The future of Geomagnetic Earth Observations

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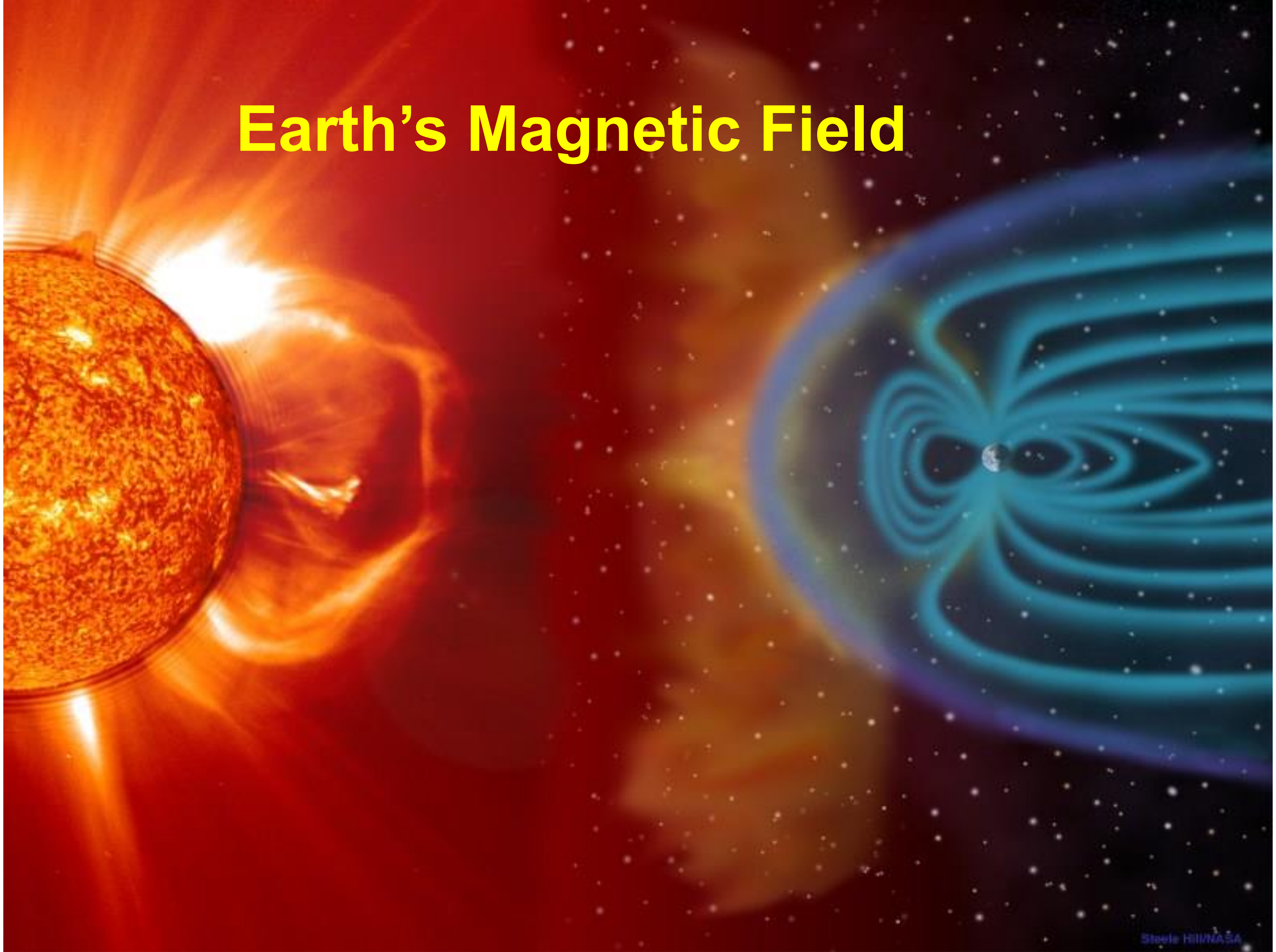
Outline

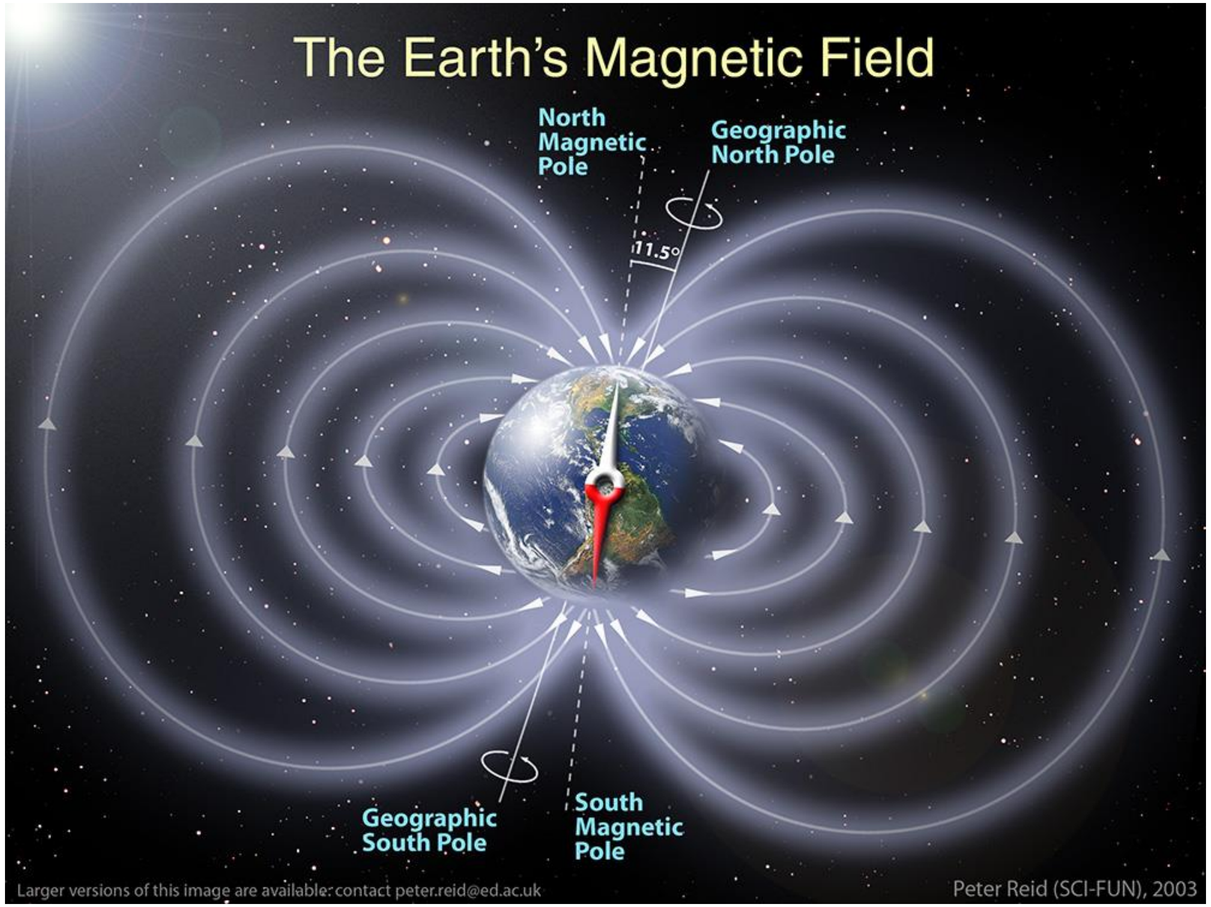
- Field basics
- Field sources
  - External
  - Core
  - Lithosphere
  - Induced
- Observations
  - Ground, air and space
- Data analysis and modelling – would be the next step
- Challenge I – Core dynamics and the Geodynamo
- Challenge II – Space weather (and even space climate)
- IAGA

Earth’s Magnetic Field



Earth's Magnetic Field

- To first approximation, the Earth has a simple, largely **dipolar** (bar magnet-like), approximately N-S, magnetic field
- The field lines form Earth's **magnetosphere**, which deflects, slows and traps highly-damaging charged particles of the solar wind
- This long-term protection allowed **life** to develop



Field Sources

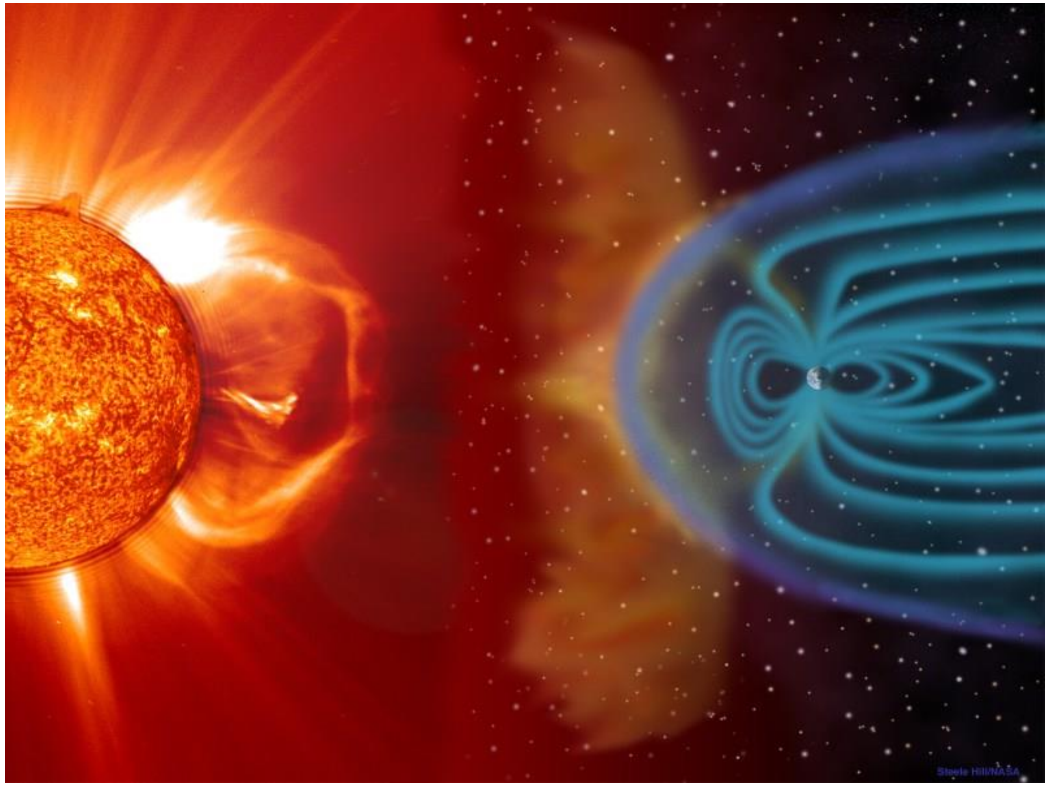
The External Field

The Core Field

The Lithospheric Field

(The Core Field and The Lithospheric Field: **Internal field**)

Induced in lithosphere and mantle



1. The External Field

Inter-planetary magnetic field (IMF)

Sun's magnetic field dominates in the solar system

Periodicity of 11 years (**solar cycle**)

Solar wind - streams from the sun (350-500 km s^{-1})

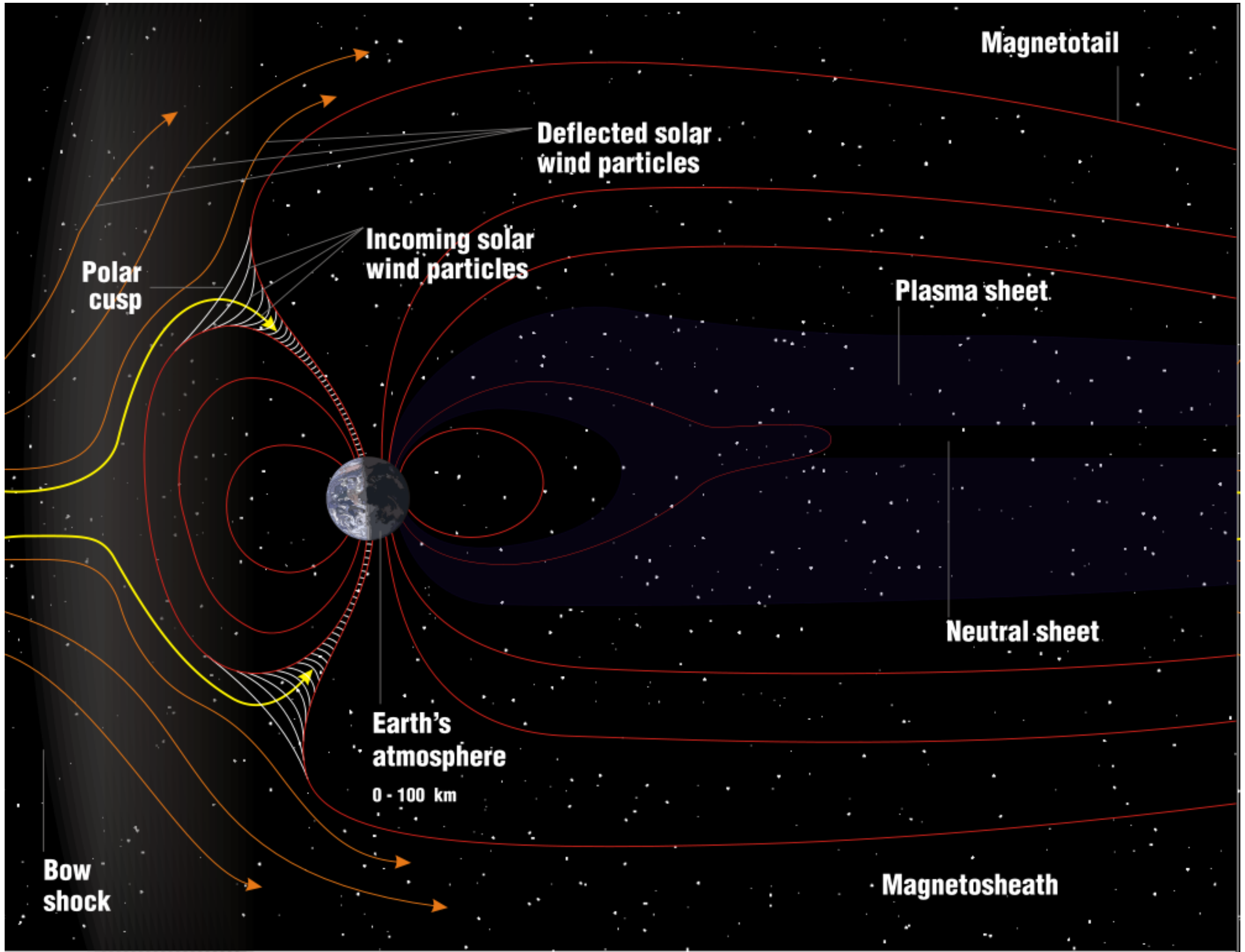
- will not normally penetrate Earth's magnetosphere
- interacts strongly with magnetosphere when strong
- produces aurorae and induces geomagnetic storms – **space 'weather'**

Earth's Magnetosphere

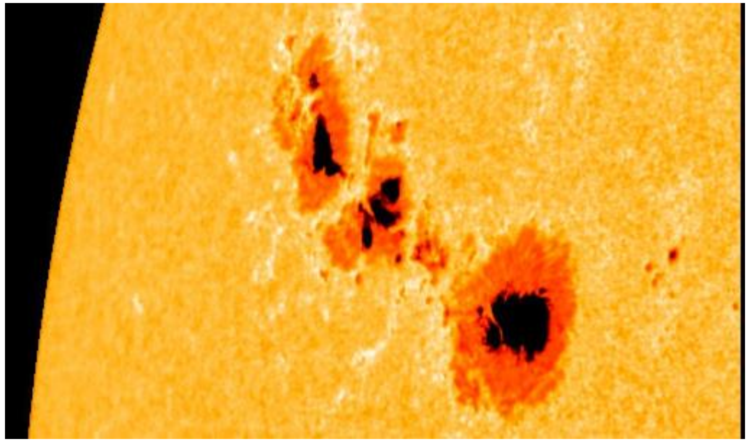
The **solar wind** distorts the dipolar field by compressing field lines facing the Sun, and forming a **magnetotail** away from it

The magnetosphere extends 60,000km to, and ~ 300,000km away from, the Sun

Most charged particles (ions) are deflected, but some make it through the **polar cusp** to the ionosphere at the poles (yellow arrows), forming the **aurorae**



A recent example: Sunspot 1302

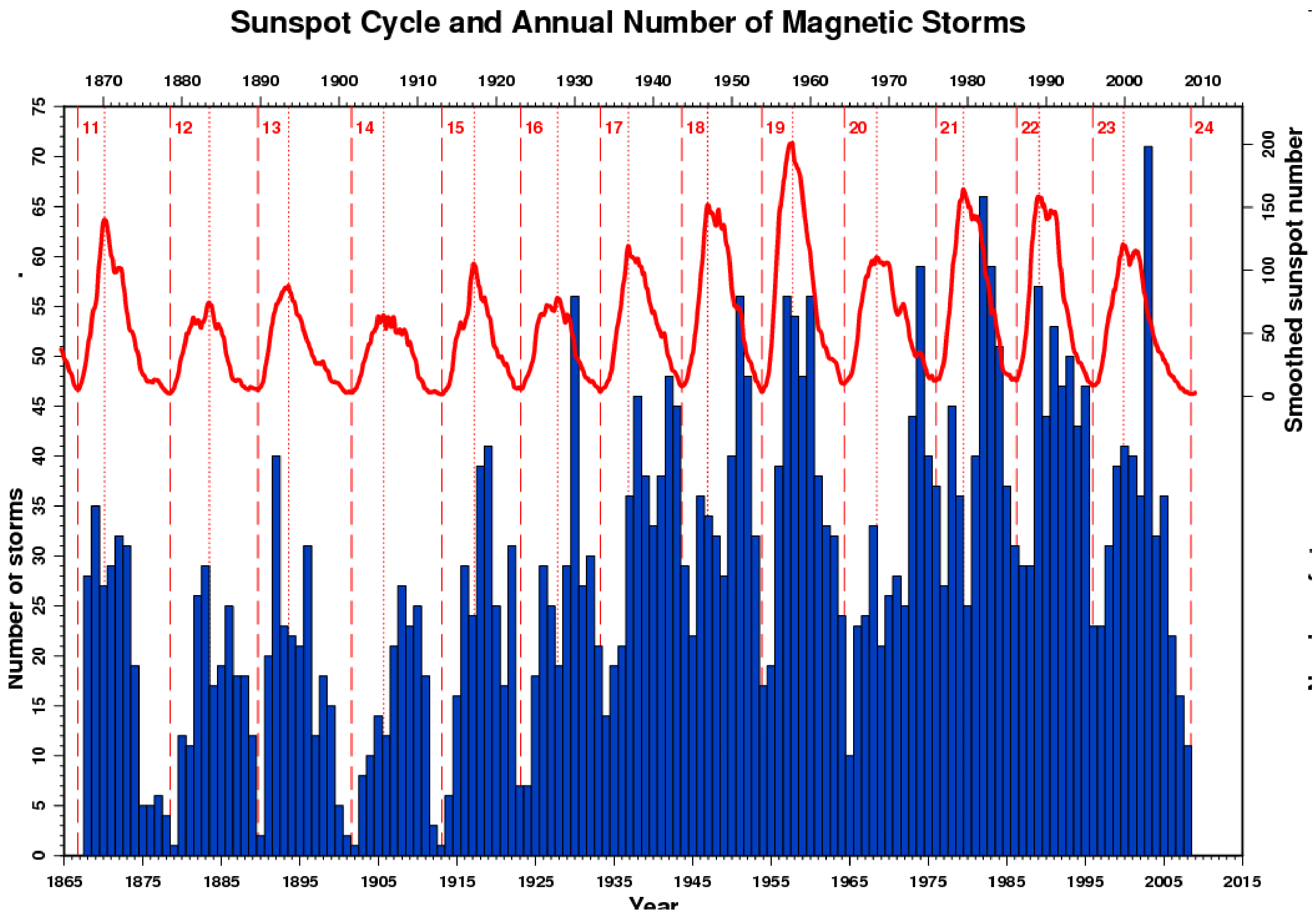


Active region was >100,000 km diameter
Produced two major coronal mass ejections (CMEs) on 22 & 24 Sept 2011

