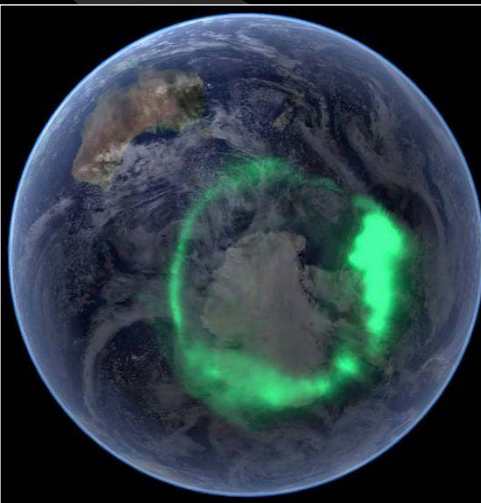


Mike Lockwood

University of Reading



movie: Aurora over Finland , 31st December 2024 by Night Light Films

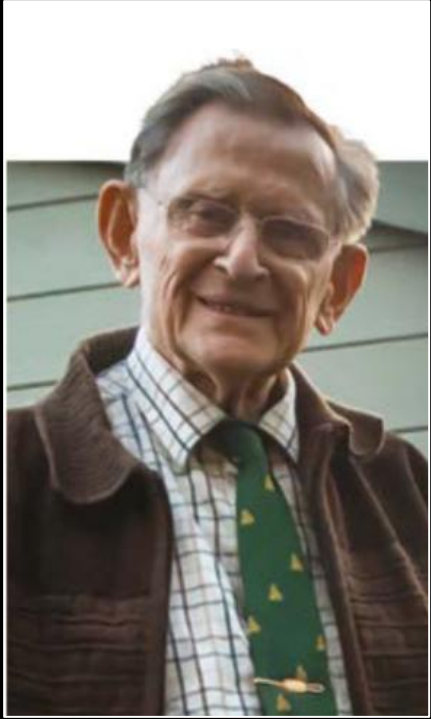


Great Auroral Events:

how the reporting has changed throughout history

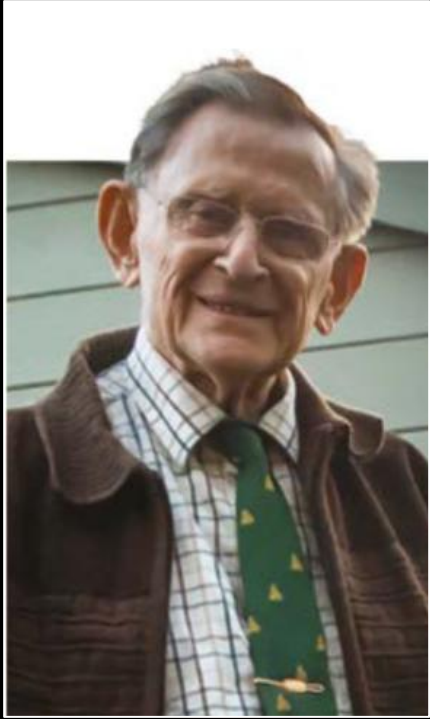
Lecture in Honour of David M. Willis, Marcham 19th September 2026

David Willis



a wonderful mentor for me

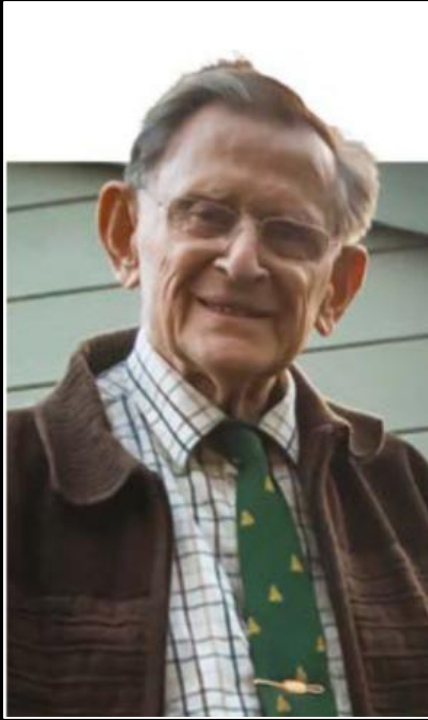
David Willis



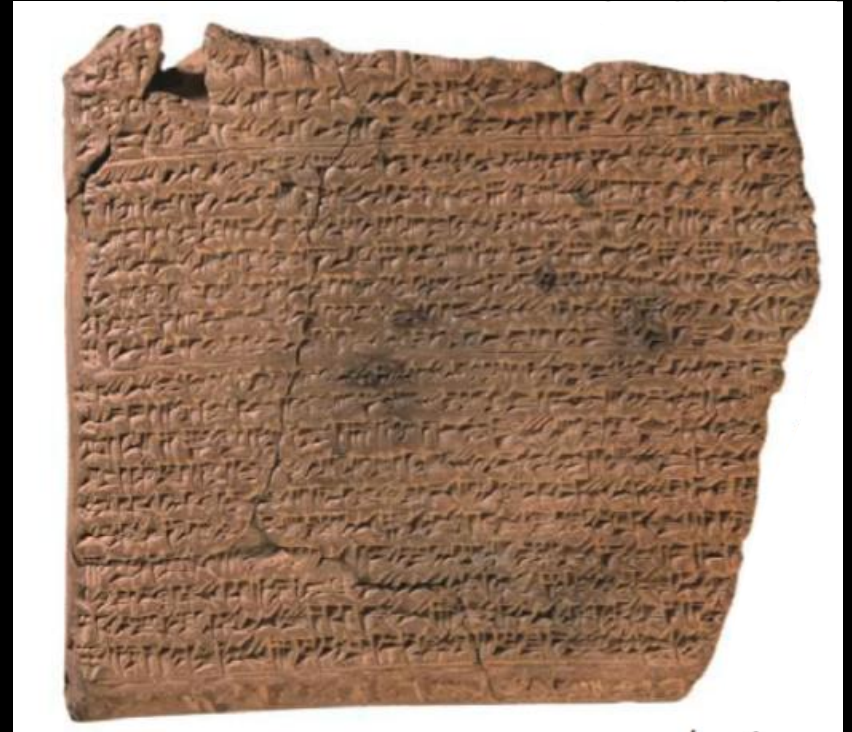
a space physicist

ahead of his time
because looking at the past
has helped us understand the present

David Willis



The Babylonian tablet
(Vorderasiatisches Museum, Berlin
(VAT4956) that contains the record of
the aurora in 567 BCE (in Akkadian)



12/13 March 567 BCE:
the first known dateable observation of an aurora
(Stephenson and Willis, 2002)

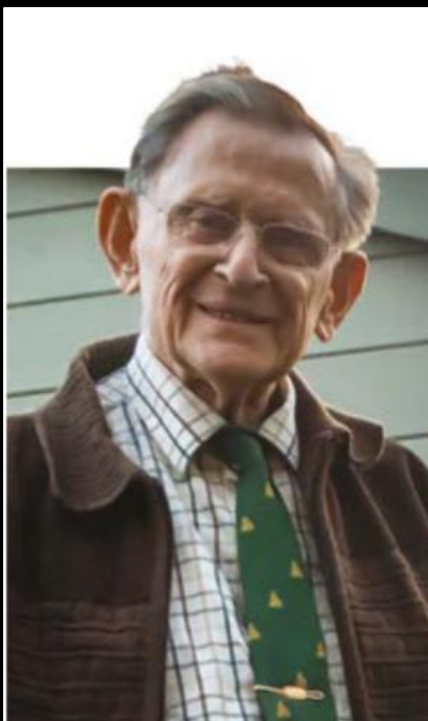


Historic Reports of Low-Latitude Aurorae



- Stephenson and Willis found other ancient texts appear to be describing aurora at low latitudes as 12/13 March 567 BCE
- Many have interpreted Ezekial's vision in the old testament Bible as aurora. S&W note it tallies with Chinese Assyrian and Babylonian texts but definitive evidence is missing
- Ezekial's description is exactly like a red coronal (overhead) aurora. He was thought to be in Nippur (Iraq) at a magnetic latitude of 41°
- This study will compare 4th May 2024 with events since 1650 CE

David Willis



Q. J. R. astr. Soc. (1996), 37, 733–742

Auroral Observations on AD 1770 September 16: the Earliest Known Conjugate Sightings

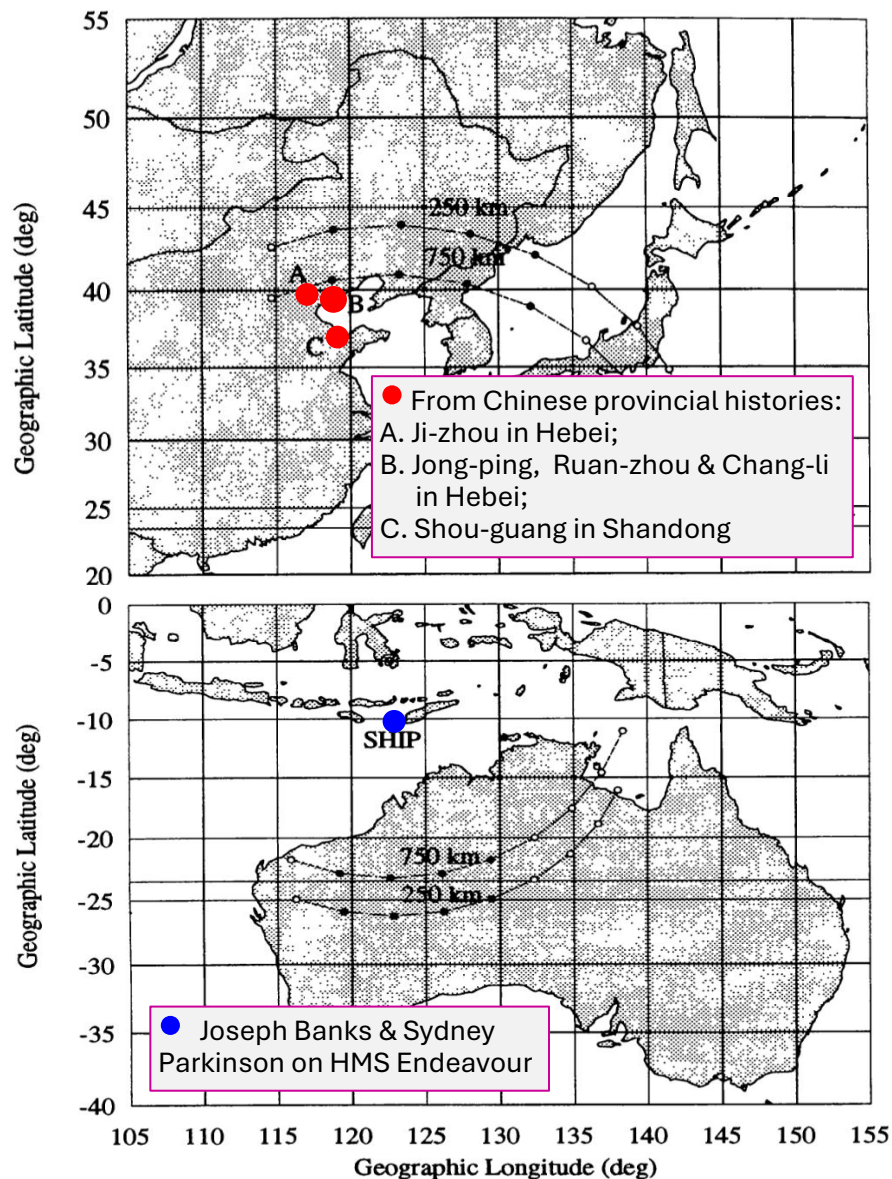
David M. Willis,^{1,*} F. Richard Stephenson² and J. Robin Singh^{1,3}

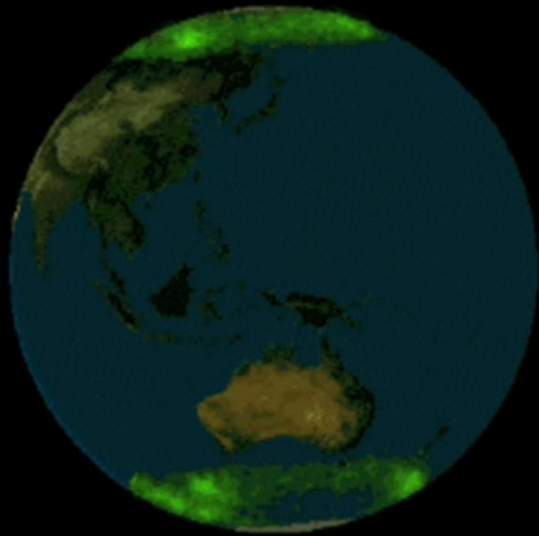
¹Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX, ²Department of Physics, University of Durham, Durham DH1 3LE, ³School of Mathematical and Information Sciences, Coventry University, Coventry CV1 5FB

736

D.M. WILLIS *et al.*

Vol. 37



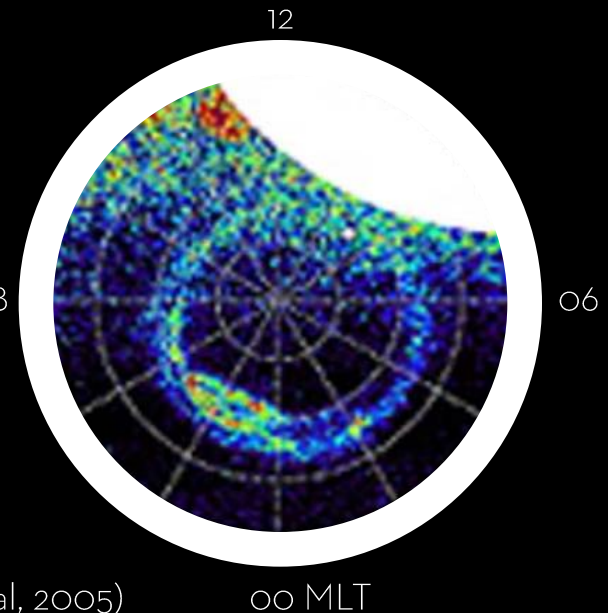
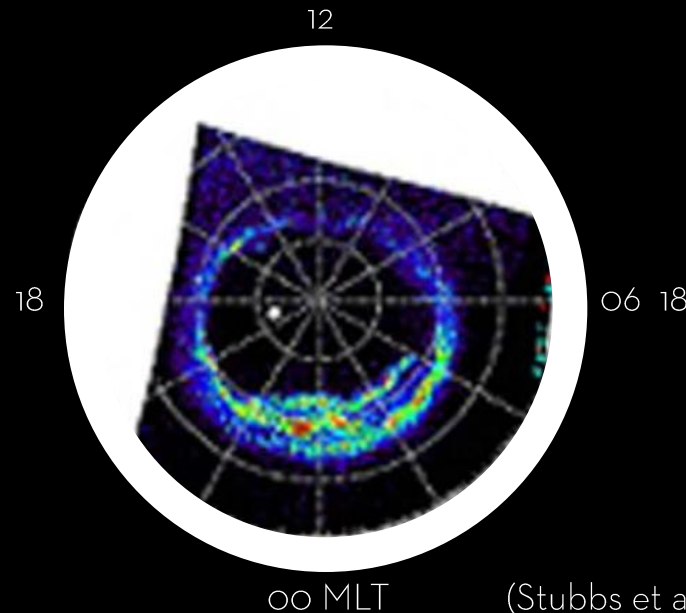


(Østgaard et al, 2011)

Polar observations (the VIS instrument) of auroras in **both hemispheres** simultaneously
07-12 UT on 22/10/2001

Northern hemisphere
12:02:02 UT on 23/10/2002
observed by the FUV-S13
instrument on Image

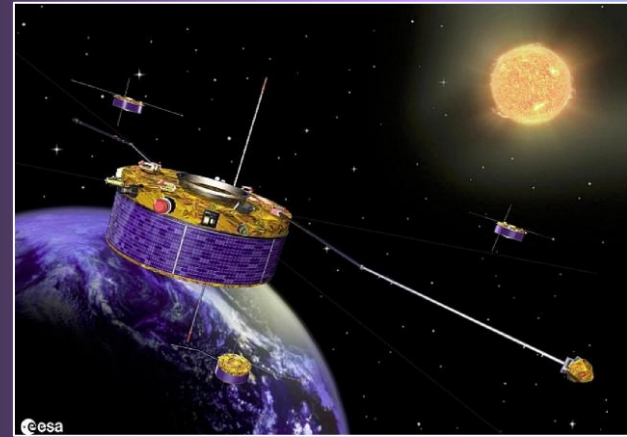
Southern hemisphere
12:02:04 UT on 23/10/2002
observed by the VIS-EC,
instrument on Polar



(Stubbs et al, 2005)

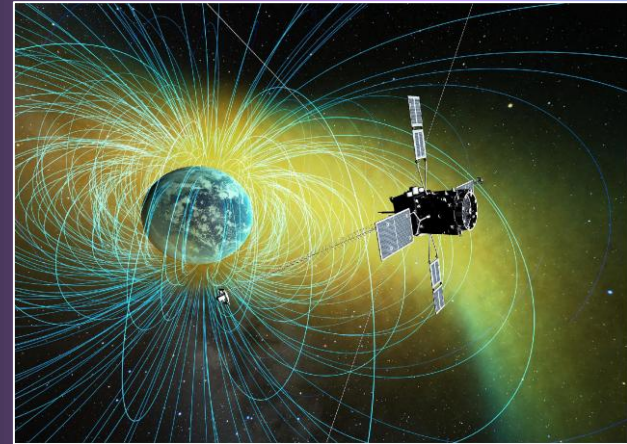
Modern Multi-Point Observations of Space

Cluster



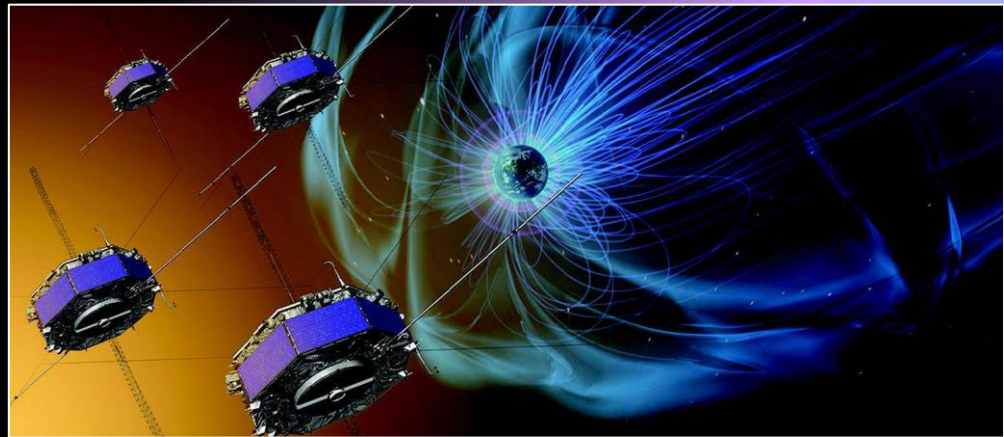
THEMIS

Time History of Events and Macroscale
Interactions during Substorms



MMS

Magnetospheric
Multiscale Mission



1722: the London watchmaker George Graham observed the fluctuations that we now call “geomagnetic activity”



1st March 1741: Olof Hiorter in Uppsala discovers geomagnetic activity is associated with aurora and disturbance on the same night is recorded by Graham in London – the first multipoint observations in space physics

“Who could have thought that the northern lights would have a connection and a sympathy with a magnet?”

