Space Weather Impact on Starlink Satellite Launches (and Implications)

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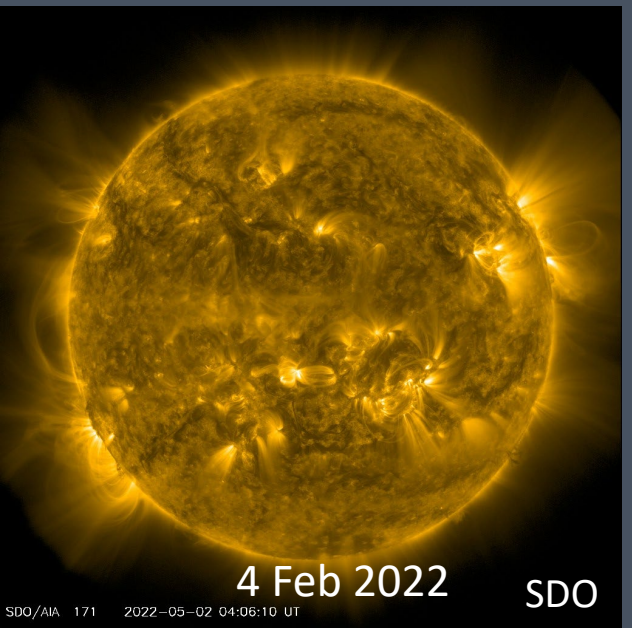
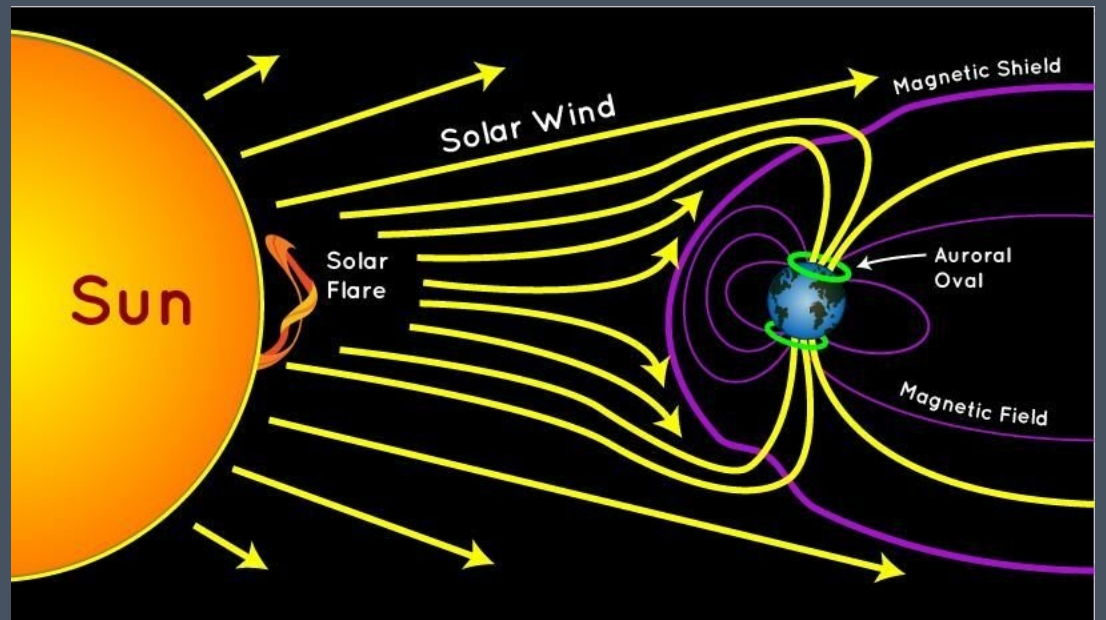
CU Space Weather Technology Research & Education Center

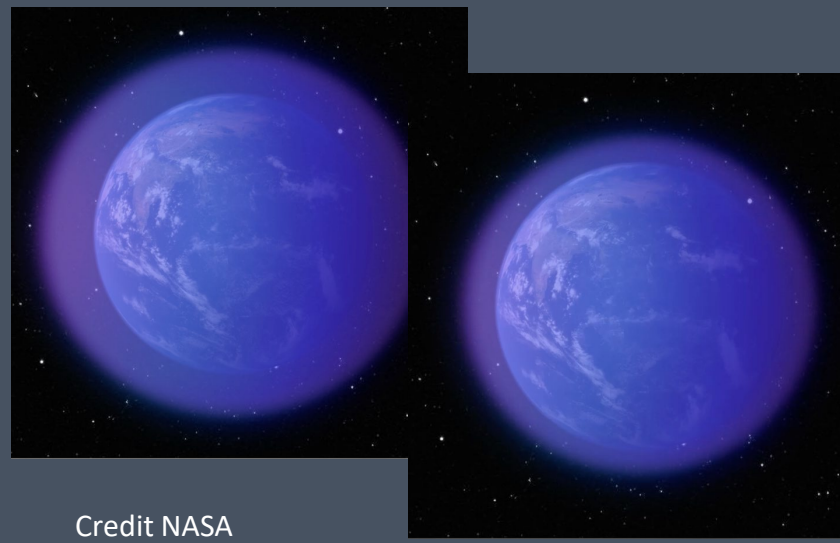
SpaceX says a geomagnetic storm just doomed 40 Starlink internet satellites
Space.com

Solar Storm Knocks 40 SpaceX Satellites Out of Orbit
Smithsonian Magazine

Contributions from
Eric Sutton CU SWxTREC,
Kent Tobiska, SET LLC
Tzu-Wei Fang, SWPC



