JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

Geospace Imaging from the Lunar Surface

A perspective on geospace imaging from the lunar surface

We can address Decadal-level science with human explorers from non-polar destinations.

- Inexpensive
- Crew compatible
- Provide information of societal and scientific importance

Dr. Larry J. Paxton
Larry.Paxton@jhuapl.edu

A simple instruments on the lunar near-side would have practical and scientific value

- The reasons for returning people to the Moon are similar to 60 years ago
  - Putting humans back on the Moon is a powerful human story.
  - Winning the Race to the Moon v2 is a powerful motivation.
- There are new reasons. For example, a lunar Earth Observatory could help us prevent a tragedy of the commons* wherein a finite resource (and Earth orbit is a finite domain) for all people is destroyed by non-optimal practices.
  - The vast increase in the number of satellites in Earth orbit brings the possibility of a Kessler Syndrome.
  - Orbital predictions and space traffic management are becoming more important to managing risk.
  - A lunar FUV hyperspectral imager could provide key information
  - Other useful sensors include ENA imager and EUV Plasmasphere imager.
- Observing the Earth's atmosphere and its response to forcing from above (solar wind/magnetosphere coupling to high latitude ionosphere) and forcing from below (lower atmosphere waves and tides) from the lunar surface will address Decadal-level science questions and motivate prioritizing this by its practical economic value.

*Garrett Hardin coined the term in 1968; he is a problematic figure.

"We choose to go to the moon. We choose to go to the moon in this decade and do the other things, not because they are easy, but because they are hard, because that goal will serve to organize and measure the best of our energies and skills, because that challenge is one that we are willing to accept, one we are unwilling to postpone, and one which we intend to win, and the others, too."

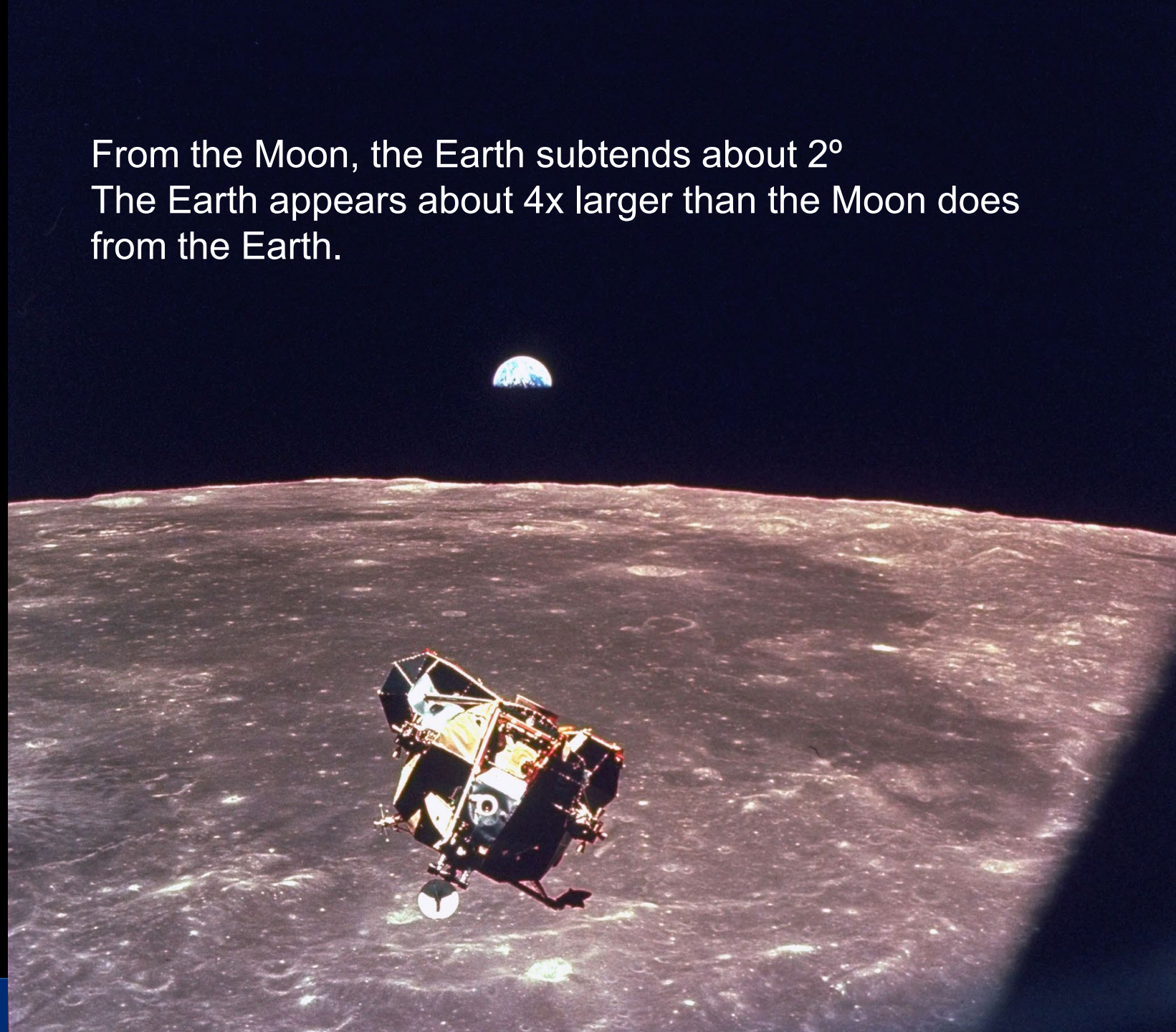
President John F. Kennedy
Rice University
12 September 1963



"We choose to go to the moon. We choose to go to the moon in this decade and do the other things, not because they are easy, but because they are hard, because that goal will serve to organize and measure the best of our energies and skills, because that challenge is one that we are willing to accept, one we are unwilling to postpone, and one which we intend to win, and the others, too."

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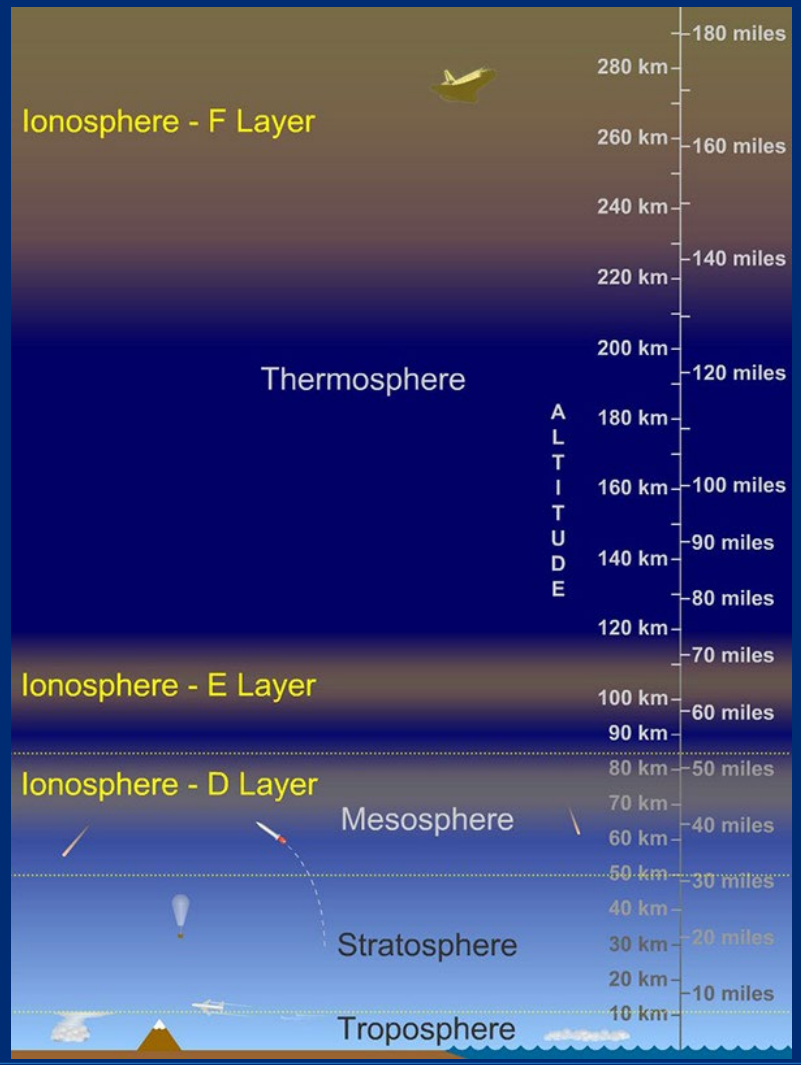
From the Moon, the Earth subtends about 2º
The Earth appears about 4x larger than the Moon does from the Earth.

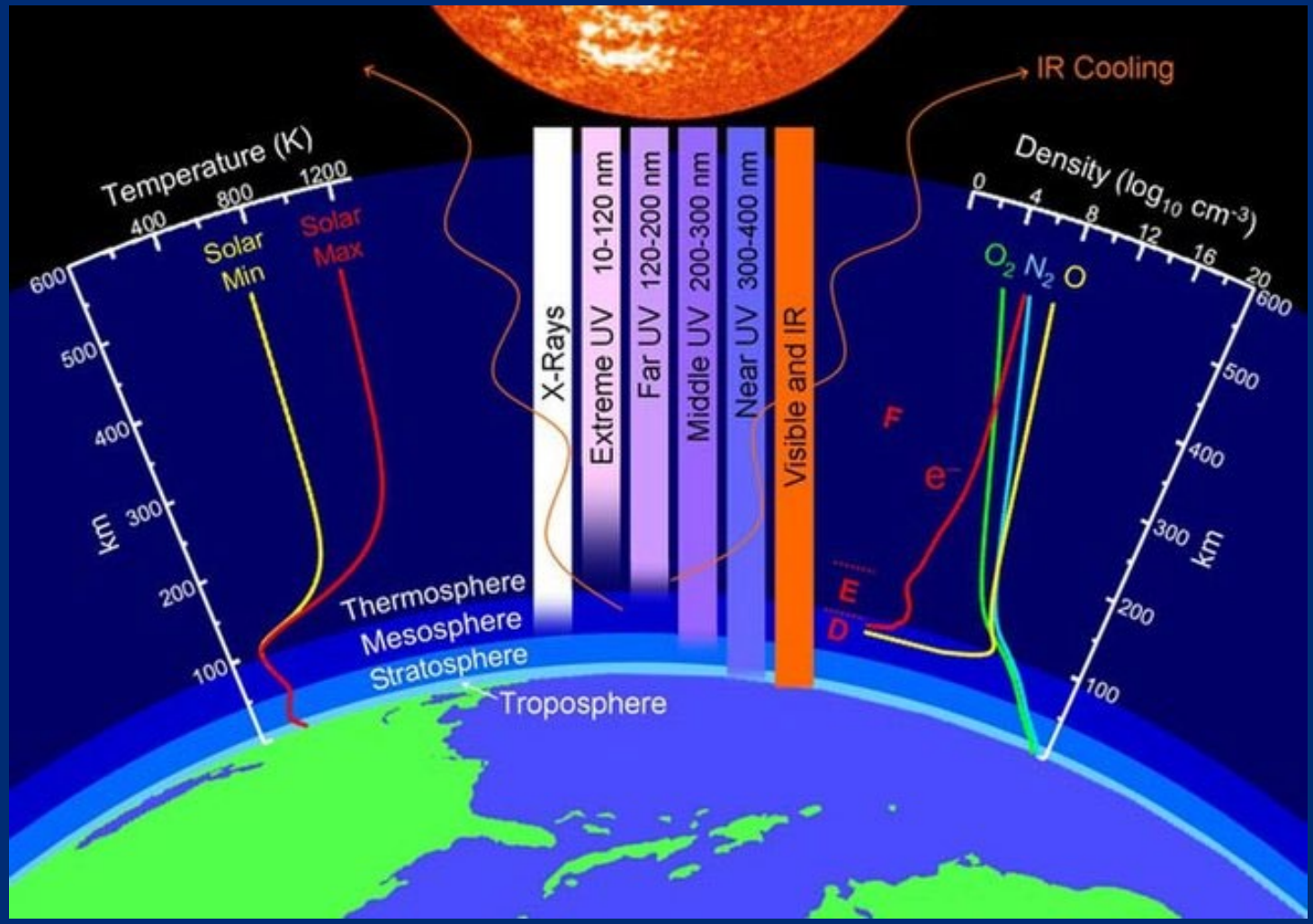


Decadal survey questions

- **Overall implementation strategy:** Conduct research within a system science paradigm that emphasizes the complex linkages between different regions, scales, domains, and processes of the ITM; quantifies the relative roles of competing causal pathways; and establishes the baselines from which emergent behavior can be distinguished.
- **Foundational implementation strategy**: Within the next decade, implement the primary GDC and DYNAMIC missions contemporaneously and ensure the availability of strategic ground-based observational assets and modeling.
- **PBR status**: GDC cancelled and DYNAMIC MIA
  - This and the cancellation of the TIMED mission means that there no missions that address the LEO environment (ITM)
- It may well be that we can return to the Moon before GDC or DYNAMIC could be launched.
  - ‘suitcase science’ – small crew-portable science payload would make a tremendous contribution

