The Ionosphere

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UNIVERSITY OF BIRMINGHAM

SERENE SPACE ENVIRONMENT

LEVERHULME TRUST

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What is the ionosphere?

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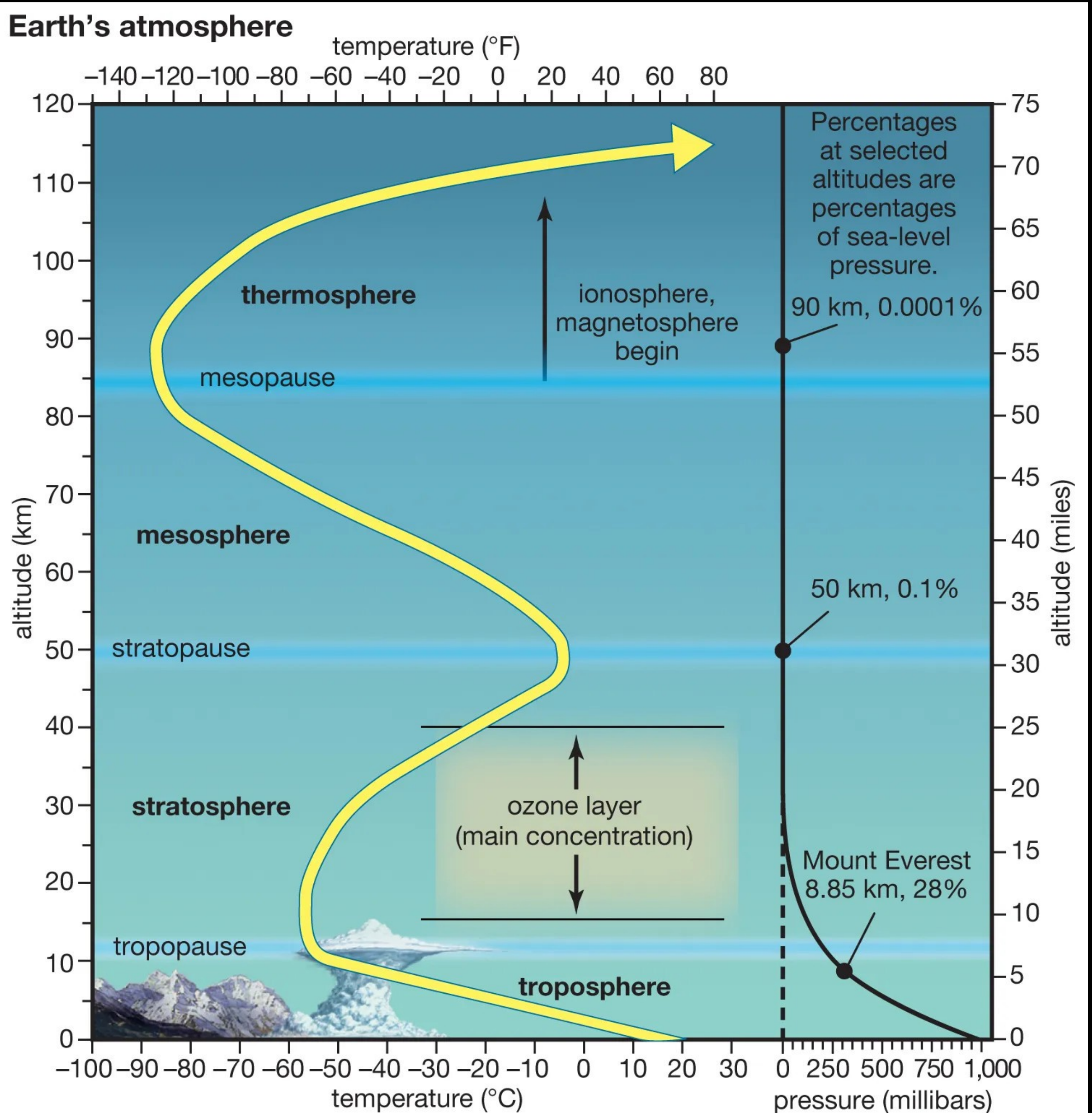
    - Ionosonde
    - Scintillation
    - in situ sampling (e.g. SWARM / Sounding Rockets etc.)
- (Optional if time allows) Planetary ionospheres / comparisons

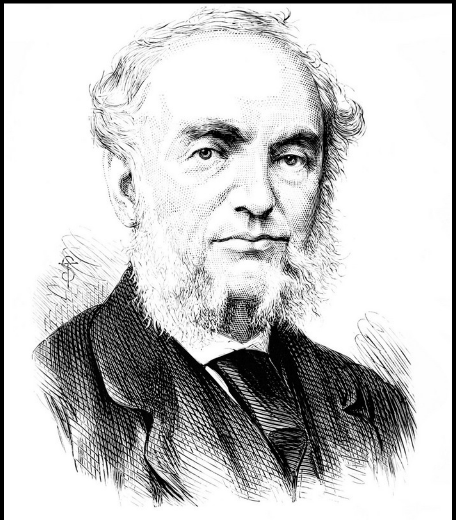
Earth’s Atmosphere



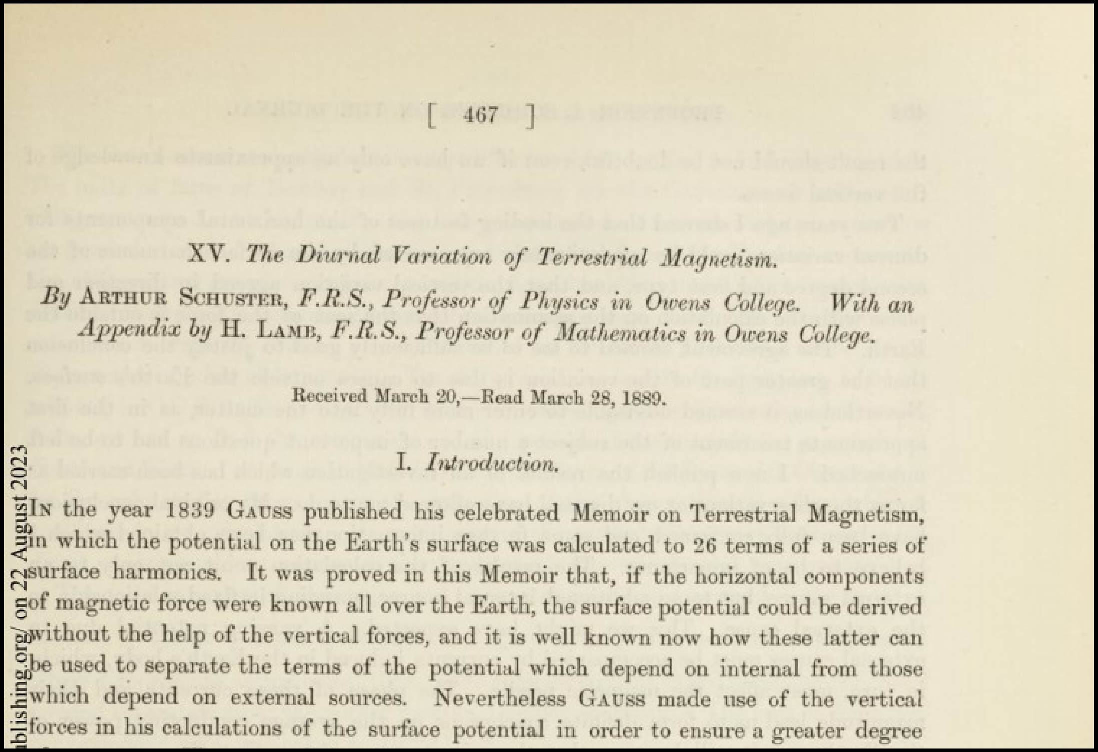
What is the ionosphere? History

Earliest suggestions of an ionised layer of Earth's atmosphere made in 1882 by Balfour Stewart who opined that diurnal variations to the Earth's magnetic field might be caused by electrical currents flowing in the Earth's upper atmosphere.

Arthur Schuster also presented this theory in letters to the Royal Society in 1889



Balfour Stewart 1828 – 1887 (alma mater : University of St. Andrews!)



[467]

XV. *The Diurnal Variation of Terrestrial Magnetism.*

By ARTHUR SCHUSTER, *F.R.S., Professor of Physics in Owens College. With an Appendix by* H. LAMB, *F.R.S., Professor of Mathematics in Owens College.*

Received March 20,—Read March 28, 1889.

I. *Introduction.*

IN the year 1839 GAUSS published his celebrated Memoir on Terrestrial Magnetism, in which the potential on the Earth's surface was calculated to 26 terms of a series of surface harmonics. It was proved in this Memoir that, if the horizontal components of magnetic force were known all over the Earth, the surface potential could be derived without the help of the vertical forces, and it is well known now how these latter can be used to separate the terms of the potential which depend on internal from those which depend on external sources. Nevertheless GAUSS made use of the vertical forces in his calculations of the surface potential in order to ensure a greater degree

Credit: Royal Society

Arthur Schuster 1851-1934

What is the ionosphere? History

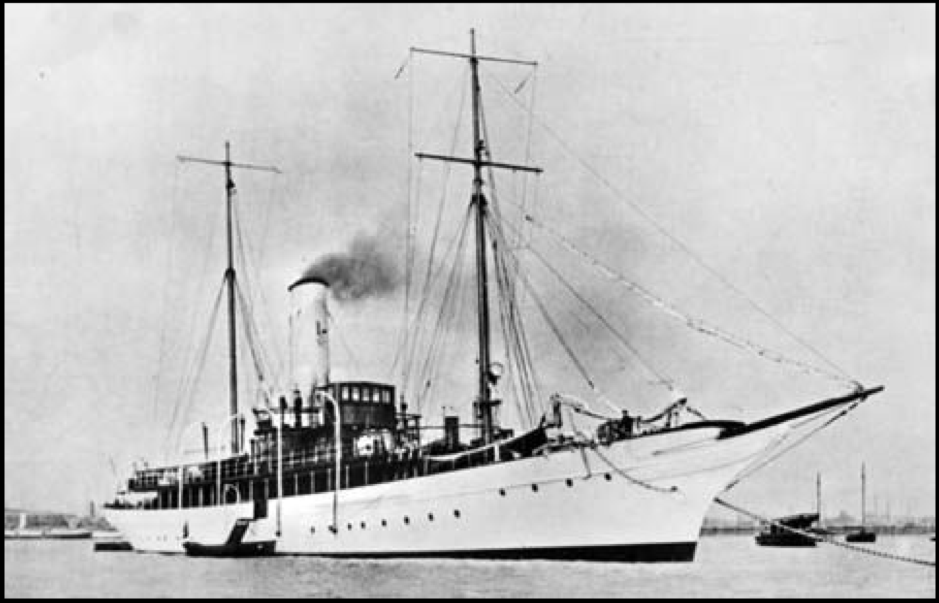
12th December 1901; Marconi's receiving equipment in Newfoundland, Canada, detected a signal from Marconi's radio station at Poldhu Cove, Cornwall, UK.