Olof Peter Hiorter (1696-1750)

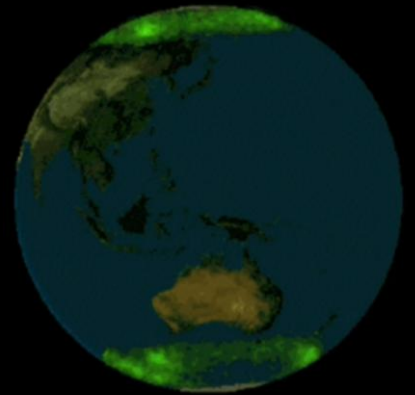




Goddess of Dawn

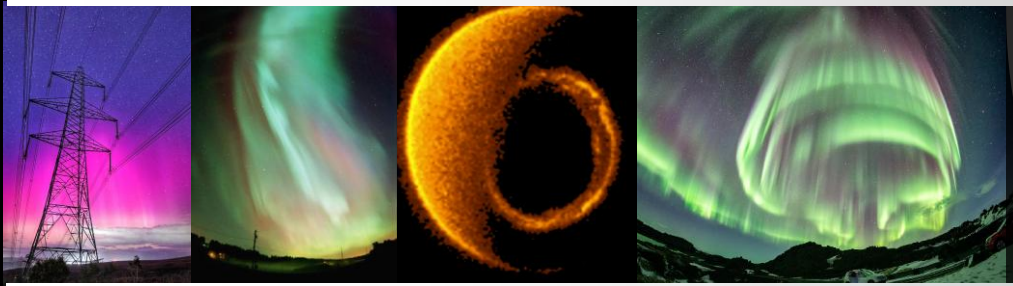
In ancient Greece she was called EOS

Adopted by the Romans
and re-named AURORA



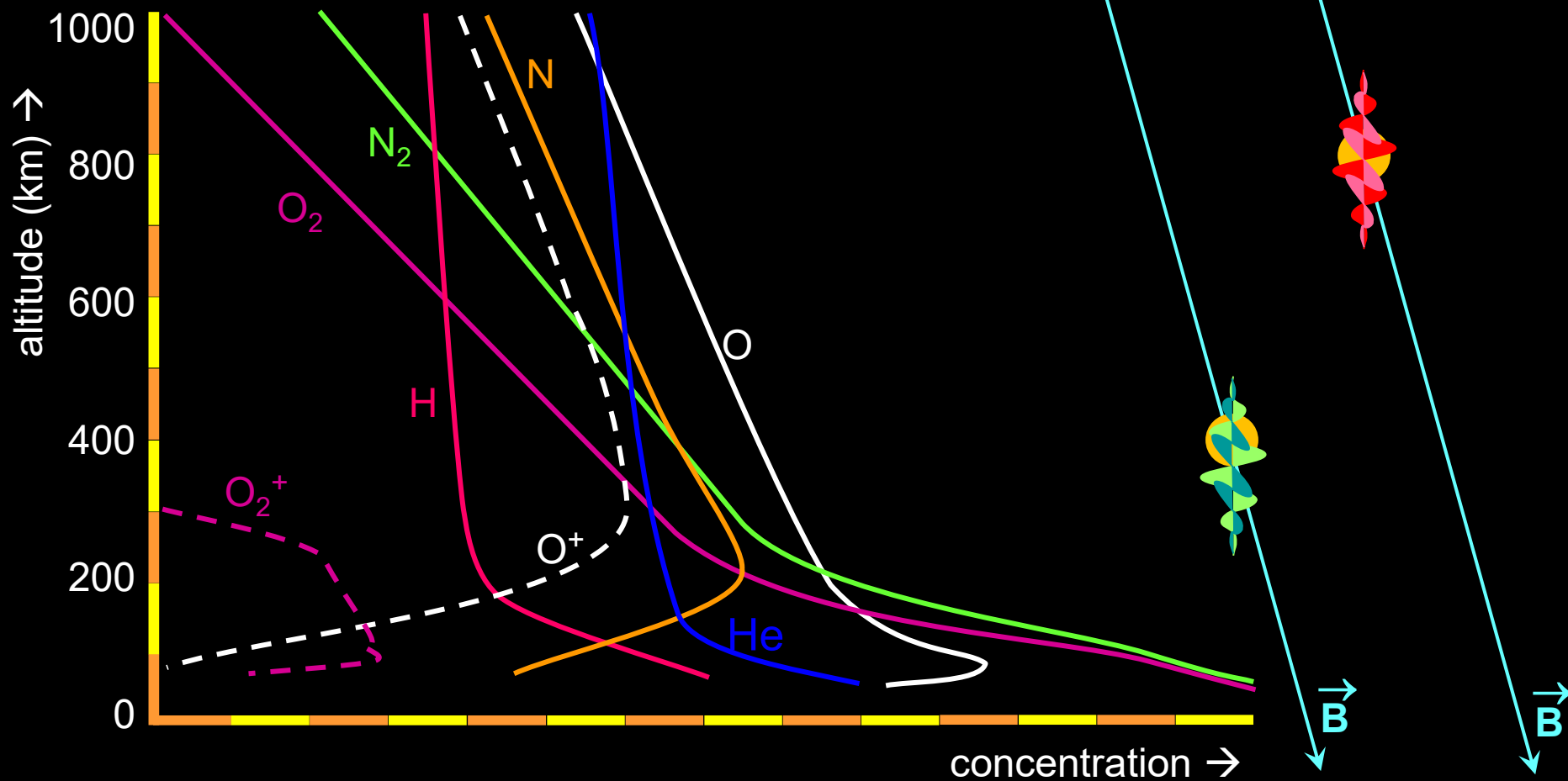
AURORA BOREALIS means “northern dawn”

AURORA AUSTRALIS means “southern dawn”



What is Aurora?

- upper atmosphere gases are excited by energetic electrons that precipitate down field lines emit light



@ ISS

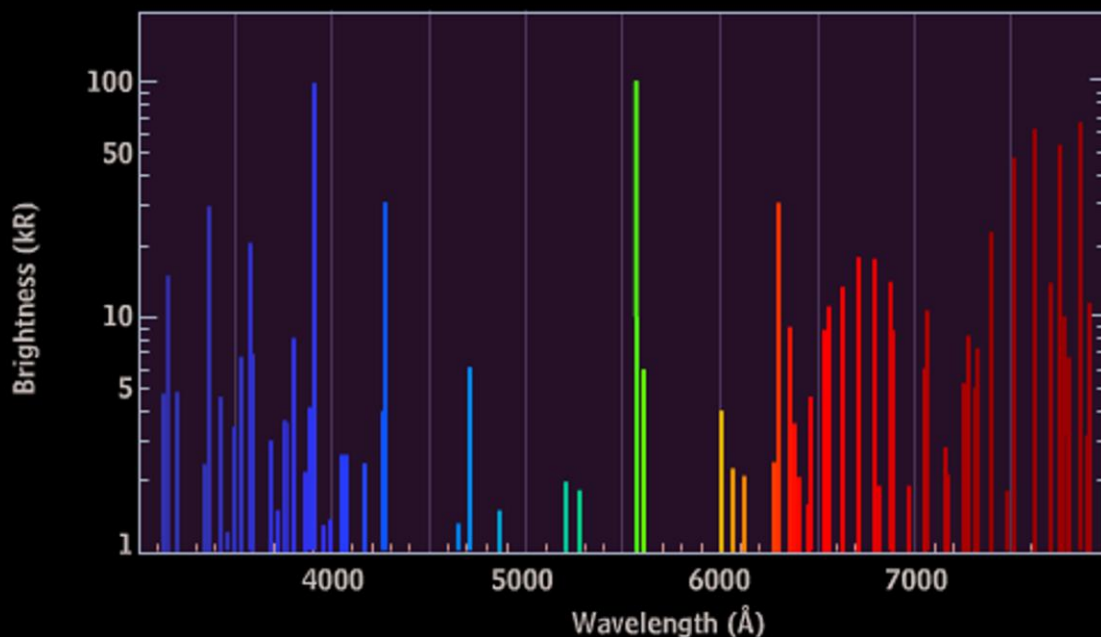


Auroral Spectrum

- higher energy electrons penetrate deeper into the atmosphere

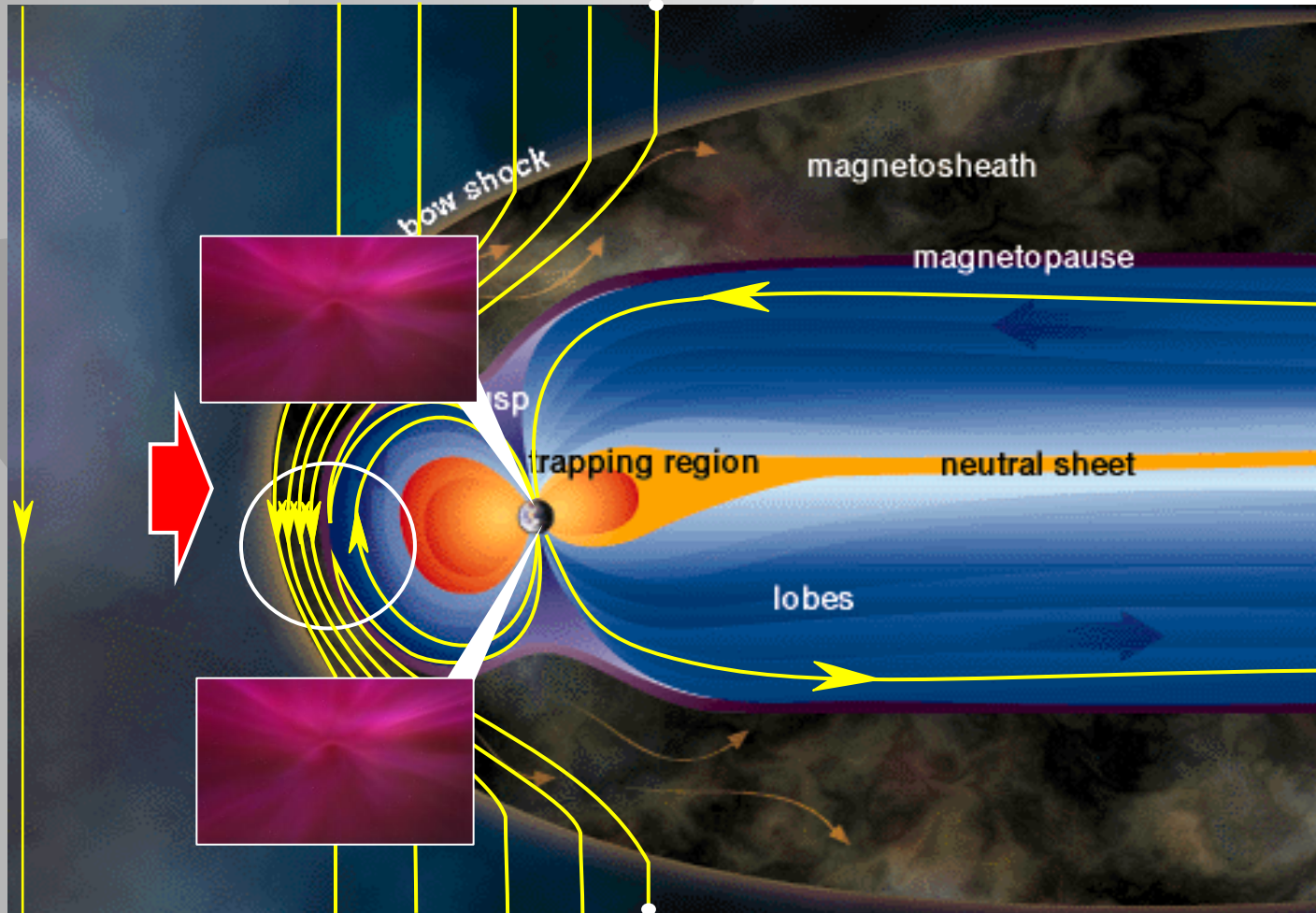
- green from higher energy electrons & oxygen atoms at $h \approx 100\text{-}120$ km
- red is from lower-energy electrons & oxygen atoms at $h \approx 250\text{-}800$ km
- red is “quenched” at low h by collisions so we see red above green
- blue/violet is from molecular nitrogen ions at $h \approx 90\text{-}100$ km or from nitrogen molecules at $h \approx 500\text{-}800$ km

Typical Auroral Spectrum



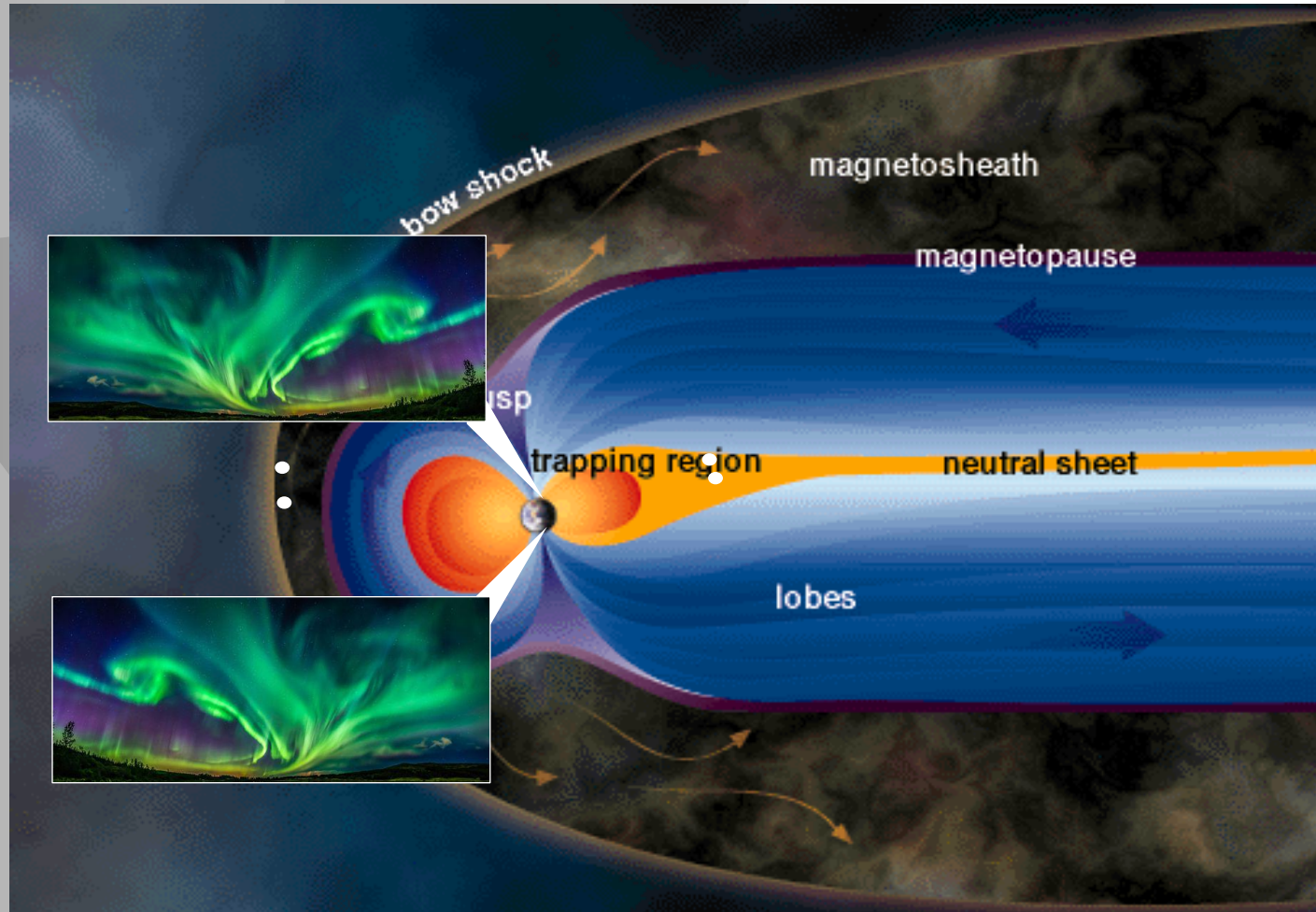
☒ H	☒ N	☒ O	☒ O ⁺
☒ N ₂	☒ N ₂ ⁺	☒ O ₂	☒ O ₂ ⁺