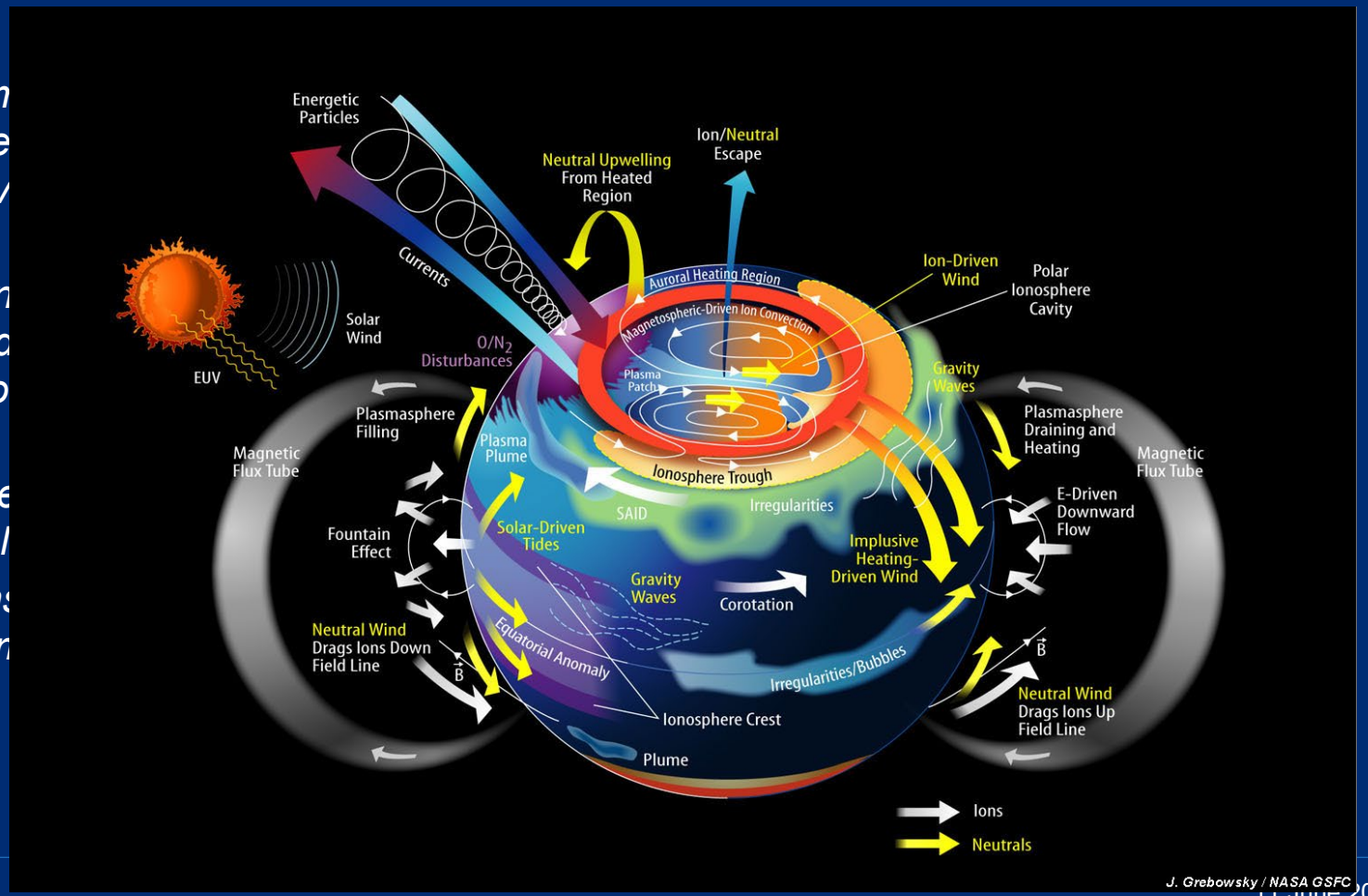
The structure of the atmosphere is defined by the solar inputs and the energy balance between heating/cooling





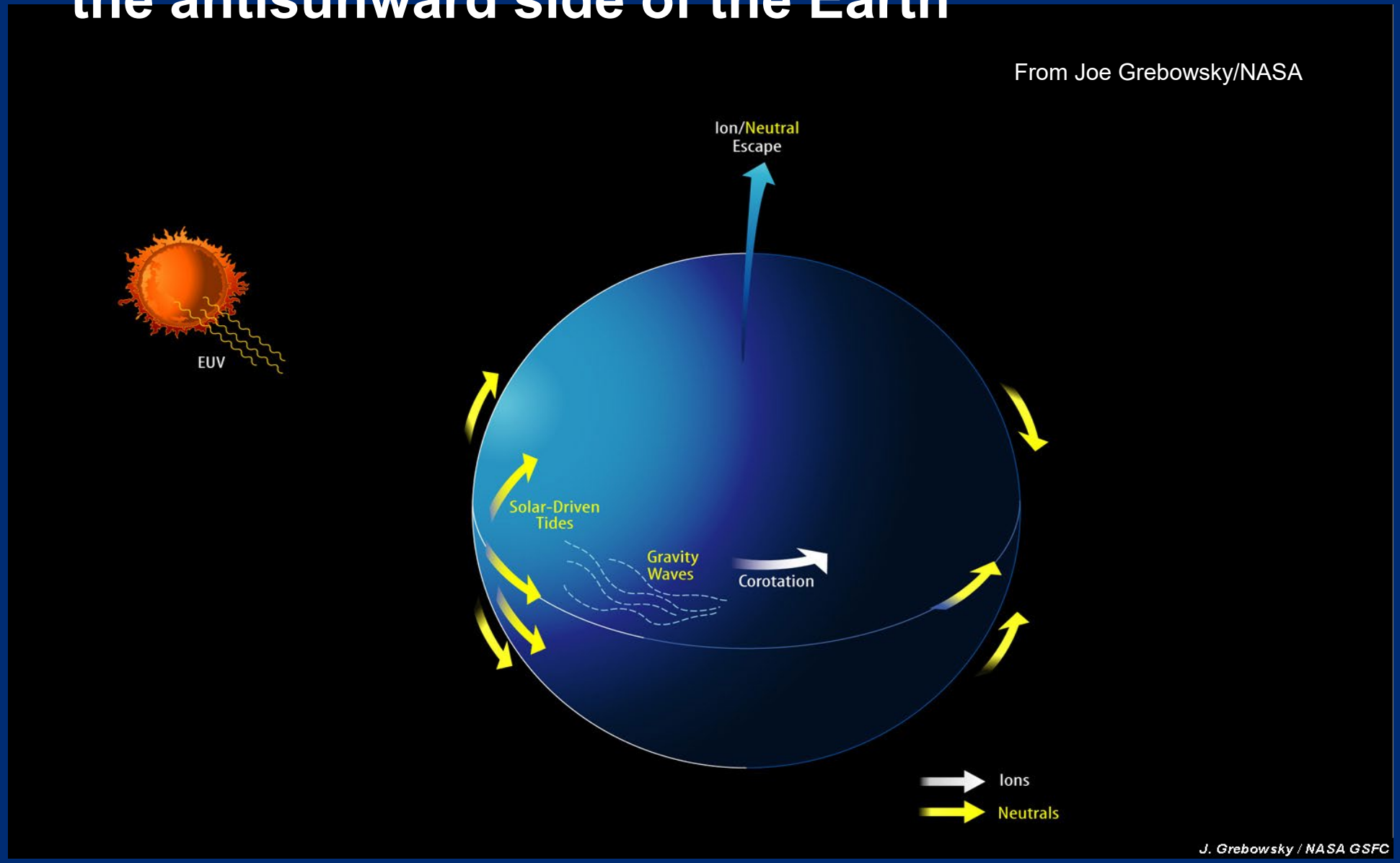
Decadal Science Questions for ITM have not Changed

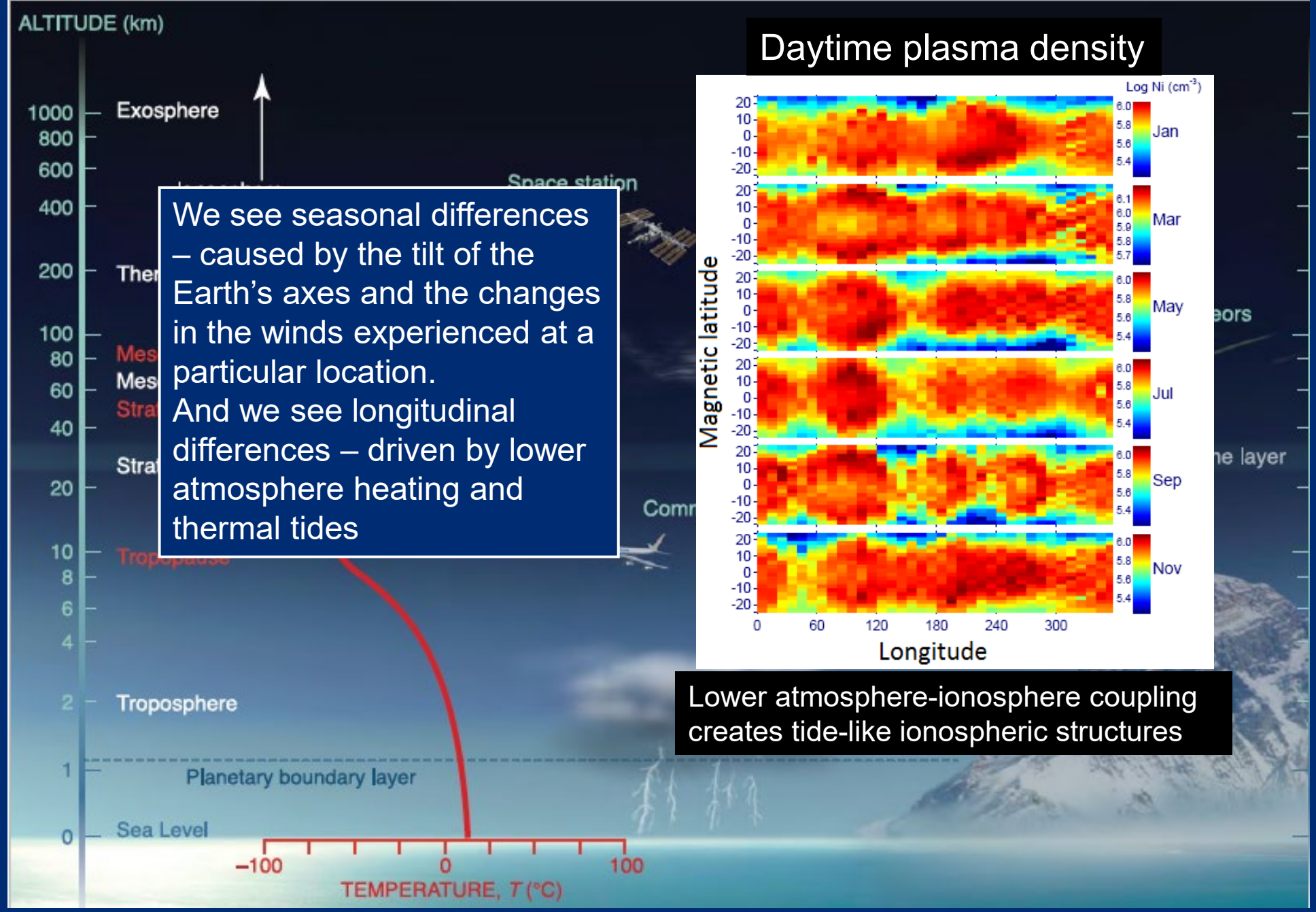
- *Priority Science Goal 1: How are mass, momentum, and energy exchanged and transformed at boundaries across and within the ITM system?*
  - *1. Determine the mechanism momentum transformation/e after extreme events (e.g., v geomagnetic storms).*
  - *2. Determine the time-varyin electrodynamic linkages and processes between the iono and magnetosphere.*
  - *3. Determine how the ITM re atmospheric forcing on local*
  - *4. Elucidate the mechanisms transition in chemical, dynam drivers across the ITM from*



Heating drives circulation from the sunward to the antisunward side of the Earth

From Joe Grebowsky/NASA



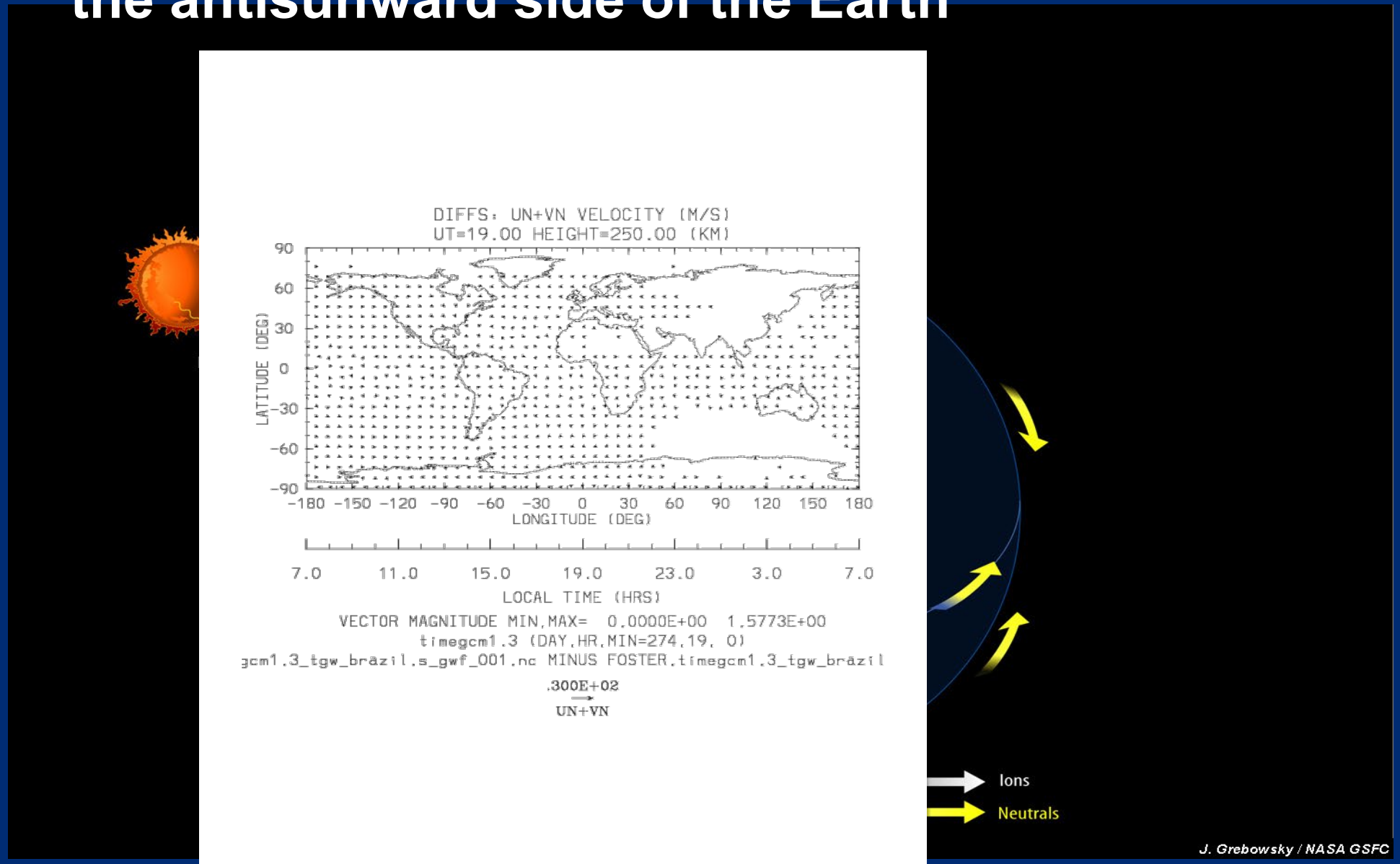


We see seasonal differences – caused by the tilt of the Earth's axes and the changes in the winds experienced at a particular location.
And we see longitudinal differences – driven by lower atmosphere heating and thermal tides

