ASTR-6000 Seminar

COLLAGE: Coronal Heating, Solar Wind, & Space Weather

March 31, 2022
Space Weather
Terrestrial Responses and Technological Impacts

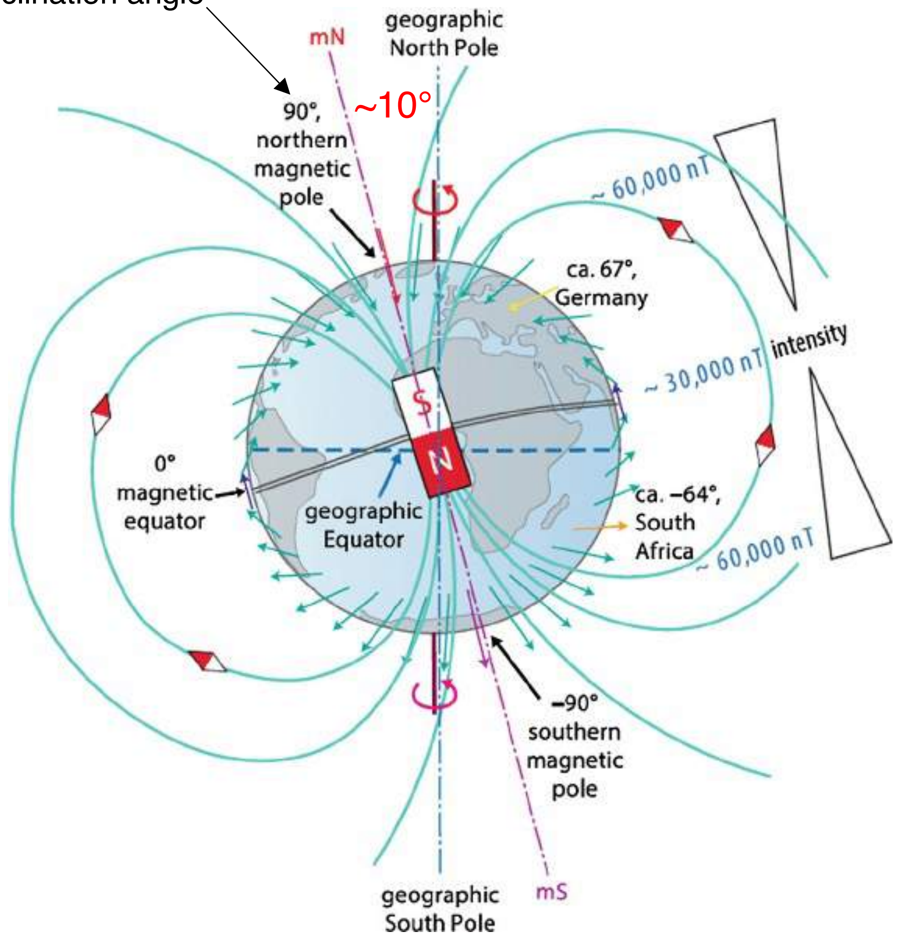
Dr. Thomas Berger
Dr. Steven Cranmer

Outline

1. The Earth’s Magnetic Field, Magnetosphere, and Radiation Belts
2. The Mesosphere/Ionosphere/Thermosphere (MIT) atmospheric system
3. Space weather at Earth
    - UV & X-ray irradiance and Solar Flare impacts
    - Solar wind triggered minor to medium geomagnetic storms
    - Next week: CME and SEP impacts – extreme events

Overview of the Geomagnetic Field

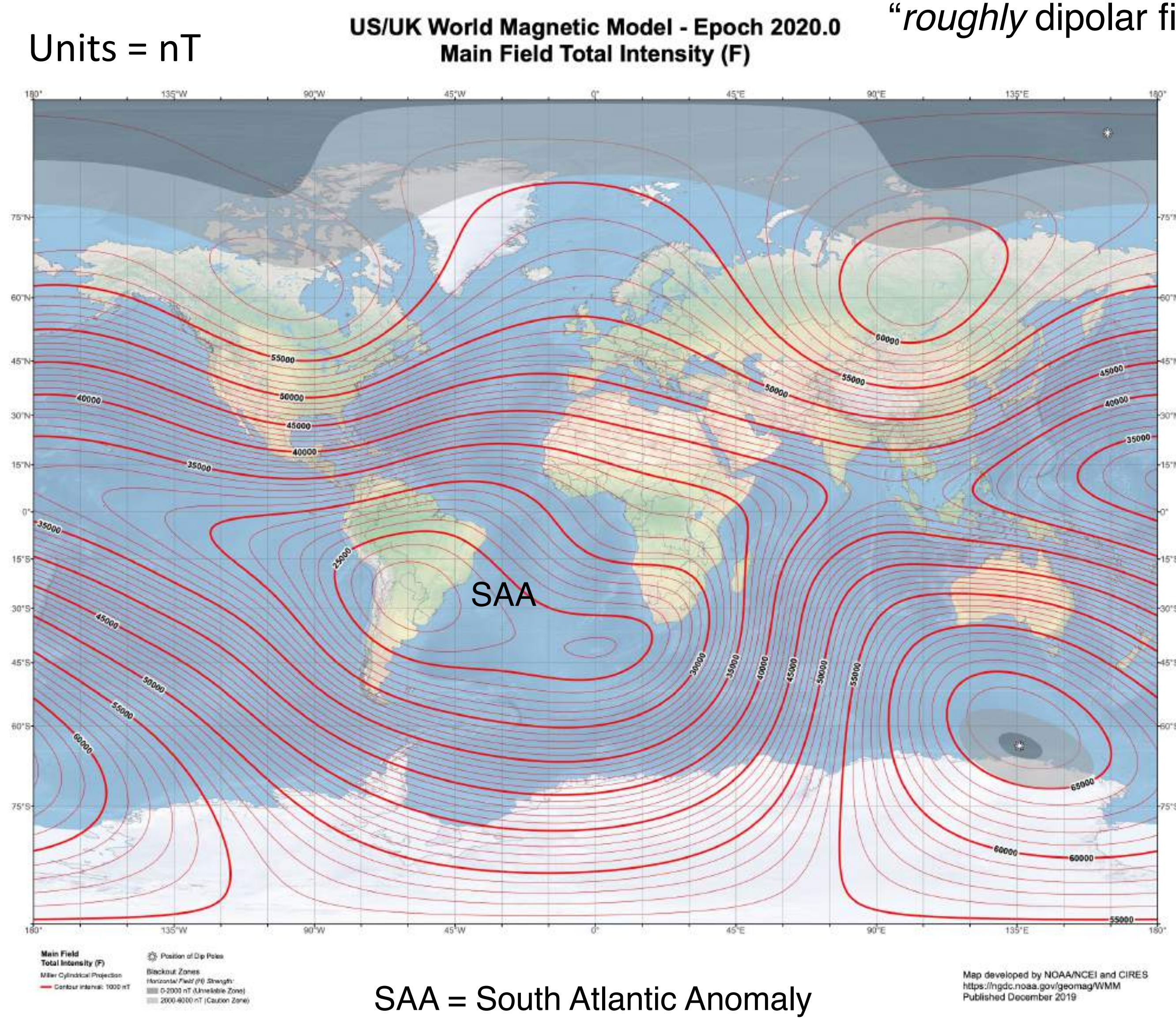
“Declination angle”



Mouritsen, H. (2013) in Galizia, C.G. and Lledo, P.-M. (eds) *Neurosciences - From Molecule to Behavior: a university textbook*. Berlin, Heidelberg: Springer Berlin Heidelberg, pp. 427–443. doi:[10.1007/978-3-642-10769-6_20](https://doi.org/10.1007/978-3-642-10769-6_20).

Units = nT

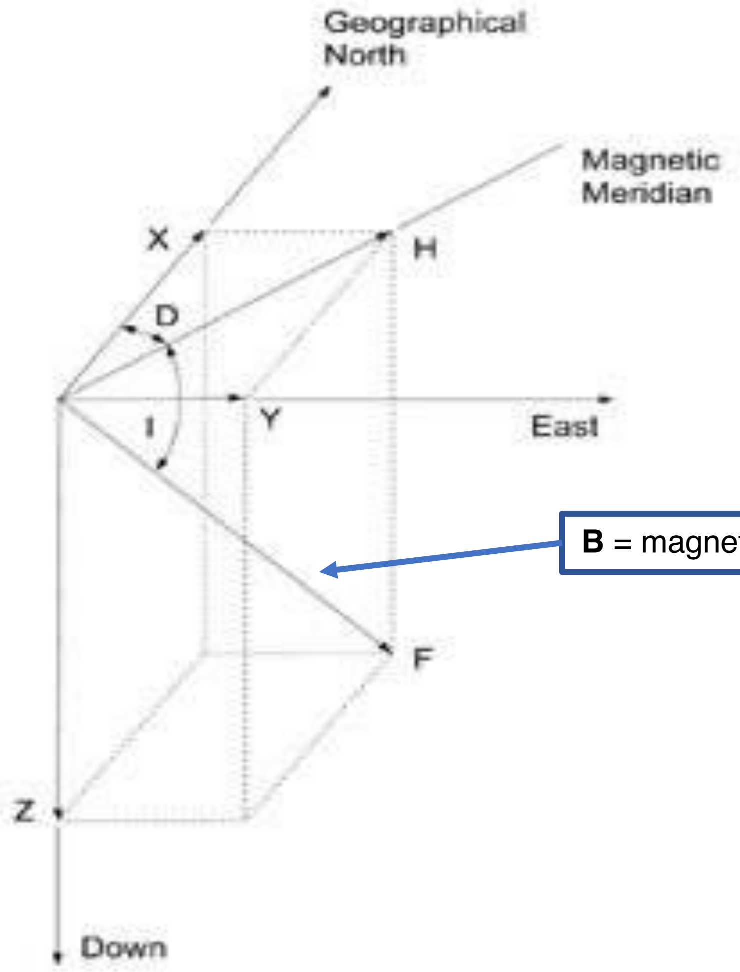
“*roughly* dipolar field”



SAA

SAA = South Atlantic Anomaly

Geomagnetic Field Vectors



B = magnetic field vector

H = $\mathbf{B}_h$ = horizontal component of **B**
D = declination, angle to geographic N
Z = B_z = vertical component of **B**
I = inclination angle
F = magnitude of **B**

Geospace Coordinate Systems

Geocentric (GEO): The origin is chosen at the center of Earth. The x-axis points from the center of Earth through the Prime Meridian (by convention chosen as the meridian in Greenwich, London, UK (longitude = 0). The z-axis points towards the north geographic pole.

Geocentric Earth Inertial (GEI): This coordinate system is fixed relative to the distant stars, so Earth rotates about the z-axis relative to it. The origin of this coordinate system is at the center of the Earth. The x-axis points to the first point in Aries (Wikipedia: Vernal Equinox) and the z-axis points to the north geographic & celestial pole. The direction of the celestial pole changes due to Earth's rotational precession (Wikipedia).

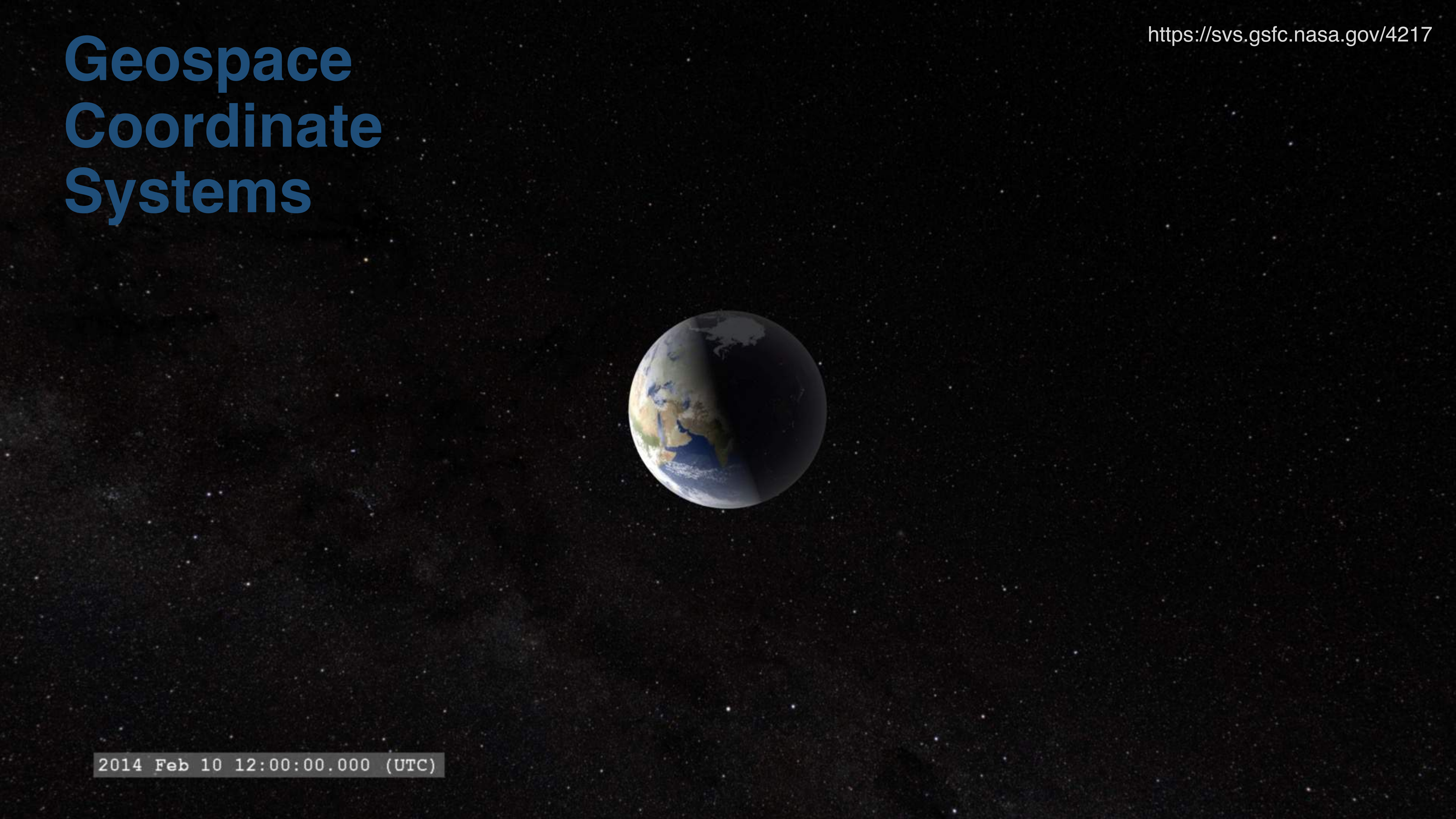
Geocentric Solar Ecliptic (GSE): The origin is at the center of the Earth. The x-axis is along the line between Earth and the Sun. The z-axis is the north ecliptic pole and is fixed in direction (but for slow changes due to Earth orbital changes).

Solar Magnetic (SM): the origin is at the center of the Earth. The z-axis is chosen parallel to the Earth magnetic dipole axis. The y-axis is chosen to be perpendicular to the z-axis and the Earth-Sun line (pointing towards dusk).

Geocentric Solar Magnetospheric (GSM): The origin is at the center of the Earth. The x-axis is defined as the Earth-Sun line (same as in GSE). The y-axis is defined to be perpendicular to the plane containing the x-axis and the magnetic dipole axis, so the magnetic axis always lies in this plane.

Hapgood, M.A. (1992) 'Space physics coordinate systems: a user's guide', *Planet Space Sci.*, 40(5), pp. 711–717.

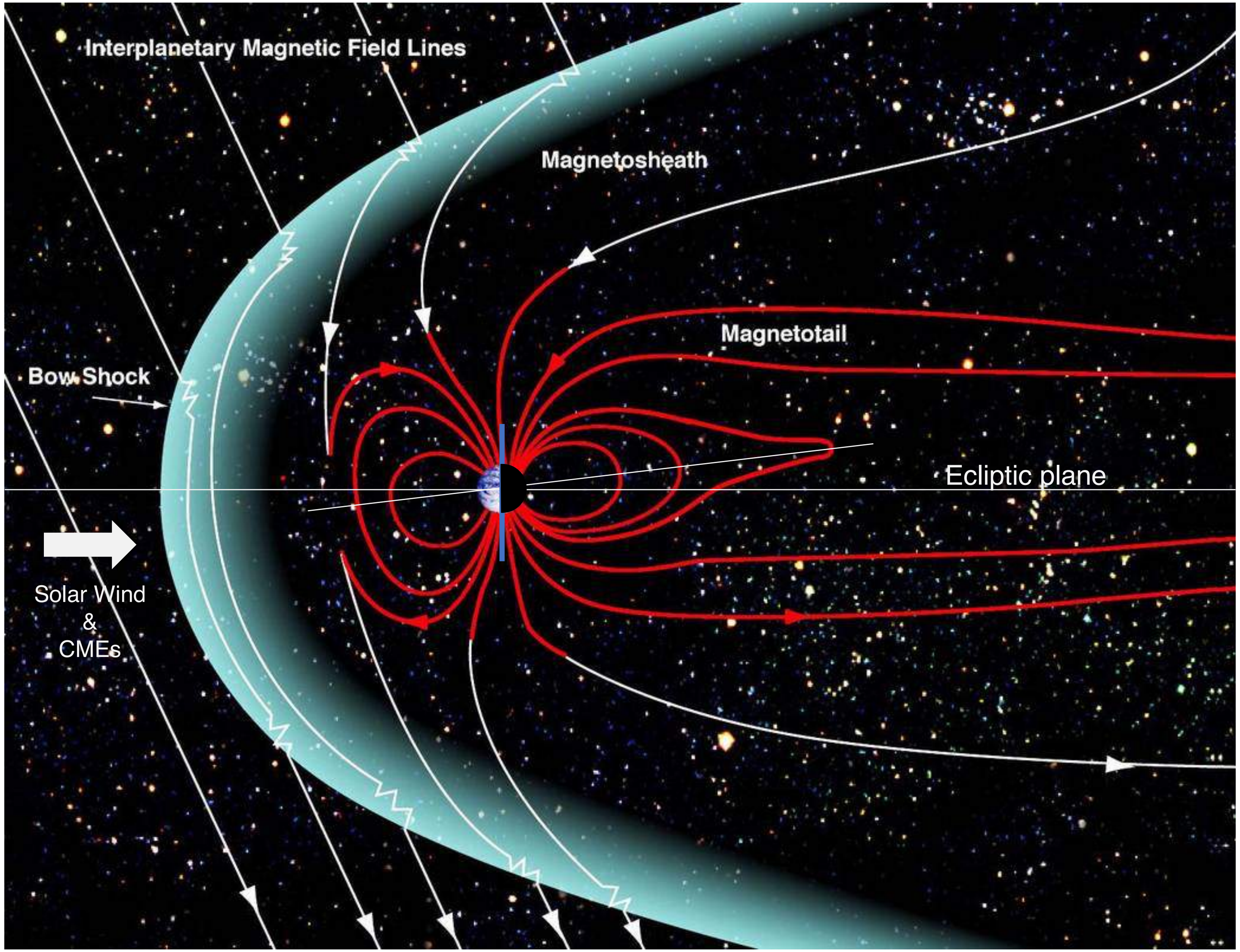
Geospace Coordinate Systems



https://svs.gsfc.nasa.gov/4217

2014 Feb 10 12:00:00.000 (UTC)

Structure of the Magnetosphere: Shaped by the Solar Wind

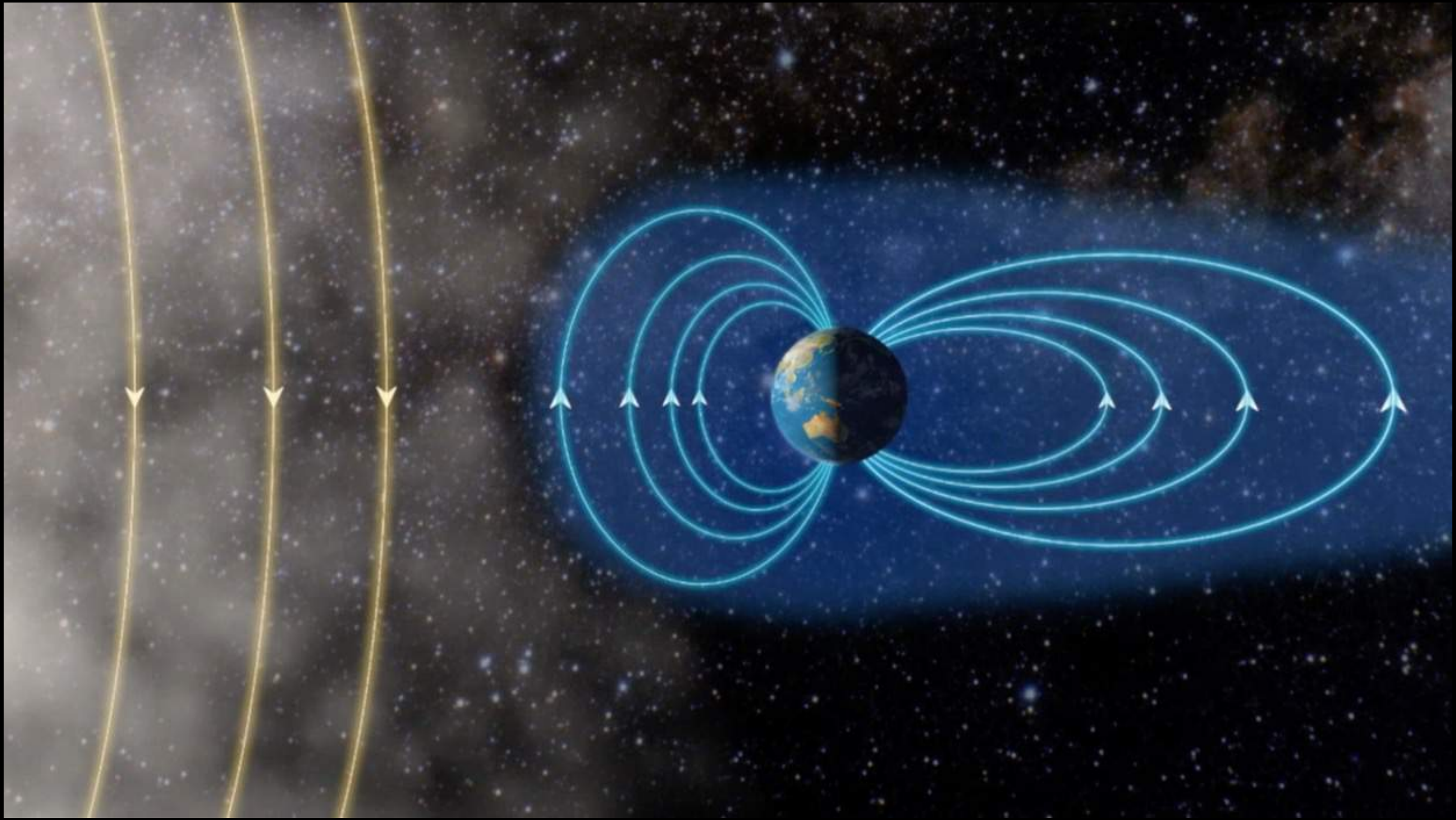


Notice tilt of magnetosphere relative to ecliptic plane.

Is this constant throughout the year?

Throughout the day?