The Magnetosphere during southward IMF

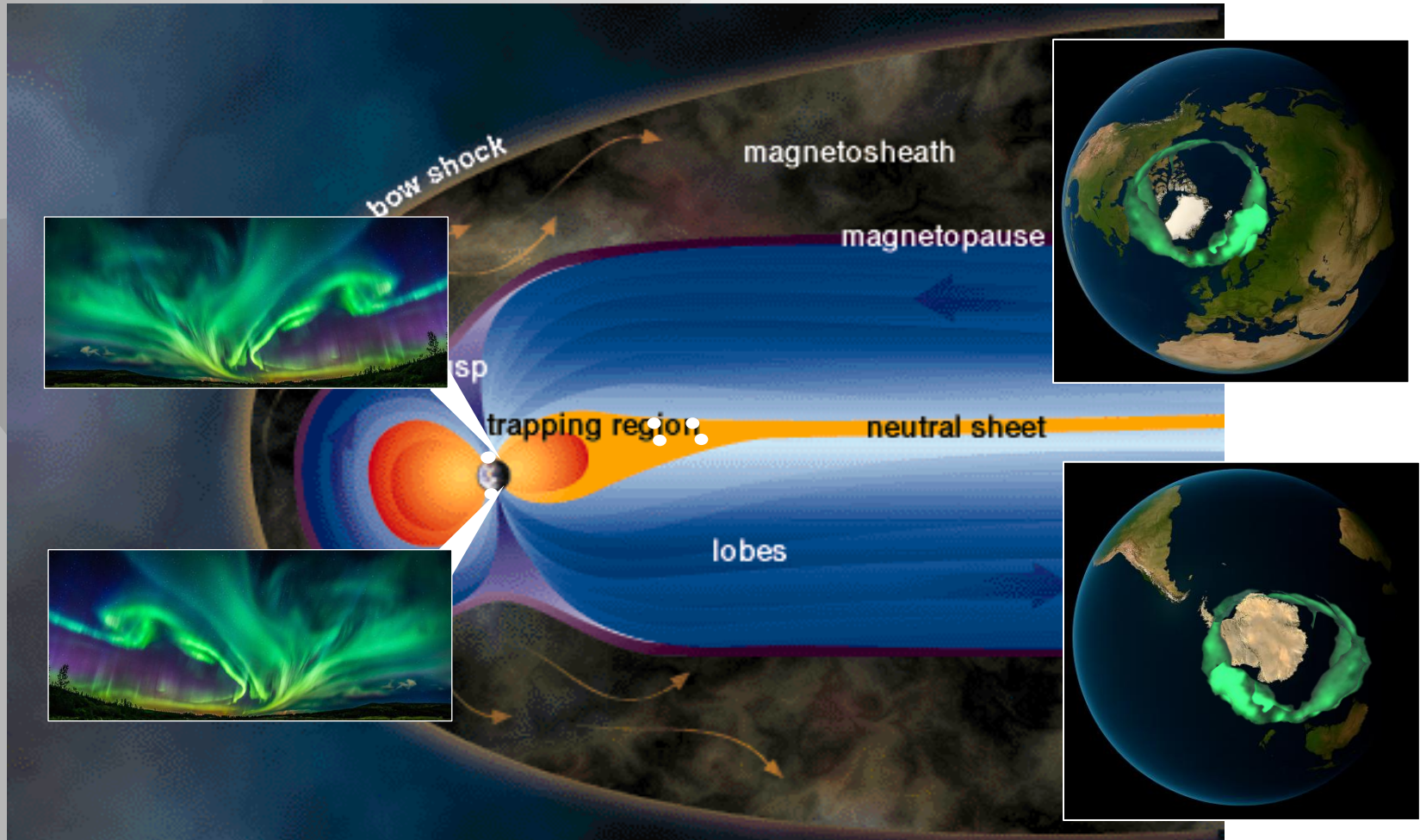




Nightside auroral particles from the solar wind

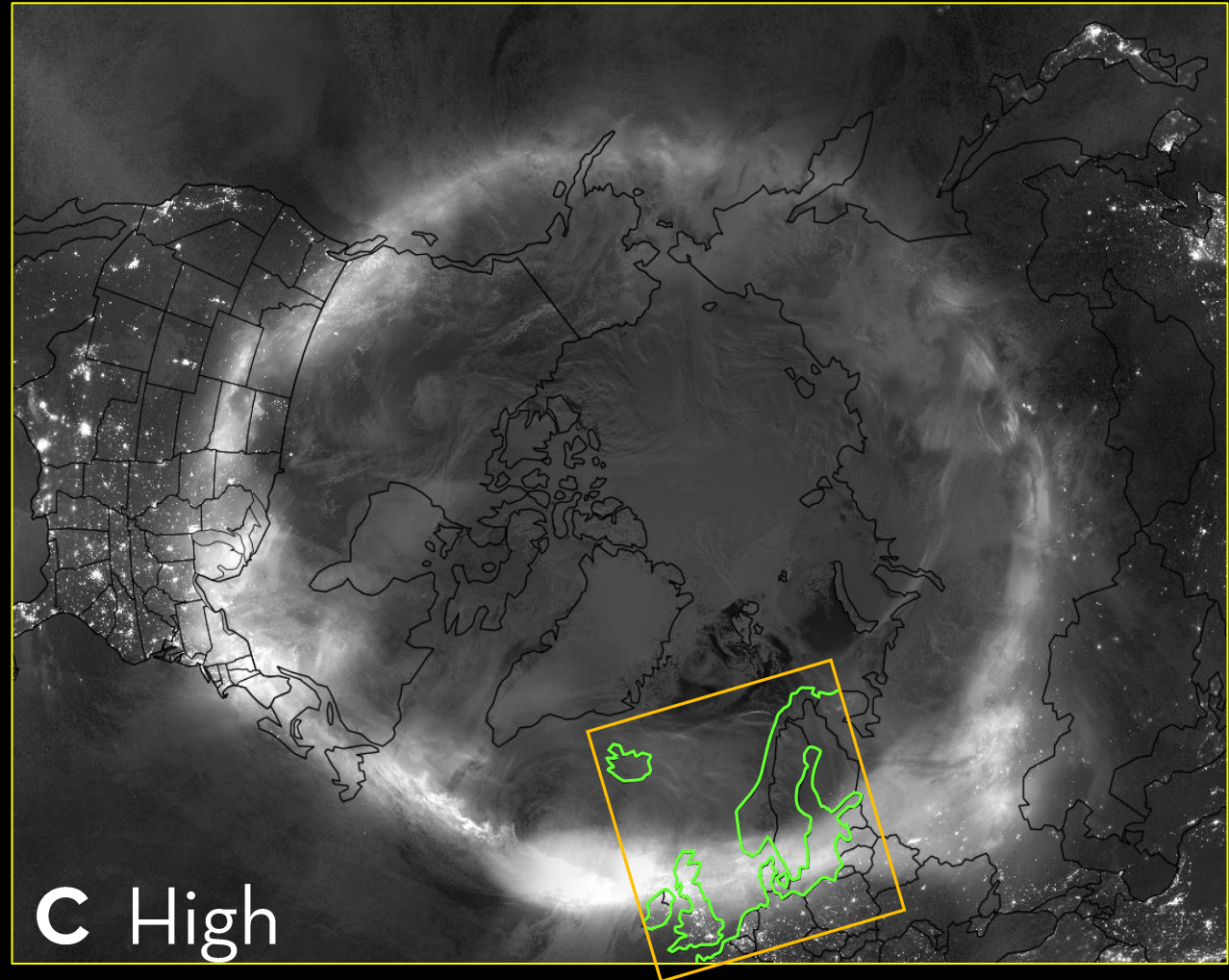
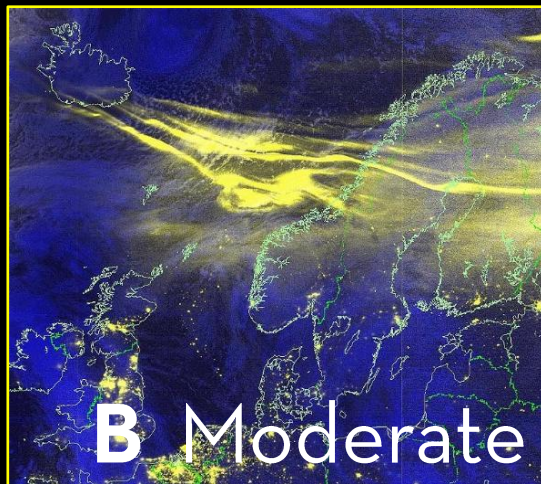
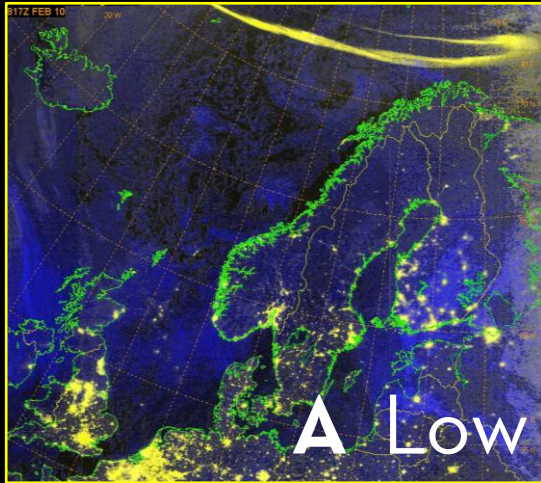


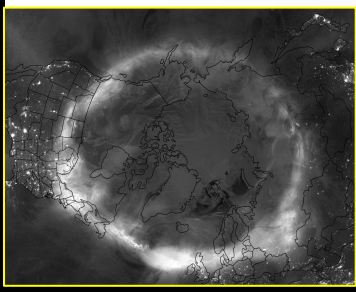
Nightside auroral particles from the ionosphere





Aurora and Activity Level





Arcs & Coronae

See arc from the side



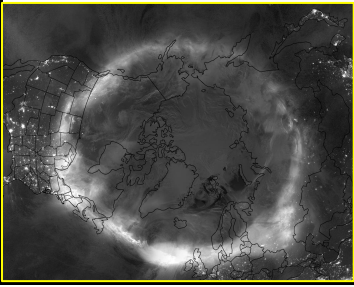
& see corona from underneath



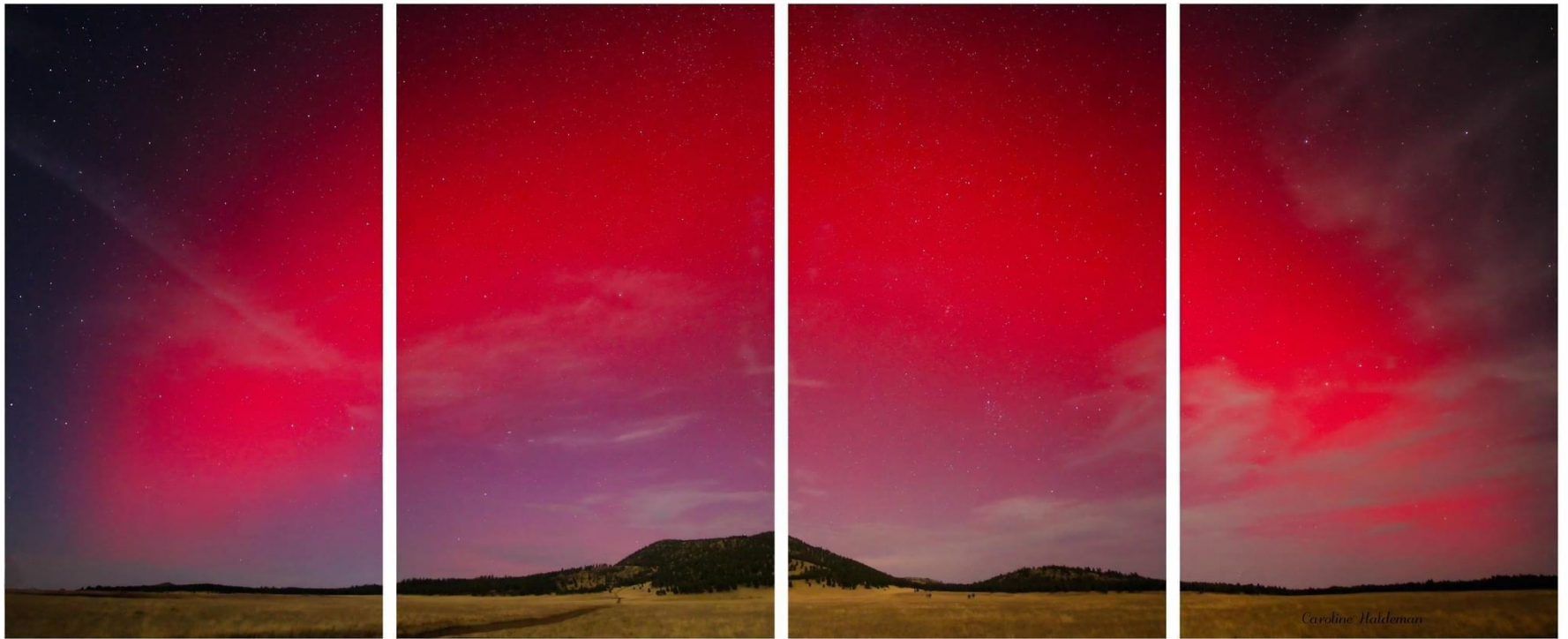
Photos: Stephane Vetter @ Jökulsárlón glacial lagoon, Iceland



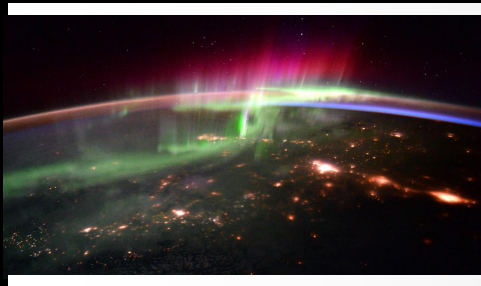
Photos: Tim Donor @ Nelchina River, Alaska



Diffuse Mid-Latitude Aurora

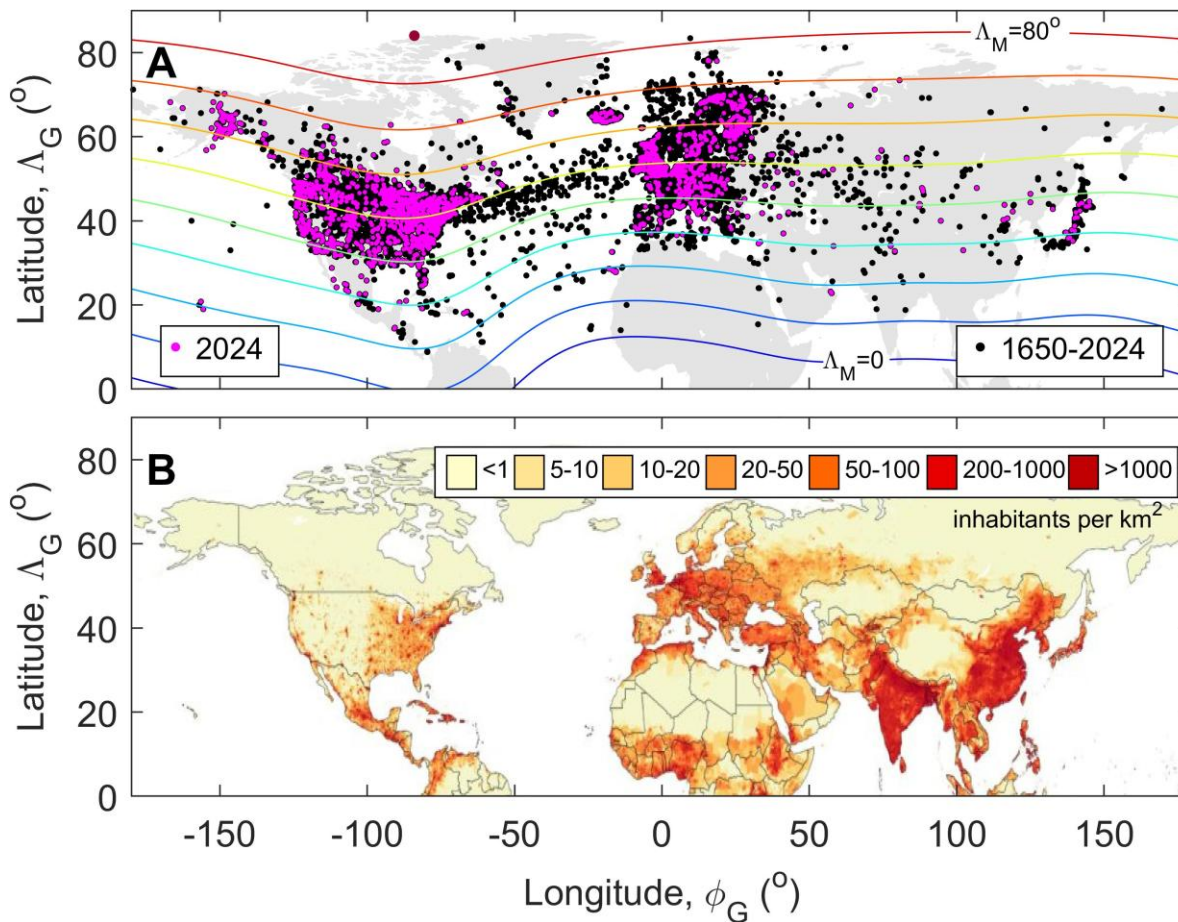


Photos: Carol Haldeman @ Flagstaff, Arizona



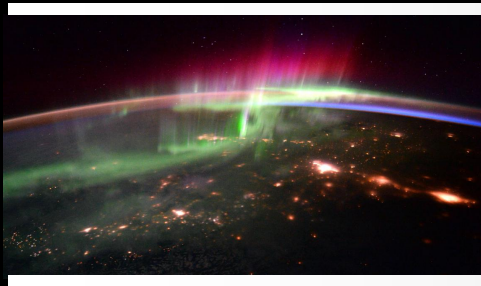
2024 in Aurorae

- Global map showing the locations of 4735 recorded sightings in 2024 (mauve dots) & of 224870 since 1650 (black dots)



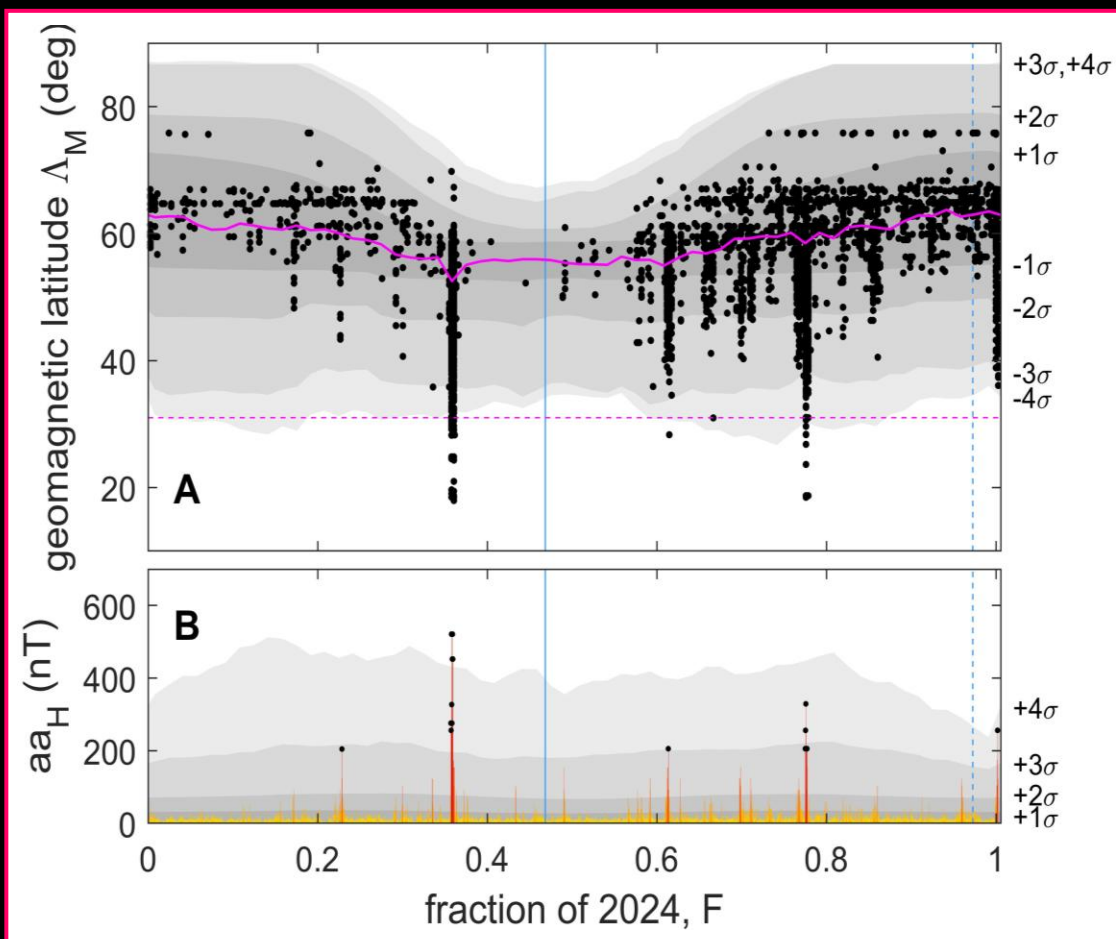
- Contours are Q-D geomagnetic latitudes, Λ_M