First trans-Atlantic radio transmission.

Guglielmo Marconi 1874 - 1937

Poldhu Cove radio station, 1901

Marconi's yacht, the *Electra* (1904)



Marconi also noted that long distance radio signals received by ships in the Atlantic were typically stronger during the day than at night. Suggestive of diurnal changes in the ionisation state of the upper atmosphere.

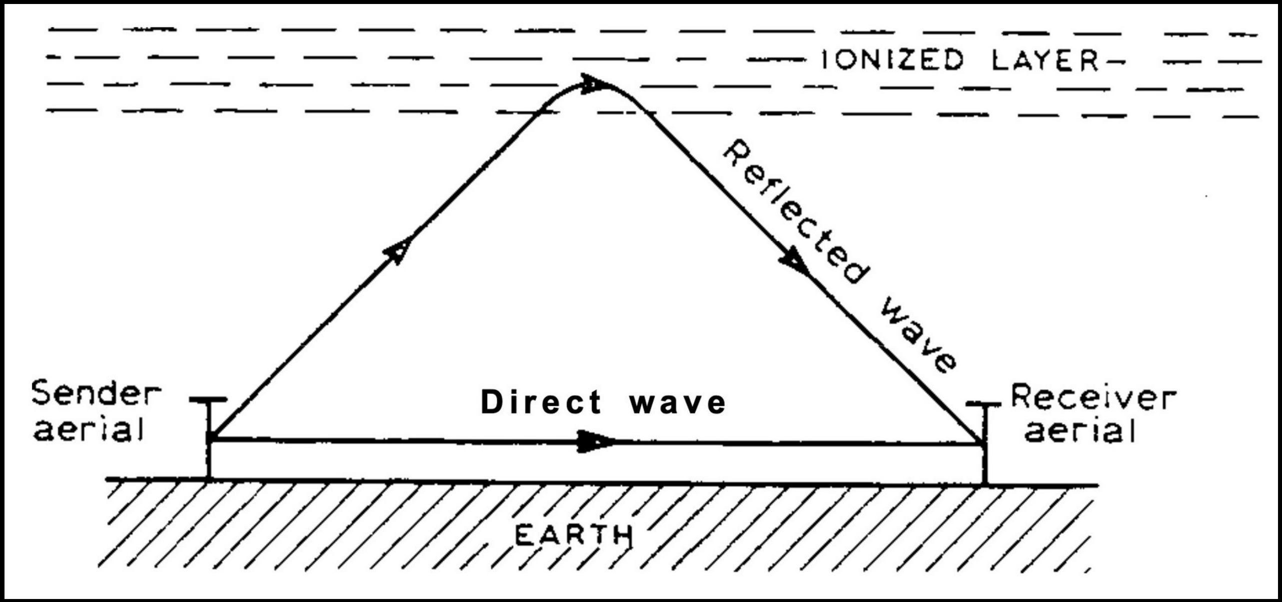
What is the ionosphere? History

Appleton (1925) directly experimented with bouncing vertically directed radio waves back to Earth off a radio-reflective layer of the Earth's atmosphere at an altitude of ~100 km.

Was referred to as the Kennelly-Heaviside layer after independent prediction by Arthur Kennelly and Oliver Heaviside following Marconi's work (now known as the E-layer)

Appleton was also the first to demonstrate the existence of a second radio-reflective layer at ~250 km. Labelled the 100 km and 250 km layers as the E- and F-layers by which they are universally known today. The lower D-layer at ~85 km was added shortly thereafter. The development of RADAR stemmed from these early radio studies of the ionosphere.

Edward Appleton
1892-1965



Appleton, 1947 Nobel Prize Lecture

Electron density (Ne) required to reflect a vertically incident radio signal (at frequency f) is proportional to f^2. $Ne \propto f^2$. Ne varies with altitude, so different frequency radio waves can be used to get echoes from different layers of the ionosphere.

So...what is the ionosphere?

“Now we have in quite recent years seen the universal adoption of the term 'stratosphere' in lieu of a previously well established misnomer 'isothermal layer', and the adoption of the companion term 'troposphere' for the 'convective layer'. The term 'ionosphere', for the region in which the main characteristic is large scale ionisation with considerable mean free paths, appears appropriate as an addition to this series.”

Sir Robert Watson-Watt (1926).

Sir Robert Watson-Watt 1892 - 1973

So...what is the ionosphere? (continued)

Ionosphere, noun:

"That part of the atmosphere in which free ions exist in sufficient quantities to affect the propagation of radio waves"

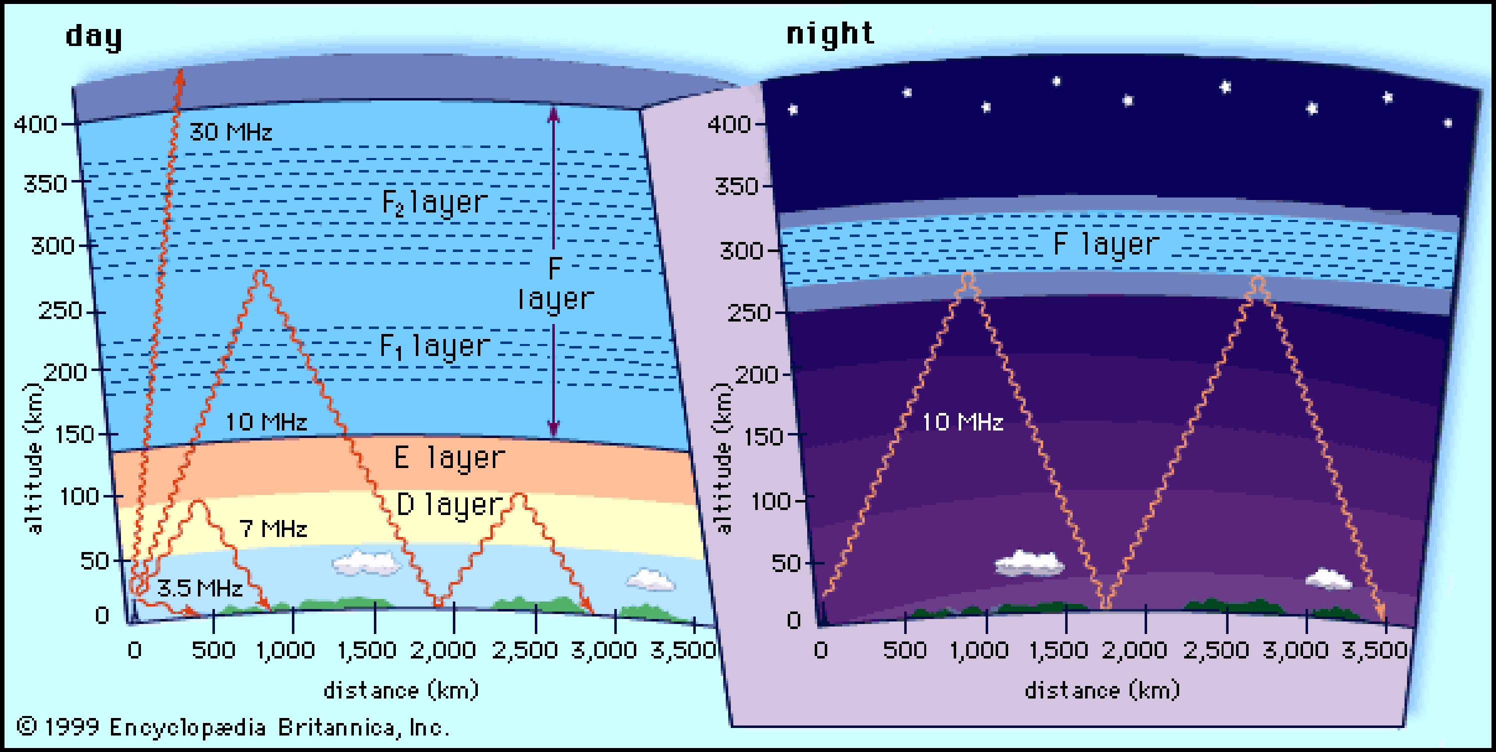
Institute of Radio Engineers, 1950

- A weakly ionized plasma, ~1% of thermospheric gas is ionized
- All of the charged particles in the Earth's atmosphere
- Atmospheric interface between the terrestrial and space environment

Ionospheric Radio Wave Propagation

Radio waves (photons) are oscillations in electric and magnetic fields; any charged medium through which they pass will respond with the photons transferring some of their energy to electrons/ions in the raypath.

Refractive index of the plasma is proportional to electron density (Ne) and inversely proportional to radio freq



Ionospheric Radio Wave Propagation (continued)

- A magnetised plasma is *birefringent* generating two separate raypaths called the ordinary (O-) and extraordinary (E-) modes.

