ASEN-5519-007,008

Space Weather Overview:

The Thermosphere and Satellite Drag

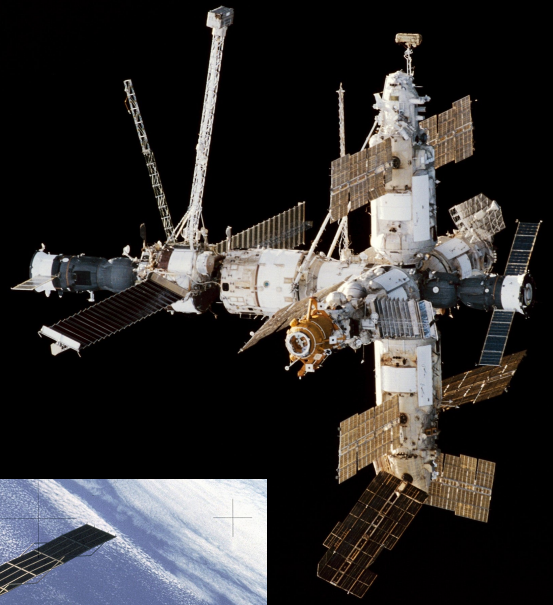
Eric Sutton

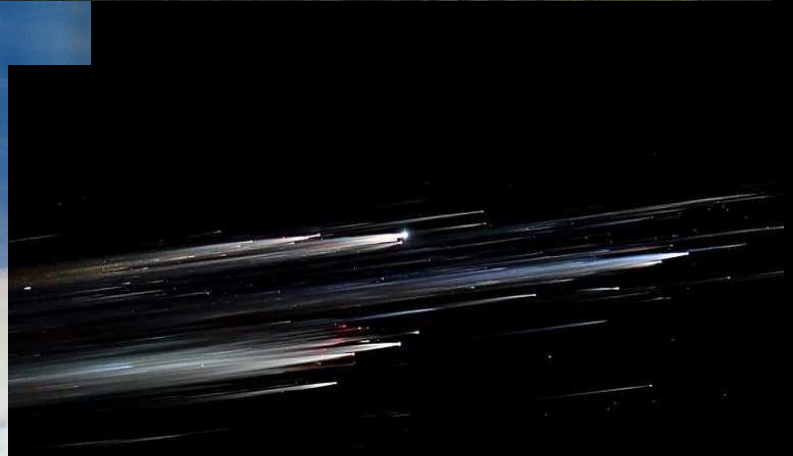
Wednesday, March 22nd, 2023

Outline

- Societal Relevance
- The Upper Atmosphere
- Satellite / Atmosphere Interactions
- Measurements of Satellite Drag
- Early and Recent Discoveries

Reentry





Operating in LEO

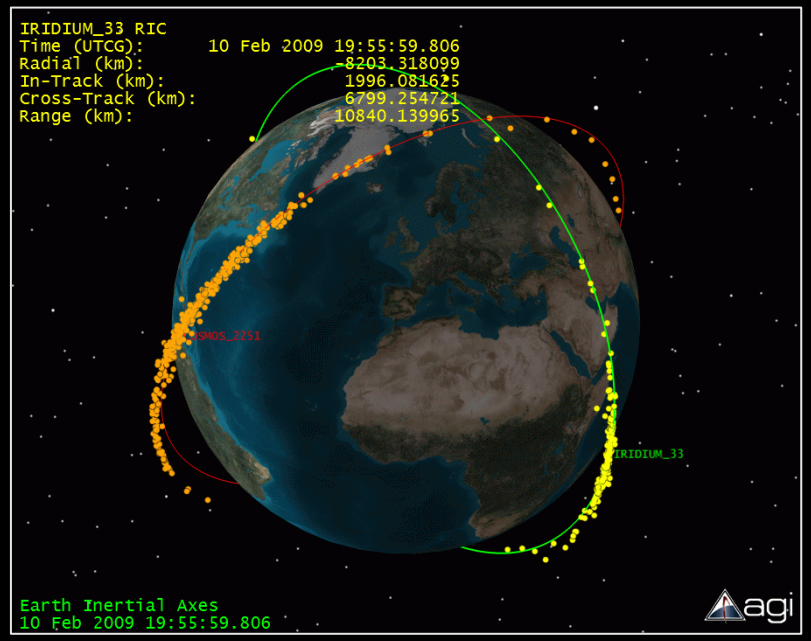
SPACEX

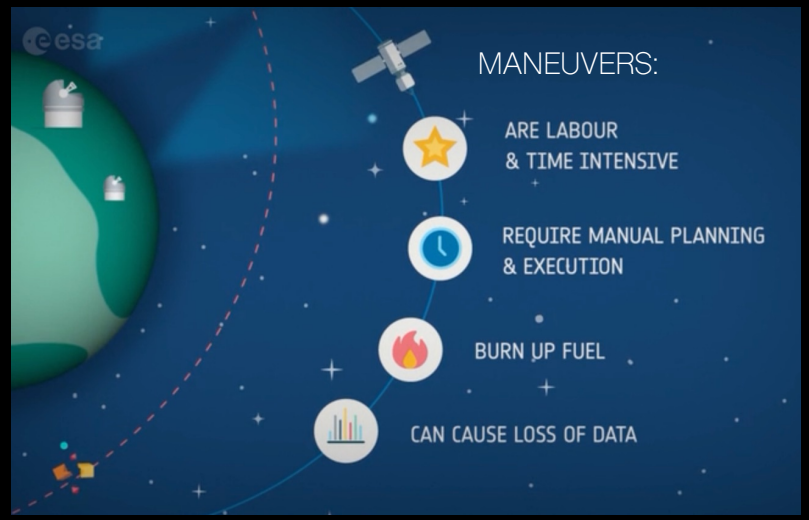
FEBRUARY 8, 2022

GEOMAGNETIC STORM AND RECENTLY DEPLOYED STARLINK SATELLITES

Loss of VLEO Assets

Collisions



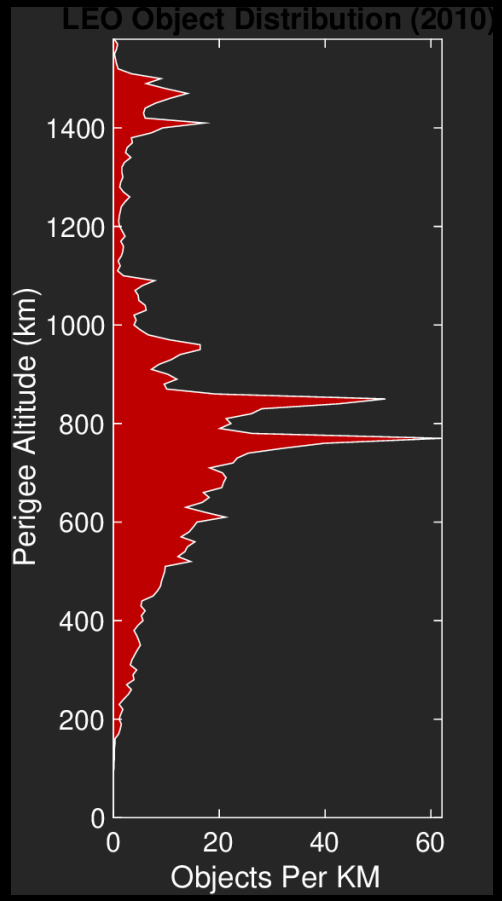


Day-to-Day Conjunction Assessment

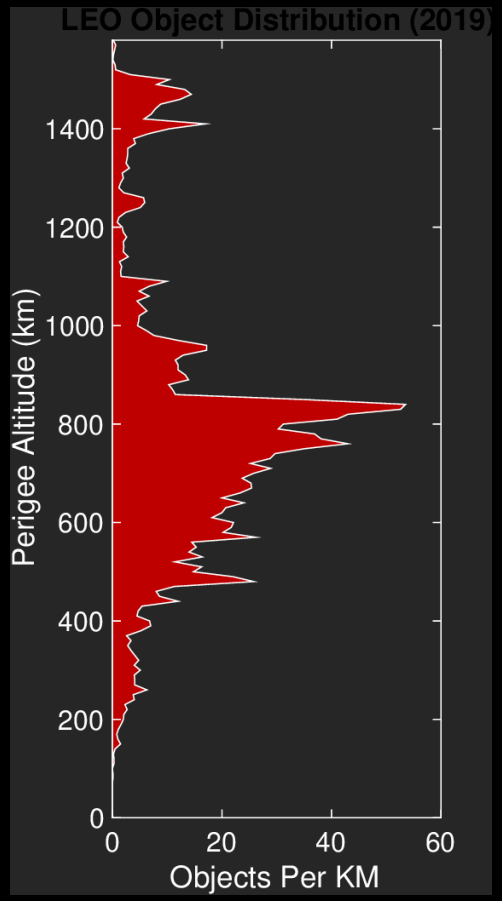
Orbital Crowdedness

LEO Tracked Objects (data from Space-Track.org)