Dynamics of the Magnetosphere: driven by the solar wind



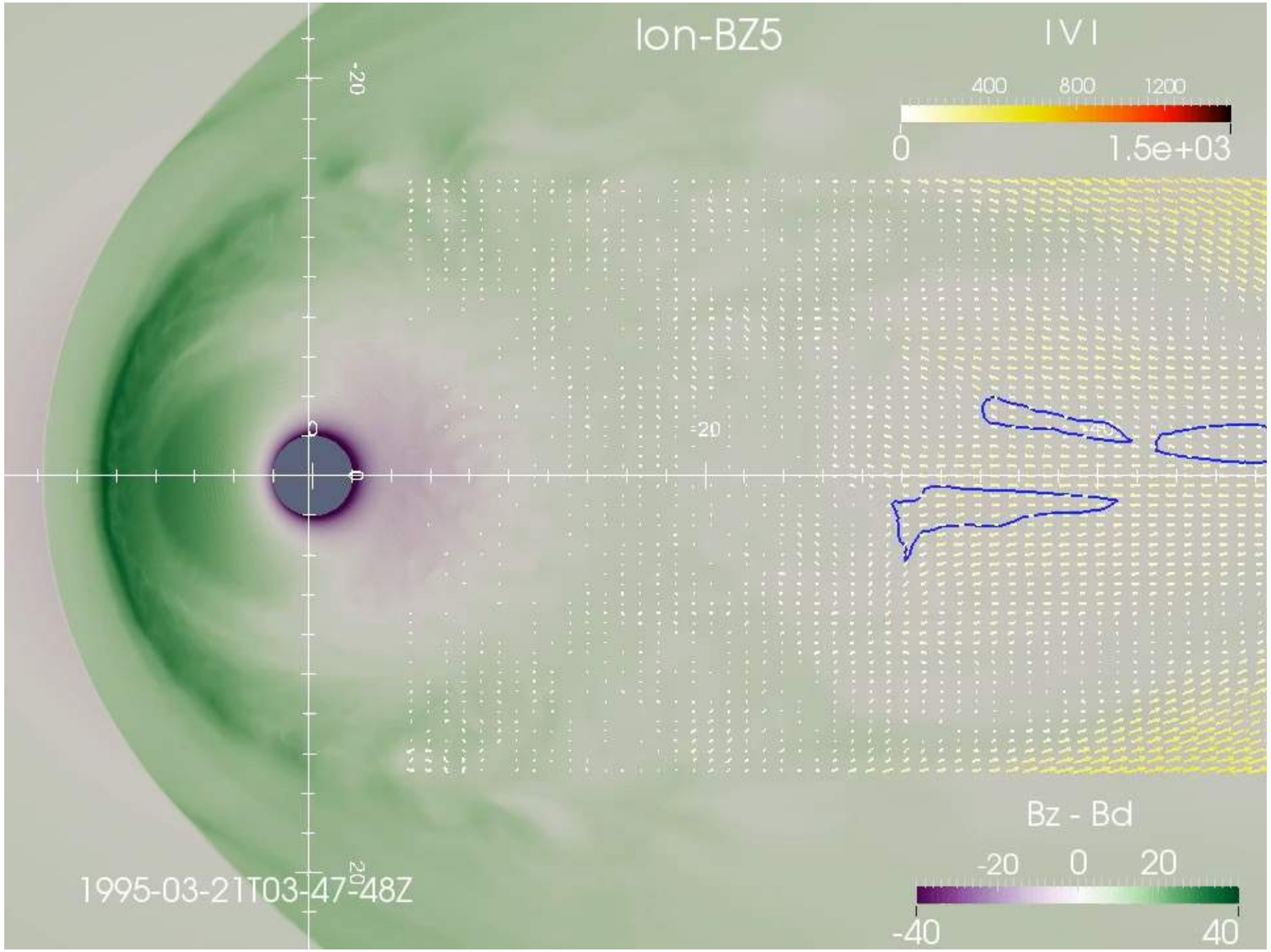
Dynamics of the Magnetosphere: driven by the solar wind

Reconnection in the magnetotail causes “**Bursty bulk flows**”

BBFs result in “**Dipolarization**”: the sudden reconfiguration of the magnetic field to be more “dipolar”

Take away: the Earth’s magnetic field is constantly changing due to reconnections with the ”Interplanetary magnetic field” (IMF)

IMF = solar wind or CME magnetic field

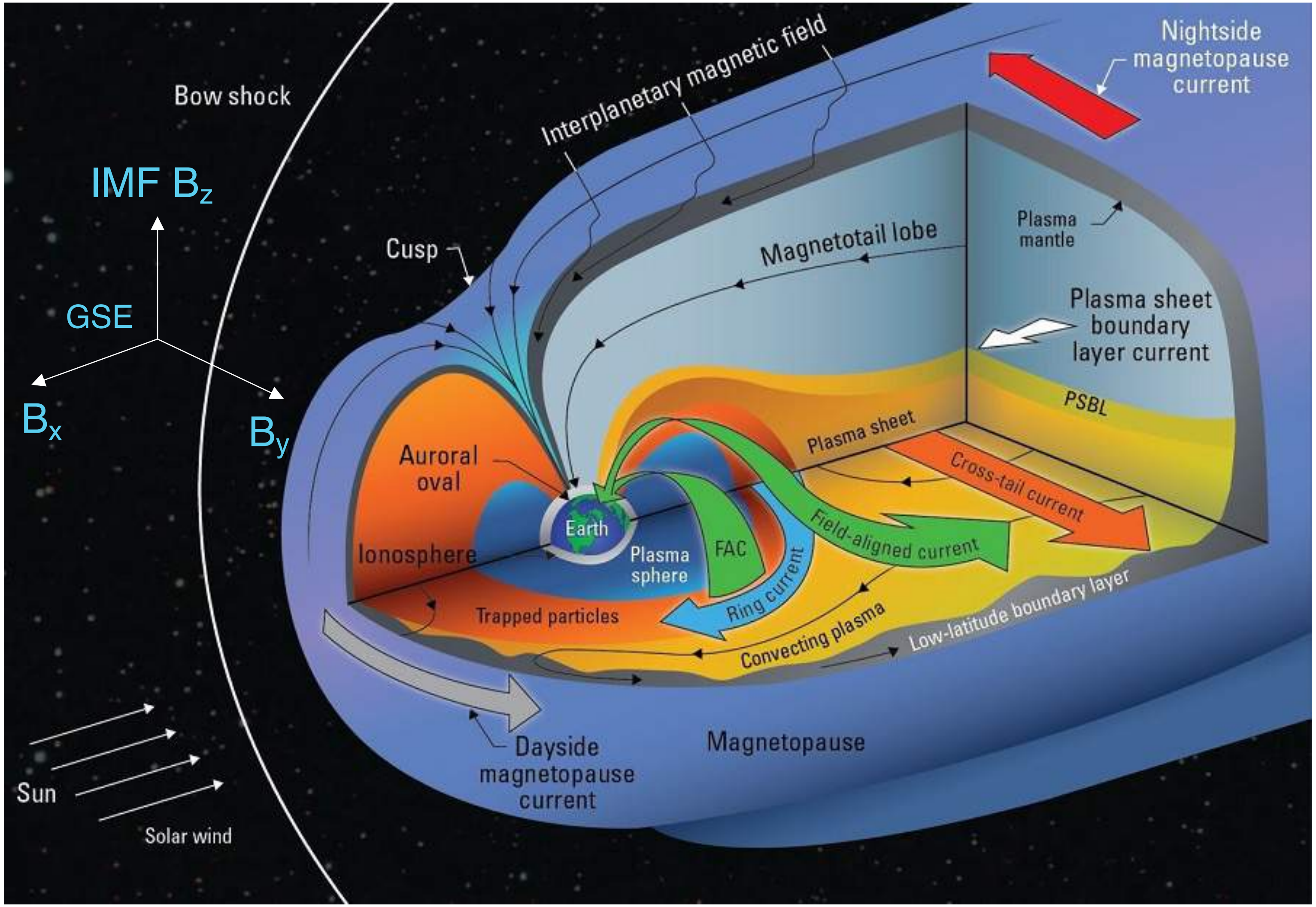


Wiltberger, M. *et al.* (2015) *Journal of Geophysical Research: Space Physics*, 120(6), pp. 4555–4566. doi:10.1002/2015JA021080.

Changing Magnetic Field = Electric Currents

Faraday's Law:

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

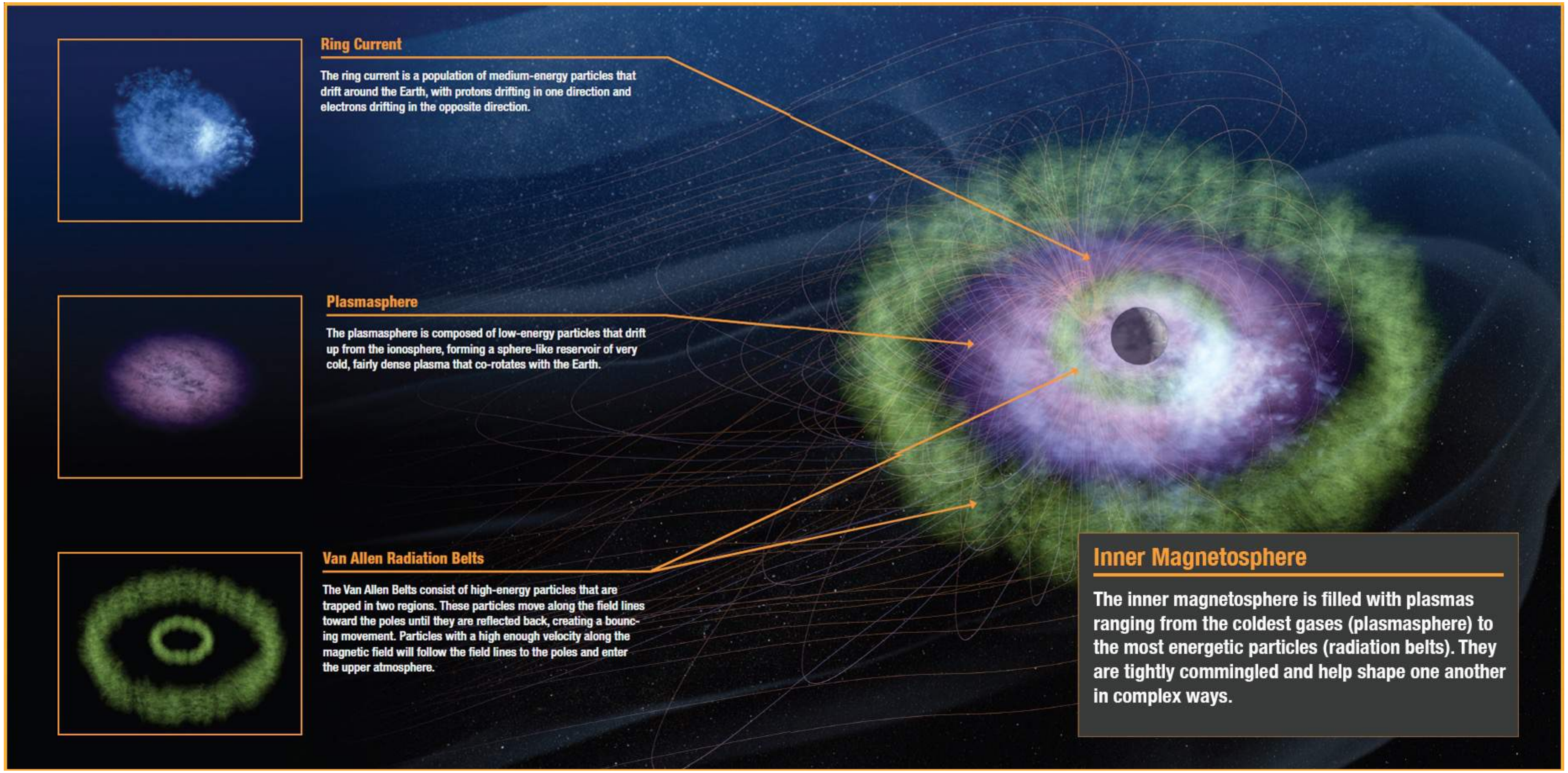


FAC = field aligned current

= source of auroral particle precipitation

Plasma fills the inner magnetosphere

Low energy to relativistic energy plasmas constitute the “background environment” out to GEO altitudes



Ring Current

The ring current is a population of medium-energy particles that drift around the Earth, with protons drifting in one direction and electrons drifting in the opposite direction.

Plasmasphere

The plasmasphere is composed of low-energy particles that drift up from the ionosphere, forming a sphere-like reservoir of very cold, fairly dense plasma that co-rotates with the Earth.

Van Allen Radiation Belts

The Van Allen Belts consist of high-energy particles that are trapped in two regions. These particles move along the field lines toward the poles until they are reflected back, creating a bouncing movement. Particles with a high enough velocity along the magnetic field will follow the field lines to the poles and enter the upper atmosphere.

Inner Magnetosphere

The inner magnetosphere is filled with plasmas ranging from the coldest gases (plasmasphere) to the most energetic particles (radiation belts). They are tightly commingled and help shape one another in complex ways.

The Van Allen Radiation Belts

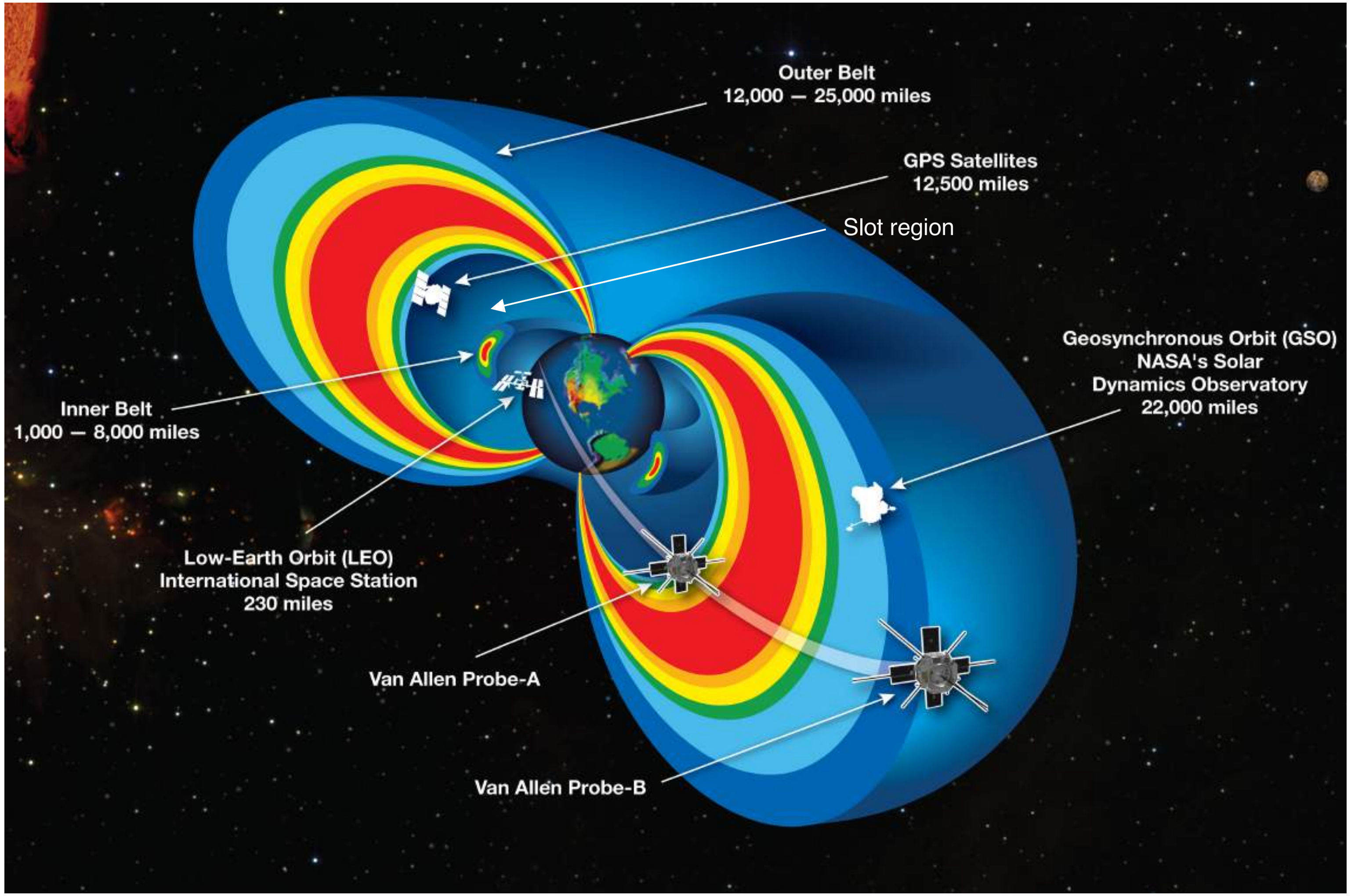
Energetic Charged Particles (ECPs) trapped on the magnetic field lines of the inner magnetosphere.

Discovered in 1958 during first US satellite mission Explorer 1 (Principal Investigator James Van Allen, U. of Iowa).

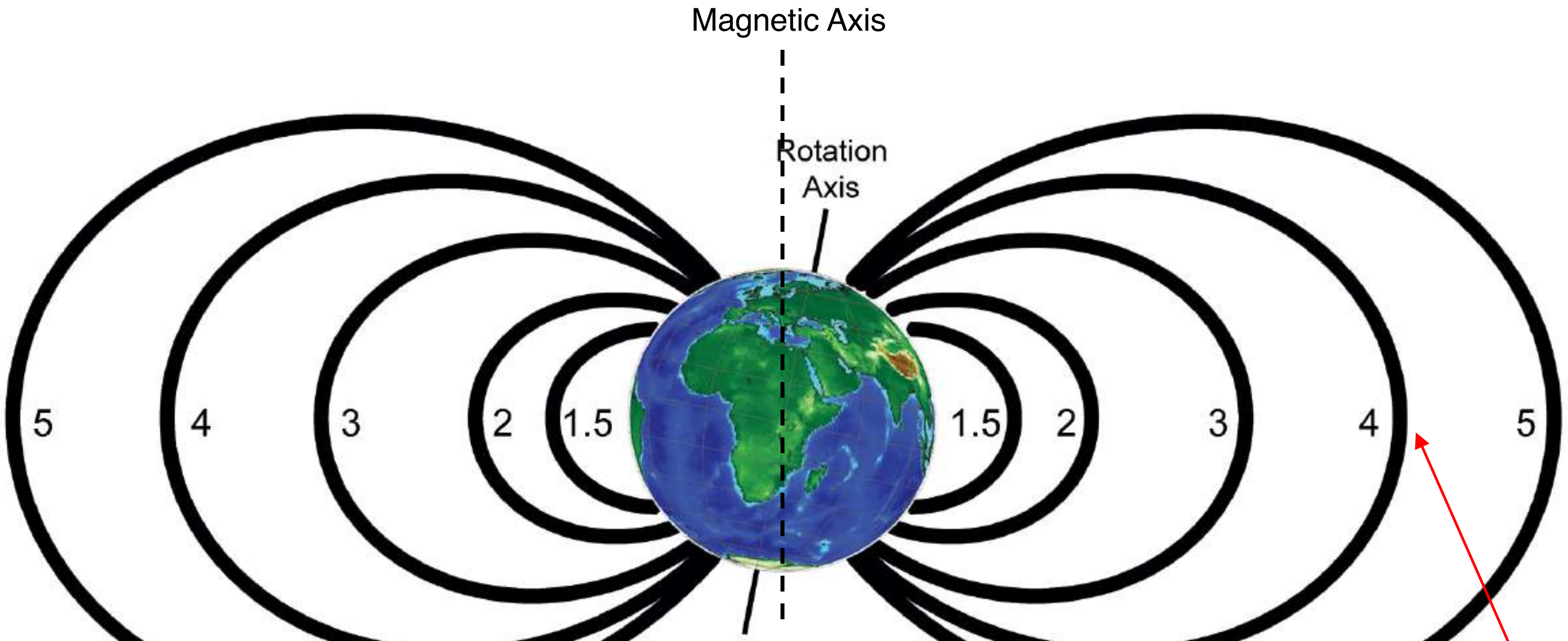
“*My God - space is radioactive!*”

Inner belt:
- 1.2 – 2 R_E , 7,600 – 12,750 km
- Predominately protons 100 keV > 100 MeV
- Electrons in the 100 keV range

Outer belt:
- 3 – 10 R_E, 19,000 – 60,000 km
- Peak intensity at 4—5 R_E , ~28,000 km
- Predominately 0.1—10 MeV electrons



The Van Allen Radiation Belts: L-Shells



“McIlwain L-value” after Carl E. McIlwain who initiated the system.

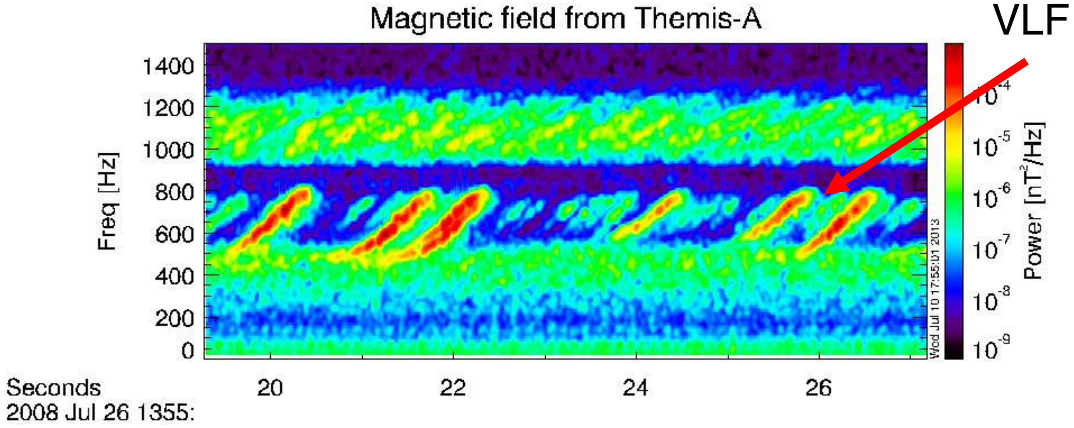
Connects common field lines on which charged particles are trapped in gyrating orbits.

Values converge at the poles where particles are “magnetically mirrored” to bounce between polar regions.