- Plasma frequency (Hz) at which radio wave just penetrates ionisation layer is called the critical frequency, usually designated foF2 / foE for F2 / E etc. layers respectively

$$\mathbf{f_o = 8.98 * Ne^{0.5}} \quad \text{OR} \quad \mathbf{f_o = 8.98 * Ne^{0.5} + B\ e / 2\ m}$$

for O- and X-mode waves, where B = magnetic field strength, e = electron charge, m = electron mass

- Radio waves at frequencies higher than critical frequency will penetrate ionised layer and escape to space (assuming they are not reflected at some other higher layer)

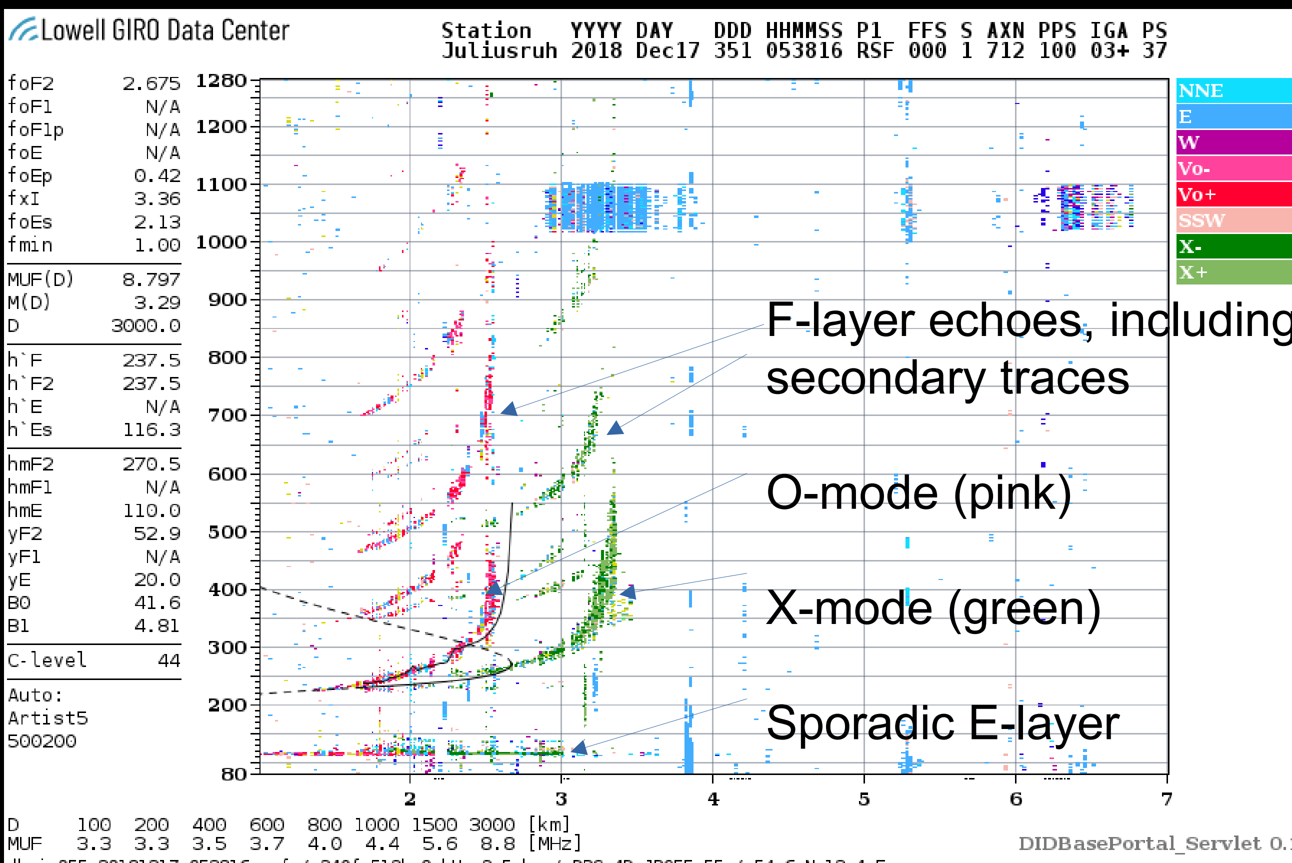
Optical birefringence

Ionosondes

Transmits vertical (and oblique) signals upwards

Echo timings used to characterise ‘virtual height’ (group velocity slows near layers, increasing echo delay and giving a non-true height)

Ionogram (see below) standard data format

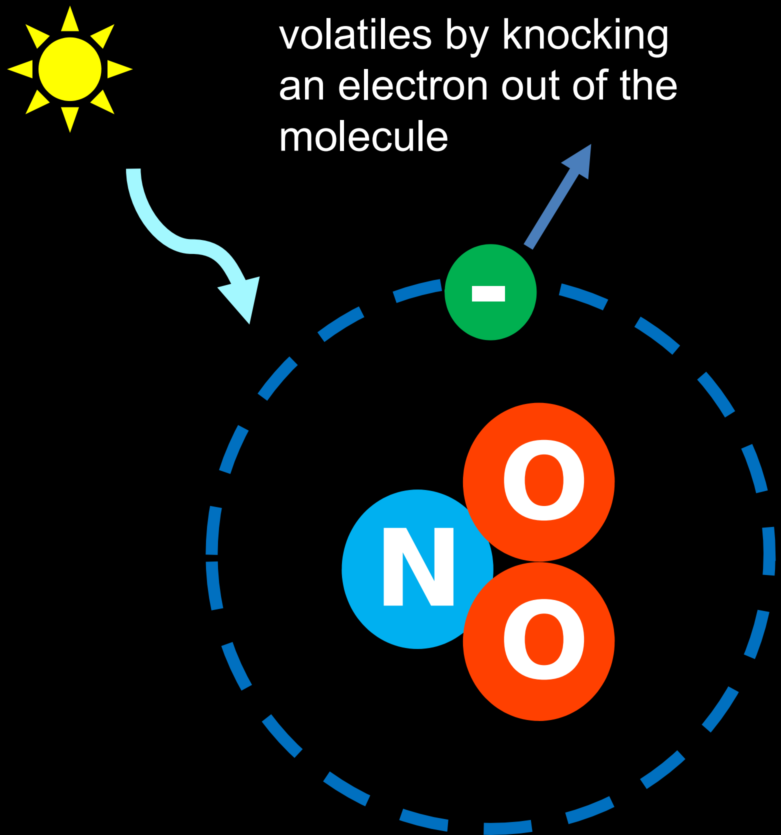


Can extract many ionospheric characteristics including plasma frequency, height of maximum plasma frequency, spread-F etc.

Can calculate plasma density at different altitudes

Plasma Formation

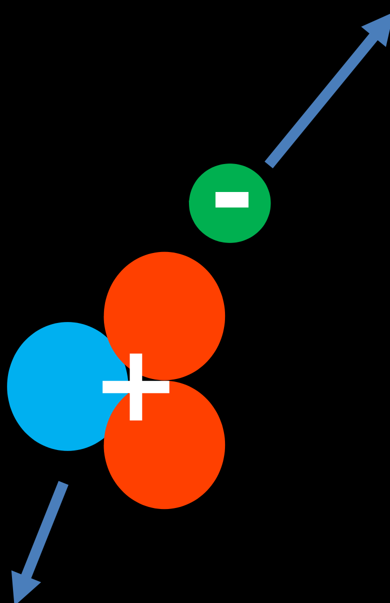
Solar-UV ionises the volatiles by knocking an electron out of the molecule



Typical thermospheric / ionospheric constituents are

O_2/O_2^+, N/N_2^+, NO/NO^+, NO_2/NO_2^+

Compositions vary with altitude



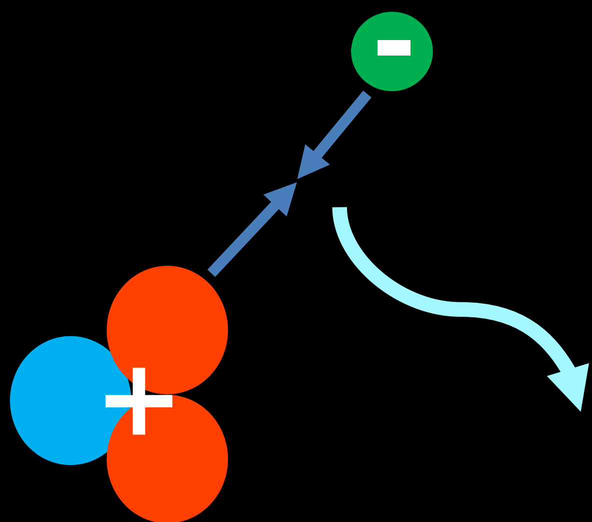
Vast majority of ionospheric plasma formed by this process

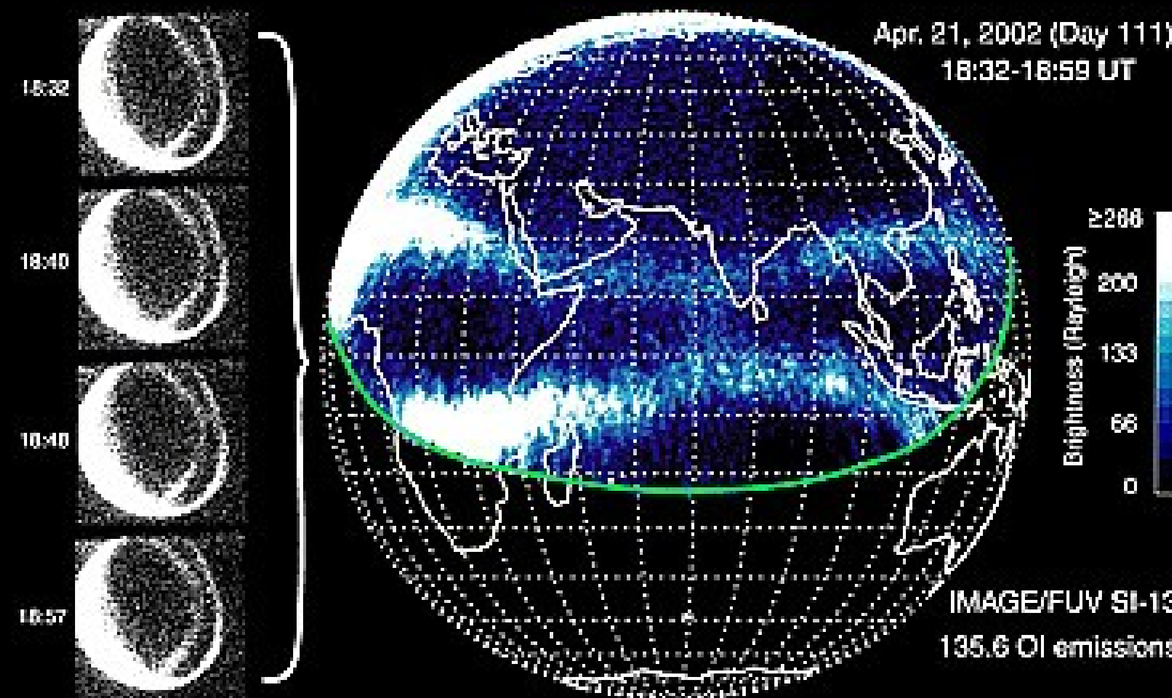
Other ionisation are high energy particle precipitation & meteors

Ionized molecules and liberated electrons are unbound, and move independently.