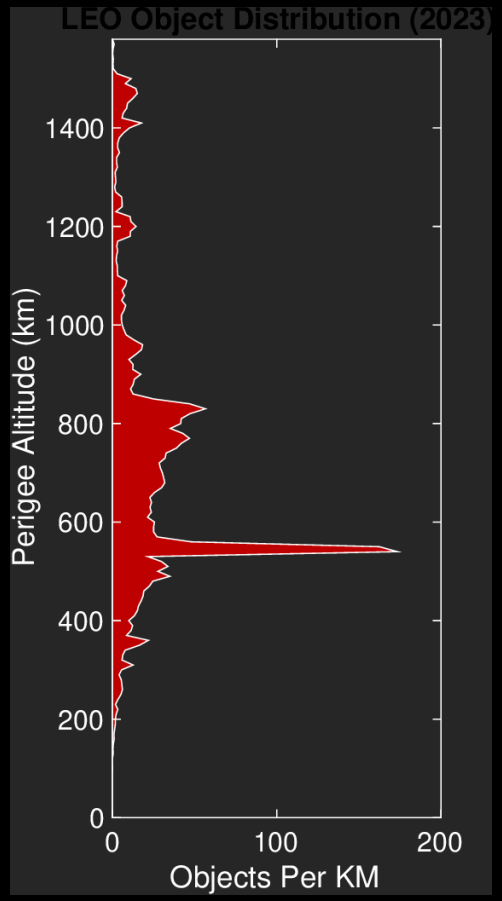
2010



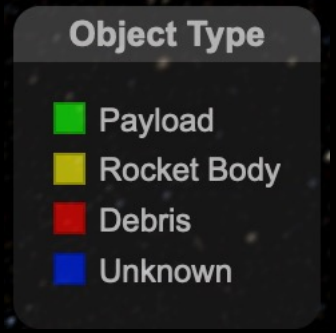
2019

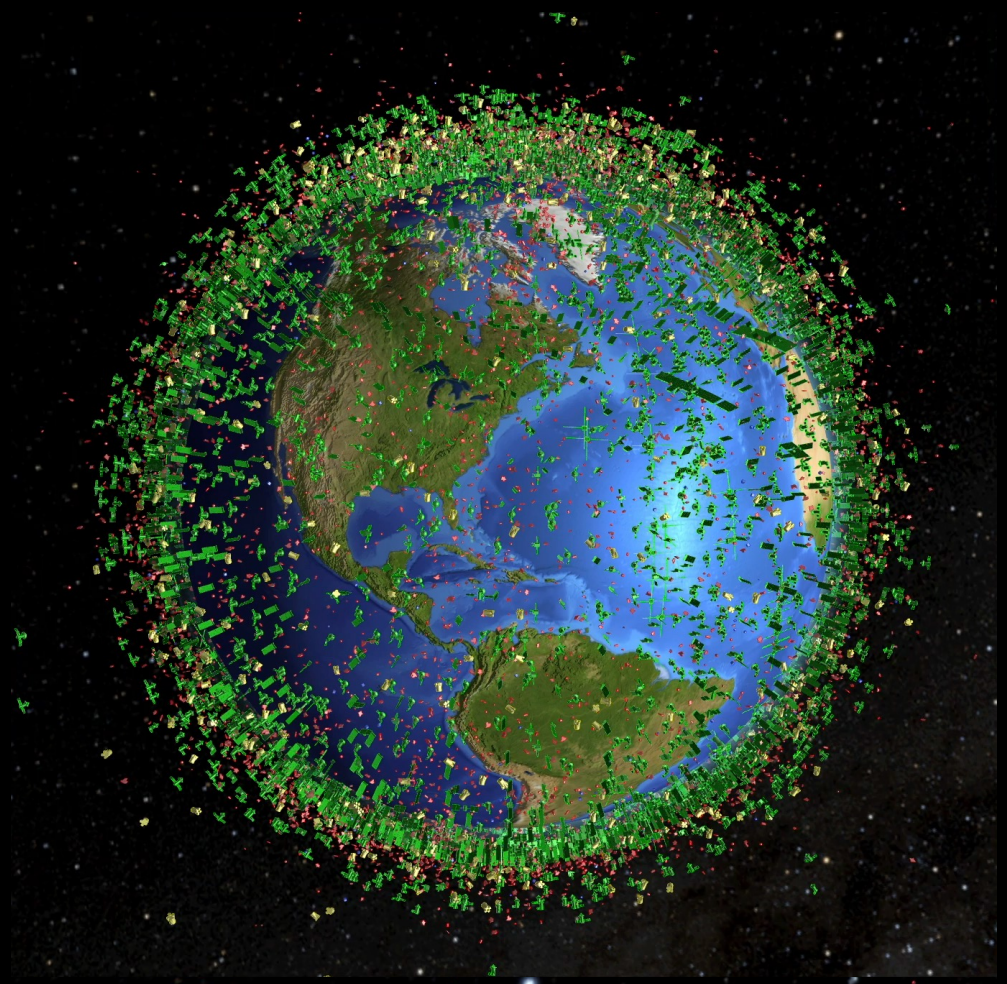


2023



Collisions and the Kepler Syndrome

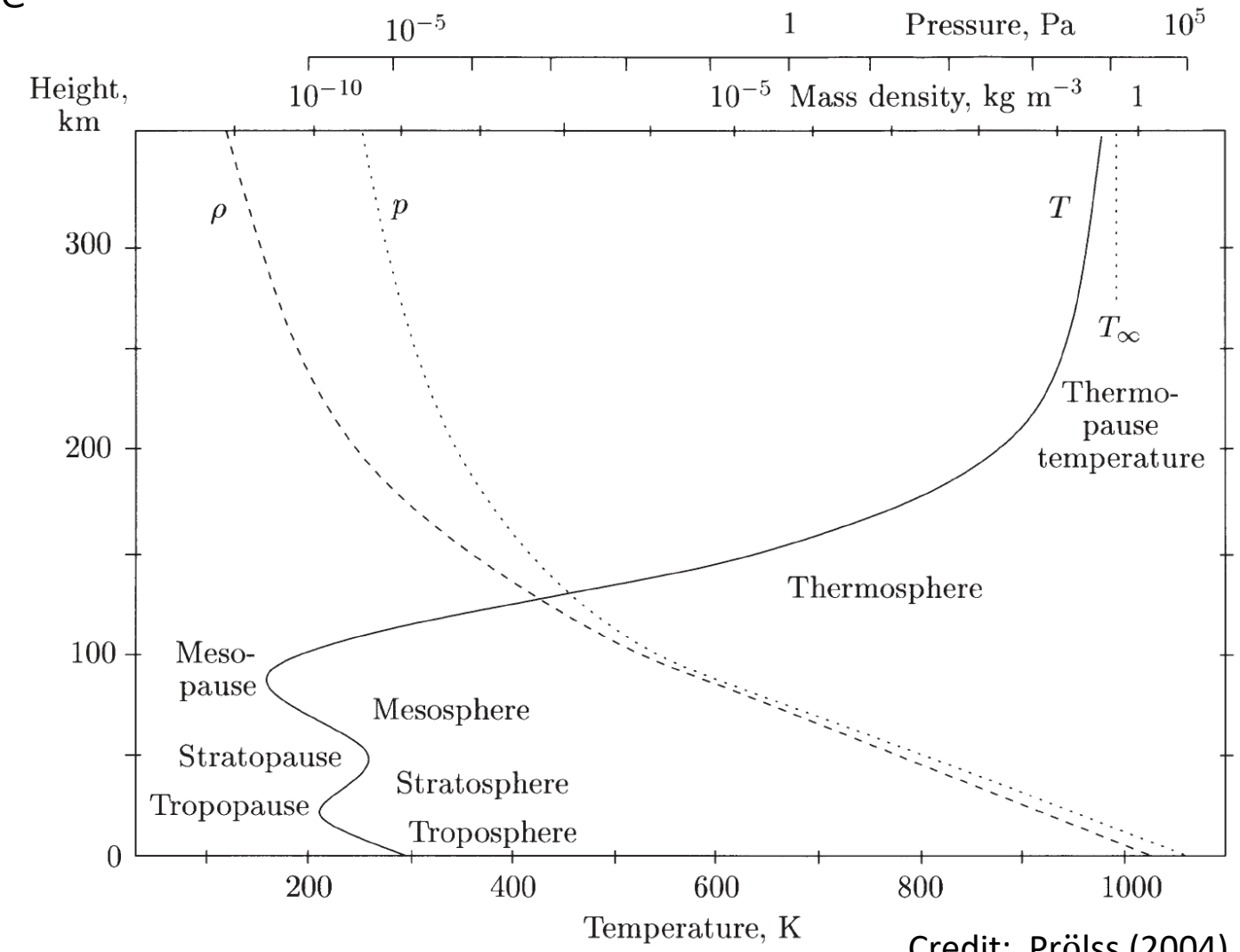




LEO LABS

Atmospheric Layers

By Temperature

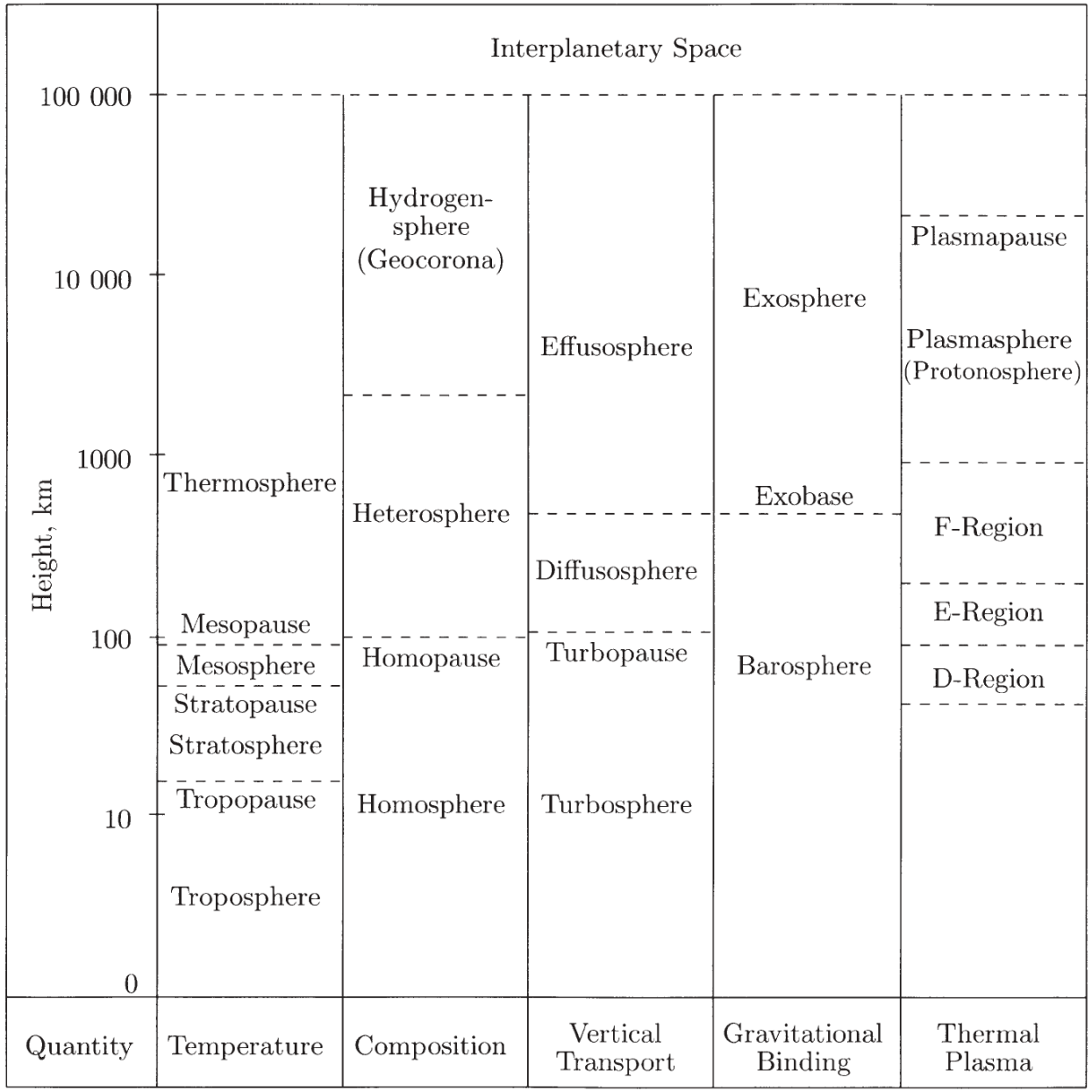


Credit: Prölss (2004)