L-Shell value = Earth Radii at magnetic equator

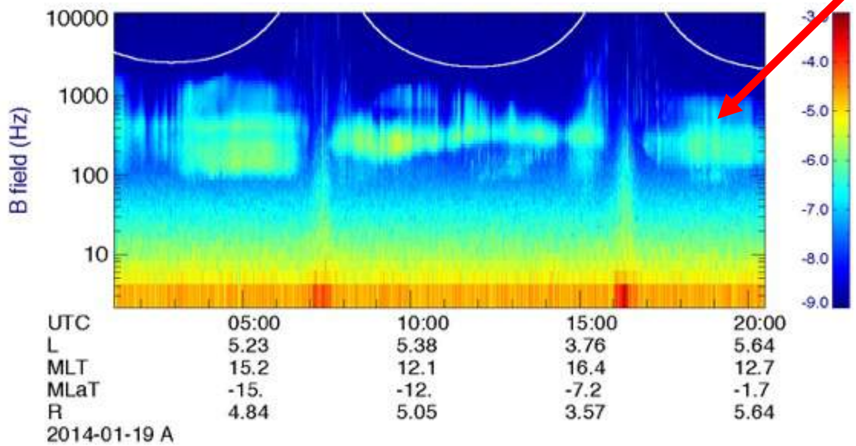
VLF B-field Waves Drive Radiation Belt Population

VLF **Chorus** accelerates electrons
filling the radiation belts



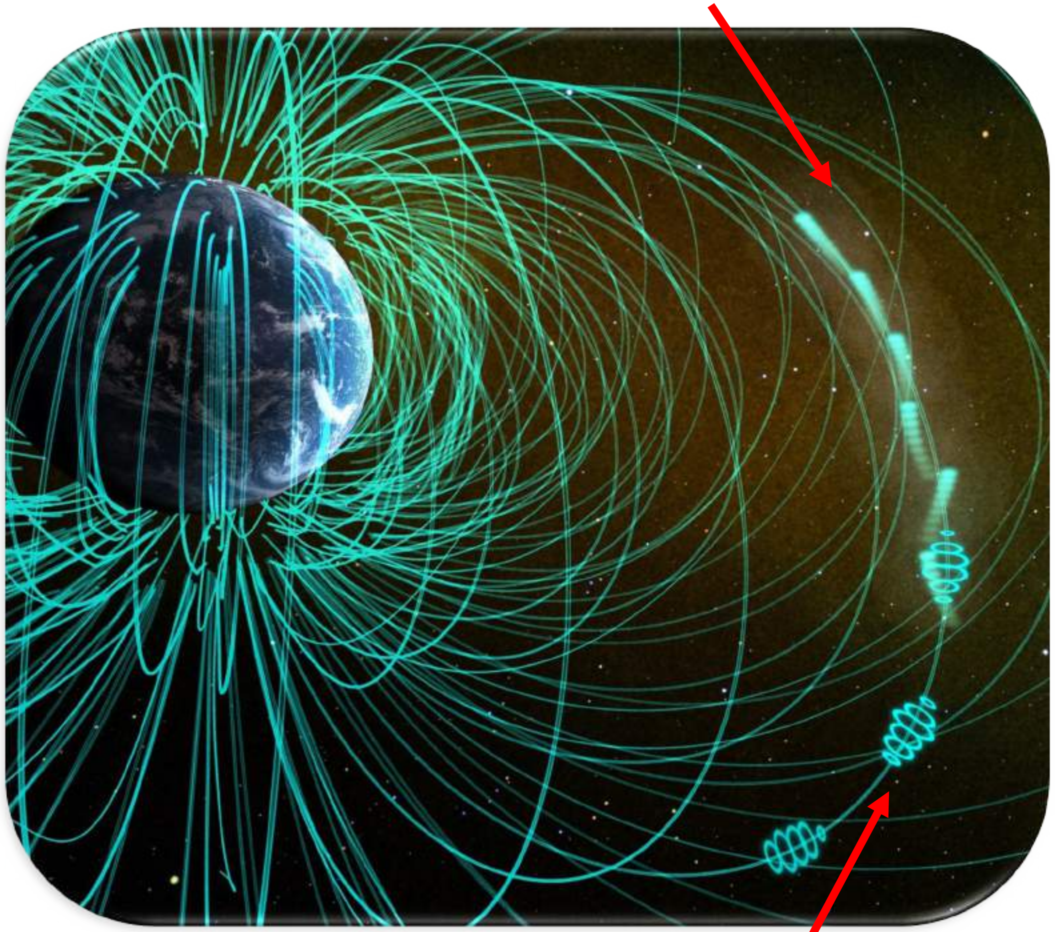
Observation of
VLF chorus waves

VLF **Hiss** scatters electrons
emptying the radiation belts



Observation of
VLF hiss waves

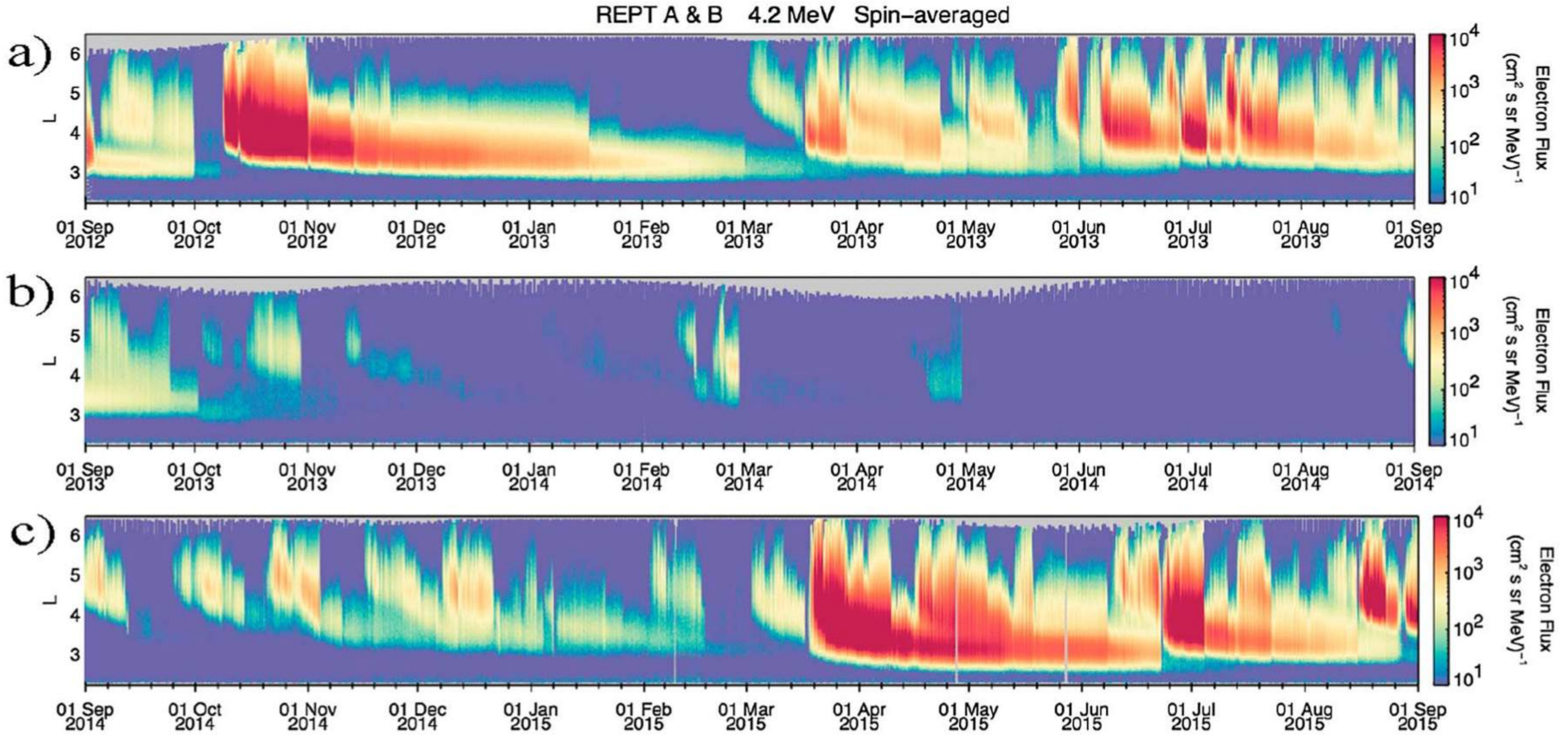
Scattered particles being lost to the atmosphere



VLF Wave packets

Outer belt electron flux vs. L Shell vs. time

2012—2015: relativistic electron flux highly variable in response to solar wind and CME conditions

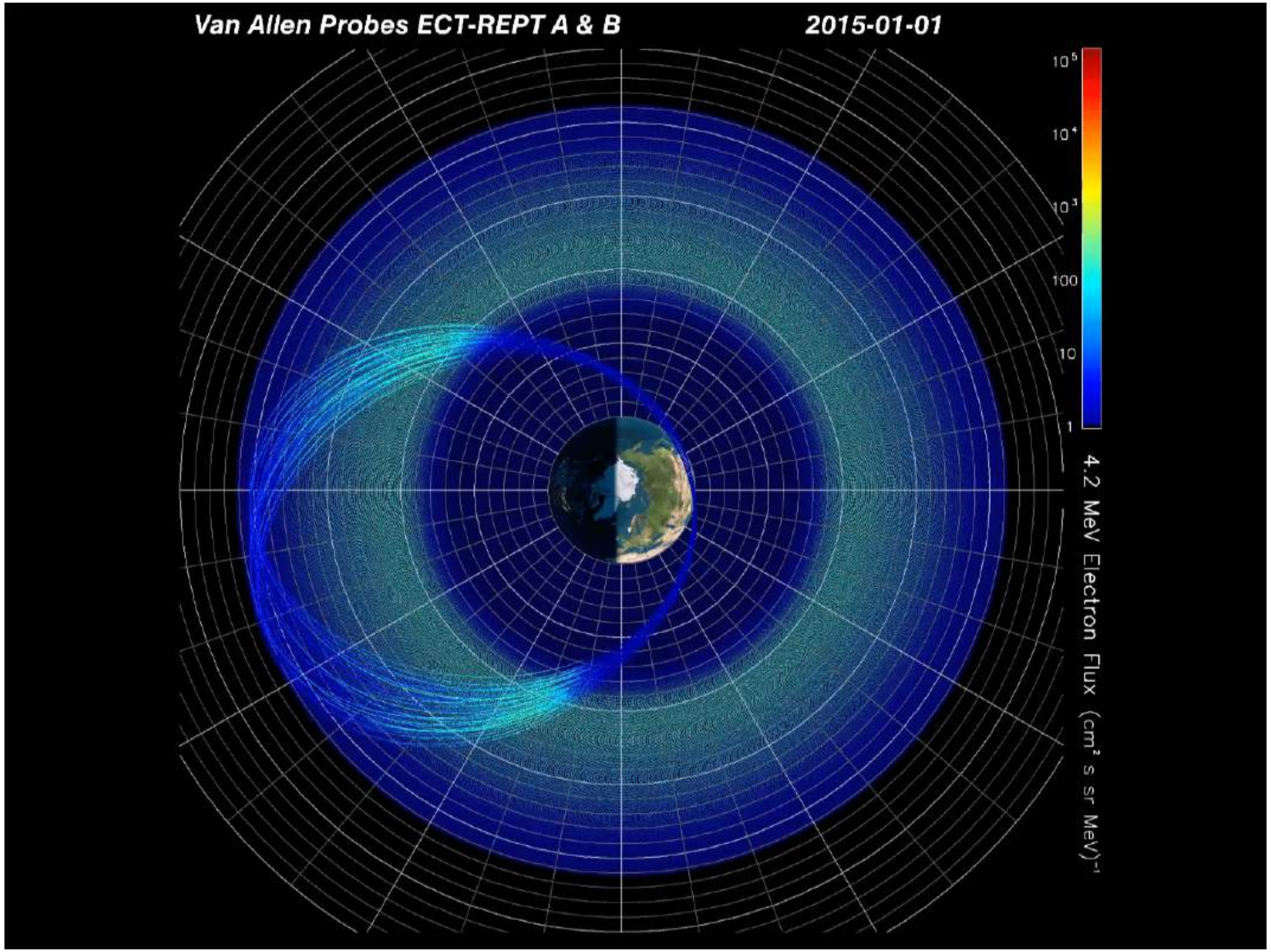


Baker, D.N. *et al.* (2016) *Journal of Geophysical Research: Space Physics*, 121(7), pp. 6647–6660. doi:10.1002/2016JA022502.

Variation of the Outer Belt electrons: 2 years near SC24 max

NASA Van Allen Probes Mission data: 2015—2017

Outer radiation belt 4.2 MeV electrons

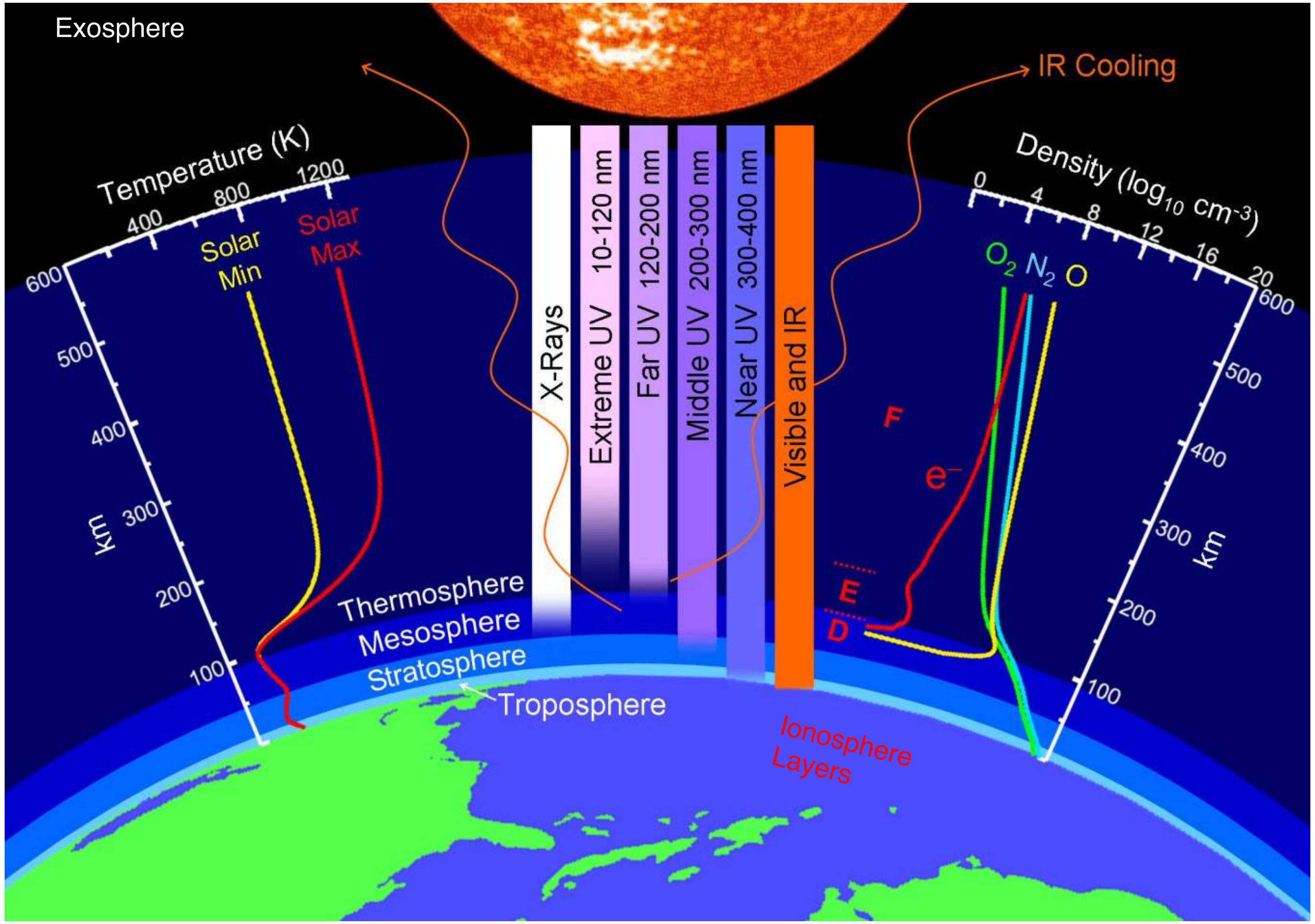


NOTE: The azimuthally symmetric structure is an *assumed extrapolation*.

The real radiation belts are certainly not perfectly symmetric as shown here.

The Mesosphere/Ionosphere/Thermosphere System

MIT: Hydrodynamics, magnetohydrodynamics, and chemistry required…



Troposphere: 75% of atmospheric mass

O_2, N_2, Ar

Thermosphere

- Altitude: 1000 –100 km
- Temperature: **1200—270 K**
- Density: **10^{3-16} cm^{-3}**
- Constituents: O_2, N_2, O, N, He, …
- Heated by solar EUV dissociation of O_2 and N_2

Mesosphere

- Altitude: 100 – 50 km
- Temperature: 270—190 K
- Density: 10^{10-16} cm^{-3}
- Constituents: O_2, N_2, O, N, …

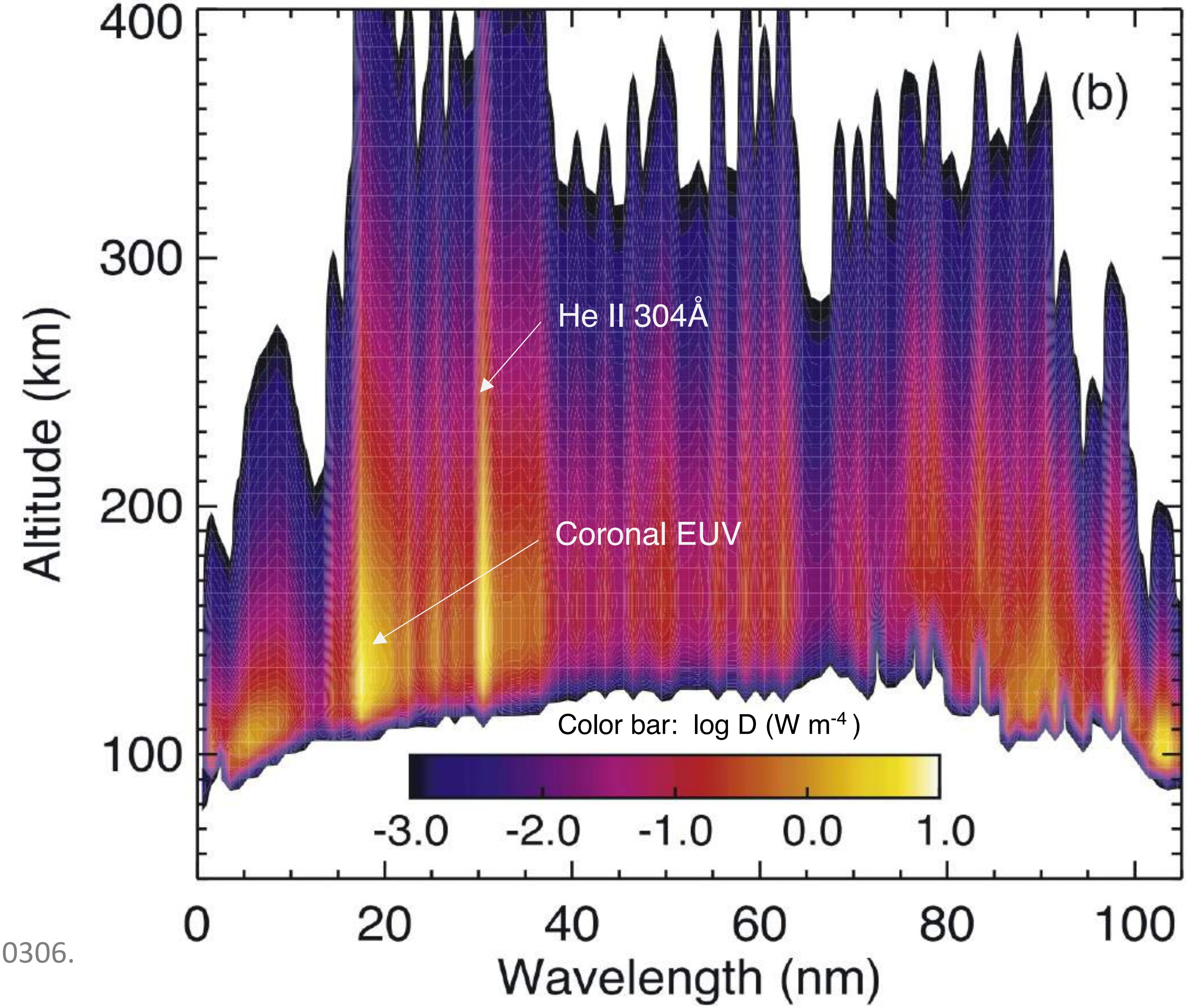
Stratosphere

- Altitude: 50 – 16 km
- Temperature: 270—220 K
- Density: 10^{16-18} cm^{-3}
- Constituents: O_2, N_2, O_3, …

Earth’s Upper Atmosphere: the Ionosphere

Solar EUV radiation both ionizes and dissociates atmospheric molecules, starting at about 100 km

Energy deposition, D, as a function of altitude and wavelength for low solar activity, i.e., low solar EUV irradiance.


He II 304Å

Coronal EUV

Color bar: log D (W m^{-4})

Solomon, S.C. (2005, *Journal of Geophysical Research*, 110(A10), p. A10306. doi:10.1029/2005JA011160.

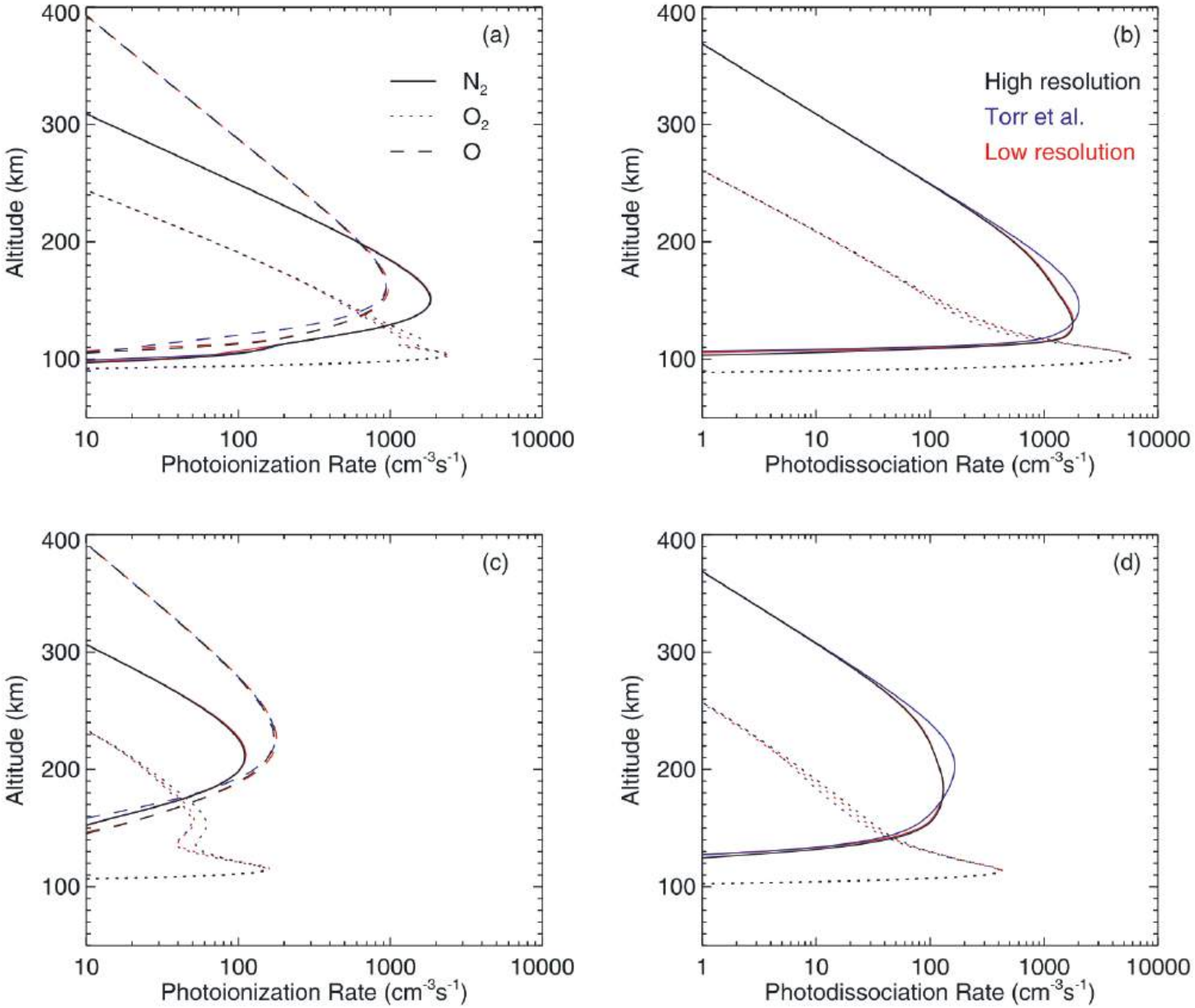
Earth’s Upper Atmosphere: the Ionosphere

Solar EUV radiation both ionizes and dissociates atmospheric molecules, starting at about 100 km

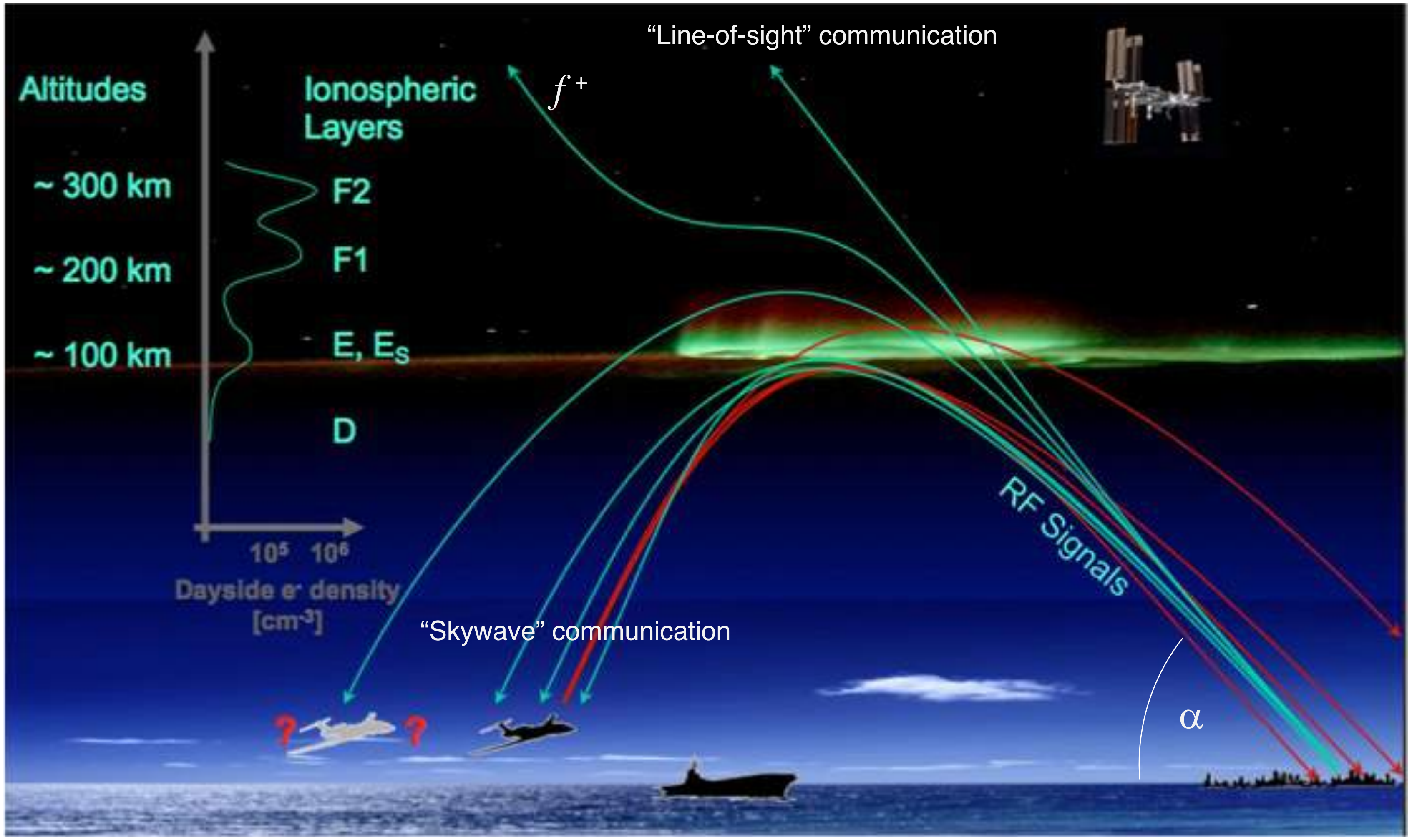
EUV Ionization (left) and dissociation (right) of major Thermosphere constituents.

