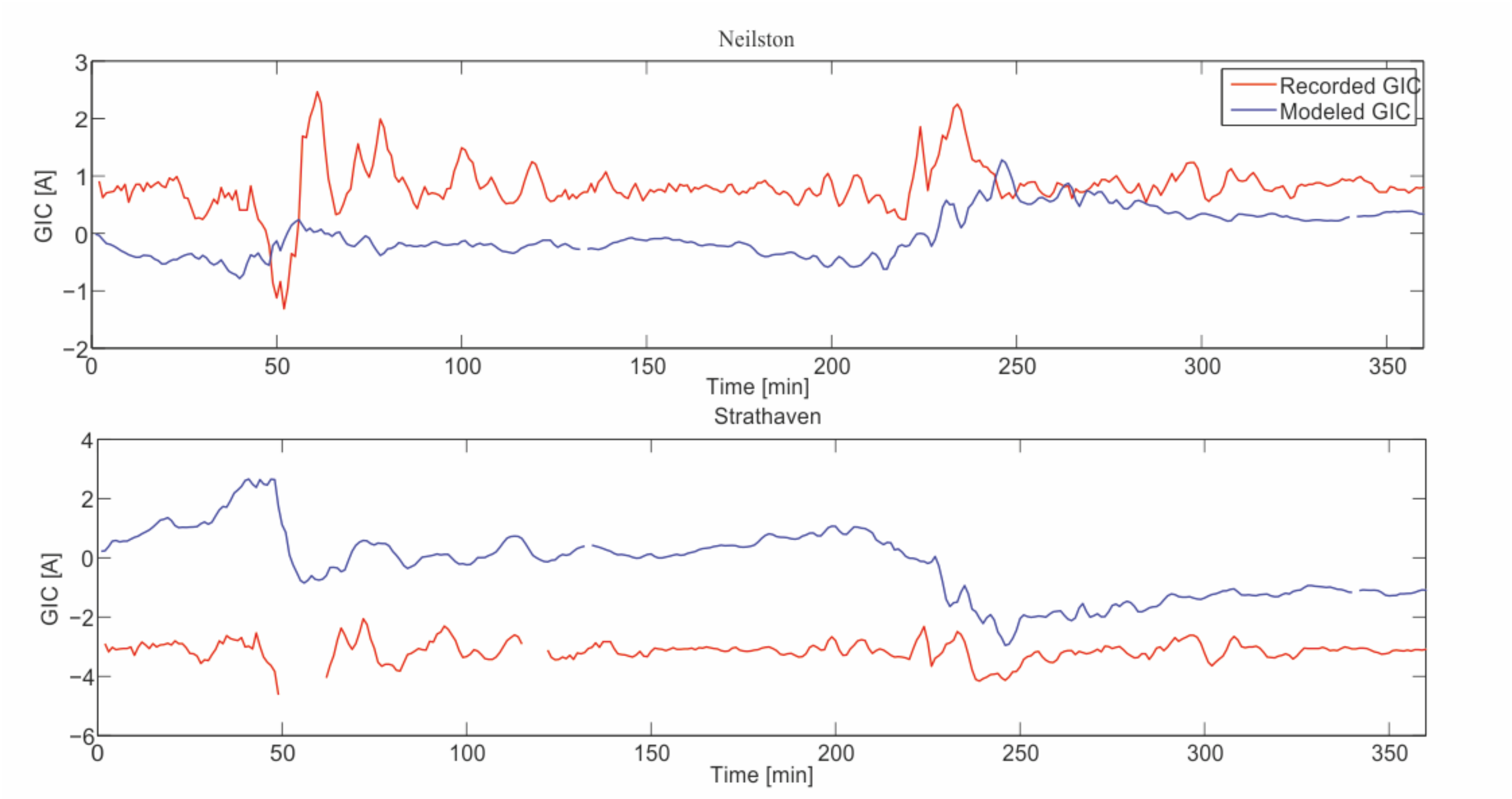
- GIC monitored at 4 power stations in Scotland
- Large spikes in measured GIC during the 3 day storm