Physics of the Earth's Space Environment

Atmospheric Layers

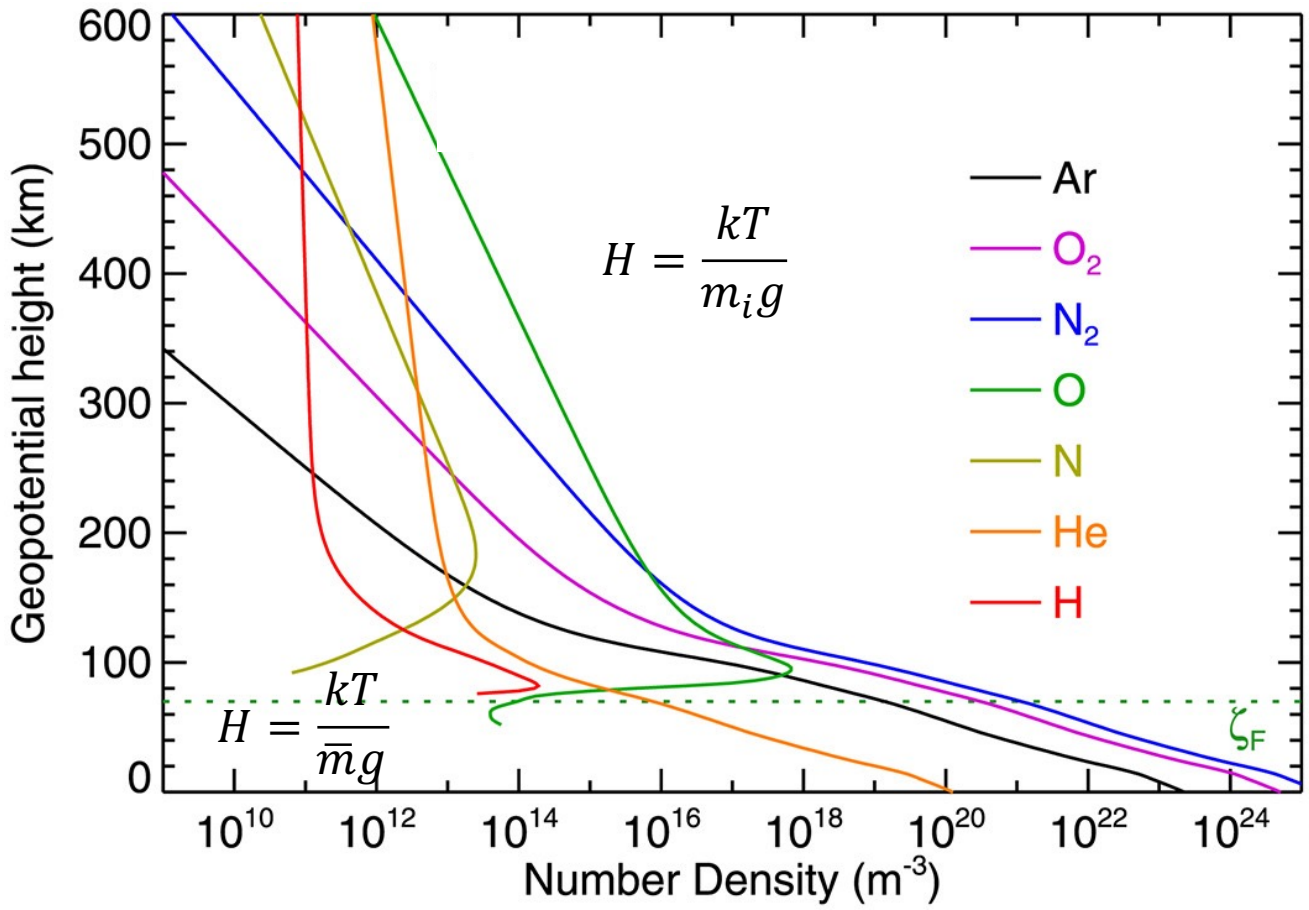
By Various Phenomena



From Prölss (2004)
Physics of the Earth's Space Environment

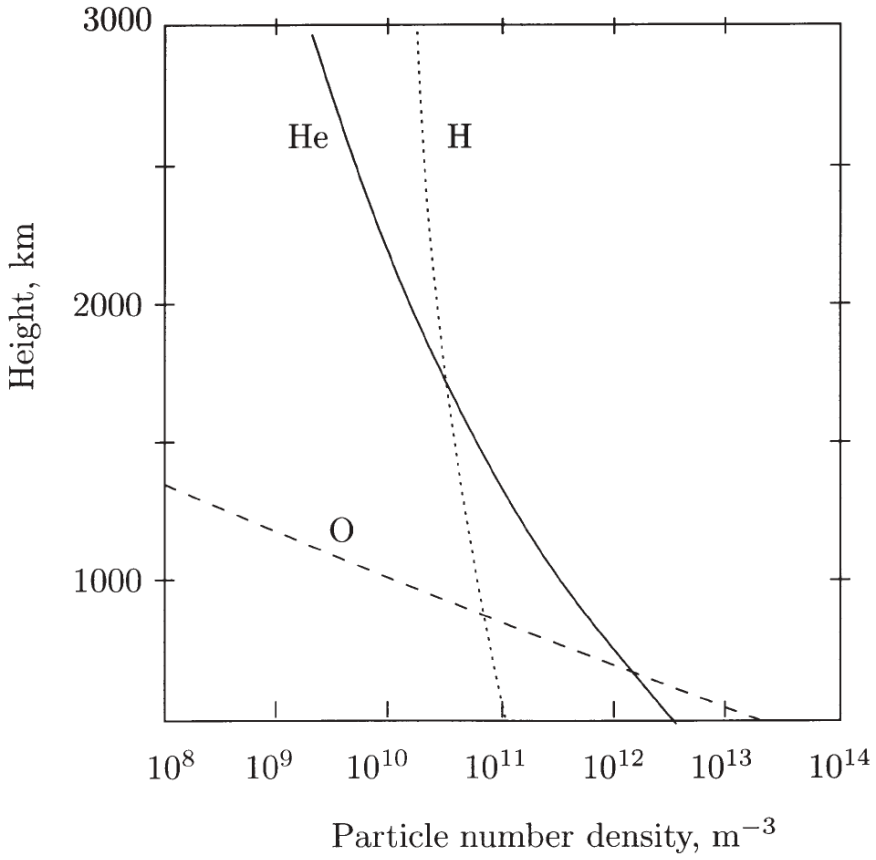
Chemical Makeup

Thermosphere



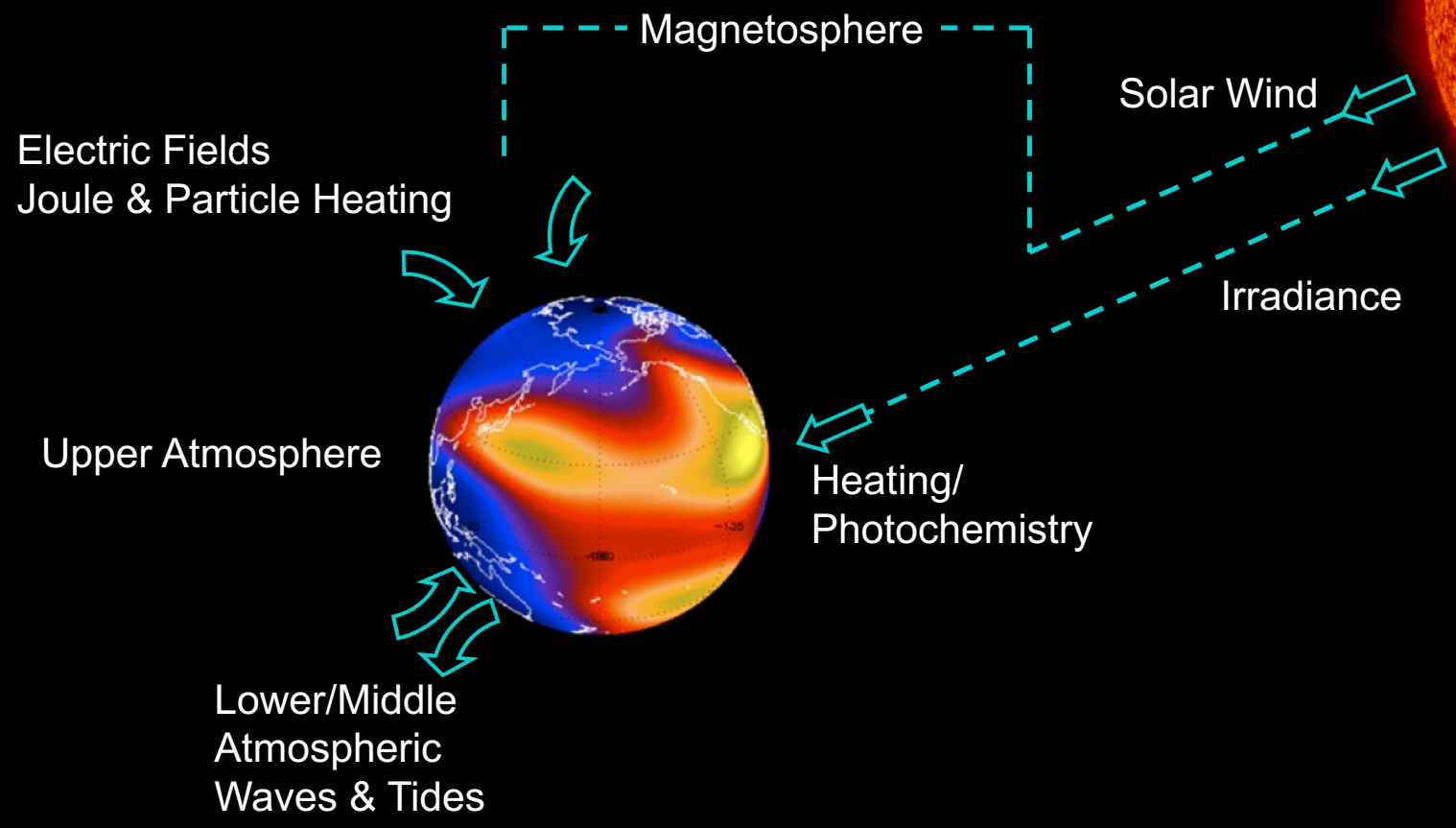
Credit: Emmert et al., 2020

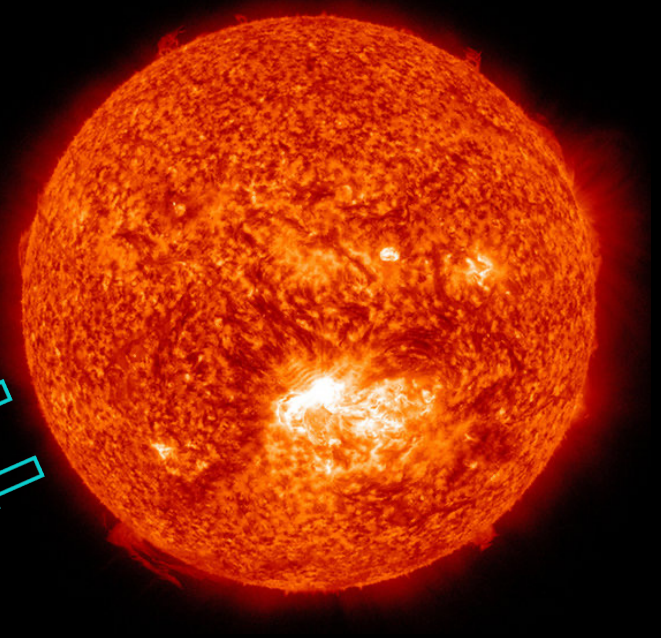
Lower Exosphere



From Prölss (2004)
Physics of the Earth's Space Environment

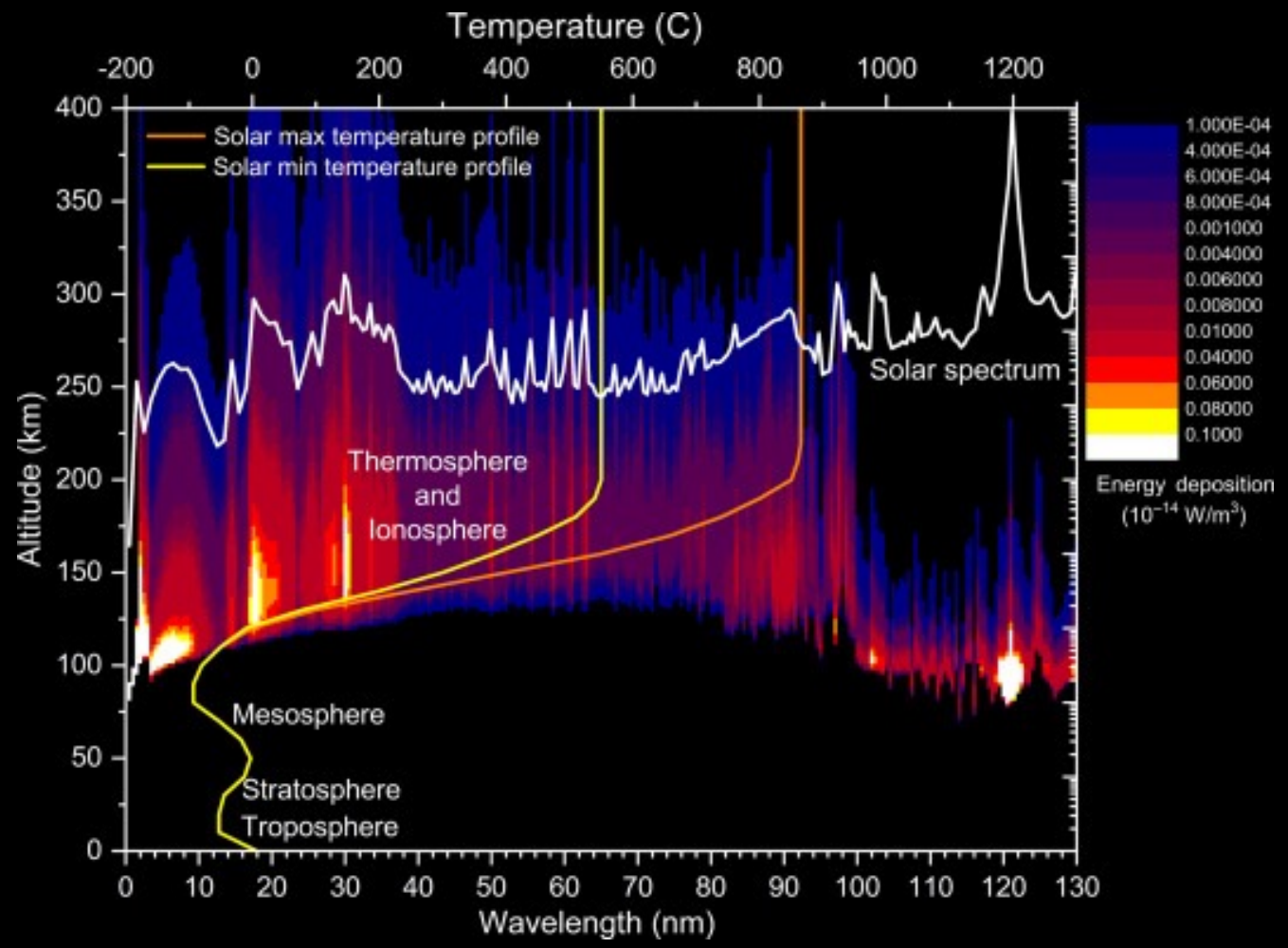
Energy Sources for the I-T





Adapted from Prölss, 2011

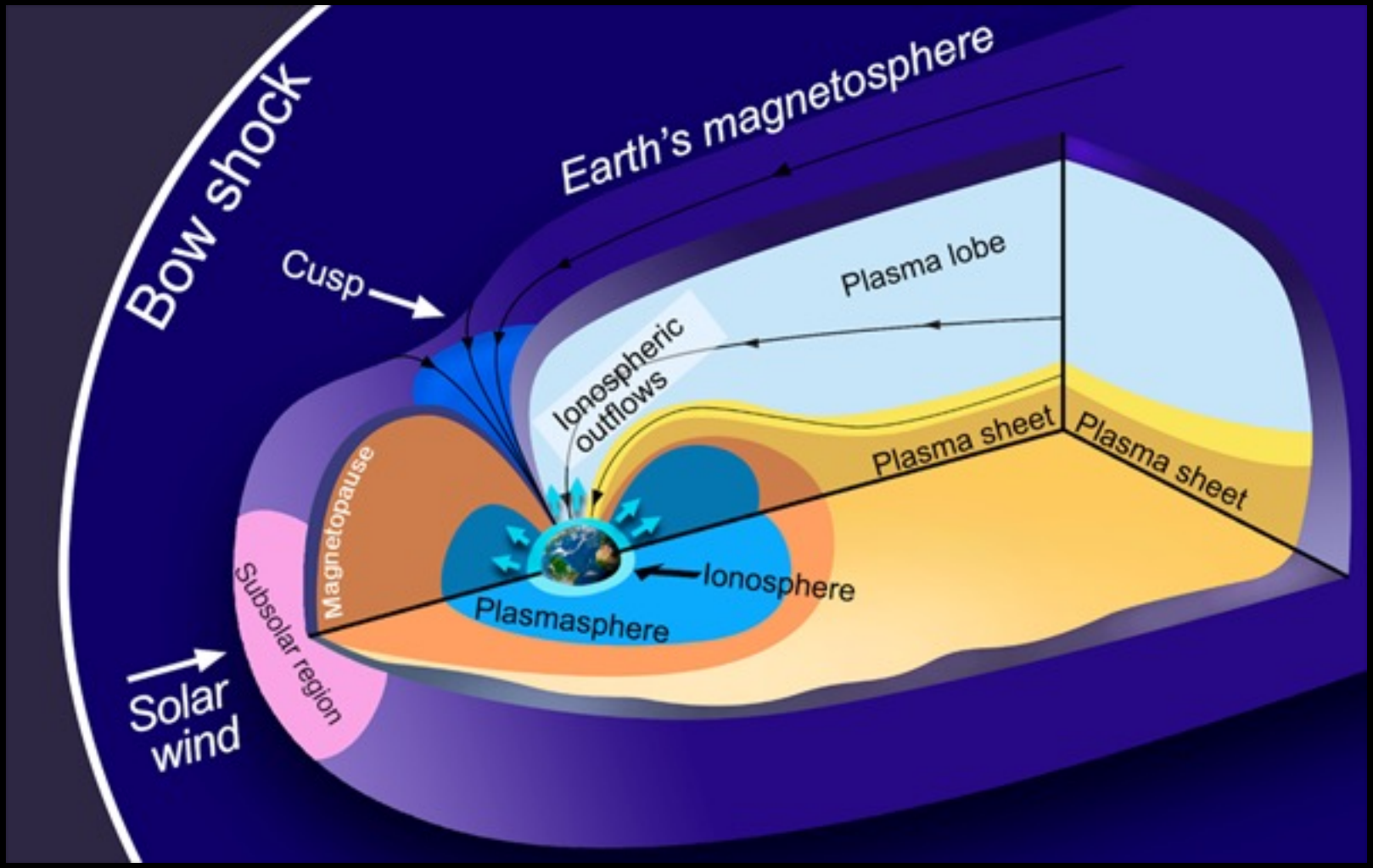
Solar Radiation



Credit: Machol et al., 2020

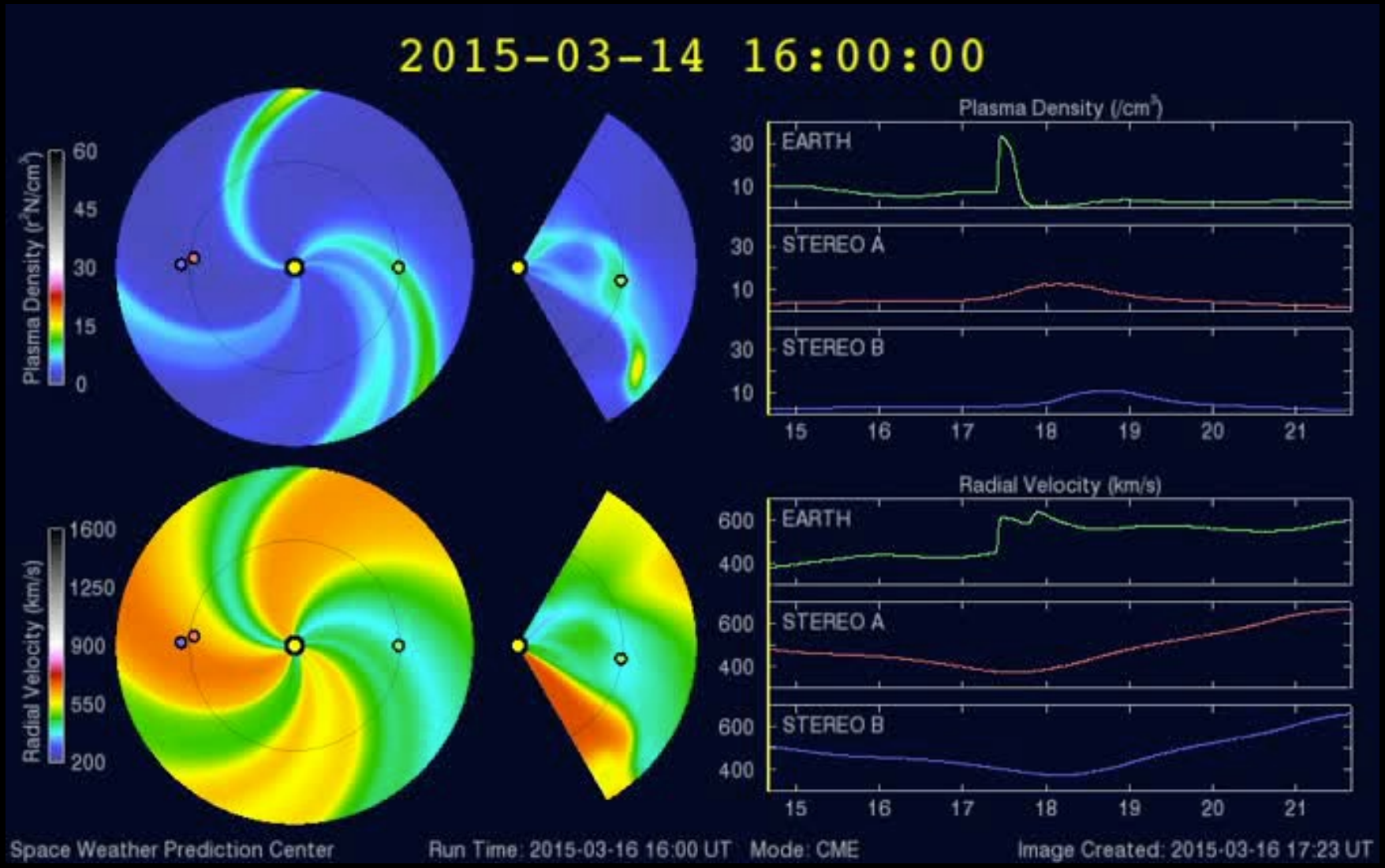
doi: 10.1016/B978-0-12-814327-8.00019-6

Magnetosphere-Ionosphere-Thermosphere System

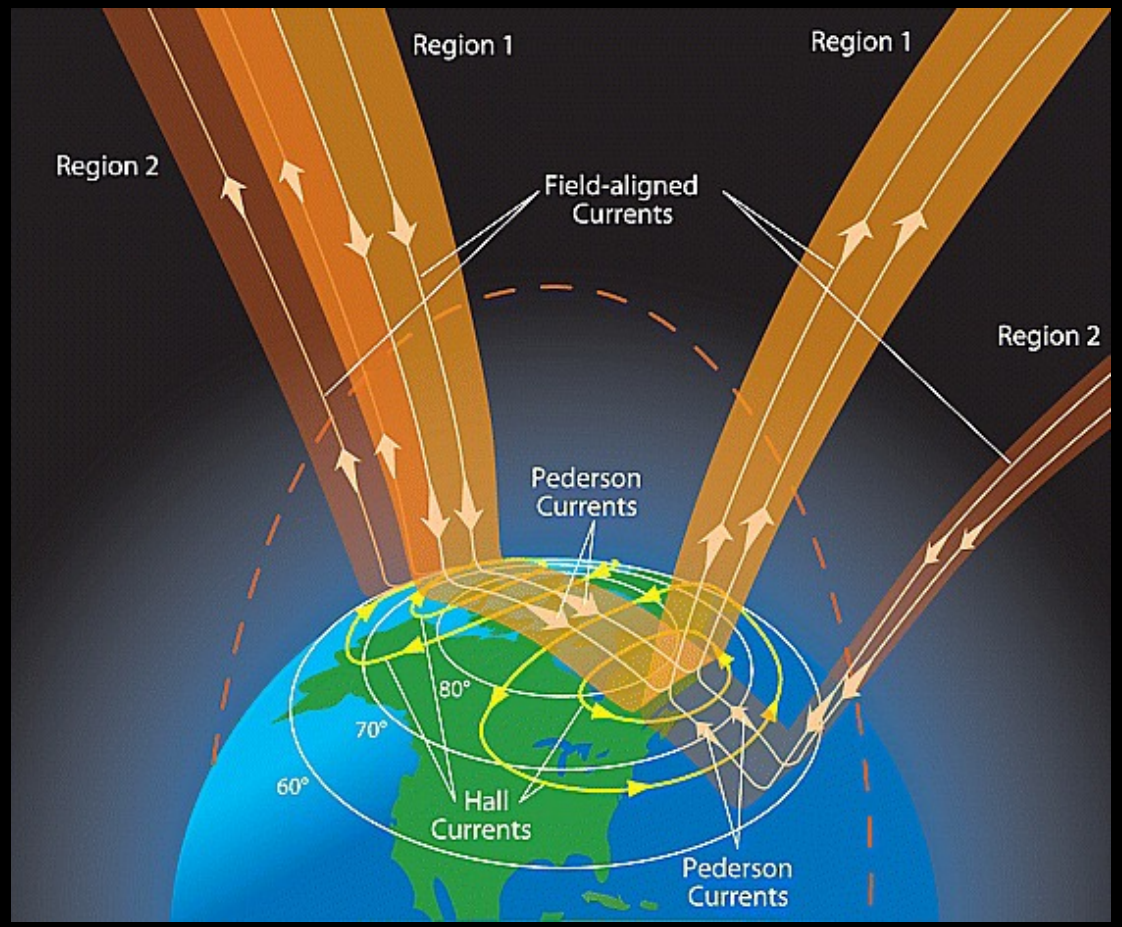


Adapted from Potemra, 1983

Solar Wind and Magnetic Clouds

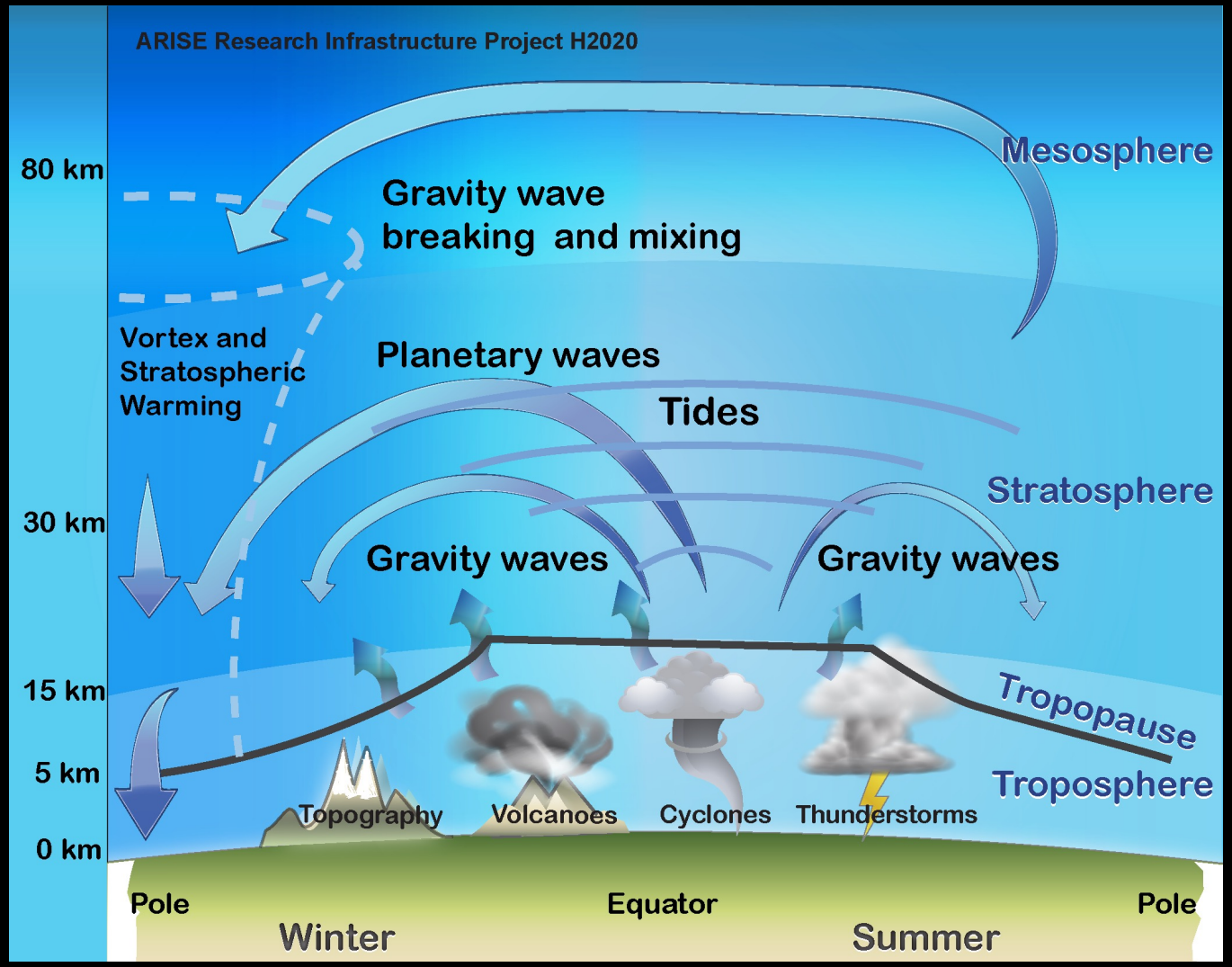


Current Closure in the Ionosphere



Credit: Le et al., 2010. doi: 10.1029/2009JA014979

Waves and Tides



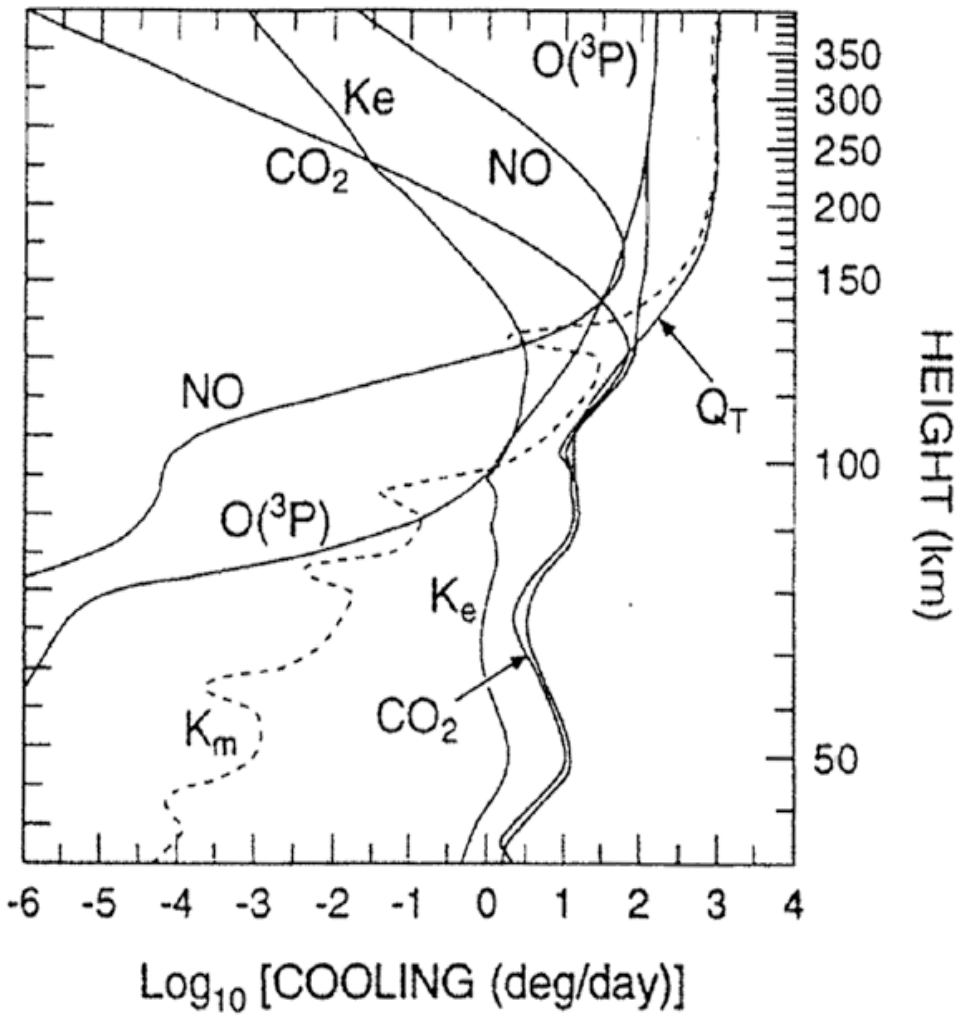
Credit: ARISE Project

Infrared Cooling of the Thermosphere

NO → 5.3 μm

CO_2 → 15 μm