Current Solar Cycle

Began in Nov 2008 - Solar Cycle 24

Maximum occurred in April 2014



Correlation between the number of sunspots and the number of storms
Also a large random component – due to ‘bursts’ of charged particles

Variations in the external field

‘Diurnal’ (daily) cycle associated with facing or not facing the sun

+ 11-year **sunspot cycle**

+ random ‘bursts’ of charged particles - **solar weather**

All interact with electrical currents in the **ionosphere** (below magnetosphere)

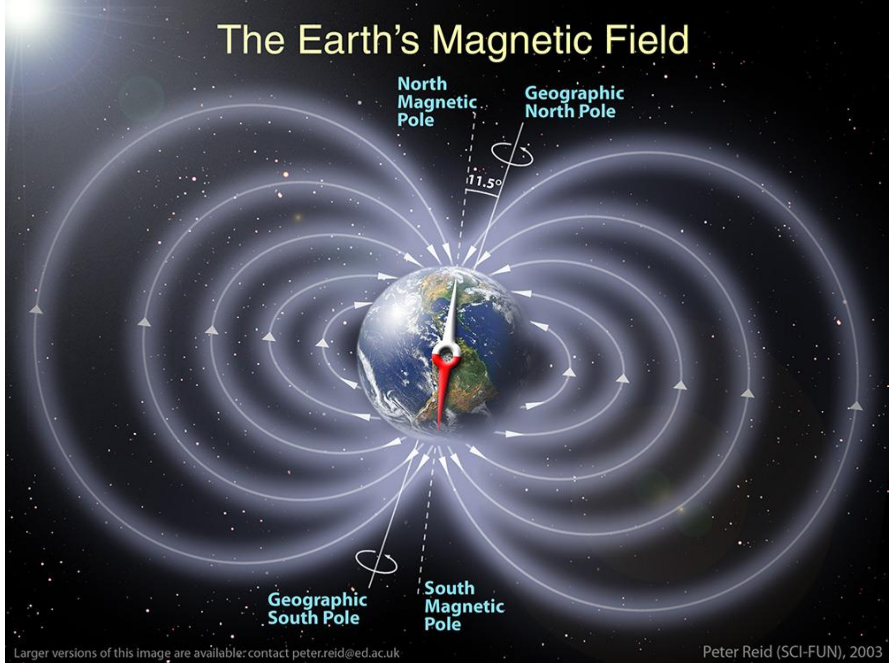
Sometimes visible as **Aurora Borealis (N)** and **Aurora Australis (S)**

In turn affects the field measured at Earth’s surface

2. The Core Field (>90%)

Core, composed mainly of Fe, has its outer radius at 3485km (depth of ~2900km)

Inner core:
1250km thick, **solid**
Outer core:
2200km thick, **liquid**

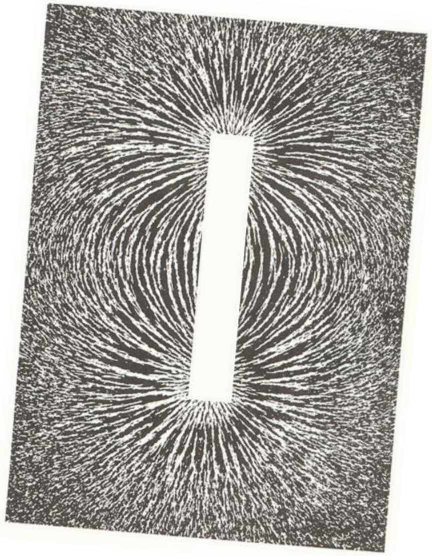


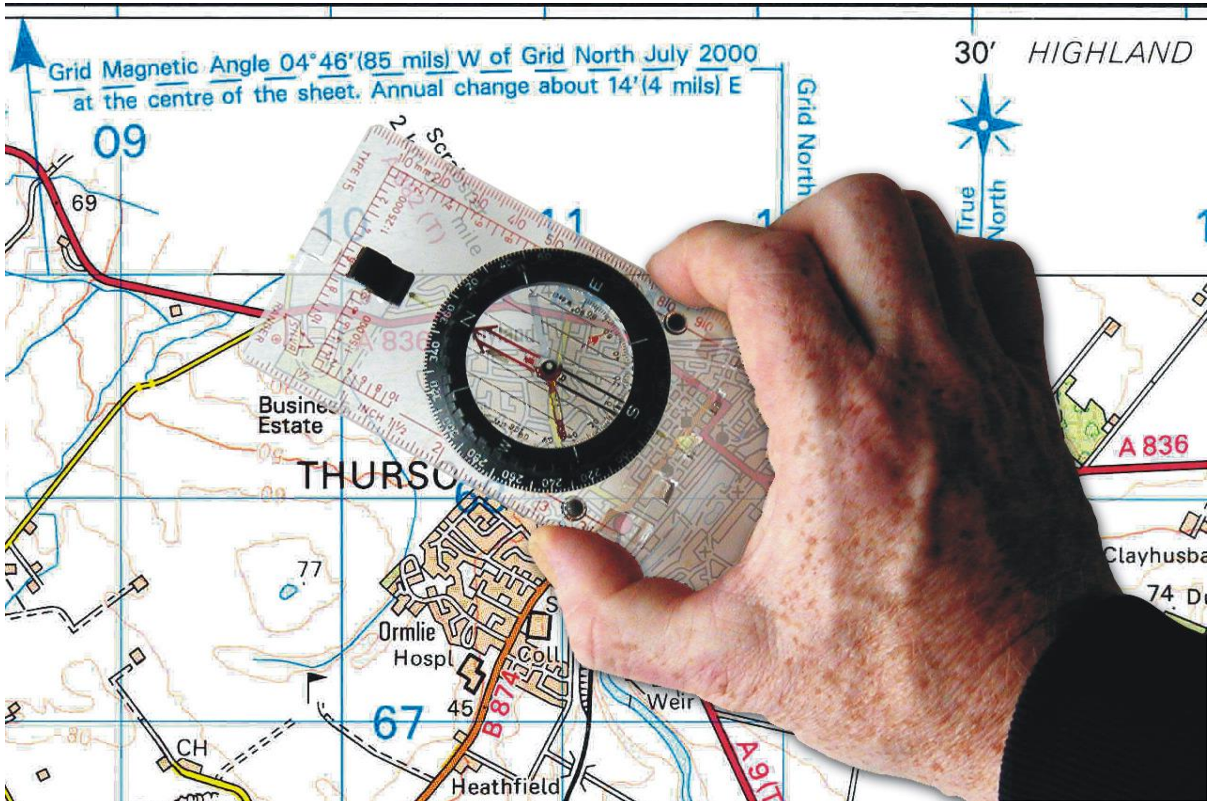
Approximates the field of a giant bar magnet or **dipole**

Strength ranges from 35,000nT (equator) to 70,000nT (polar) as measured at the surface

Magnetic poles in constant motion (**secular variation, total field reversals**) – magnetic north **not static**

Implies a **dynamic** driving mechanism





Technical Information

NORTH POINTS

Difference of true north from grid north at sheet corners

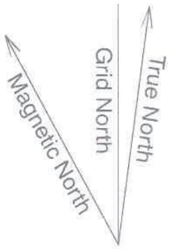
NW corner
1°35′(28 mils) E

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



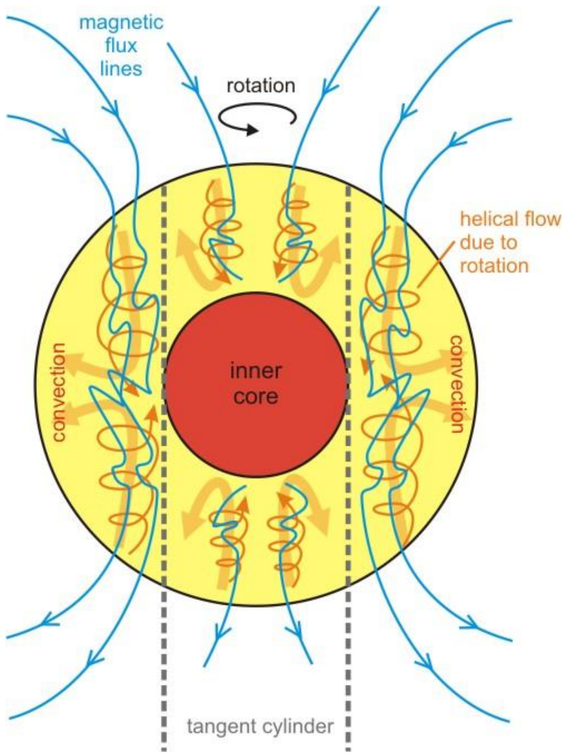
Diagrammatic only

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

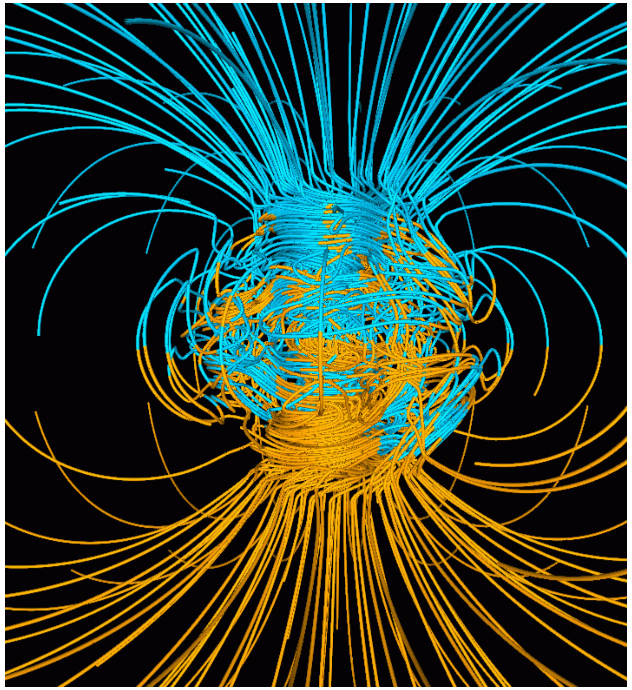
Magnetic data supplied by the British Geological Survey

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

Earth’s Core dynamo



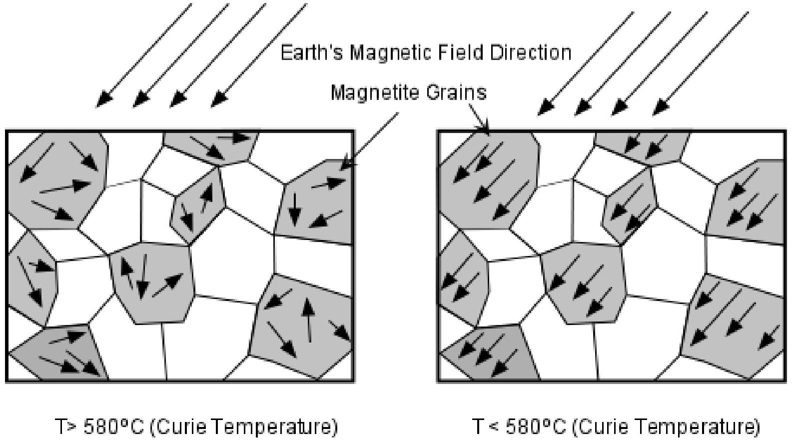
Conceptual model of a **self-exciting dynamo** in a rotating Earth. A mobile conductor (liquid iron) forms helixes aligned with the rotational axis that maintain the field. The helical convection is chaotic - producing time changes and sign ‘flips’.



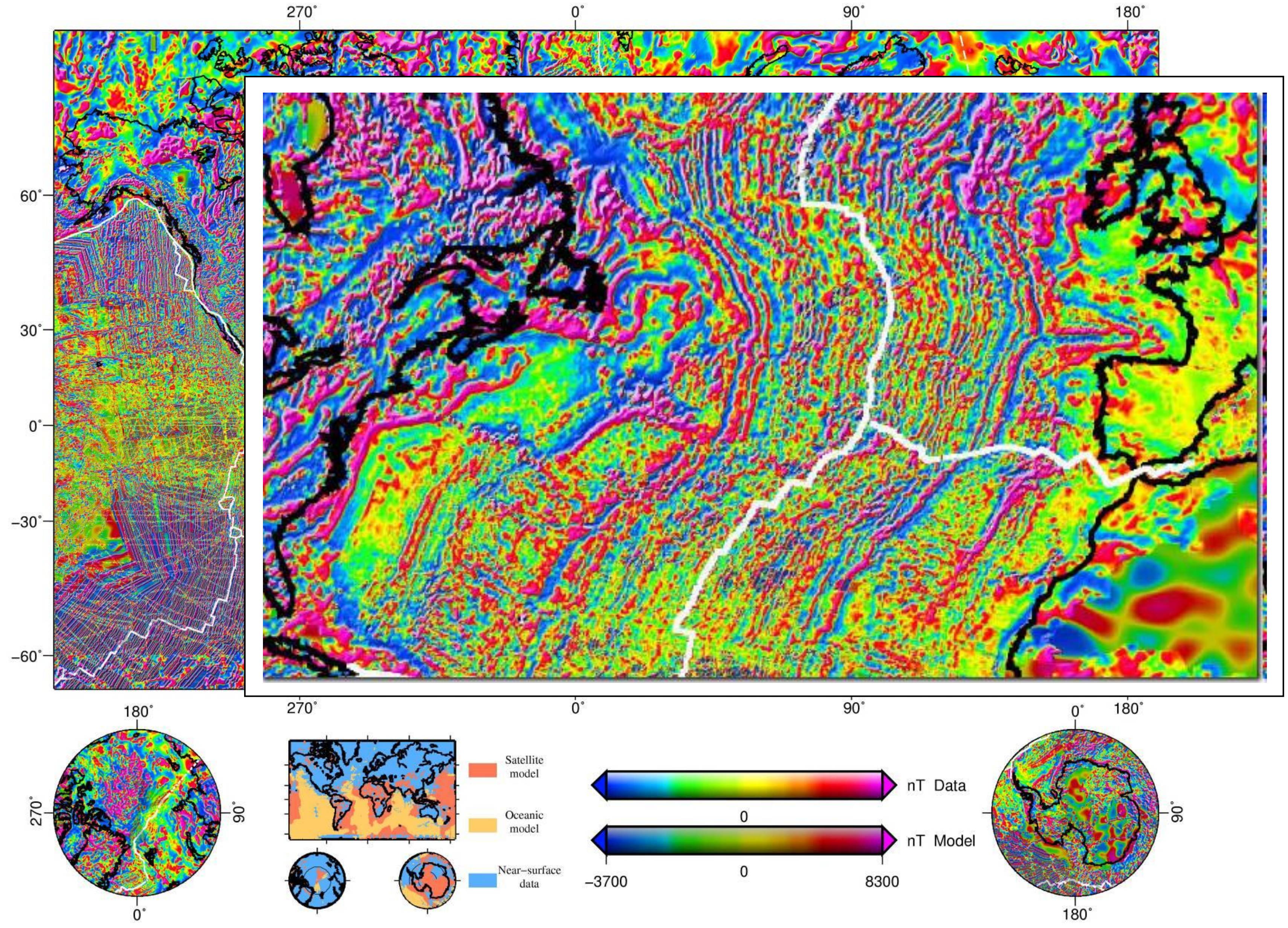
A numerical model of field lines
Blue - North, brown - south

3. The Lithospheric Field

- Due to variations in occurrence of **magnetic minerals** in the lithosphere
- Forms predominantly in crystalline rocks on cooling below the **Curie temperature** ~580°C, when the magnetic field becomes permanent and aligned with the ambient field at the time
- Restricted to rocks cooler than the Curie temperature, so concentrated in the crust
- Produces **small anomalies**, ~0.25% of the total field
- but very important geophysically



Hot **Cold**

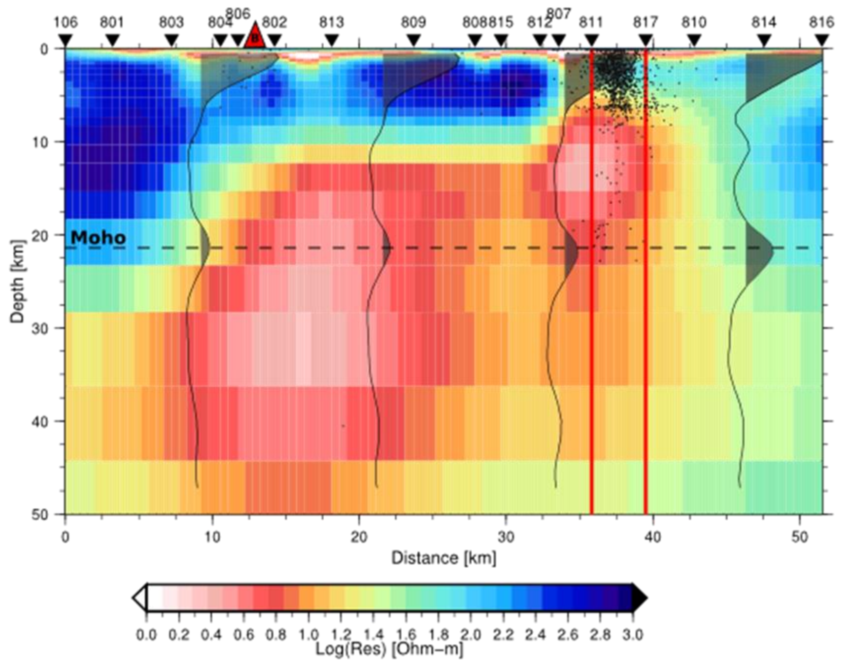


The lithospheric field – what's left after removal of the external and core fields

Variations in intensity due to magnetic properties of crustal rocks – note magnetic stripes