Post-match analysis



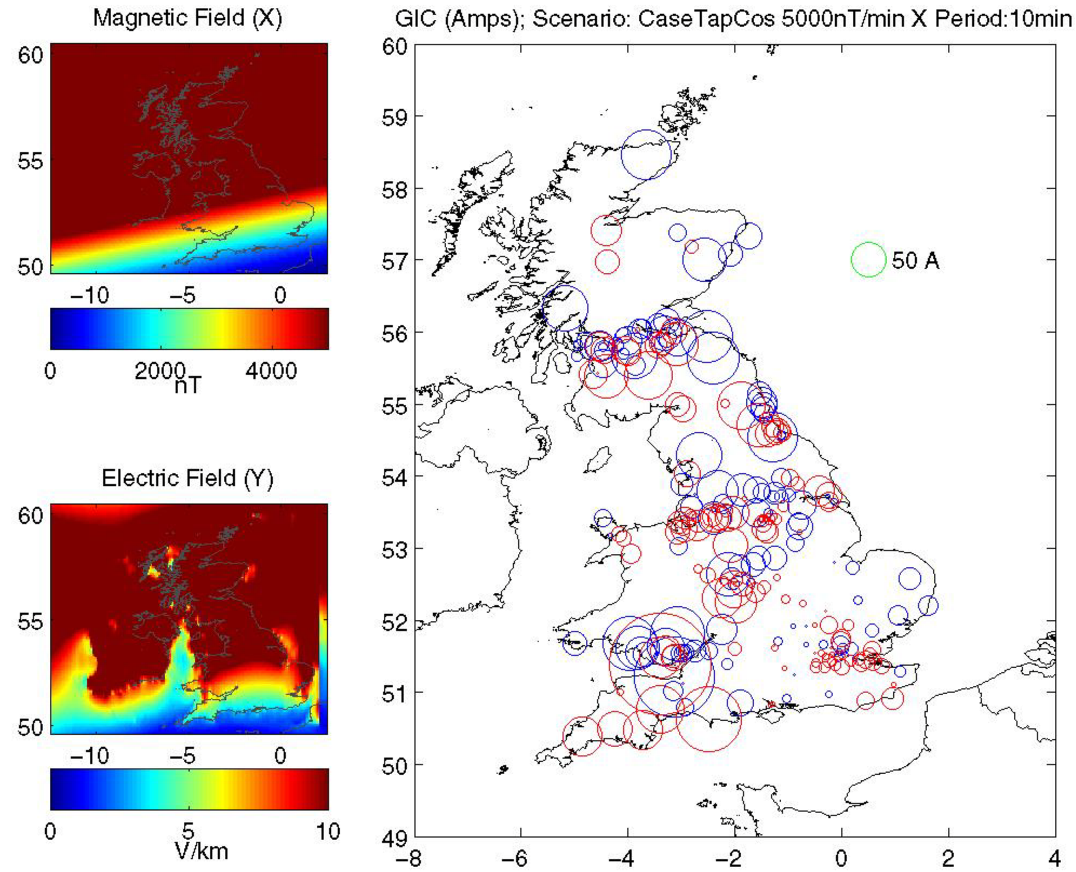
GIC modelling versus measurements



- Modelling GIC: we are improving – not quite there yet!

Extreme Scenarios?

- What are the largest magnetic fields that can be expected?
- What are the largest GIC possible?
- Research is on-going ...



What Experience Has Taught Us:
Major Knowns in GIC Research

- **Science**
  - Solar storms that cause high GICs are statistically more likely during periods close to solar maximum and in the descending phase of the solar cycle, but they do also occur at all other times in the solar activity cycle
  - GICs are larger in countries and regions where the geology is generally more resistive and a multi-layered and laterally varying ground conductivity model gives better prediction of GICs, than the simpler assumption of an homogeneous Earth
  - The magnetospheric and ionospheric currents that drive GICs are different at different latitudes and the dominant cause of GICs in power grids is the time rate of change of the Earth's magnetic field

- **Industry**
  - GICs have been shown to affect power systems at all latitudes and can affect many power transformers simultaneously at multiple points across regional and continental scale networks.
  - Series capacitors in transmission lines may interrupt GIC flow, but are expensive. However some strategies involving capacitors may increase GIC and reactive power demands.
  - Transformer dissolved gas analysis identifies GIC-initiated damage before complete transformer failure occurs. This is especially true if the rate of gassing simultaneously increases in widely separated transformers across a network

Summarised from Thomson *et al*, Advances in Space Research, 45 (2010),1182–1190

What Experience Has Taught Us:
Major Unknowns driving Research Requirements

- **Science**
  - What are the solar and interplanetary events and signatures that are most 'geo-effective'?
    - Event magnitude, duration, location, onset time
  - What are the characteristics of extreme geomagnetic storms that pose the highest risk to power systems?
    - Better geophysical modeling and prediction of ground and ionosphere currents & fields
    - Spatial and temporal scales
  - What is an adequate distribution of magnetometers for GIC modeling in any country?