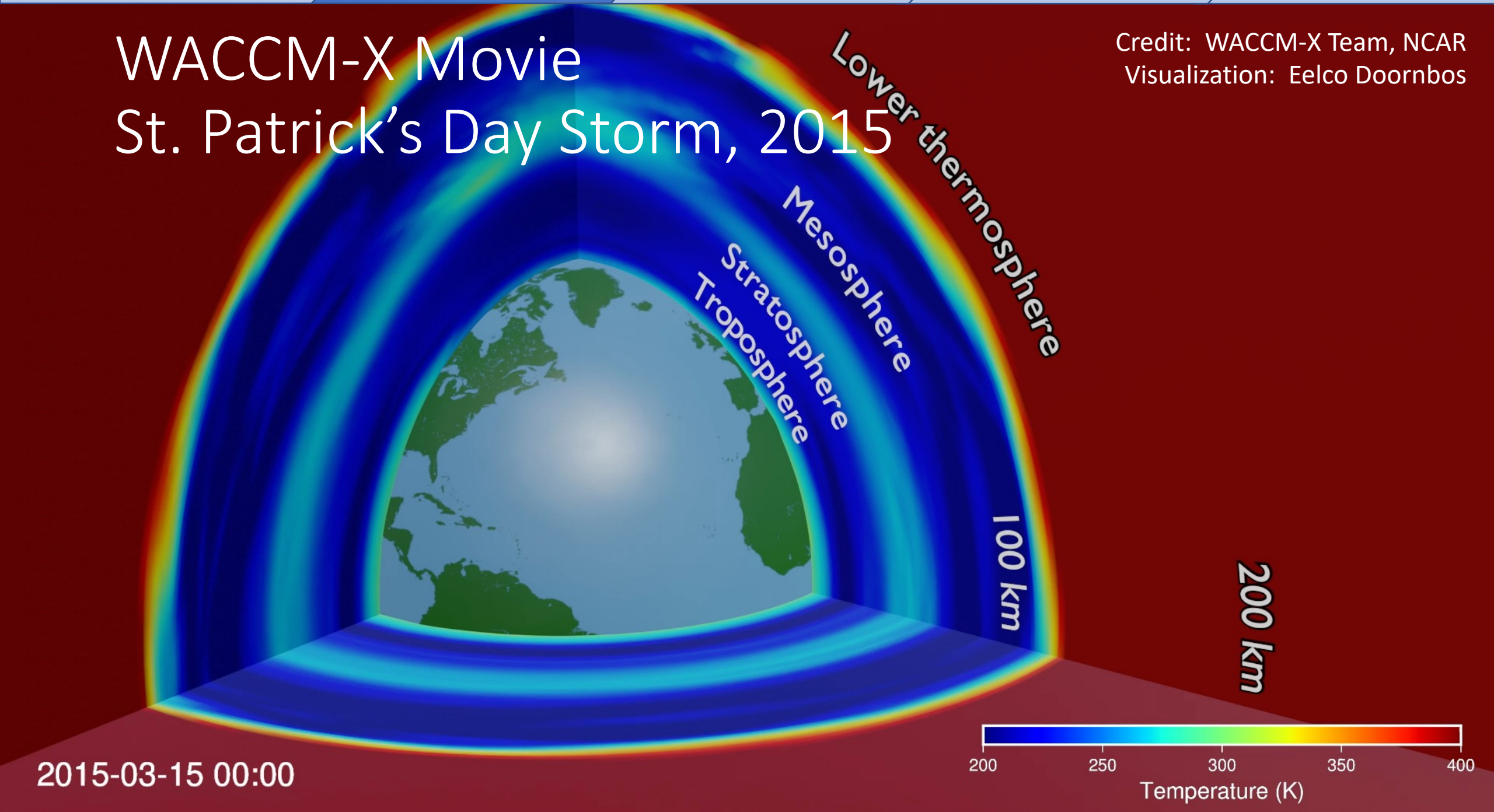
$O(^3P)$ → 63 μm



Credit: Roble, 1995

WACCM-X Movie
St. Patrick's Day Storm, 2015

Credit: WACCM-X Team, NCAR
Visualization: Eelco Doornbos



Non-Conservative Accelerations

Contributions vs. Altitude

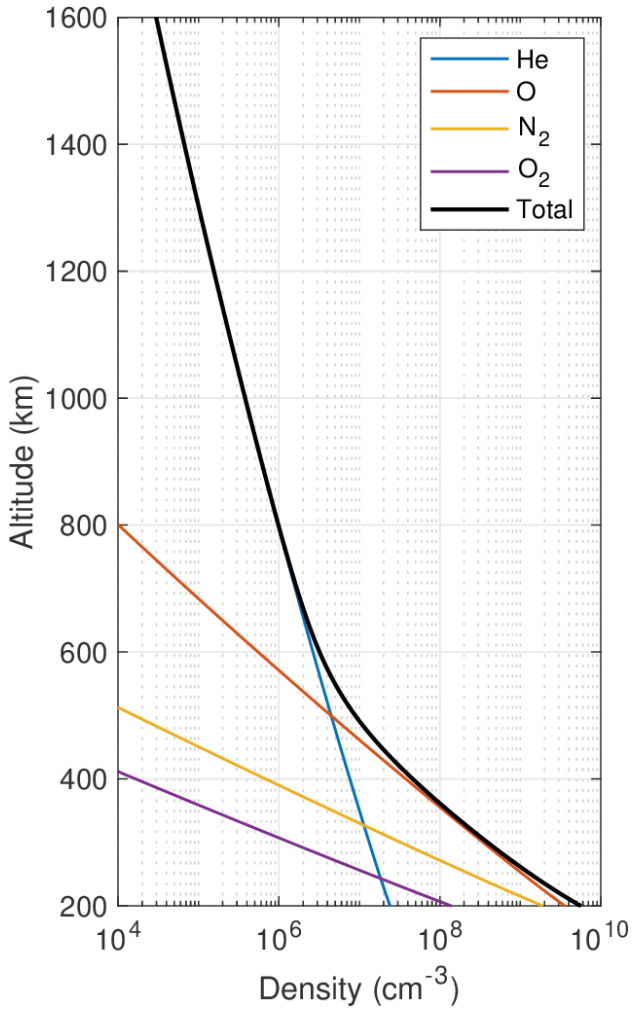
Credit: Marcin Pilinski

Drag Acceleration:

$$\vec{a}_D = -\frac{1}{2}\frac{C_D\, A_{proj}}{m}\, \rho\, |\vec{v}_{rel}|^2\, \hat{v}_{rel}$$

Solar Radiation Pressure (SRP) Acceleration:

$$\vec{a}_{SRP} = -\frac{R\, A\cos(\phi_{inc})}{m\, c} \times \left(2\left(\frac{c_{rd}}{3} + c_{rs}\cos(\phi_{inc})\right)\hat{n} + (1 - c_{rs})\,\hat{s}\right)$$



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

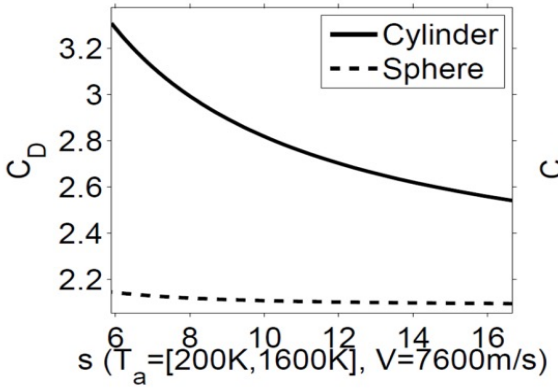
free-molecular flow

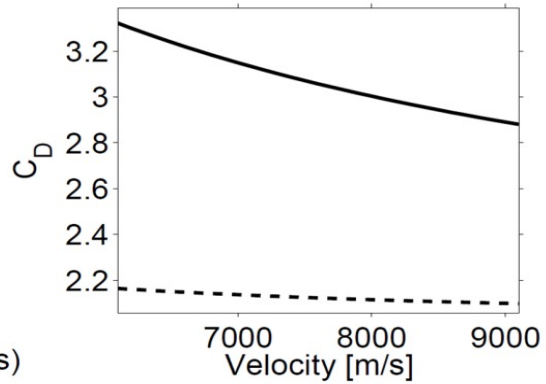
composition and temp. drives gradual changes in C_D

re-entry, extreme C_D variability

Drag Coefficient Sensitivities

Thermal to bulk velocity ratio

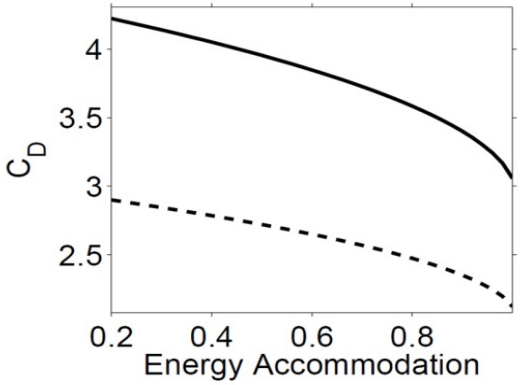


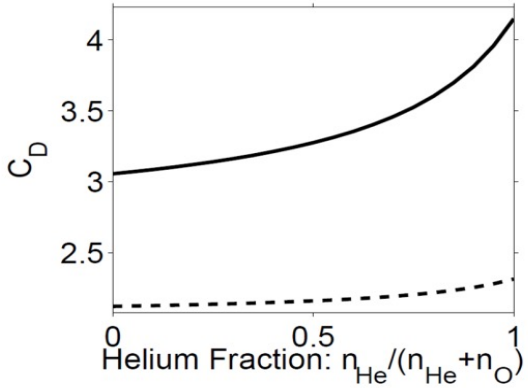


Spacecraft velocity

L / D = 3 unless otherwise stated

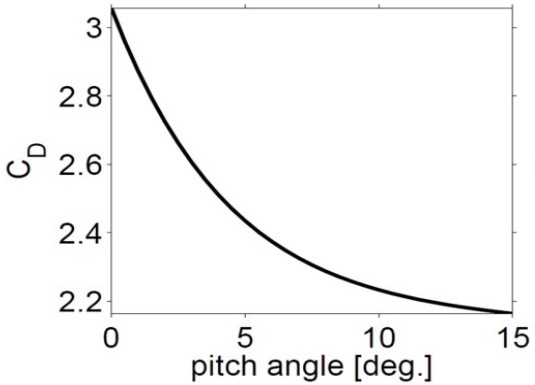
Energy exchange with surface (Energy-Accommodation)