Plasma Loss

Plasma loss by ion/electron collision and recombination





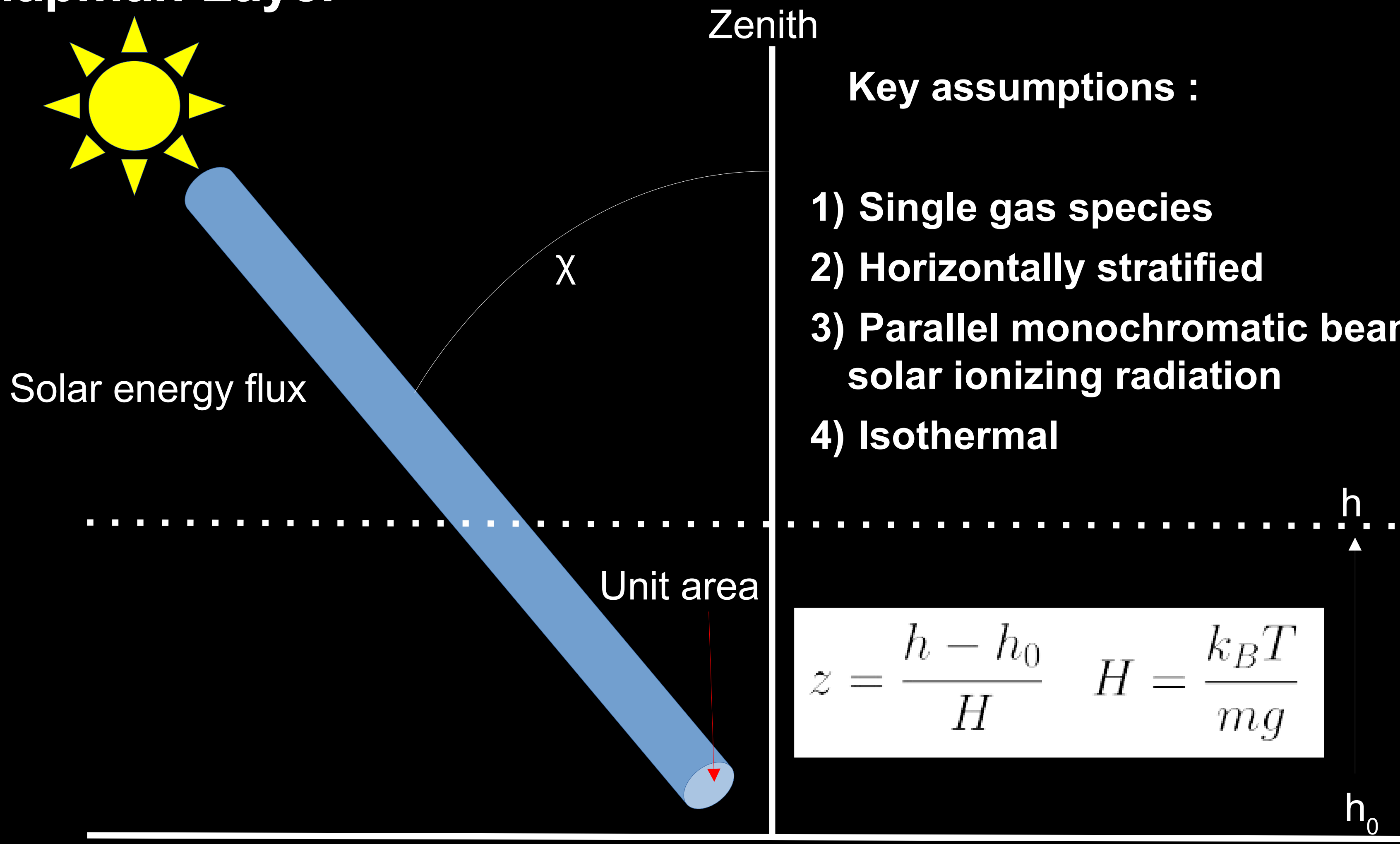
Recombination releases photons often at UV-wavelengths.

UV equatorial recombination airglow emission (135.6 nm).

Recently recombined neutrals can be in an excited state – more airglow

Geophysical Research Letters, Volume: 33, Issue: 15, 2006, DOI: (10.1029/2006GL026161)

Chapman Layer



Key assumptions :

1) **Single gas species**
2) **Horizontally stratified**
3) **Parallel monochromatic beam of solar ionizing radiation**
4) **Isothermal**

$$z = \frac{h - h_0}{H} \qquad H = \frac{k_B T}{mg}$$

$$q(\chi, h) = q_0 exp(1 - z - sec(\chi) exp(-z))$$

Production and Loss

- Global ionosphere is therefore a consequence of plasma production and loss mechanisms

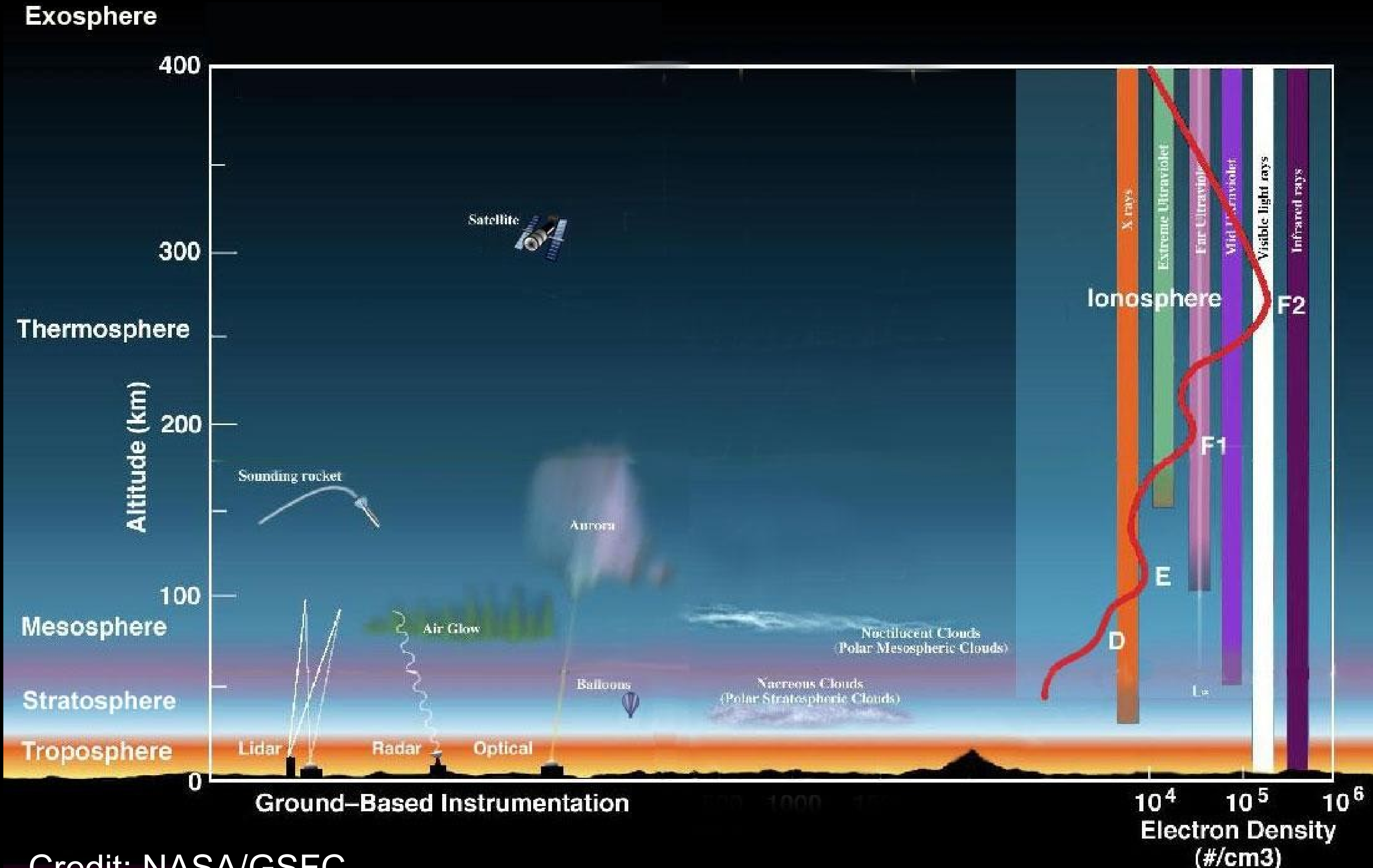
- Localised plasma density loss mechanisms include transport processes as well as recombination
  - Vertical / lateral wind transport out of volume
  - Recombination
  - Motion along terrestrial magnetic field lines

$$\frac{d}{dt} N(e) = q - \alpha N(e)$$

Question / Discussion:

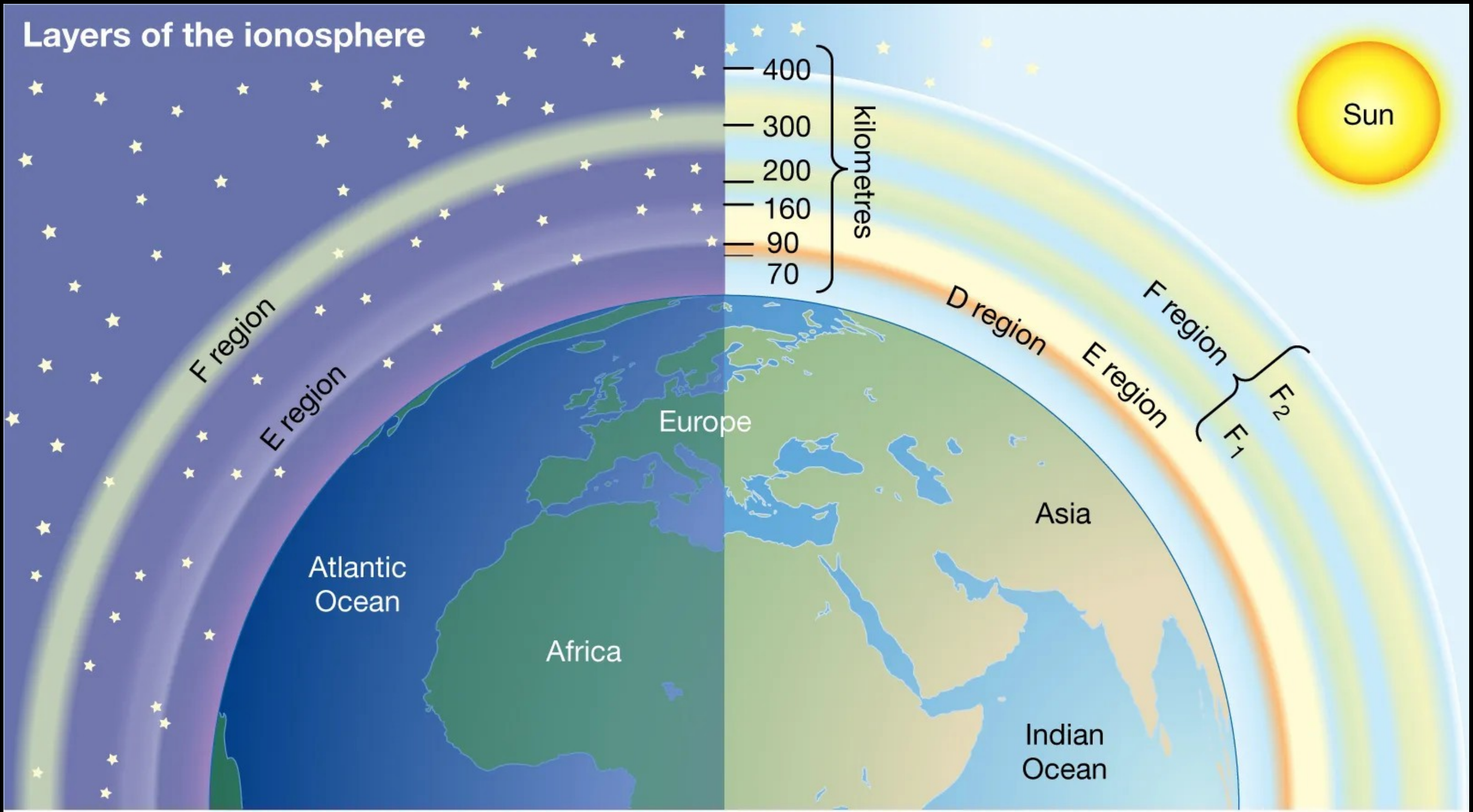
Why is the true ionosphere not Chapman like?

Layers of the Earth's atmosphere, with different altitude penetrations for different wavelengths



Credit: NASA/GSFC

Ionospheric Layers



Note diurnal variation

Ionospheric Layers & Solar Cycle Dependence

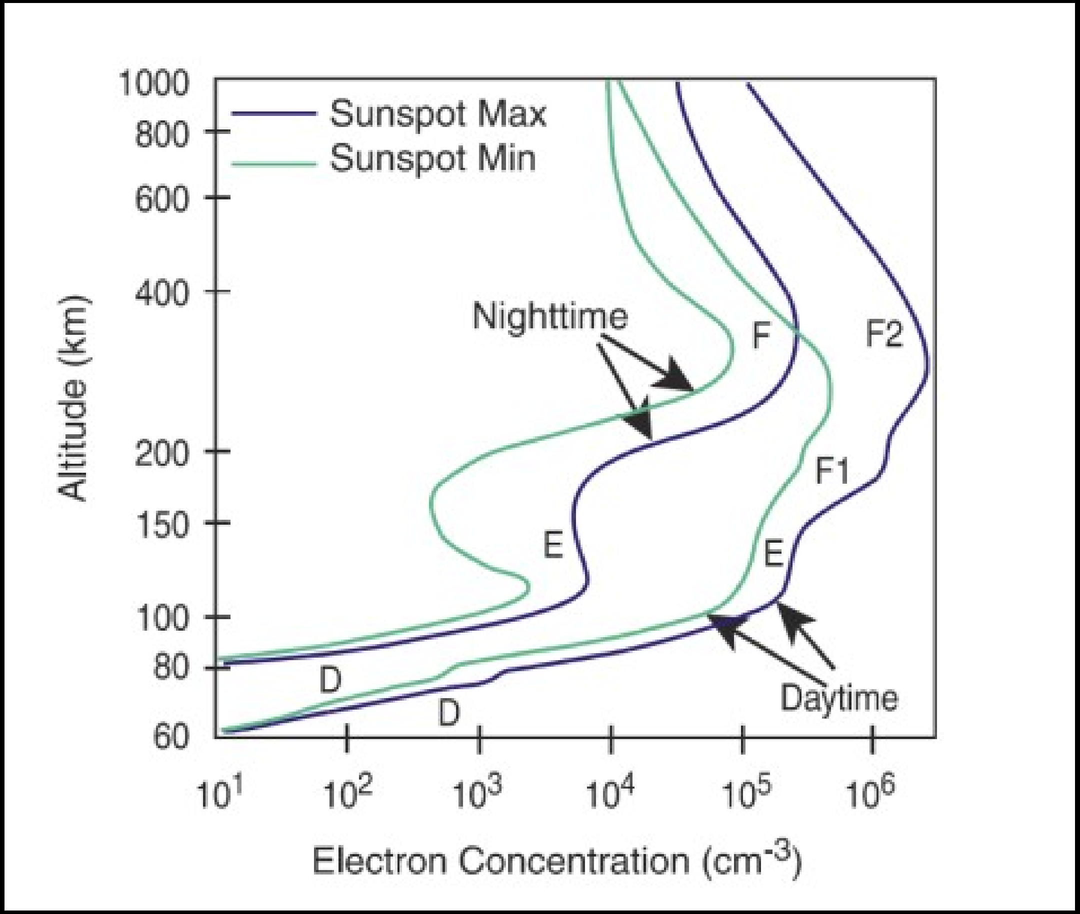


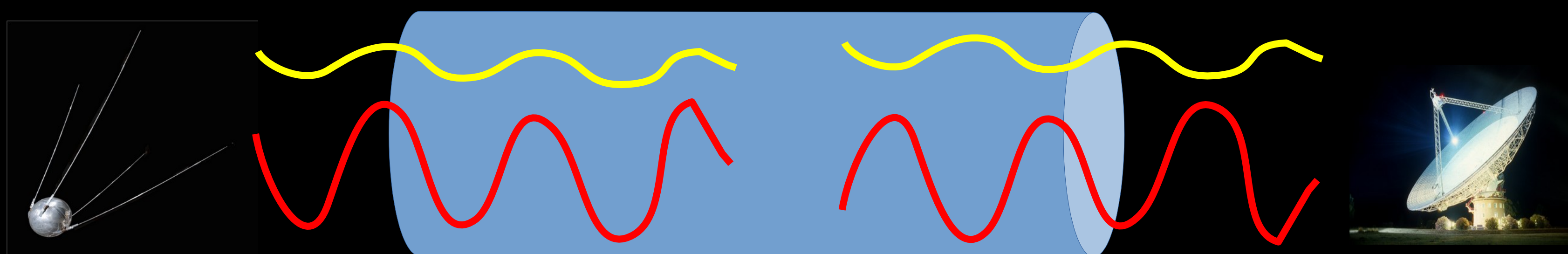
Image Credit: Hargreaves, (1997) after W. Swider, Wallchart, Aerospace Environment, US Air Force Geophysics Laboratory.

- F-region is split into 2 sub-regions labelled F1 & F2
- F1 disappears at night
- E-region retained but much reduced plasma concentration at night
- Column integrated plasma is referred to as *Total Electron Content*
- 1 TECu = 10^{16} el m^{-2}
- Note substantial dependence in typical TEC at solar maximum / solar minimum

Measuring TEC with GNSS signals

GNSS satellites typically transmit on a small number of discrete frequency channels in the GHz range (usually referred to as L1 & L2, 1.575 GHz & 1.23 GHz respectively)