4. The Induced Field

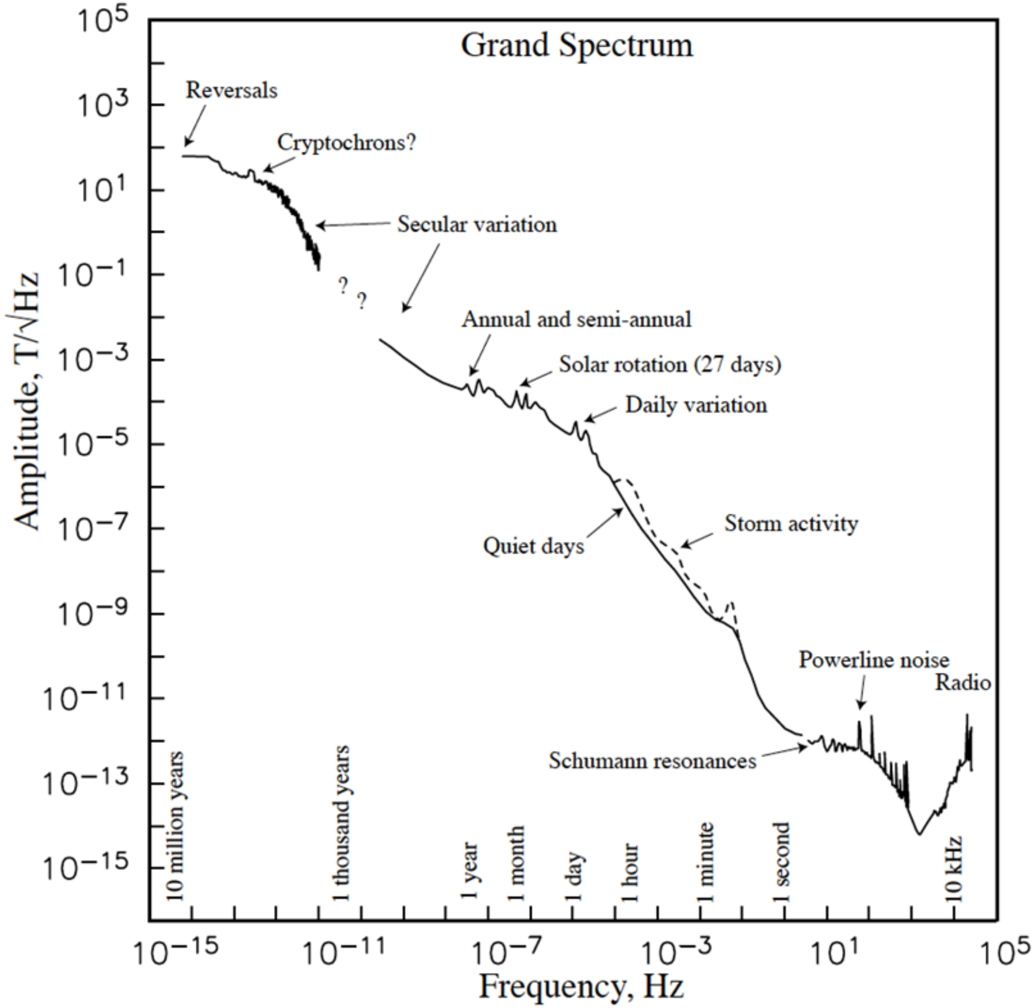
- Temporal variations in the external field induce electric currents in the crust and mantle
- Sources are micropulsations, energy from lightning strikes (sferics) trapped in the ionosphere, and solar activity
- Strength and geometry of induced electric and magnetic fields depend on the sub-surface resistivity distribution
- Obtain depth resolution since longer periods sample deeper
- Used e.g. in geothermal exploration, probing lithosphere and mantle structure



Warm colours are conductive material
- here inferred to be magma/partial melt associated with continental plate rifting

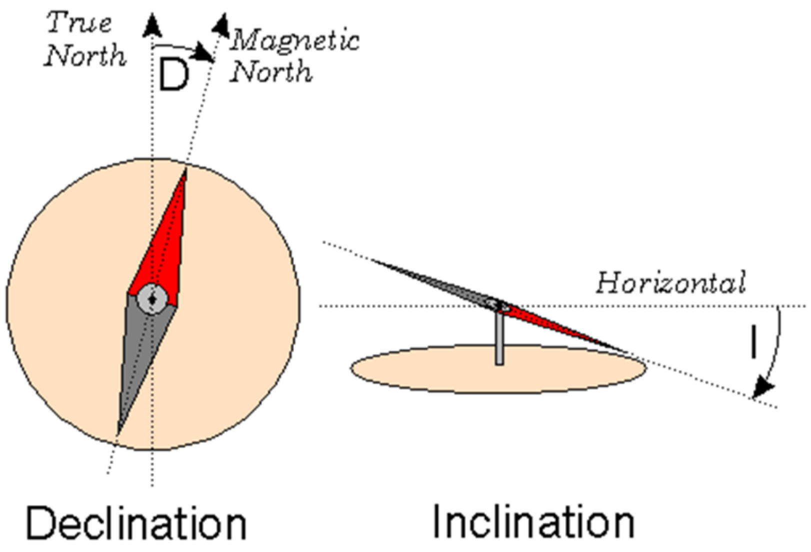
What do we need to measure?

- Field changes on a huge variety of timescales (< 1 second to > million years) …
- … and length scales (planetary scale to the size of rock units)
- It is challenging to separate changes on a rapid timescale from changes on a rapid lengthscale
- and to separate internal field changes from external field changes



Magnetic Field Measurement

Magnetic field is a vector, so **intensity (amplitude)** and **direction** are needed (or three orthogonal components)



Direction is normally described by two angles:
Declination (D) and **Inclination (I)**

Intensity is typically measured by a **proton precession magnetometer**

A **fluxgate magnetometer** measures field components – a magnetic gradiometer measures difference between two vertical component fluxgates

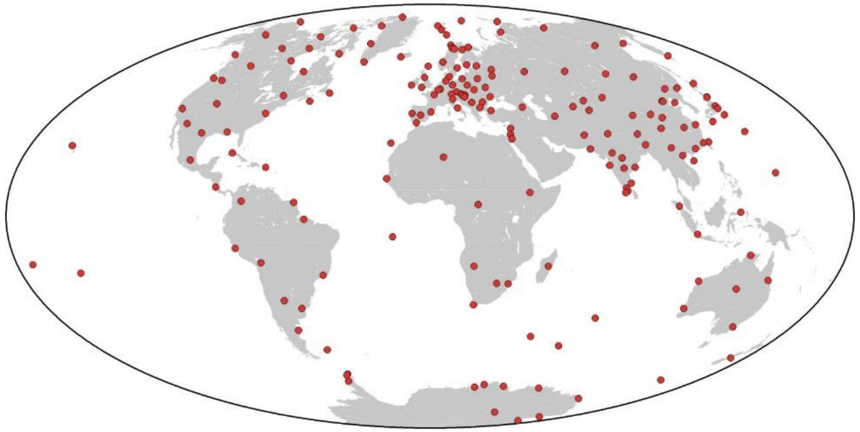
SI unit is the Tesla but **nanoTesla** or **nT** is useful unit

Magnetic gradiometer

Observatories and satellites

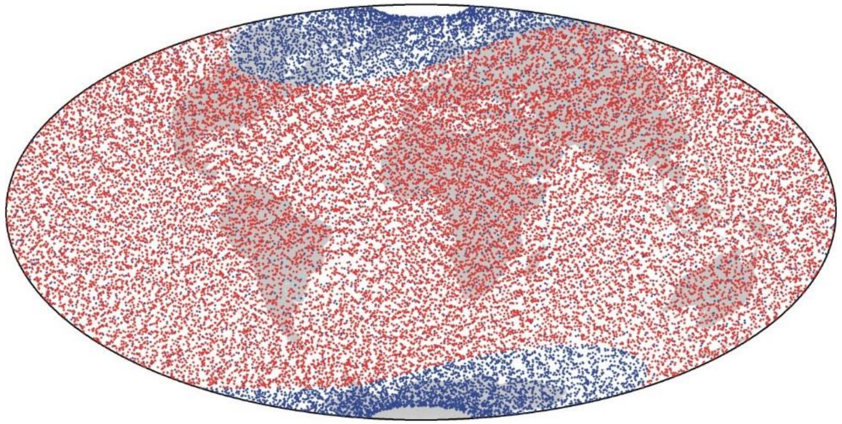
Eskdalemuir observatory

Observatory locations



Ørsted

Selected Ørsted data (6 months)

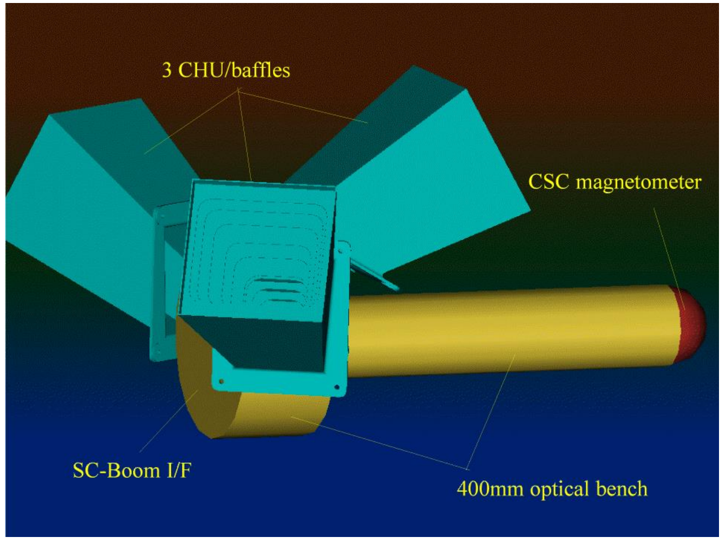


The satellite magnetic field package

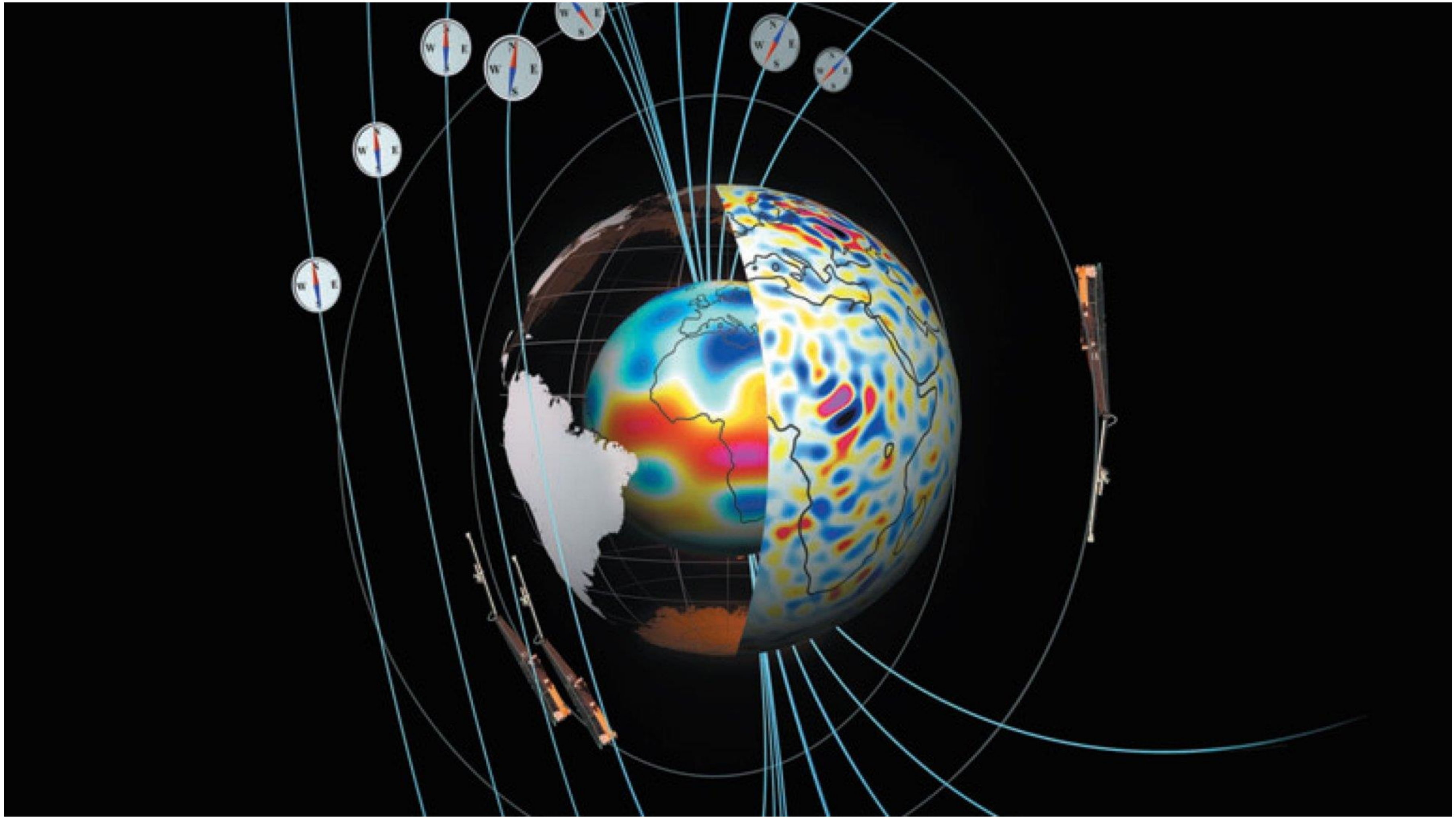
CSC (Compact Spherical Coil)
Fluxgate Sensor

One of the three ASC
(Advanced Stellar Compass)
cameraheads

Optical bench mounted with
triple-head ASC and vector
magnetometer

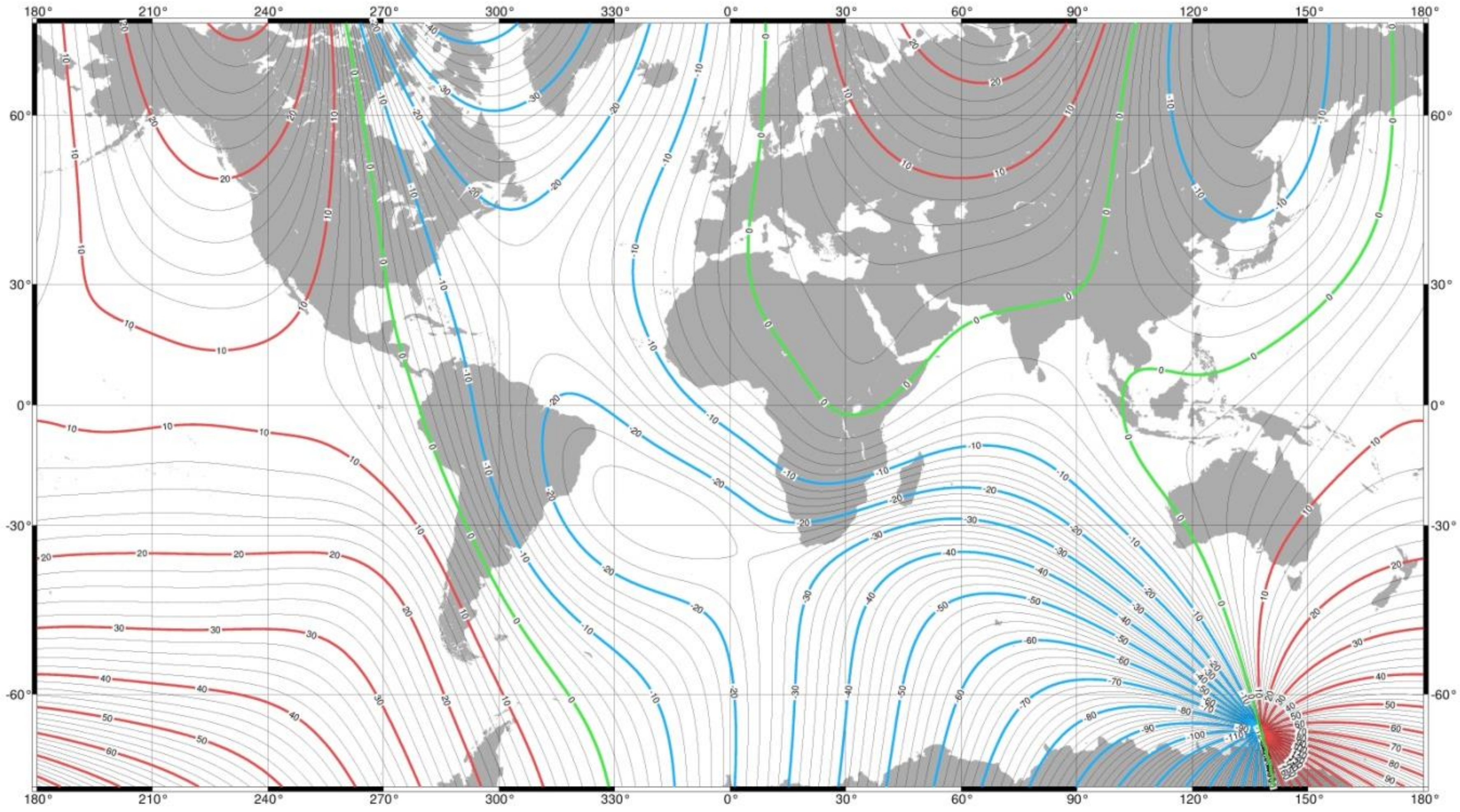


Swarm



Current ESA LEO constellation mission to study the field

Two satellites side-by-side at ~450 km; a third at ~700 km



A map of Earth's Declination. Green – the 'Agonic' Line (compass points to true geographic N). Blue – compass points W of true. Red – compass points E of true.

Movement of the Pole

1600-2001

In 2001, North Magnetic Pole was near Ellesmere Island, N Canada.