Top: Noon Sun

Bottom: Sunset



Ionospheric EM Wave Reflection and Transmission



E_S = "Sporadic E-layer"
Note: most skywave communications are via F2 layer reflection, not Es as shown.

The ionosphere acts as a reflector of electromagnetic (EM) waves used in "Over-the-Horizon" (OTH) radio communications and radar.

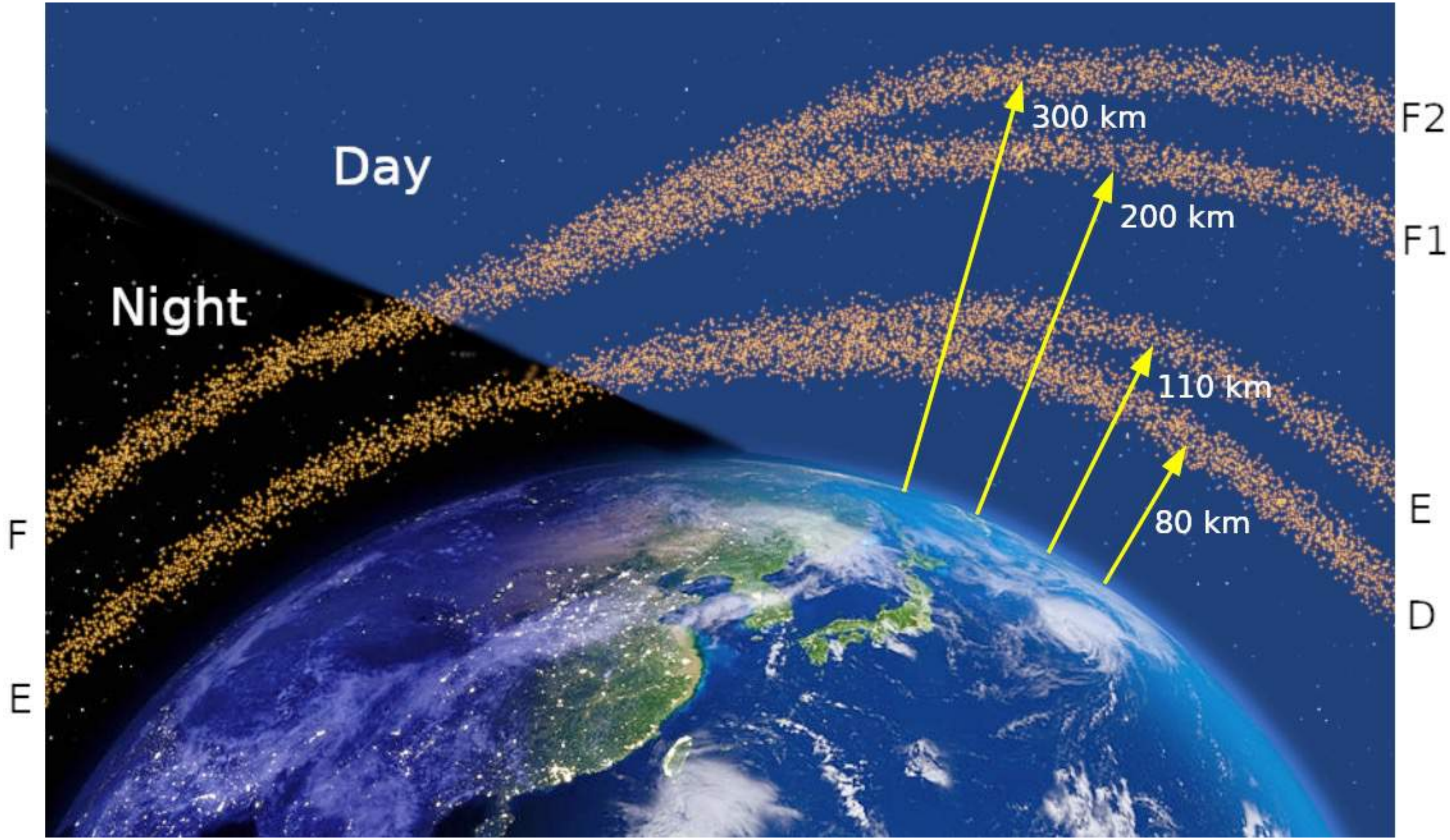
Maximum Usable Frequency (MUF):

$$f_{\mathrm{MUF}} \approx \frac{9\sqrt{N}}{\sin\alpha}$$

where N is the electron density (cm^{-3}) in the reflection layer, and α is the angle of the beam to the horizon.

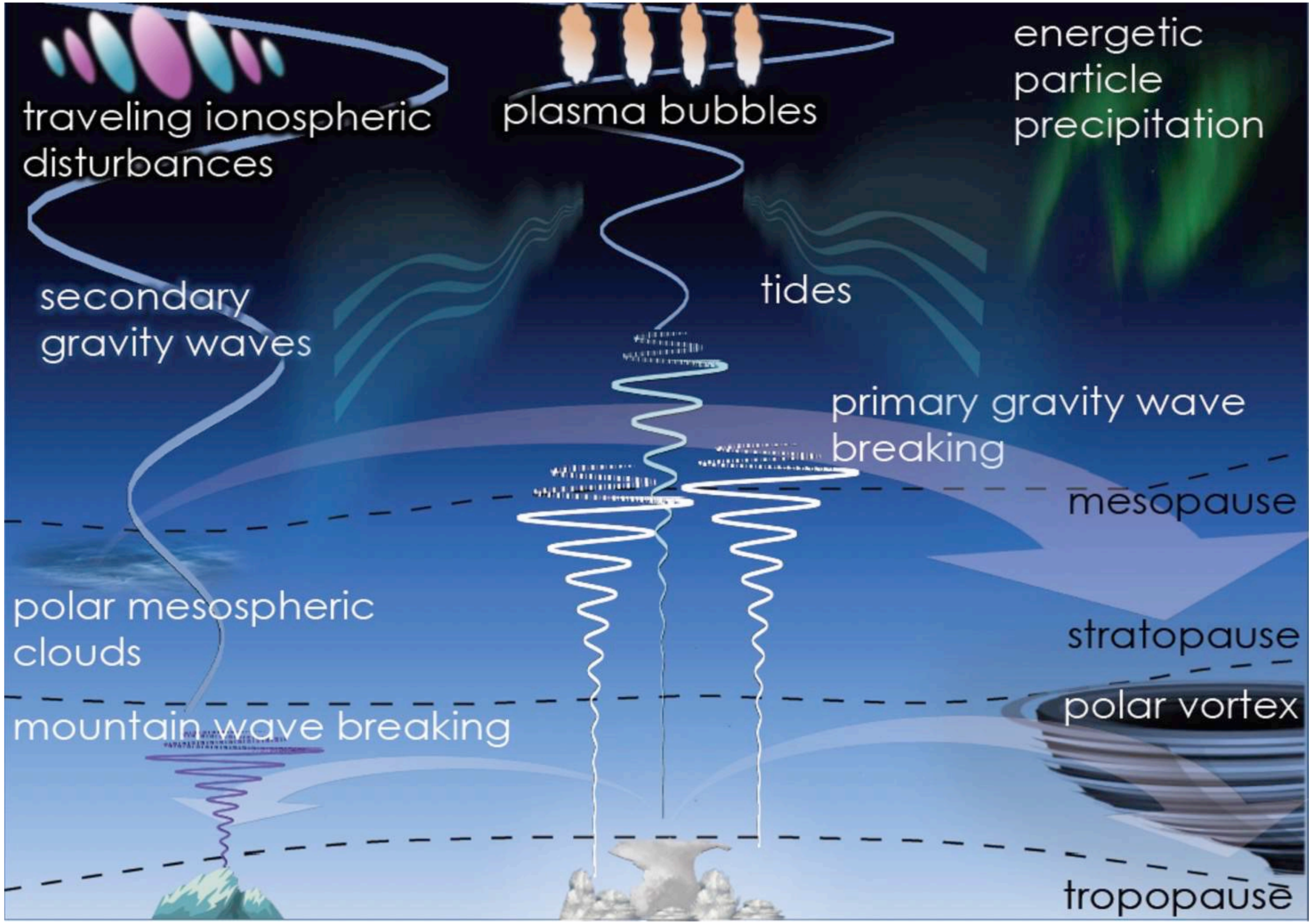
Radio frequencies higher than the MUF (f^+) are above the plasma frequency of the ionosphere at a given e- density – the ionosphere cannot re-radiate (reflect) the wave.

Ionospheric Layers contract on the night side



By Carlos Molina - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=103515276~

Coupling of Atmospheric layers



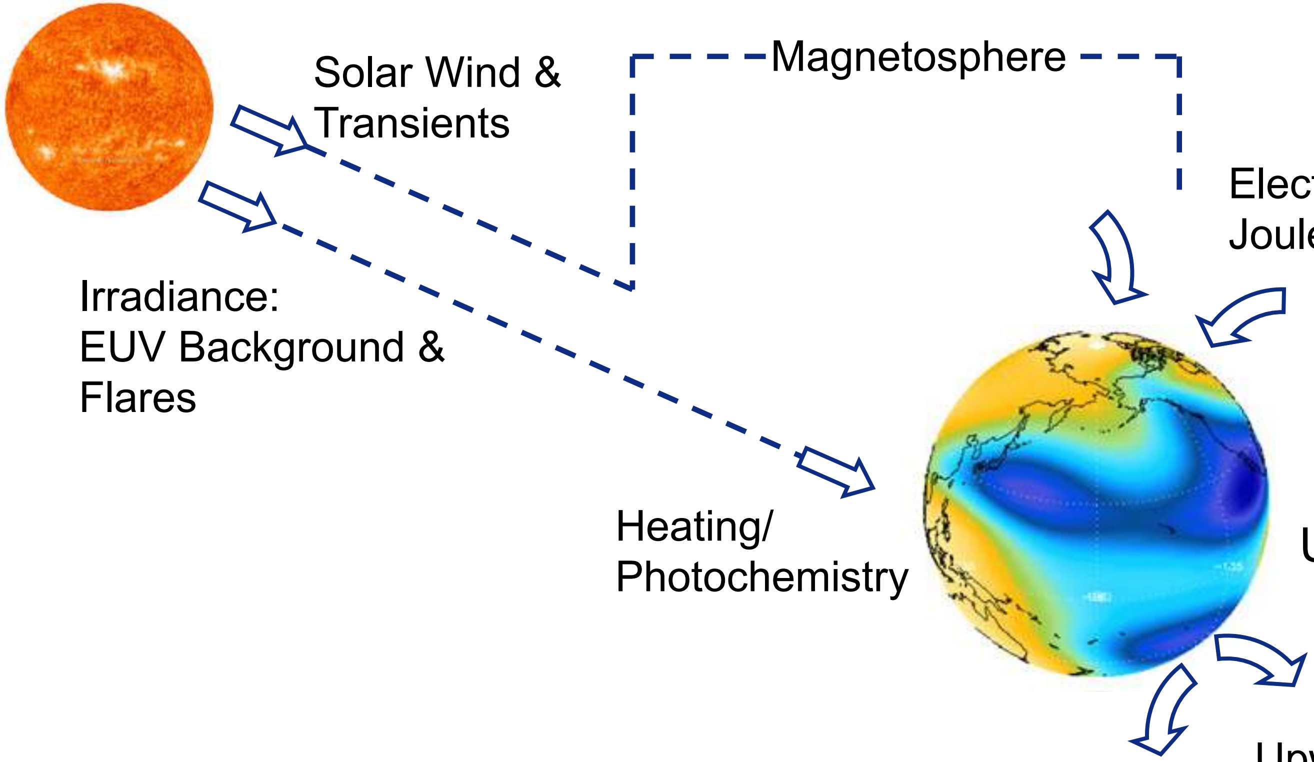
Courtesy Cora Randall, CU/LASP

Gravity waves from thunderstorms, particularly in the tropics, seed a Rayleigh-Taylor (RT) instability that creates “plasma bubbles” in the F-region ionosphere.

These “Spread-F” bubbles interfere with radio signals from GPS satellites causing “**GPS scintillation**”

Similarly, **Traveling Ionospheric Disturbances** (TIDs) can be triggered by energy deposition in the polar regions by energetic particles “precipitating” along polar field lines during geomagnetic storms.

Summary: Drivers of the MIT System



Sun

Solar Wind &
Transients

Magnetosphere

Irradiance:
EUV Background &
Flares

Electric Fields
Joule & Particle Heating

Heating/
Photochemistry

Upper Atmosphere

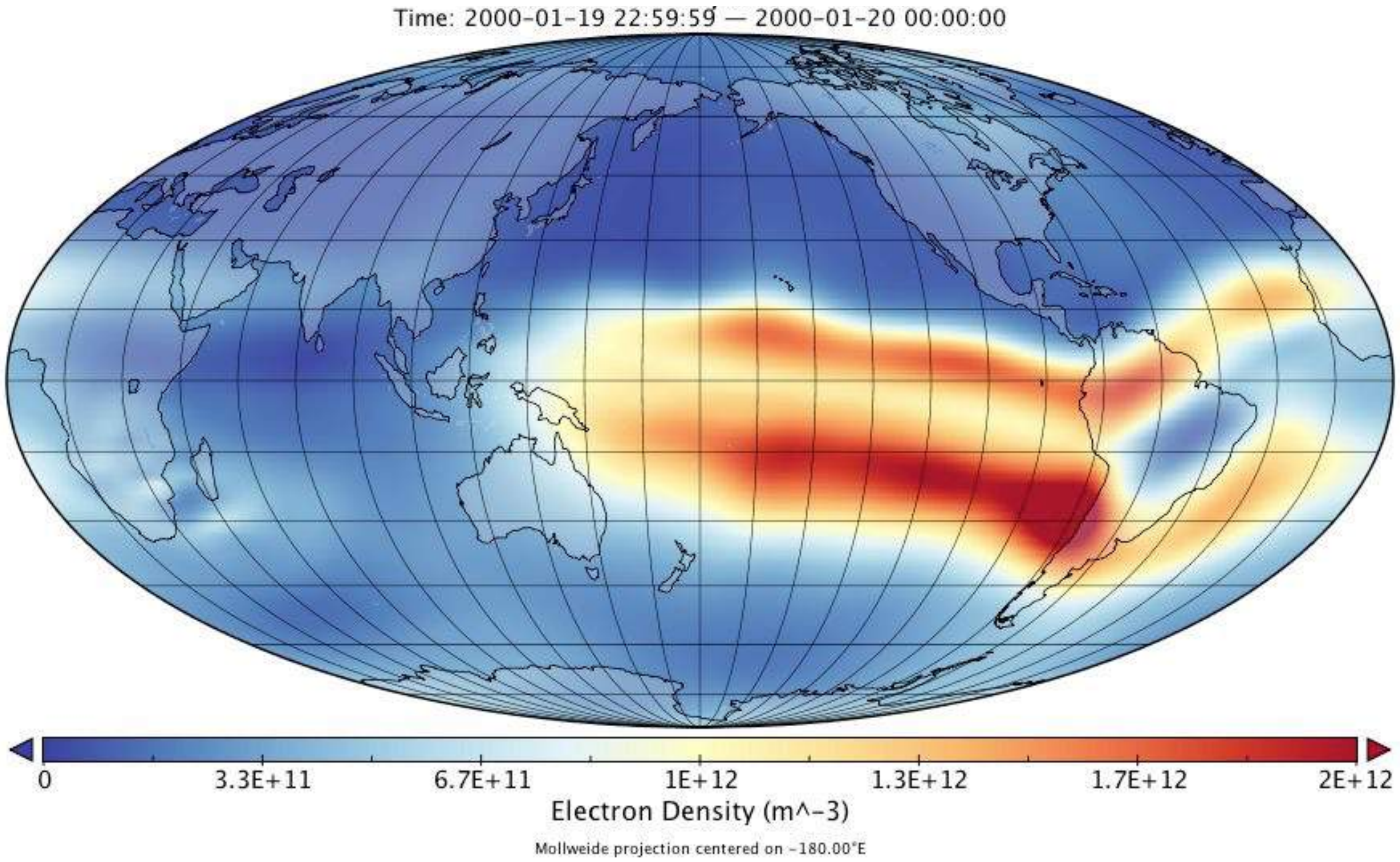
Upward Propagating
Waves and Tides

Adapted Prölss, G.W. (2011), *Surveys in Geophysics*, 32(2), pp. 101–195. doi:10.1007/s10712-010-9104-0.

Models of global MIT structure

NCAR/HAO Whole Atmosphere Community Climate Model – Extended (WACCM-X 2.0)

F-region ionosphere at ~300 km



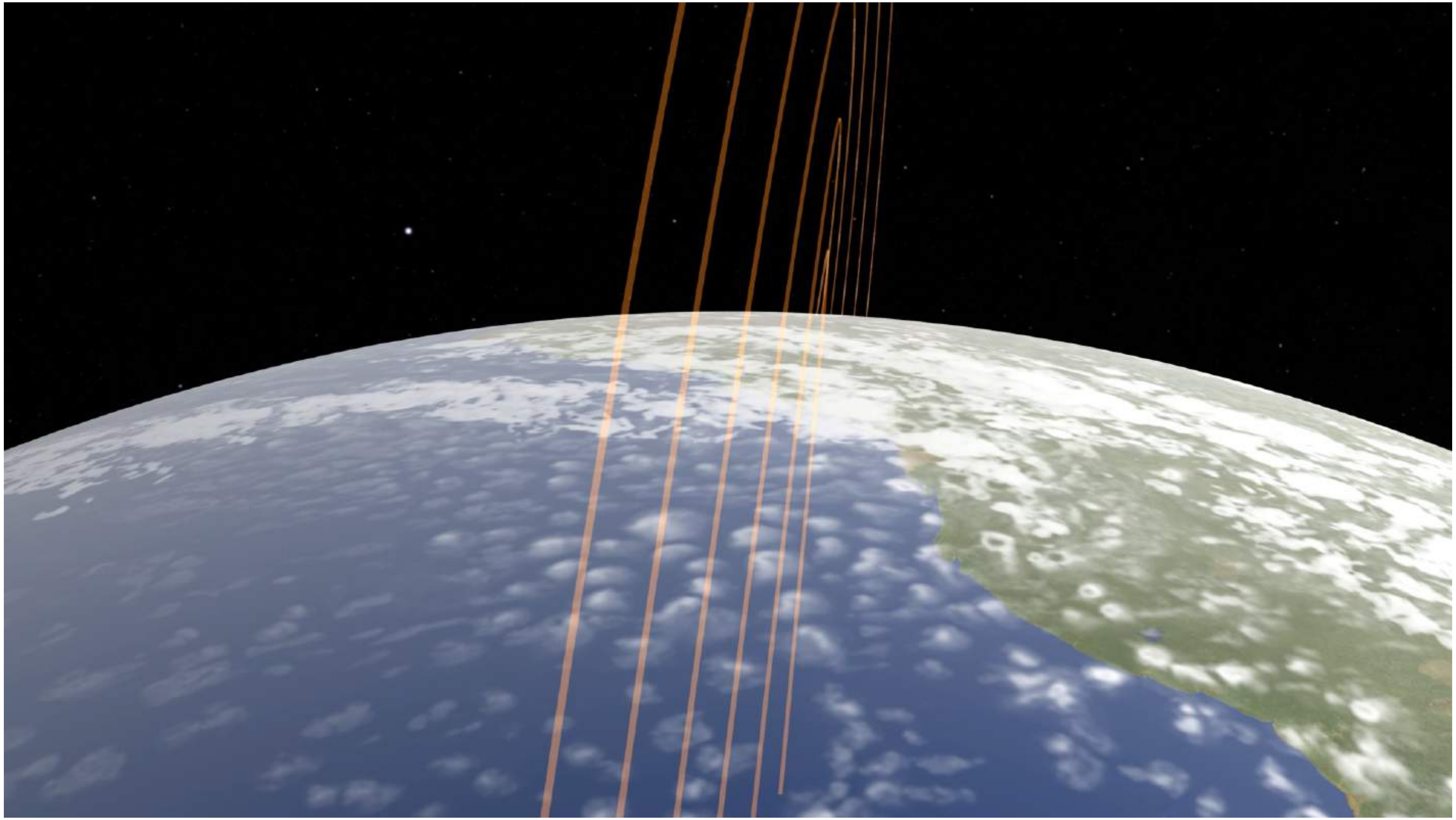
Atmosphere simulated from 0—700 km

Detailed chemistry with O^+, O_2 , NO^+, N^+, and N_2^+, electrons, and 74 neutrals.

Liu, H. *et al.* (2018) *Journal of Advances in Modeling Earth Systems*, 10(2), pp. 381–402. doi:10.1002/2017MS001232.