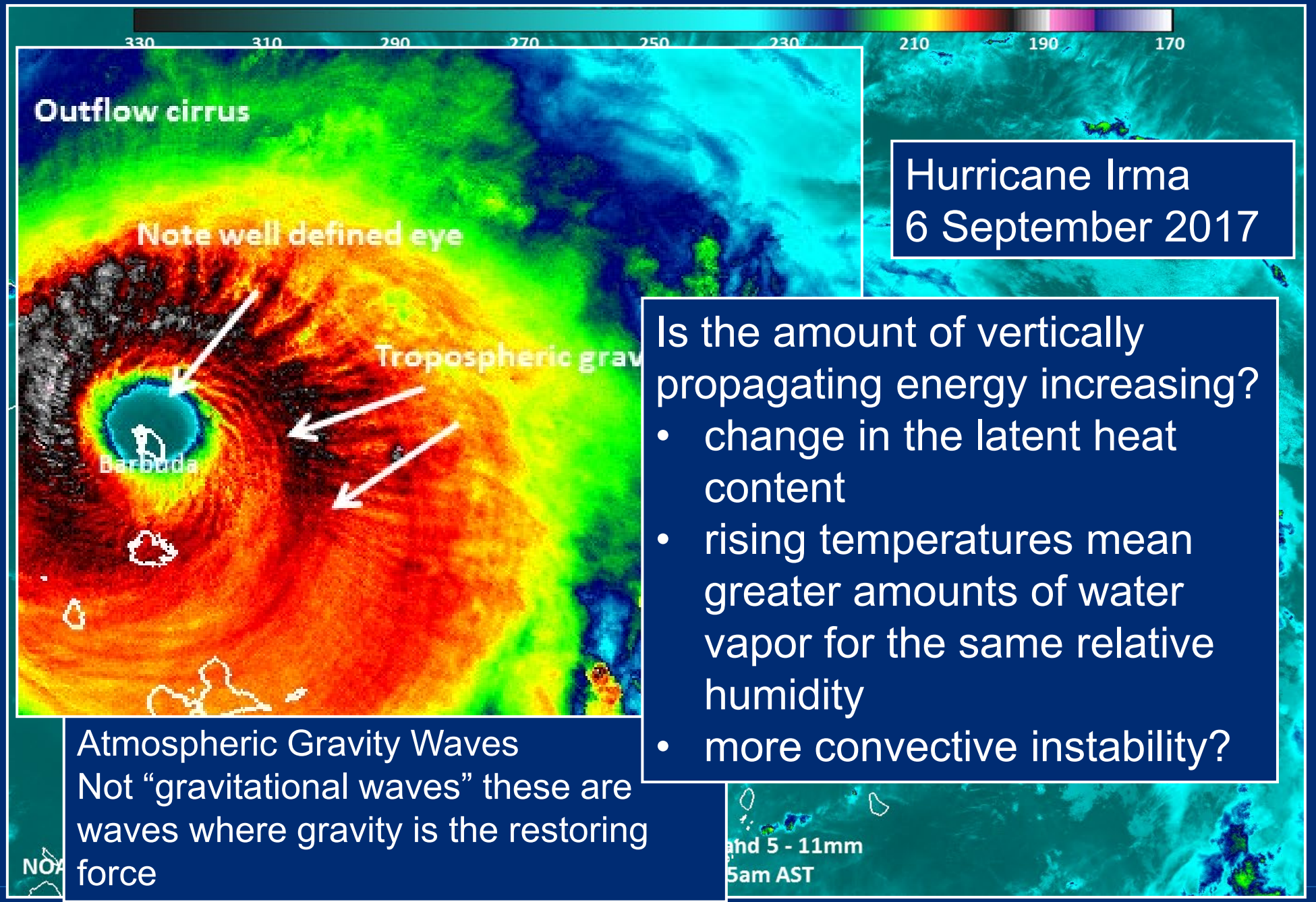
Daytime plasma density

Lower atmosphere-ionosphere coupling creates tide-like ionospheric structures

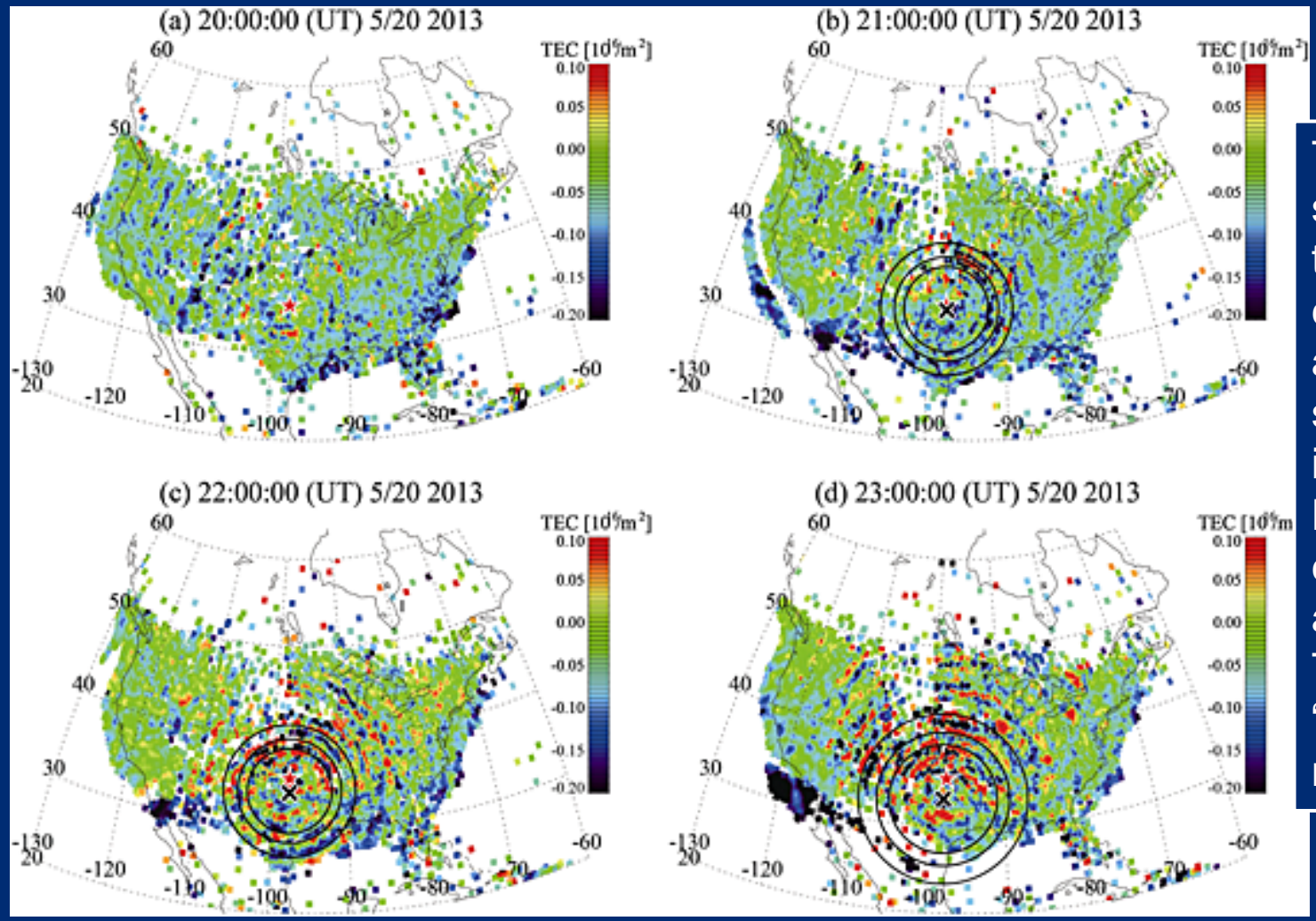
Heating drives circulation from the sunward to the antisunward side of the Earth



Movie from Sharon Vadas


330
310
290
270
250
230
210
190
170
Outflow cirrus
Note well defined eye
Tropospheric grav
Barbuda
Hurricane Irma
6 September 2017
Is the amount of vertically propagating energy increasing?
• change in the latent heat content
• rising temperatures mean greater amounts of water vapor for the same relative humidity
• more convective instability?
Atmospheric Gravity Waves
Not “gravitational waves” these are waves where gravity is the restoring force
hd 5 - 11mm
5am AST

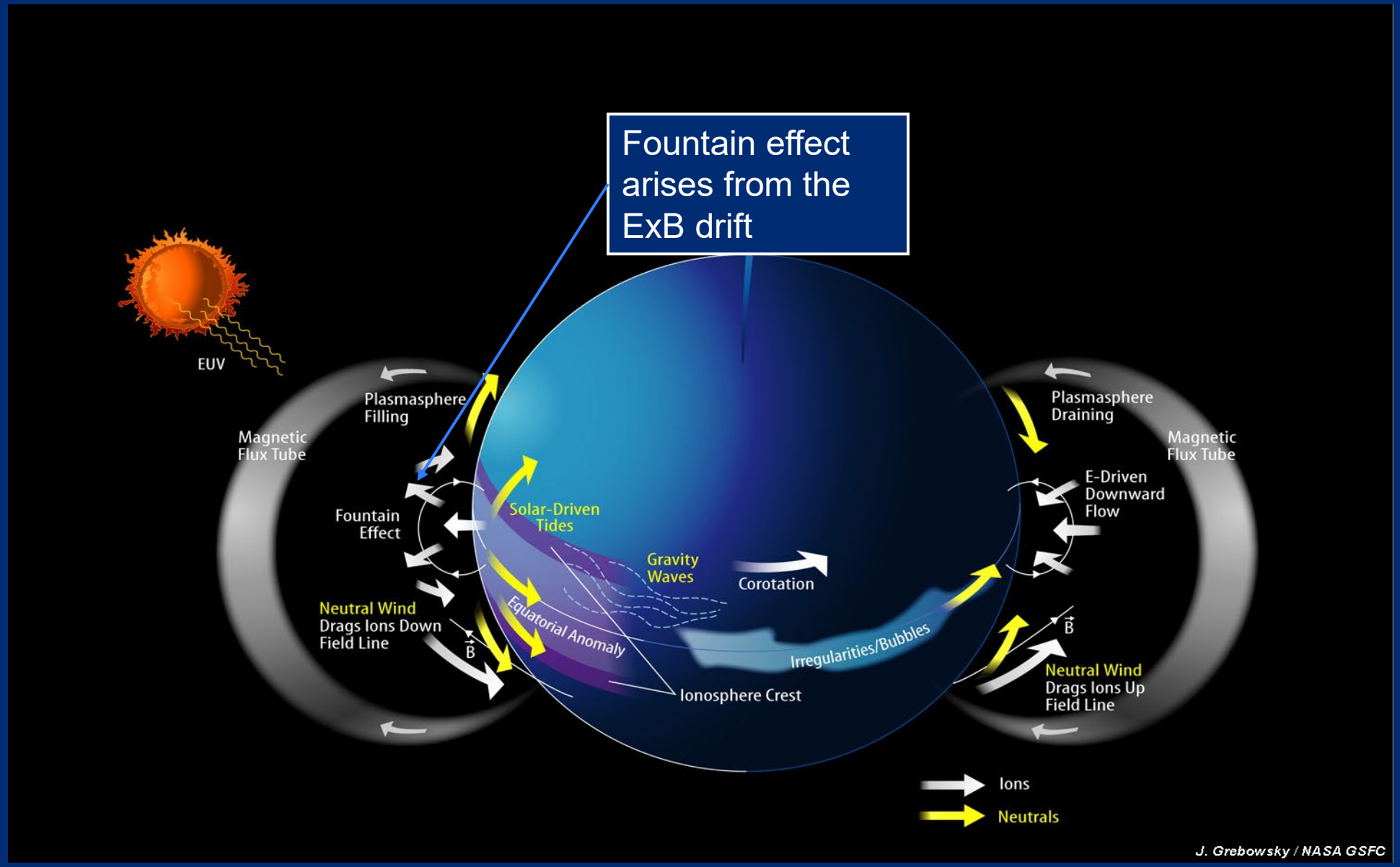
Concentric waves and short-period oscillations observed in the ionosphere after the 2013 Moore EF5 tornado – How?



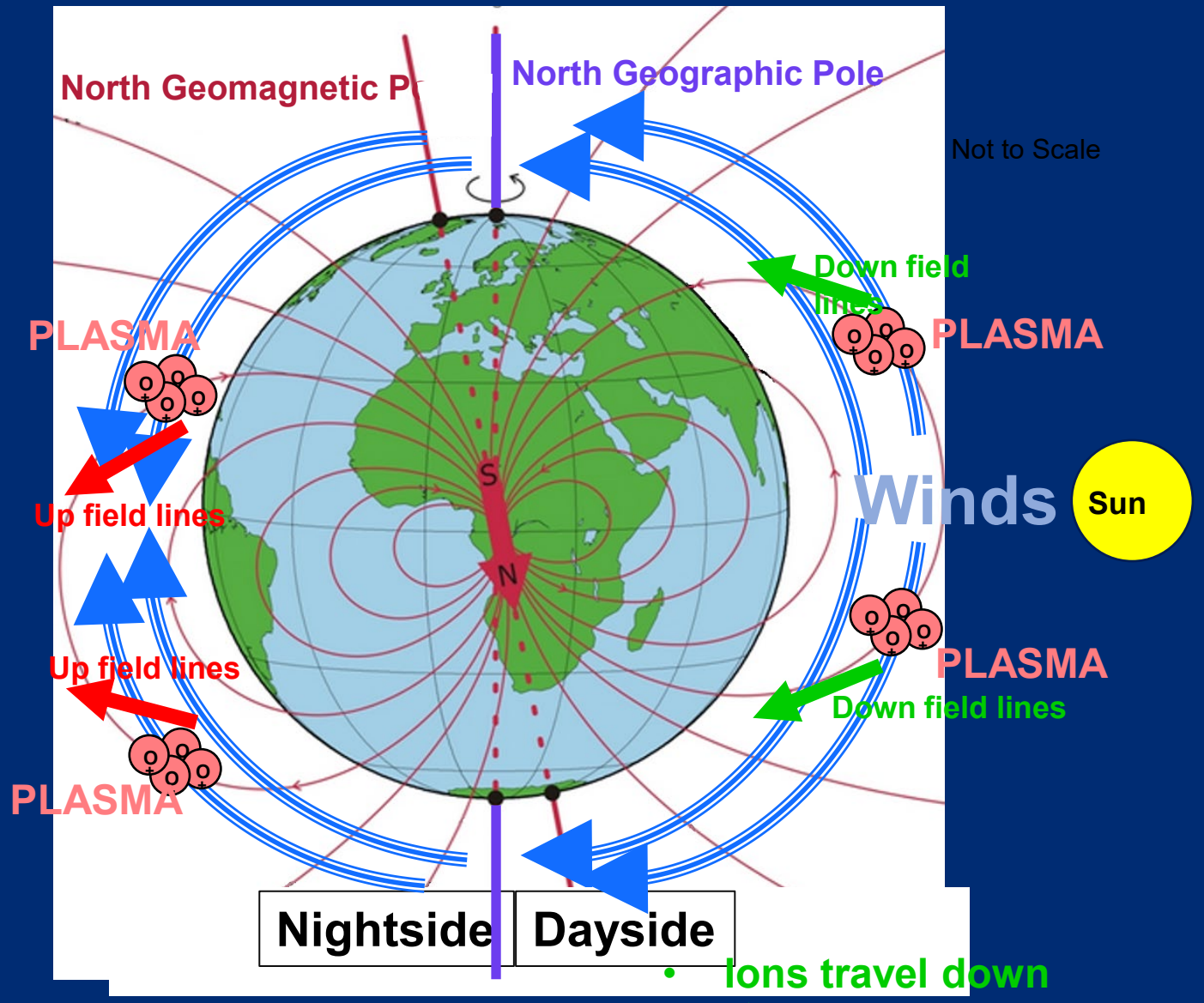
These maps show changes in total electron content (TEC) – an important signature of the ionosphere
Note that the change is only about 0.1%
These are "difference" maps