- Modern sightings at a fixed value of Λ_M correlate with population density

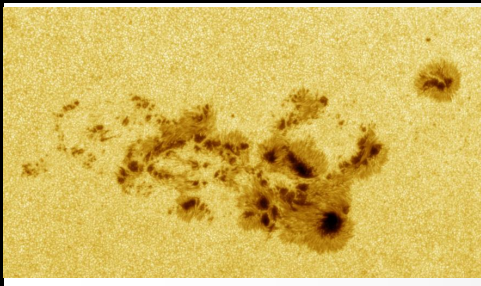


2024 in Aurorae

- Black dots are the 4735 recorded sightings in 2024 plotted by date & the geomagnetic latitude of the observer's location



- Blue line is the summer solstice
- Light-to-dark gray areas cover where aurora has been seen (since 1650) 99.99%, 99.73%, 95.45% and 68.25% of the time at that time of year
- Major auroral events are accompanied by “geomagnetic storms” as seen in the aa_H geomagnetic activity index

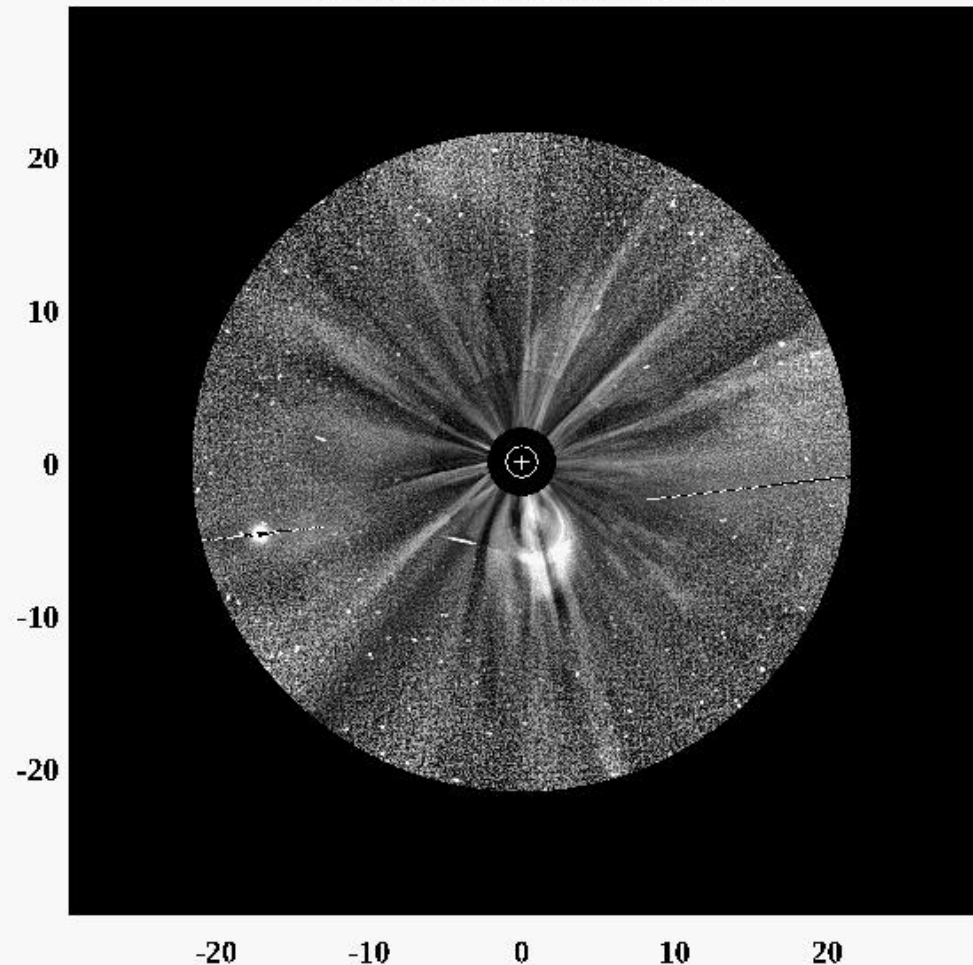


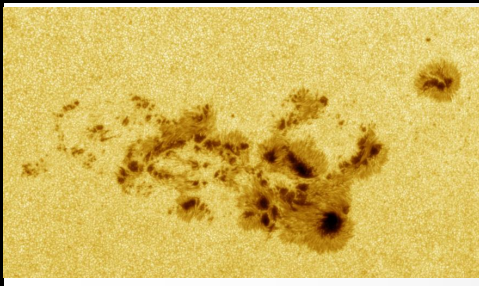
Coronal Mass Ejections

Launched from AR 3664

- Observed by SoHO Lasco C3 coronagraph
- Processed by Huw Morgan (Aberystwyth)
- These are after the main May 10/11 event and generally missing the Earth

soho c3 20240512_000606



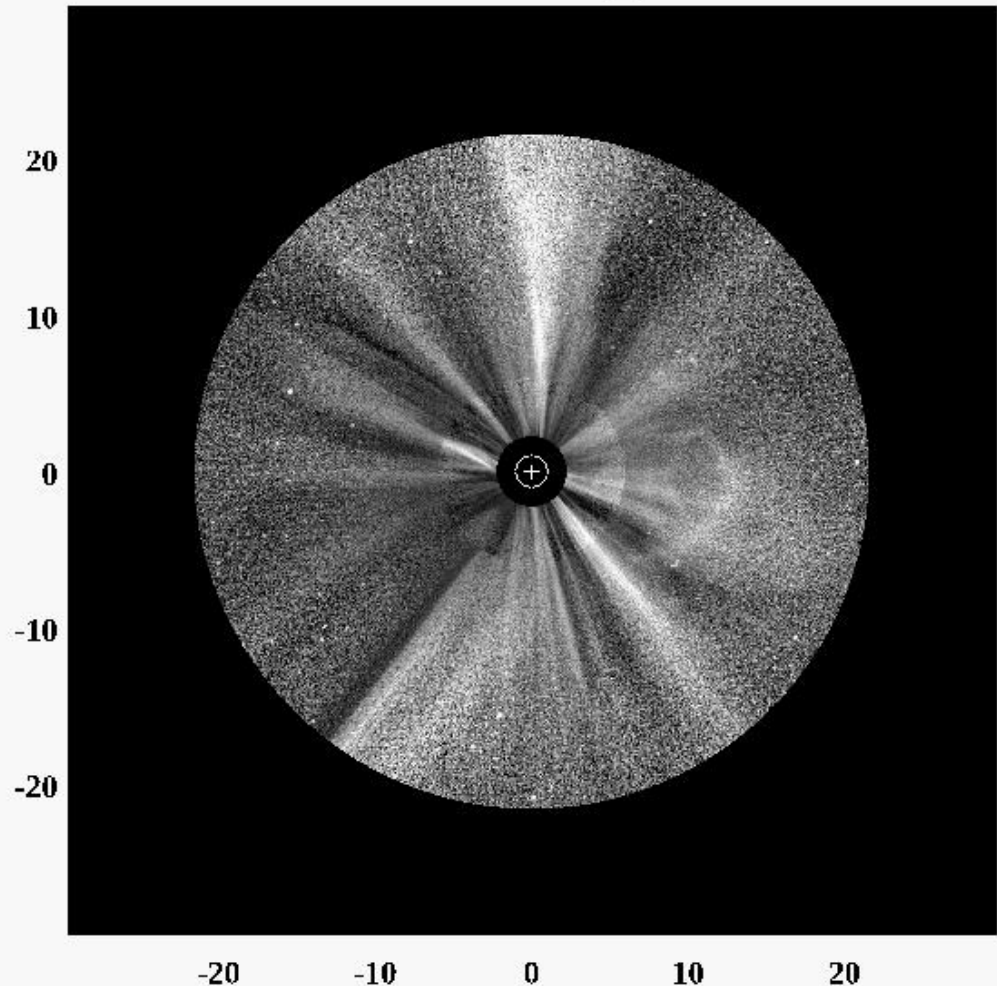


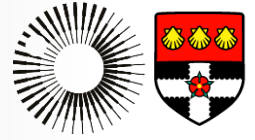
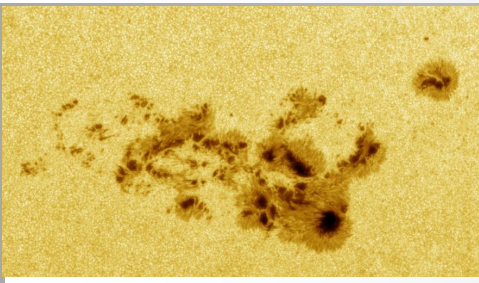
Coronal Mass Ejections

Launched from AR 3664

- Observed by SoHO Lasco C3 coronagraph
- Processed by Huw Morgan (Aberystwyth)
- These are the Earth-directed events that caused the May 10/11 event

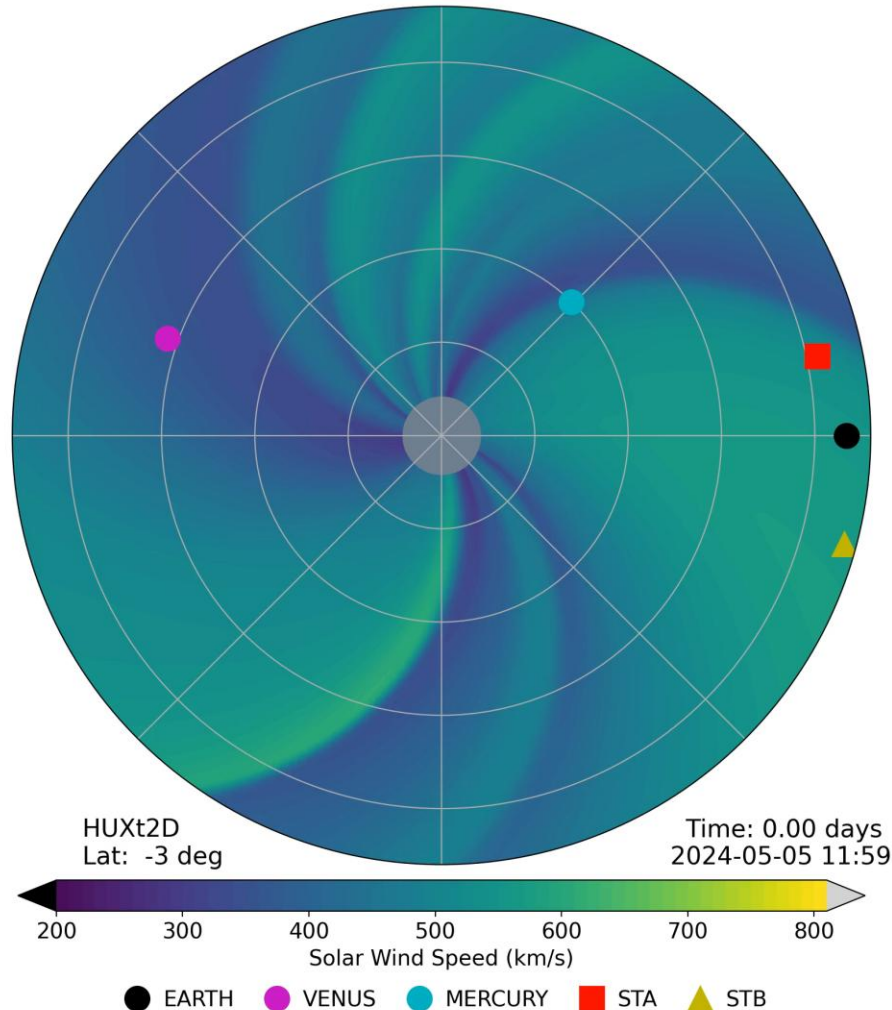
soho c3 20240507_000607





Coronal Mass Ejection

Launched from AR 3664



Forecast made
00 UT 10 May 2024

Uses the reduced-
physics HUXt model
(Mat Owens & Luke
Barnard at UoR)

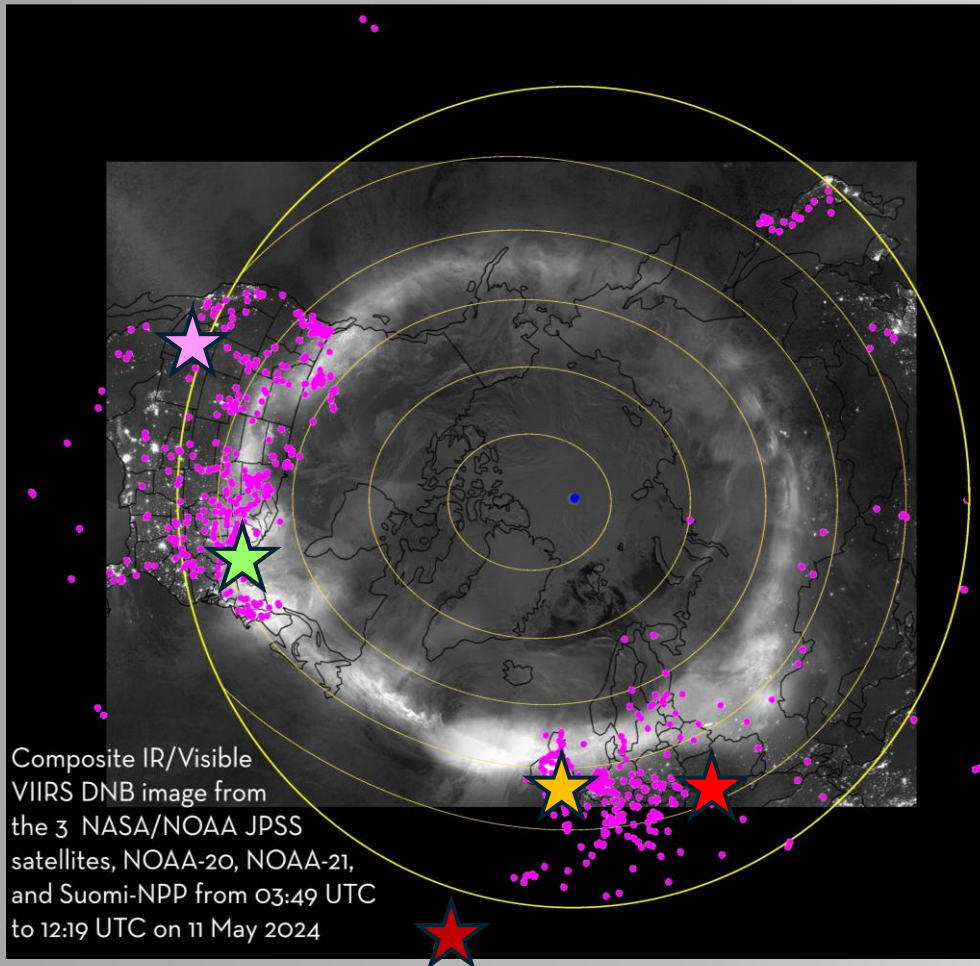
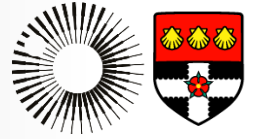
Can be run many times
to give large ensemble
of predictions and
hence probabilities of
effects at Earth

Storm commenced 17
UT, as predicted



The Event of 10-11 May 2024

The 3rd Lowest Latitude reached since records began

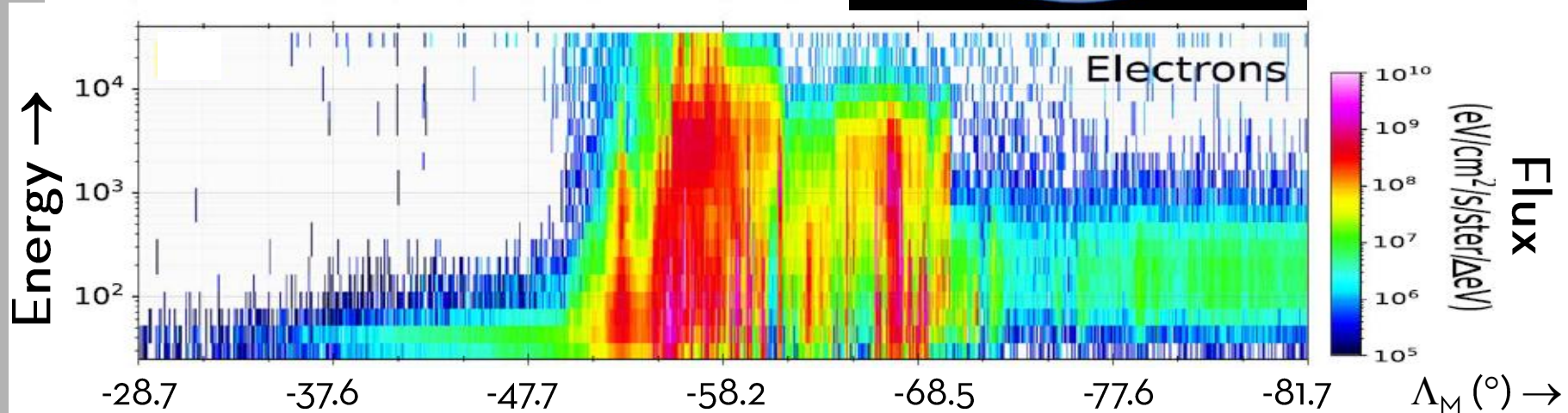
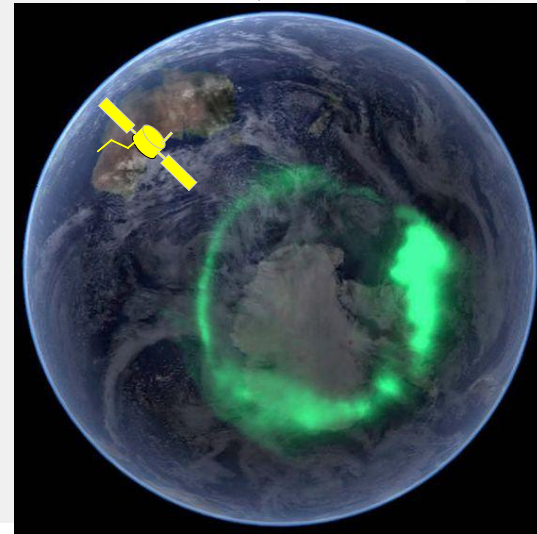
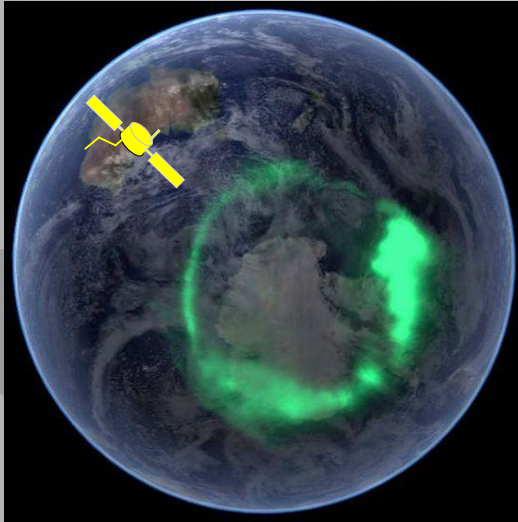




DMSP-F18 Satellite Data

- Observations of precipitating electrons

(Vichare et al, Ap. J., 2024)

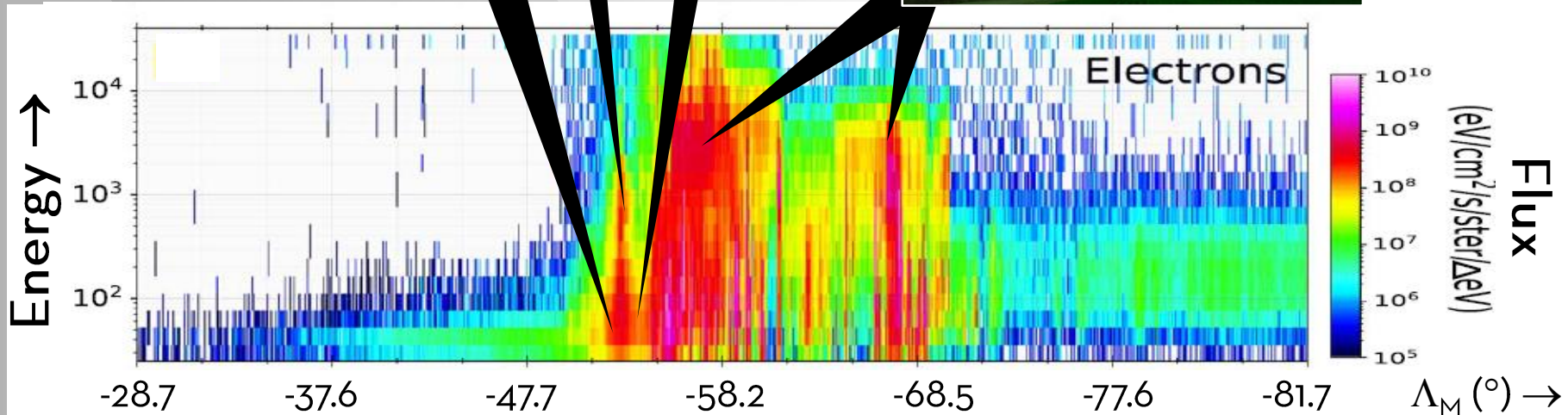




DMSP-F18 Satellite Data

- Observations of precipitating electrons

(Vichare et al, Ap. J., 2024)





Aurora and Activity Level

Lower latitudes

Tends to be more diffuse and sluggish but more varied in colour (seen more clearly by digital cameras than the human eye)

@ North Cascades National Park, Washington State



High latitudes

tends to be more structured and dynamic, with multiple arc curtains and fast-changing curls. Dominated by atomic oxygen green line.