Equatorial Ionospheric Anomaly (EIA)

Upflows of plasma in the equatorial region follow the magnetic field lines above



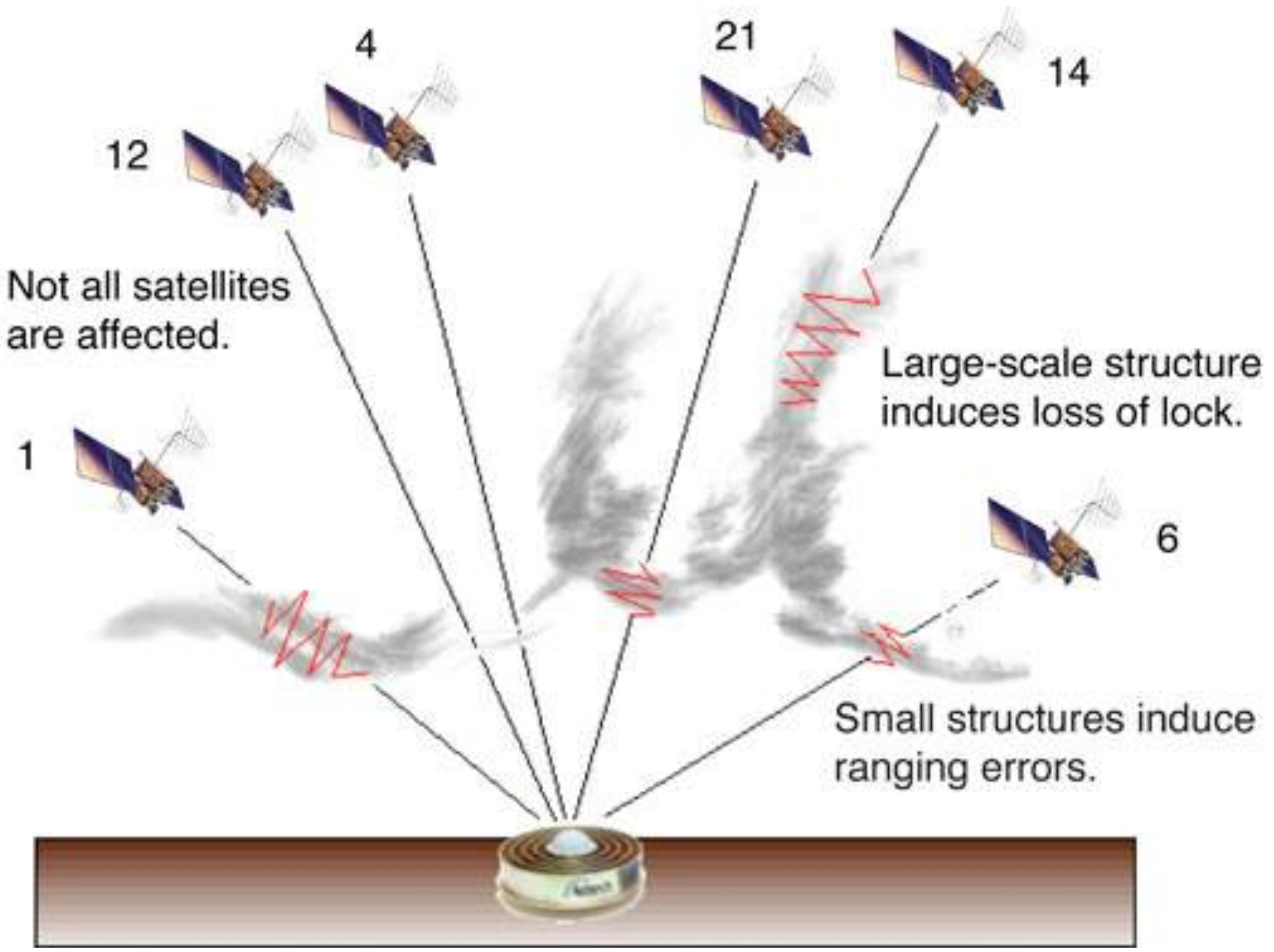
Sometimes called the
Appleton Anomaly
after discoverer
E. V. Appleton
(Nobel Prize, 1947)

“*Space Weather from Below*”: GNSS (GPS) Scintillation

US Global Positioning Satellite (GPS) system
Generic term: Global Navigation Satellite System (GNSS)

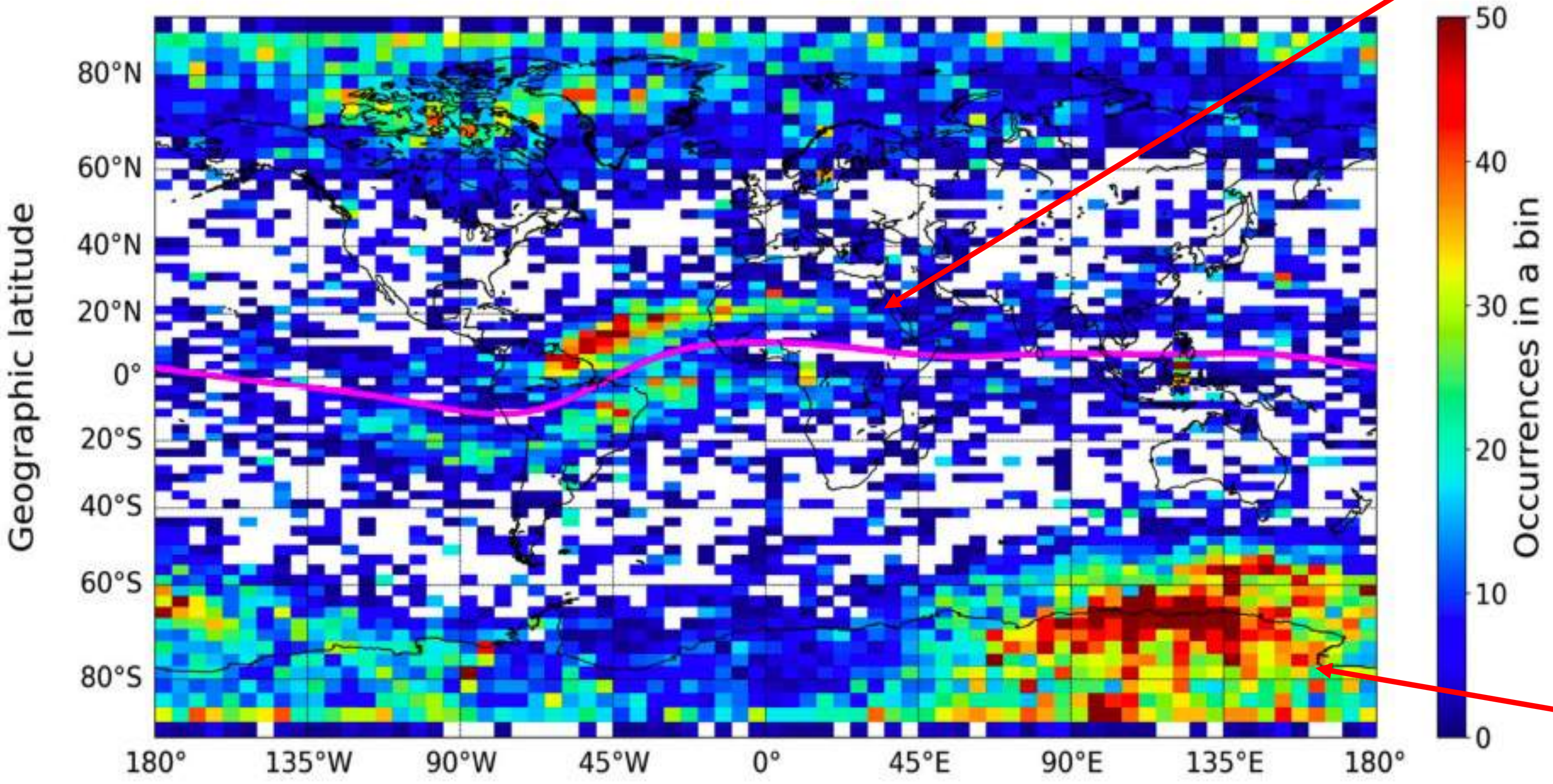
Large variation in **Total Electron Content** (TEC) along line of sight to GPS satellites causes phase and amplitude variations.

$$\mathrm{TEC} = \int n_e(s)\, ds$$



“*Space Weather from Below*”: GNSS (GPS) Scintillation

US Global Positioning Satellite (GPS) system
Generic term: Global Navigation Satellite System (GNSS)



Plasma bubbles along the EIA

Geographic distribution of all GPS loss of lock occurrence affecting Swarm A, B, and C from Dec. 2013 to Dec. 2020.

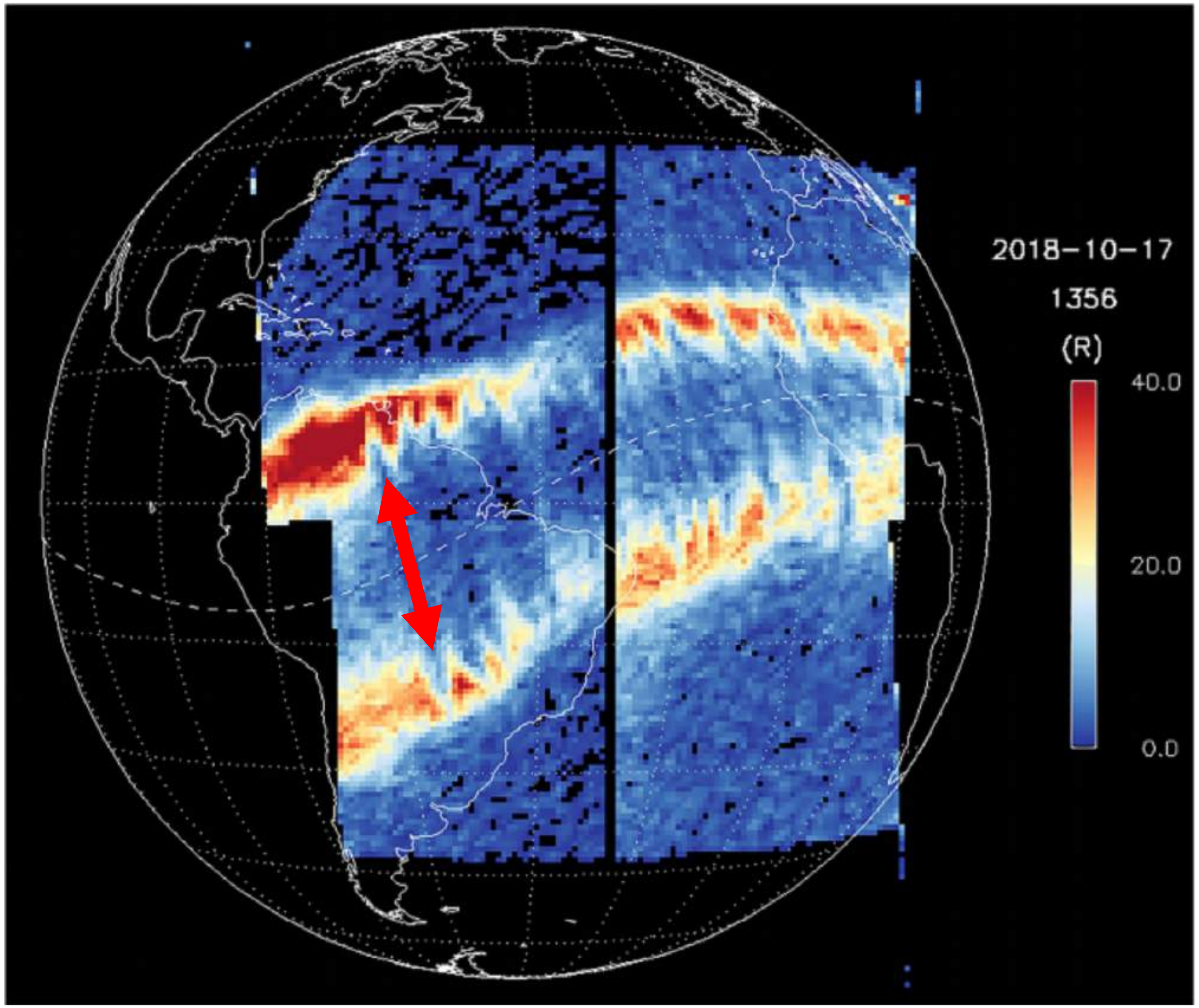
TIDs in polar region also cause scintillation.

Pezzopane, M. *et al.* (2021) *Remote Sensing*, 13(11), p. 2209. doi:10.3390/rs13112209.

“*Space Weather from Below*”: GNSS (GPS) Scintillation

NASA GOLD mission O/N2 ratio on nightside Hemisphere
17-October-2018

Depletions along magnetic field lines in EIA mark “Spread-F” plasma bubbles caused by the magnetic Rayleigh-Taylor Instability



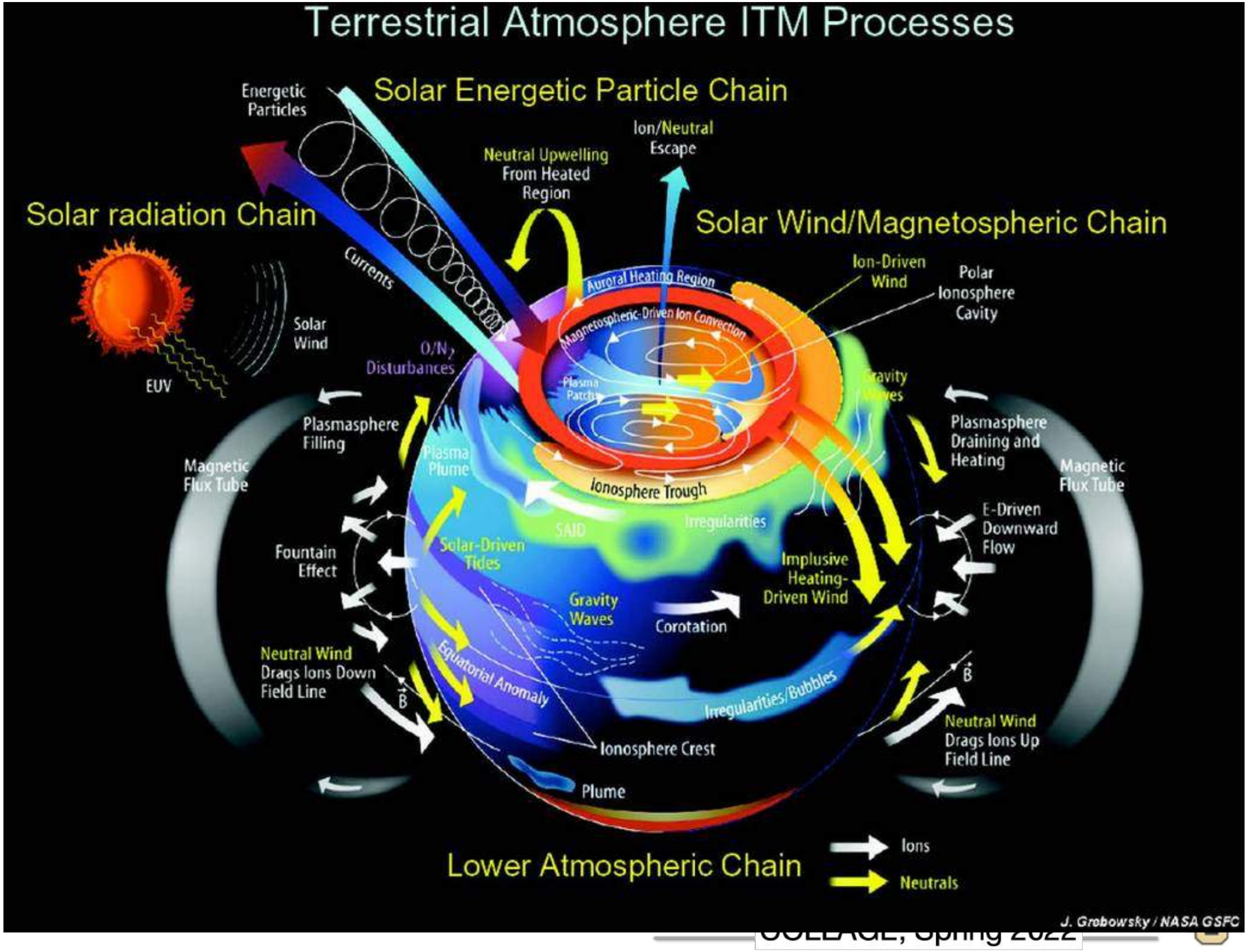
Eastes, R.W. *et al.* (2019) *Geophysical Research Letters*, 46(16), pp. 9318–9326. doi:10.1029/2019GL084199.

Fitting everything on one slide…

Not recommended!

Only shown because this is a very common slide in space weather.

Never make diagrams like this unless you want to spend 15 minutes on a single slide…



J. Grobowsky / NASA GSFC

Interlude: “How to Speak”

Patrick Winston
MIT OpenCourseWare
https://www.youtube.com/watch?v=Unzc731iCUY

Possibly the most important video for science career advancement ever made

Space Weather at Earth

Review: Solar sources of space weather

Photons, plasma, and charged particles

- Background EUV & Flare X-ray irradiance: “primes the system” but *does not cause geomagnetic storming*

- Solar wind High Speed Streams (HSS) and Co-rotating Interaction Regions (CIRs): *minor to strong geomagnetic storms*

- Solar Magnetic Eruptions (SMEs): *minor to extreme storms*
  - Coronal Mass Ejections (CMEs)
  - Solar Energetic Particles (SEPs)

Solar UV,EUV, and X-ray Irradiance Variations

Set the background level of heating and ionization in the upper atmosphere

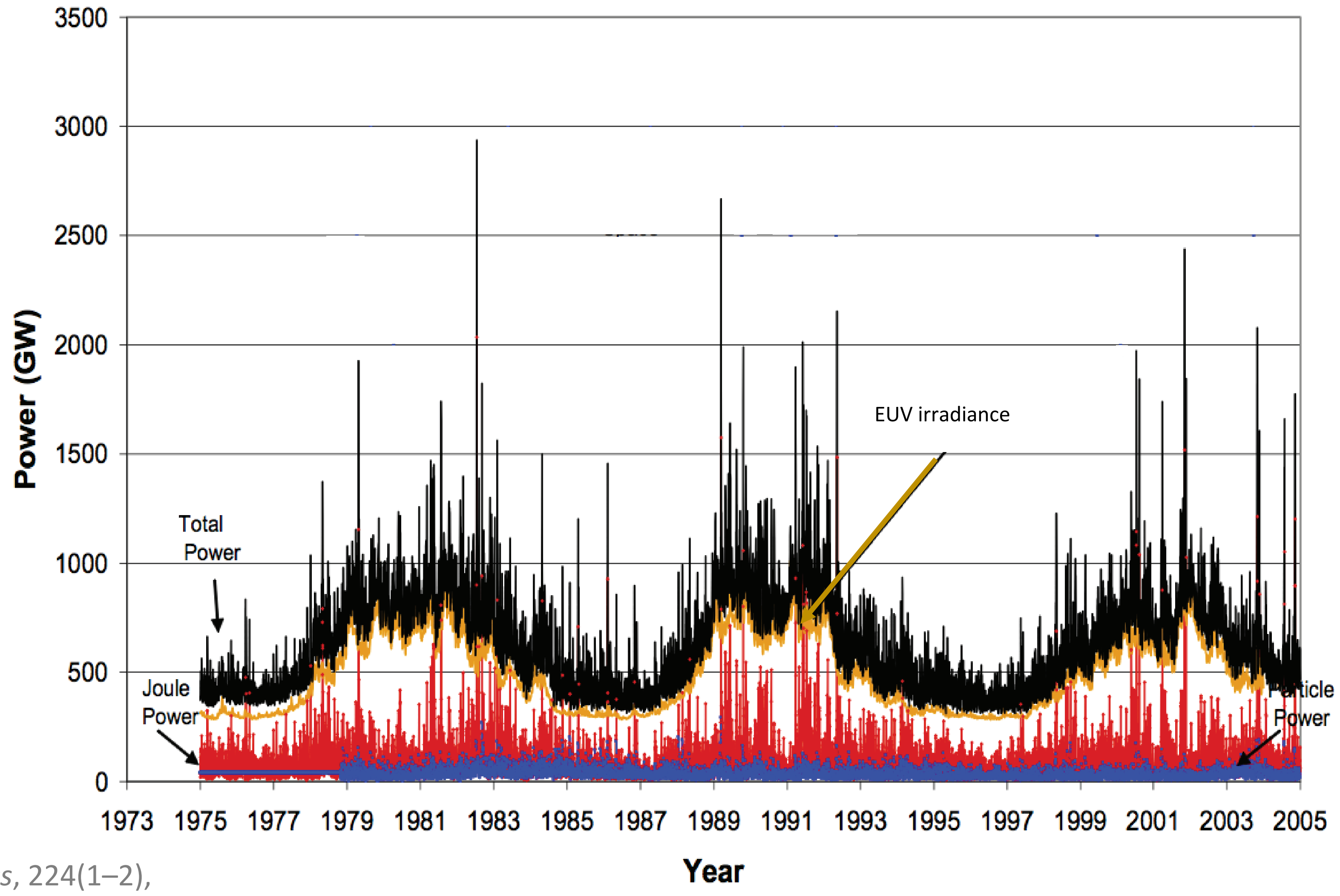
Gold line: EUV and UV irradiance input

Red line: geomagnetic storm input due to Joule heating by magnetospheric currents (ring current, FACs).

Blue line: energetic charged particle input, primarily electrons and protons precipitating in the auroral zones.

Black line: total power input. *What are the spikes?*

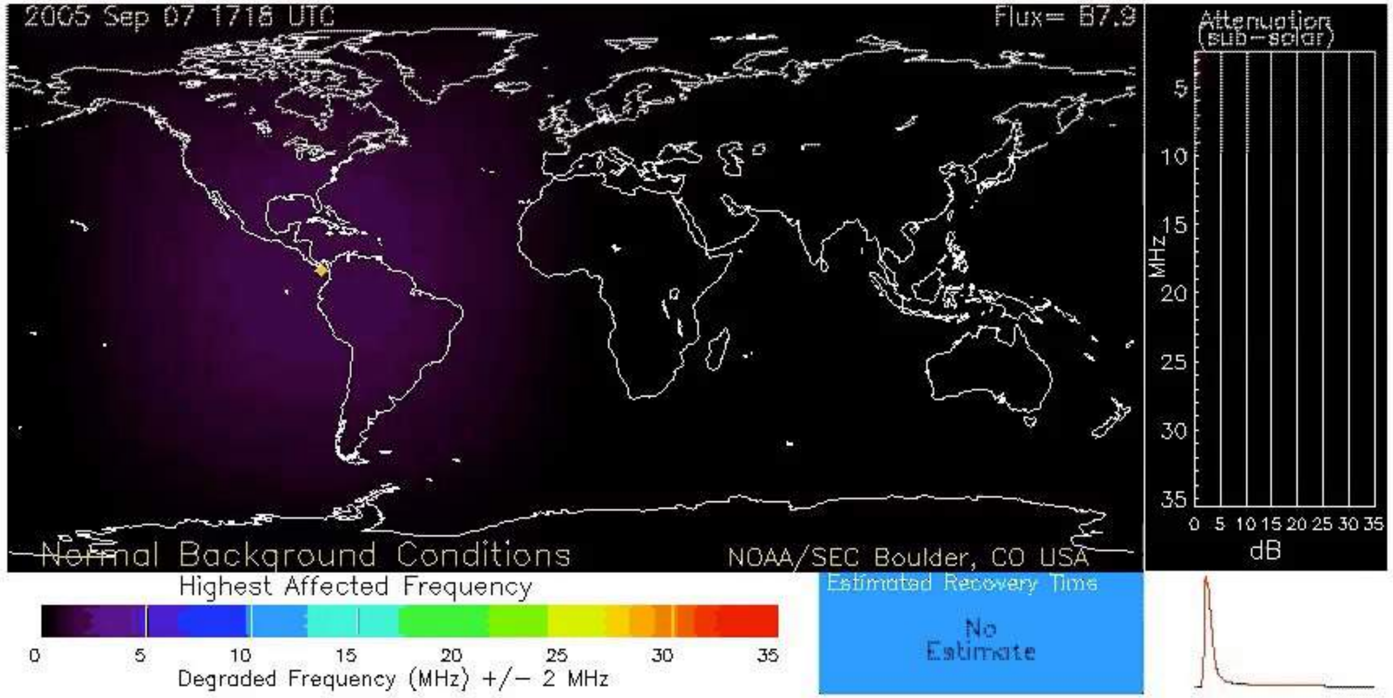
Daily Average Power Input to the Thermosphere: Solar Cycles 21—23



Knipp, D.J., Tobiska, W.K. and Emery, B.A. (2004) *Solar Physics*, 224(1–2), pp. 495–505. doi:10.1007/s11207-005-6393-4.

Solar Flare EUV impacts to Radio and Radar

Impulsive flare EUV & X-ray irradiance causes "Sudden Ionospheric Disturbance" ***on sunlit side of the Earth only*.**



07-Sep-2005 X1.7 Flare

D-Region Absorption Product (D-RAP) model from NOAA/SWPC.

"Short wave fade" is the operator term for loss of HF comms during flares.

Airlines often switch to Satellite comms (e.g., Iridium) during solar flares.