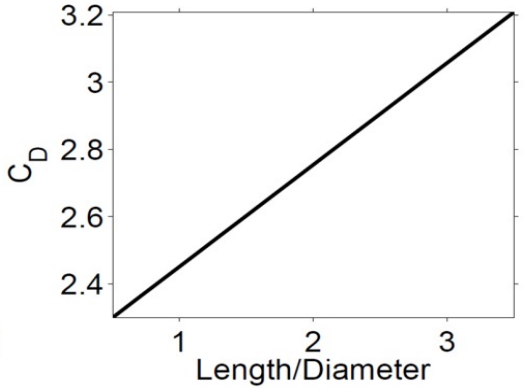




Composition

Attitude

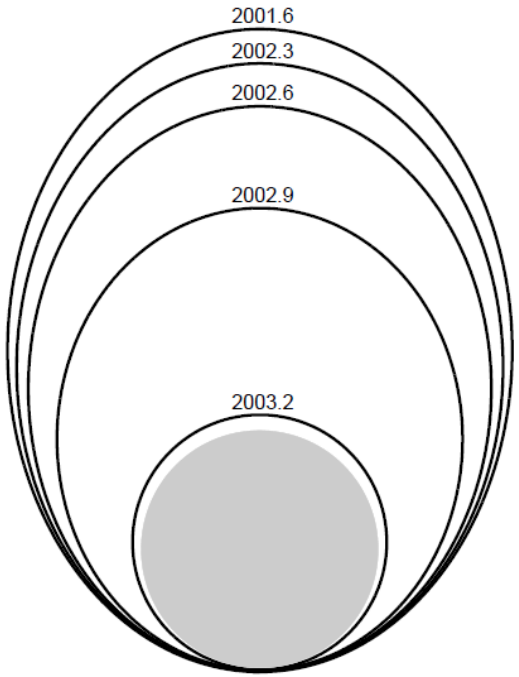




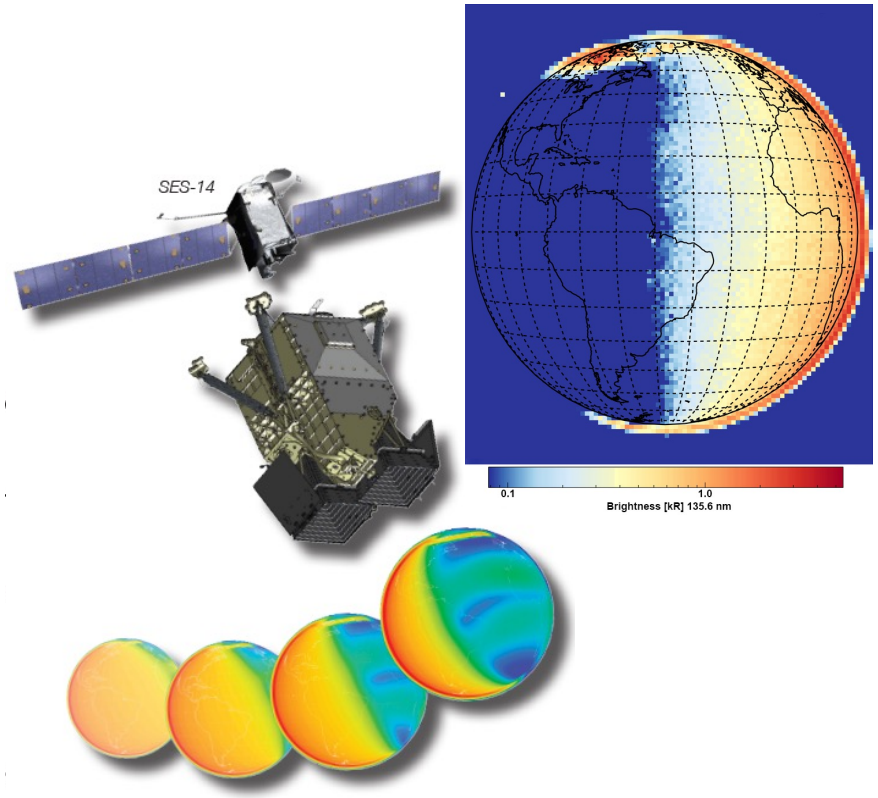
Shape

Credit: Marcin Pilinski

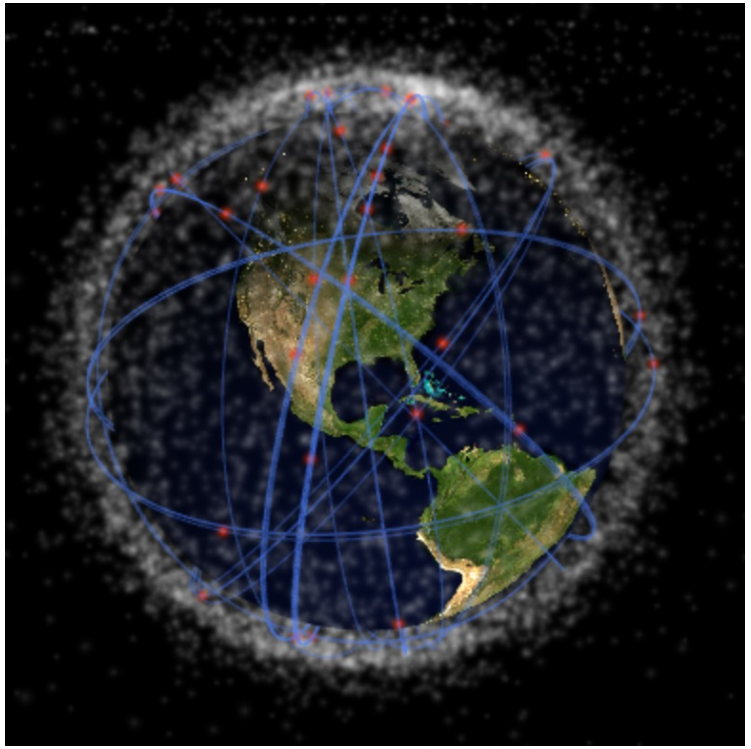
Satellite Drag Measurements



Traditional: e.g., Ground-Based Satellite/Object Tracking

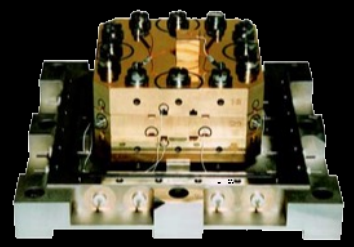


Dedicated NASA Missions: e.g., GOLD O/N_2 & Temperatures, CHAMP/GRACE/GOCE densities



Signals of Opportunity: e.g., New Constellations of GNSS-Equipped Small-Sats and CubeSats

High-Precision Accelerometers

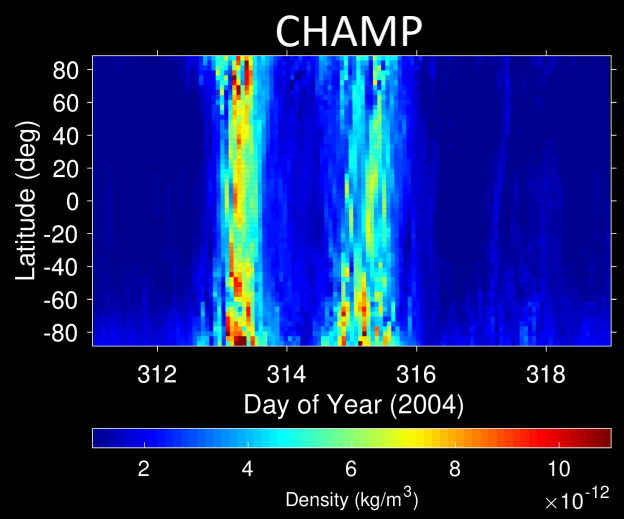


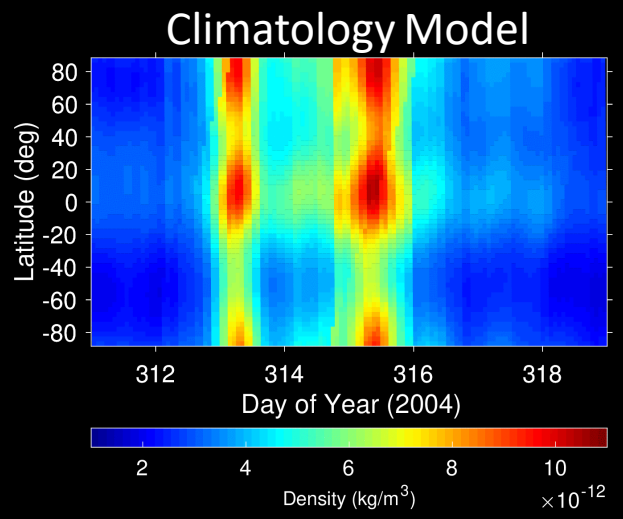
High-Precision (~1 nano-G) Accelerometer

Total mass density derived from measurements of satellite acceleration

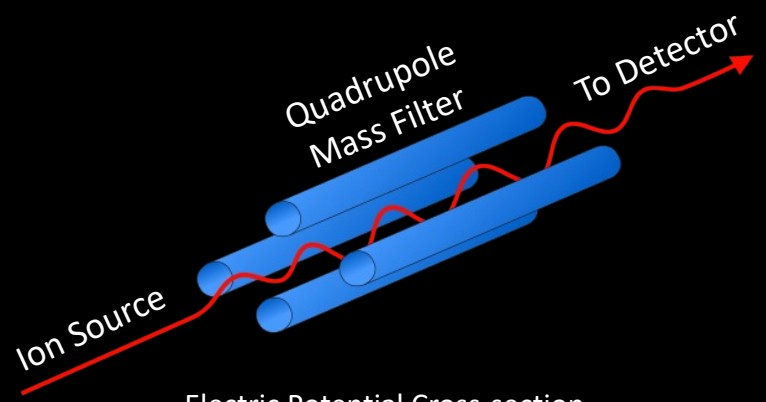
Recent Satellite Missions:

- CHAMP (2001 – 2010)
- GRACE (2002 – present)
- GOCE (2009 – 2012)
- Swarm (2014 – present, degraded)
- GRACE-FO (2018 – present)

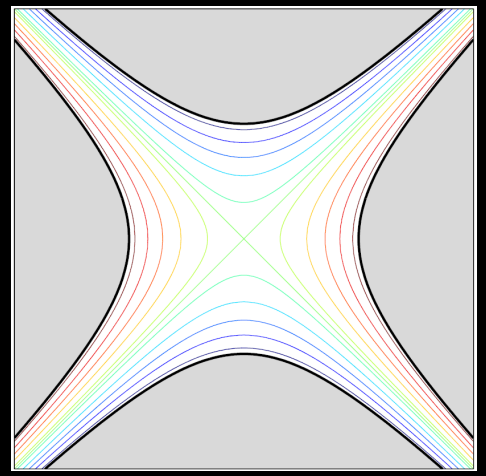




Mass Spectrometers



Electric Potential Cross-section

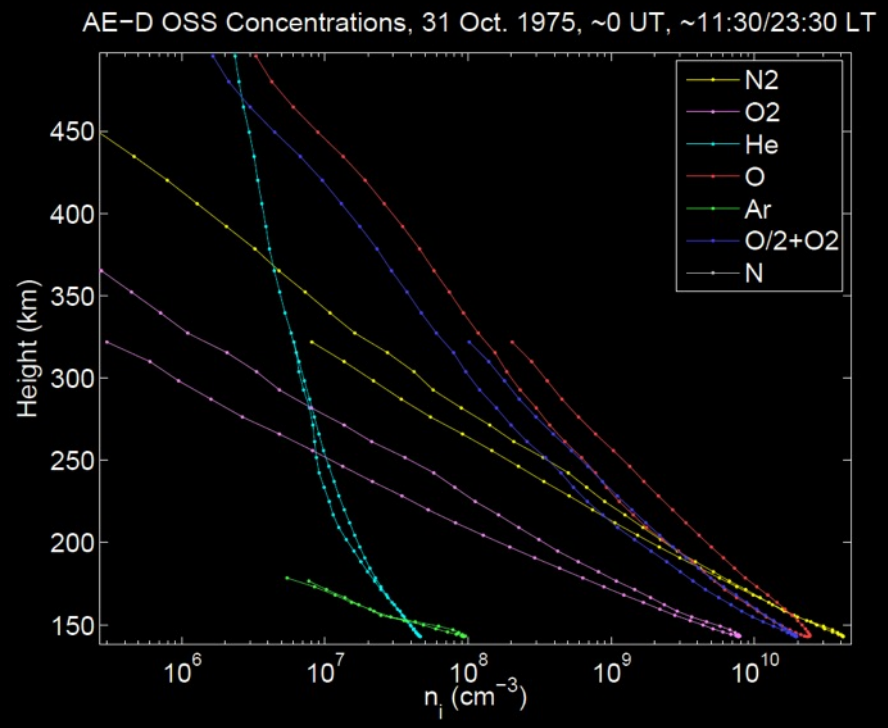


$$\phi = U + V \cos \omega t$$

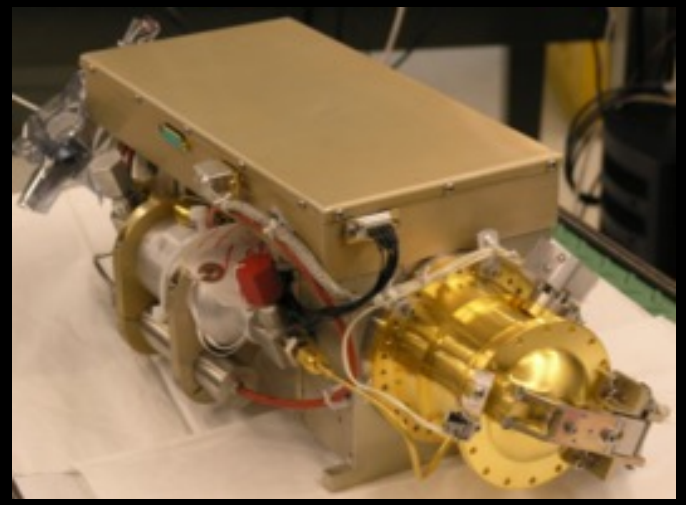
Scanning of various mass-to-charge ratios is done by holding ω constant, and sweeping through V while U is kept as a constant fraction of V

Satellite Missions:

- OGO-6 (1969 – 1971)
- AE-C, -D, and -E (1973 – 1981)
- DE-2 (1981 – 1983)
- Cassini (1997 – 2017)
- MAVEN (2015 – present)
- GDC mission in development (x6 sats)



Provides densities of individual components (e.g. O_2, O, N_2, He, Ar).