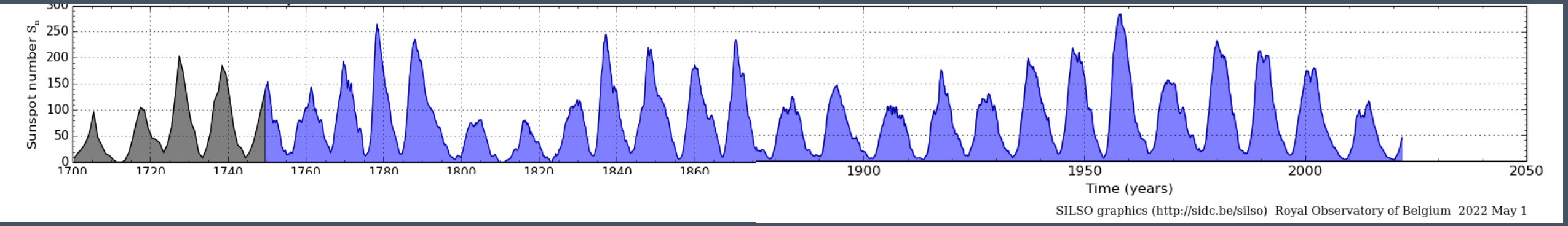




Credit NASA

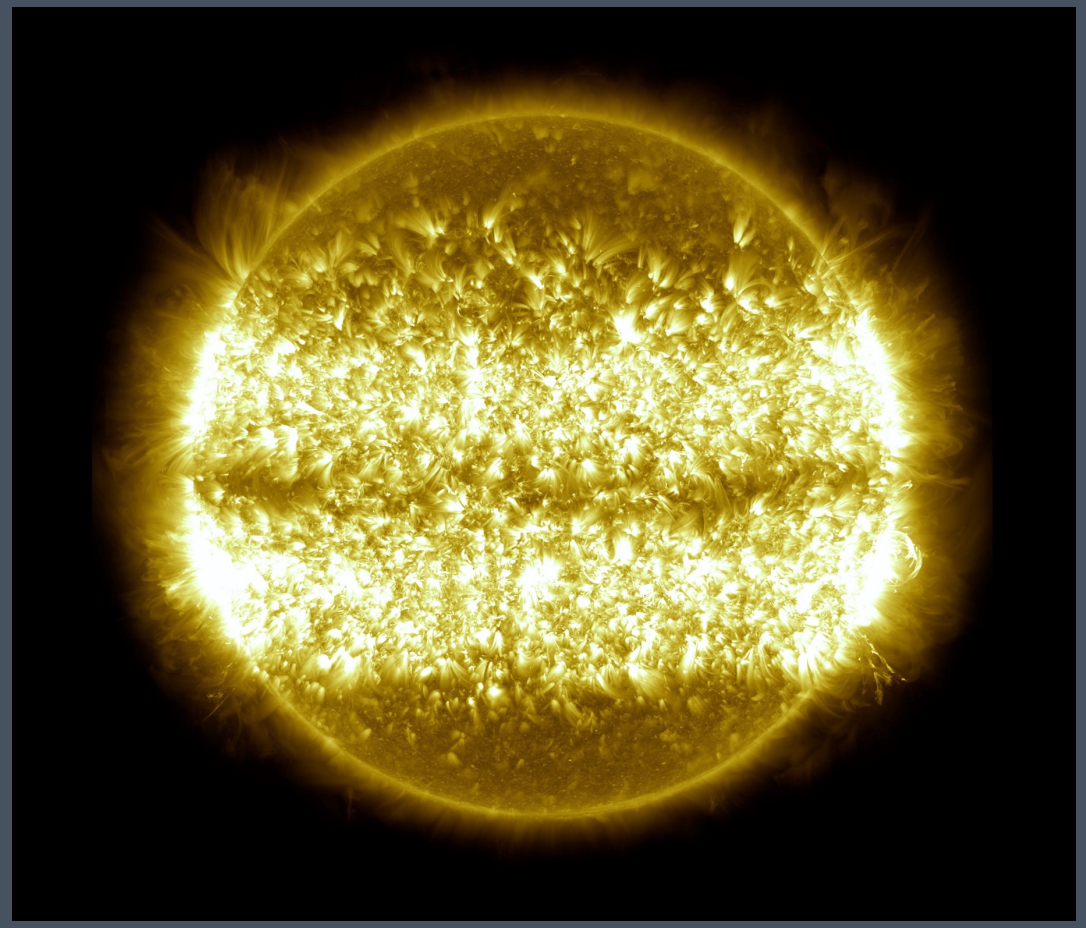
Overview

- Space Weather and Its Roots
- Starlink: Early February 2022
- Vulnerabilities/Opportunities in the Rising Solar Cycle
  - Hardware in Crowded Low Earth Orbit
  - Radio Signal Propagation and Use
    - GNSS Assumed Availability for Many Operations



Roots of Space Weather:

Sun is a Magnetically Active Star with an Outflowing Atmosphere



Active Regions in 17.1 nm,
151 frames selected from 10 yrs of SDO
NASA Goddard Space Flight Center

- Sunspots provide a daily visual of
- Intense magnetism in ‘Active Regions’
- 11 year activity cycle
- Form in mid and low latitude bands
- 22 year polarity cycle of ‘dipole’ field

- Differential rotation winds the magnetic field

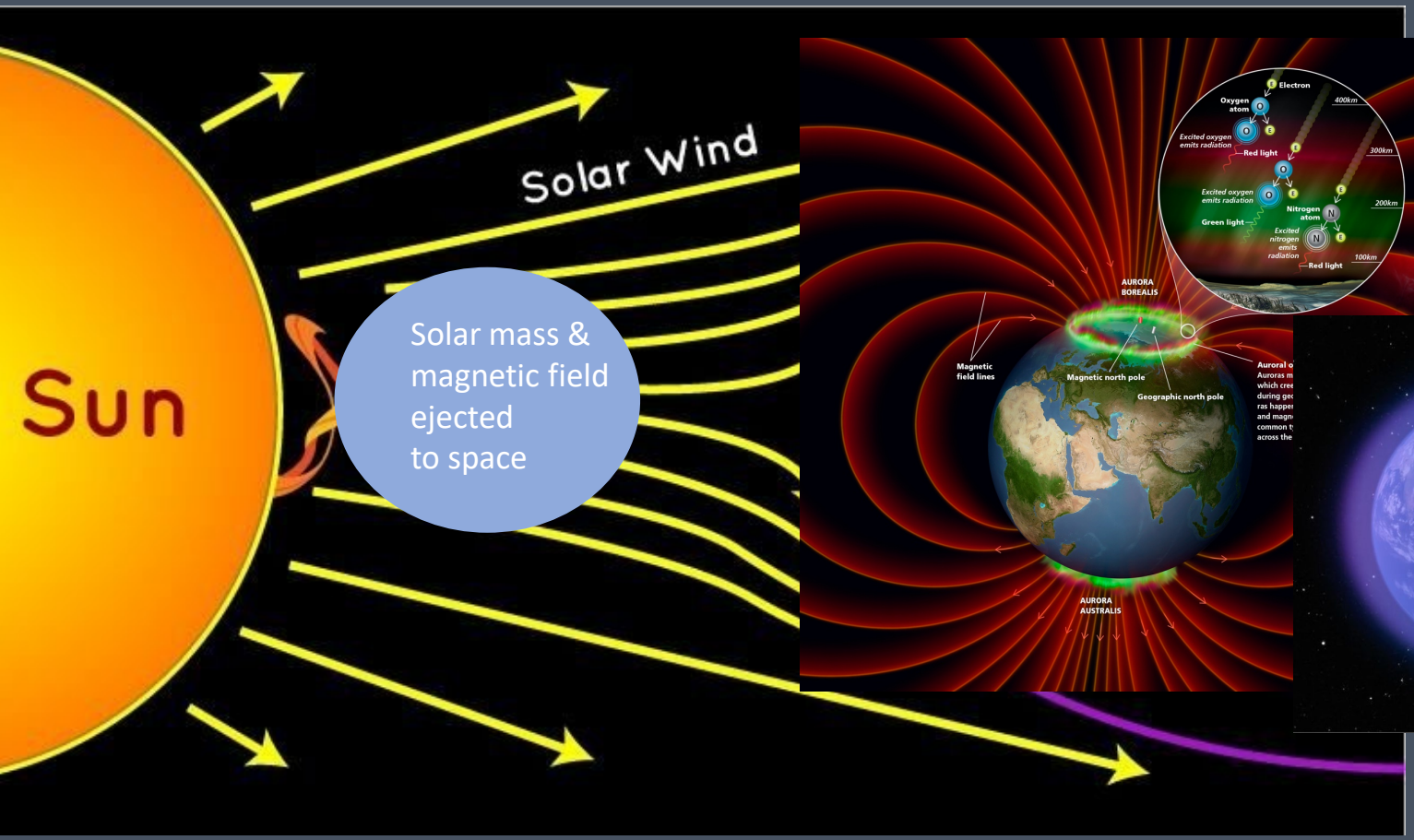
- Sun’s outflow is a supersonic wind
  - Draws out the Sun’s magnetized atmosphere into streams