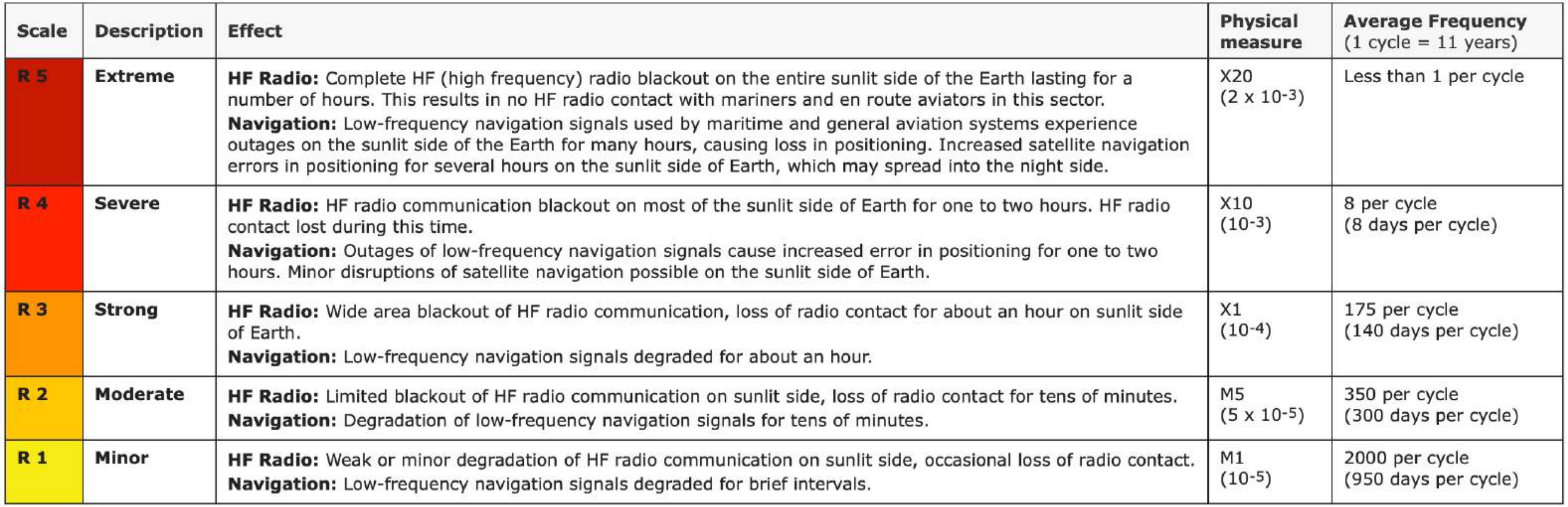
https://www.swpc.noaa.gov/products/d-region-absorption-predictions-d-rap

Quantifying Flare Impacts to the Ionosphere

NOAA Space Weather Prediction Center (SWPC) R-scale

R = “Radio blackout”

GOES XRS irradiance

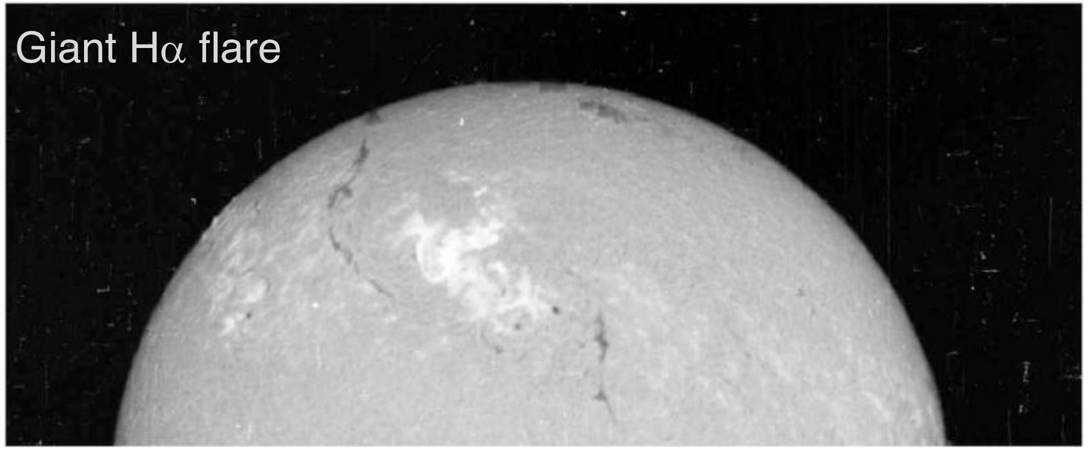


Scale	Description	Effect	Physical measure	Average Frequency (1 cycle = 11 years)
R 5	Extreme	**HF Radio:** Complete HF (high frequency) radio blackout on the entire sunlit side of the Earth lasting for a number of hours. This results in no HF radio contact with mariners and en route aviators in this sector. **Navigation:** Low-frequency navigation signals used by maritime and general aviation systems experience outages on the sunlit side of the Earth for many hours, causing loss in positioning. Increased satellite navigation errors in positioning for several hours on the sunlit side of Earth, which may spread into the night side.	X20 (2 x 10^{-3})	Less than 1 per cycle
R 4	Severe	**HF Radio:** HF radio communication blackout on most of the sunlit side of Earth for one to two hours. HF radio contact lost during this time. **Navigation:** Outages of low-frequency navigation signals cause increased error in positioning for one to two hours. Minor disruptions of satellite navigation possible on the sunlit side of Earth.	X10 (10^{-3})	8 per cycle (8 days per cycle)
R 3	Strong	**HF Radio:** Wide area blackout of HF radio communication, loss of radio contact for about an hour on sunlit side of Earth. **Navigation:** Low-frequency navigation signals degraded for about an hour.	X1 (10^{-4})	175 per cycle (140 days per cycle)
R 2	Moderate	**HF Radio:** Limited blackout of HF radio communication on sunlit side, loss of radio contact for tens of minutes. **Navigation:** Degradation of low-frequency navigation signals for tens of minutes.	M5 (5 x 10^{-5})	350 per cycle (300 days per cycle)
R 1	Minor	**HF Radio:** Weak or minor degradation of HF radio communication on sunlit side, occasional loss of radio contact. **Navigation:** Low-frequency navigation signals degraded for brief intervals.	M1 (10^{-5})	2000 per cycle (950 days per cycle)

Solar “Radio Bursts”

Flare photon emission in the NORAD Ballistic Missile Early Warning System radar: 23-May-1967


“white light” flare


Giant Hα flare

“Jamming” of radars initially interpreted as Russian prelude to attack

Knipp, D.J. *et al.* (2016), *Space Weather*, 14(9), pp. 614–633. doi:10.1002/2016SW001423.

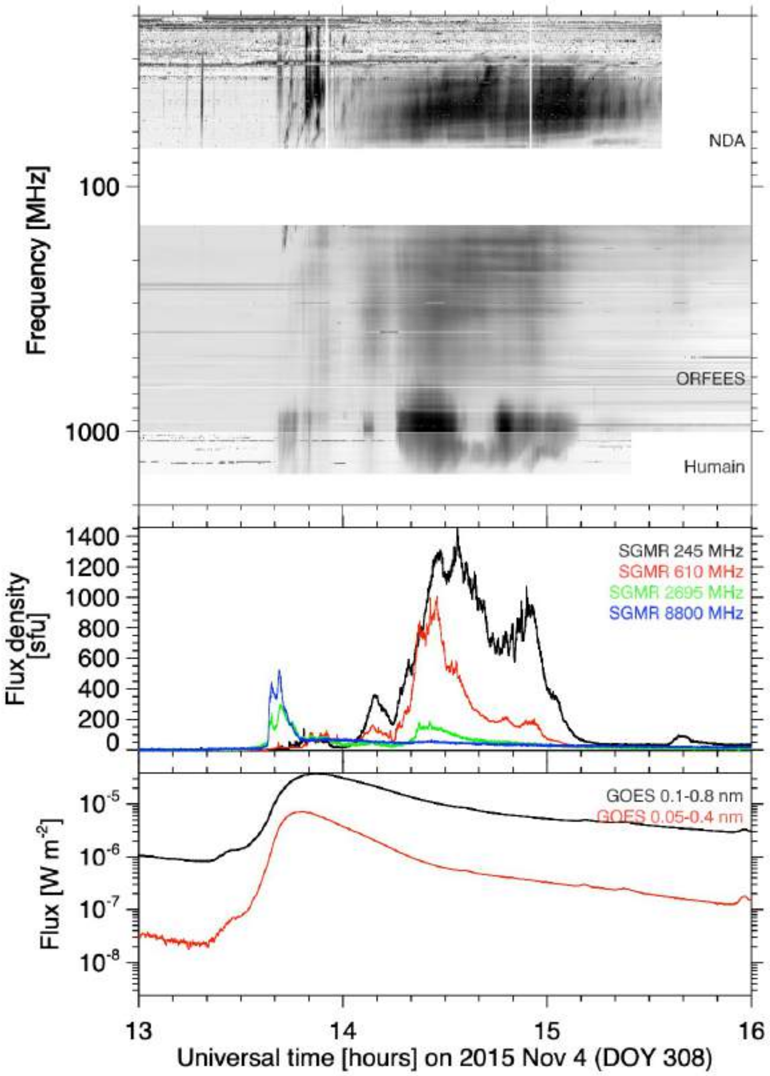
Solar “Radio Bursts”

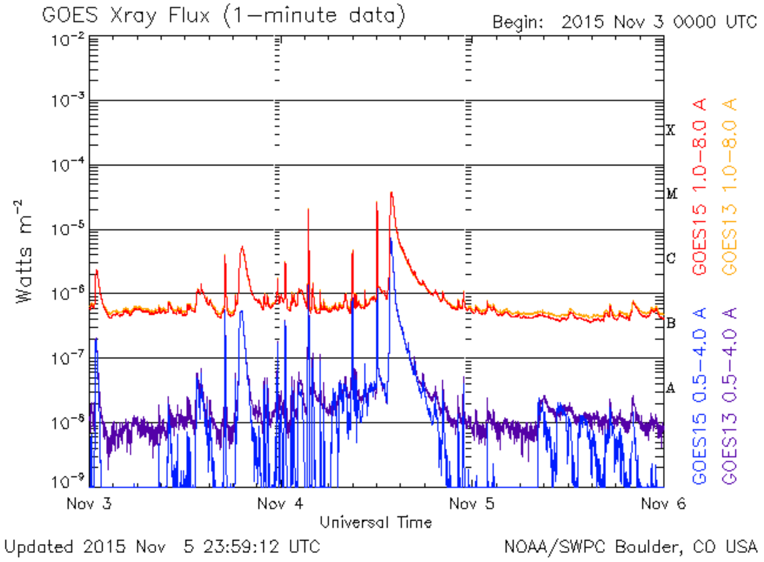
Flare photon emission in the ATC radar frequencies: 04-Nov-2015

Medium X-ray flare (M4) but it occurred at sunset in Sweden and Air Traffic Control radars were pointed directly at the Sun.

Note the very broadband radio signal recorded by the Sagamore Hill (SGMR) US Air Force solar radio telescope.

Duration: ~1.25 hours, corresponding to **impulsive phase**.





Solar storm knocks out flight control systems in Sweden

November 4, 2015

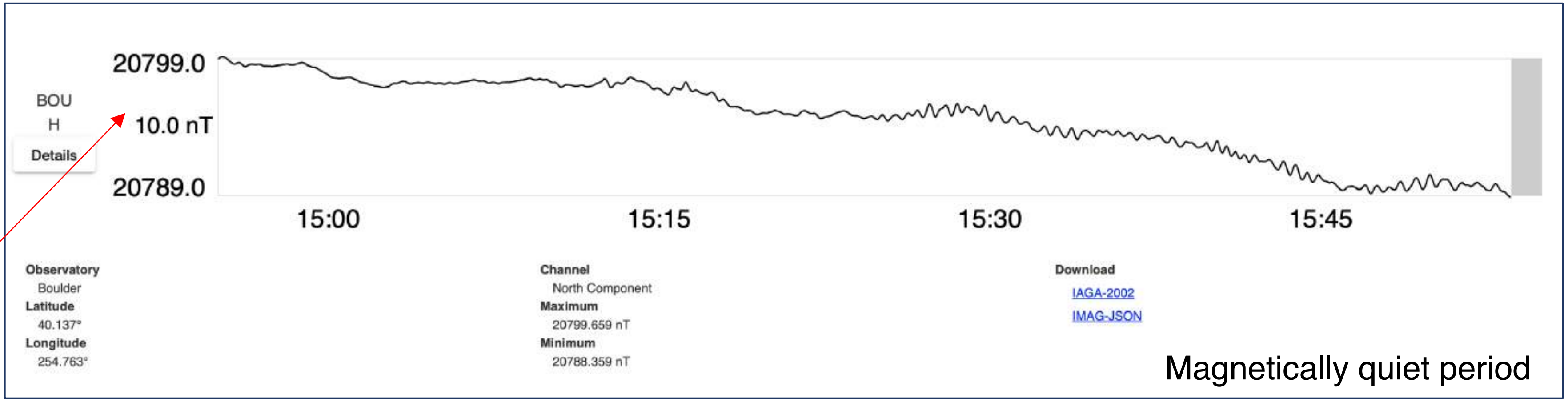
Travellers wait in the terminal building at Stockholm's Arlanda on August 17, 2013

Aviation officials say a solar storm knocked out the air traffic control systems in Sweden on Wednesday, prompting them to close the country's airspace for more than an hour.

Solar Wind HSSs and CIRs: Geomagnetic Storming

A ”geomagnetic storm” is simply an impulsive and chaotic disturbance of the geomagnetic field

Note scale change
and different latitudes

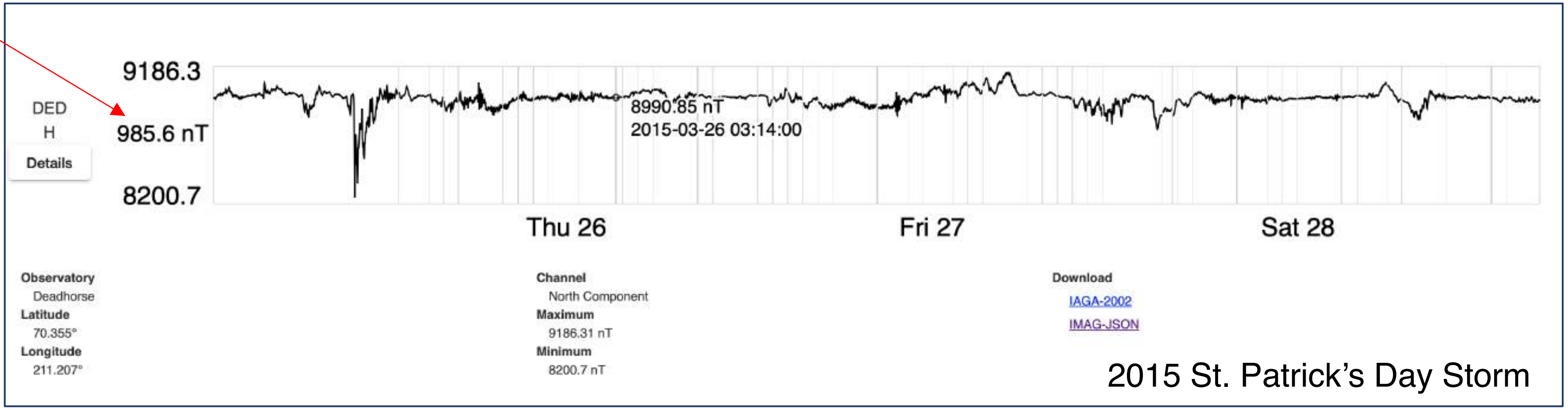


Observatory
Boulder
Latitude
40.137°
Longitude
254.763°

Channel
North Component
Maximum
20799.659 nT
Minimum
20788.359 nT

Download
IAGA-2002
IMAG-JSON

Magnetically quiet period



Observatory
Deadhorse
Latitude
70.355°
Longitude
211.207°

Channel
North Component
Maximum
9186.31 nT
Minimum
8200.7 nT

Download
IAGA-2002
IMAG-JSON

2015 St. Patrick’s Day Storm

https://www.usgs.gov/natural-hazards/geomagnetism/data-tools

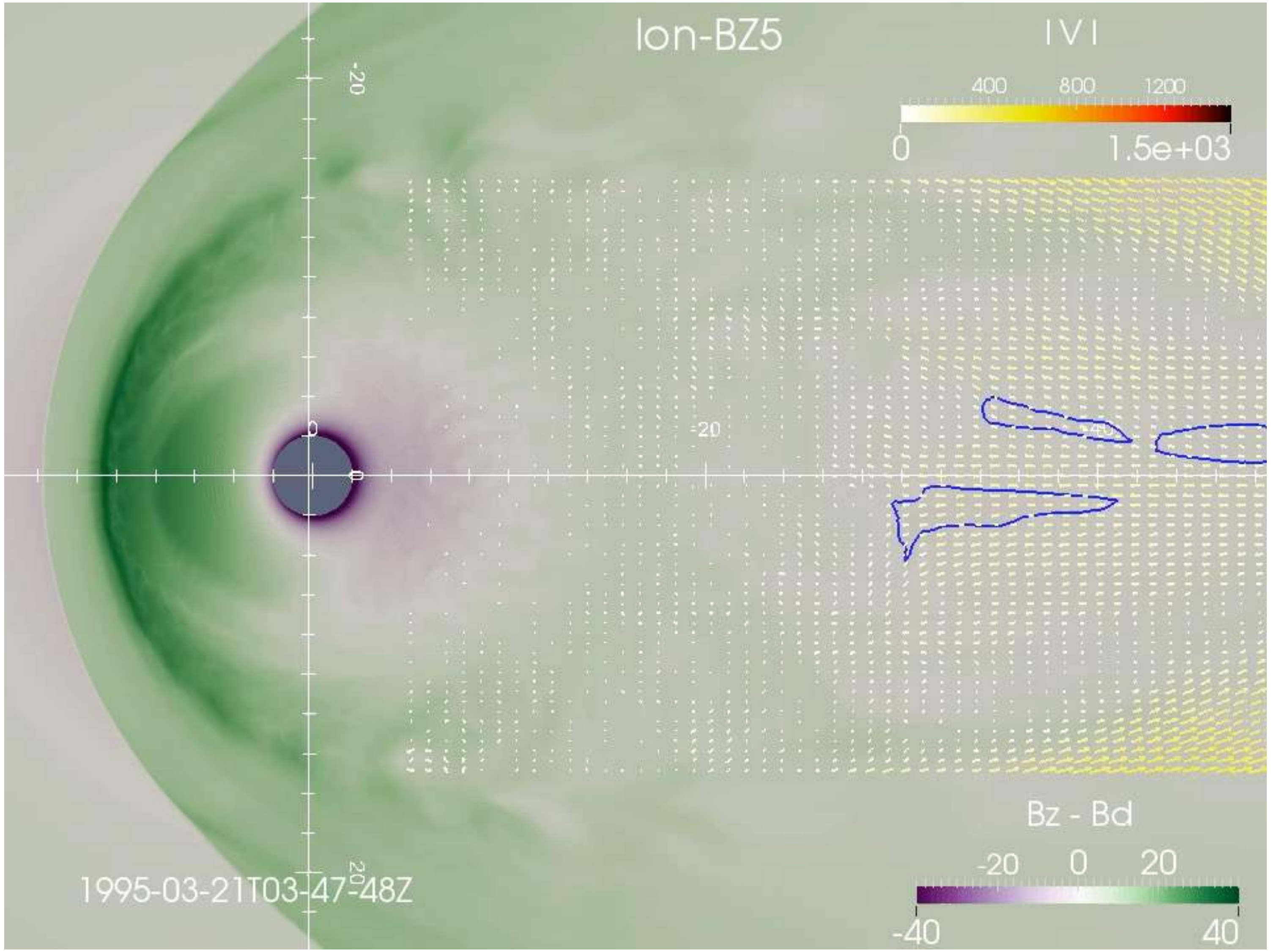
Dynamics of the Magnetosphere: driven by the solar wind

Reconnection in the magnetotail causes “**Bursty bulk flows**”

BBFs result in “**Dipolarization**”: the sudden reconfiguration of the magnetic field to be more “dipolar”

Take away: the Earth’s magnetic field is constantly changing due to reconnections with the ”Interplanetary magnetic field” (IMF)

IMF = solar wind or CME magnetic field



Wiltberger, M. *et al.* (2015) *Journal of Geophysical Research: Space Physics*, 120(6), pp. 4555–4566. doi:10.1002/2015JA021080.

Geomagnetic Activity Indices

Measurements from various collections of ground-based magnetometers averaged over times

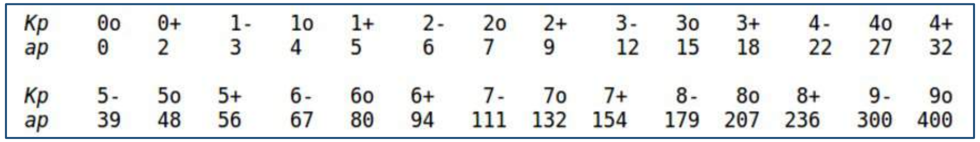
K_p

- The global *Kp* index is obtained as the mean value of the disturbance levels in the two horizontal field components (Bx, By) from 13 mid- to high-latitude stations. Derived every **3 hours**.
- The name *Kp* originates from "planetarische Kennziffer" (= planetary index).
- Range: 0 – 9 in scale of thirds.   0o, 0+, 1-, 1o, 1+, 2-, 2o, 2+, …, 8-, 8o, 8+, 9-, 9o
- NOAA geomagnetic storm G-scale is based on Kp: https://www.swpc.noaa.gov/noaa-scales-explanation
- Definitive data: https://www.gfz-potsdam.de/en/kp-index/

Kp	5	6	7	8 to 9-	9
NOAA G	1	2	3	4	5

a_p

- Linear scale derived from Kp.
- Derived every **3 hours**.
- **Ap** = **daily** average of 8 $\mathbf{a_p}$ index measurements

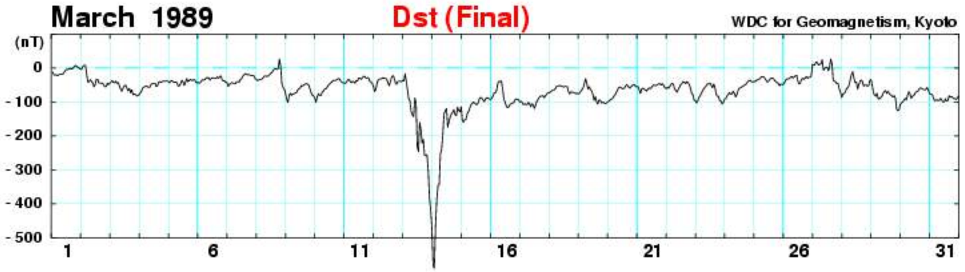


Kp	0o	0+	1-	1o	1+	2-	2o	2+	3-	3o	3+	4-	4o	4+
ap	0	2	3	4	5	6	7	9	12	15	18	22	27	32
Kp	5-	5o	5+	6-	6o	6+	7-	7o	7+	8-	8o	8+	9-	9o
ap	39	48	56	67	80	94	111	132	154	179	207	236	300	400

Dst

- **Disturbance Storm Time** "index". Measure of geomagnetic storm intensity (not a global magnetic variation index). Units of **nT** – not an index scale like Kp.
- Depth of H field reduction at 4 *equatorial* stations: proxy for ring current intensity.
- Cadence = **1 hour**.
- **SYM-H**: "symmetric ring current" scale, same measurement as Dst but cadence = **1 minute**.
- Definitive data: http://wdc.kugi.kyoto-u.ac.jp/dstdir/