Geophysical Research Letters
Volume 40, Issue 21, pages 5581-5586, 4 NOV 2013 DOI: 10.1002/2013GL057963
http://onlinelibrary.wiley.com/doi/10.1002/2013GL057963/full#grl51069-fig-0001

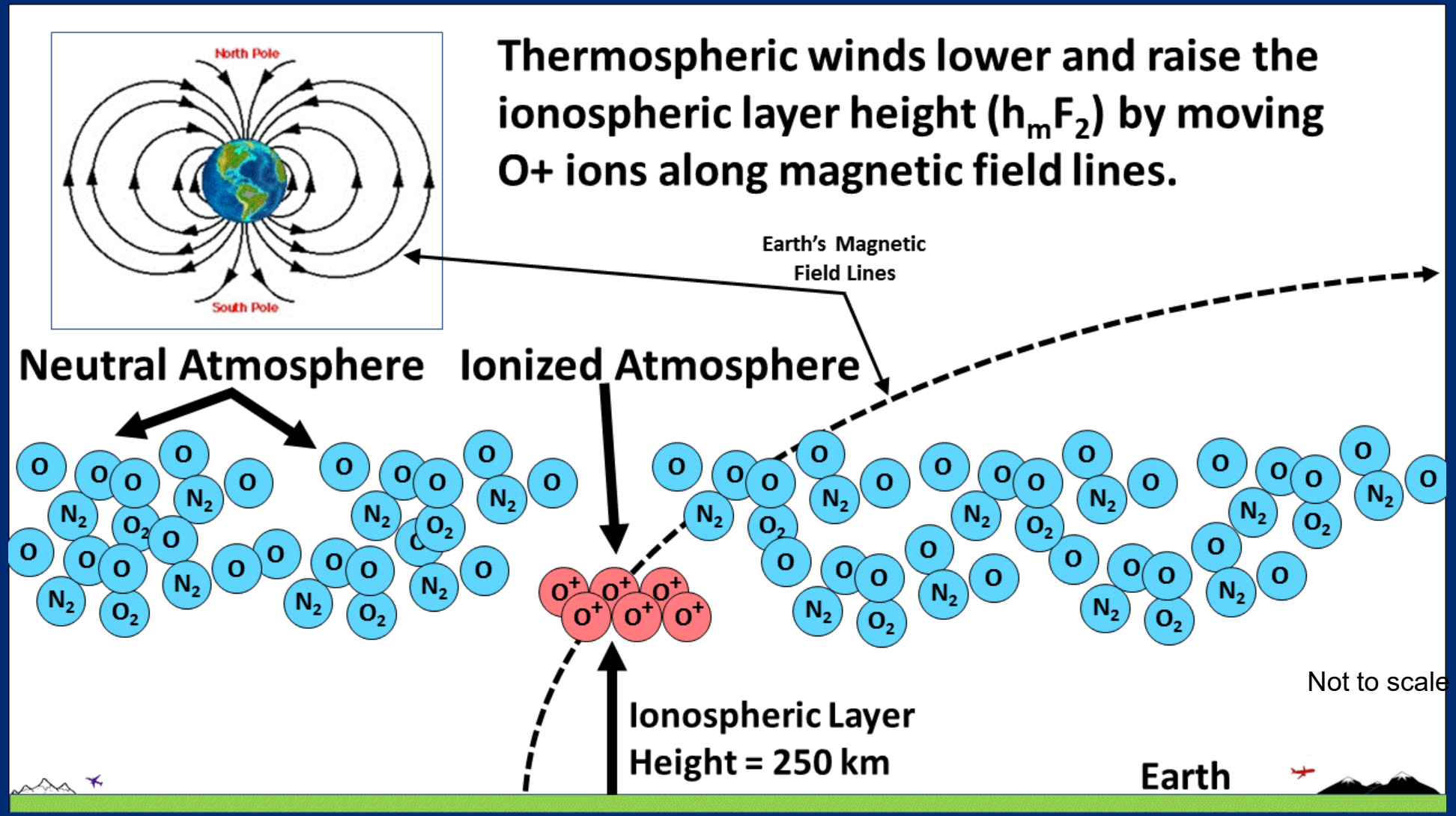
Add the Earth's magnetic field and it constrains the flow of the ions produced by solar ionization



- Thermospheric winds lower/raise ionospheric layer height (h_mF_2) by forcing O^+ ions (plasma) along Earth's magnetic field lines ($\vec{B}$)

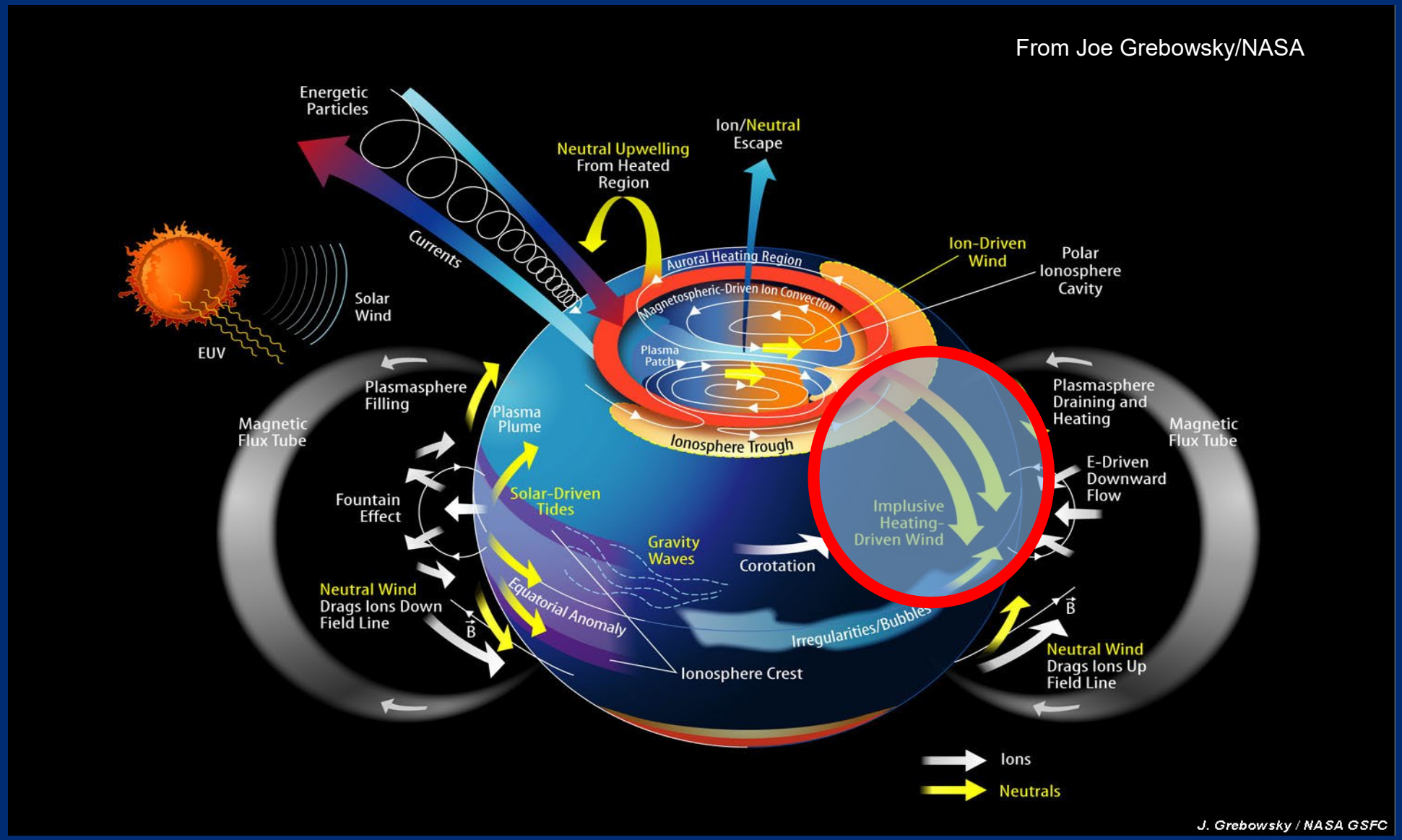


Picture by Pat Dandenault



Picture by Pat Dandenault

The interaction of the magnetosphere with the solar wind energizes particles and creates currents



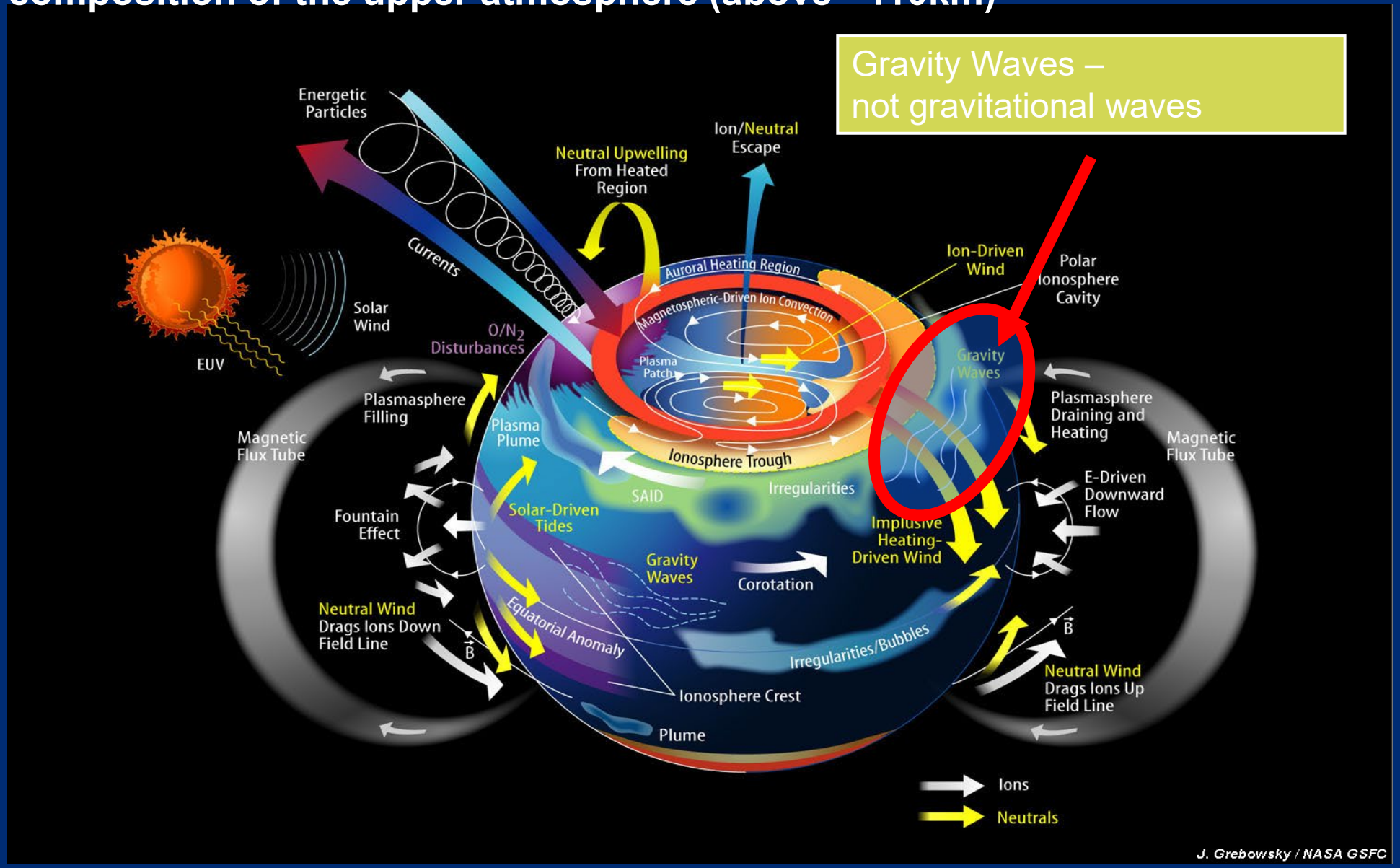
The Ability to Observe from Meso- (1-100s km) to Large-Scale Behavior Would Transform our Understanding

- *Priority Science Goal 2: How Do Internal ITM Processes Transform Energy and Momentum Across a Continuum of Spatial and Temporal Scales?*
  - *1. Determine how the gravity wave spectrum cascades throughout the thermosphere and impacts the ITM system.*
  - *2. Determine how small-scale structuring in high-latitude ITM state parameters leads to mesoscale conductivity enhancements, which have aggregate global significance.*
  - *3. Determine how nonlinear coupling between mean neutral atmosphere circulation, tides, and planetary waves drives ITM variability.*
  - *4. Determine how plasma irregularities are driven by and regulate large-scale ITM phenomena.*



GITM model O/N_2 – May 2024 storm
Aaron Ridley, UMichigan

Geomagnetic storms create global effects and change the density and composition of the upper atmosphere (above ~110km)