@ Tromsø fjord, Norway



GREEN 557.7nm 1-10 keV electrons excite atomic oxygen at 120-180 km ($\tau=0.5s$)

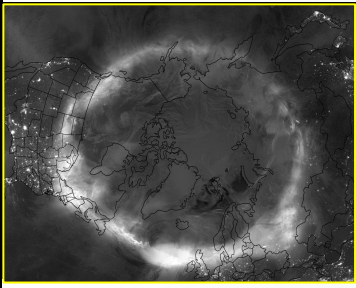
RED 630.0nm ~100eV electrons excite atomic oxygen at 250-500 km ($\tau=110s$)

MAUVE ~5 keV electrons excite ionized molecular nitrogen at 100-120 km ($\tau=0$, "prompt")

BLUE 427.8 nm ~ 1keV electrons excite molecular nitrogen at 300-400 km

PALE GREEN & BLUE 656.3nm & 486.1nm ~10keV protons at 110-120km

Other colours (**WHITE, PINK, PURPLE, ORANGE**) come from mixtures of above emissions

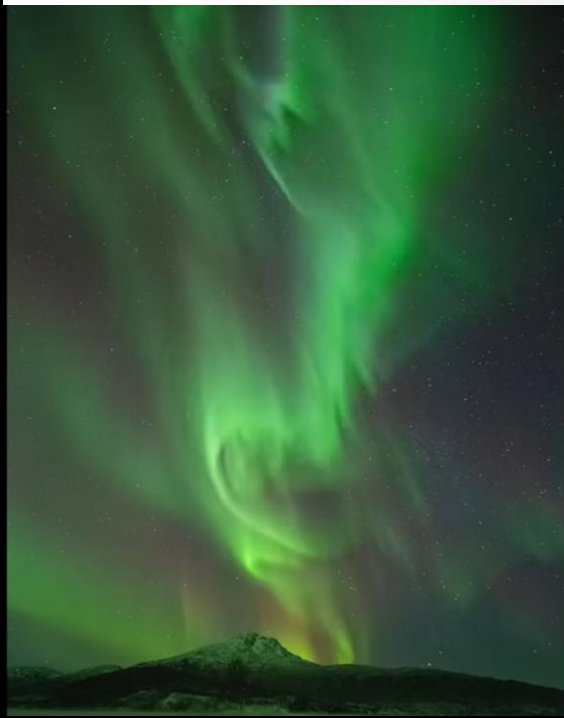


Aurora of 10-11 May, 2024



@ St Mary's Lighthouse in Whitley Bay,
Tyne and Wear (photo by Owen Humphreys)

@ Whiteford Burrows, Gower Peninsula, Wales (photo by David Spencer)



Many things have changed in the last 400 years

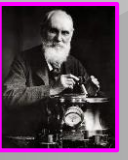
- The nature and motivations of observers ↑
- The size and distribution of the world's population ↑
- The geomagnetic latitudes of centres of population ↓↑
- Digital cameras – in particular on mobile 'phones ↑
- Education & information how to observe ↑
- Better forecasts to plan when to observe ↑
- The internet to disseminate observations ↑
- Auroral tourism ↑
- Citizen science projects ↑
- Light pollution ↓



Evolution of auroral observers



Doctors and clergymen with spare time on their hands



Affluent gentlemen scientists



Lighthouse keepers on solitary nights



Professional observers



Robotic spacecraft and the public

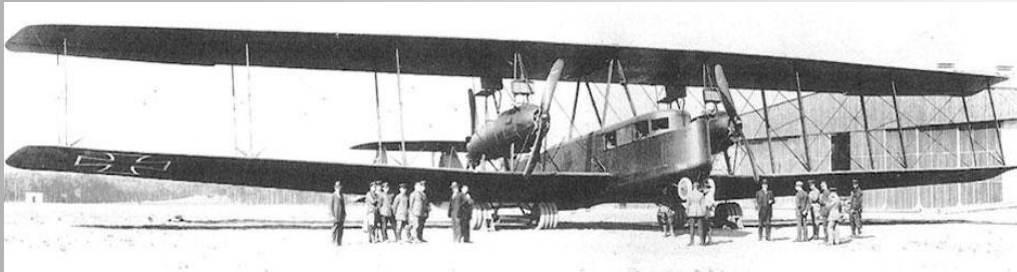


WW1 Bombing of London

the night of March 7–8, 1918

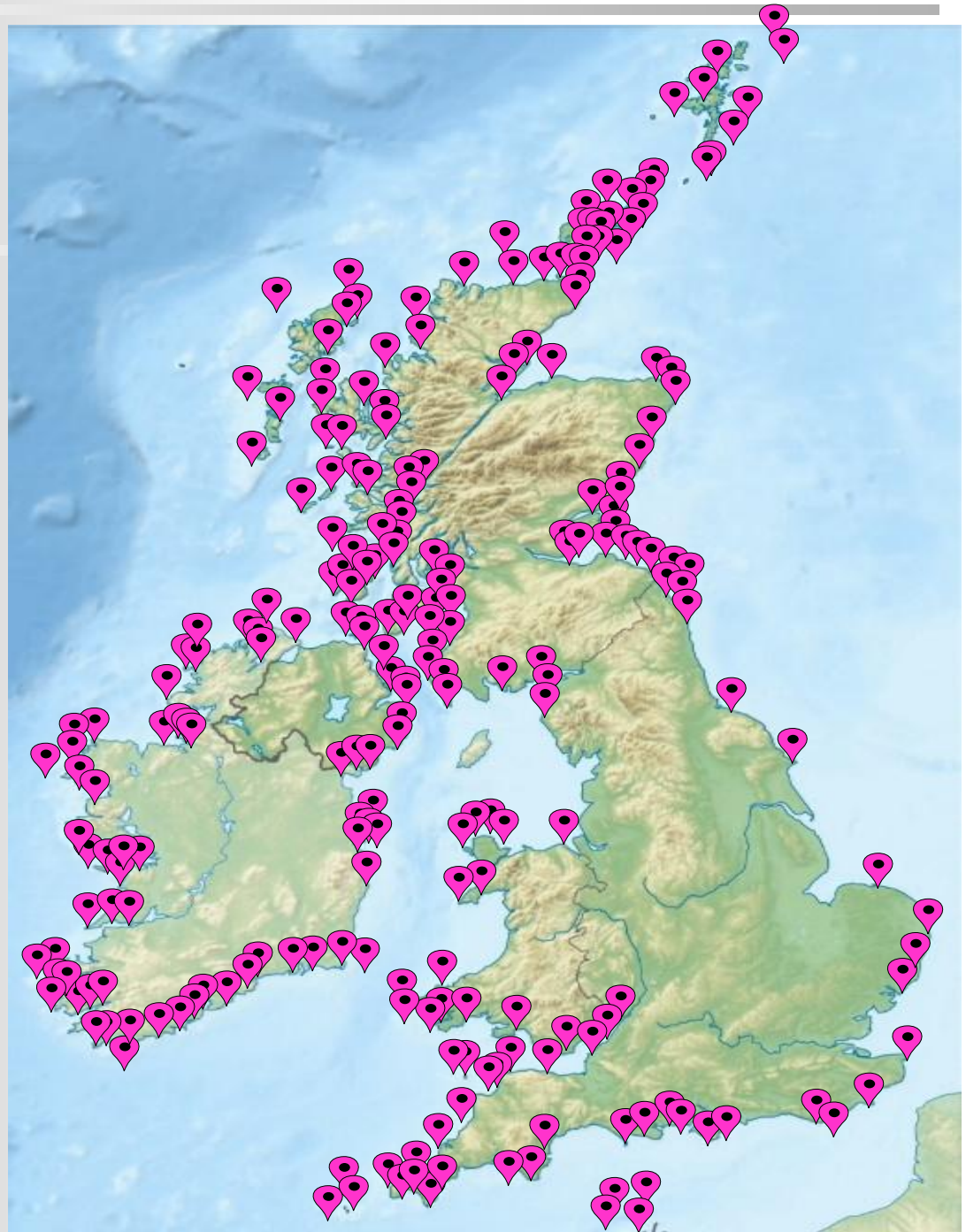


Zeppelin Staaken R.VI – The “German Giant”

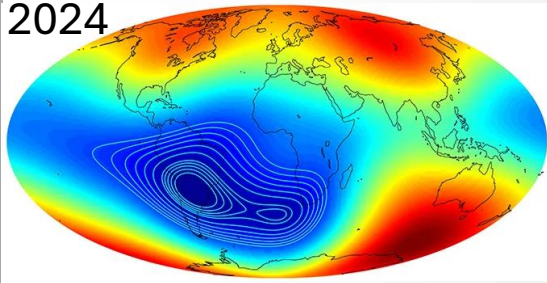


- WW1 aircraft navigation was very crude
- So London was not defended at new moon
- But on night of 7/8 March 1918, 2 out of 7 planes were able to reach London by following the Thames reflecting auroral light
- Lords Cricket Ground hit.

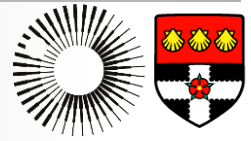
Photo: Alan Dyer



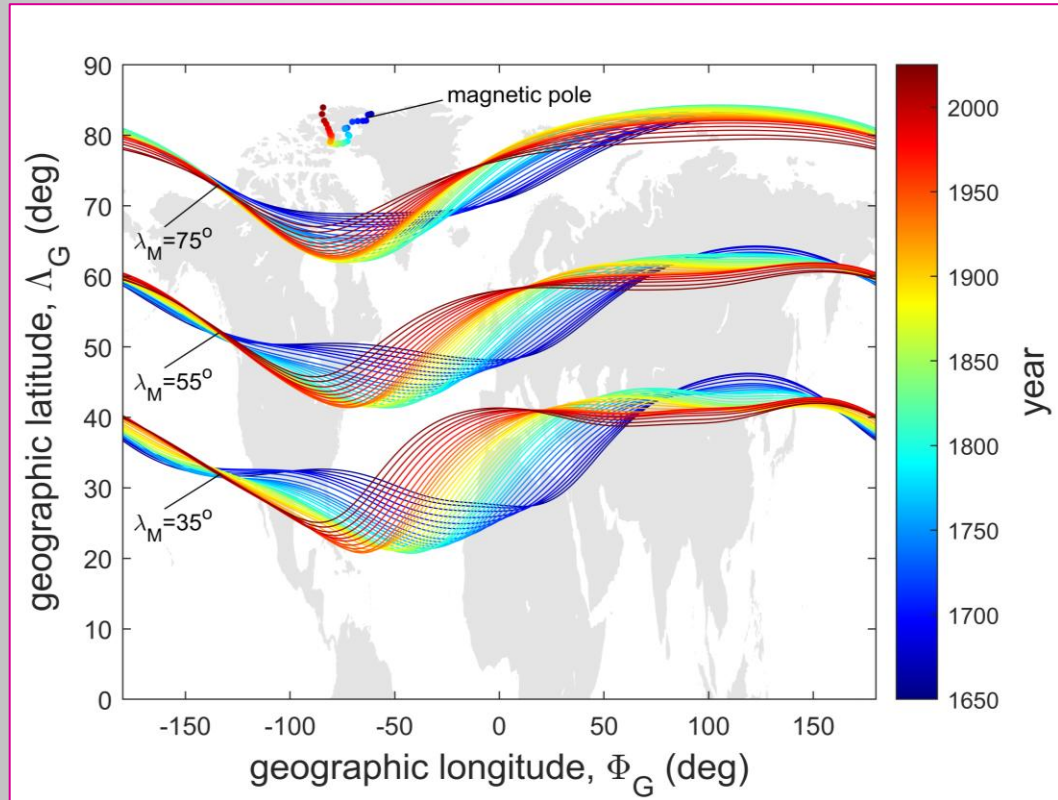
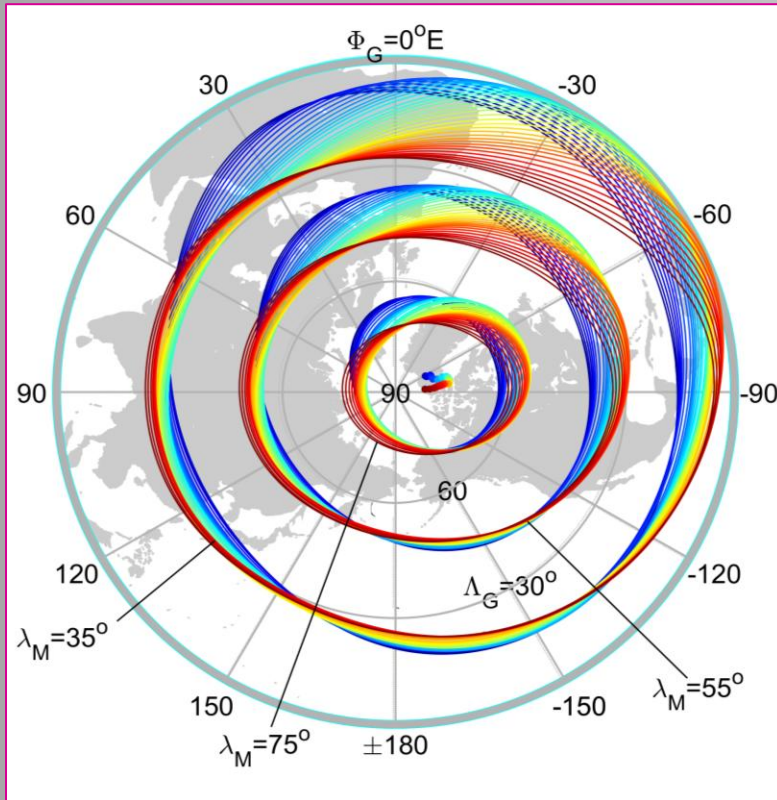
2024



Long-Term Changes in the Geomagnetic Field

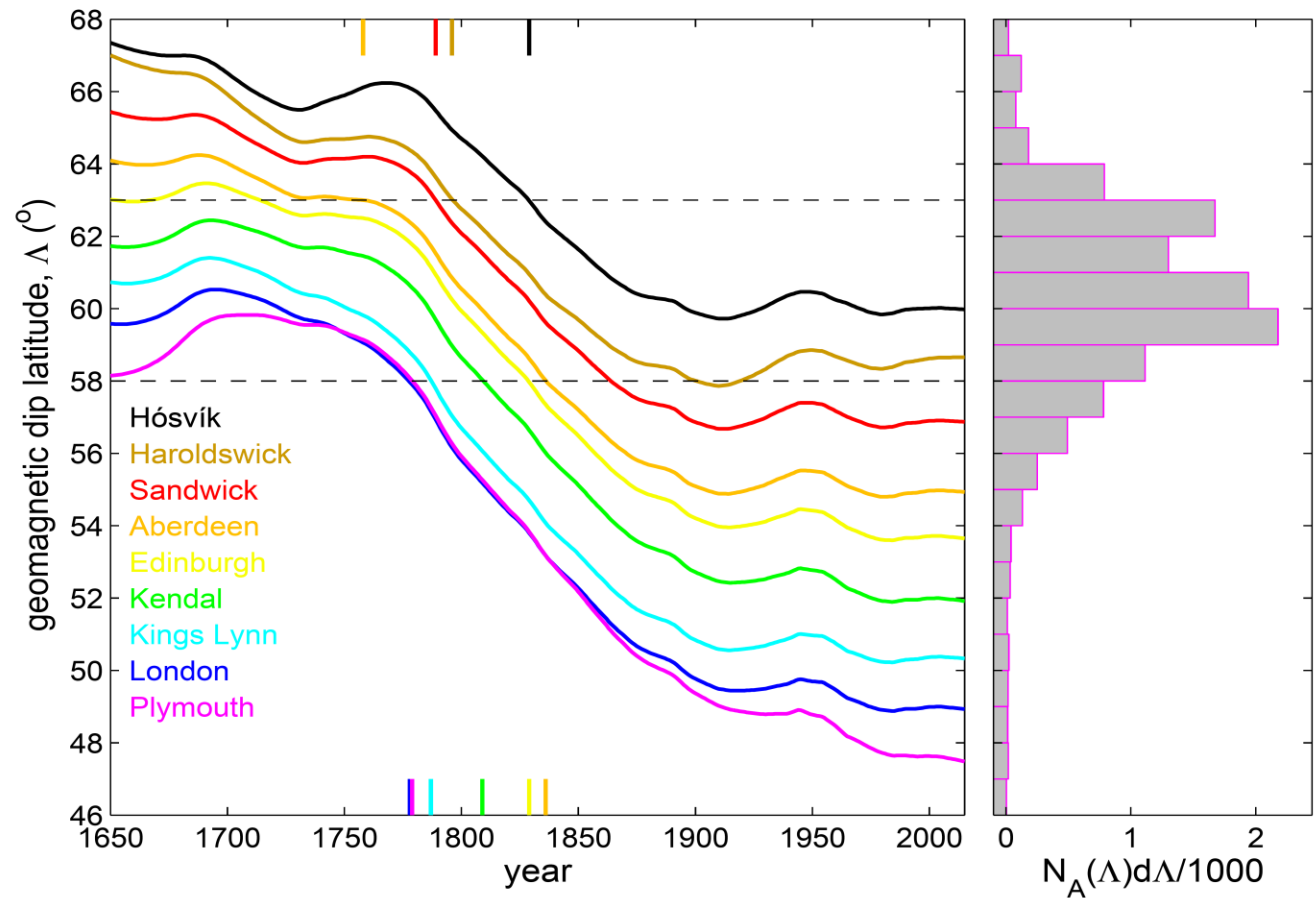
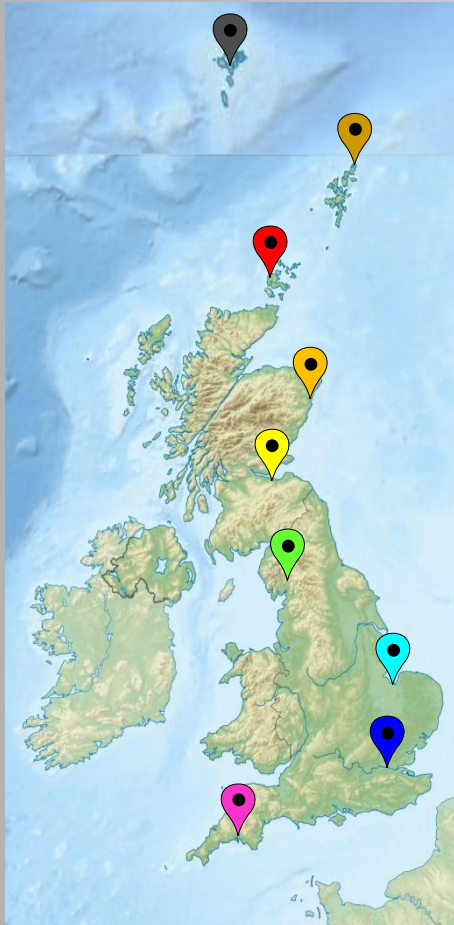