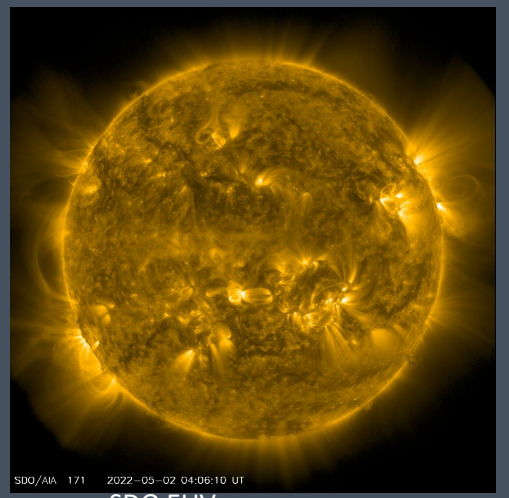
- Both outflow and magnetic bursts produce space weather (sometimes together)

1) Space Weather External to Earth's Atmosphere

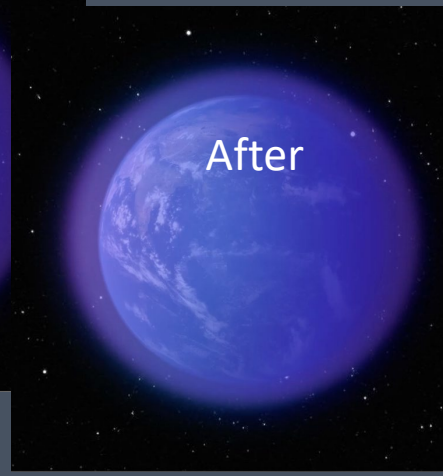
Solar Flare › Mass Ejection › Geomagnetic Storm › Auroral Heating › Atmospheric Expansion › Orbit Perturbations

Joule Heating





SDO EUV



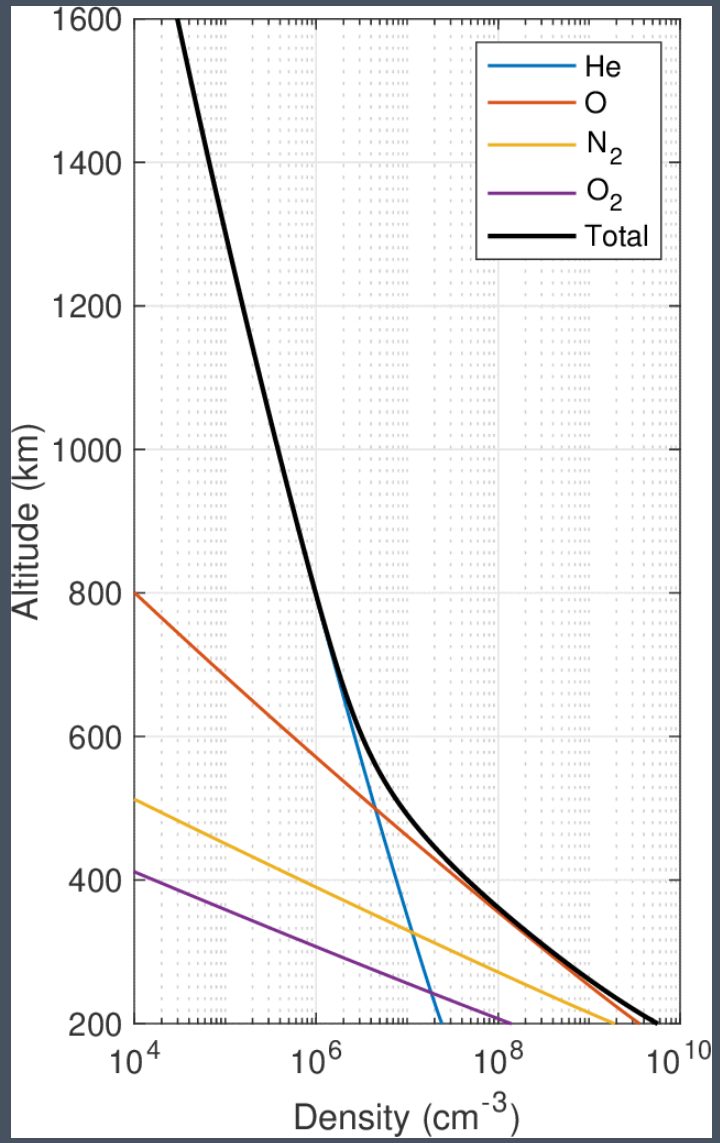
Inset courtesy of Discover Magazine

LEO: a Dynamic & Crowded Environment

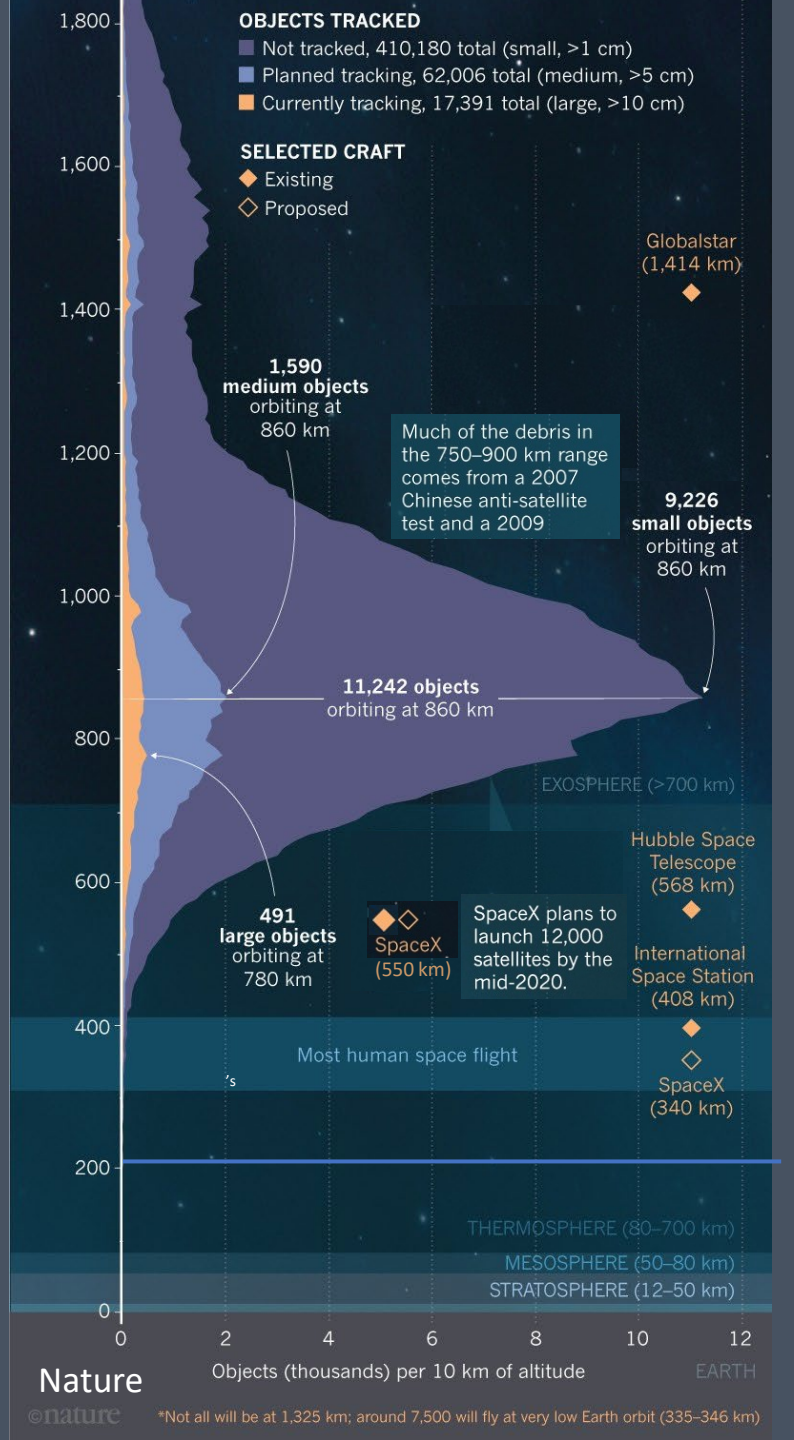
While SRP[1] is larger in magnitude, aerodynamic drag is the most variable force and the primary contribution to orbit errors