Transmission timing is encoded in the signal so that phase can be established

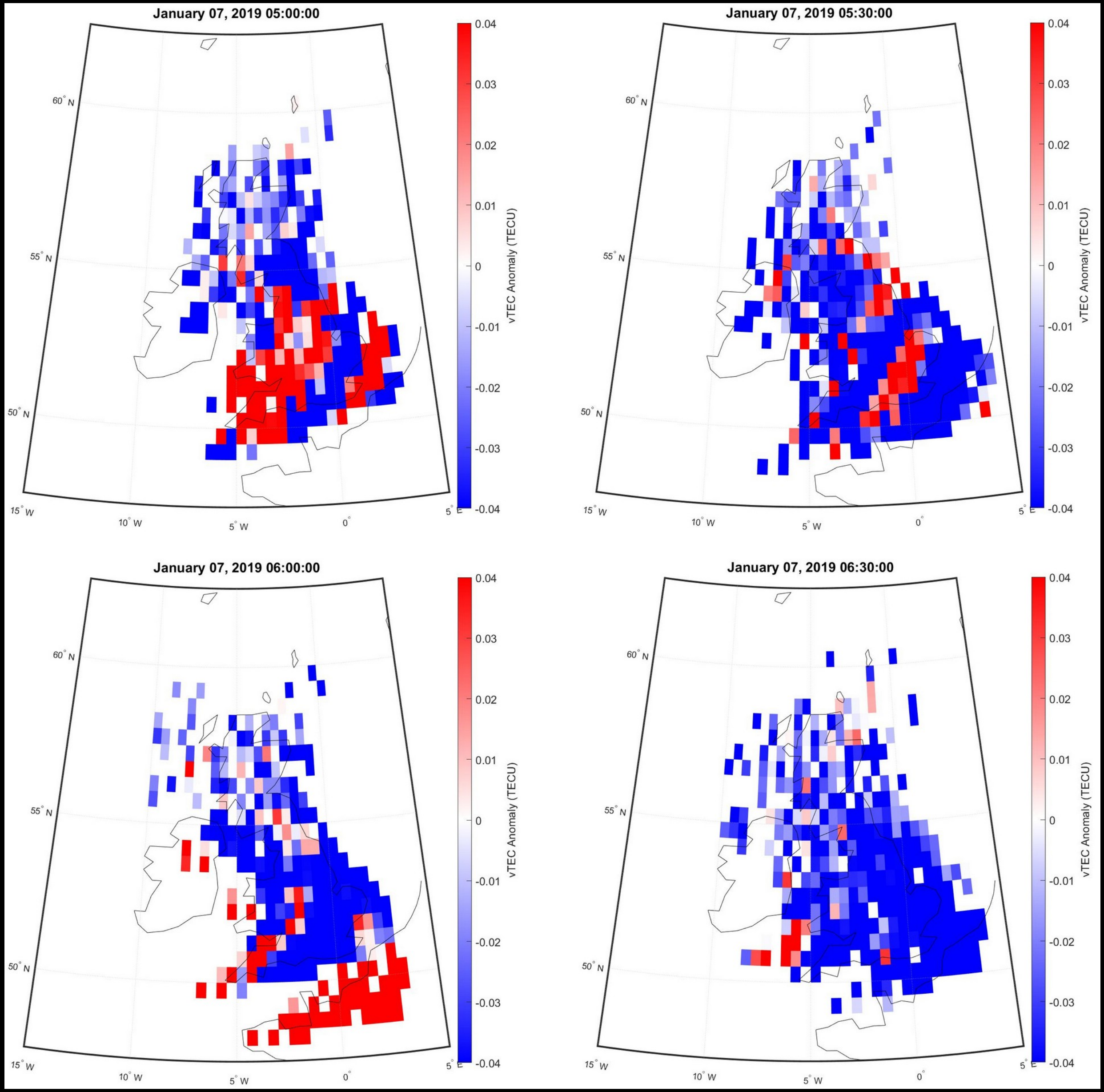


Phase delay observed between two frequencies is proportional to TEC

$$TEC_{phase} = \frac{f_1^2 f_2^2}{40.3(f_2^2 - f_1^2)}(\Phi_2 - \Phi_1)$$

$$TEC_{range} = \frac{f_1^2 f_2^2}{40.3(f_2^2 - f_1^2)}(R_1 - R_2)$$

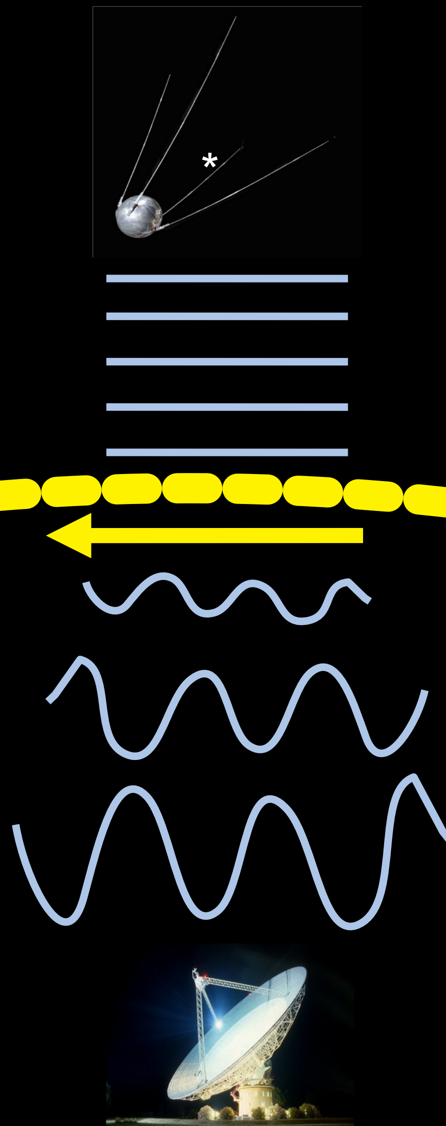
TEC mapping



- Can use many lines-of-sight to GNSS satellites simultaneously to produce ‘TEC maps’
- Sensitivity depends on density of lines-of-sight, and accuracy of measuring phase delays
- Effective technique for observing ionospheric features over large areas / distances
- Dorrian et al., (2023)

Ionospheric Scintillation (basics)

Coherent radio transmissions from satellites, typically at one or a small number of frequencies, transition through highly structured ionospheric plasma.



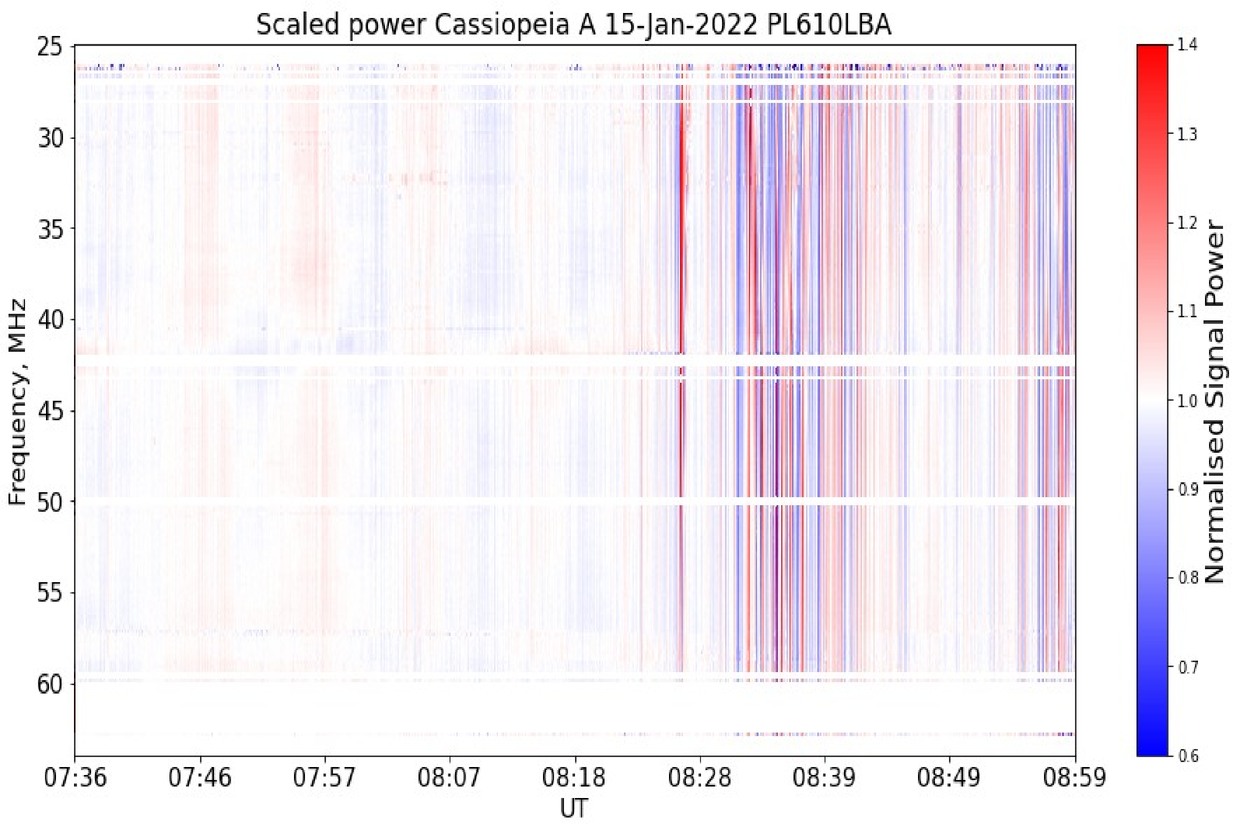
Rapid variation in refractive index induces many phase changes along the wavefront, generating interference pattern

If plasma in motion then interference pattern drifts across raypath

Wavelets constructively and destructively interfere with distance from scattering plasma, resulting in scintillation pattern which varies in time (if scattering plasma is in motion)

*FYI: Sputnik 1 transmitted on 2-channels: 20 & 40 MHz

Ionosphere scintillation (continued)



LOFAR dynamic spectra showing quiet conditions and perturbed ionospheric conditions

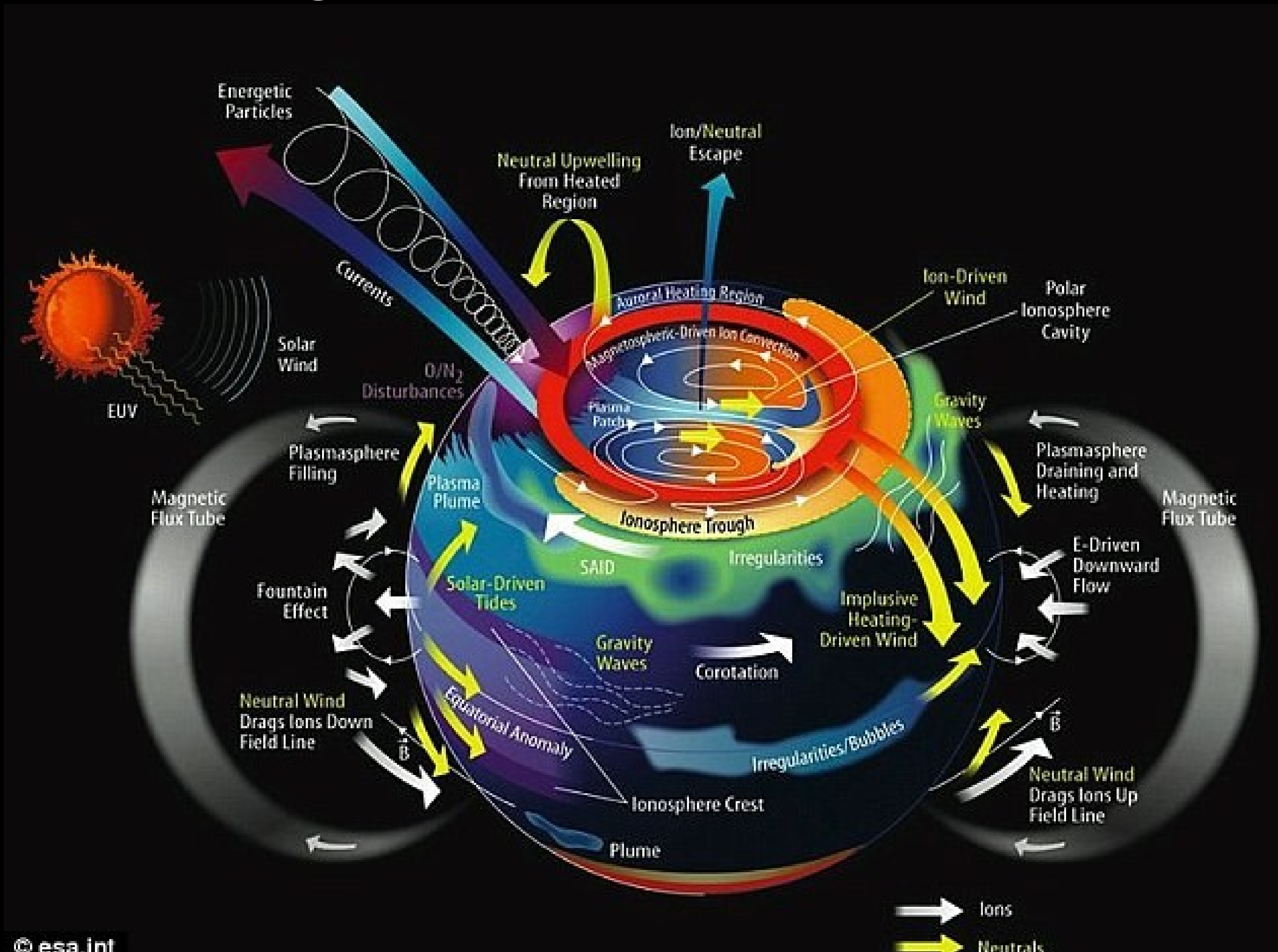
- Ionospheric scintillation is often characterised statistically by the S_4 index