- **Industry**
  - Which information (e.g. monitoring & forecasts), given on what timescale, is most useful in managing GIC risk?
  - What are the characteristics of power transformers that determine susceptibility to GICs and therefore determine the damage sustained under different levels of GICs?
  - What are the transformer failure mechanisms initiated by GICs?

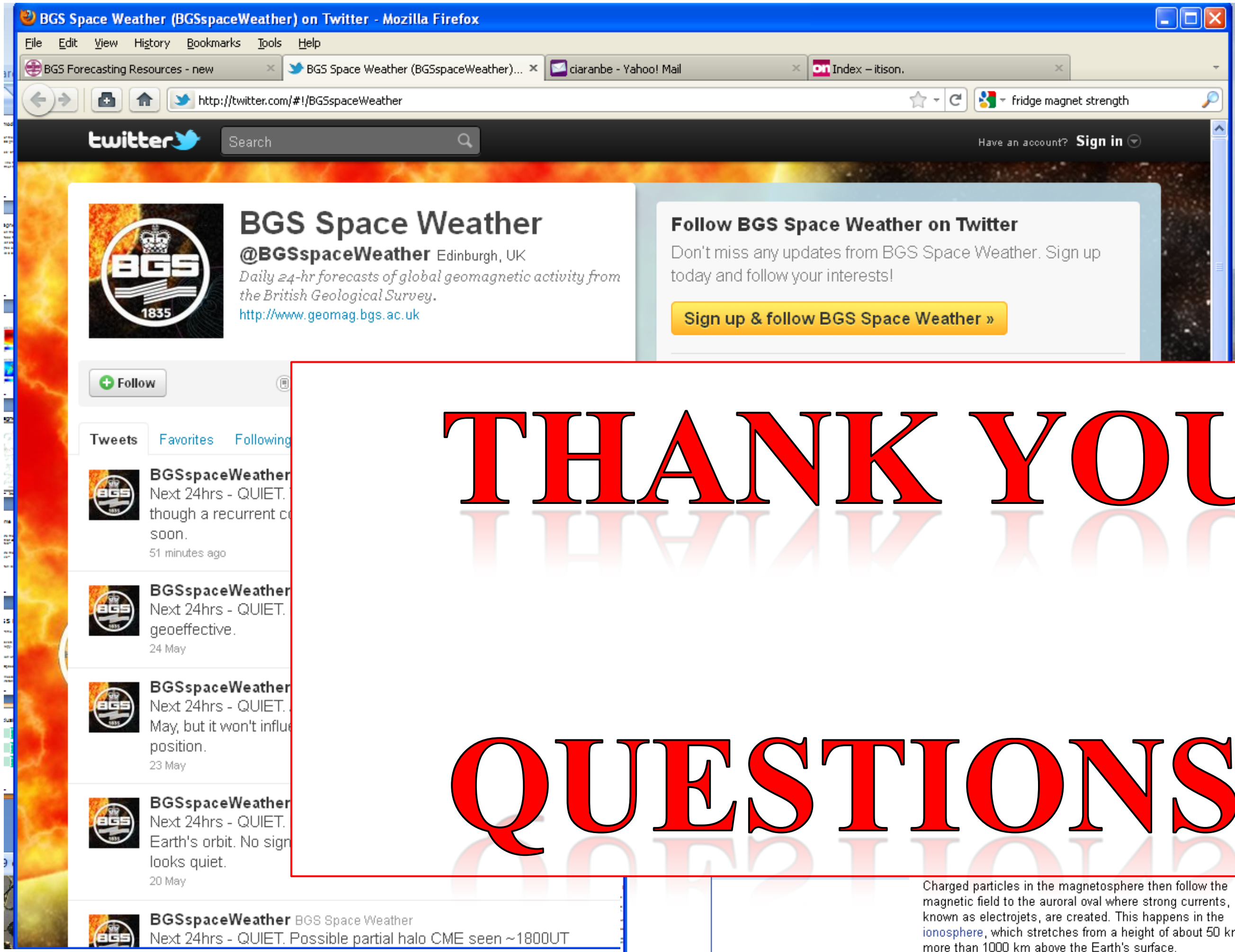
Summarised from Thomson *et al*, Advances in Space Research, 45 (2010),1182–1190