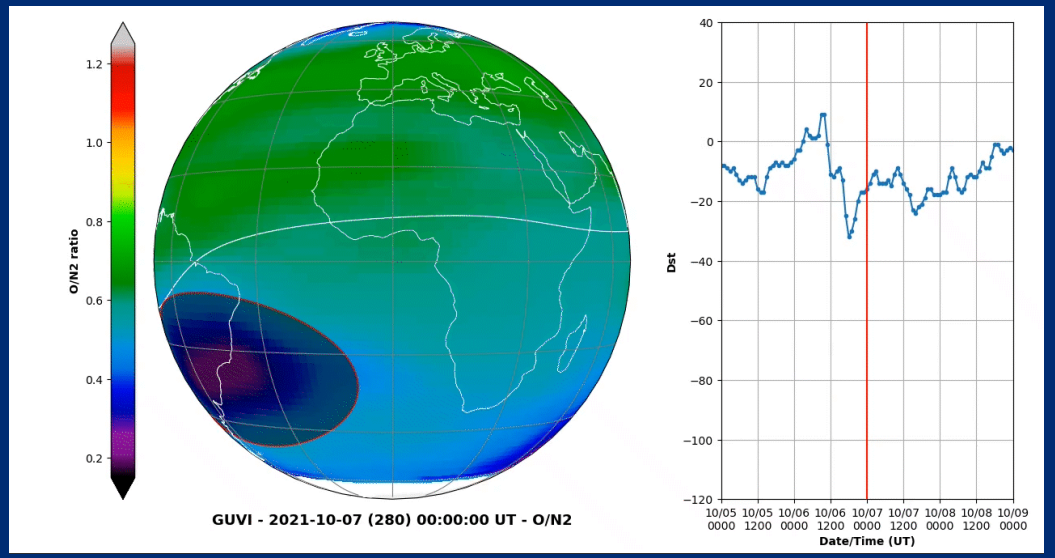
Lunar observations: A platform for science and applications

MAGE simulation of February 2022 storm in which ~40 Starlink satellites in VLEO were lost
Slava Merkin is PI of MAGE.
https://svs.gsfc.nasa.gov/vis/a000000/a005100/a005193/multiField_2-7-2025b_magnetosphere_pc_anim_satellites_1080p30.mp4



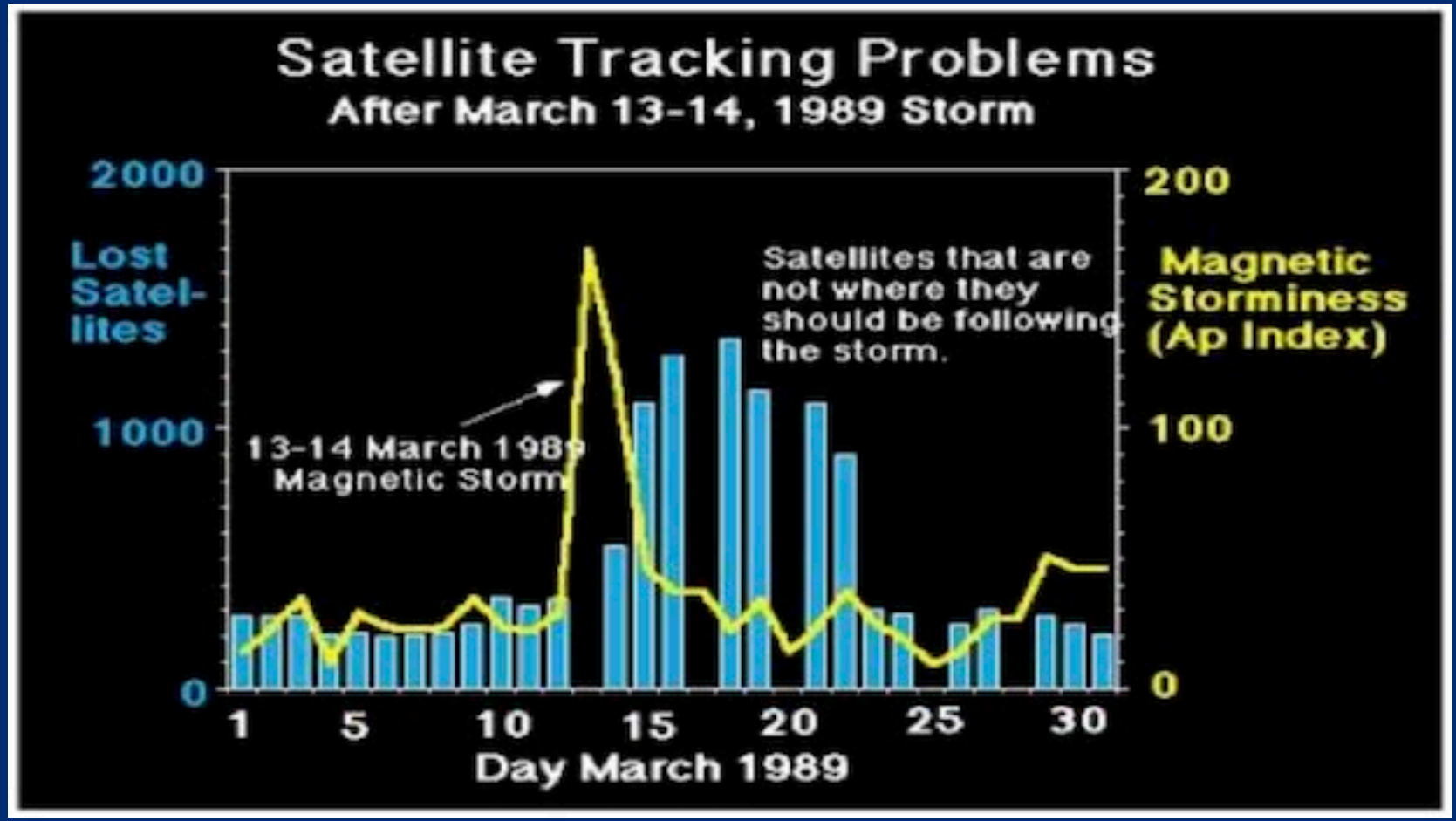
Fundamental Open Questions Impact Predictions

- *Priority Science Goal 3: Quantitatively, What Is the Relative Significance of Competing Physical Processes That Govern the ITM State and Its Variability?*
  - *1. Quantify the relative roles of preconditioning and seeding mechanisms in controlling the emergence and evolution of ionospheric irregularities.*
  - *2. Quantify the relative significance of competing drivers of day-to-day variability in the ITM system.*
  - *3. Quantify the most salient factors governing the global ITM response during and following geomagnetic activity.*
  - *4. Quantify the origin of interhemispheric asymmetries in geospace and their effects on the ITM system.*



Making Observations of the Earth from the Moon Makes Sense

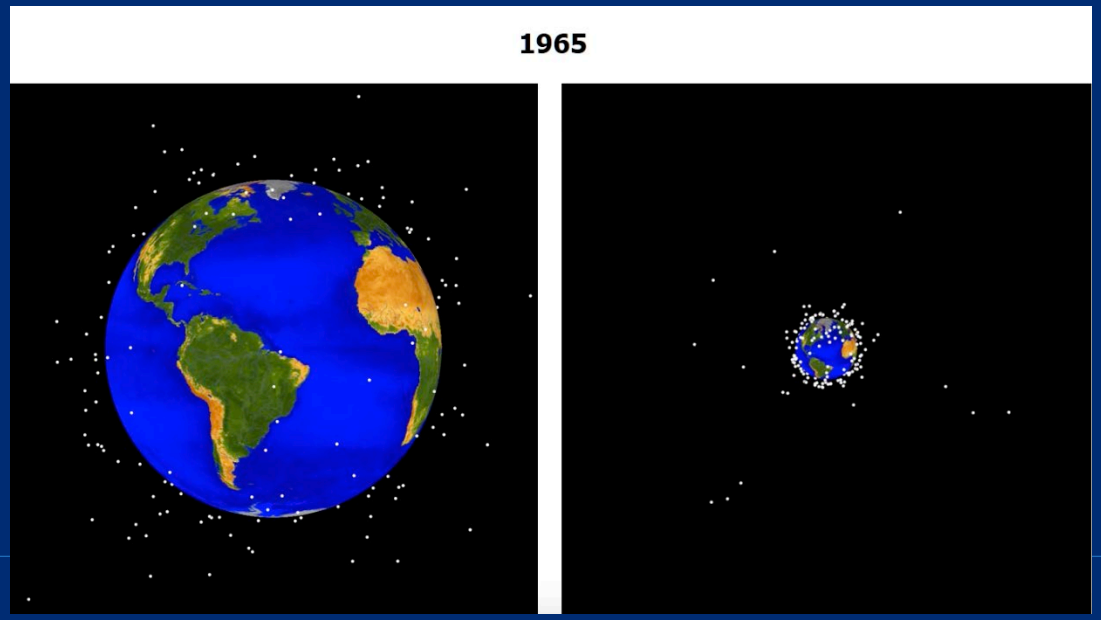
- Once we choose to go to the Moon, we gain a unique and invaluable vantage point for studying the Earth's upper atmosphere.
- The Earth's upper atmosphere (above 130 km) is where the major impacts of space weather are evident.
  - Space weather is generated by the interaction of the solar wind with the magnetosphere and the injection of energy into the auroral zone
- Space weather is called out in the 2024 Helio Decadal.

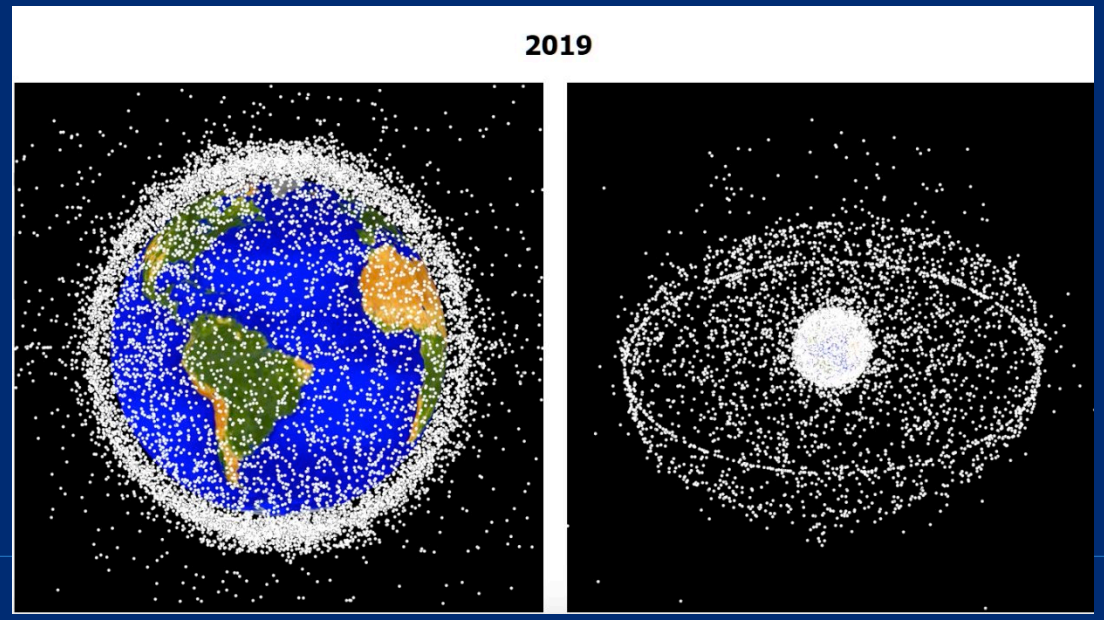


https://www.swpc.noaa.gov/impacts/satellite-drag

By returning to the Moon we can make an enduring contribution to the outward journey

- The lunar surface (and cislunar space) provides a unique and valuable perspective
- We've been there before but the world has move on in the last half century
- By 2035, there are projected to be 60,000 to 100,000 satellites
- World Economic Forum estimates ~$2Trillion space economy



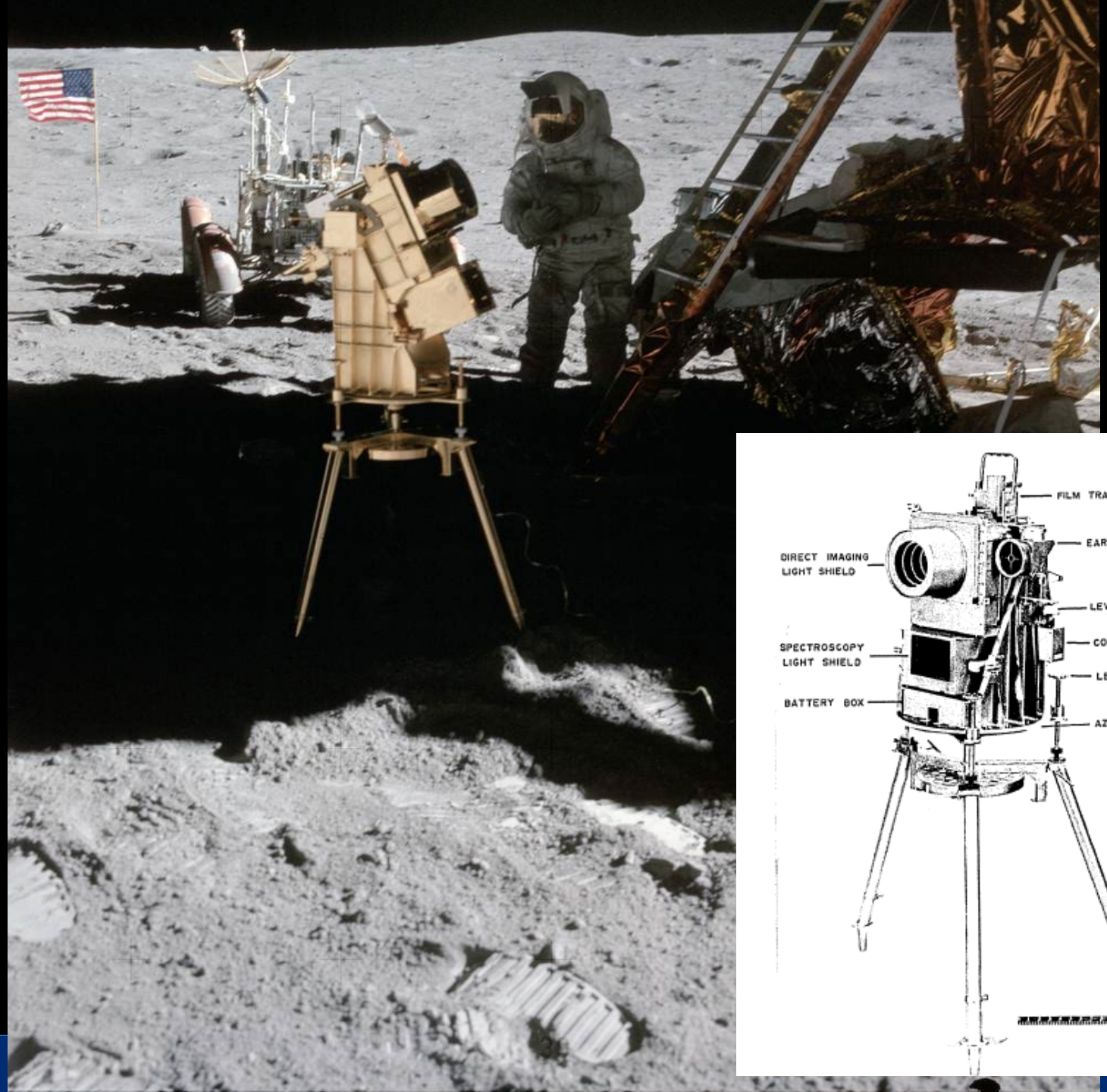


- At the observatory site, local midnight allov us to observe the illuminate Earth disk.
- At local noon the Sun may within the instrument keepout zone
- We would be able to obser the Earth ove all Earth Loca Solar Times.