$$S4 = \sqrt{\frac{\langle I^2 \rangle - \langle I \rangle^2}{\langle I \rangle^2}}$$

- *I* is received signal power, usually time-averaged over 60-seconds

- S_4 of < 0.4 (quiet)
- S_4 of > 0.4 & < 0.8 (moderate)
- S_4 > 0.8 (disturbed)

Ionosphere regions



Ionosphere regions : Equatorial

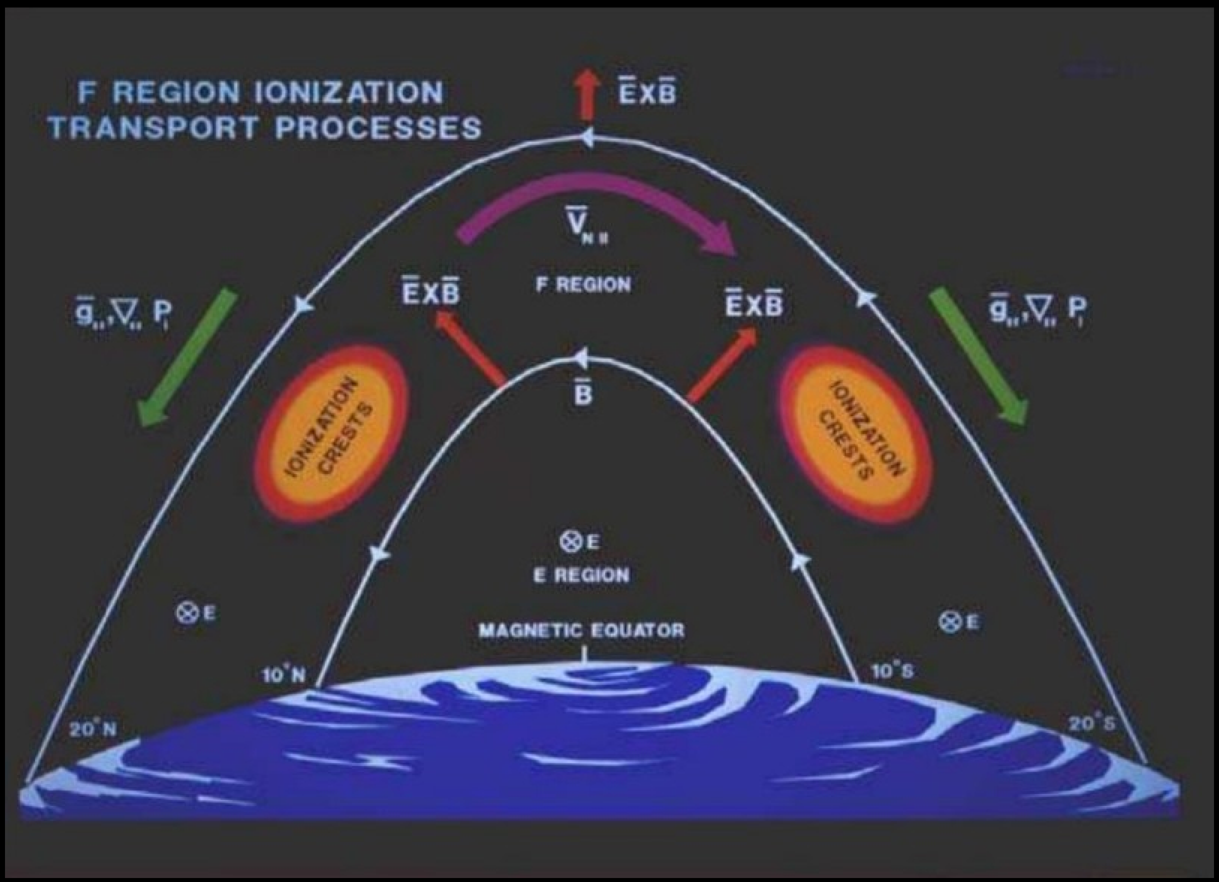
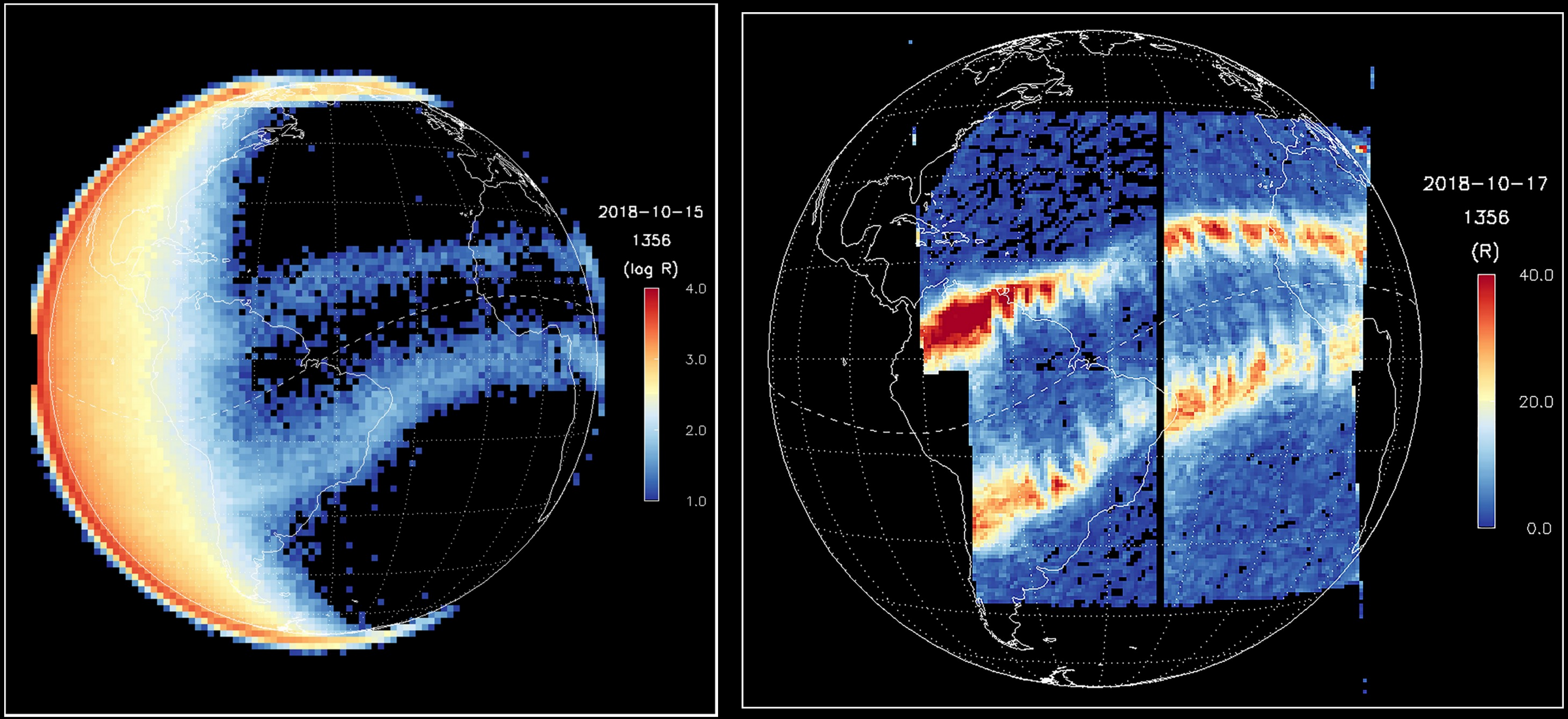