Closed-Source Mass Spectrometer

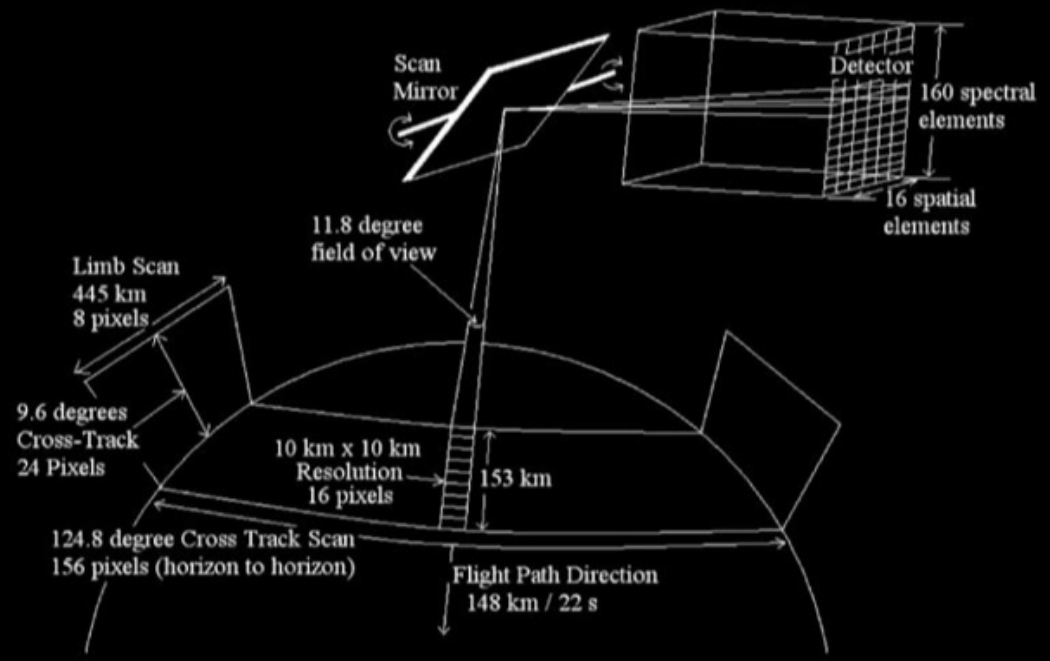
Remote Sensing of FUV

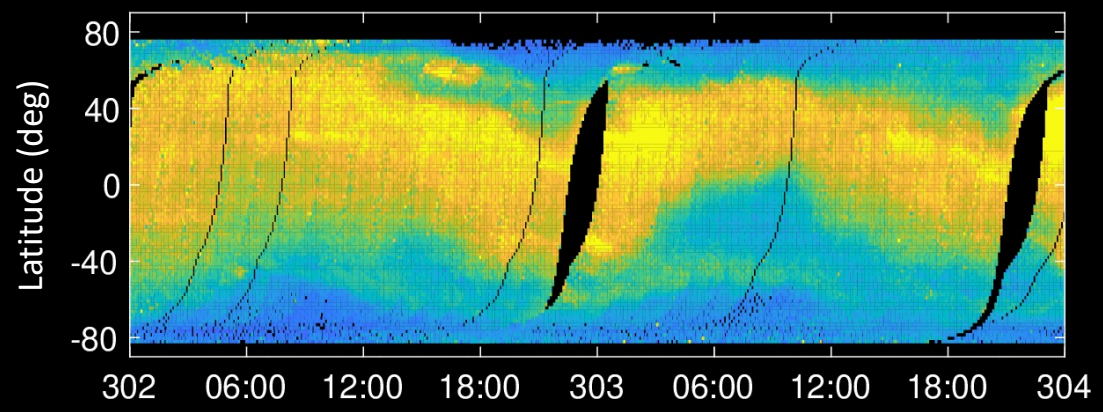
Provide daytime measurements of:

- $\sum O/N_2$: Ratio of column-integrated atomic oxygen to molecular nitrogen content
- Column-integrated temperature

Satellite Missions:

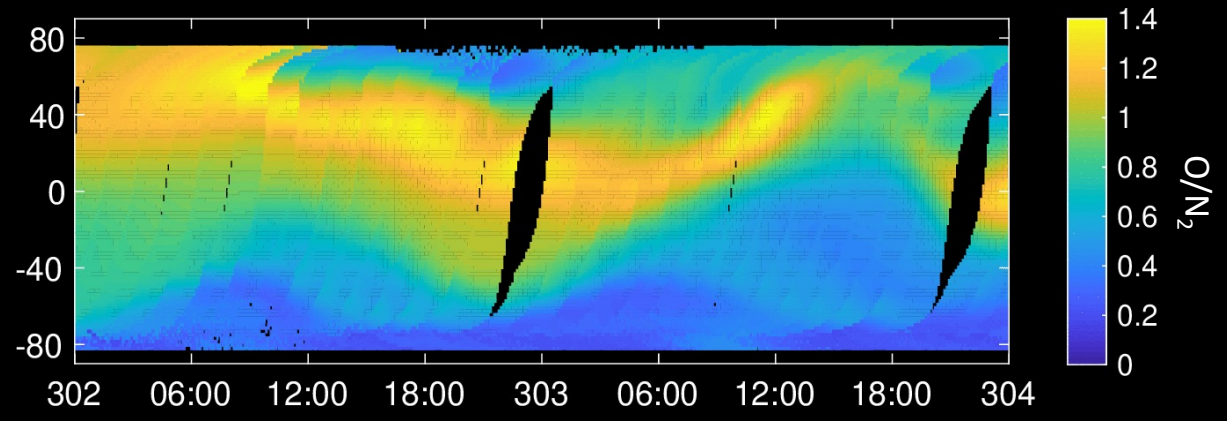
- TIMED/GUVI (2001 – present)
- DMSP/SSUSI (2003 – present)
- GOLD (2018 – present)





TIMED/GUVI Data

Time (Day/Hour)

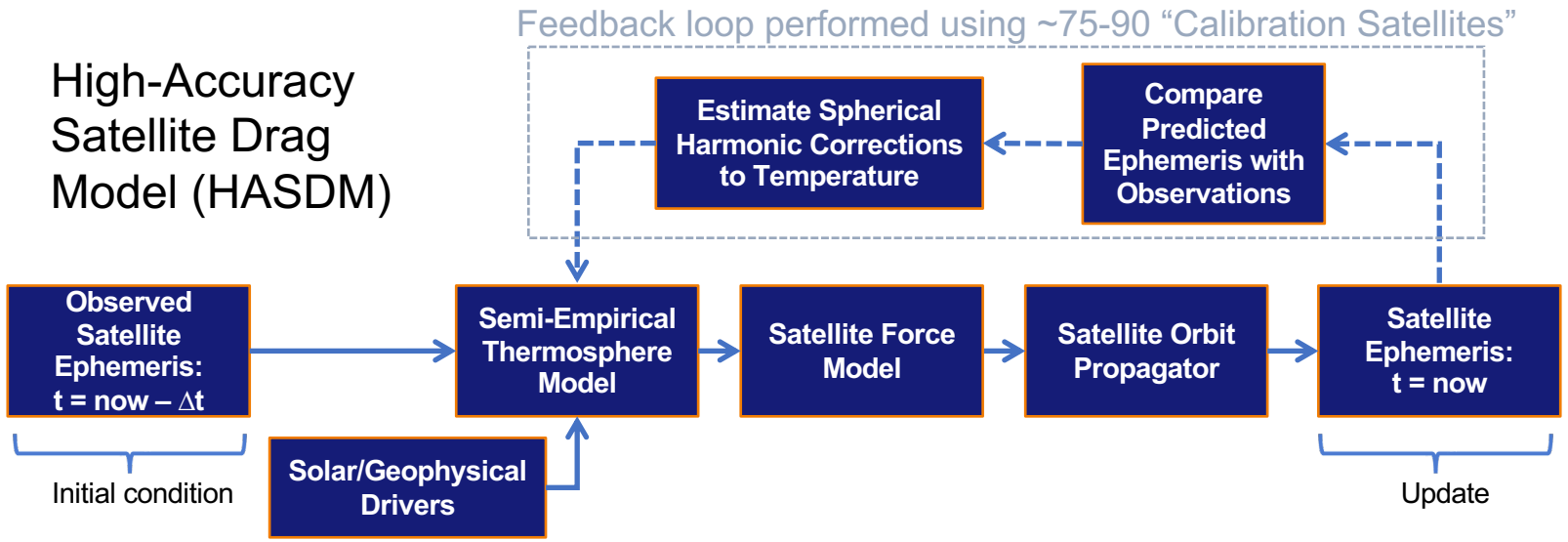


Time (Day/Hour)

TIE-GCM Model

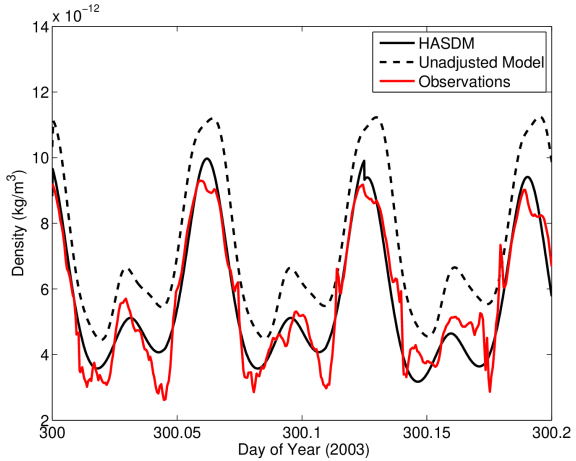
Constraining Models

High-Accuracy Satellite Drag Model (HASDM)



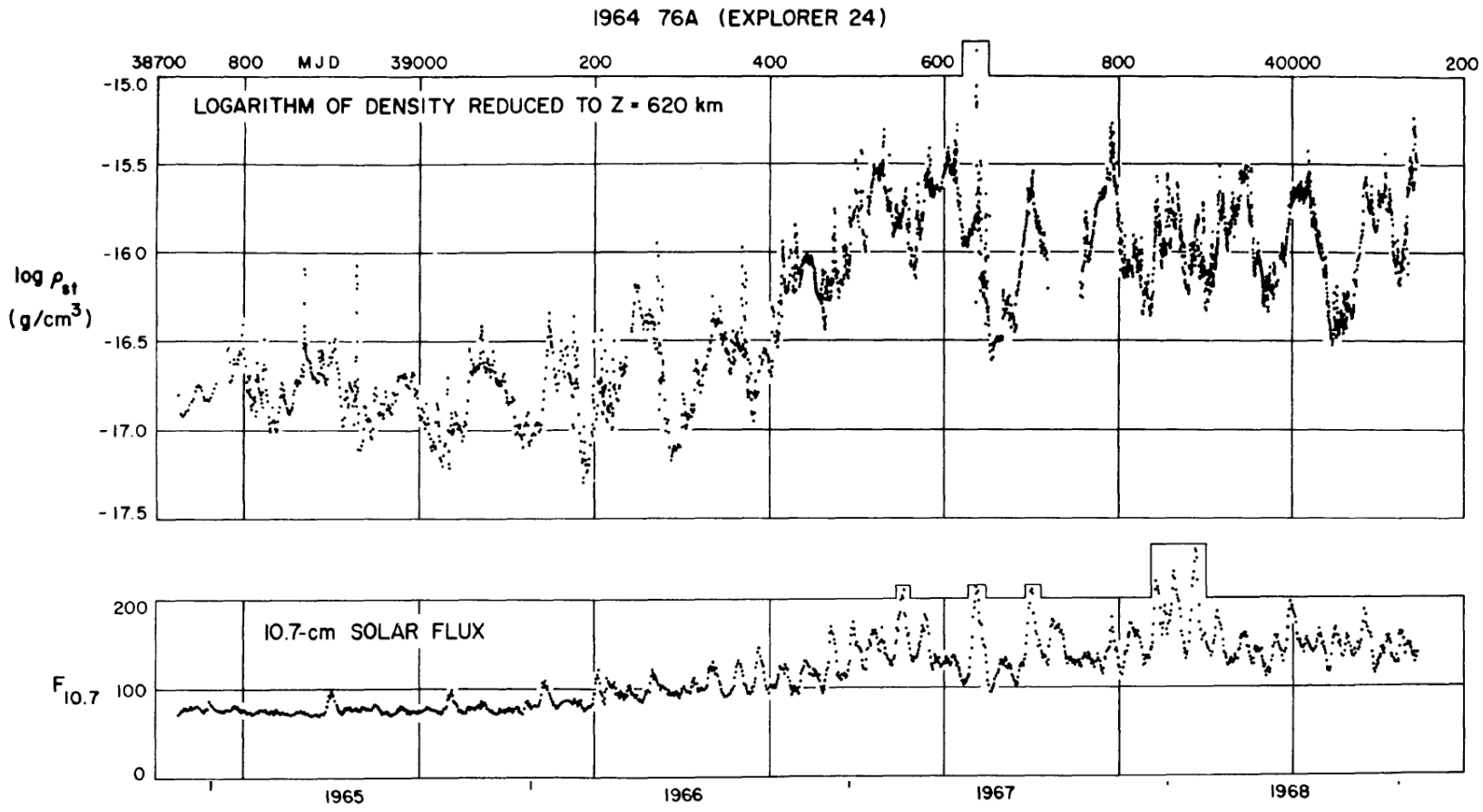
Example:

- Adjusted/unadjusted model vs. observations for several orbits
- Day 300, 2003
- Approx. altitude = 400 km
- Note: these observations are measured by a satellite accelerometer -- data from the normal "calibration satellites" is much less frequent (i.e. 1 per several orbits to 1 per day)



Early Discoveries:

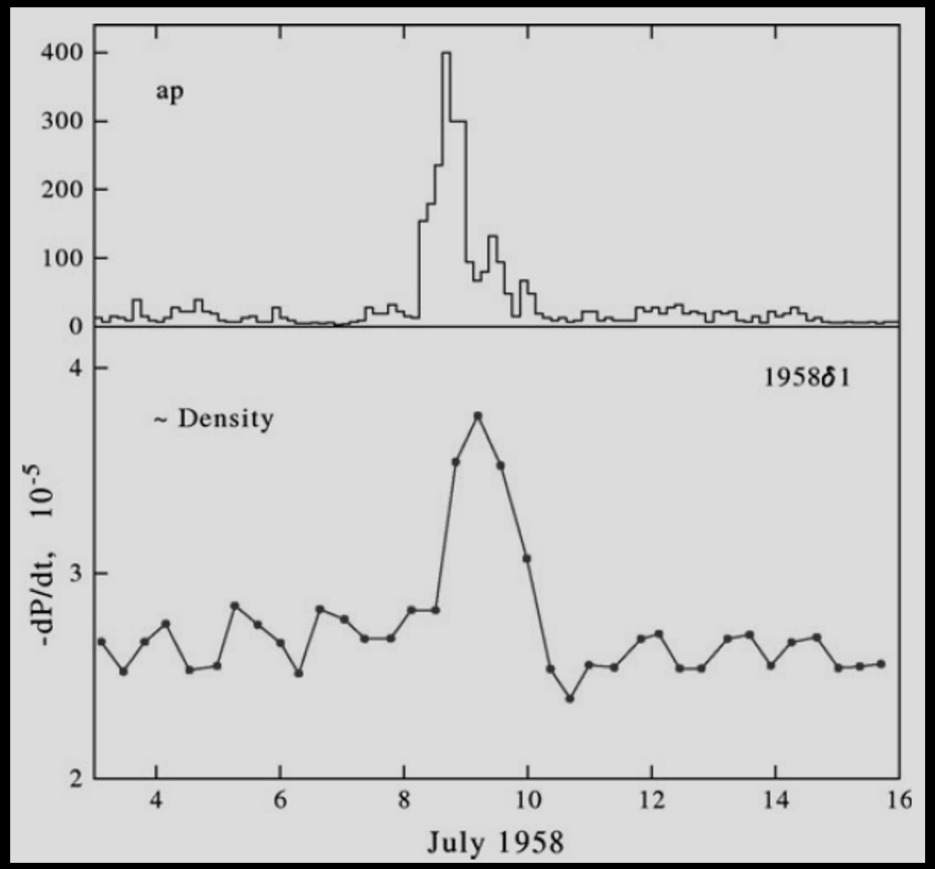
Solar Flux Signatures



Credit: Jacchia and Slowey, 1972

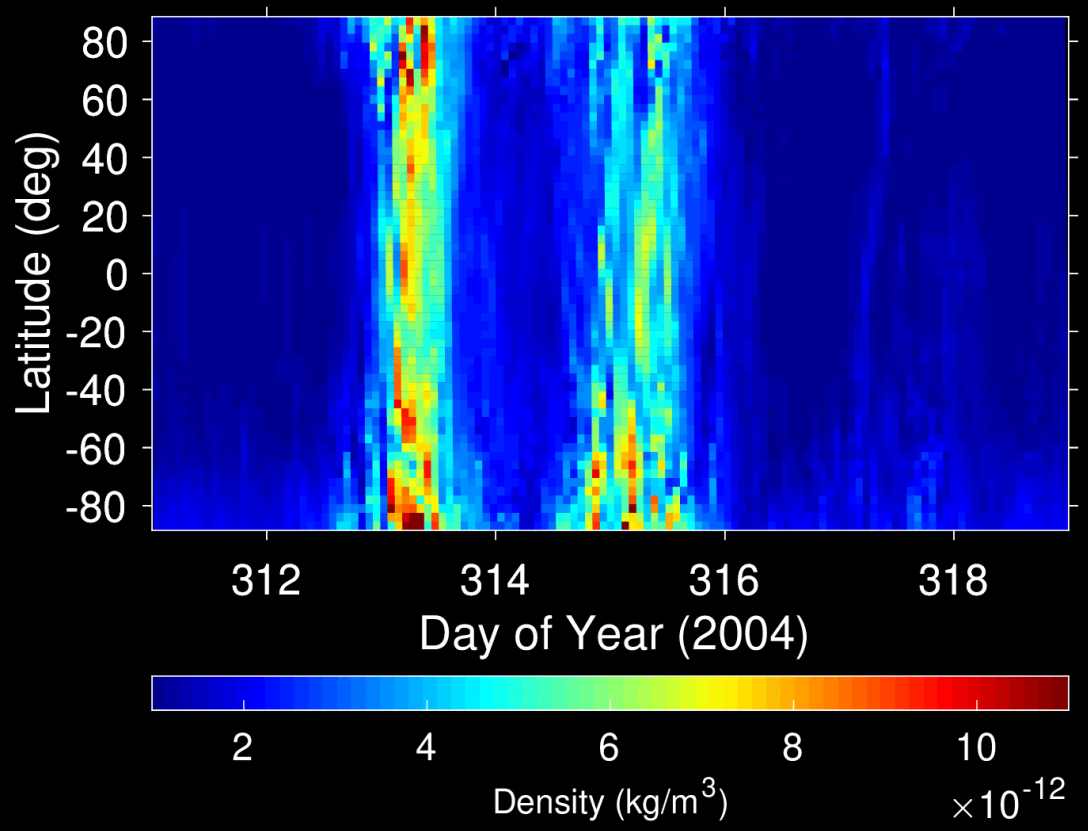
Early Discoveries:

Geomagnetic Influences



Credit: Jacchia, 1959

More recently,
from the CHAMP Satellite



Credit: Sutton, 2008

Early Discoveries:

Annual / Semi-Annual Variation

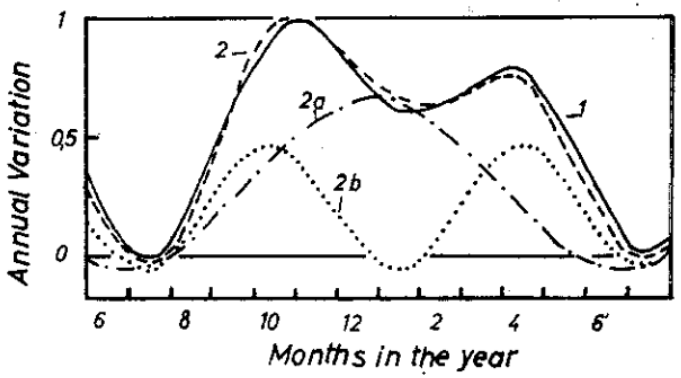
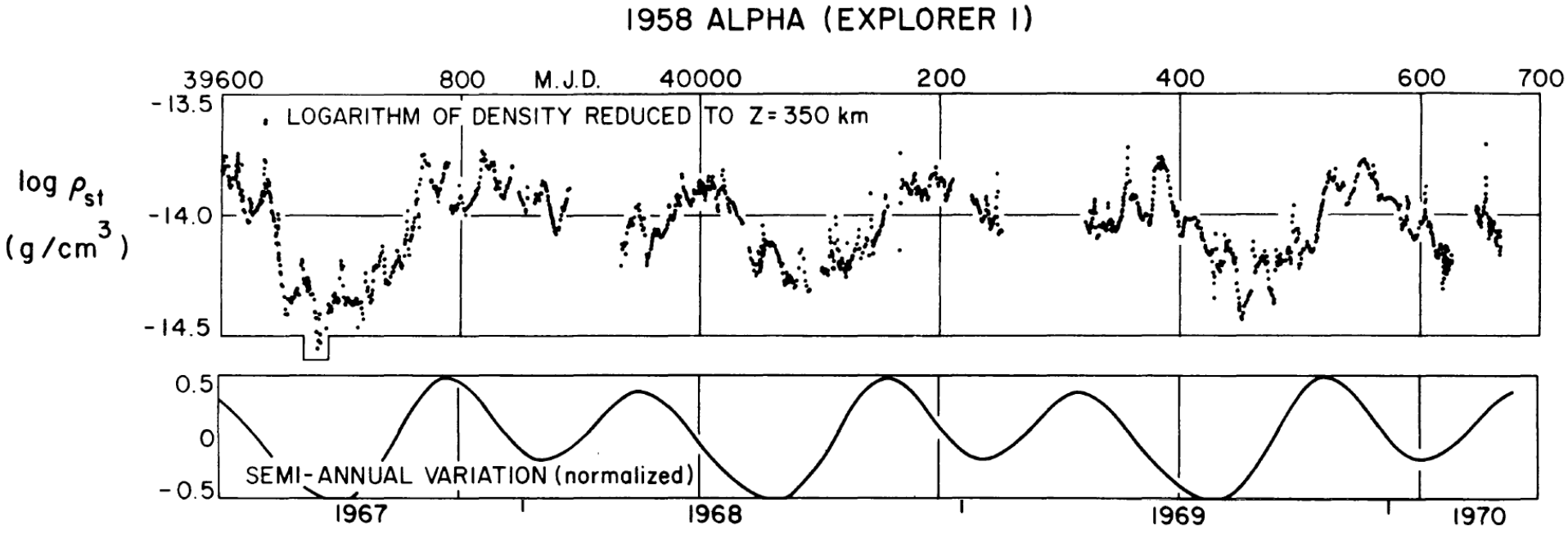


Fig. 5 - *Harmonic analysis of the annual variation.*

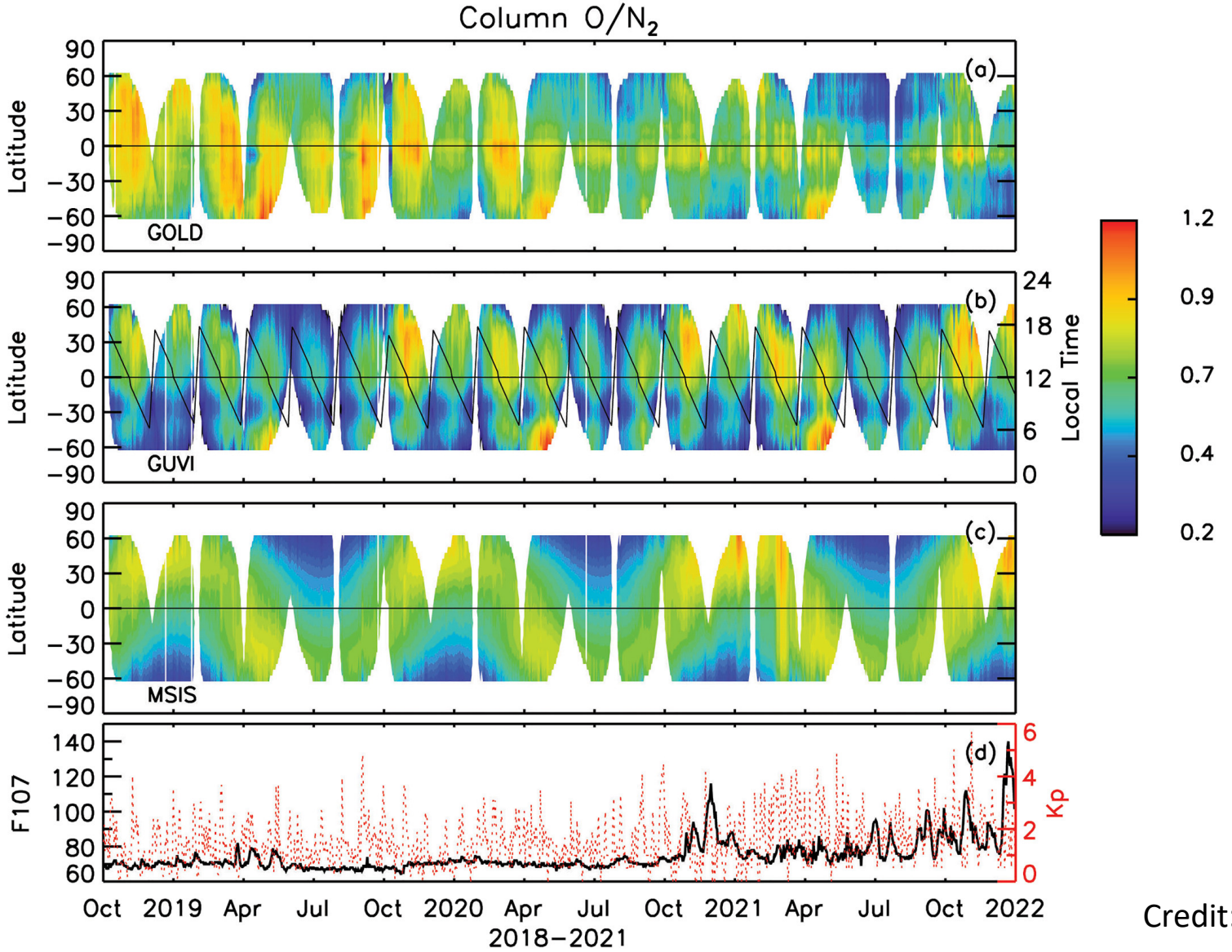
Paetzold and Zschorner, 1961



Jacchia and Slowey, 1972

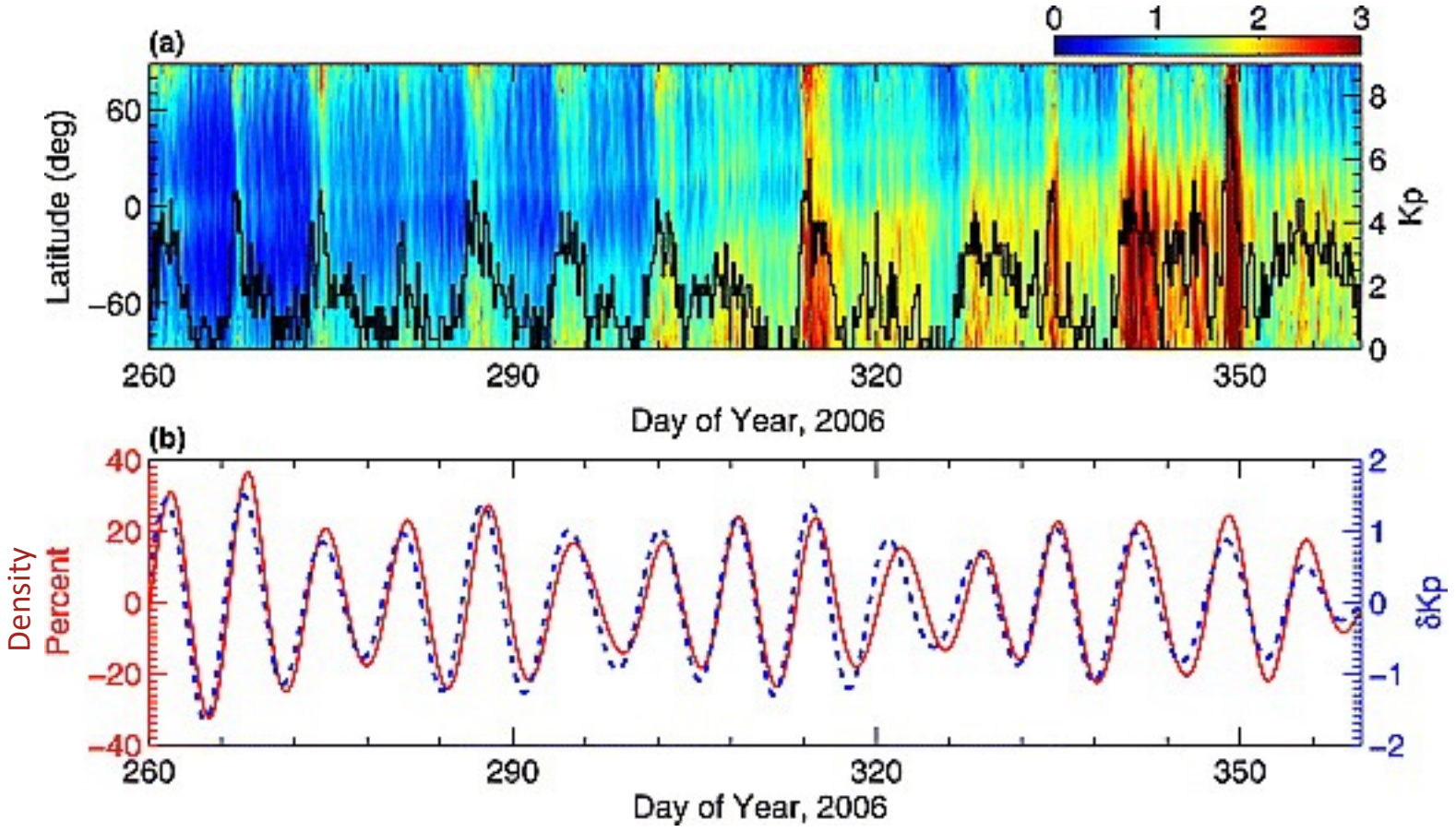
Seasonal Dependencies

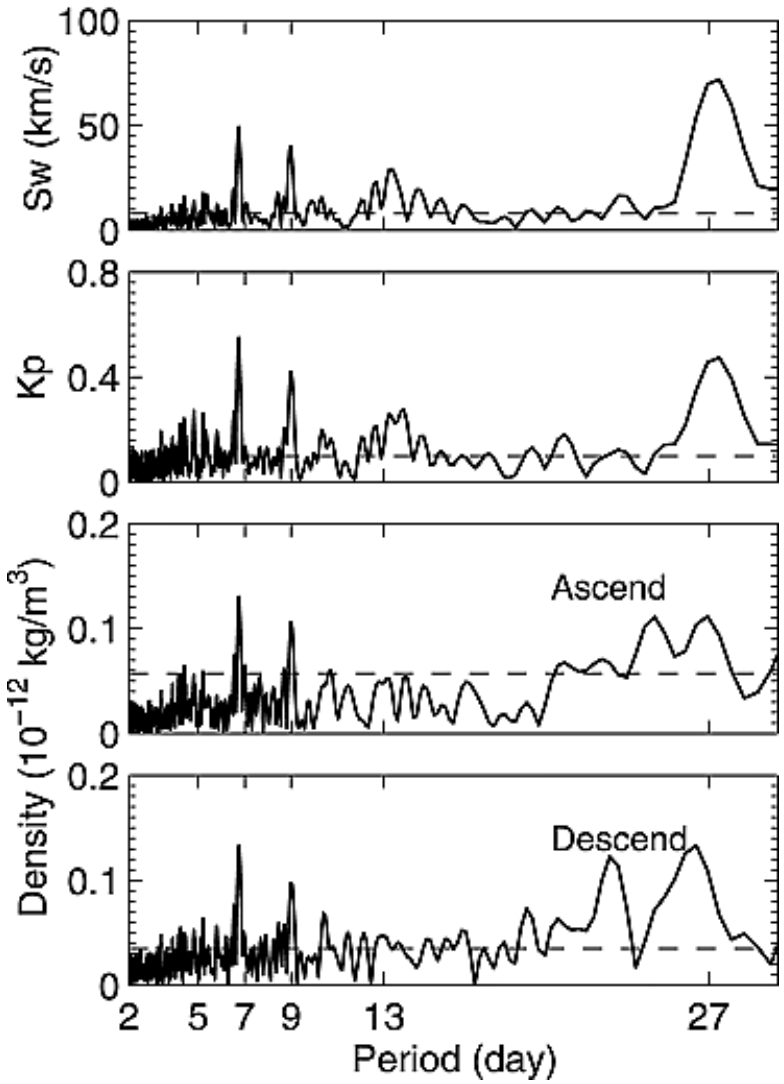
Composition



Credit: Qian et al., 2022

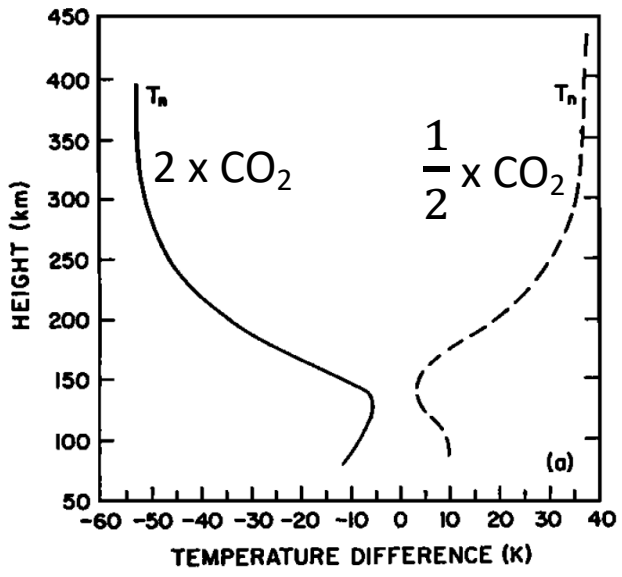
High-Speed SW Streams and Co-Rotating Interaction Regions (CIRs)