- Changes in the Earth's magnetic field
- Described by IGRF & the gufm1 models
- Causes migration of the magnetic poles
- & big changes in the contours of constant geomagnetic latitude, Λ_M

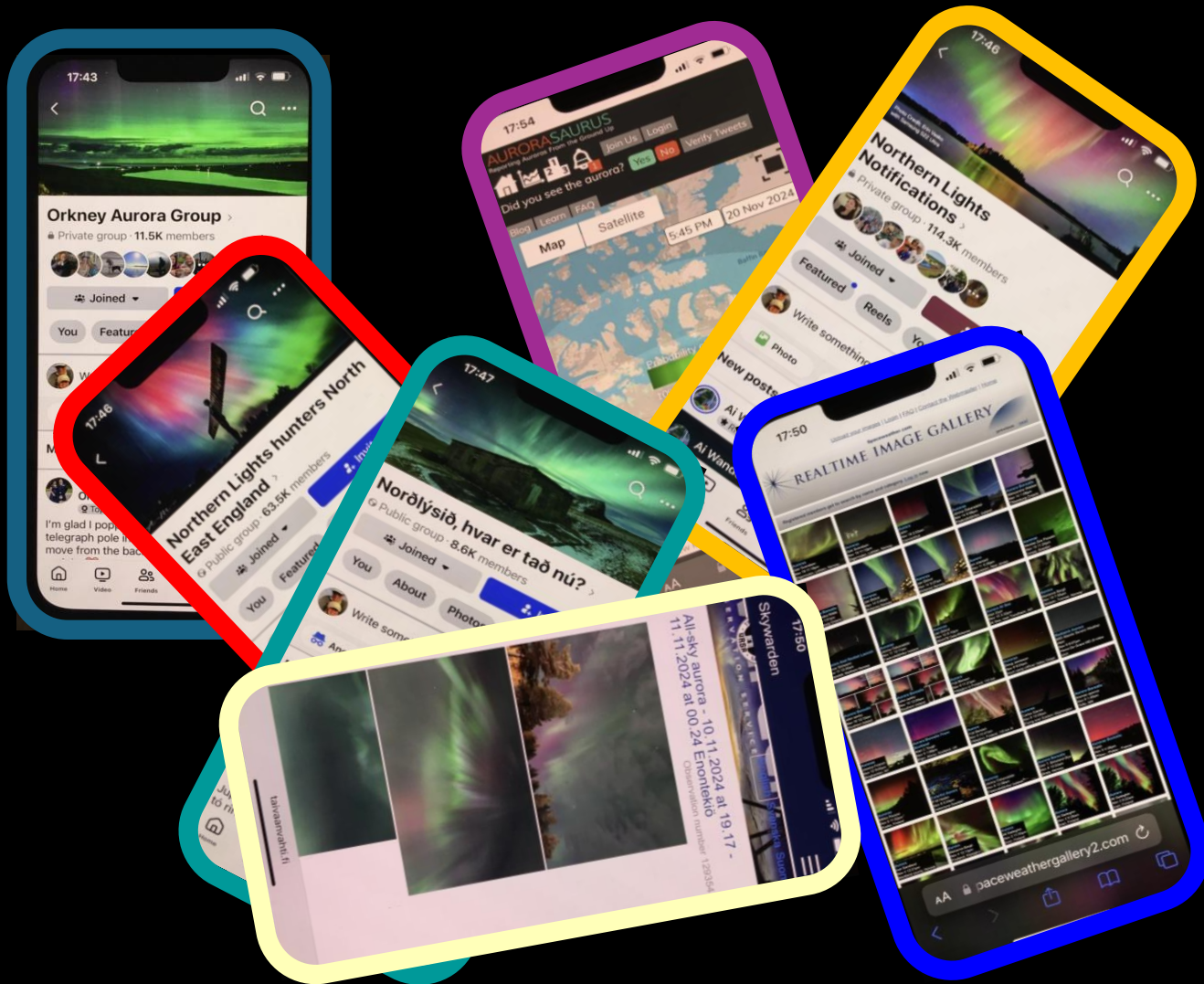




Geomagnetic latitude changes



Evolution of auroral observers: The effect of mobile 'phones

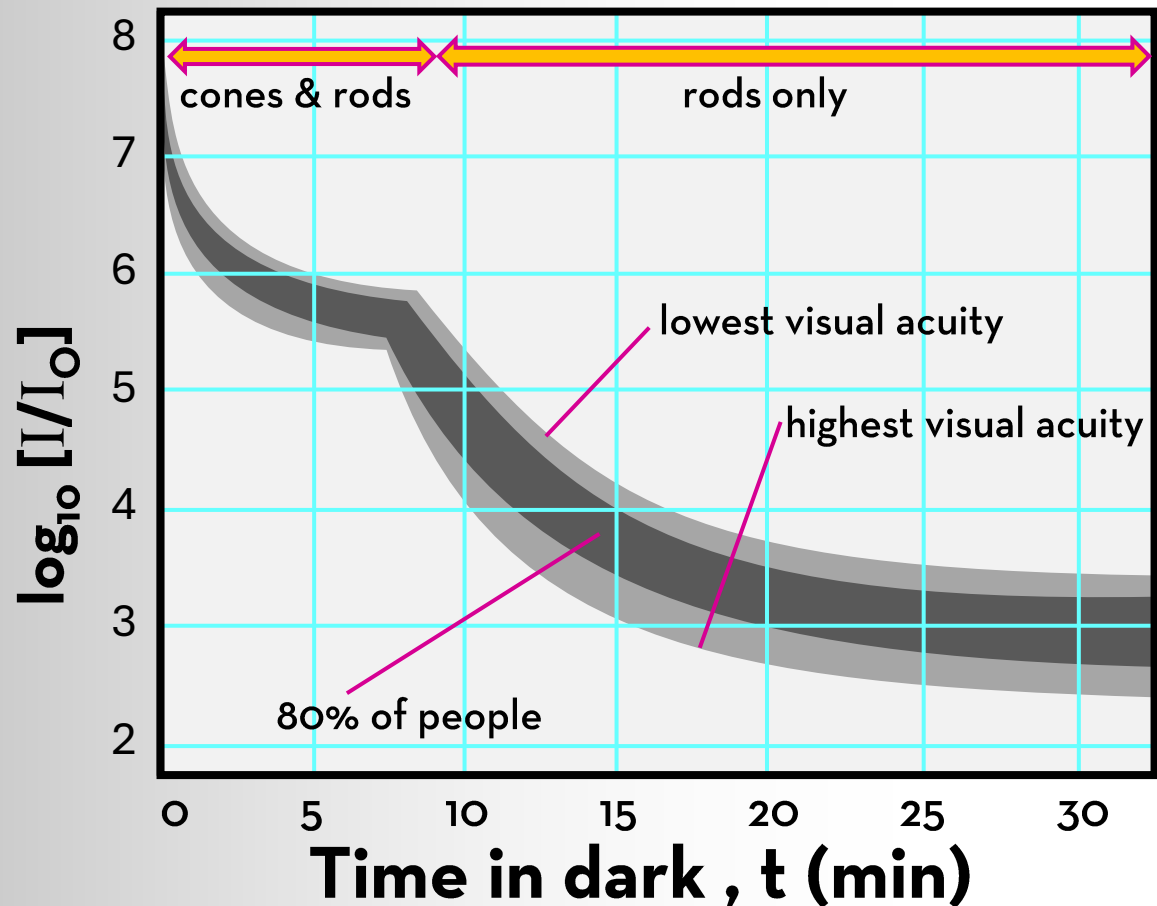




Camera v. Human Eye

Dark adaptation time (Tredici & Miller, 1985)

Minimum Detected Intensity, I



FAKES !!!



Light Painting



AI



Recycling





Easily Identified Observation Locations



Andy Morkot's photo on 10/11 May 2024
@ Angel of the North, Gateshead





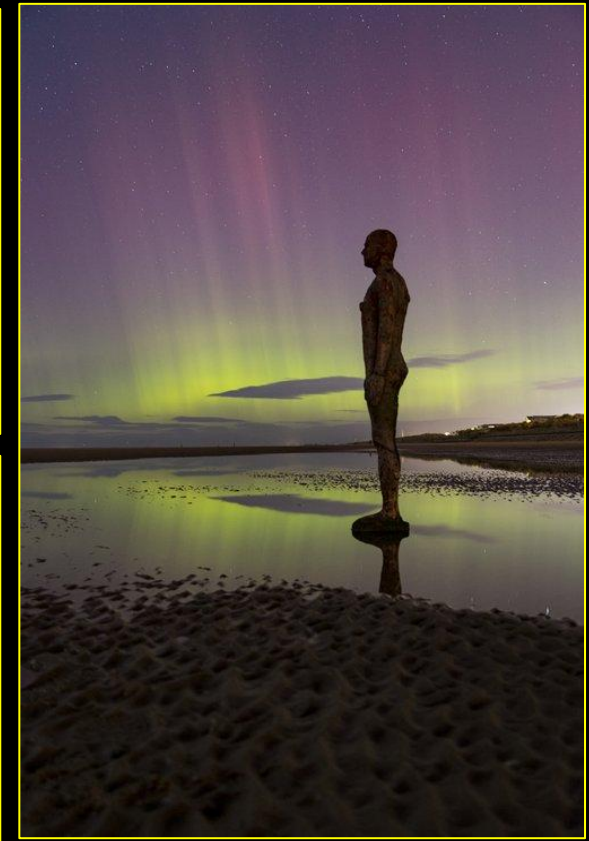
Easily Identified Observation Locations

Anthony Gormley's Statues
@ Crosby Beach on 10/11 May 2024

(photo by
Peter Byrne)



(photos by Colin Lane)



(photo by Dominic Darvell)



Easily Identified Observation Locations

@ Calton Hill, Edinburgh
(photo: Jacob Anderson)



@ Ring 'o Brodgar, Orkney
(photo: Anne-Marie Clouston)



Easily Identified Observation Locations

Nick Bull's photos of @ Silbury Hill, Wiltshire
& @ Stonehenge



(10/11 May 2024)

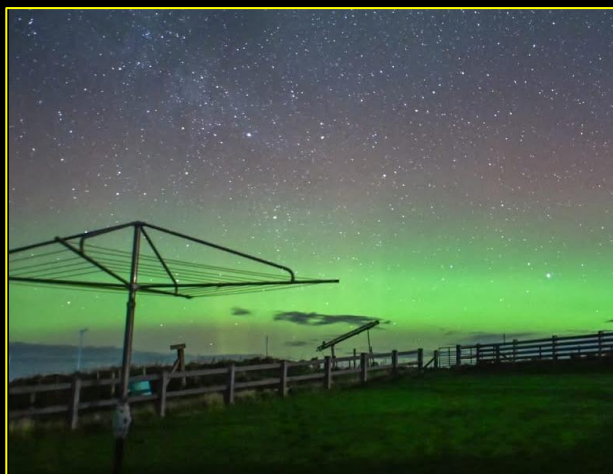


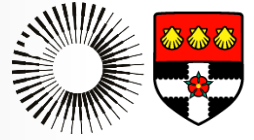
(23/124 March 2023)



Easily Identified Observation Locations

Alan Flett's famous washing line @ Birsay, Orkney



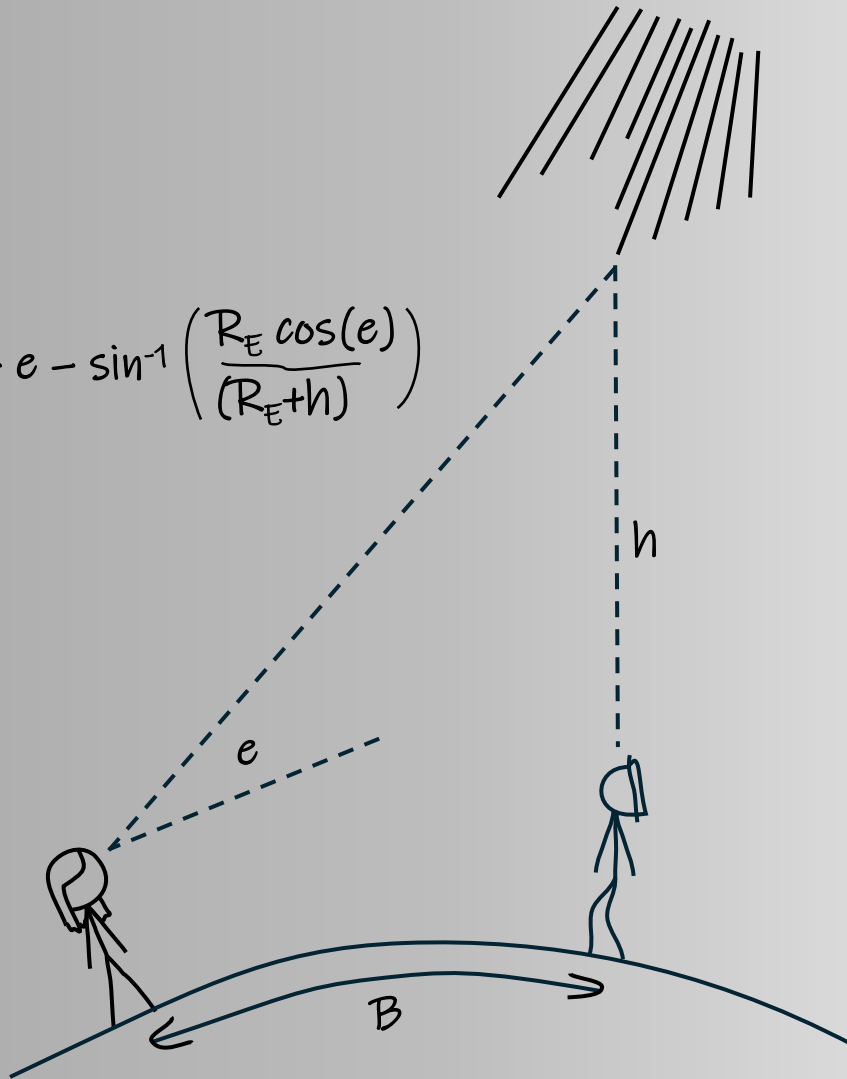


Separation of 2 observers seeing the same aurora

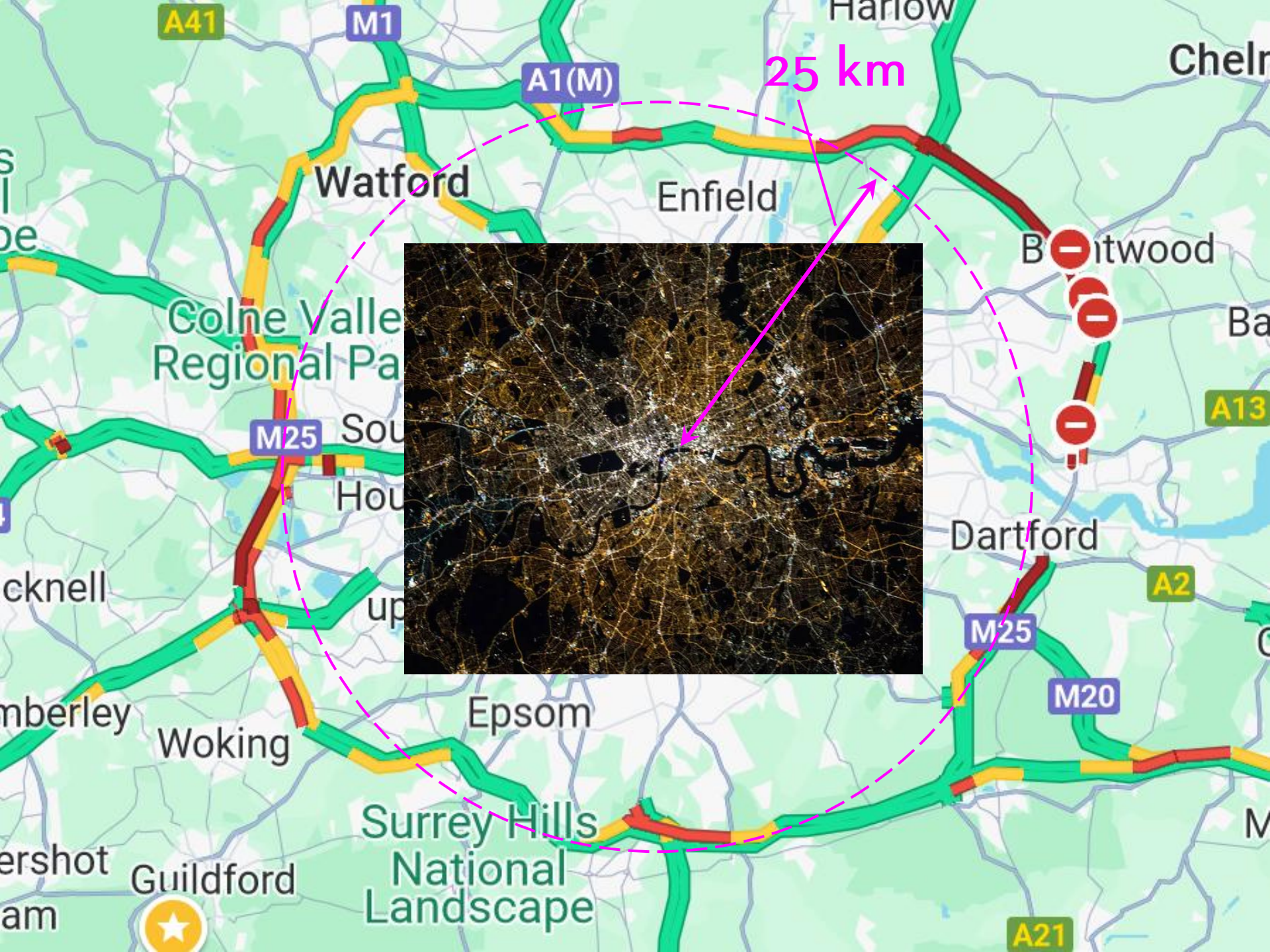
$$B = \frac{\pi}{2} - e - \sin^{-1} \left(\frac{R_E \cos(e)}{R_E + h} \right)$$