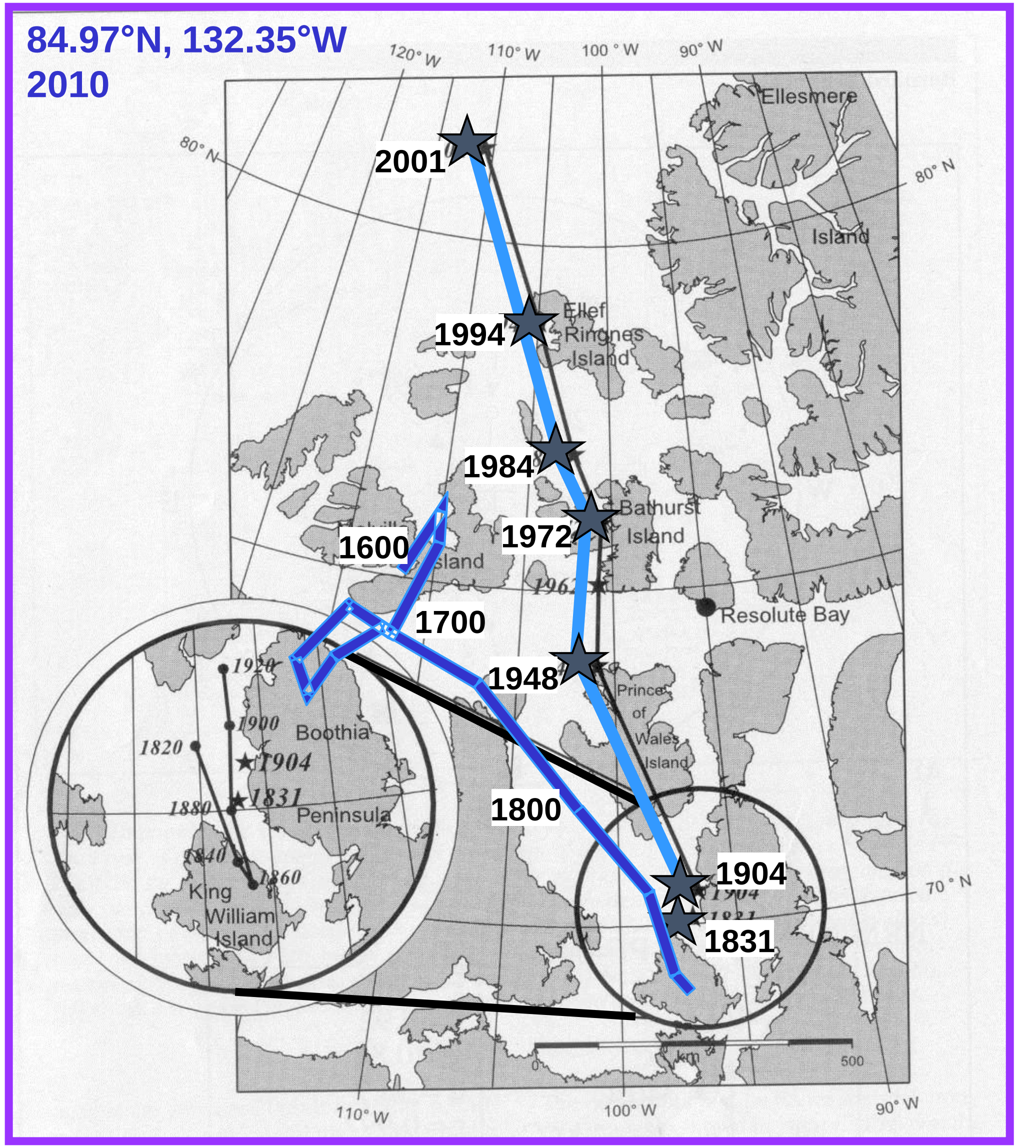
★ **Direct measurement of pole (modern instruments)**

Solid line – inferred from ship's logs (compass inclination and declination)

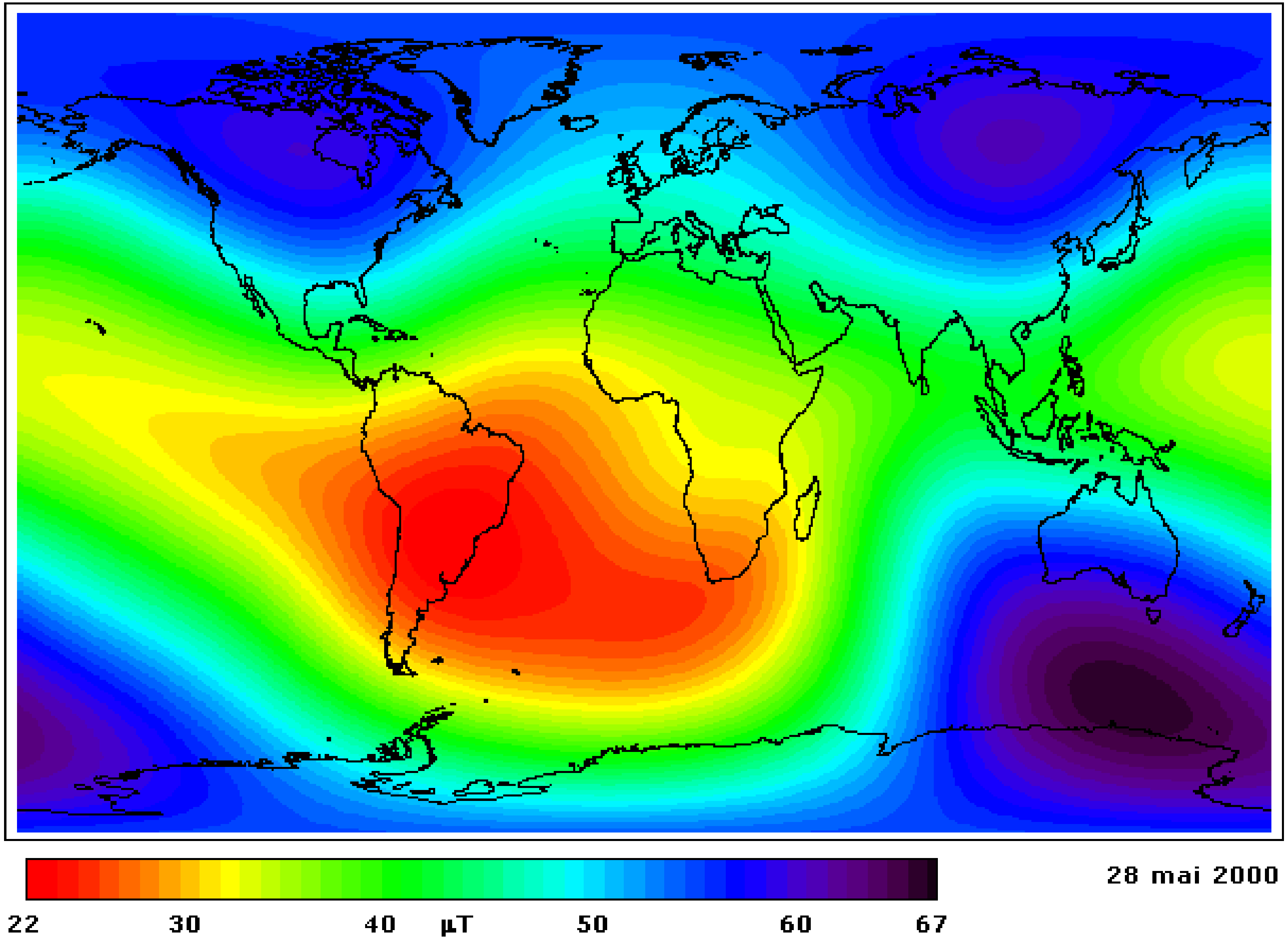
The pole moved ~1650 km between 1910 and 2010

Since ~1970 > 40 km per year

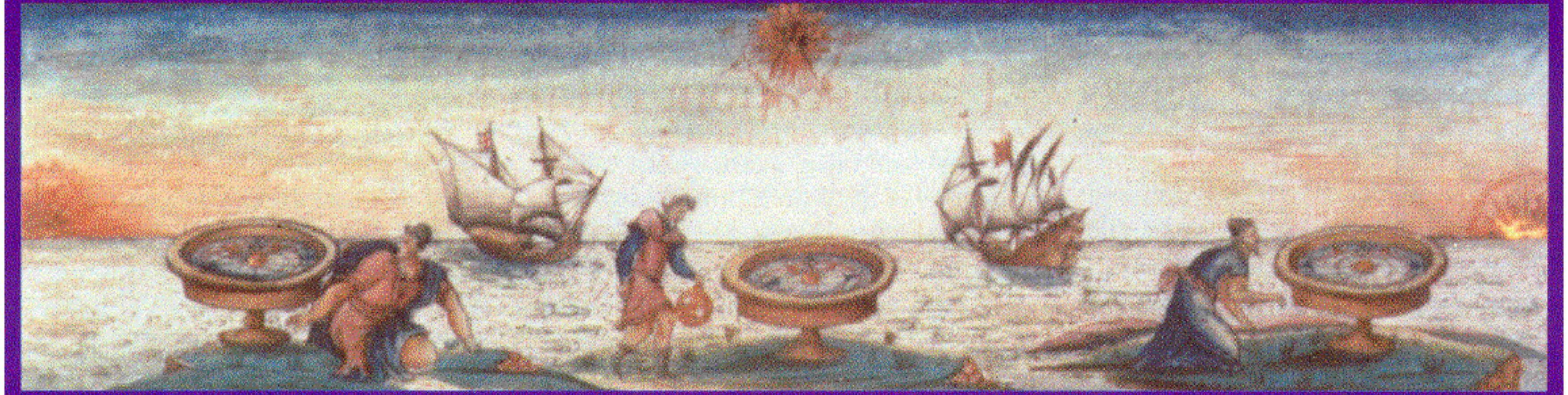
The historical change in the magnetic field is called the **Secular Variation**



Field strength



Historical data – data mining



6 *Les premieres Ouevres de lacques de Vaulx, pilotte en la Marine, Havre de Grace 1583.* Three methods of determining declination: at sunrise, at noon and at sunset. The central observer has an astrolabe, to ensure that the Sun has reached its highest point. (Courtesy of Bibliotheque Nationale, Paris; ms. inv. FR 150.)

1719 July. Ship King Geo.^r from Cape Lagullas

Thurs.^dy 2	H.	K.	F.	Cour.^s	Winds	Observation's.
	1.	1.	5	N E.	SE b S.^o	Fair Weather.
	2.	1.	—			
	3.	—	—		Calme	
	4.	—	—			
	5.	o	5			Varr.^n ⅌ Az.^o 21. 30 W.
	6.	—	3			
	7.	—	3			
	8.	—	4			
	9	—	—			
M.D.E. 34.39	10	—	—			
	11	—	—			
	12	—	—			
Obs.^n 28.28	1	—	—			
	2	—	—			
	3	—	—			
	4	—	—		Calme.	The Carpent.^r & Armo.^r Employ.
	5	—	—			
	6	—	—	a Swell fr y.^e S.^o ard		ab.^t y.^e Rudder.
	7	—	—			
	8	—	—			
	9	—	—			
	10	—	—			
	11	—	—			
	12	—	—			

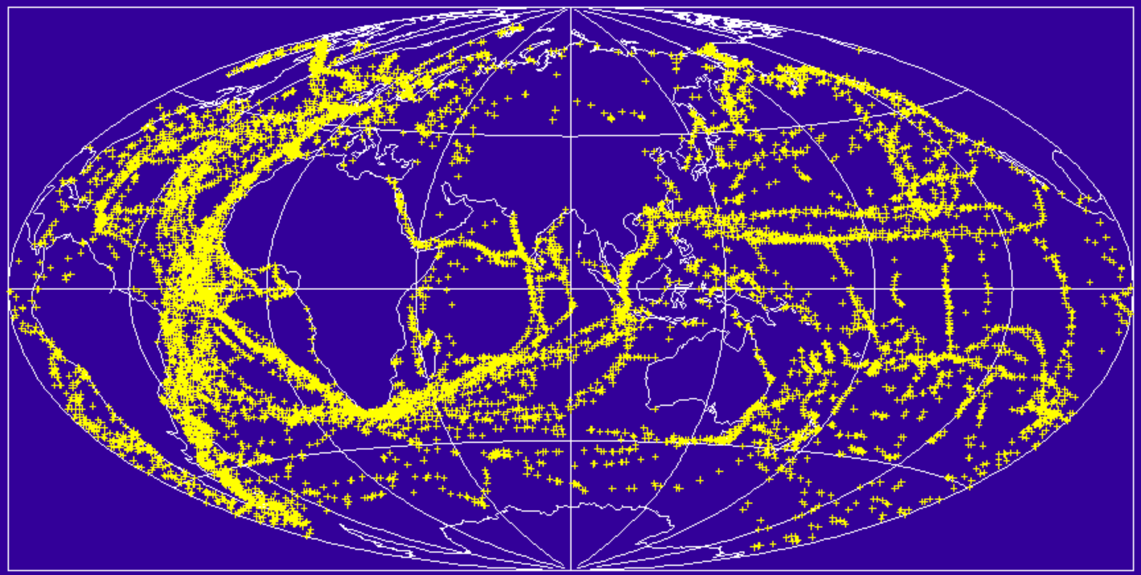
All this 24 Hours, Wee have had in a Mann.^r Calm Only a Great Tumbling Swell from y.^e S.^o ard.

At Noon had Latt: ⅌ Obs.^n 28. 28

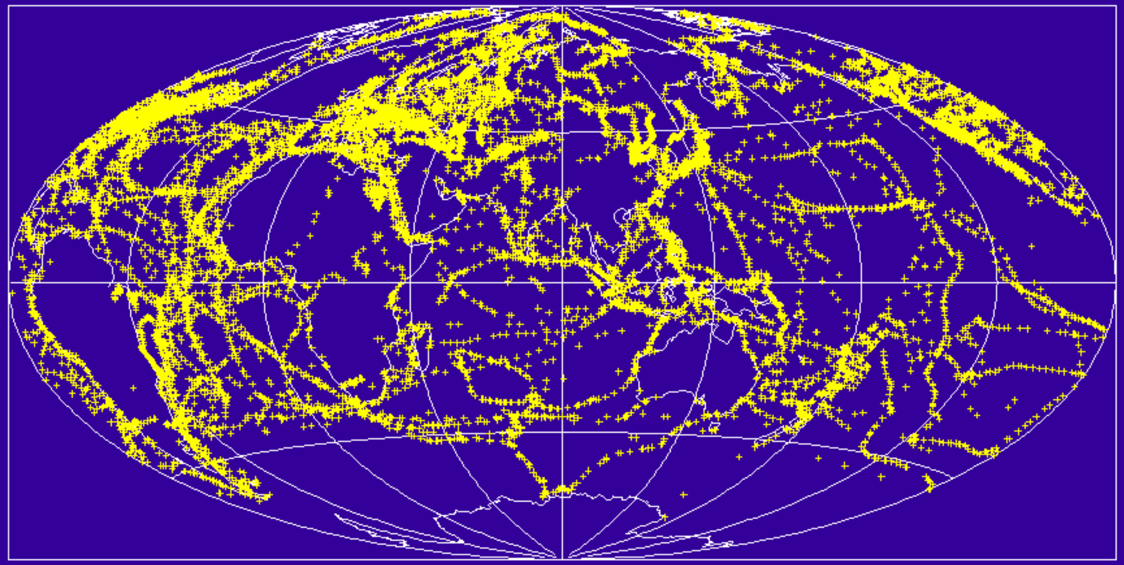
Mer: Dis. All as Yest. 34. 39

Yesterd.^y Evening, and this Morn: Our Carp. & Armour.^r has been Employ'd to Fix y.^e Ruther for our Pres.^t Necessitys, When please God to Favour us with an Opportunity to Hang Him. The Ruther Wee find very much Decay'd by the Worm, And When-ever Wee come, to any Secure Place; He must have a Thorough Repair — For by y.^e Negligence of the Carpent.^r not looking well to it, when Wee fitted out of y.^e River, And my Carpenters not giving me, a True Acco.^t at that, Any Otherwise, then all was Well, when at the Same time, The Worm had Eaten it to the Heart, and the Pintles & Braces Iron Sick.

1700–1799 Data



1850–1899 Data

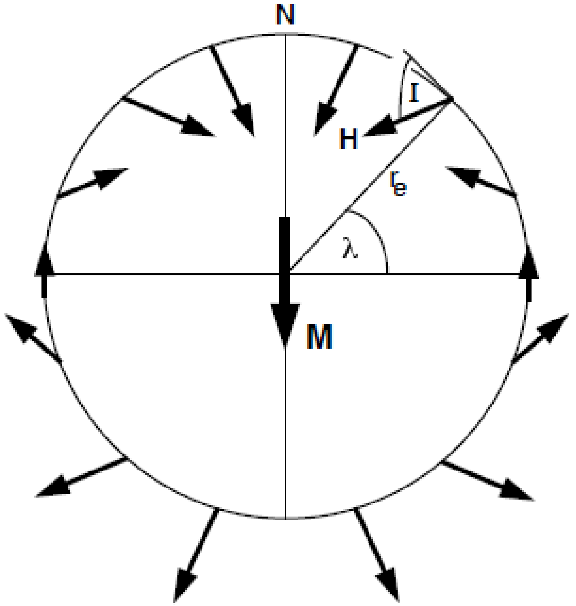


Further back in time ...

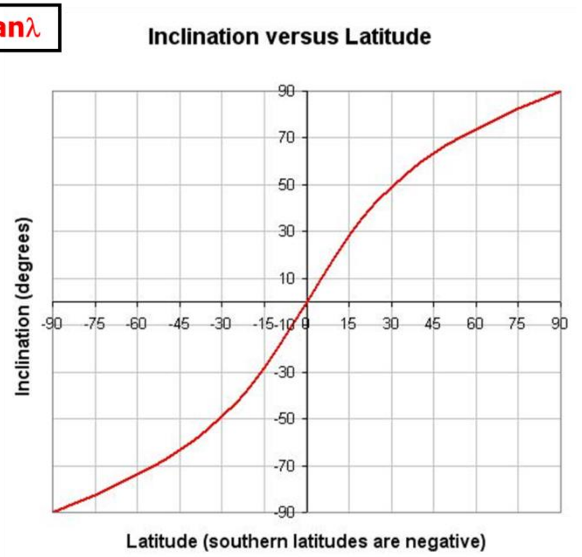
- Palaeomagnetic rock samples (lavas, sediments)
- Pottery shards
- Kilns
- Lake cores
- Characterise physical properties of samples …
- … and make laboratory measurements of the field (strength and/or direction)

Geocentric Axial Dipole Hypothesis

Averaged over time, the magnetic field is that of a geocentric axial dipole



tanI = 2tanλ

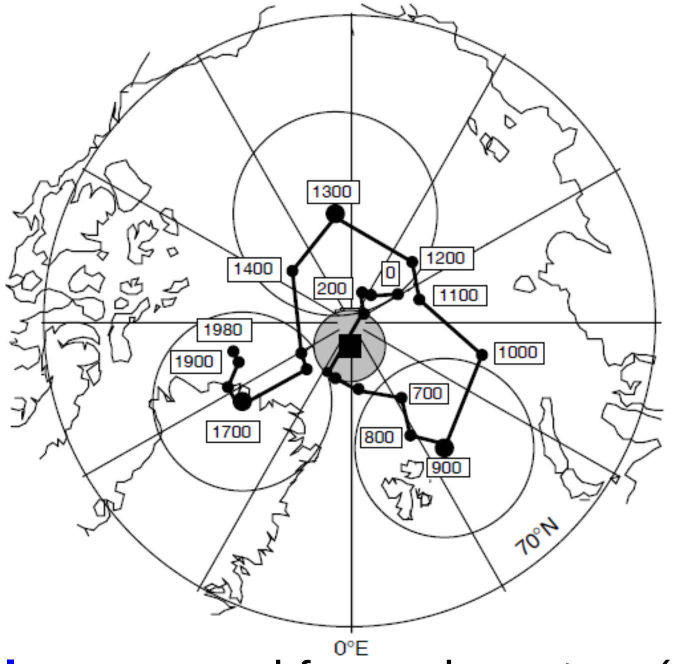


Magnetic North = Geographic North

Inclination depends only on latitude **tan I = 2 tan λ**

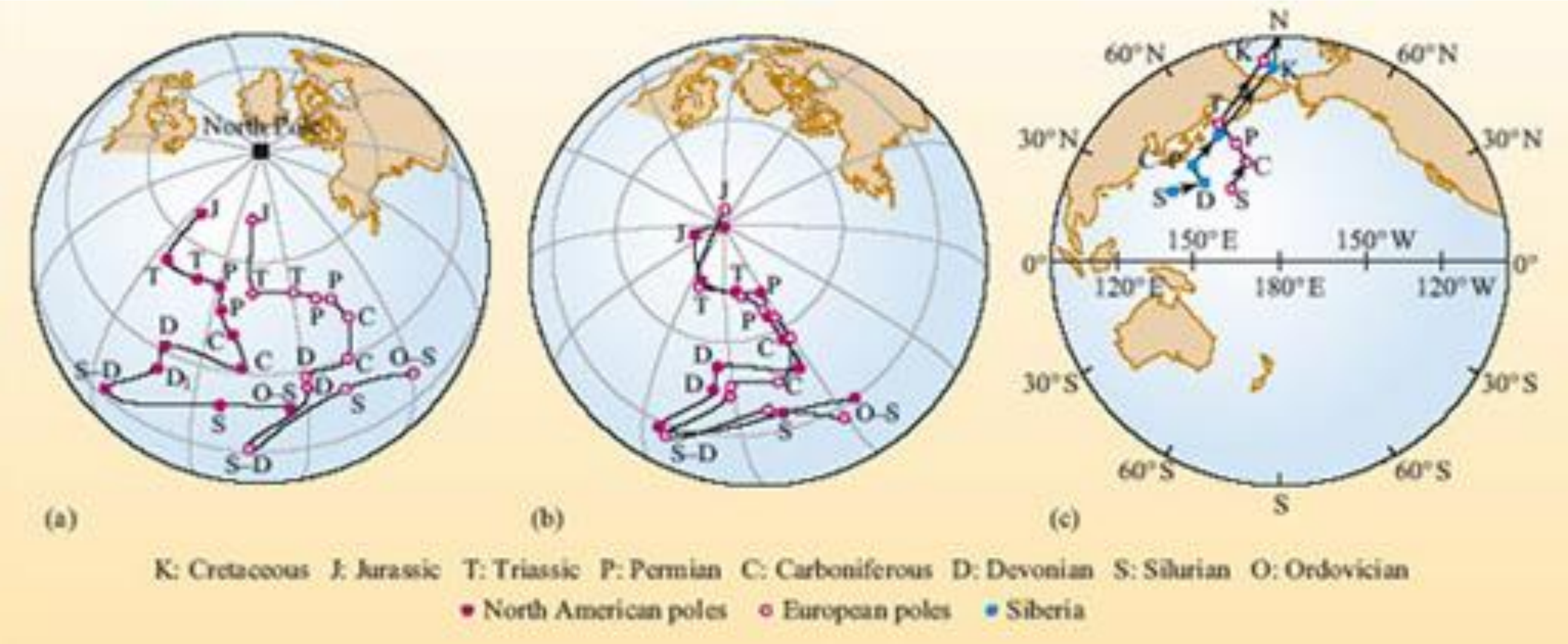
Declination always points towards geographic North