In April 1972 Apollo astronaut John Young made observations from the Moon of the Earth and other celestial targets.
This was an FUV imager – collecting light from 115nm to 180nm to form an image.
The electrographic camera used film that was developed when they returned to Earth.

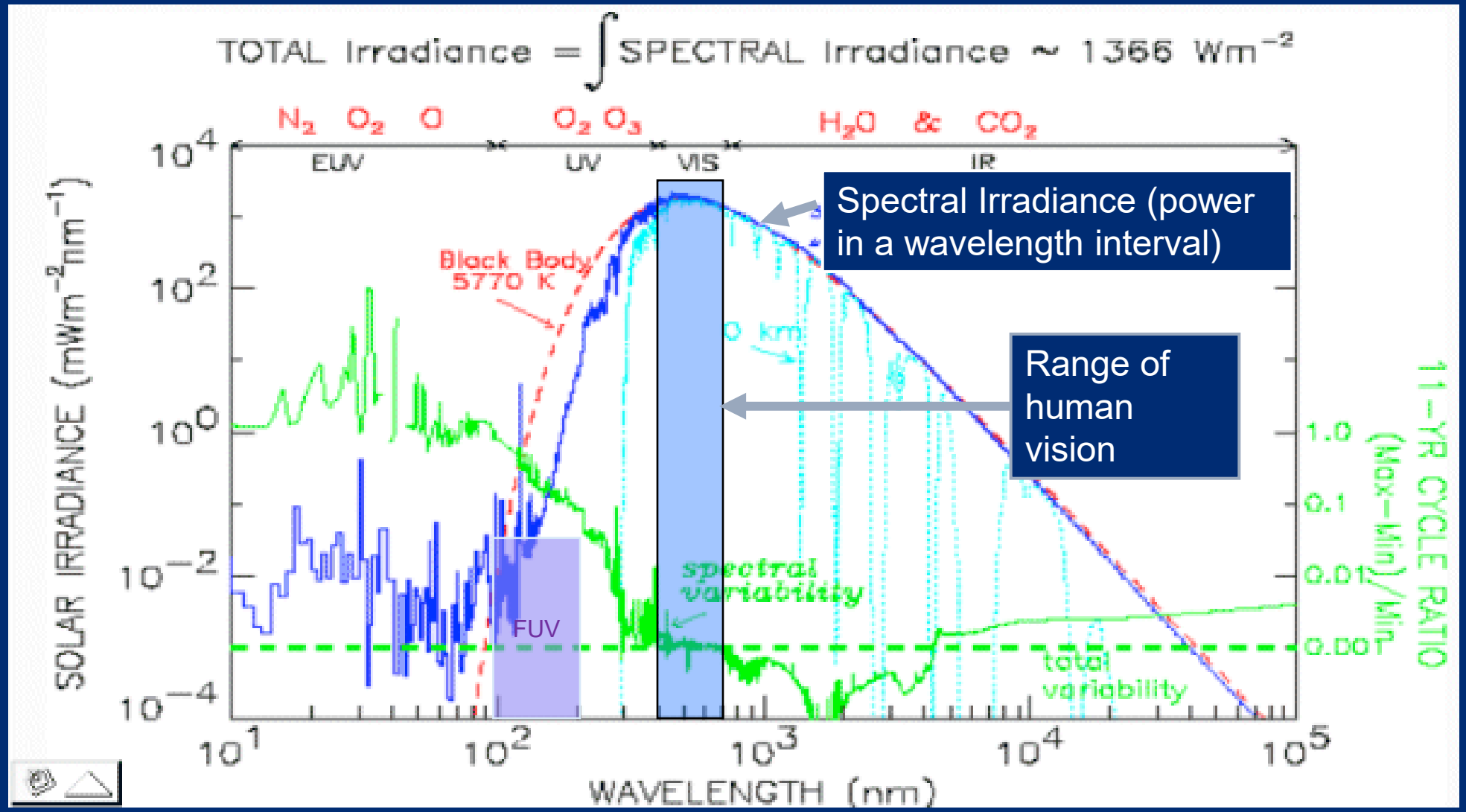
https://www.nasa.gov/history/remembering-the-first-moon-based-telescope/



Dr. George Carruthers, right, and William Conway, a project manager at the Naval Research Institute, examine the gold-plated ultraviolet camera/spectrograph, the first moon-based observatory that Carruthers developed for the Apollo 16 mission.
U.S. Naval Research Laboratory

Consider this an existence proof – it can be done.

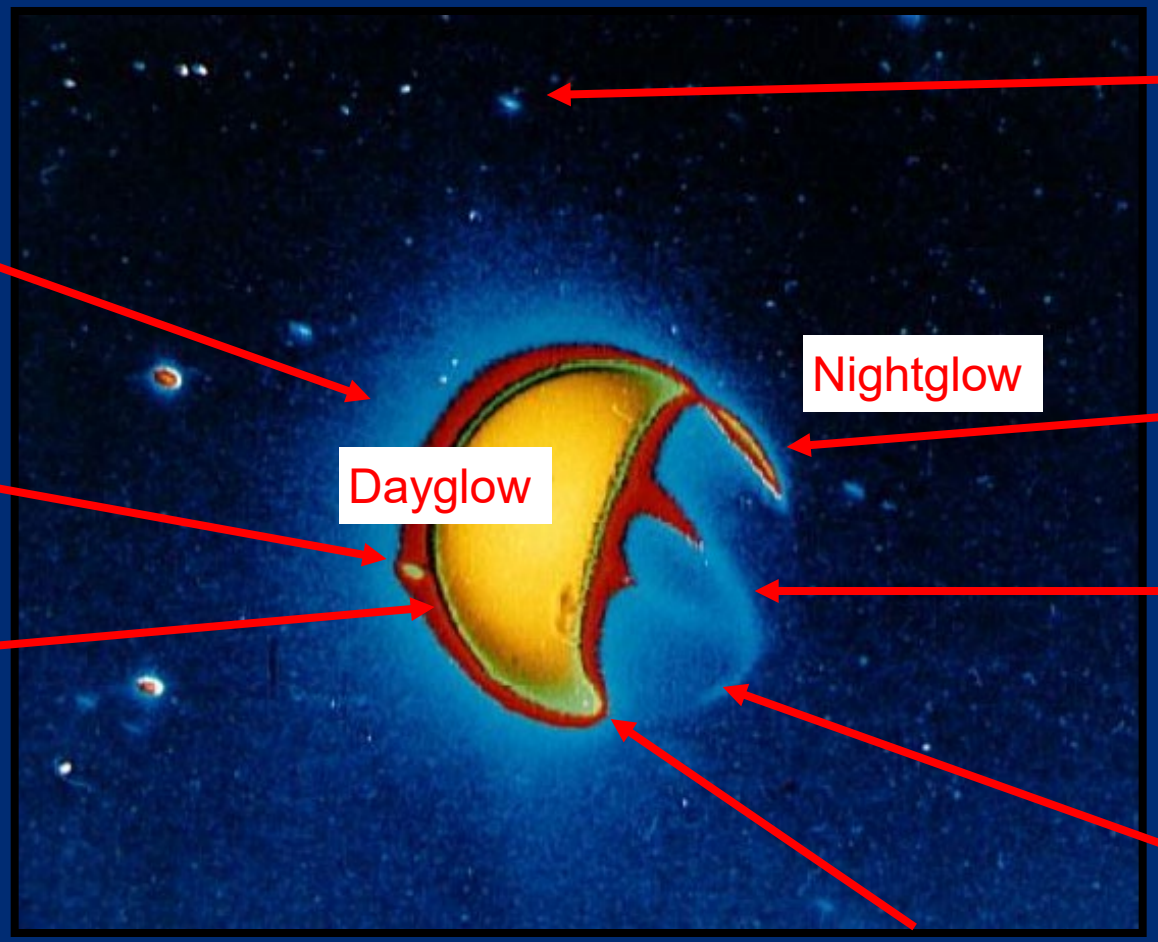




This image, courtesy of Dr. Judith Lean at the US Naval Research Laboratory, shows the spectrum of solar radiation from 10 to 100,000 nm (dark blue), its variability between Solar Maximum and Solar Minimum (green) and the relative transparency of Earth's atmosphere at sea level (light blue). At wavelengths shorter than about 300 nm, there is a relatively large variation in the Sun's extreme UV and x-ray output (greater than 1%), but the Earth's atmosphere is nearly opaque at those wavelengths.

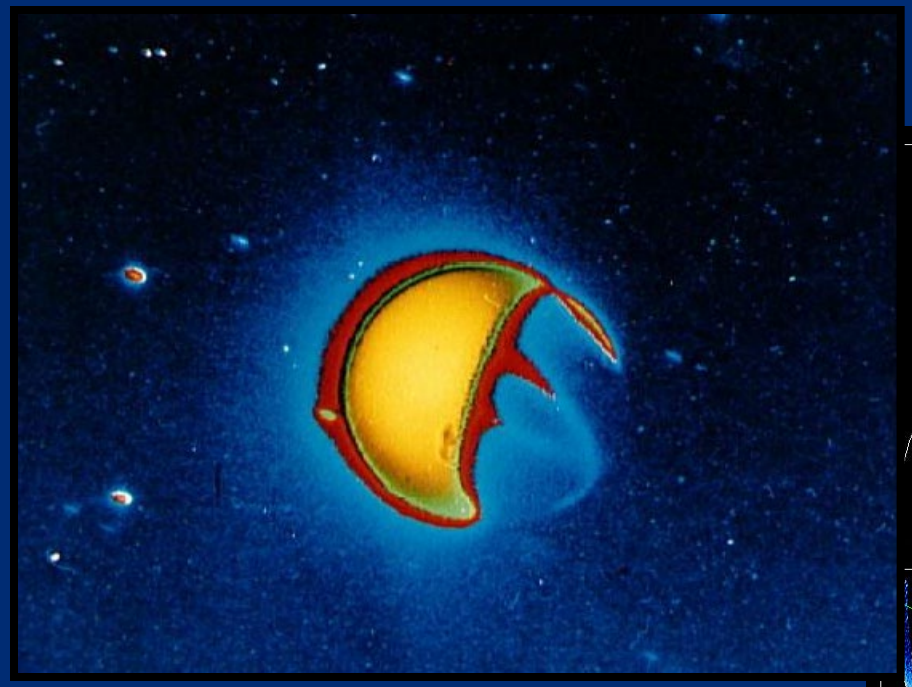
Image from NASA Science | Science News

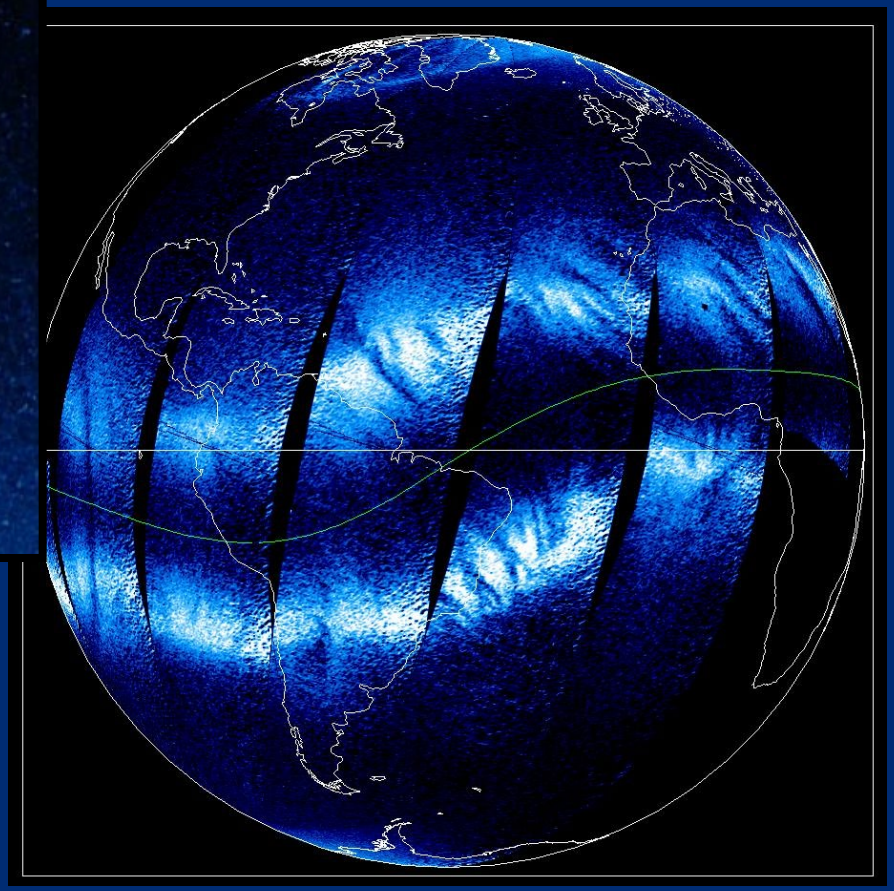
The Earth in the FUV: The Object of this Talk



First FUV image of the Earth- taken from the Moon by the Apollo 16 crew
Carruthers and Page, 1972

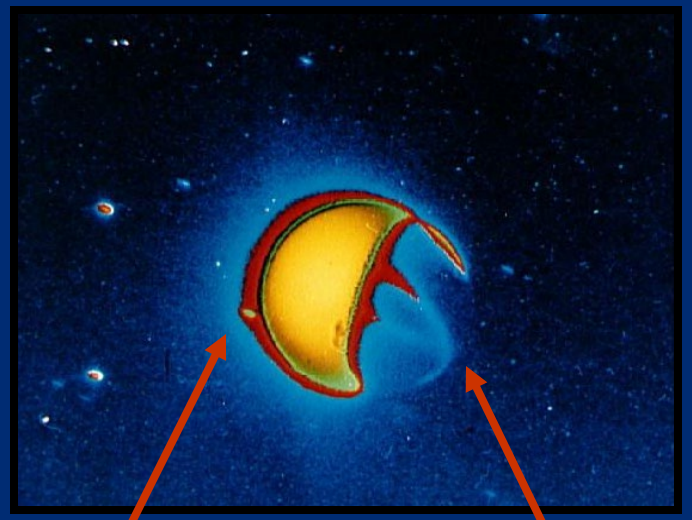
A Simultaneous, Global Picture of the Ionosphere at High Spatial Resolution is Needed





Ionospheric irregularities that affect RF communications.
Each pixel has a 25km resolution – the ionospheric bubbles imaged here have length scales of 100s to 1000s of km.