March 1989 Superstorm: -589 nT

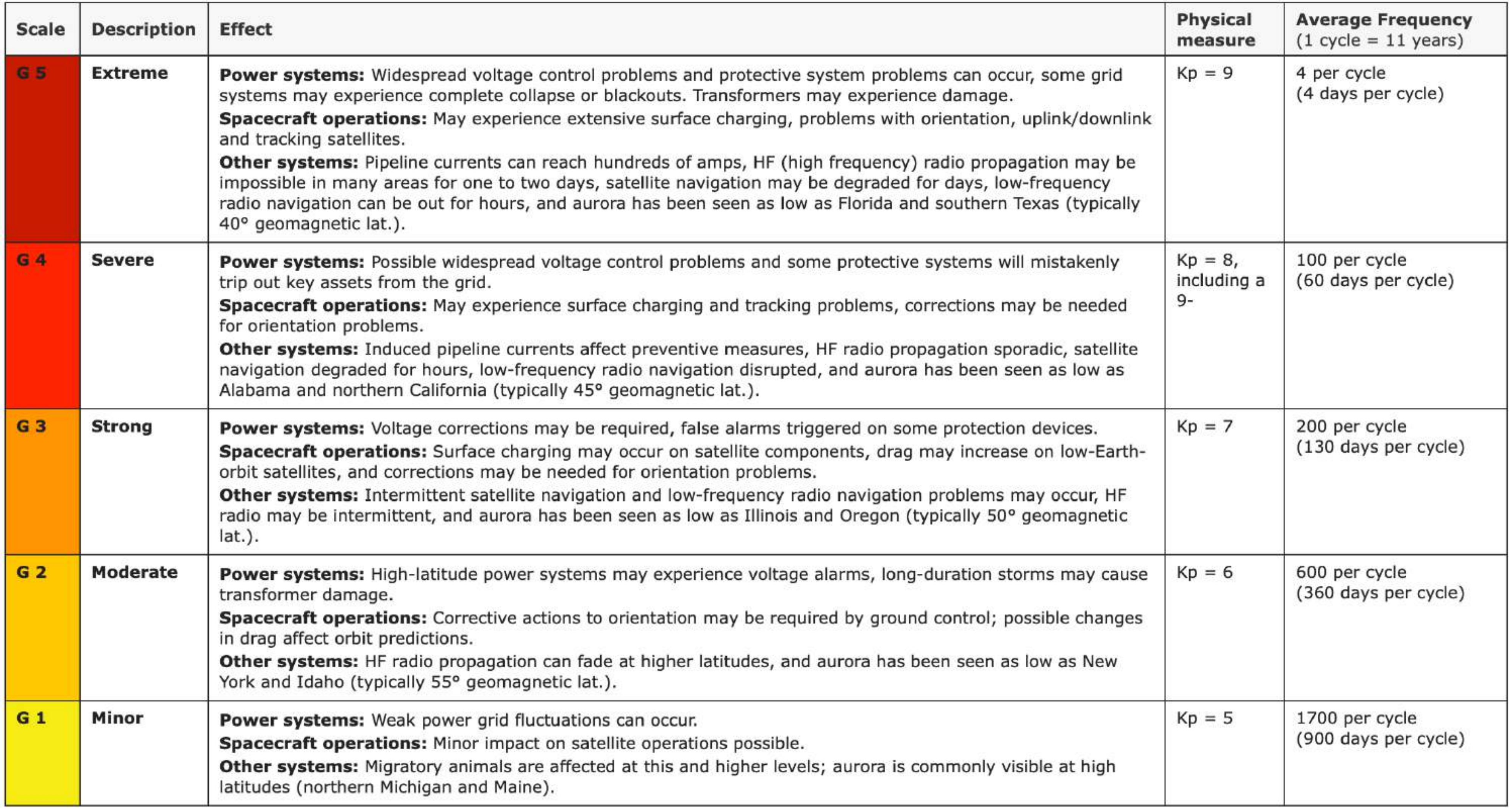


https://isds-datadoi.nict.go.jp/wds/10.17593__14515-74000.html

NOAA/SWPC G-scale

Operational Geomagnetic storm scale

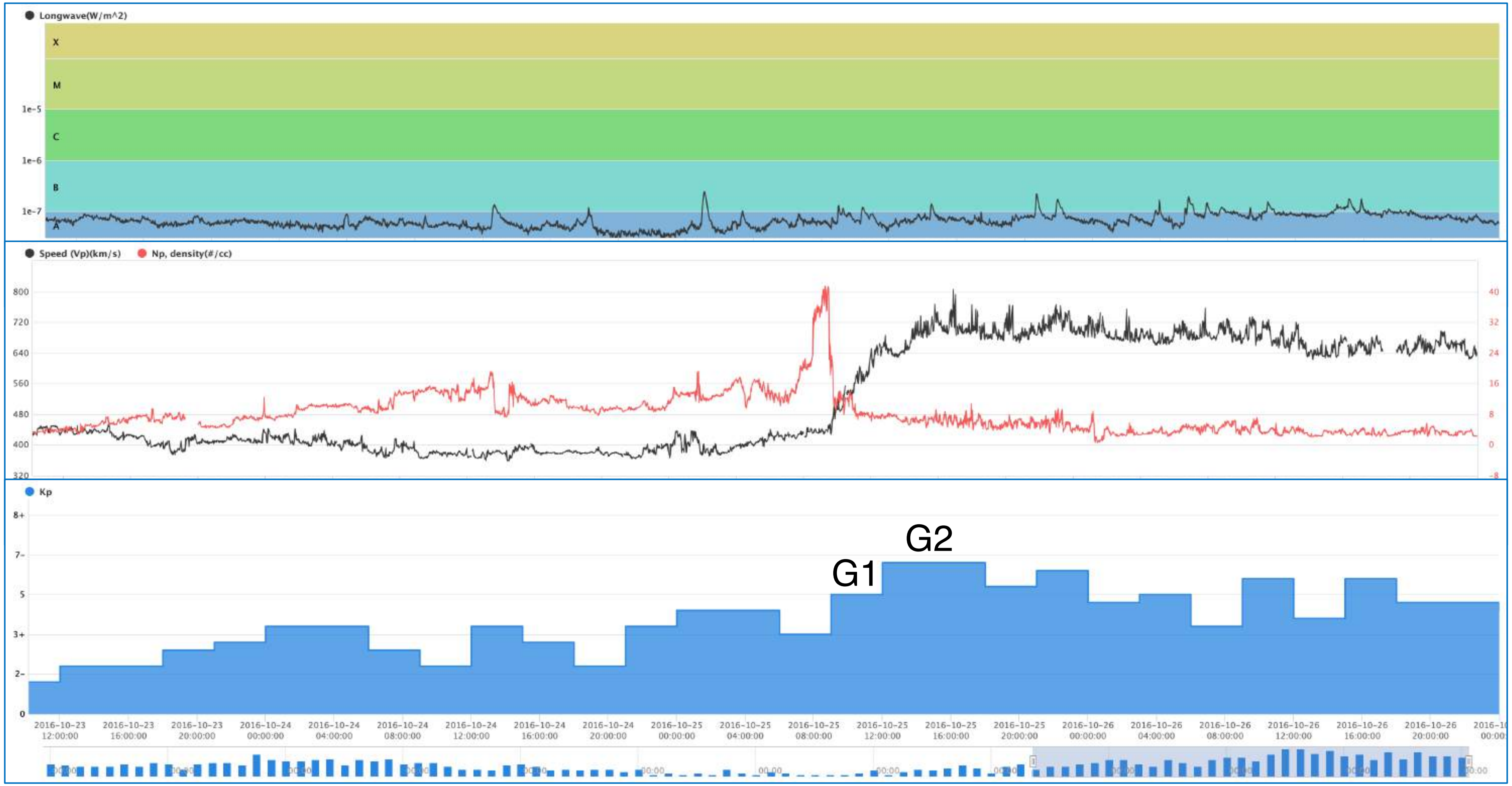
Based on Kp



Scale	Description	Effect	Physical measure	Average Frequency (1 cycle = 11 years)
G 5	**Extreme**	**Power systems:** Widespread voltage control problems and protective system problems can occur, some grid systems may experience complete collapse or blackouts. Transformers may experience damage. **Spacecraft operations:** May experience extensive surface charging, problems with orientation, uplink/downlink and tracking satellites. **Other systems:** Pipeline currents can reach hundreds of amps, HF (high frequency) radio propagation may be impossible in many areas for one to two days, satellite navigation may be degraded for days, low-frequency radio navigation can be out for hours, and aurora has been seen as low as Florida and southern Texas (typically 40° geomagnetic lat.).	Kp = 9	4 per cycle (4 days per cycle)
G 4	**Severe**	**Power systems:** Possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid. **Spacecraft operations:** May experience surface charging and tracking problems, corrections may be needed for orientation problems. **Other systems:** Induced pipeline currents affect preventive measures, HF radio propagation sporadic, satellite navigation degraded for hours, low-frequency radio navigation disrupted, and aurora has been seen as low as Alabama and northern California (typically 45° geomagnetic lat.).	Kp = 8, including a 9-	100 per cycle (60 days per cycle)
G 3	**Strong**	**Power systems:** Voltage corrections may be required, false alarms triggered on some protection devices. **Spacecraft operations:** Surface charging may occur on satellite components, drag may increase on low-Earth-orbit satellites, and corrections may be needed for orientation problems. **Other systems:** Intermittent satellite navigation and low-frequency radio navigation problems may occur, HF radio may be intermittent, and aurora has been seen as low as Illinois and Oregon (typically 50° geomagnetic lat.).	Kp = 7	200 per cycle (130 days per cycle)
G 2	**Moderate**	**Power systems:** High-latitude power systems may experience voltage alarms, long-duration storms may cause transformer damage. **Spacecraft operations:** Corrective actions to orientation may be required by ground control; possible changes in drag affect orbit predictions. **Other systems:** HF radio propagation can fade at higher latitudes, and aurora has been seen as low as New York and Idaho (typically 55° geomagnetic lat.).	Kp = 6	600 per cycle (360 days per cycle)
G 1	**Minor**	**Power systems:** Weak power grid fluctuations can occur. **Spacecraft operations:** Minor impact on satellite operations possible. **Other systems:** Migratory animals are affected at this and higher levels; aurora is commonly visible at high latitudes (northern Michigan and Maine).	Kp = 5	1700 per cycle (900 days per cycle)

Solar Wind HSSs and CIRs: Minor to Strong Geomagnetic Storming

2016-Oct-26 CIR-induced geomagnetic storm



Solar
Eruptions:
nil

Solar Wind
Speed &
Density

Kp

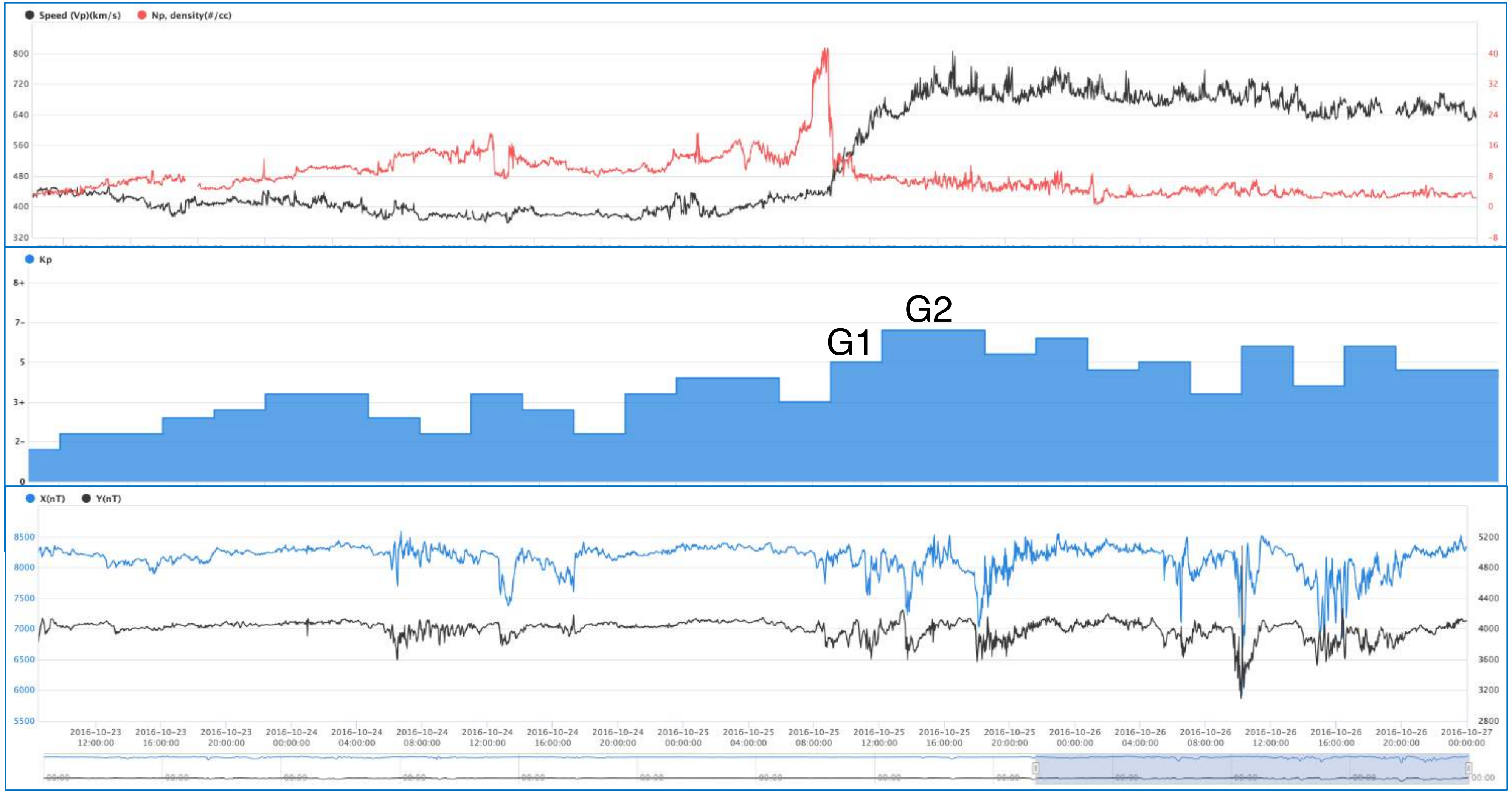
Solar Wind HSSs and CIRs: Minor to Strong Geomagnetic Storming

2016-Oct-26 CIR-induced geomagnetic storm

Solar Wind Speed & Density

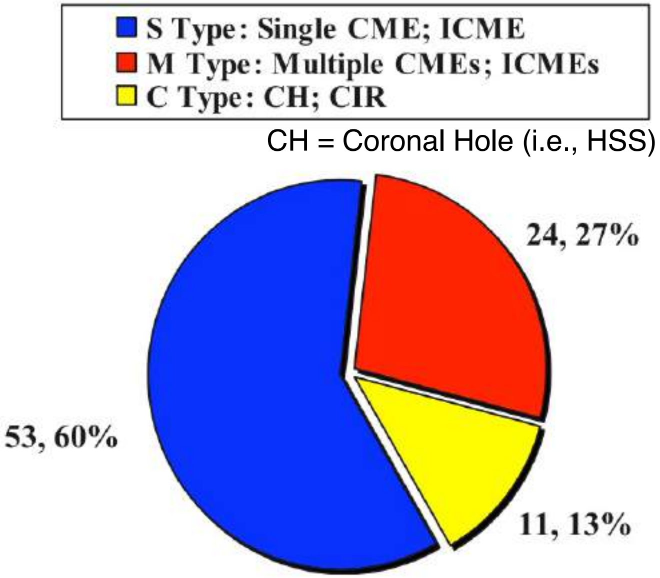
Kp

Barrow, AK Horizontal Magnetic Field



How Frequent and How Strong are Solar Wind HSS and CIR storms?

- Geomagnetic storm magnitude quantification is a complex and evolving field.
- Many different indices in use…



CH = Coronal Hole (i.e., HSS)

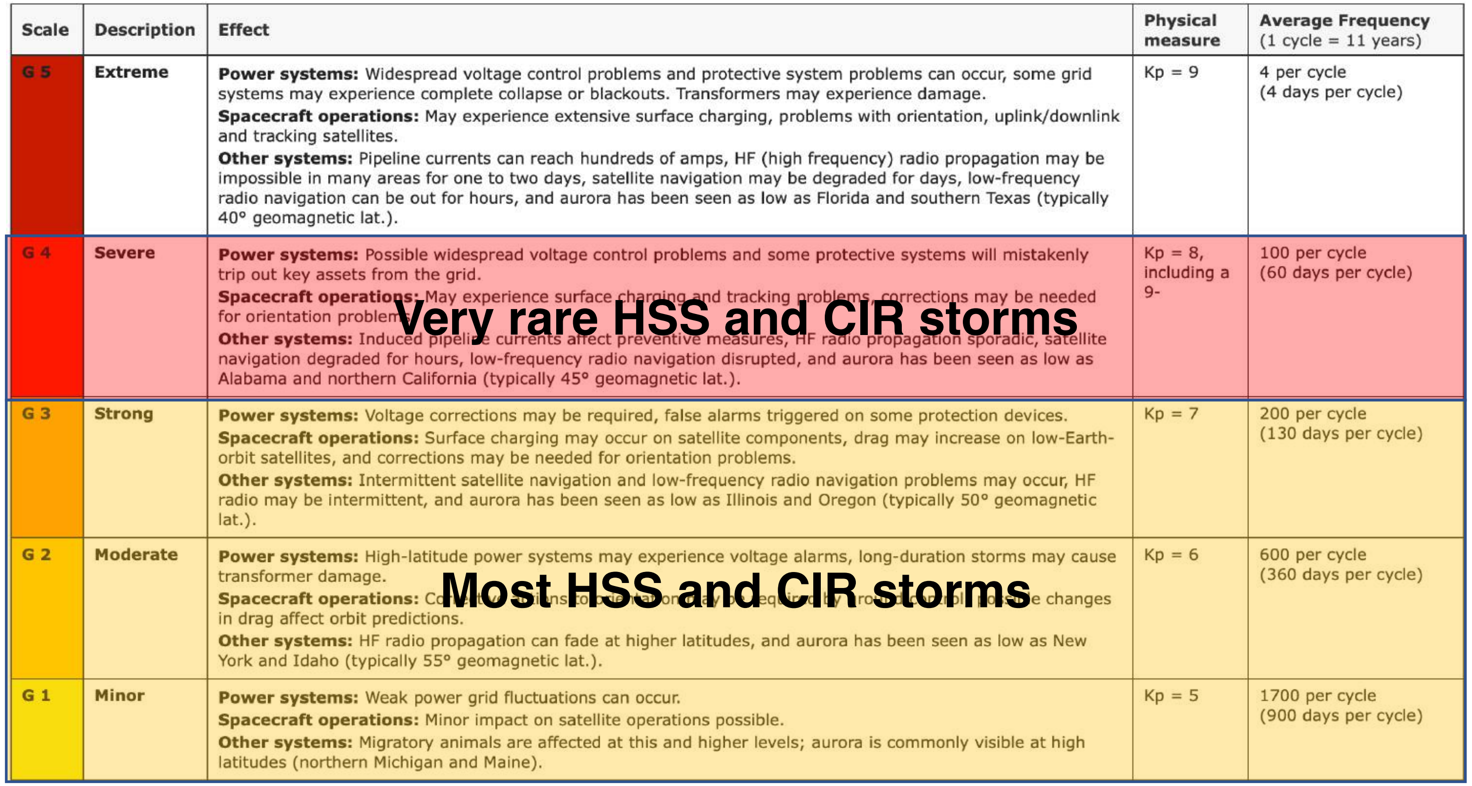
Geomagnetic storm sources

88 "major" storms in 1996—2005

Dst < -100 nT

Zhang et al., 2007

Geomagnetic Storm strength: NOAA/SWPC G-scale



Scale	Description	Effect	Physical measure	Average Frequency (1 cycle = 11 years)
G 5	Extreme	**Power systems:** Widespread voltage control problems and protective system problems can occur, some grid systems may experience complete collapse or blackouts. Transformers may experience damage. **Spacecraft operations:** May experience extensive surface charging, problems with orientation, uplink/downlink and tracking satellites. **Other systems:** Pipeline currents can reach hundreds of amps, HF (high frequency) radio propagation may be impossible in many areas for one to two days, satellite navigation may be degraded for days, low-frequency radio navigation can be out for hours, and aurora has been seen as low as Florida and southern Texas (typically 40° geomagnetic lat.).	Kp = 9	4 per cycle (4 days per cycle)
G 4	Severe	**Power systems:** Possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid. **Spacecraft operations:** May experience surface charging and tracking problems, corrections may be needed for orientation problems. **Other systems:** Induced pipeline currents affect preventive measures, HF radio propagation sporadic, satellite navigation degraded for hours, low-frequency radio navigation disrupted, and aurora has been seen as low as Alabama and northern California (typically 45° geomagnetic lat.).	Kp = 8, including a 9-	100 per cycle (60 days per cycle)
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Very rare HSS and CIR storms

Most HSS and CIR storms

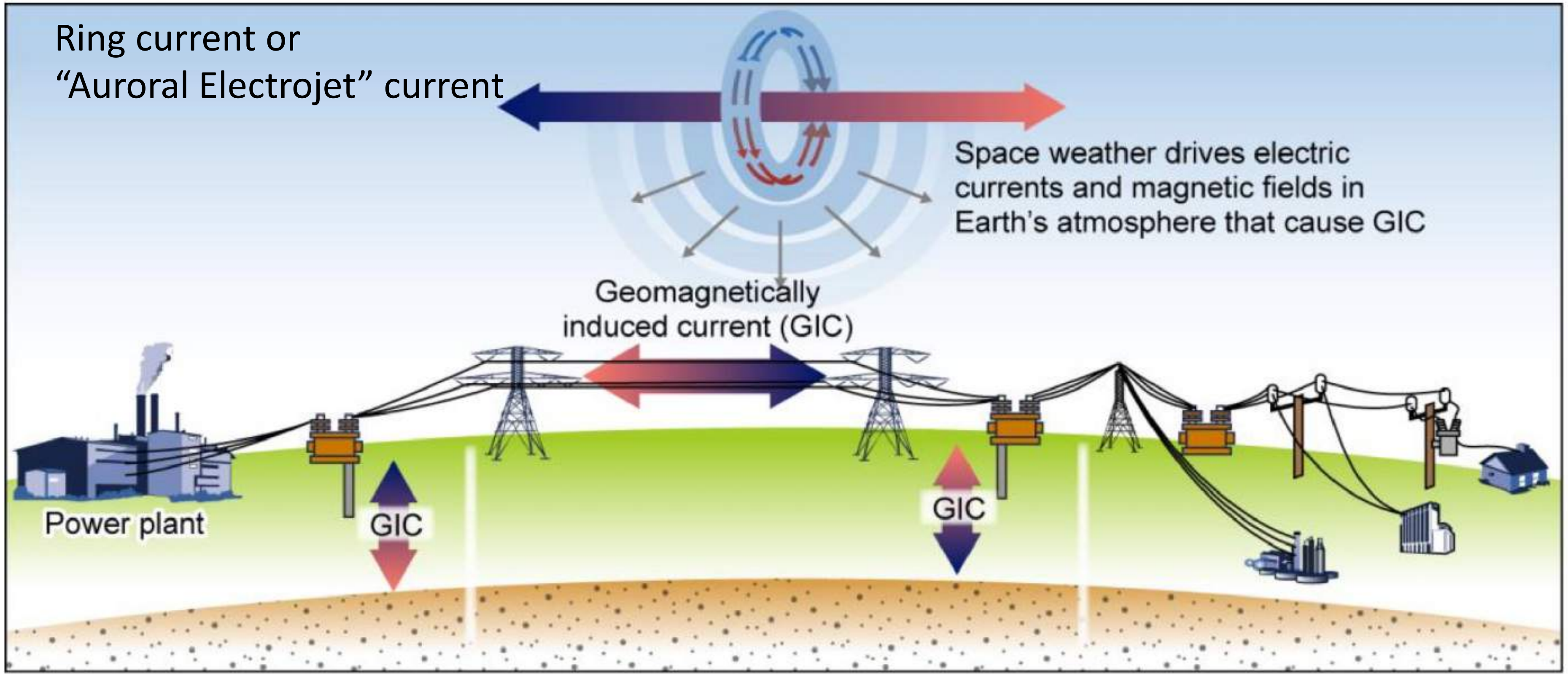
https://www.swpc.noaa.gov/noaa-scales-explanation

Impacts of geomagnetic storms

"Geomagnetically Induced Currents" in Electric Power Grid distribution lines

Ampere Induction law

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J}$$



https://www.gao.gov/assets/files.gao.gov/assets/gao-19-98.pdf

Impacts of geomagnetic storms

Physical mechanism of GICs

Faraday Induction law

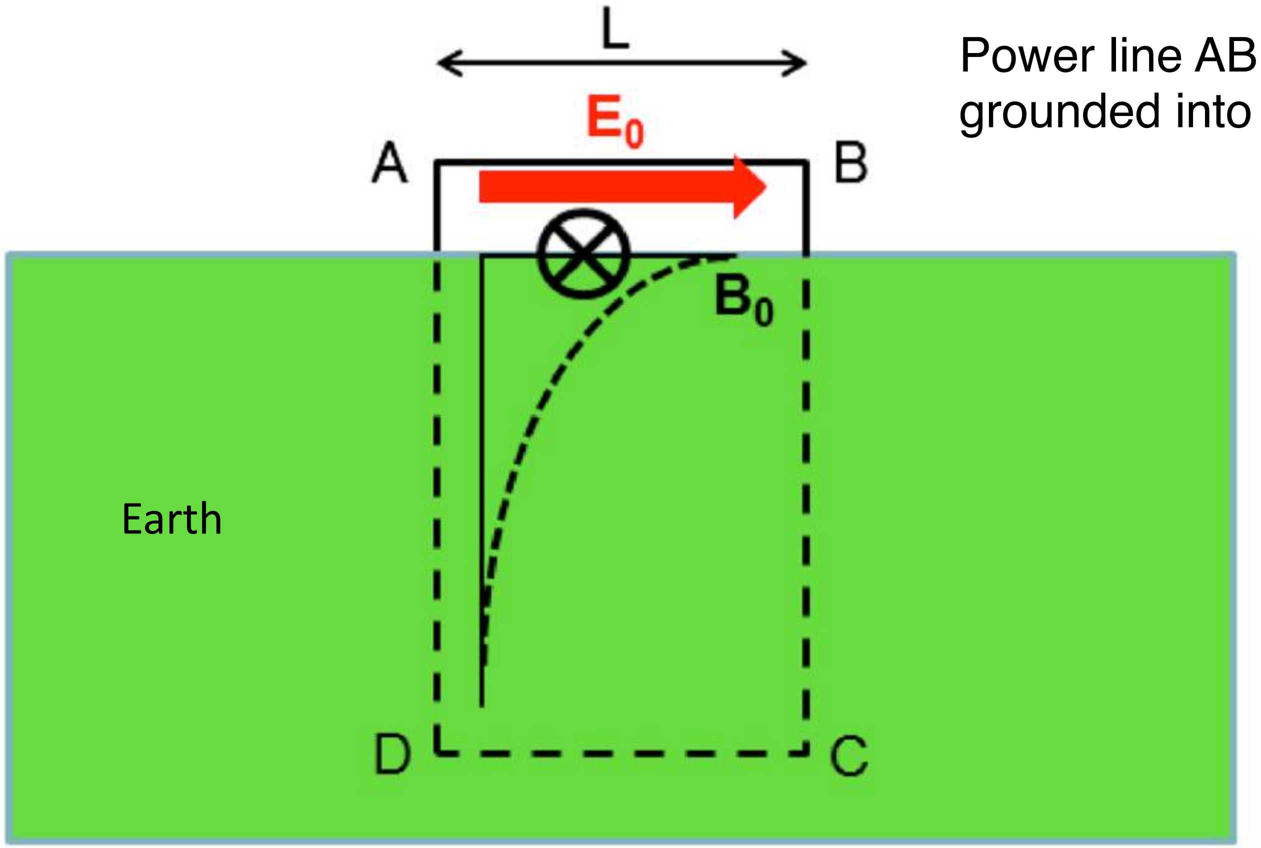
$$\oint_{\partial\Sigma} \mathbf{E} \cdot \mathrm{d}\boldsymbol{\ell} = -\frac{\mathrm{d}}{\mathrm{d}t} \iint_{\Sigma} \mathbf{B} \cdot \mathrm{d}\mathbf{S}$$