Palaeomagnetism and Polar Wander



Geomagnetic North Poles averaged for each century (dots) with 95% confidence limits (circles) for 900, 1300, & 1700 AD

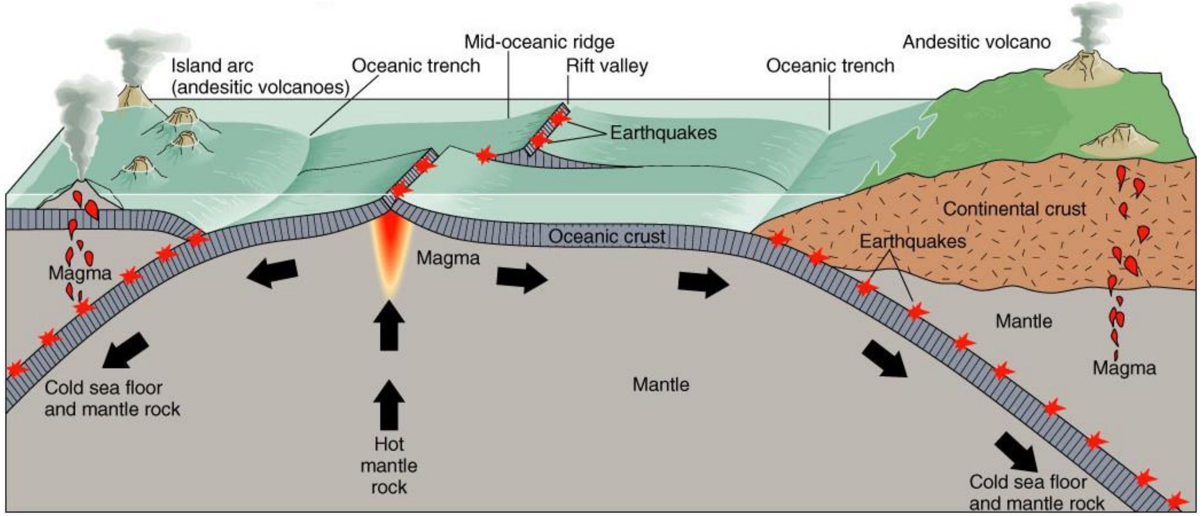
The average **geomagnetic pole position** (black square) with 95% confidence (grey circle) is quite near the geographic pole – consistent with geocentric axial dipole hypothesis

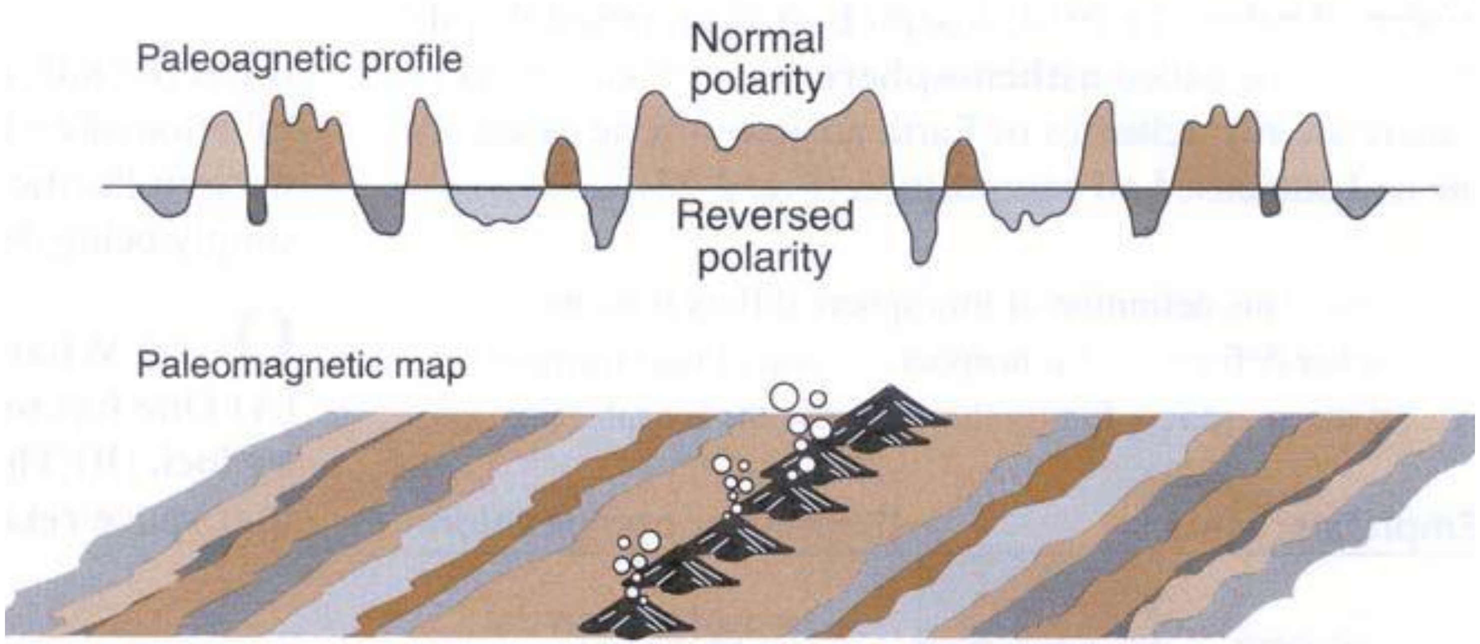


Polar wander was critical in proving **continental drift** over geological time

Continental drift evidenced by polar wander is still the only quantitative technique available to determine pre-Mesozoic palaeo-geography. All older ocean lithosphere has been recycled into the mantle.

Magnetic reversals – the key evidence for **sea-floor spreading**



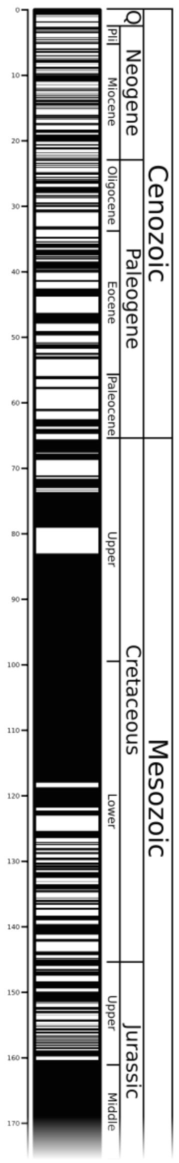


Get pattern of magnetic stripes symmetric to mid-ocean ridge

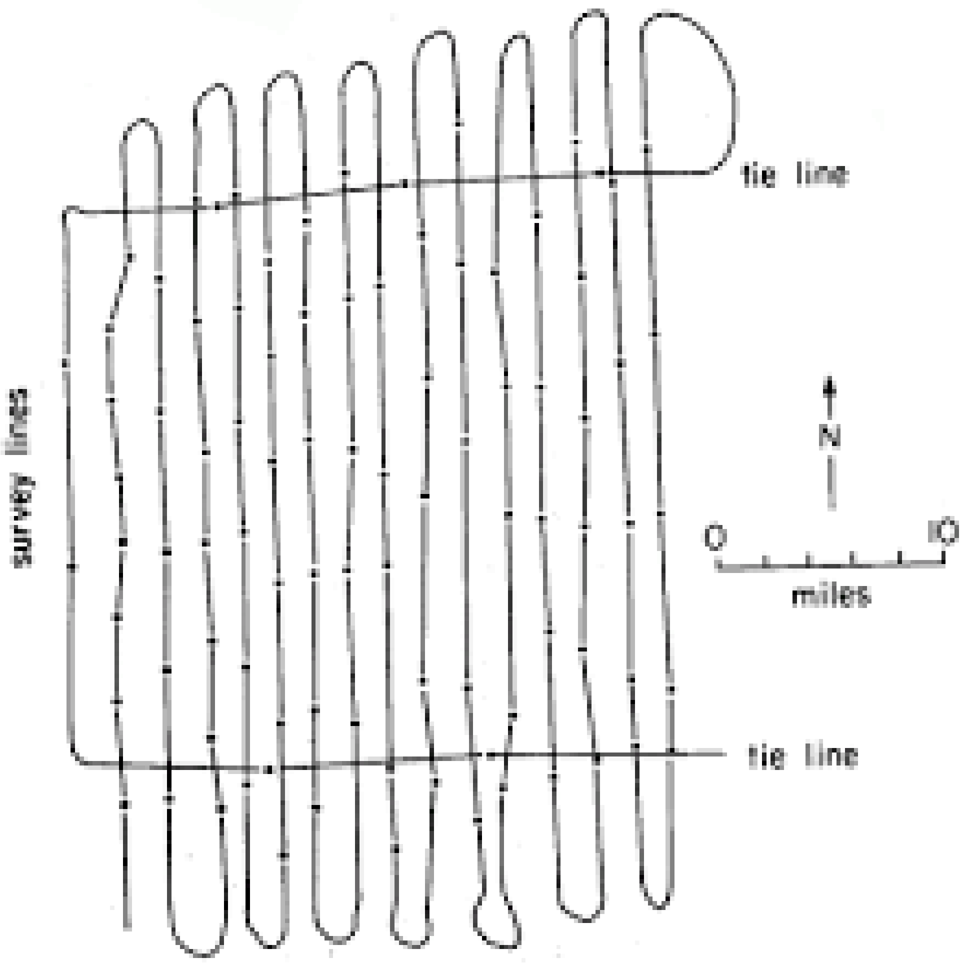
Earth's field sometimes completely flips (reverses)
Consistent with the **self-exciting dynamo** mechanism

Magnetic polarity timescale

- Field flips about every half a million years on average
- But last reversal was ~¾ million years ago
- Reversal rate not constant
  - Long Cretaceous 'superchron'
- Reversals take 10,000-20,000 years
- Dynamo simulations produce similar features, but process(es) not fully understood



Aeromagnetic surveying



Dedicated survey companies use fixed wing or helicopter

Magnetometer in a stinger (as here) or towed bird, often with other instrumentation

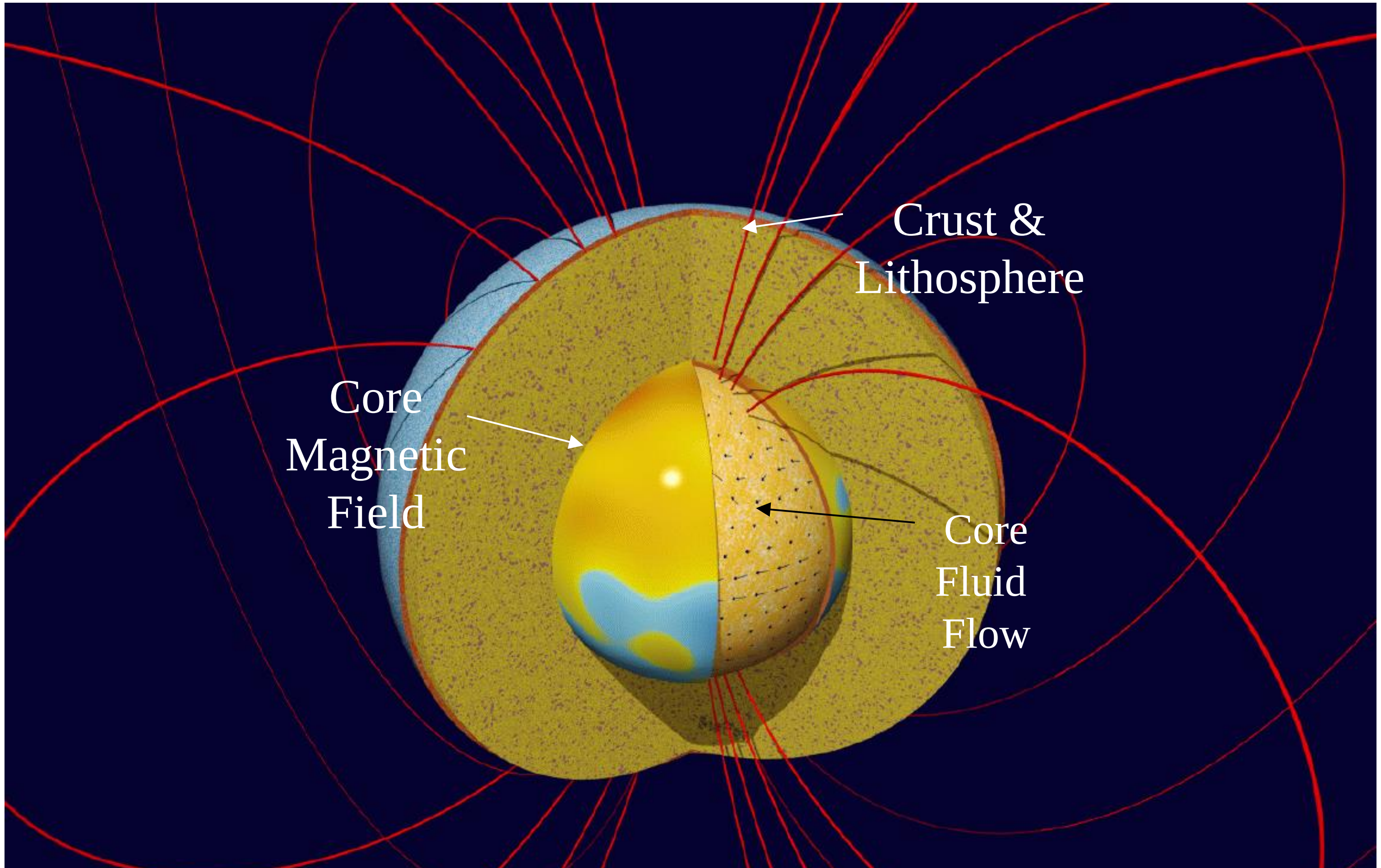
Fly closely-spaced survey lines perpendicular to dominant geological strike direction, and tie lines to help remove changing external fields

Also use a base station to help remove external fields, and advise of magnetically noisy conditions

Magnetic surveying

- Much data post-processing, including removing main and external fields
- Gradient data do this automatically, but are noisier and have shallow sampling depths
- Treat the Earth as flat, analyse data in the wavenumber (Fourier) domain
- Many different modelling and interpretation methods
- Several commercial packages, some freeware
- Data and expertise often found in national or state Geological Surveys
- Useful for mineral and hydrocarbon exploration, archaeology

Earth's Magnetic Field

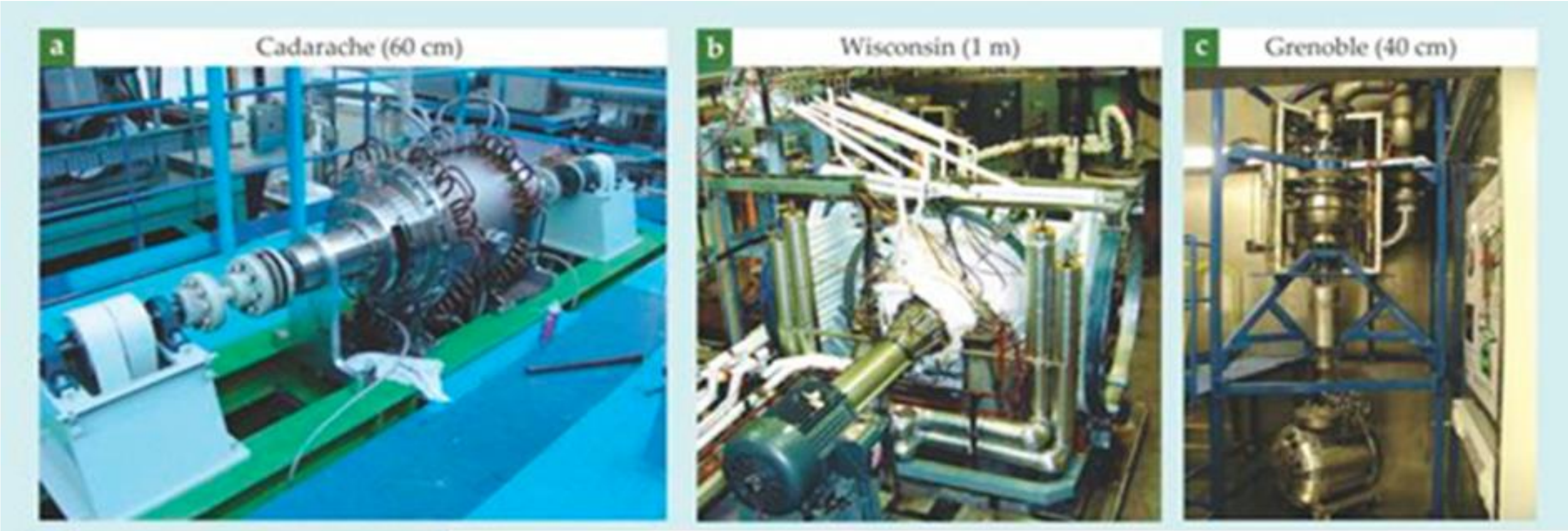


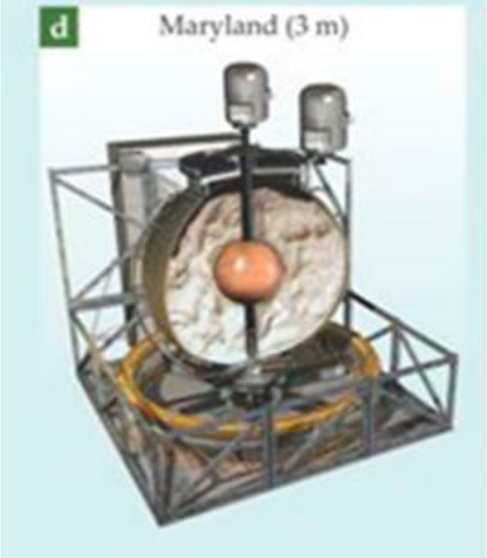
No other measurable physical parameter can be used to sense so many diverse regions of the solid Earth

Challenge I – Core dynamics and the geodynamo

- Allegedly, Einstein described it as one of the great unsolved problems
- It still is, many decades later
- Why? – difficult to do experiments, and to simulate numerically
- Experiments: need an electrically conducting fluid and a large vessel
- Most such fluids are dangerous, expensive and difficult to image
- Computers: can’t make any simplifying approximations to geometry; need very short time steps to approximate equations adequately
- Short time steps take too long, even with the most powerful computing resources, so models are not in Earth-like regimes