Drag is the dominant non-conservative force

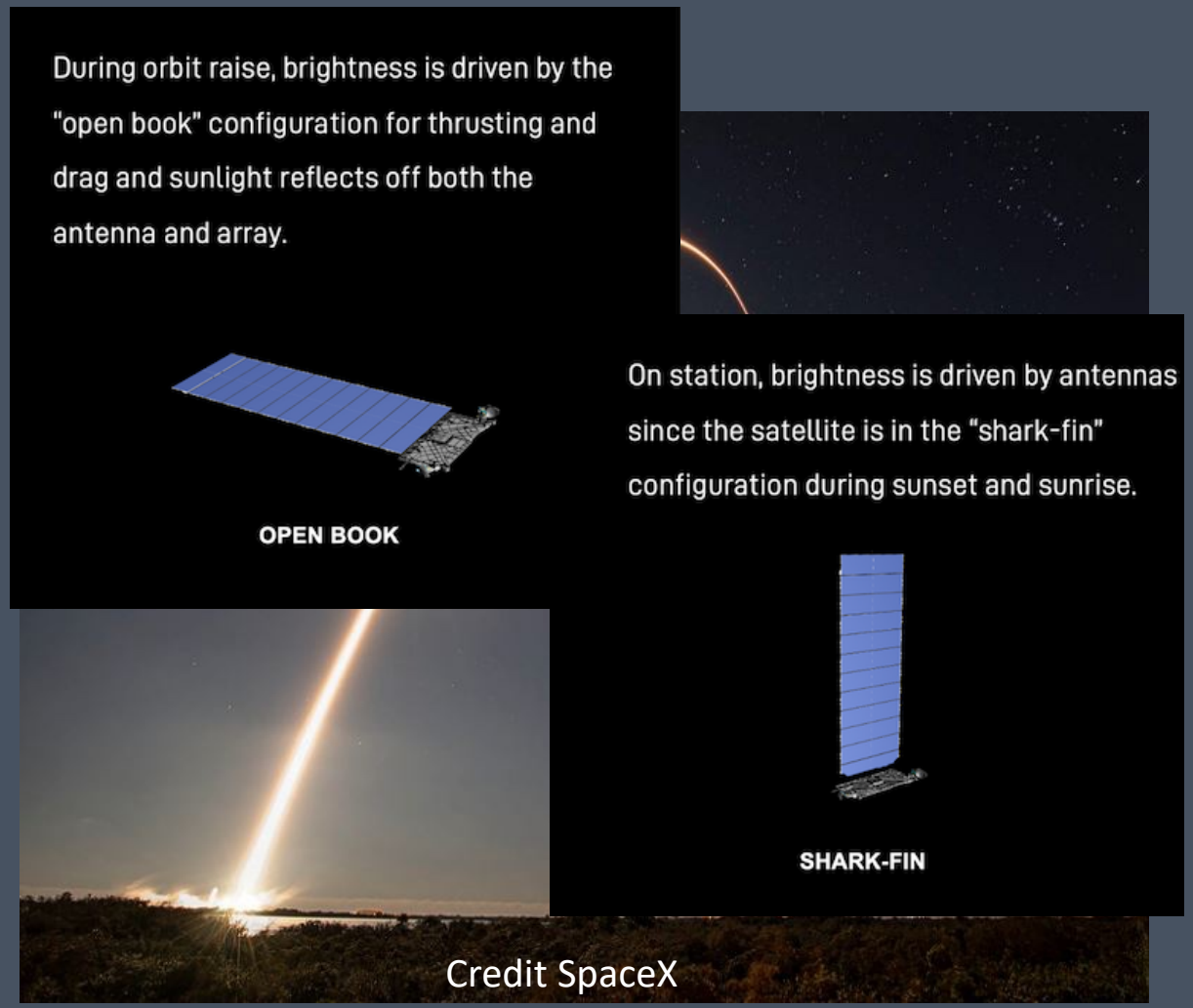
[1]SRP=solar radiation pressure
Courtesy of Marcin Palinski, LASP



Neutral Density Variation
Courtesy of Eric Sutton, SWxTREC



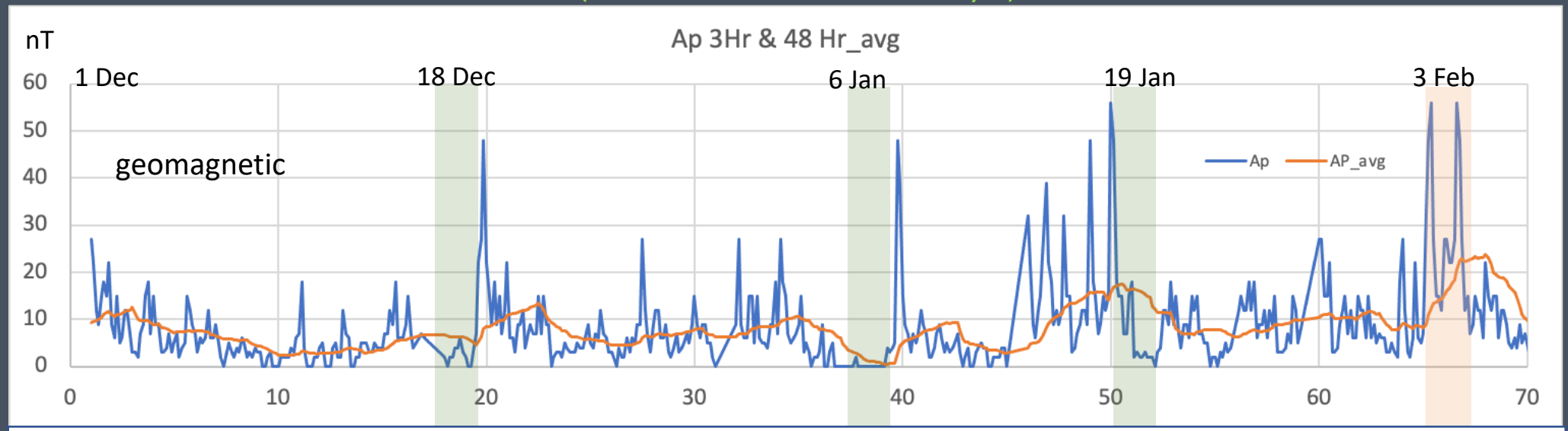
Initial On-orbit Conditions: Starlink, 4 Feb 2022