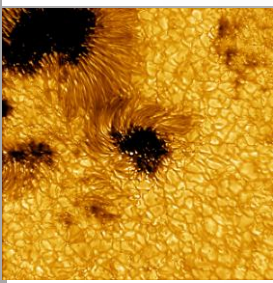
R_E = mean Earth radius
= 6370 km

Typically $e > 30^\circ$ in an urban or suburban environment



with apologies to
Randall Munro and xkcd



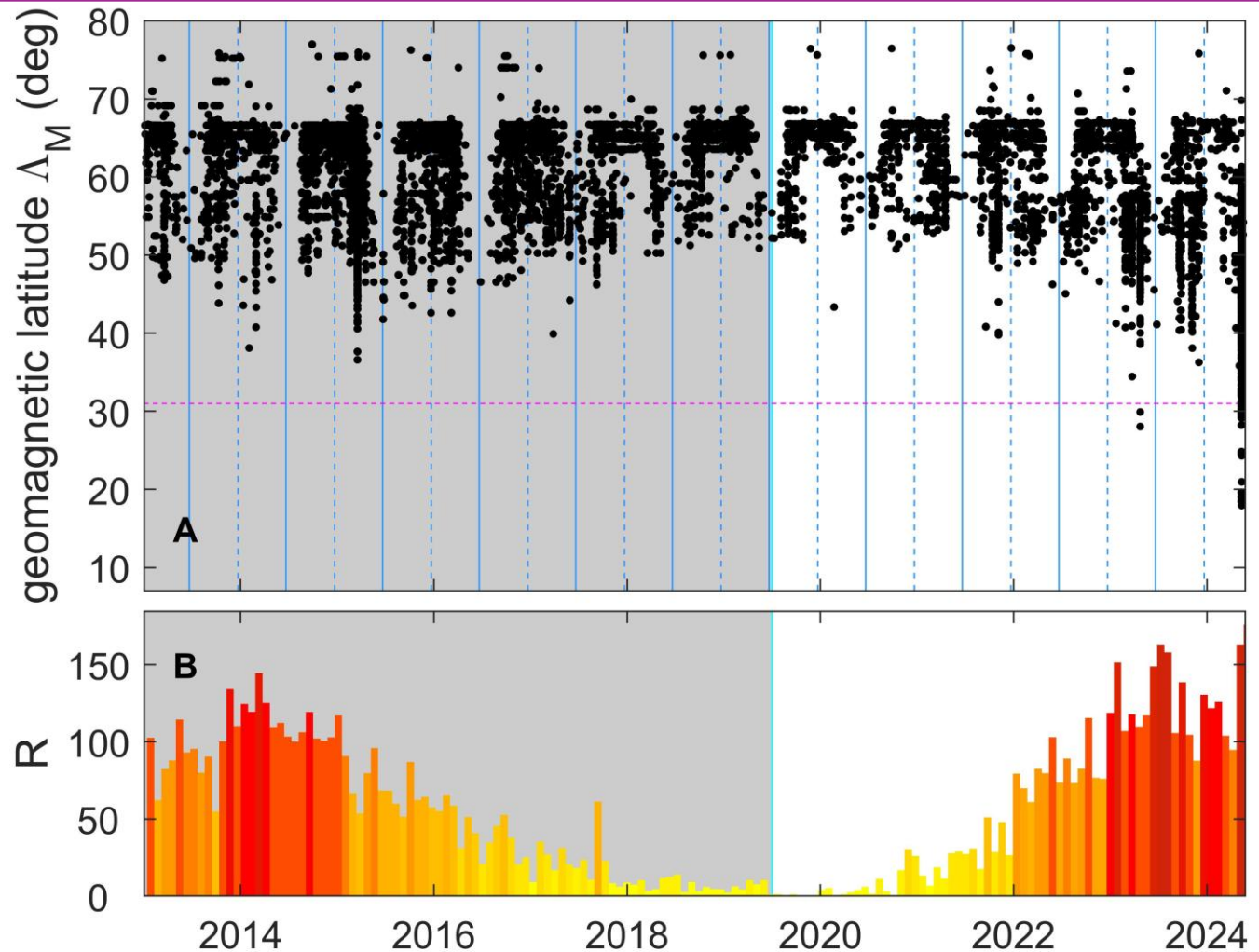


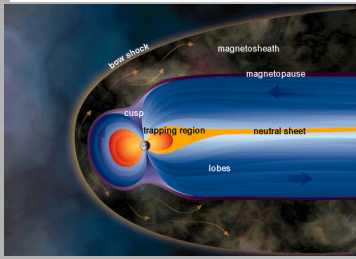
Solar & Auroral Activity

The Last Solar Cycle

magnetic
latitude of
auroral
sightings

sunspot
number

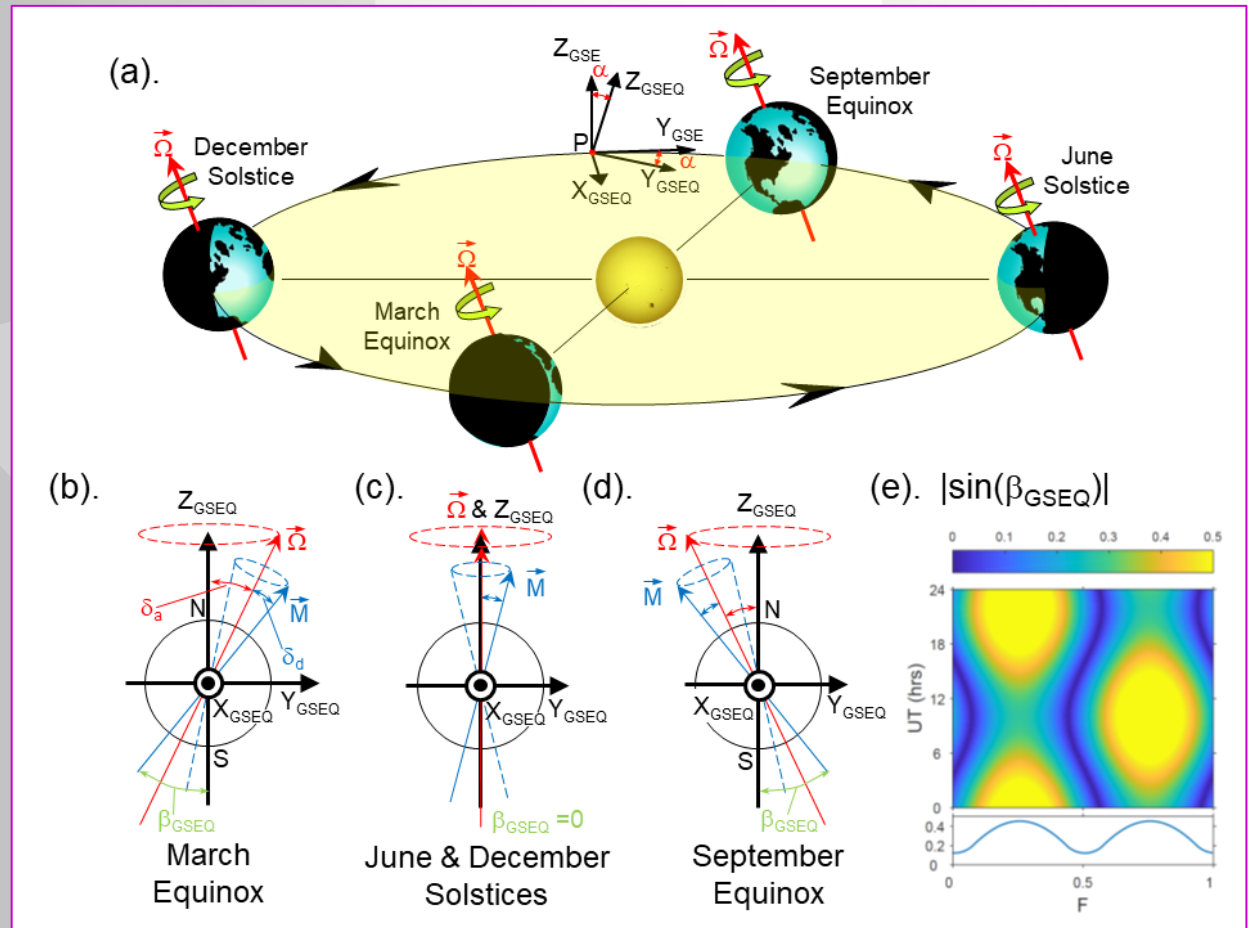




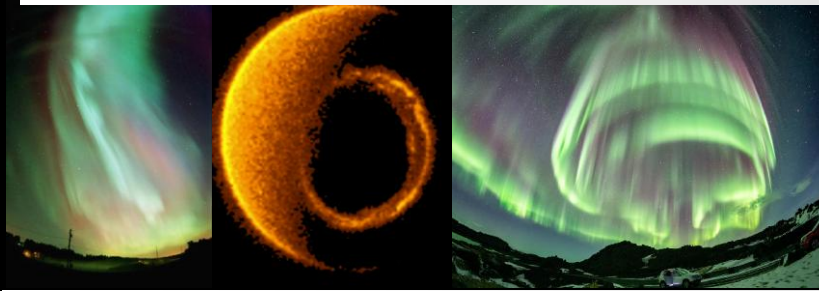
The Russell-McPherron Effect

(Russell & McPherron, 1973)

- The average IMF orientation in GSEQ has $[B_Z]_{\text{GSEQ}} = 0$ (but not big events are not average)
- Solar wind-magnetosphere coupling depends on $[B_Z]_{\text{GSM}} (< 0)$
- GSM orientation depends on geomagnetic axis, $\vec{M}$



From: Lockwood et al. (2020a), Semi-annual, annual and Universal Time variations in the magnetosphere and in geomagnetic activity: 1. Geomagnetic data, doi: 10.1051/swsc/2020023



Russell-McPherron Effect



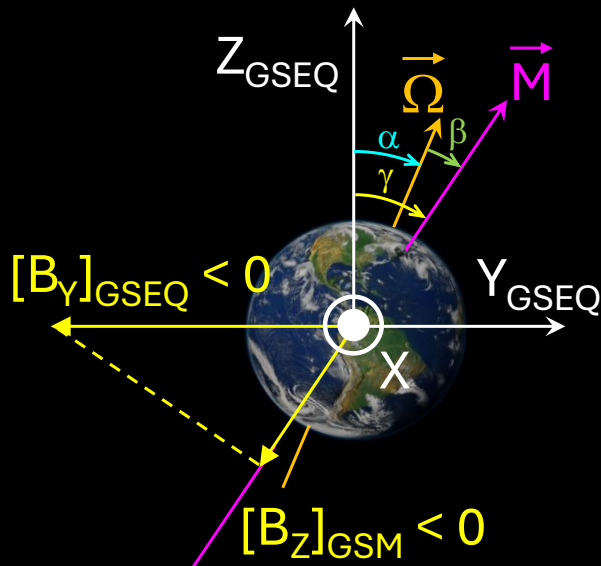
A

March Equinox

($F \approx 0.22$)

at UT ≈ 22 hrs

negative IMF $[B_Y]_{GSEQ}$
gives southward IMF in GSM



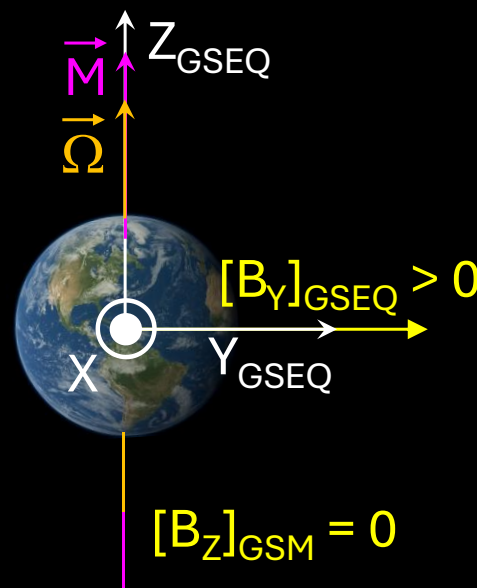
B

Solstices

($F \approx 0.48$ or ≈ 0.98)

at UT ≈ 4 or UT ≈ 16 hrs

IMF $[B_Y]_{GSEQ}$ has no effect
on southward IMF in GSM



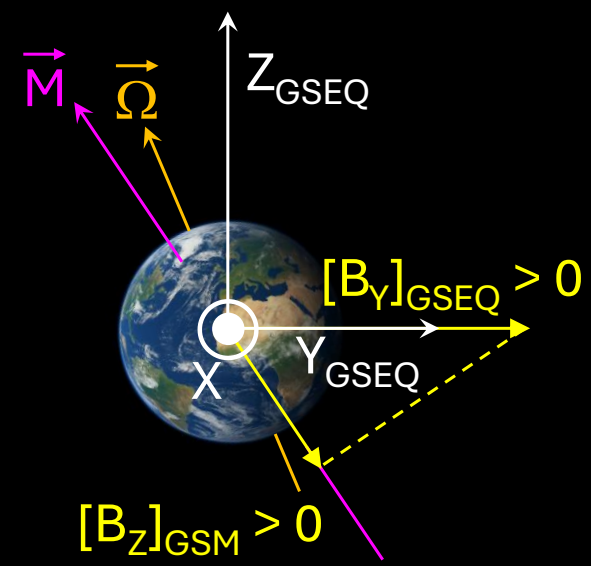
C

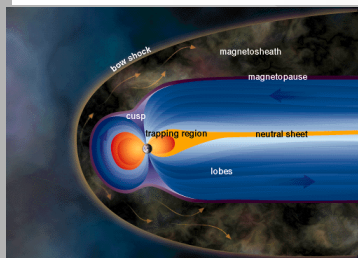
September Equinox

($F \approx 0.73$)

at ~ 10 hrs UT

positive IMF $[B_Y]_{GSEQ}$
gives southward IMF in GSM

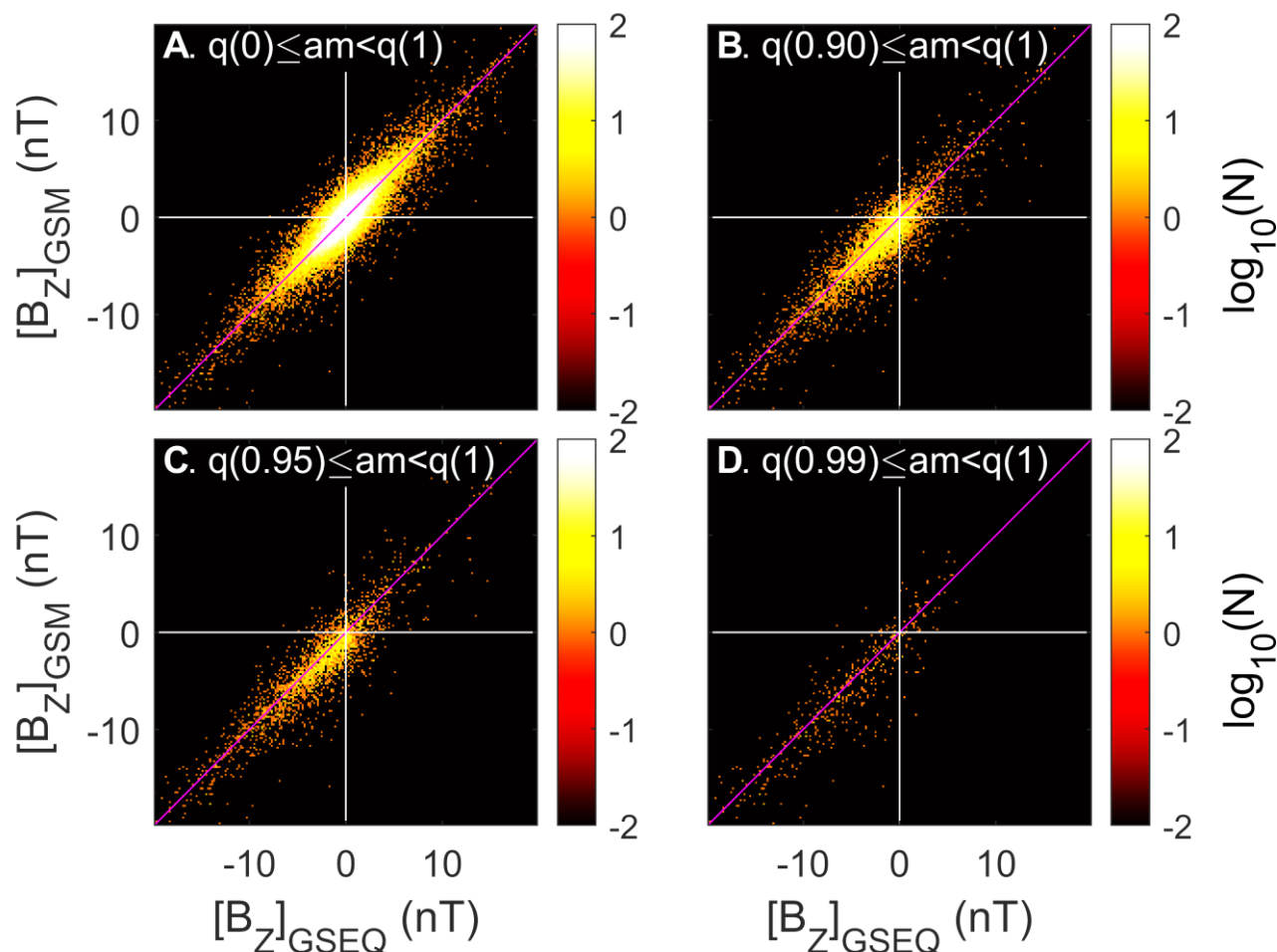




The Russell-McPherron Effect

(Russell & McPherron, 1973)

- Note $[B_Z]_{\text{GSM}} < 0$ mainly determined by $[B_Z]_{\text{GSEQ}} < 0$
- Southward IMF ($[B_Z]_{\text{GSM}} < 0$) is only slightly enhanced by R-M effect
- So equinox helps but events mainly caused by the Sun at any t-o-y