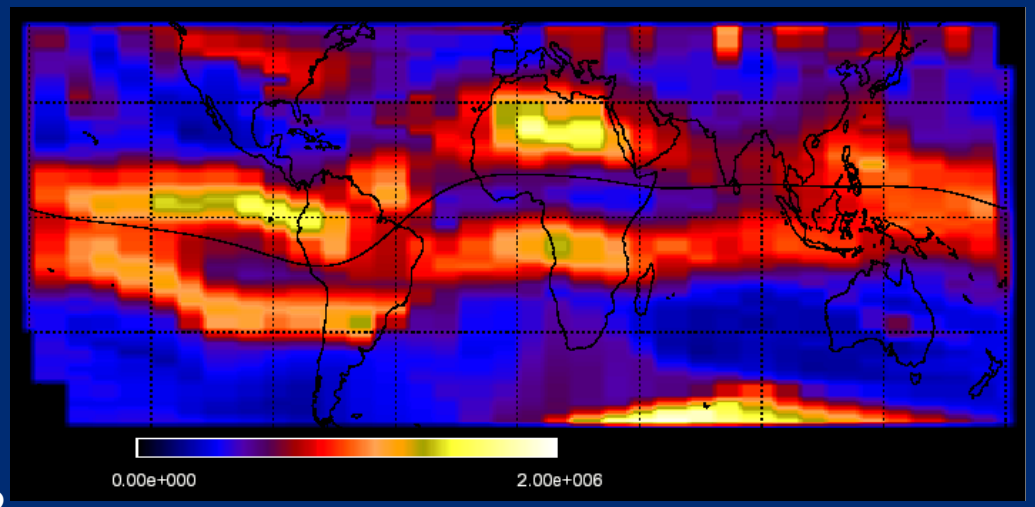
A Continuous Imaging of the Limb Would Enable us to Construct Maps of Ionospheric Key Parameters



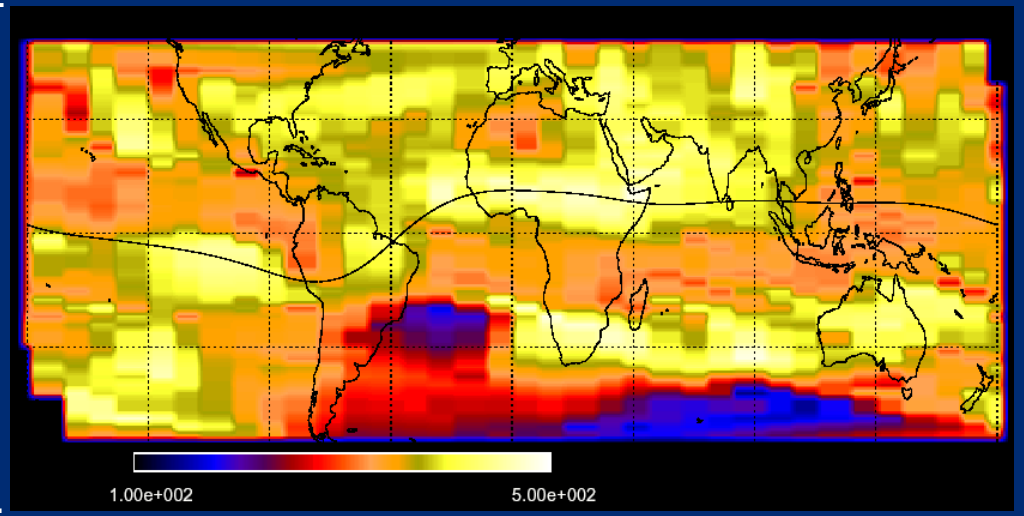
Dayside limb has information about the ionosphere above 300km. The dayside signature is the combination of the dayglow and the ionospheric signature.

The nightside limb is readily converted into ionospheric products.

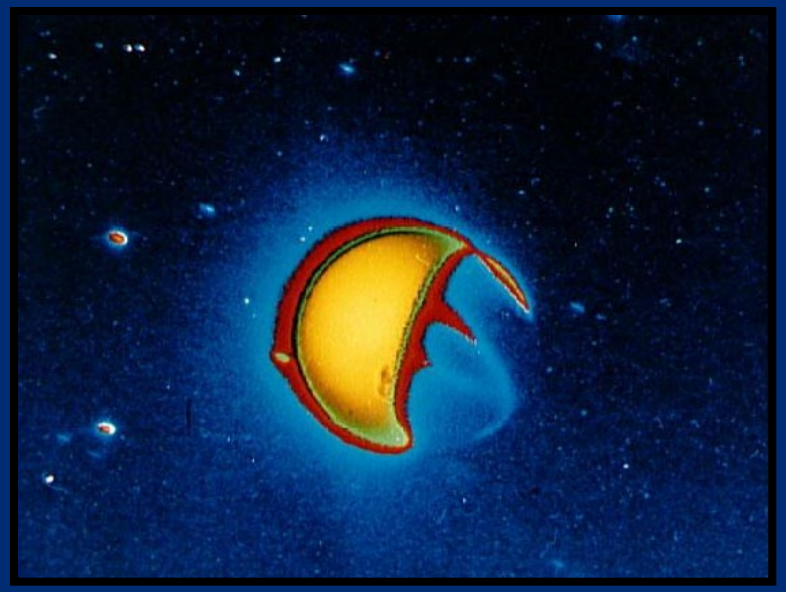
NmF2

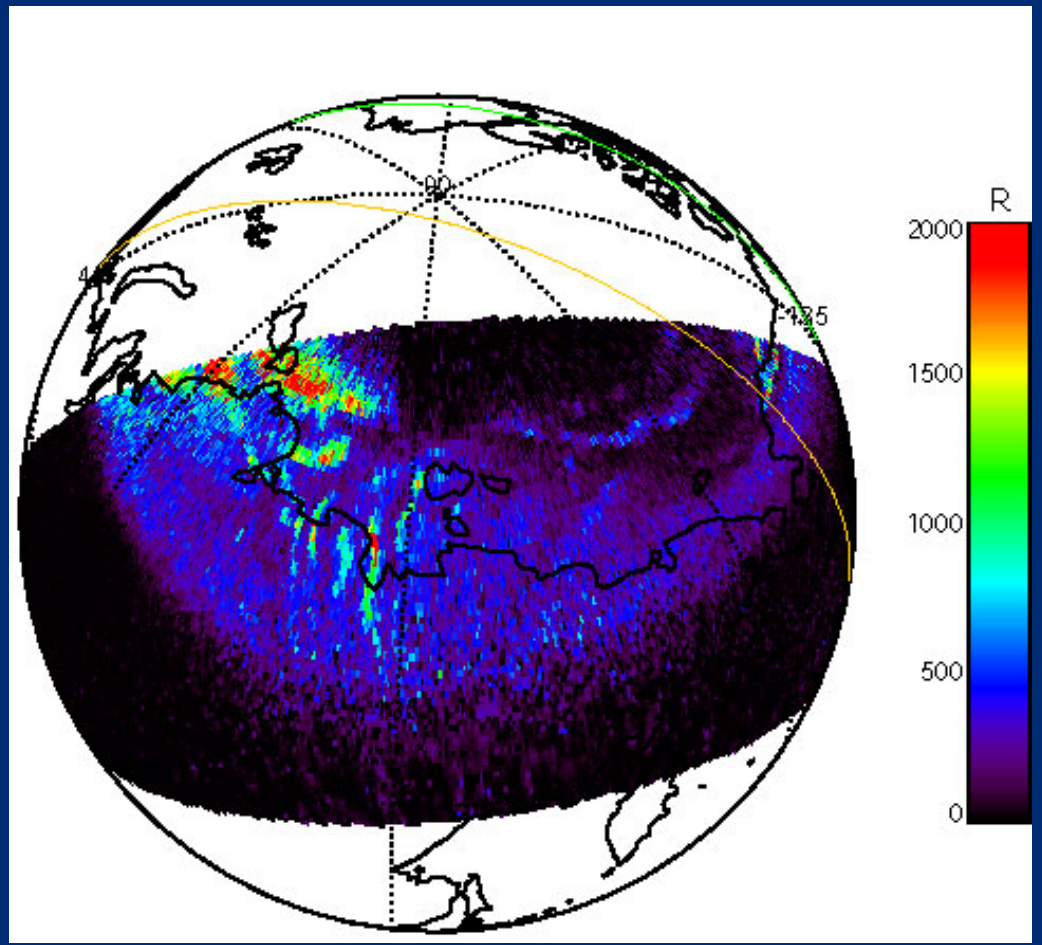


HmF2



Auroral Imagery from the Moon Would Enhance our Understanding of the High Latitude Inputs that Drive the I/T and Couple it to Geospace

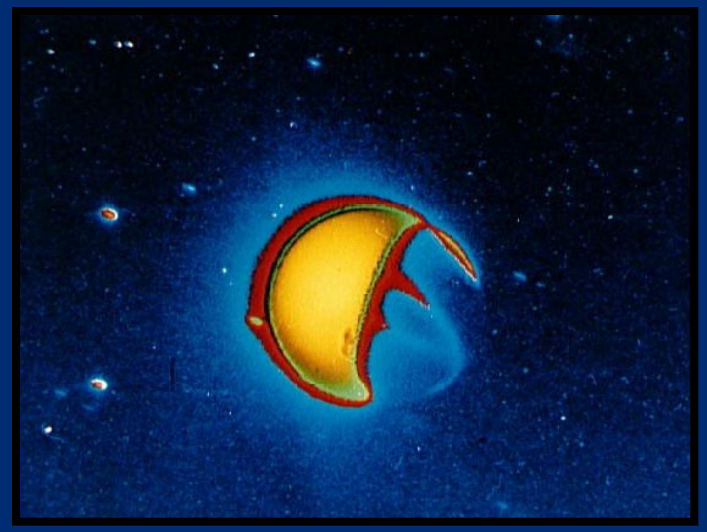


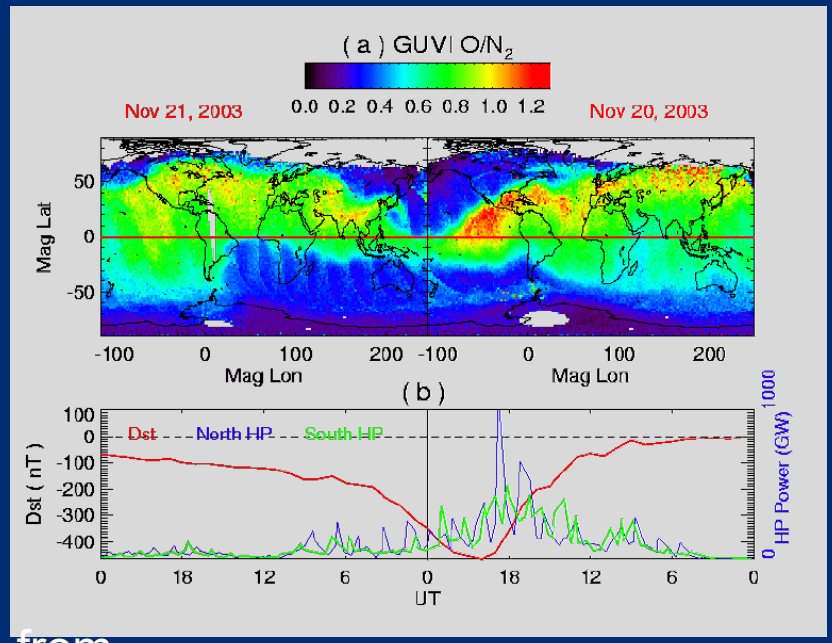


Even from a lunar perspective we can image the aurora continuously and at high spatial resolution.

Energy deposited at high latitudes causes changes in the neutral and ion density that propagate toward the equator and alter the global circulation pattern of the upper atmosphere.

Imaging the Dayside will Provide us a Unique Opportunity to Study the Coupling of the Upper Atmosphere to the Geospace Environment





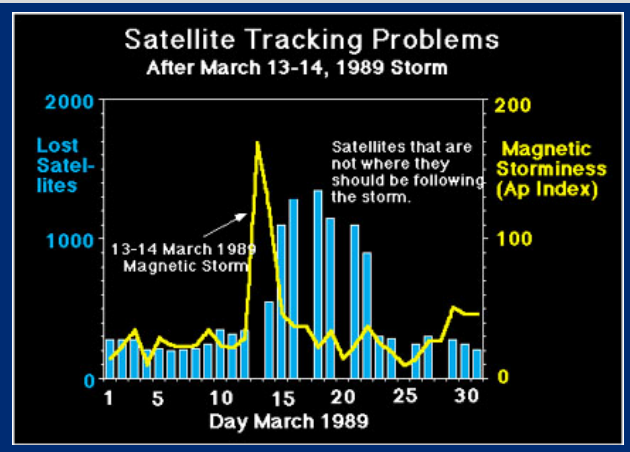
We see that during a geomagnetic storm composition changes propagate equatorward from the poles.

Why is the response asymmetric?

How does it vary as a function of local solar time?