Minor to Strong storms:

$E_0 \sim 1 — 5$ V/km

Extreme storms:

$E_0 > 10$ V/km



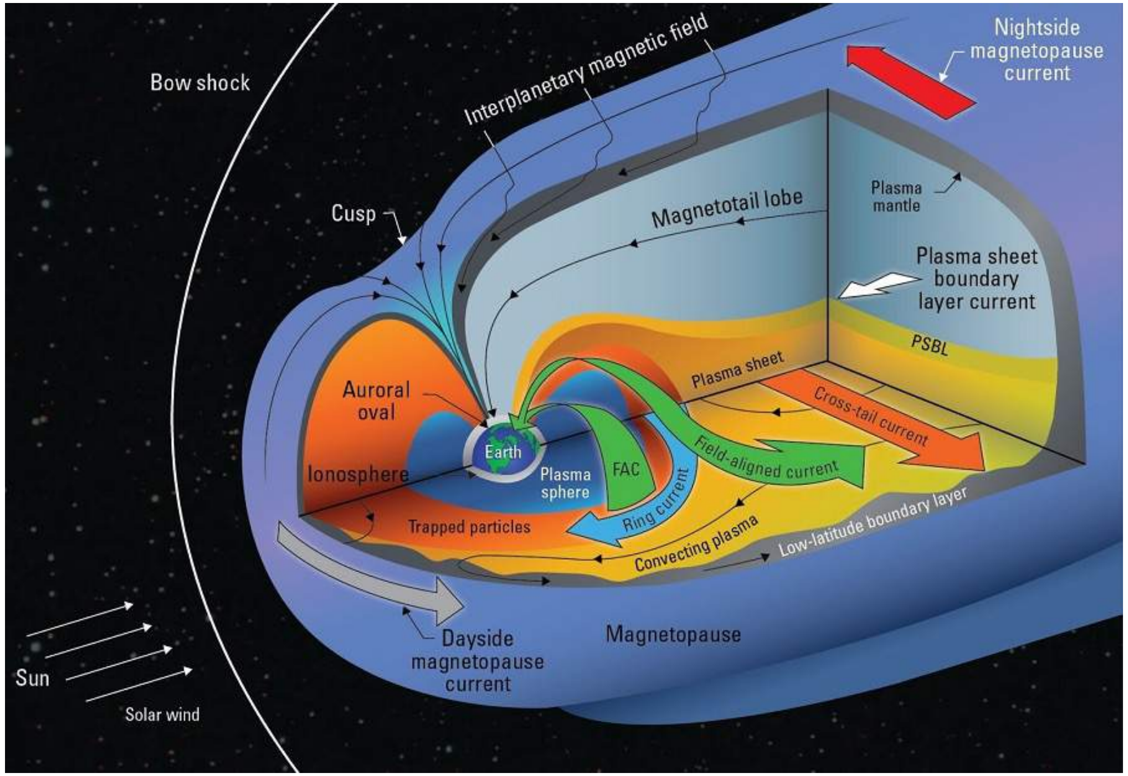
Power line AB of length L grounded into conducting Earth

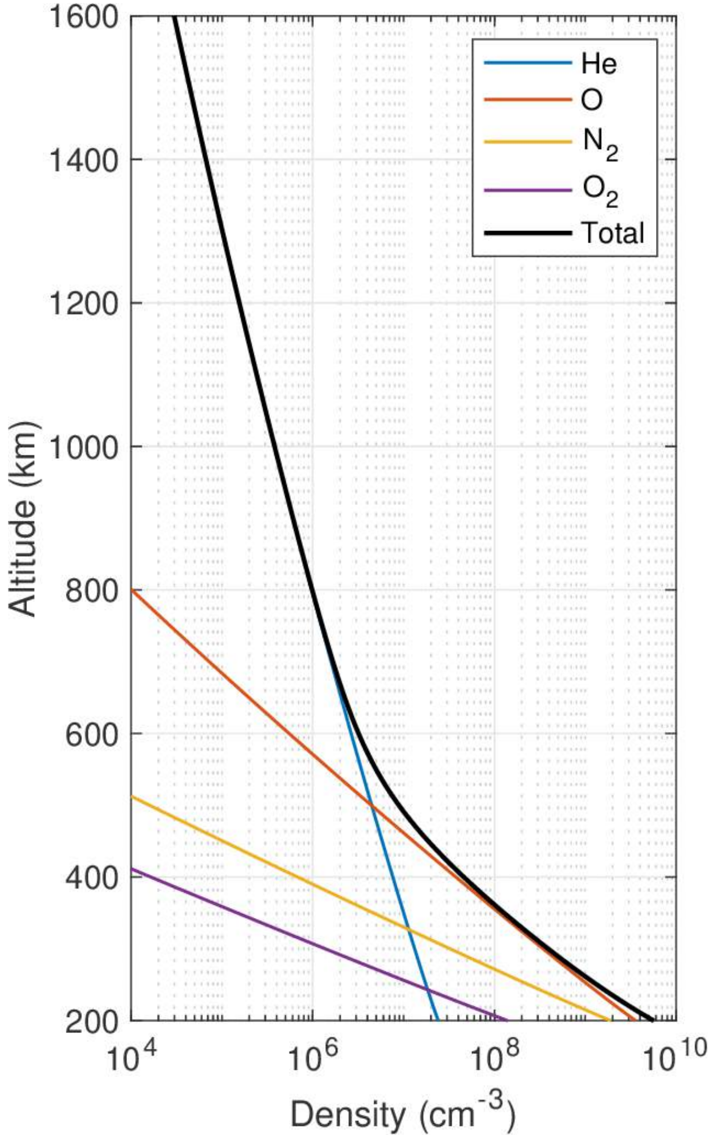
Figure 2. Geomagnetic induction in the loop ABCD.

Boteler, D.H. and Pirjola, R.J. (2017) *Space Weather*, 15(1), pp. 258–276. doi:10.1002/2016SW001499.

Impacts of geomagnetic storms

Joule heating of thermosphere due to Ionospheric currents: increased density in Low Earth Orbit (LEO)





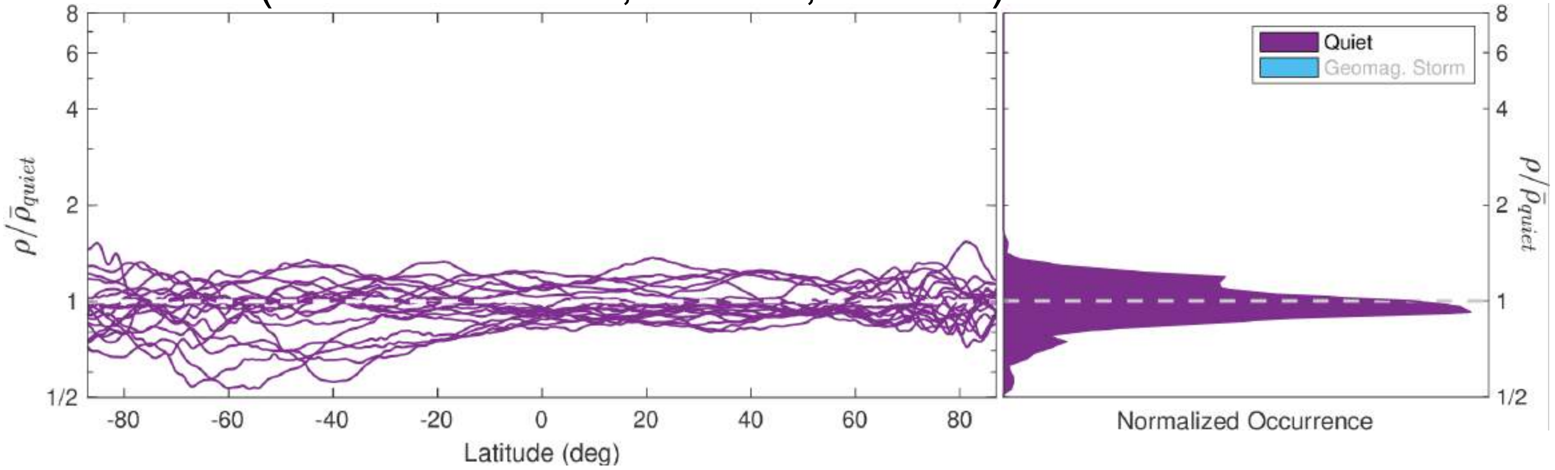
Thermosphere neutral density response to geomagnetic storms

Quiet Time

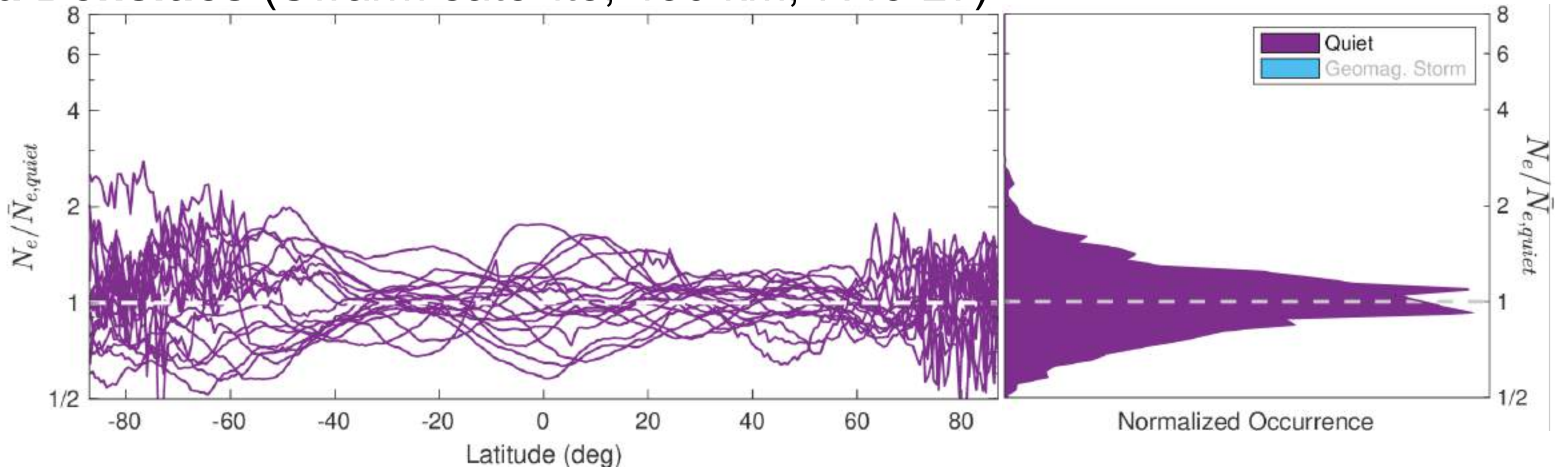
Quiet-time orbits preceding the 2015 St. Patrick's Day G4 Geomagnetic Storm:

- Neutral and Plasma Densities, normalized by their average quiet-time values
- ±50–100% observed even during quiet-time
- Densities can be enhanced by a factor of ~8 during disturbed periods

Neutral Densities (GRACE satellite, 410 km, 5:30 LT)



Plasma Densities (Swarm satellite, 450 km, 7:45 LT)



Courtesy Eric Sutton, SWx TREC

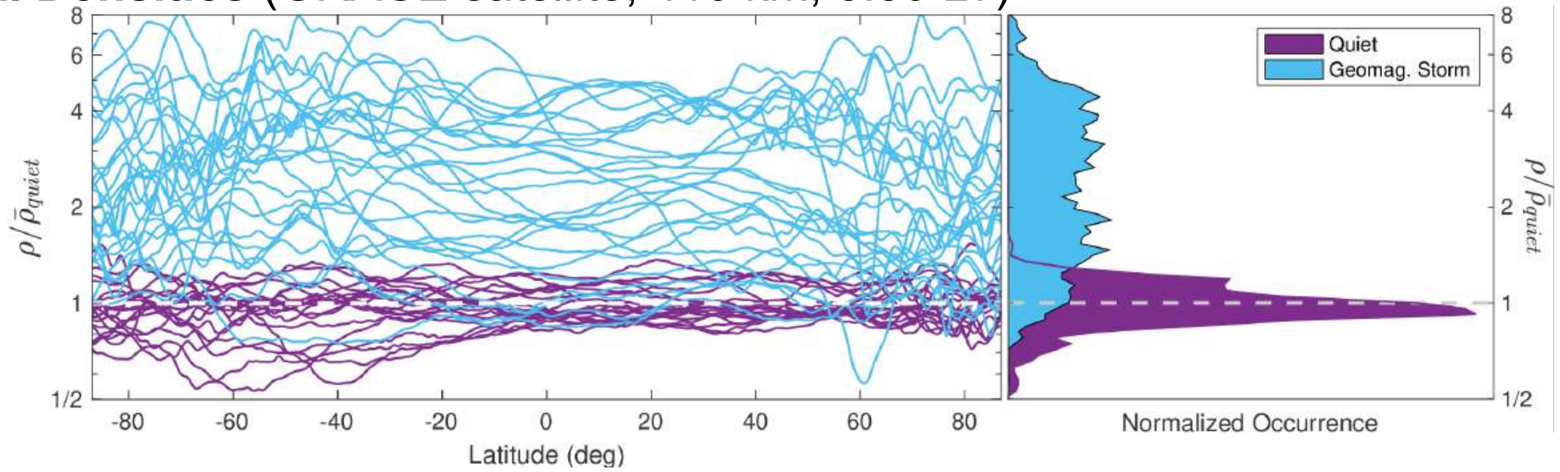
Thermosphere neutral density response to geomagnetic storms

Geomagnetic Storm

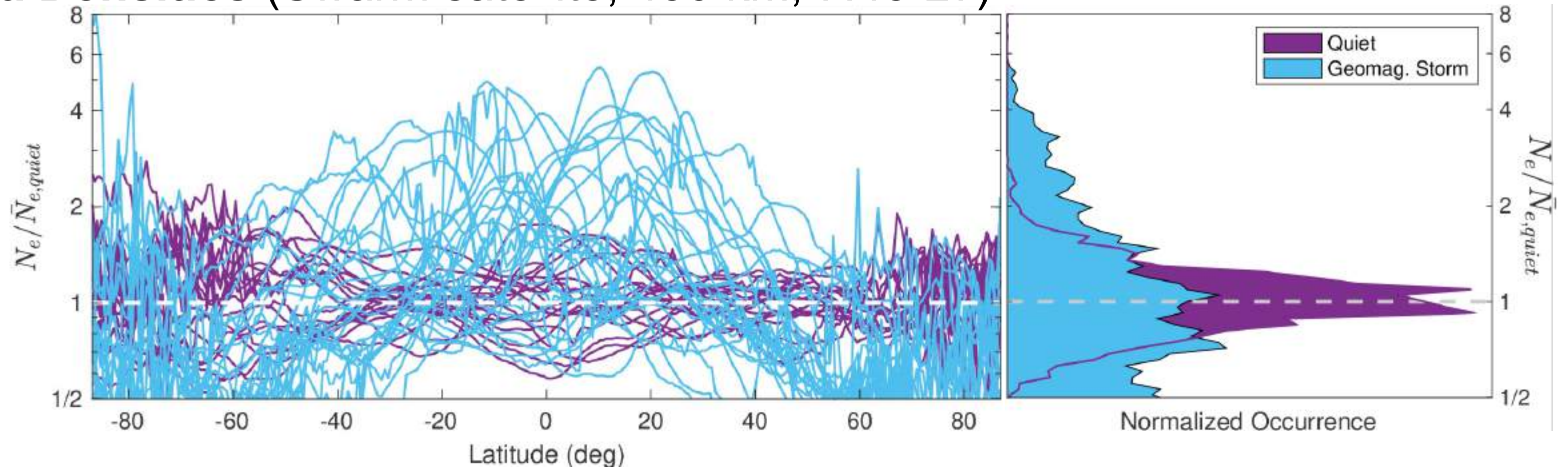
Quiet-time and Geomagnetically Disturbed orbits during the 2015 St. Patrick's Day G4 Geomagnetic Storm:

- Neutral and Plasma Densities, normalized by their average quiet-time values
- ±50–100% observed even during quiet-time
- **Densities can be enhanced by a factor of ~8 during strong storms**

Neutral Densities (GRACE satellite, 410 km, 5:30 LT)



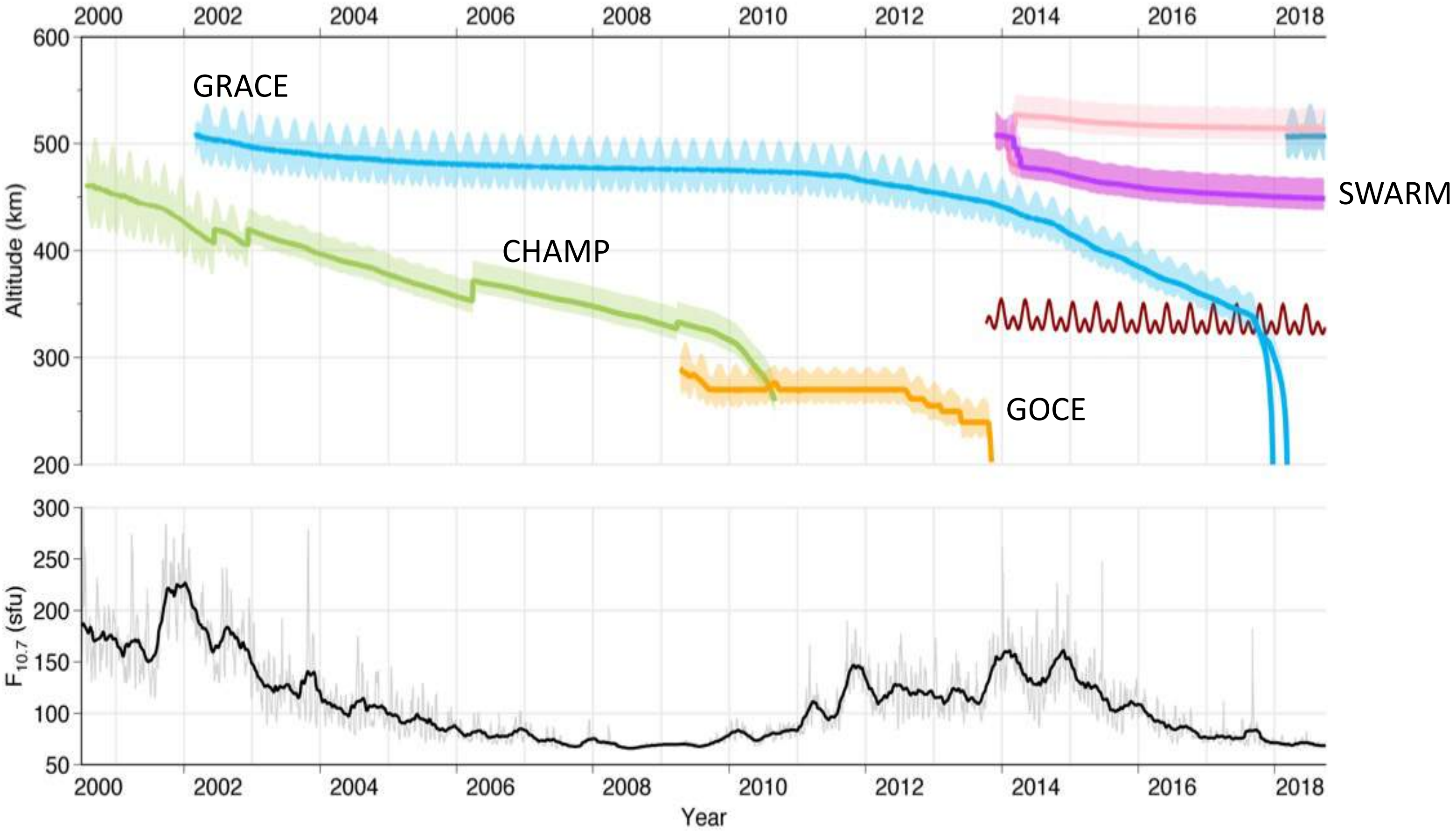
Plasma Densities (Swarm satellite, 450 km, 7:45 LT)



Courtesy Eric Sutton, SWx TREC

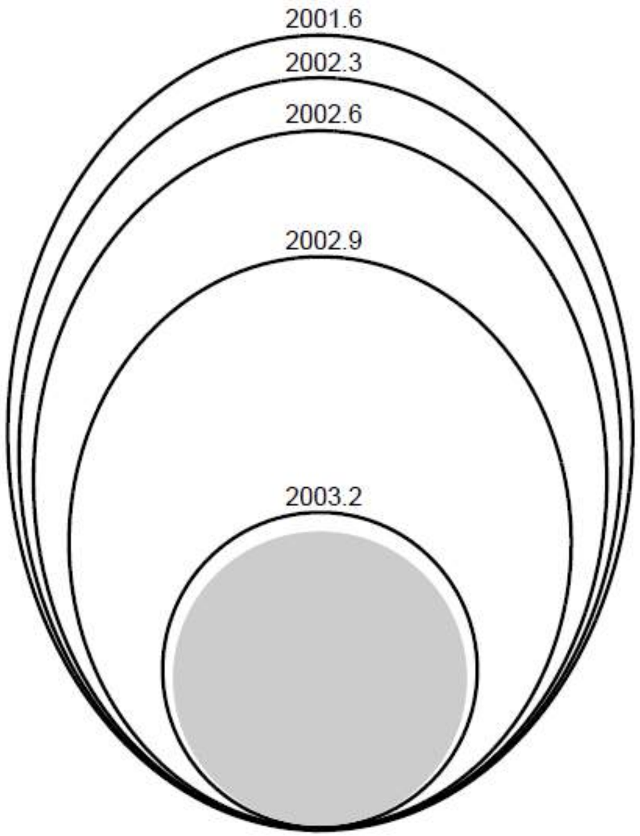
Increased density in LEO = Satellite Drag

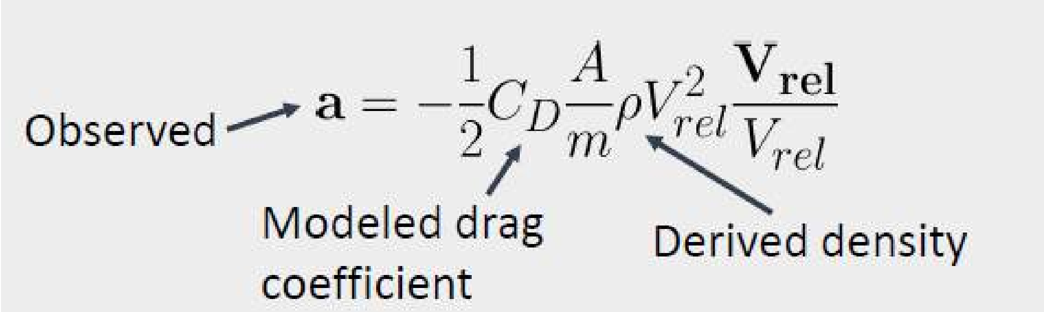
Increased drag leads to orbital altitude decay and eventual re-entry



From density to drag force to acceleration…

- Low-Earth-Orbit satellites experience drag in a thermosphere composed primarily of O and He
- Drag coefficients (C_d) are used in the construction, validation, and assimilation of atmospheric density models
- **Densities derived from satellite orbital drag data carry drag coefficient mismodeling errors, which can lead to altitude-dependent biases**





$$\mathbf{a} = -\frac{1}{2} C_D \frac{A}{m} \rho V_{rel}^2 \frac{\mathbf{V_{rel}}}{V_{rel}}$$

Observed

Modeled drag coefficient

Derived density

$$C_D \frac{A}{M}$$ = “Ballistic Coefficient”

Highly dependent on satellite orientation to ram direction

Reading for Lecture 3

Knipp, D.J. *et al.* (2021) ‘Timelines as a tool for learning about space weather storms’, *Journal of Space Weather and Space Climate*, 11, p. 29. doi:10.1051/swsc/2021011.