From: Lockwood et al. (2026), *The contribution of the Russell-McPherron effect to the semiannual variation in thermospheric density*, doi: 10.1029/2025JA034732, 2026



Solar & Auroral Activity

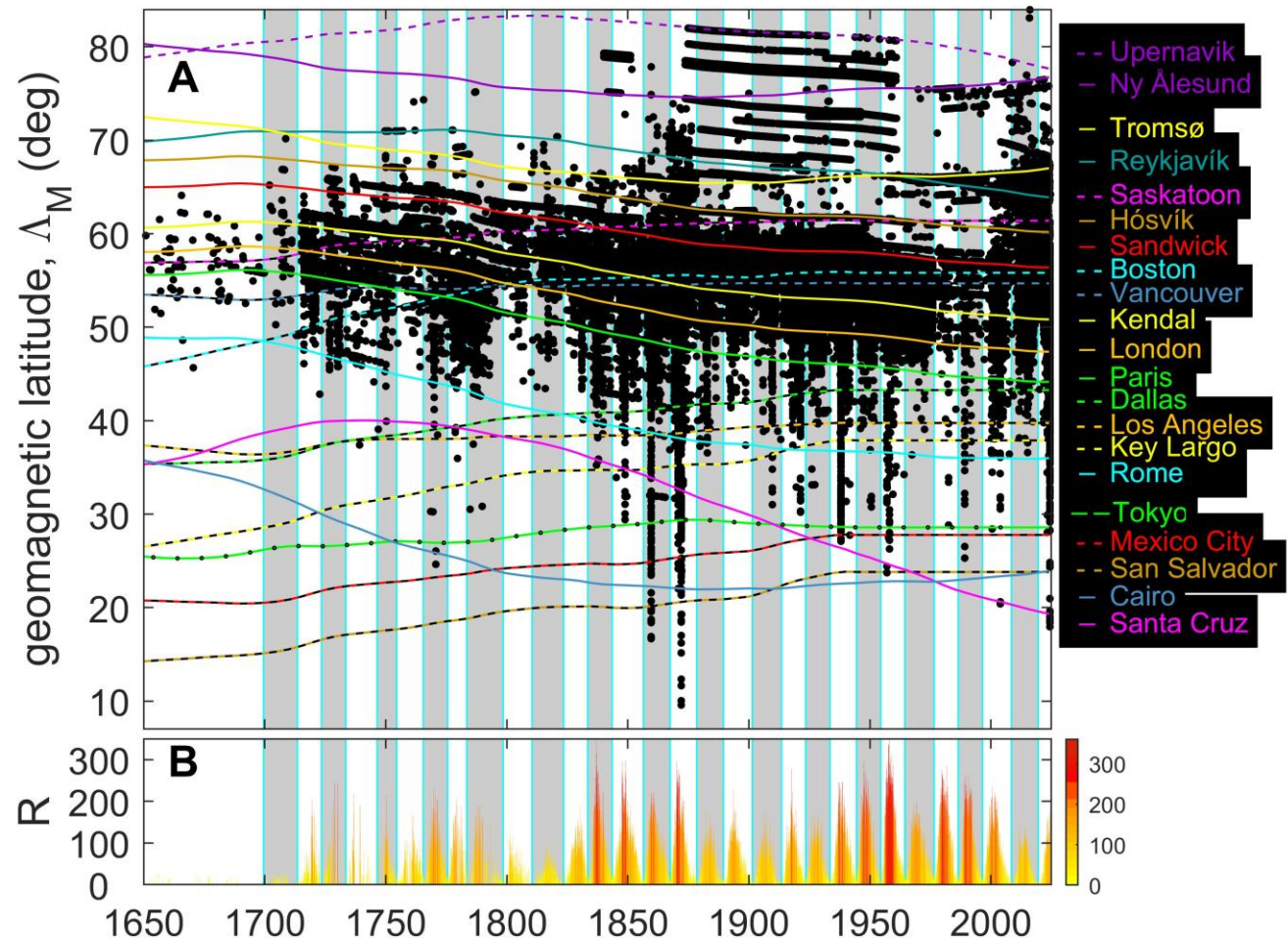


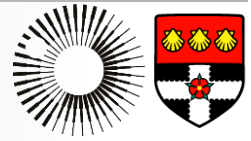
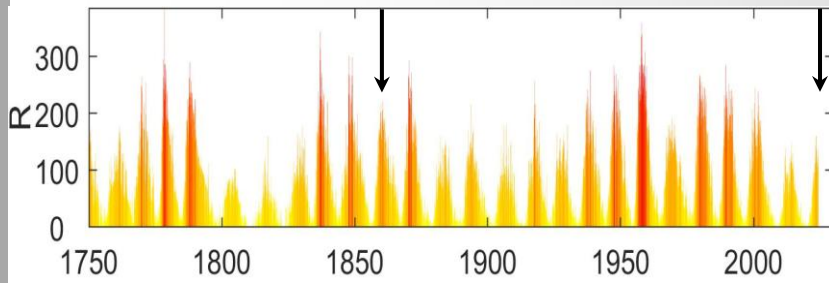
Geomagnetic latitudes of auroral sightings & annual means of sunspot number

Survey of 224870 auroral sightings in the Northern Hemisphere between 1650 and 2024

magnetic latitude of auroral sightings

sunspot number

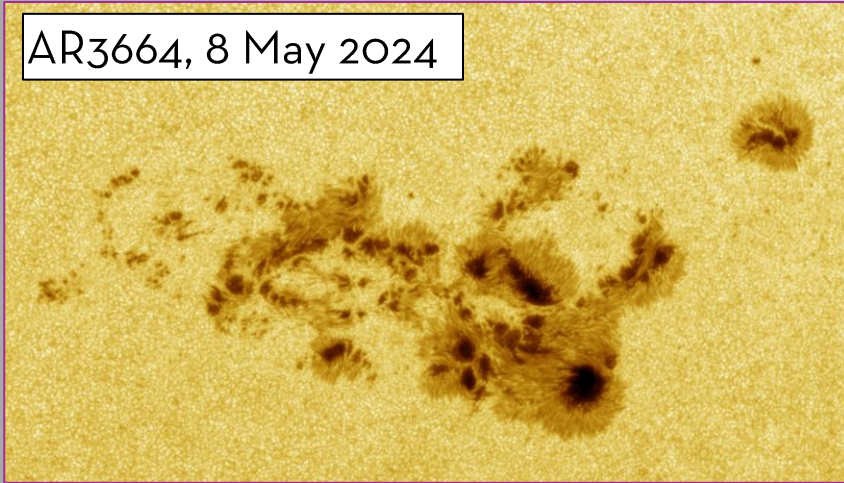




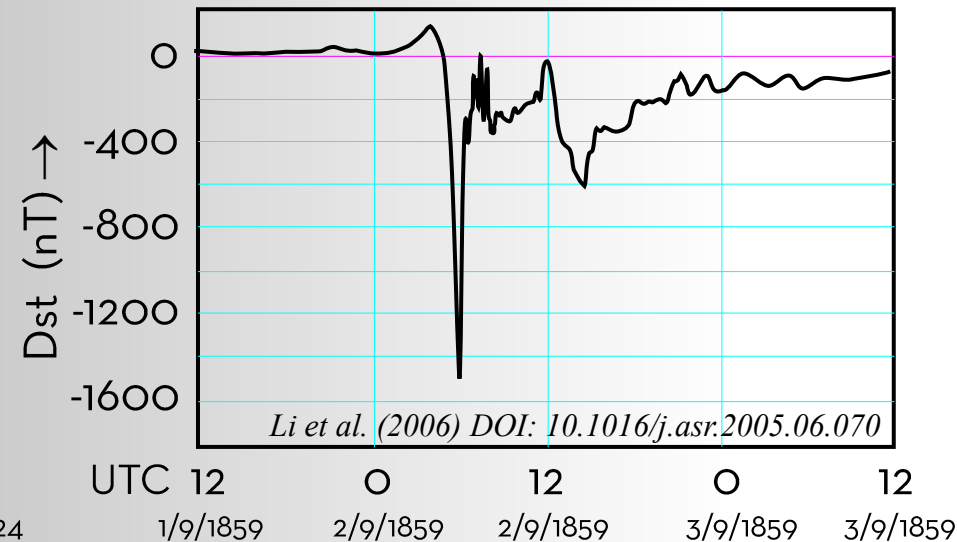
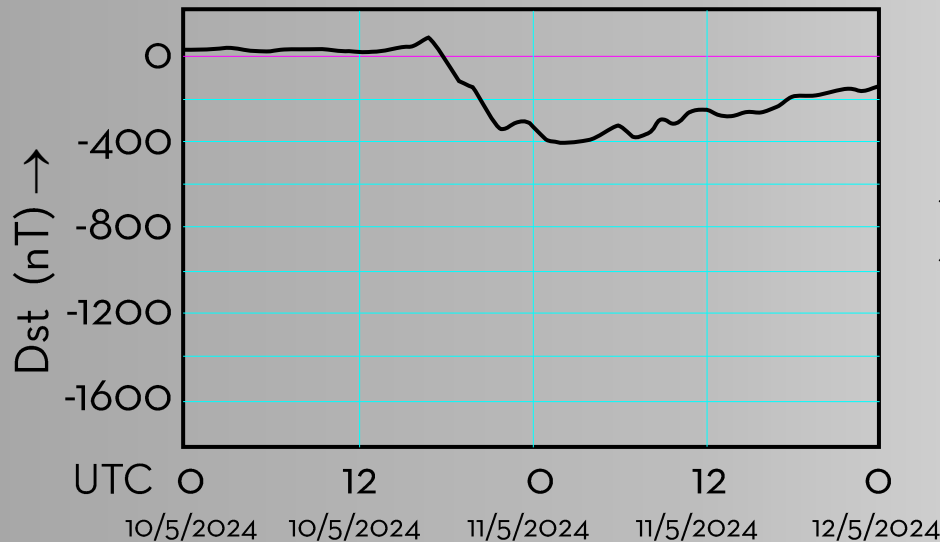
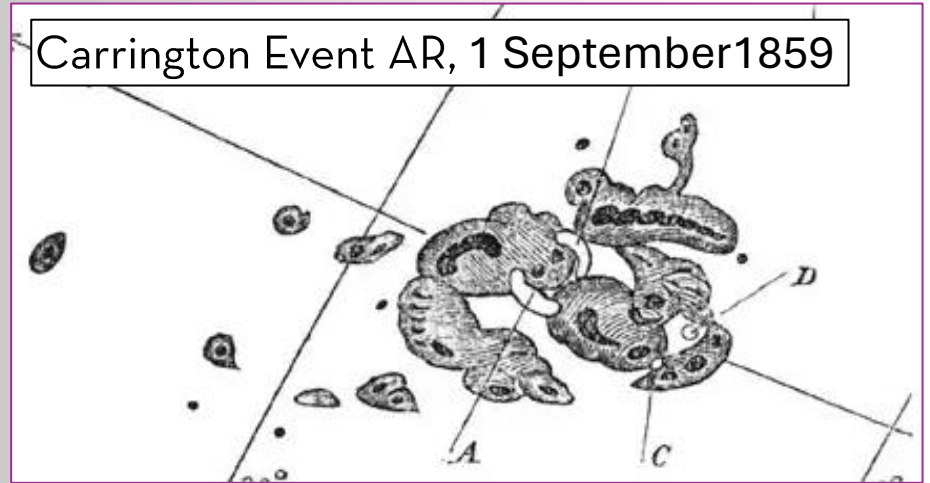
Sunspot Groups

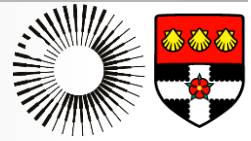
AR 3664 and Carrington Event AR

AR3664, 8 May 2024



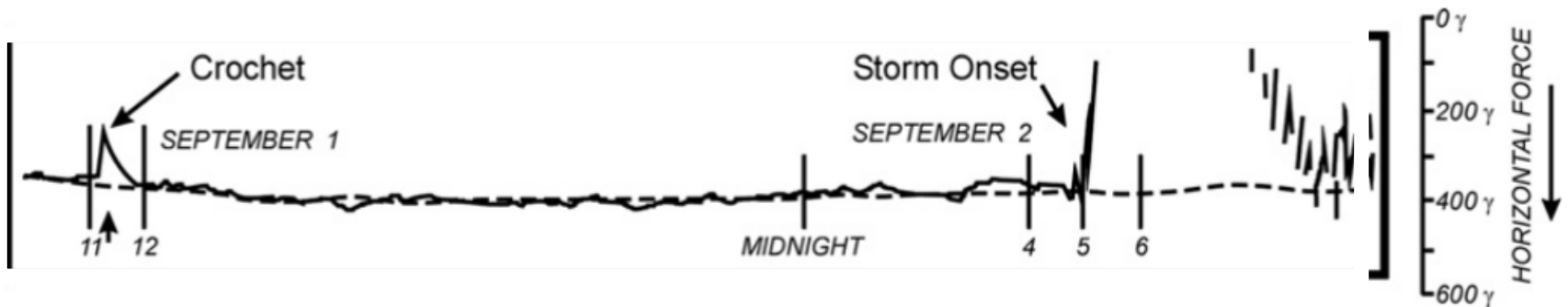
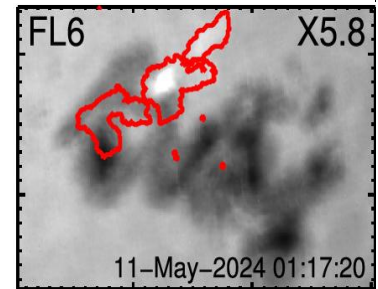
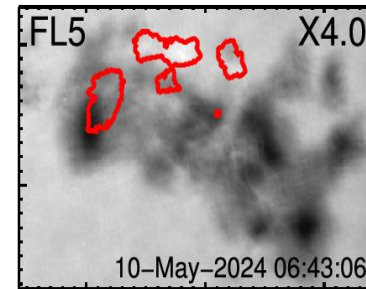
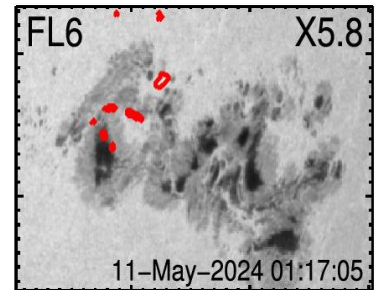
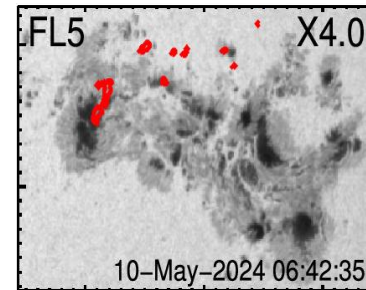
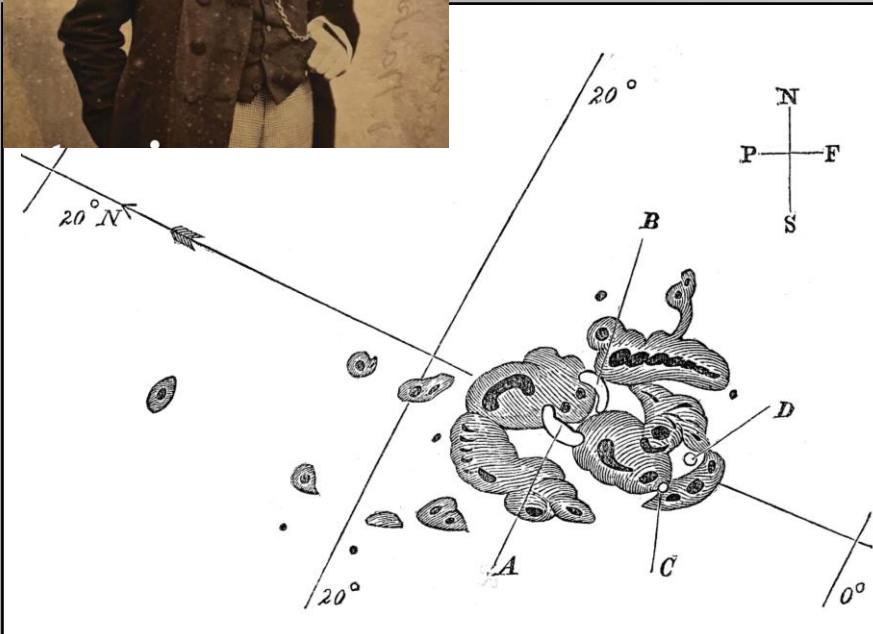
Carrington Event AR, 1 September 1859





Sunspot Group Flares

AR 3664 and Carrington Event AR



THE FIRST KNOWN SPACE WEATHER EVENT

19th of March, 1847

Aurora seen over much of England
GICs detected in the telegraph system
of the Midland Railway

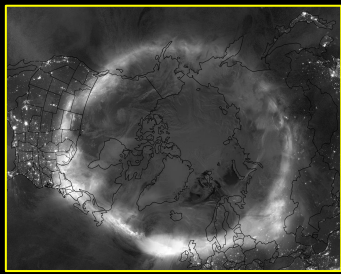


Barlow, W.H (1849) On the spontaneous electrical currents observed in wires of the electric telegraph, Phil. Trans. Roy. Soc., London, 139, 61-72, doi: [10.1098/rstl.1849.0006](https://doi.org/10.1098/rstl.1849.0006)



Great Western Railway (GWR) engine
"Swallow" seen near Chippenham c.1875

Photo: Hutton Archive

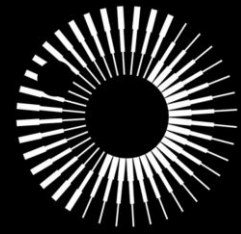


SO.... WHERE IS 2024 IN THE LEAGUE TABLE OF GREAT AURORAL EVENTS?



- Top-ten events ranked by the minimum geomagnetic Q-D latitude, Λ_M , from which aurora was observed

	Date	Λ_M	Location	Name
1	4 Feb 1872	5.85°	Khartoum, Sudan	Secchi event
2	28 Aug 1859	16.68°	USS Sarnac @ Panama City	Precursor Carrington
3	11 May 2024	18.08°	Ad-Dāhiliyah, Oman	Day2, May 2024 Event
4	2 Sep 1859	18.40°	La Unión, El Salvador	Day 2, Carrington event
5	1 Sep 1859	18.60°	Ship 'St Marys' El Salvador	Day 1, Carrington event
6	10 Oct 2024	18.62°	St. Mateo, Gran Canaria	October 2024 Event
7	10 May 2024	19.12°	Mogán, Gran Canaria	Day 1, May 2024 Event
8	20 Nov 2003	20.41°	Mount Teide, Tenerife	Halloween Storms + 1CR
9	24 Oct 1870	22.03°	Giza, Cairo, Egypt	Donati event
10	21 Jan 1957	22.03°	Arrecife, Lanzarote	IGY January storm



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Former President, Royal Astronomical Society



movie: Aurora over Boardhouse Loch, Orkney 18 March 2018, by Orkney Aurora Photography



Read more at