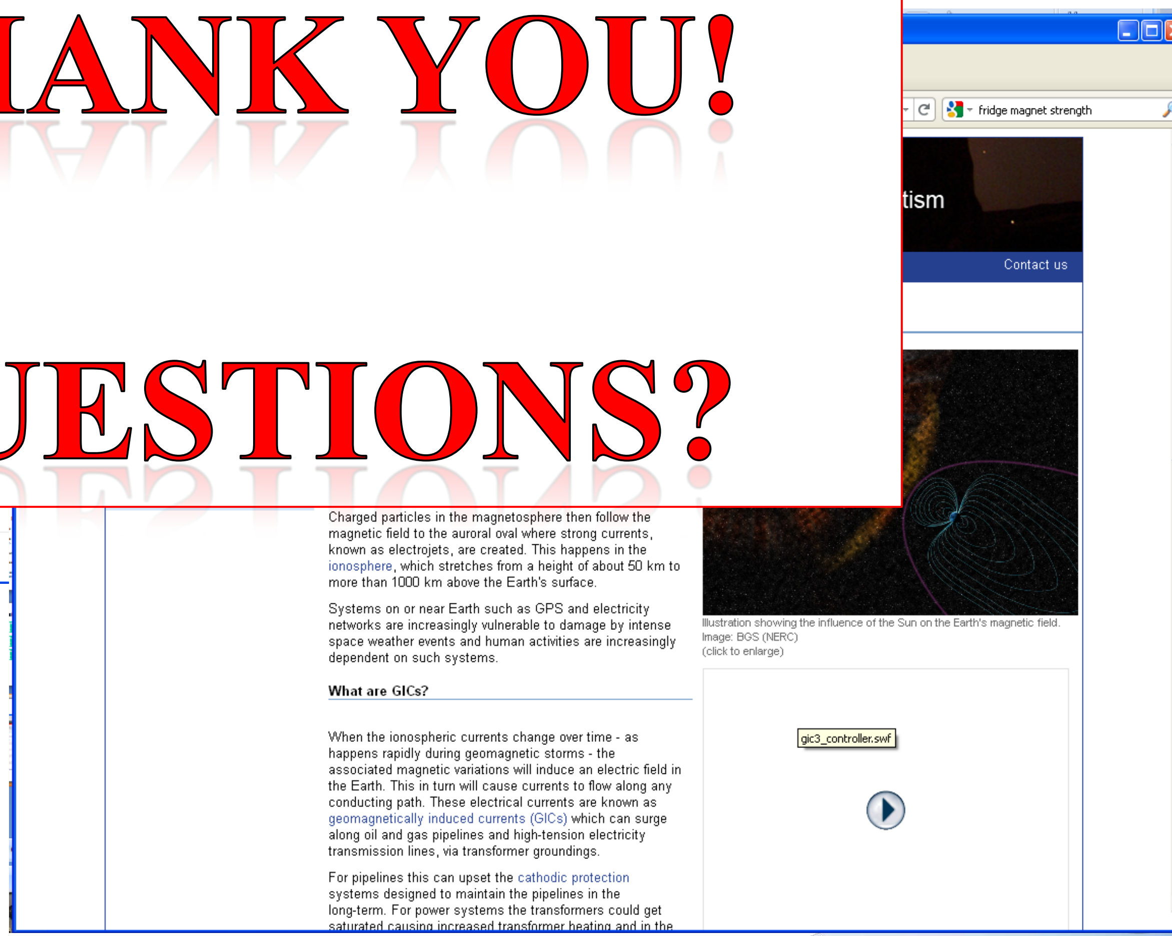
Inputs to GIC monitoring

- Real-time monitoring from UK magnetic observatories
- Improved understanding of GIC through basic research (geology, conductivity)
- Liaison with industry and government
- BGS Space Weather website for monitoring and forecasting

Outcomes

- Enhanced awareness of incoming events
- Preparation for impacts
- Effective preventative actions available
- Cost-benefit analyses from potential extreme scenarios





THANK YOU!

QUESTIONS?

Find out more at:

www.geomag.bgs.ac.uk