- Starlink satellites achieved initial controlled flight at 210 km, inclination = ~53 deg.
- Minor geomagnetic storm in progress
- Little margin for density variations at these low altitudes
- Density variations
  - ~ 50% above climatology, globally
  - >125%, locally (Fang et al., 2022 SWPC)
- Spacecraft ..”commanded into a safe-mode where they would fly edge-on (like a sheet of paper) to minimize drag — to effectively ‘take cover from the storm’ — ….”
- Maneuver/thrusting /orbit raising operations did not /could not begin

Space Weather Indices and Trends

(Each Launch + 2 Days)



Preliminary Ap data provided by the GFZ German Research Centre for Geosciences

Served by SwXTREC Data Portal

S10 data provide by Space Environment Technologies (SET) LLC

Plot inspired Tzu-Wei Fang SWPC

Space Weather Insights from Starlink Event

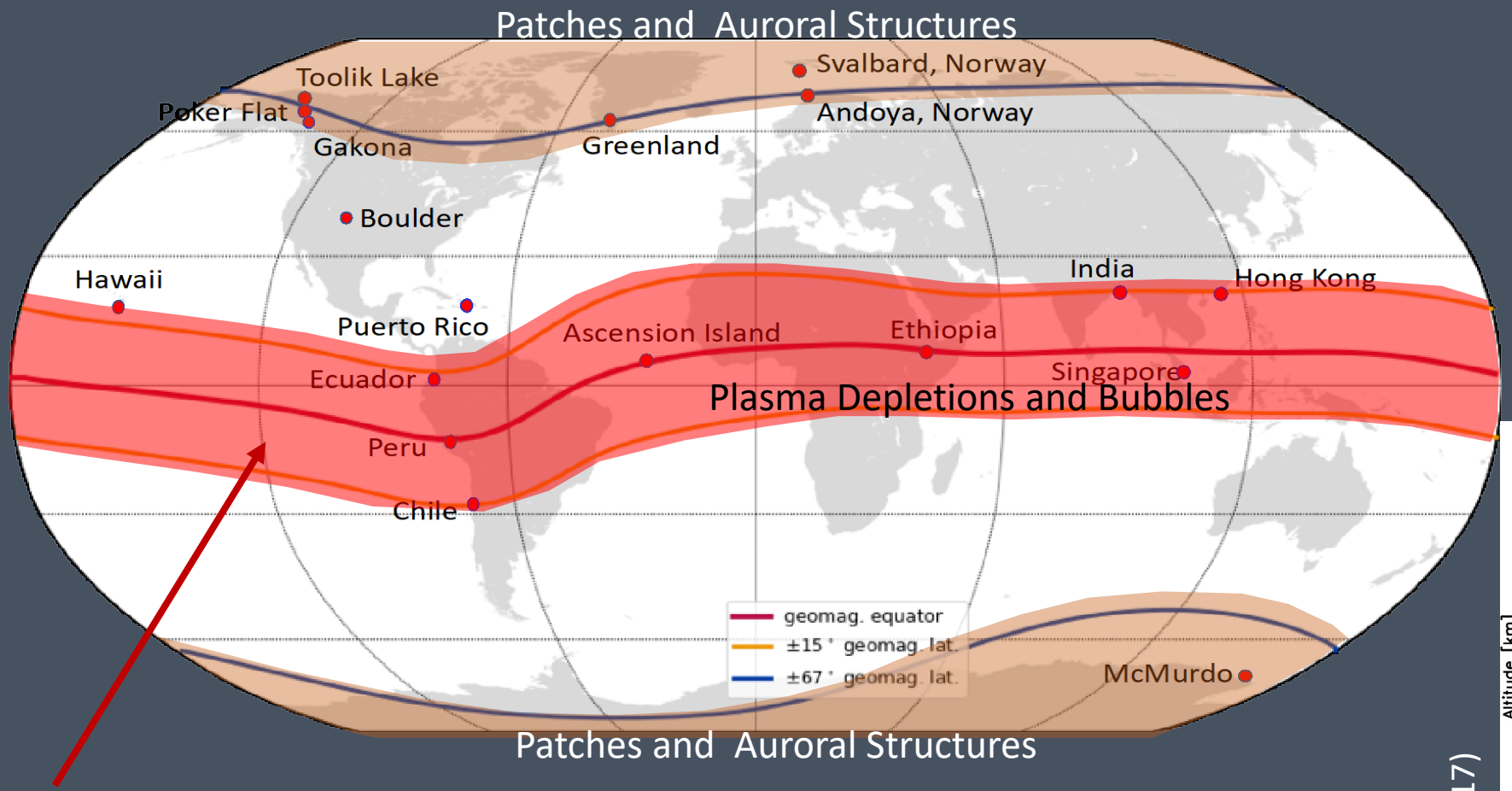
- Early Feb 2022 SpaceX Starlink Launch
  - Minor geomagnetic storm during launch
  - Another minor storm post launch
  - Small upward trend in geomagnetic activity

  - Upward trend in EUV flux was significant in January 2022

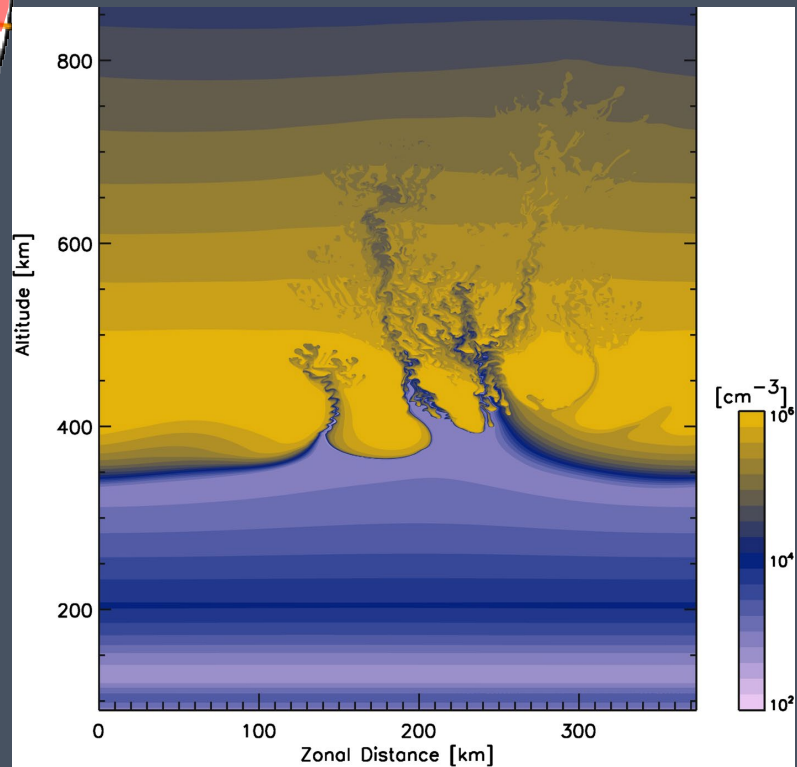
- Combination of these not previously seen in low altitude Starlink Ops
  - Most previous launches during intervals of much lower solar EUV

- Low-altitude LEO environment is very poorly characterized
  - Opportunities with mega-constellations to provide more density observations
    - GNSS tracking could play a role

2) Space Weather Internal to Earth's Atmosphere



Produces impacts on signals and engineered systems



Yokoyama, T, (2017)

- GNSS Signals scintillated by vertical plumes of low electron density mixing into regions of higher electron density
- Prevalent at dusk, but can be driven at other times/sectors by geomagnetic storms & can expand to mid latitudes