Laboratory experiments

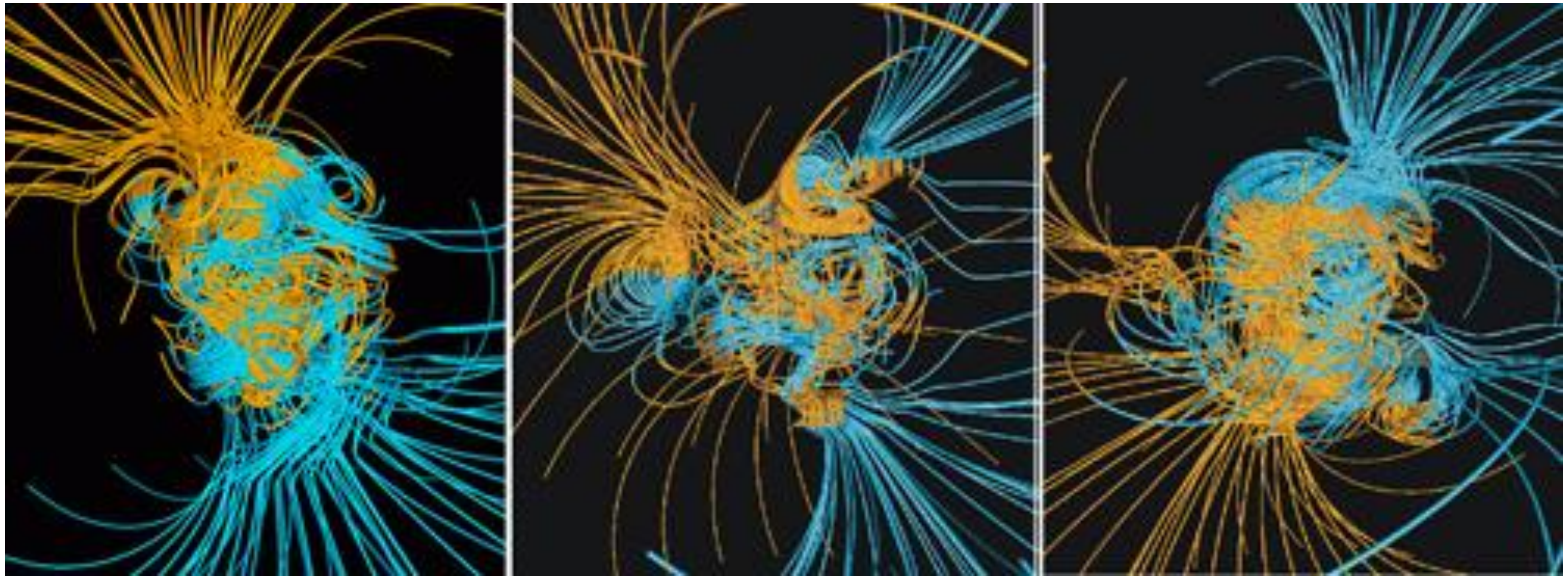


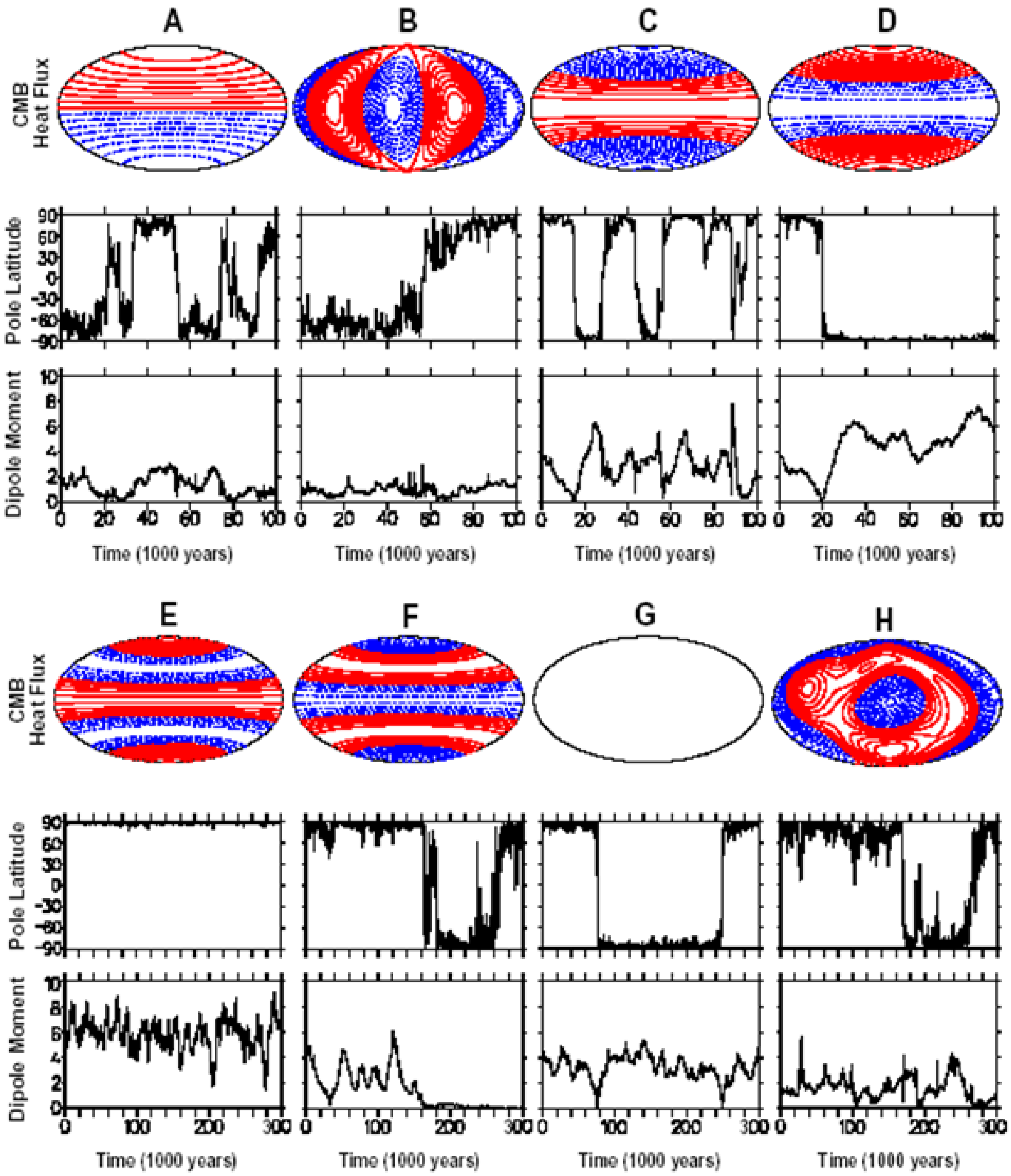


Rotating liquid sodium dynamo experiments. (a)-(c) are photographs of actual laboratory dynamo experiments, and (d) is a schematic of a model under construction. The diameters of the rotating fluid containers are given in the heading to each panel.

Geodynamo simulations

- Although not in the correct parameter range, simulations (using lots of computer resources) produce Earth-like models
- Dynamo community has established benchmark tests for code
- Models reverse, undergo excursions, are predominantly dipolar with the rotation axis on average, have little dipole field strength when a reversal occurs





The base of the mantle has hot and cold patches, affecting core convection

Where is magnetic the pole?

What is the bar magnet strength

Investigating inhomogeneous boundary conditions

Why data mining?

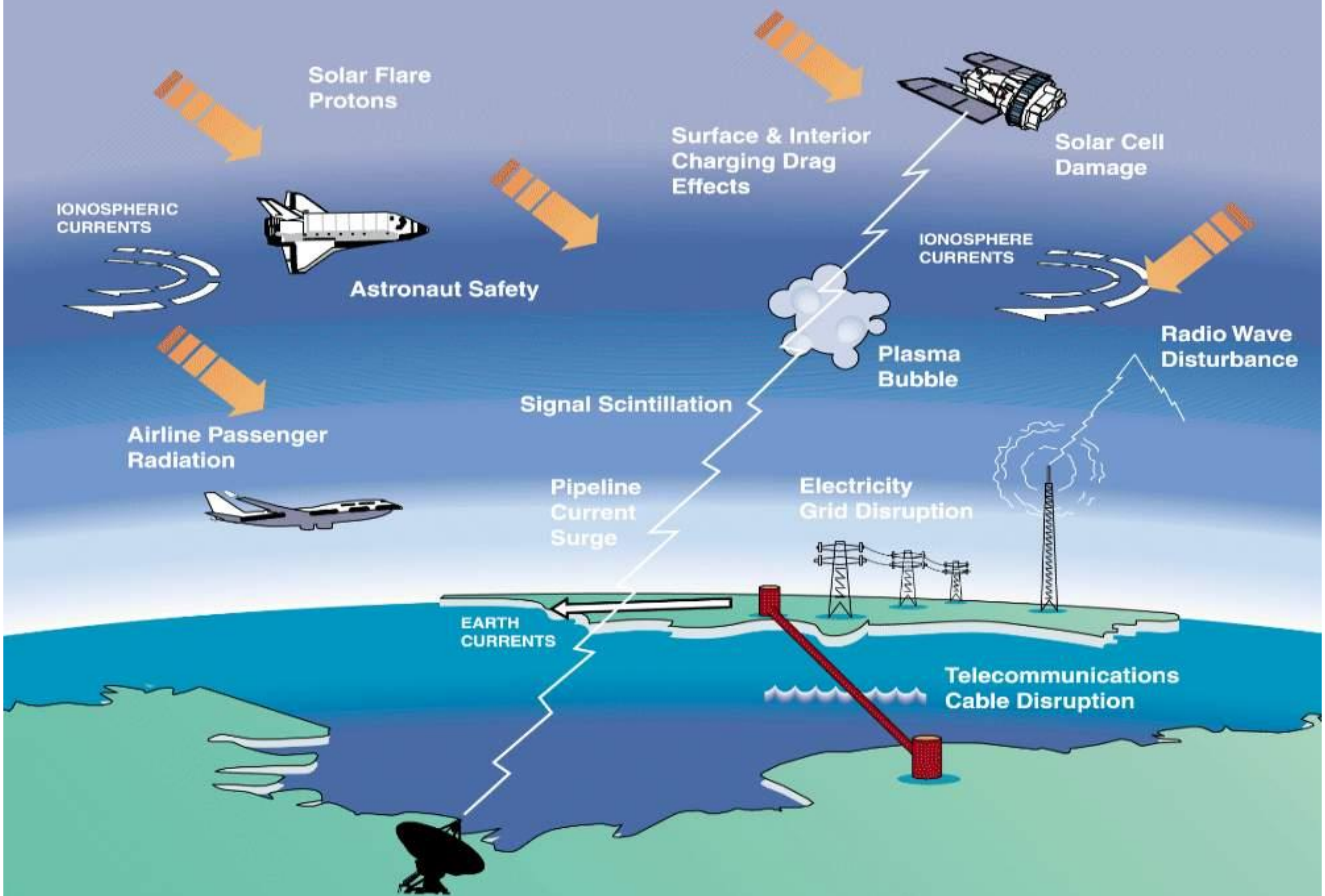
- To understand behaviour of convecting outer core liquid iron and origin of magnetic field
- Flow speeds are slow (km per year)
- Think in terms of weather – a week’s meteorological weather is like a century’s core ‘weather’
- These data are now an important component of data assimilation into numerical dynamo simulations

What is space weather?

A novel natural hazard

Aurora Borealis – Northern Lights

"Solar wind disturbances that affect Earth's space, atmosphere and surface environments and that can disrupt technology"



Examples of space weather impacts

Examples of space weather extremes

- Oct 2003
  - last big event, many impacts
- Mar 1989
  - biggest of modern era
  - power failures, spacecraft problems, …
- Feb 1986
  - big storm at solar minimum
- Aug 1972
  - major telephone failures
- Feb 1956
  - short intense radiation event

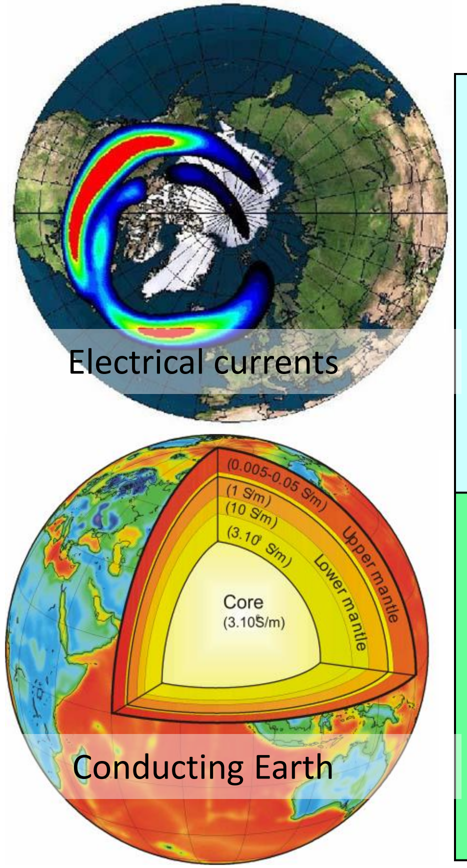
1989: Aurora over Oxfordshire, England

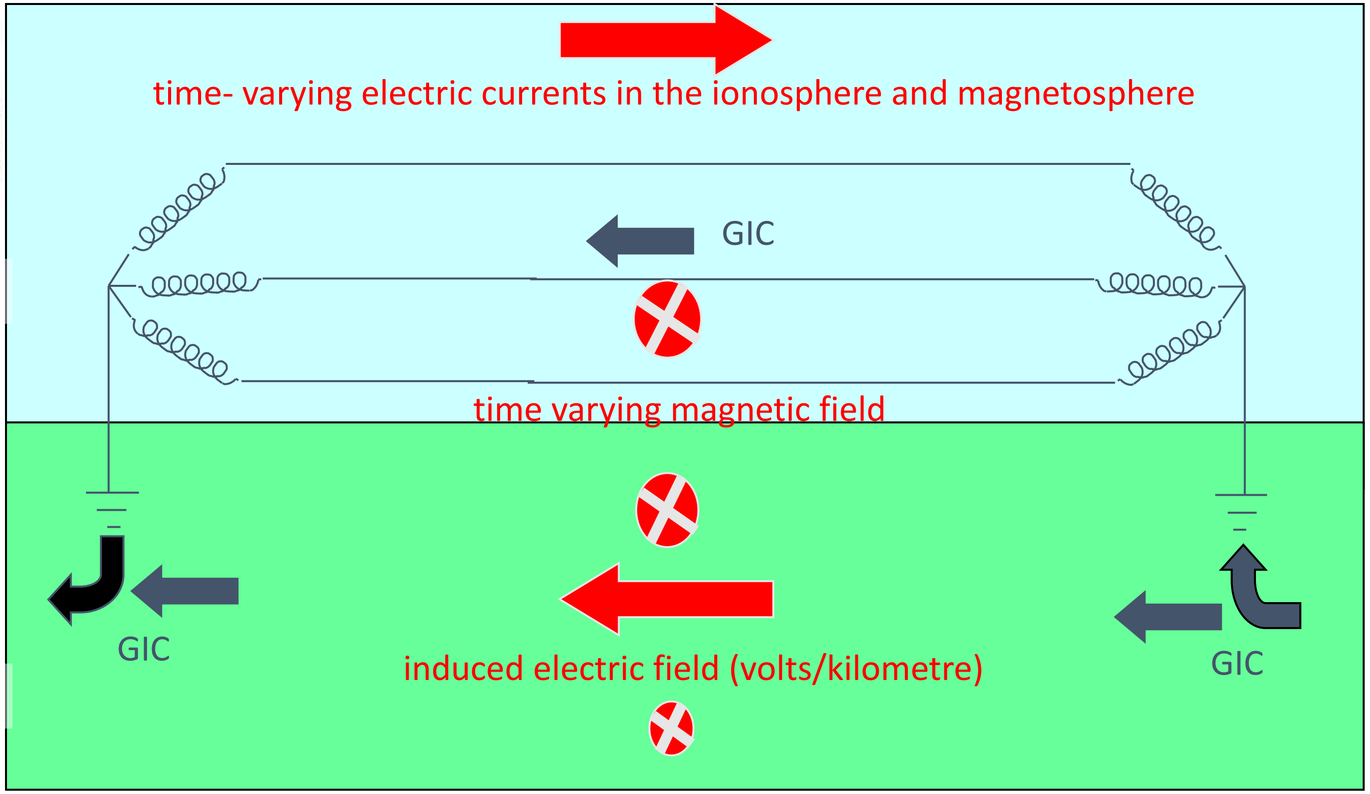
- Mar 1941
  - Intense magnetic effects over SE England
- May 1921
  - intense event with high rate of change of field
- Sep 1909
  - Intense magnetic effects over SE England
- Sep 1859
  - strong magnetic & radiation storms
  - Widely used as worst case event
- & many others …

Impact – power grids

- Failure of Hydro-Quebec system in March 1989
  - cascaded shutdown of entire grid in 90sec
  - 9 hours to restore 80% of operations
  - 5 million people without power (in cold weather)
  - estimated C$2Bn economic cost (incl. C$12M directly to power company)
- Other known impacts
  - 1940s: in US
  - 2003: UK (2 transformers failed), Sweden (1 hour blackout), Finland, Canada, South Africa (15 transformers failed), Japan, China ...
  - some evidence of effect on pricing movements in electricity supply markets
- Mitigation strategies?
  - DC blocking devices, power re-routing, maintenance re-scheduling, load adjustment

Why does space weather cause grid problems?