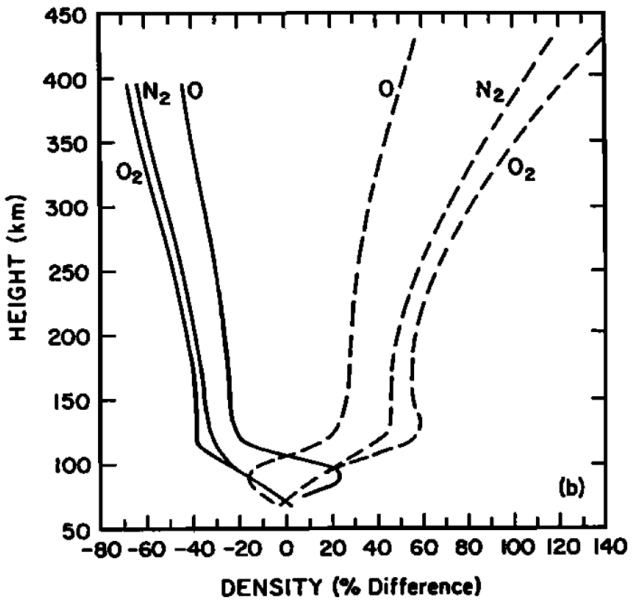




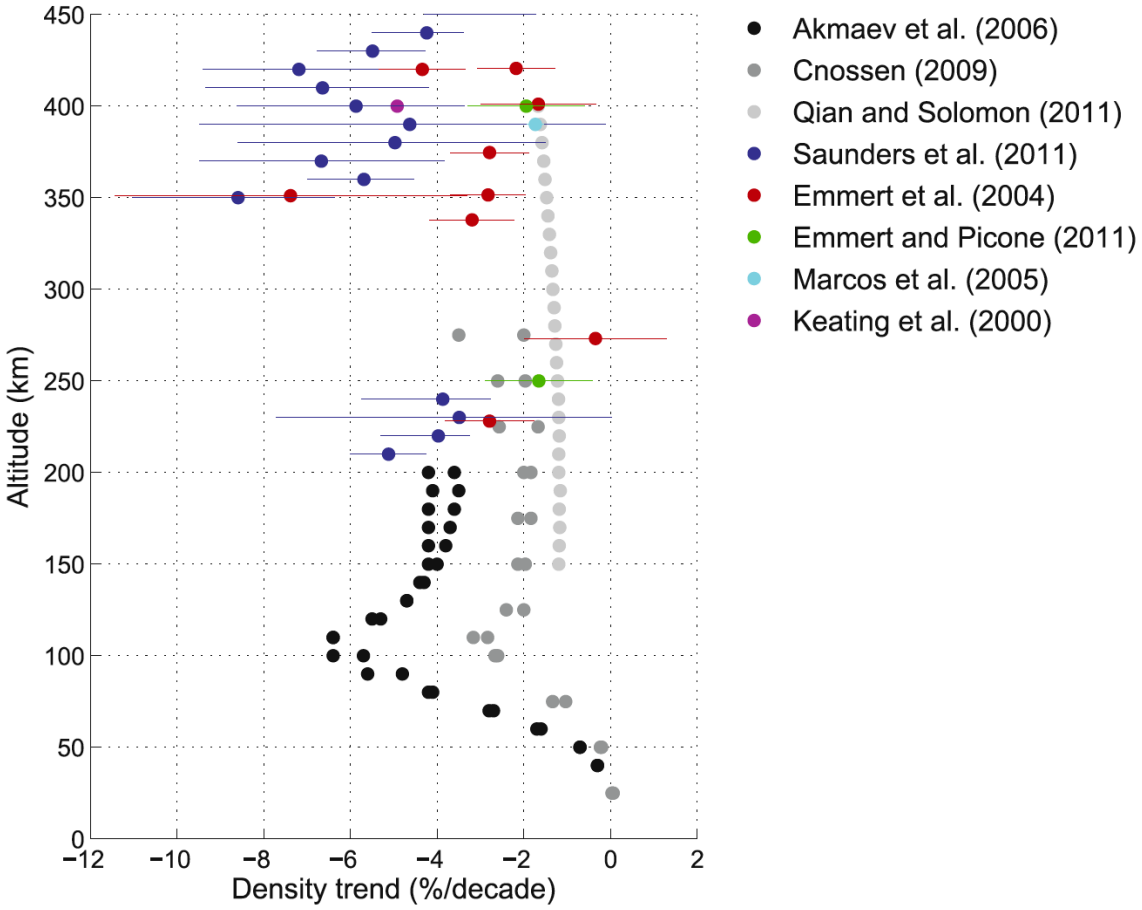
Credit: Thayer et al., 2008

CO_2 Cooling



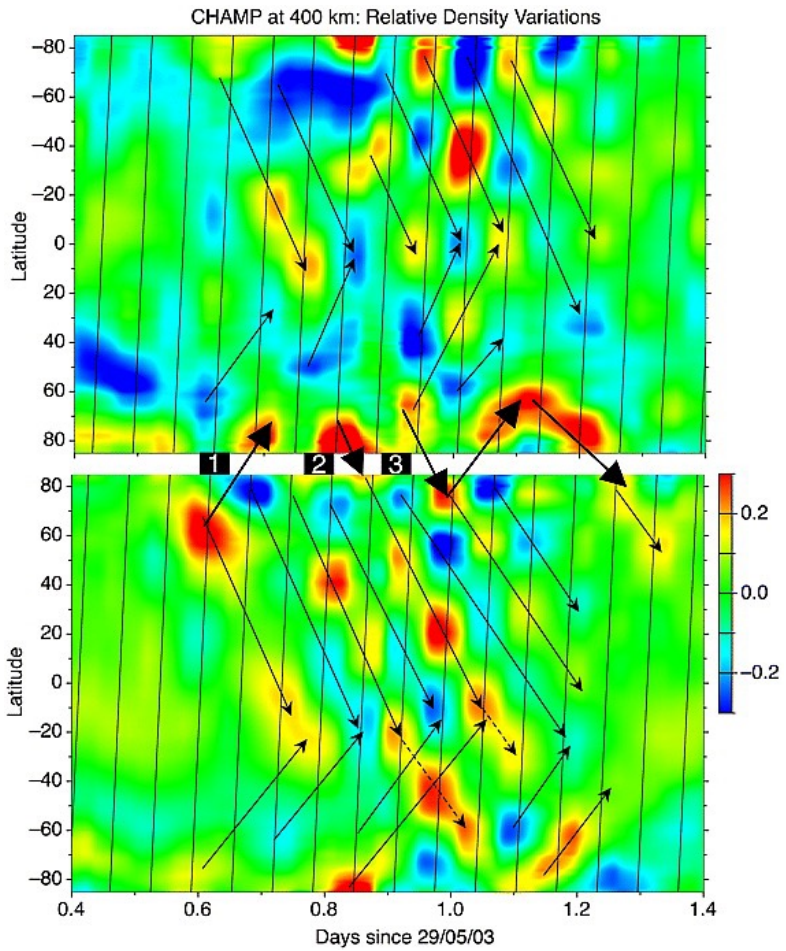


Credit: Roble and Dickinson, 1989

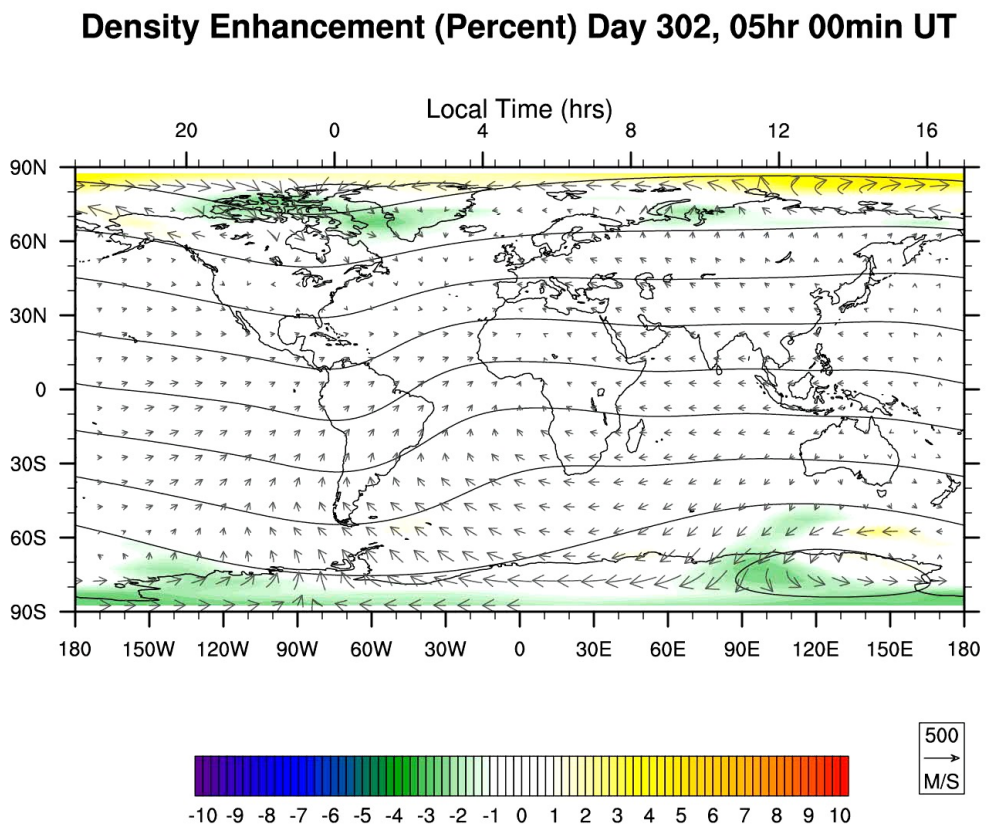


Credit: Emmert, 2015

Traveling Atmospheric Disturbances

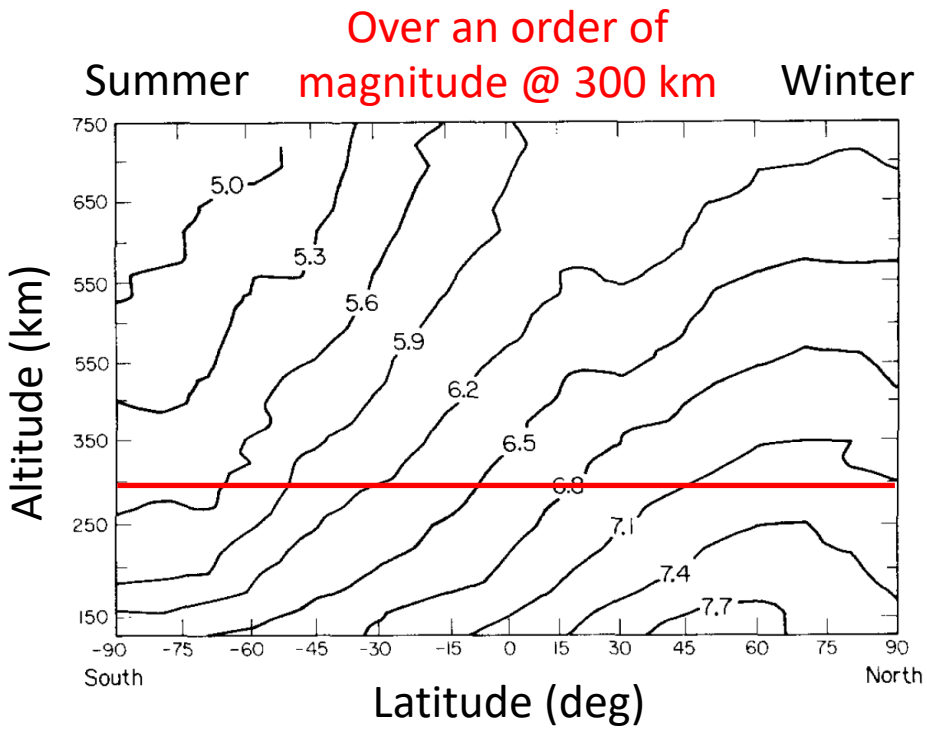


Credit: Bruinsma and Forbes, 2007
doi: 10.1029/2007GL030243

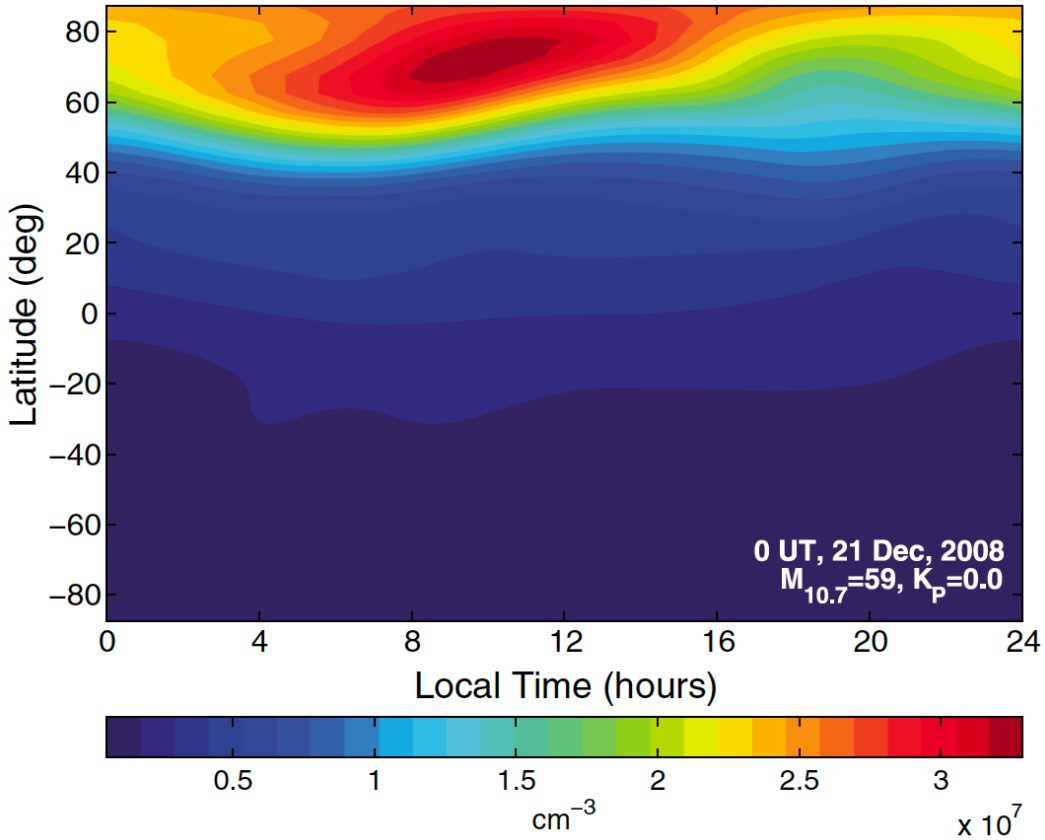


Credit: Sutton, 2008

Helium Winter Bulge



Credit: Cageao & Kerr, 1984 – AE-D Satellite



Credit: Sutton et al., 2015