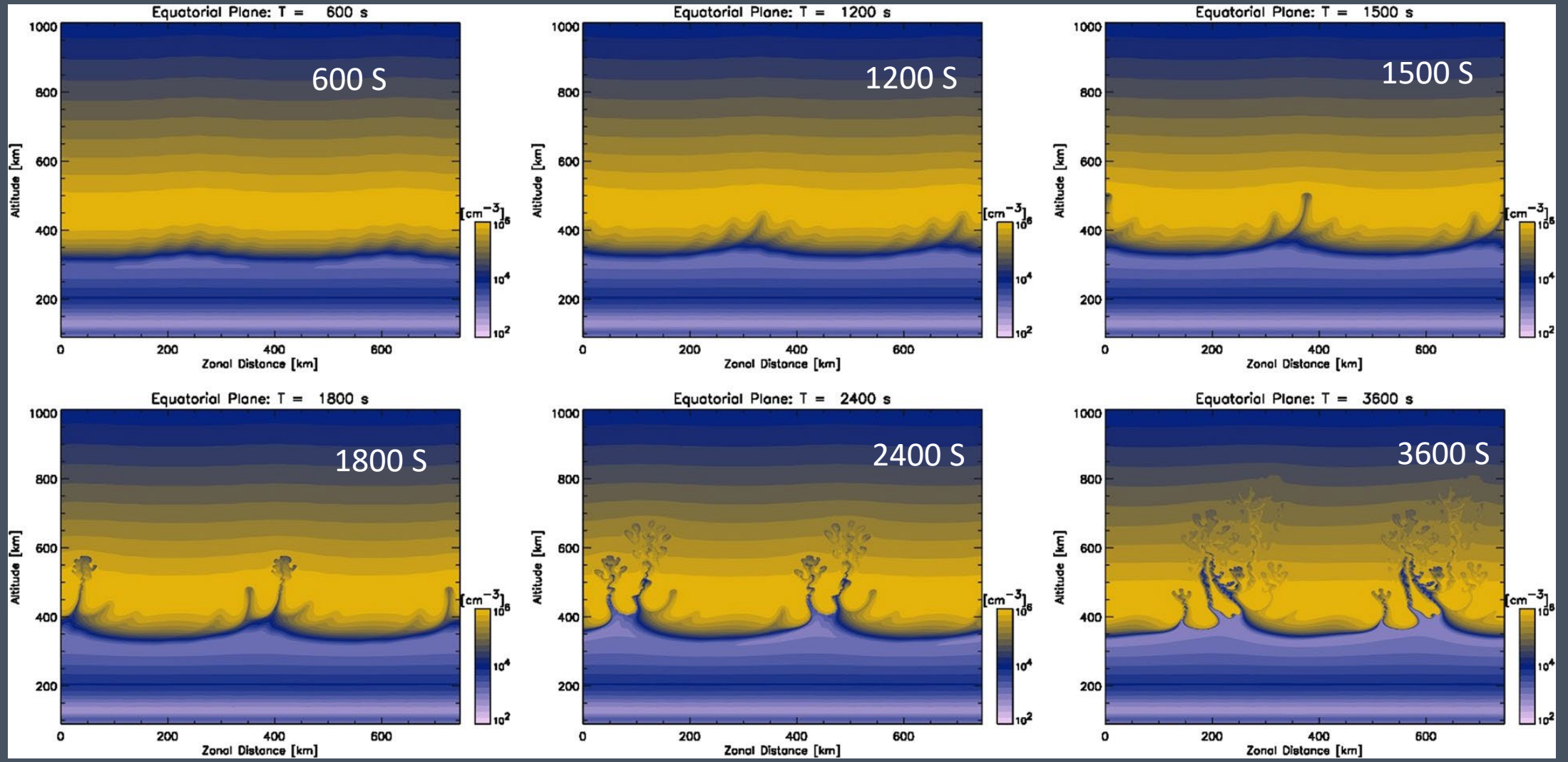
GNSS and Operations in Crowded LEO

- Possible/Likely GNSS Roles in
  - Collision Avoidance
  - Tracking
  - Station Keeping
  - Maneuvering/Orbit Raising
  - Formation Flying
  - Autonomous Operations for all of these

  - Pointing/Attitude Control

  - Drag/density estimates from PNT data

Temporal Development of Equatorial Plasma Bubbles



Yokoyama, T, (2017)

Fig. 8 East–west asymmetry of EPBs simulated using the HIRB model. Reproduced from Yokoyama et al. (2015)

3D View of Single Plume Structure

- Instabilities

- Dusk-Midnight (Quiet)
- Anywhere (Storm time)

T. Yokoyama, A review on the numerical simulation of equatorial plasma bubbles toward scintillation evaluation and forecasting, Progress in Earth and Planetary Science, 4:37, 2017.