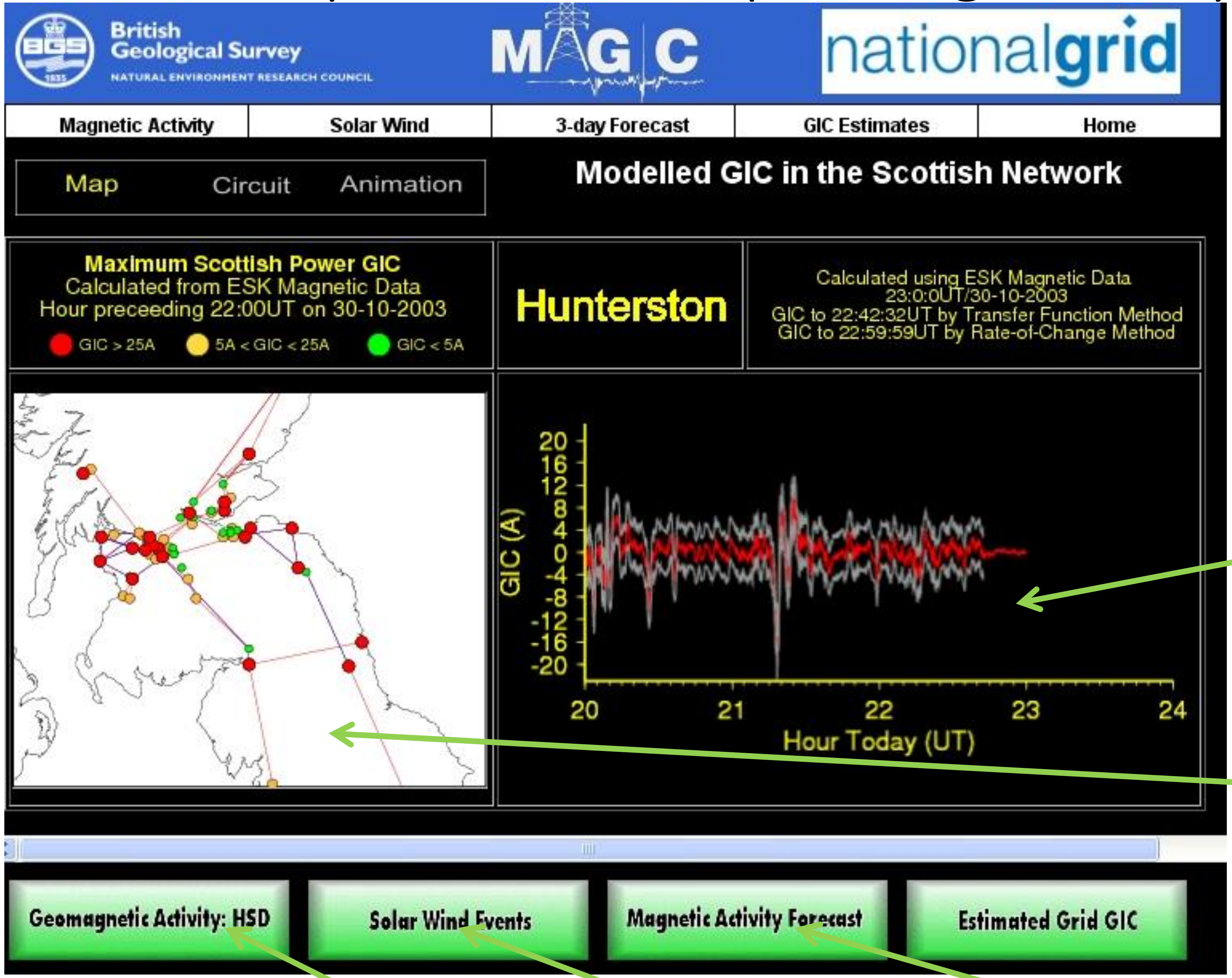
Why does space weather cause grid problems?

Transformers may overheat

System voltage can drop

Protective devices malfunction

An operational UK power grid analysis system



In association with National Grid Company

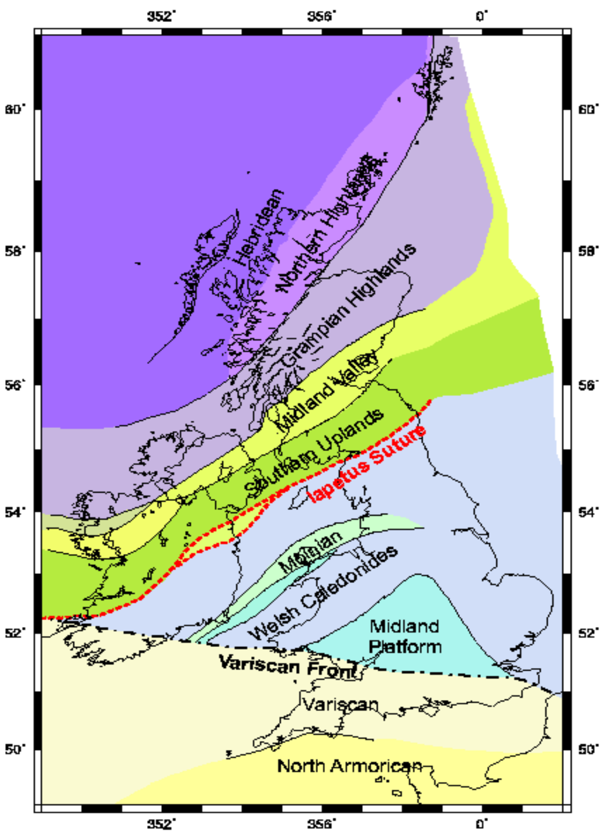
Updated every 10 minutes

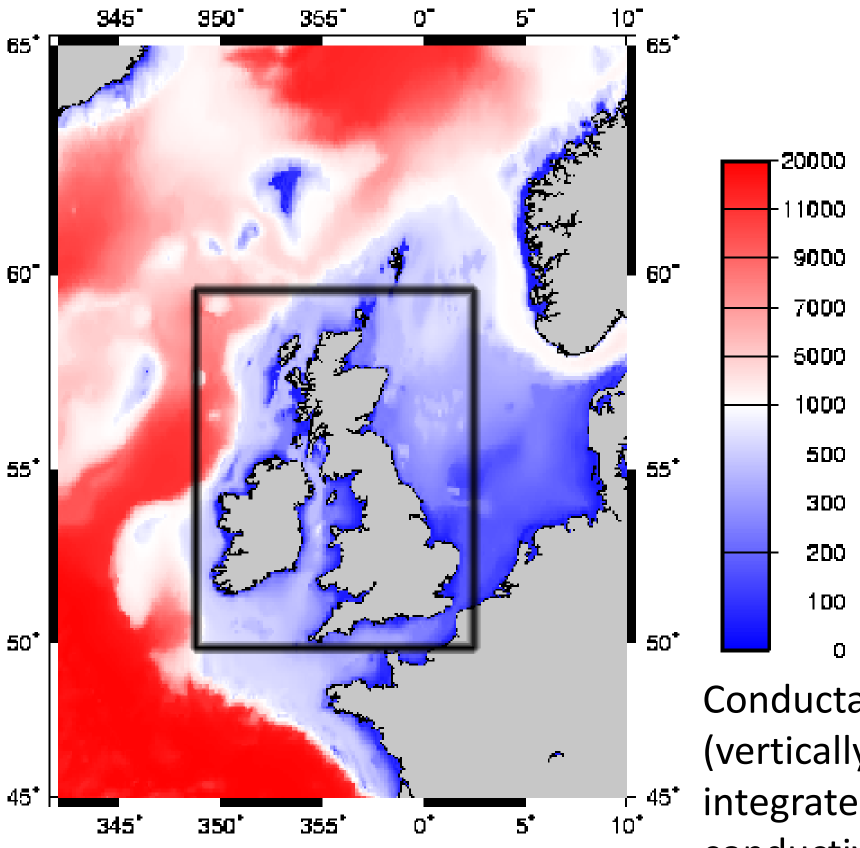
Time series displays for the 4 GIC measurement sites

Animation of complete grid response to GIC

Near real-time geomagnetic, solar wind monitors & geomagnetic forecasts

UK – Islands & Geology (makes things worse)

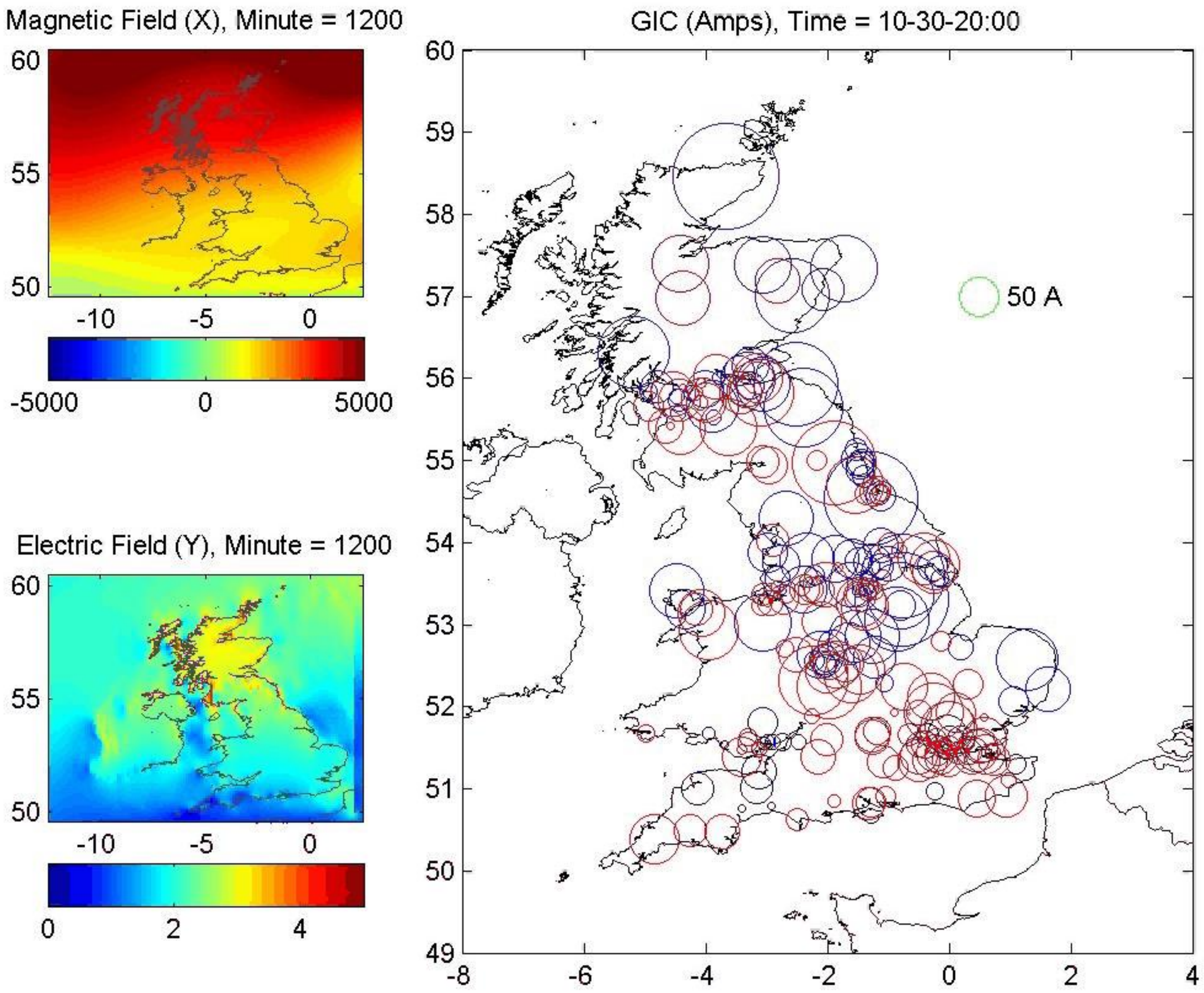




Conductance (vertically integrated conductivity) of top 3 km in mS

- **Northerly latitude (near the auroral zone)**
- **Geologically 'resistive' rocks particularly in Scotland**
- **Surrounded by (electrically conductive) seawater on all sides**

Analysis of a geomagnetic storm



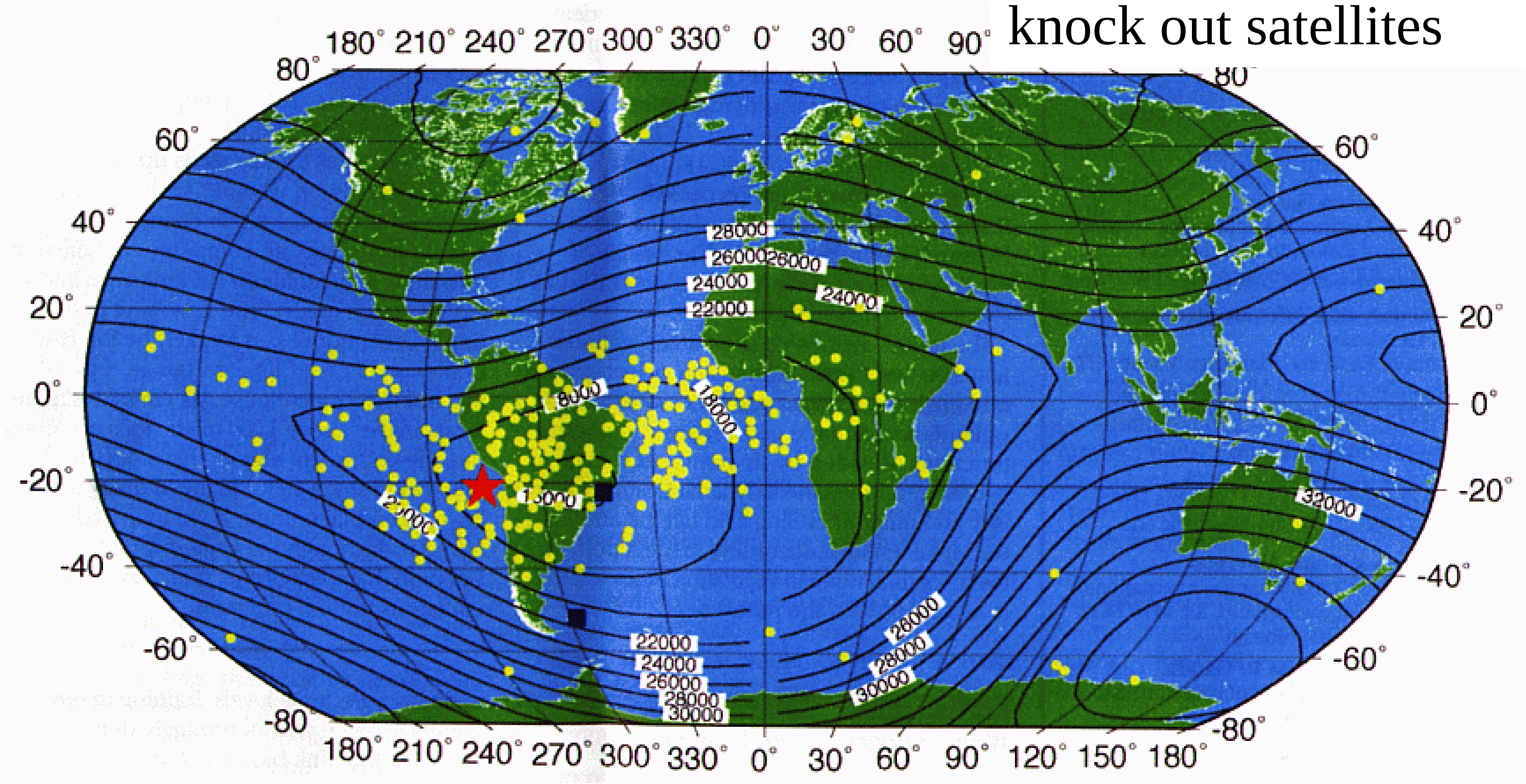
Red = current flows into ground;

Blue = current flows into power grid

Satellite electronic failures

Weak field over South Atlantic Anomaly allows energetic particles to reach lower altitudes, affecting orbiting satellites

Geomagnetic storms can knock out satellites



Sites of 'Topex' satellite anomalies 1992-98, at approximately 1000km altitude.
Red star is site of MODIS satellite failure.

Satellite electronic failures

Geomagnetic storms can knock out satellites

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04/20/10 02:05 PM ET

Orbital Blames Galaxy 15 Failure on Solar Storm

By Peter B. de Selding

ShareThis

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.

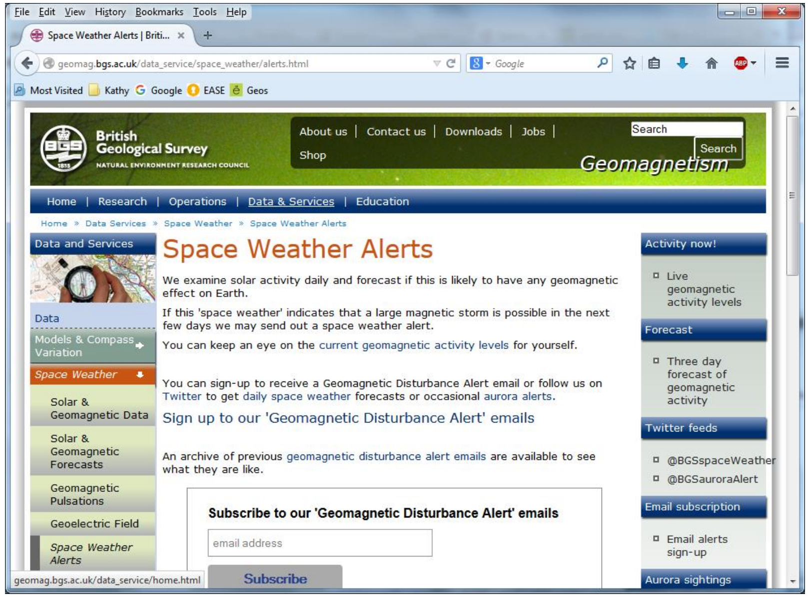
Galaxy 15 satellite. Credit: Orbital Sciences' photo

Enlarge Image

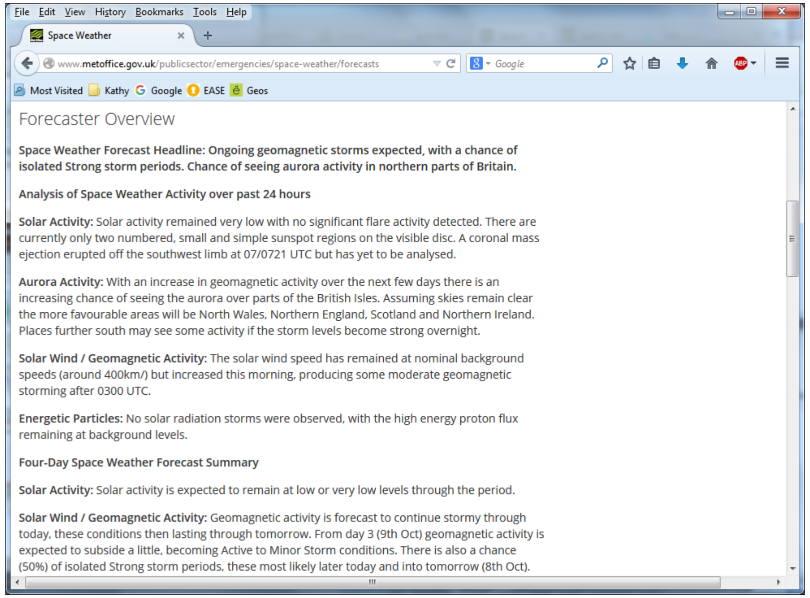
Similar events have occurred, if less severely, on other Orbital spacecraft over the years, and all of these satellites were returned to service. Company officials said they remain confident that once Galaxy 15's commercial traffic has been off-loaded to another Intelsat satellite and full testing of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

Space weather alerts and forecasts



British Geological Survey issues space weather alerts



… and the Met Office space weather forecasts

Sun-Climate interaction theories

- Galactic Cosmic Rays
  - GCR interact with atmosphere creating clouds
  - Sun's magnetic field deflects intergalactic GCR when active; less so when quiet
  - Partially explains relation to sunspots
  - Paper by CERN (2011) partially confirms this mechanism

Atmos. Chem. Phys., 10, 1635–1647, 2010
www.atmos-chem-phys.net/10/1635/2010/

Atmospheric Chemistry and Physics

Results from the CERN pilot CLOUD experiment

J. Duplissy[1], M. B. Enghoff[2], K. L. Aplin[3], F. Arnold[4], H. Aufmhoff[4], M. Avngaard[2], U. Baltensperger[5], T. Bondo[2], R. Bingham[3], K. Carslaw[6], J. Curtius[7], A. David[1], B. Fastrup[8], S. Gagné[9], F. Hahn[1], R. G. Harrison[10], B. Kellett[3], J. Kirkby[1], M. Kulmala[9], L. Laakso[9], A. Laaksonen[11], E. Lillestol[12], M. Lockwood[3], J. Mäkelä[13], V. Makhmutov[14], N. D. Marsh[2], T. Nieminen[9], A. Onnela[1], E. Pedersen[8], J. O. P. Pedersen[2], J. Polny[2], U. Reichl[4], J. H. Seinfeld[15], M. Sipilä[9], Y. Stozhkov[14], F. Stratmann[16], H. Svensmark[2], J. Svensmark[2], R. Veenhof[1], B. Verheggen[5], Y. Viisanen[17], P. E. Wagner[18], G. Wehrle[5], E. Weingartner[5], H. Wex[16], M. Wilhelmsson[1], and P. M. Winkler[18]

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Are there connections between the Earth's magnetic field and climate?