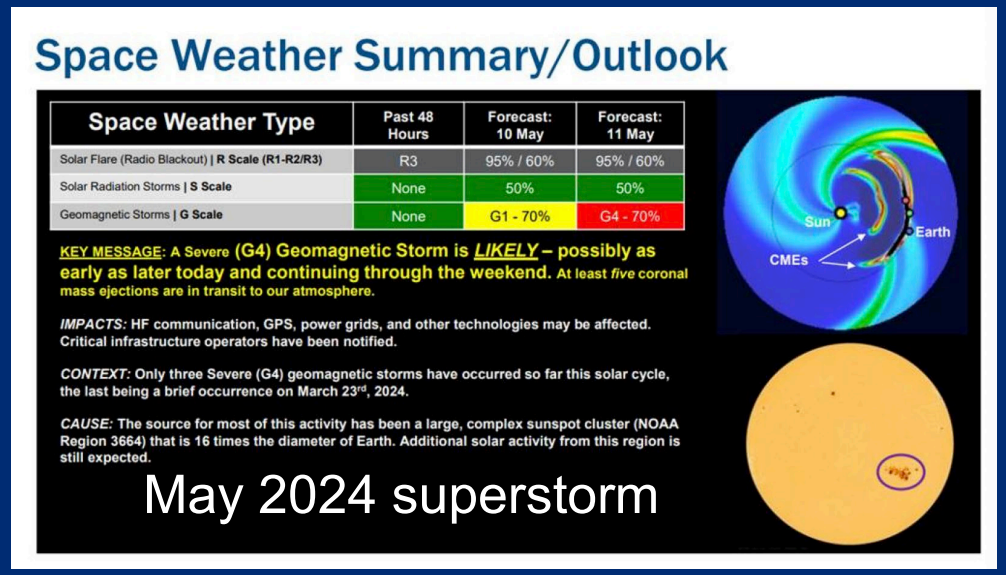
Why can't our models reproduce the behavior (what are we missing)?

What is the effect of changes in atmospheric composition on orbit propagation products?

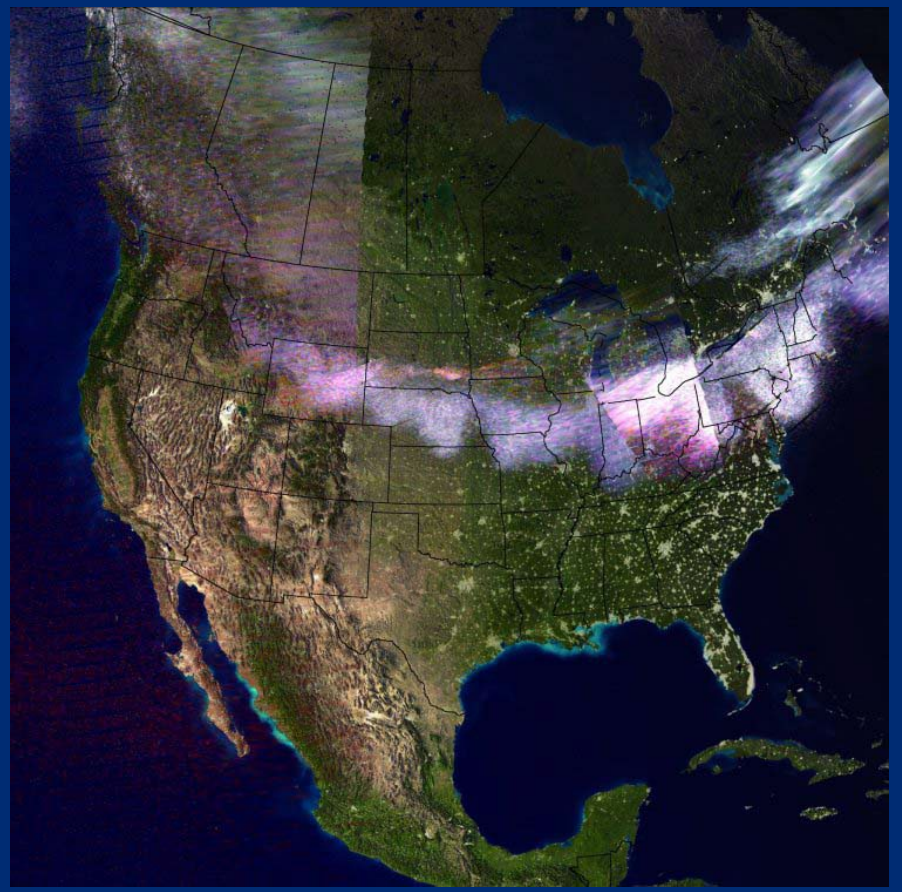


The 2024 Decadal Emphasized Space Weather impacts

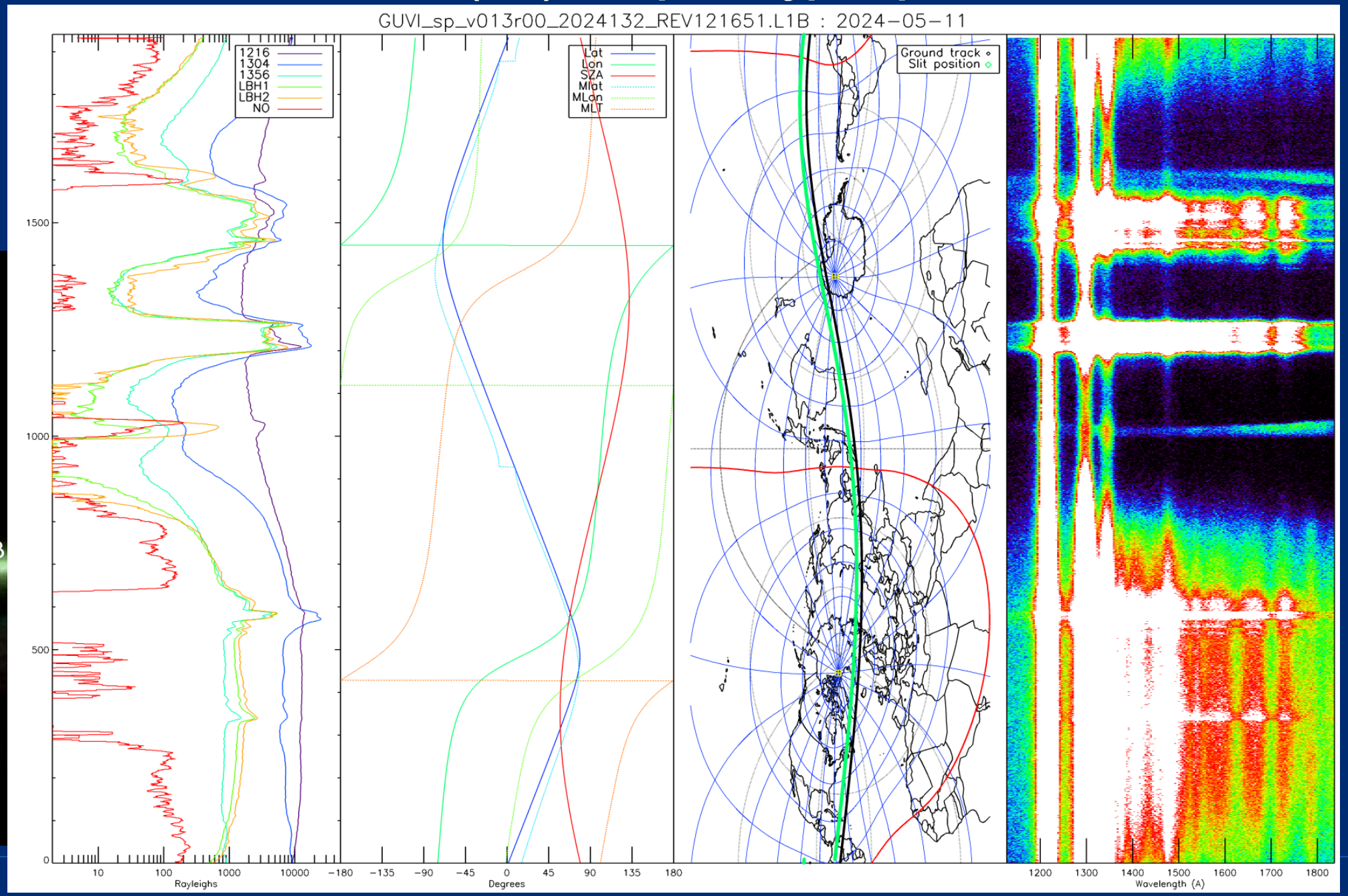
- During geomagnetic storms, the aurora can extend equatorward.
- Currents can be induced in conductors on the surface.



May 2024 superstorm



We can build small(ish) compact hyperspectral sensors

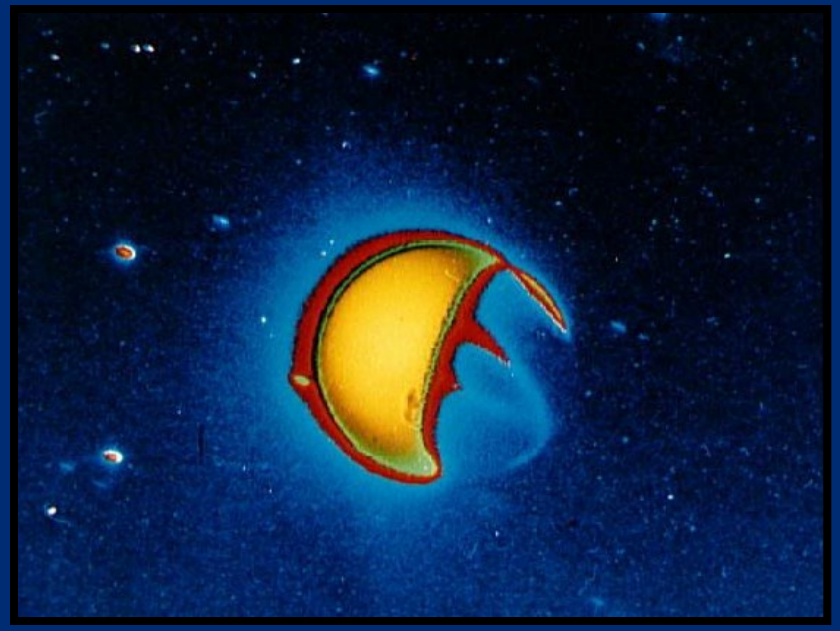


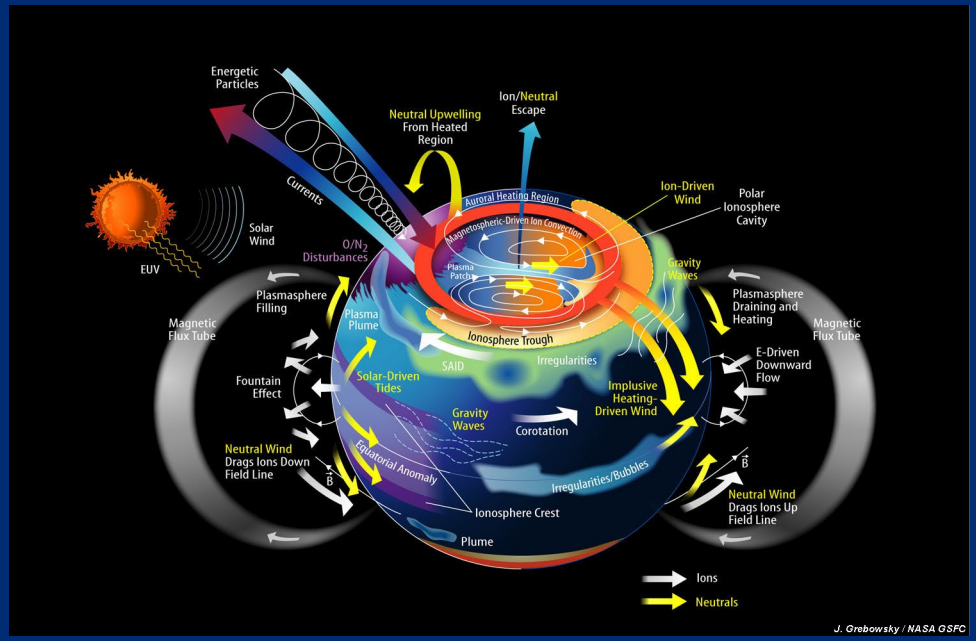
An FUV Hyperspectral Imager can Provide Information that Sets the Scene for Groundbased and Spacecraft-based Observations

- Hyperspectral sensors are spectrographs that image along the slit.
- A scan mirror is used to provide the second spatial dimension – this produces an image cube - 2D spatial and 1D spectral

	HI (121.6 nm)	OI (130.4 nm)	OI (135.6 nm)	N_2 (LBHs)	Nitric Oxide	N_2 (LBHI)
AURORAL ZONE (Disk)	• Region of proton precipita-tion • H precipita tion Doppler shift	Auroral Boundary and amount of column O_2 present[1] O outflow O Doppler shift	Region of electron and (possibly) proton precipitation O outflow O Doppler shift	• Used with LBHI to form Eo and the ionization rate and conductance information • Hemispheric power • Radar clutter • Charging	NO production	Measure of the effective precipitating flux, used with LBHI to form Eo and the ionization rate and conductance information
AURORAL ZONE (Limb)	H profile	O outflow	O outflow	N_2 outflow	NO outflow	N_2 outflow
DAYSIDE LIMB	H profiles and escape rate[1]	Amount of O_2 absorption[1]	O altitude profile	Amount of O_2 as seen in absorption	NO profile	N_2, Temperature
DAYSIDE DISK	Column H	Amount of O_2 absorption[1]	Used with LBHs to form O/N_2	N_2, Solar EUV	NO column density	Solar EUV
NIGHTSIDE LIMB	H profile and escape rate	• Ion/ENA precipitation	• EDP • HmF2 • NmF2 • T_{plasma}	• Ion/ENA precipitation characteristic energy		• Ion/ENA precipitation characteristic energy
NIGHTSIDE DISK	Geocorna and Ion/ENA precipitation	Ion/ENA precipitation	• TEC • Ion/ENA precipitation	Ion/ENA precipitation		Ion/ENA precipitation

We've Talked About Many of The Processes in the Coupled IT System and How UV Remote Sensing Can Be Used to Inform Our Exploration of Geospace





FUV remote sensing is a tool that has evolved over the last 50 years.

We have the tools and means in place to address the fundamental processes that shape the ionosphere-thermosphere (I/T) system and connect the I/T to the rest of geospace and the lower atmosphere.

There are other sensors that could provide remote sensing of the Earth that complement this picture but some design work needs to be done.

FUV Imaging from the Moon is the Ideal Starting Point for Proving the Value of a Lunar Observatory

- FUV hyperspectral images from the Moon map to 2024 (and 2013) Decadal Survey science questions.
- FUV hyperspectral images from the Moon also map to 2024 Decadal space weather drivers.
- The instruments can be readily designed for the lunar environment – and past performance indicates that they can be used for science as well as operational support.
  - See papers by Paxton et al. on GUVI and SSUSI
- The initial infrastructure requirement can be “zero”.
  - We can do good and important things with a “suitcase science” approach.
- As more infrastructure becomes available the scalable architecture for Earth observations can take advantage of this.
  - Key issues for a more capable system will be data delivery to Earth and continual operations.
  - Larger aperture provides higher spatial resolution (for a given SNR).
  - Increasing the number of colors imaged improves the products – this may be accomplished by a more complex design.



JOHNS HOPKINS

APPLIED PHYSICS LABORATORY