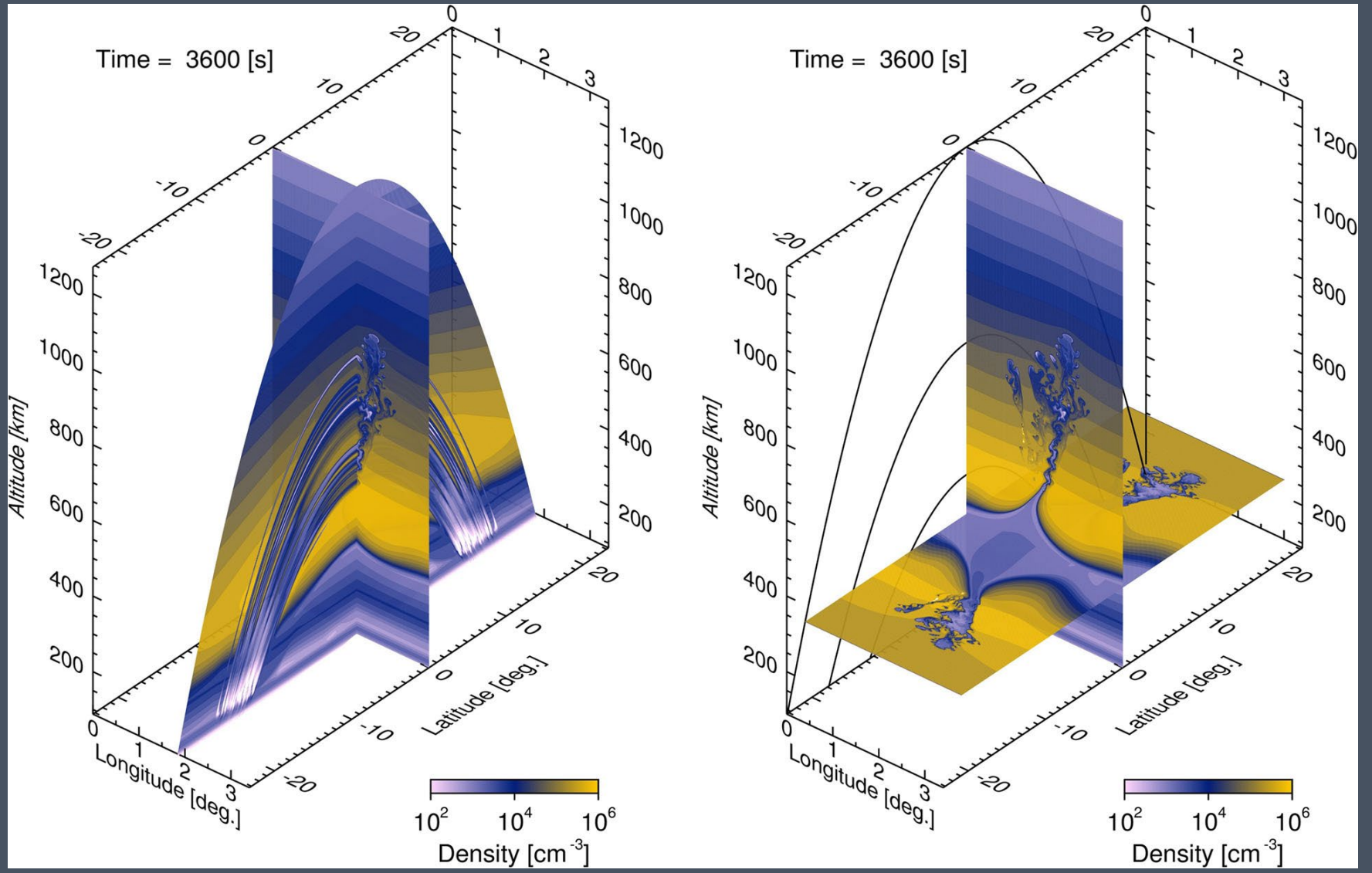


Fig. 7 3D view of HIRB model results. Reproduced from Yokoyama et al. (2014)

GNSS and Operations in Crowded LEO

- Possible/Likely GNSS Roles in
  - Collision Avoidance
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Potential Disruptions

- Ground-based Receivers
- LEO-based Receivers
- Radio-Occultation Ops

Summary

- Starlink's launch and operations –Early February 2022
  - Double minor geomagnetic storm
  - Strong influence of Extreme UV flux in rising solar cycle 25
  - Limited knowledge of neutral density at ~200 km
  - Thin margin of operations for start of orbit raising

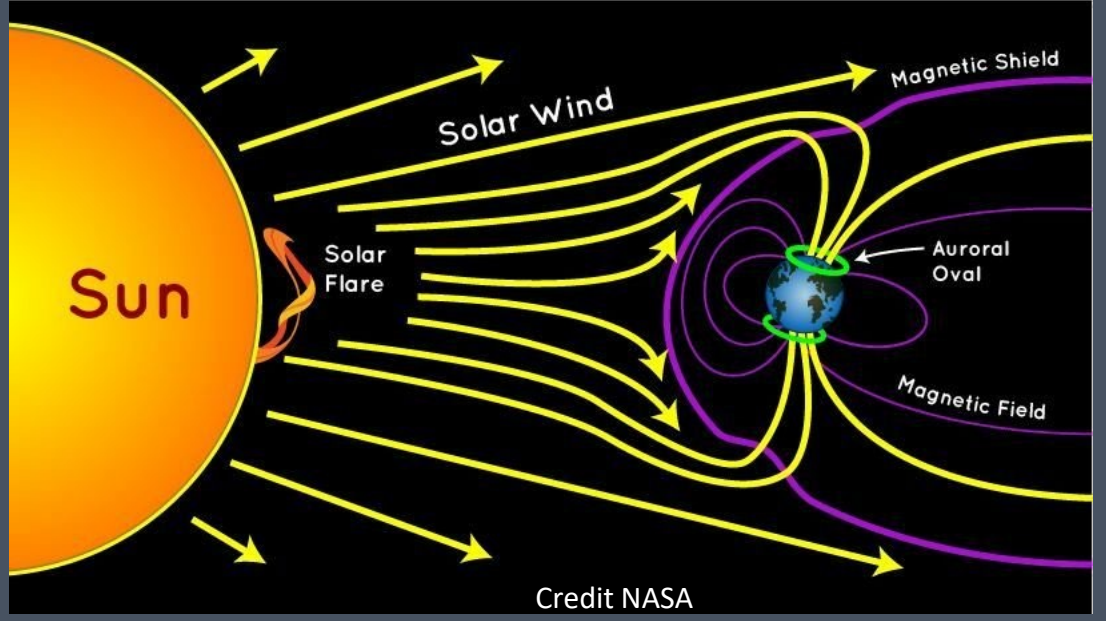
- GNSS signals (and their stability)
  - Likely have a large role in mega constellation ops
  - Station keeping, orbit raising, collision avoidance, autonomous operations
  - Opportunity for reporting much more info on space environment variations

Thank You
Questions?

NASA: ISS, Aurora, Starlink

Backup Slides

Solar Eruptive Events



- Three primary types of eruptive events
  - SOLAR FLARES: bursts of radiation across large segments of E&M spectrum
    - Immediate Impacts…a few minutes to hours of impact
  - SOLAR ENERGETIC PARTICLES (SEPs): blasts of energetic ions
    - Effects at Earth in 20 min to hours….may last for days
    - Individual particles with extreme energy—Mega to Giga electron volts
  - CORONAL MASS EJECTIONS (CMEs): bursts of magnetized plasma
    - 1-4 days travel time with effects lasting 1-2 days
    - Magnetic and plasma measurements made up-stream from Earth (~1 hr travel time)