Vincent Courtillot[a,*], Yves Gallet[a], Jean-Louis Le Mouël[a], Frédéric Fluteau[a], Agnès Genevey[b]

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Available online 20 December 2006
Editor: R.D. van der Hilst

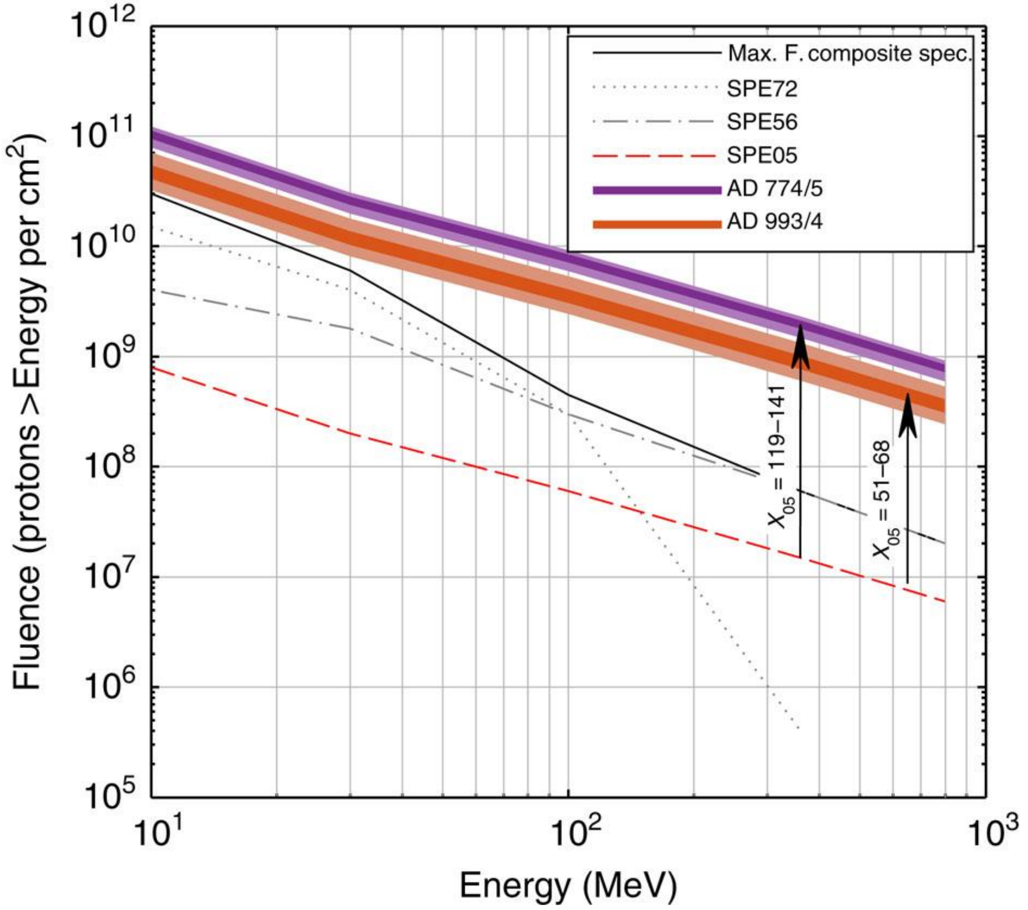
Abstract

Understanding climate change is an active topic of research. Much of the observed increase in global surface temperature over the past 150 years occurred prior to the 1940s and after the 1980s. The main causes invoked are solar variability, changes in atmospheric

Solar proton events

- Energetic particle expulsion from sun – solar proton events (SPE)
- SPEs deplete ozone and thus possibly affect weather and atmospheric circulation
- SPEs are quantitatively described by their fluence (i.e., number of incident particles per cm^2) of protons with kinetic energies above 30 MeV
- The Carrington (1859) event was characterized by a fluence ≥30 MeV of 1.9×10^{10} protons per cm^2
- Ice core records – radiocarbon spikes originated from extreme SPEs

Fluence spectra from ice cores



- Associated with the AD 774/5 and 993/4 events and of a very hard (SPE56) and a soft (SPE72) SPE that occurred during the instrumental era
- Black curve represents a composite series of the highest fluences recorded during the instrumental period between 1956 and 2005 based on previously published data
- The strongest event (AD 775) had a fluence at least five times larger than any observed SPE during the instrumental period

IAGA services and activities

- Aims to involve, build and strengthen the community
- Runs biennial Summer School, sponsors Workshops and Topical Meetings
- Supports geomagnetic observatories in producing the highest quality data
- INTERMAGNET sets digital data equipment, measuring and reporting standards (member of ICSU World Data System)
- Many now provide near-real time data
- Sampling rate is increasing → minute means
- Observatory data freely available from World Data Centres


IAGA OBSERVATORY WORKSHOP
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ON
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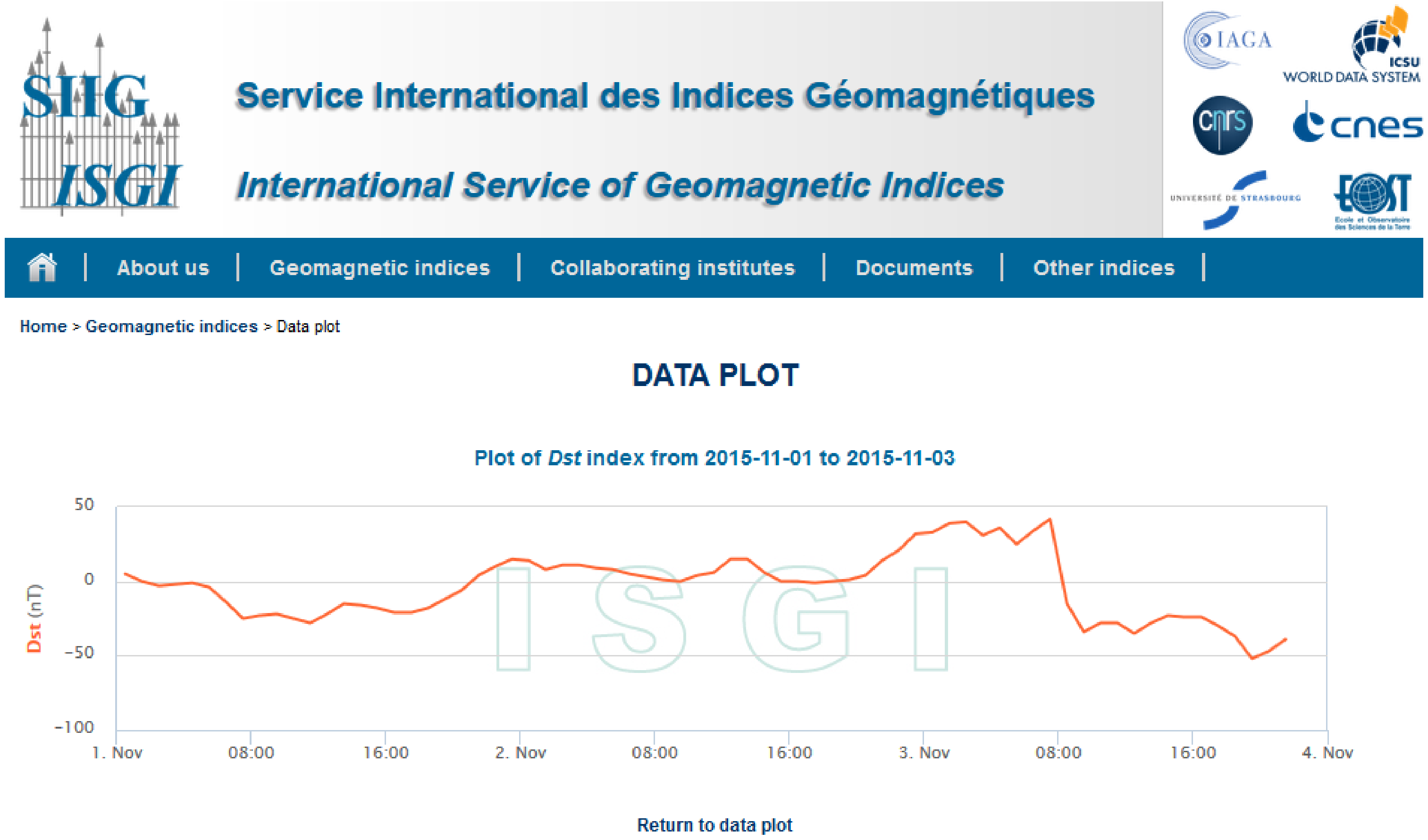
Indian Institute of Geomagnetism
Navi Mumbai - 410218 Maharashtra, India

Summer Schools

IAGA services and activities

- IAGA sets the specifications for indices – typically calculated every 3 hours – measuring magnetic activity, and for magnetic field models
- The International Geomagnetic Reference Field (IGRF) describes the main field and its secular variation (updated every 5 years)
- Candidate IGRF models are evaluated by an IAGA team
- IGRF is used for navigation, working out the trajectory of charged particles, …
- The World Magnetic Model compiles and integrates lithospheric field data

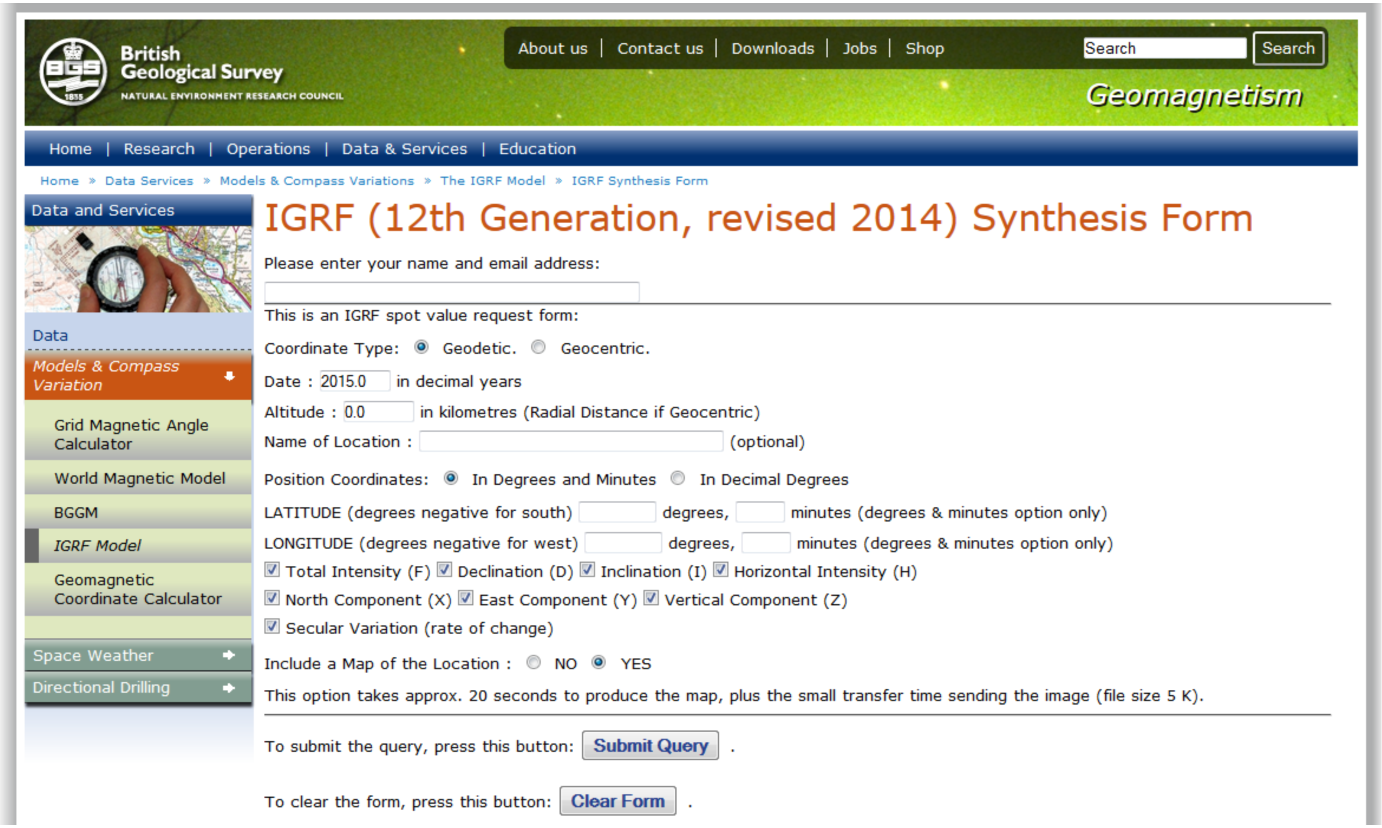
Example of indices – Dst



Dst ('Disturbance storm time') monitors the strength of magnetospheric currents

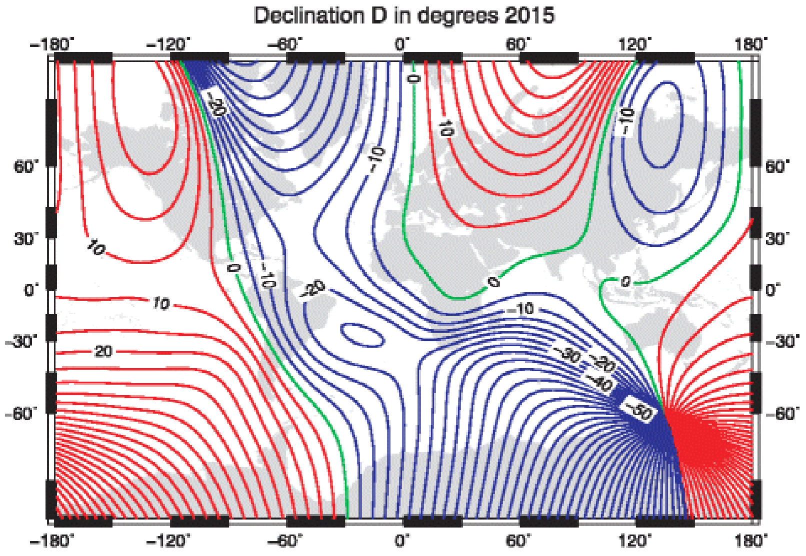
Calculated every hour

Online calculator for IGRF



Reference:

Thébault *et al.*, International Geomagnetic Reference Field: the 12th generation *Earth, Planets and Space*, 2015



World Digital Magnetic Anomaly Map

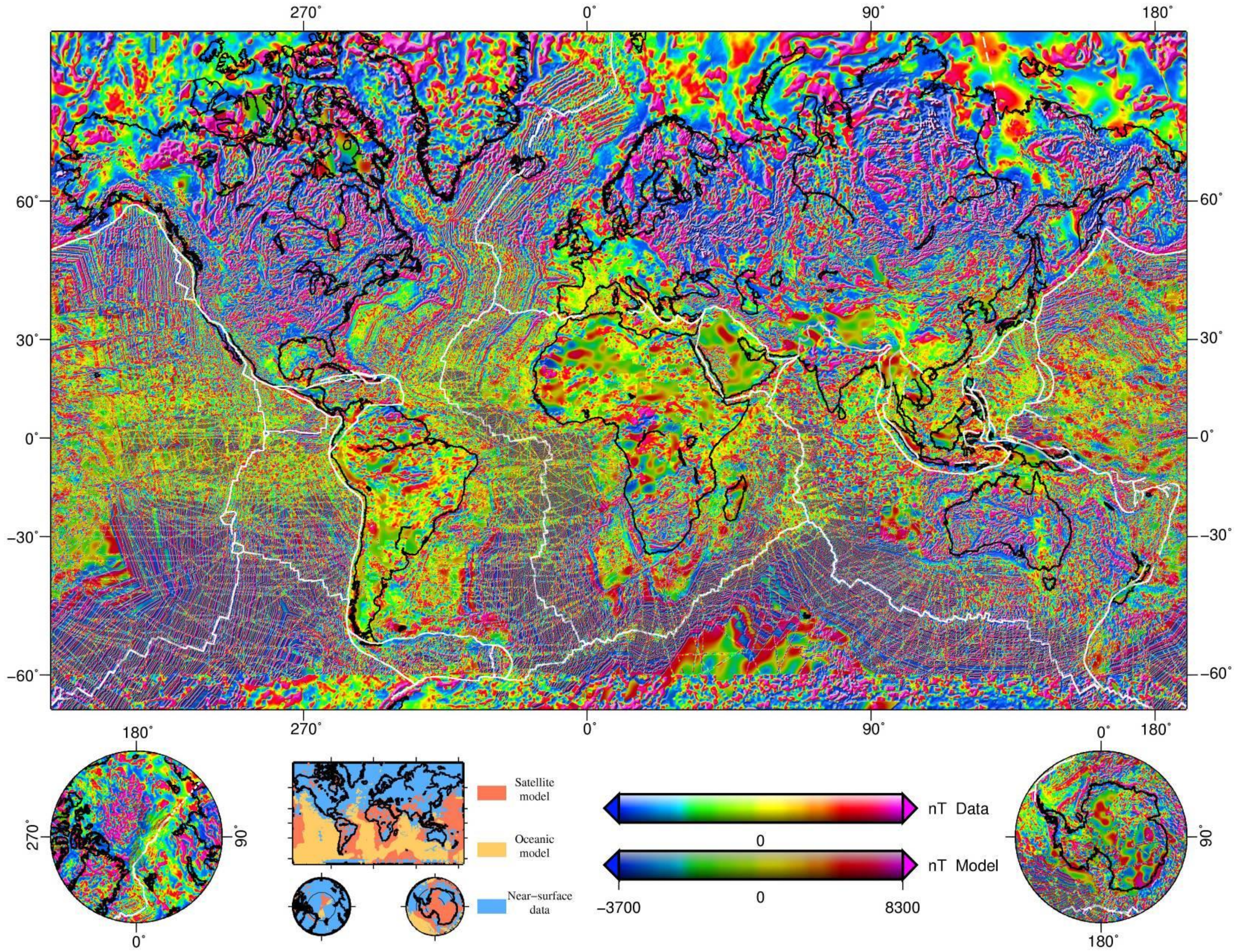


Image: Korhonen, J.V., Fairhead, J.D., Hamoudi, M., Hemant, K., Lesur, V., Mandea, M., Maus, S., Purucker, M., Ravat, D., Sazonova, T.,and Thebault, E., 2007, Magnetic Anomaly Map of the World (and associated DVD), Scale: 1:50,000,000, 1st edition, Commission for the Geological Map of the World, Paris, France.

Summary and challenges

- Many countries run observatories to international standards despite the cost and there being no obvious benefit
- Observatory staff tend to be highly skilled and very dedicated
- Observatories and instruments for monitoring space weather require steady power supply, internet/phone connections, magnetically quiet areas etc – not easy to maintain in many developing countries
- Satellite data cannot replace observatories – the space environment where they measure is very different and much more complex
- Potential for ‘citizen science’ measurements using smart phones, but data are noisy
- Grand challenge problems are very resource/data intensive – not easy for isolated researchers or observatory staff to contribute