Developing Sensitivity to Space Weather

Wired

Communications

- Civil
  - Industrial
  - Personal
  - Governmental
- Military

Radio

Communications,
Navigation, Control
Remote Sensing,

- Civil
- Military
- Space

GNSS

Navigation, Location
Communications,
Remote Sensing
Control, Timing

- Ubiquitous

Navigation by Magnetism

Northern Lights-Magnetism

Electricity -Batteries

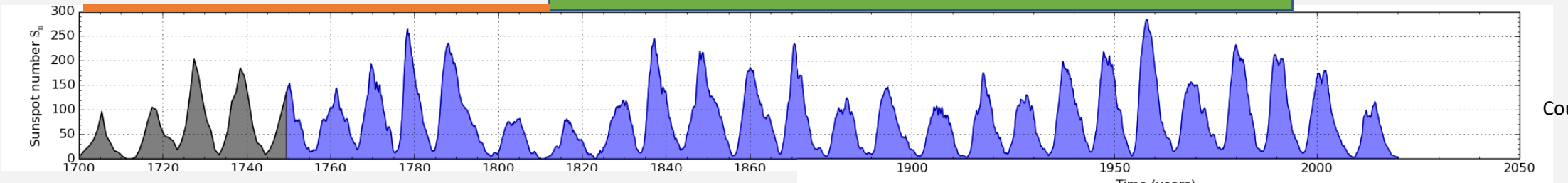
Currents & E&M

E&M Waves

Radio

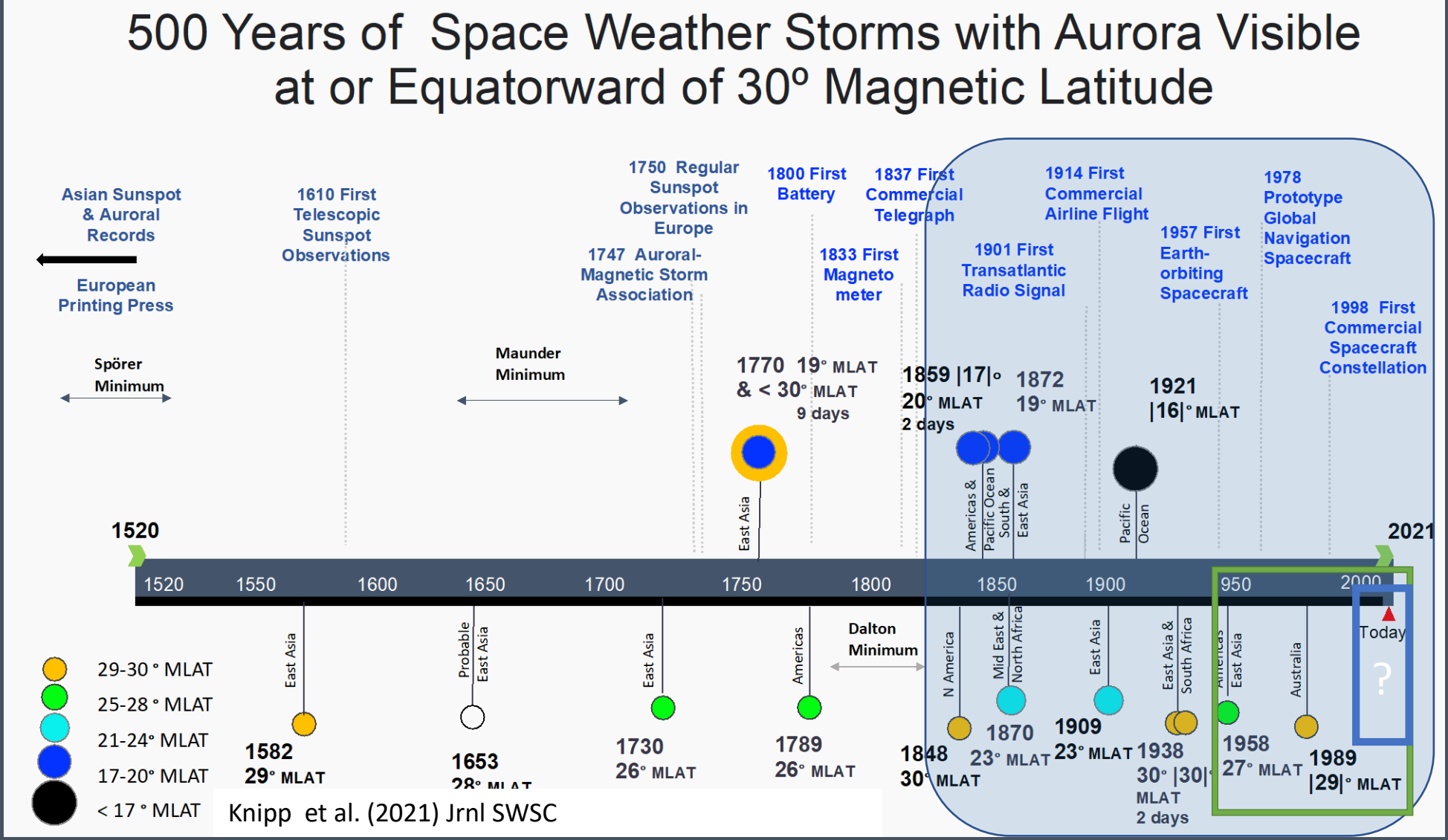
Navigation by E&M

?



Courtesy of SILSO

Superstorms: ➡ Society Impacts

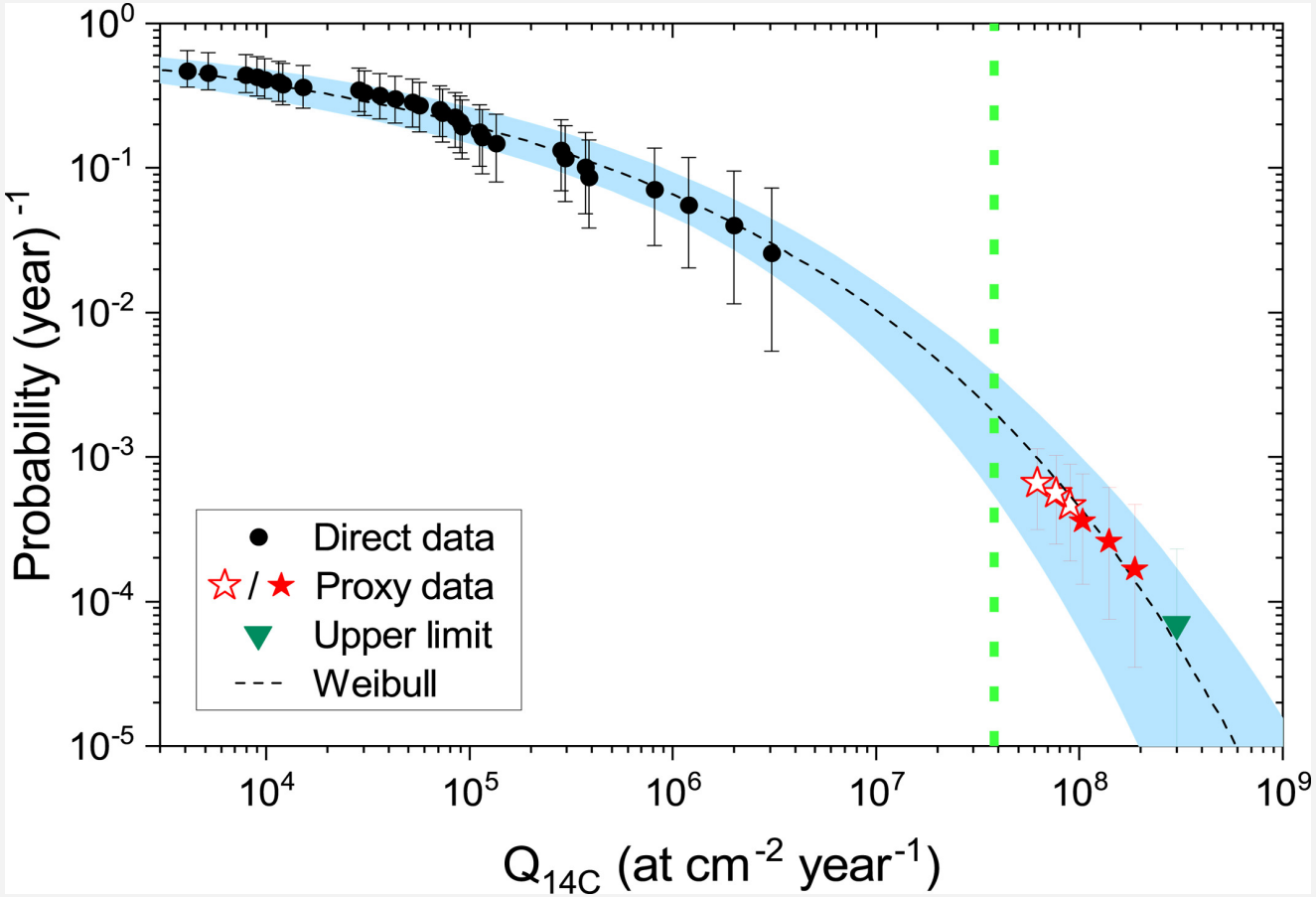


14 Visual 'Great' Events in 500 Years

- All since 1859 disrupted conducting technologies: telephones, submarine cables, power grids via magnetic perturbations
- Latest in 1989
  - -HydroQuebec grid collapse
  - -2000 'lost' objects from space catalogue had to be 're-acquired'; weeks of effort

SWx TREC

What Gives Me Pause? SEPs



Usoskin et al. 2021

Rogue solar energetic particle events

High particle fluxes

Sufficient energy to create
Atmospheric radionuclides

Carbon 14 created lasting for months

Shows up in tree rings

Change atmospheric chemistry