Image Credit: de La Beaujardière, 2004

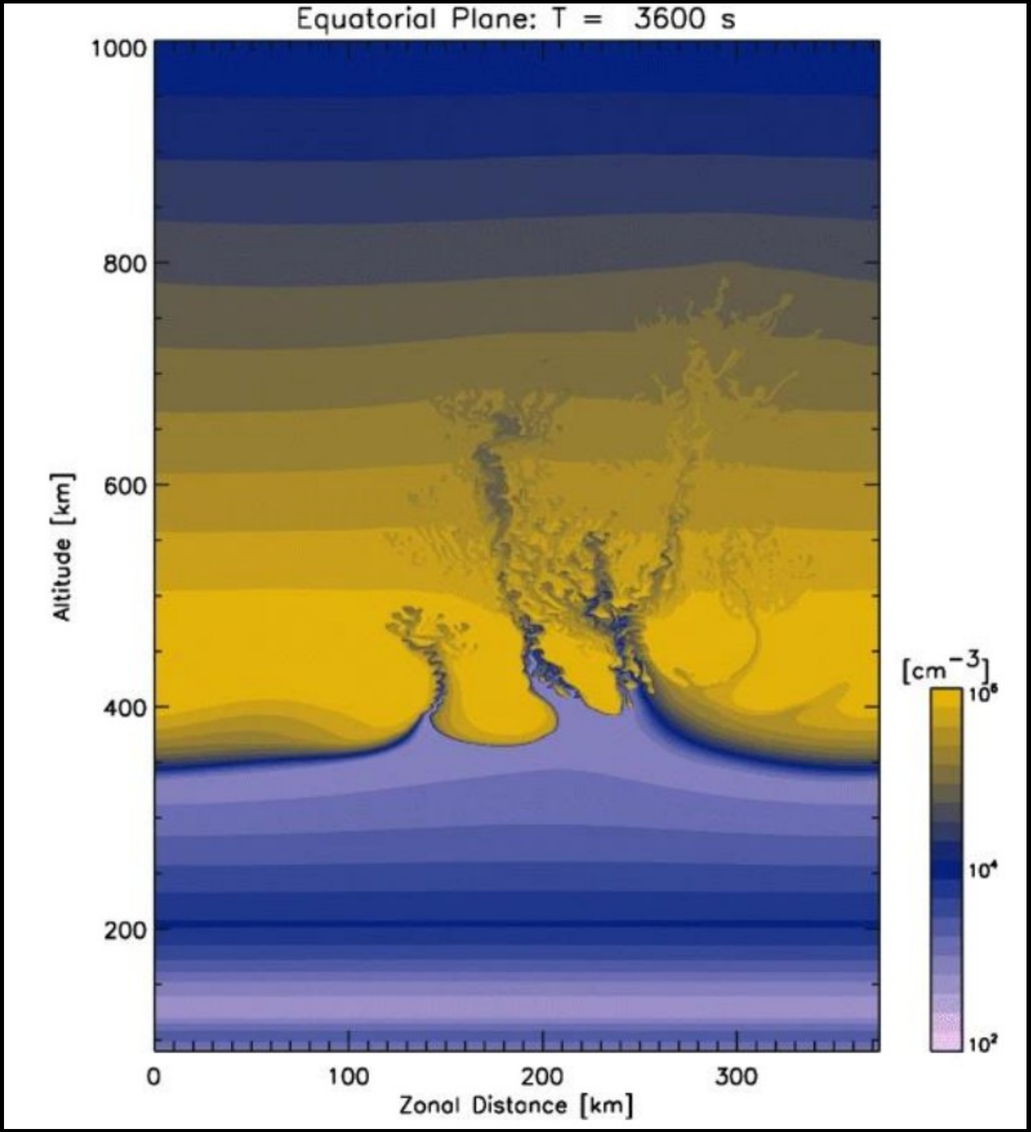
- Plasma rises by convection over the magnetic equator
- Gravity robs momentum from upwellings
- Plasma sinks back down, but follows terrestrial magnetic field lines
- Causes plasma depletion over equator and enhancements to North & South
- Called the *Equatorial Anomaly* or *Appleton Anomaly* (Appleton, 1948)

Ionosphere regions : Equatorial Anomaly



Eastes et al., (2019)

Ionosphere regions : Equatorial Plasma Bubbles



- Equatorial plasma bubbles result from *Rayleigh-Taylor instabilities*
- Imperfections in a boundary between two fluids of different densities (with the higher density fluid atop the lower density fluid) can grow rapidly into large 'bubbles'
- Boundary imperfections common in strongly convecting fluids (e.g. equatorial ionospheric plasma)
- EPBs cause significant enhancements in ionospheric scintillation by increasing variability of refractive index as a function of space & time

Image Credit: Yokoyama, 2017

Ionosphere regions : Mid-latitude

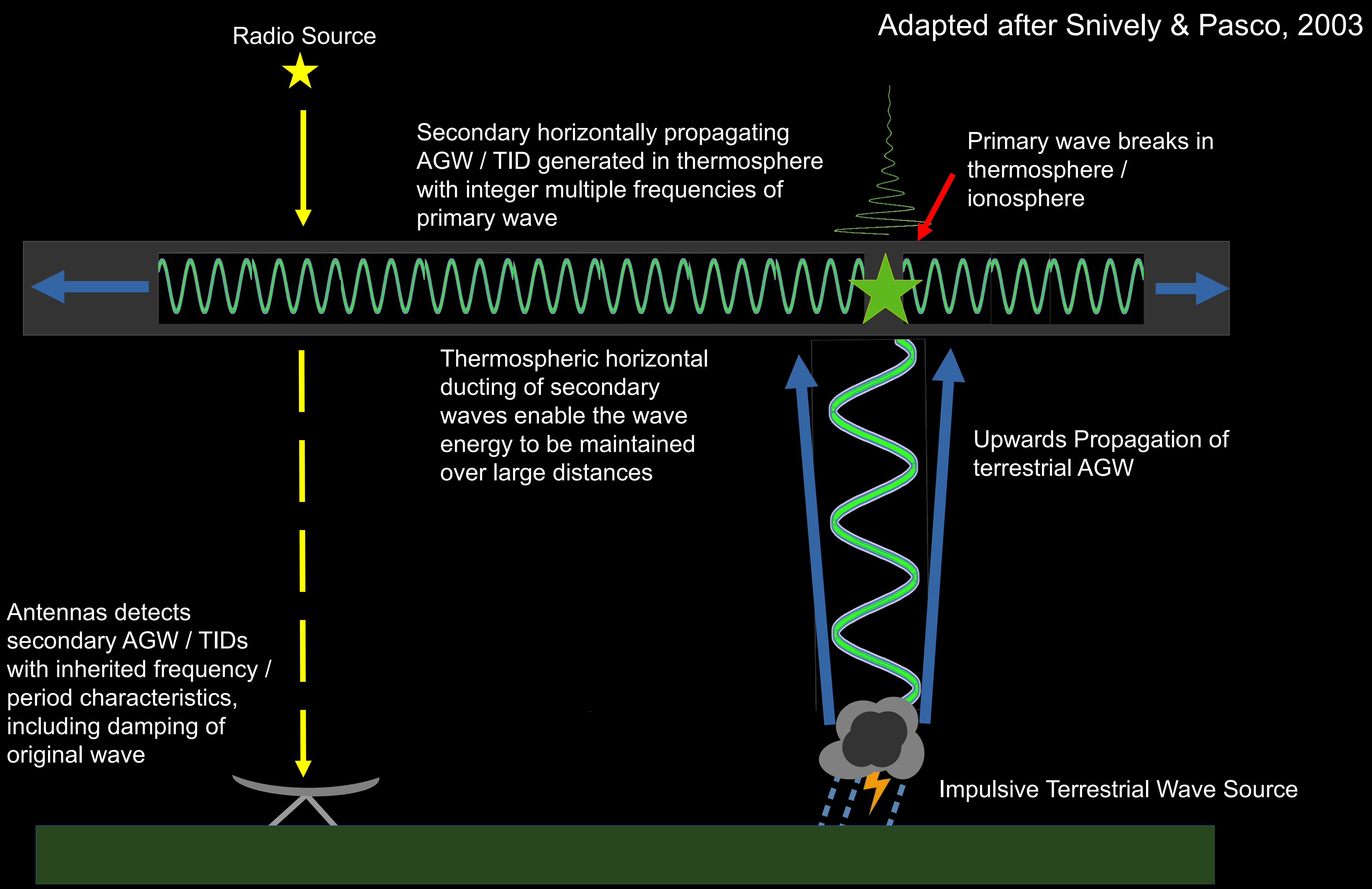
Extends from ~ 30^{o} – 60^{o} magnetic latitude
Dip angle varies from ~20^{o} – 60^{o}

- Solar illumination (solar zenith angle SZA) more variable as a function of latitude than at equator
- Larger χ angle means generally weaker illumination and ionisation than at equator; plasma bubbles not present
- Generally regarded as the ‘quieter’ part of the ionosphere, however…
- Perturbations which dominate here are *travelling ionospheric disturbances* (TIDs)

Travelling Ionospheric Disturbances (TID)

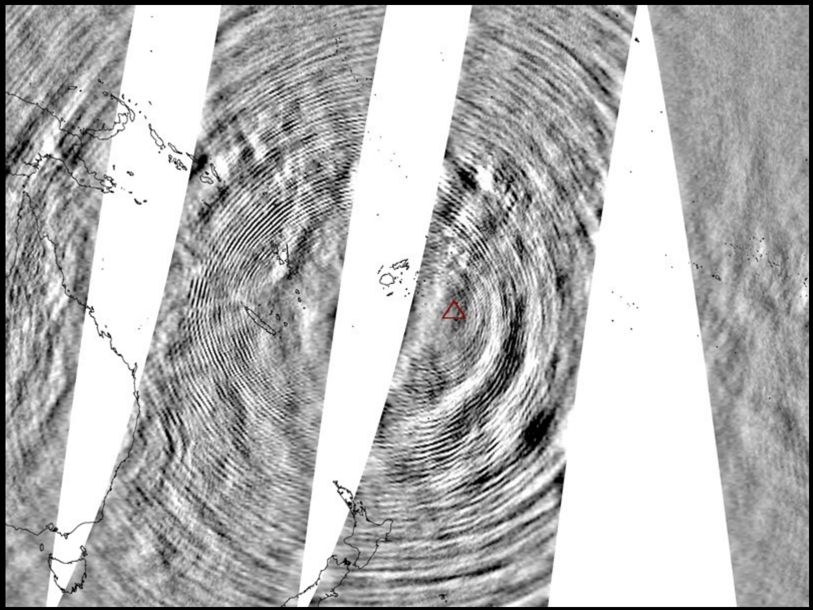
- Internal atmospheric gravity waves (AGW) are ubiquitous in Earth’s atmosphere
- Generated by two categories of sources, space weather, and terrestrial
- Space weather (auroral substorms) form supersonic ionospheric current systems
- Terrestrial sources are many and varied
- Some examples : Thunderstorm systems, tropical cyclones, sunrise, orographic lateral wind deflection, volcanic eruptions, earthquakes, meteor impacts
- Terrestrial sources generate upwardly propagating AGW which can reach the ionosphere and manifest as TIDs

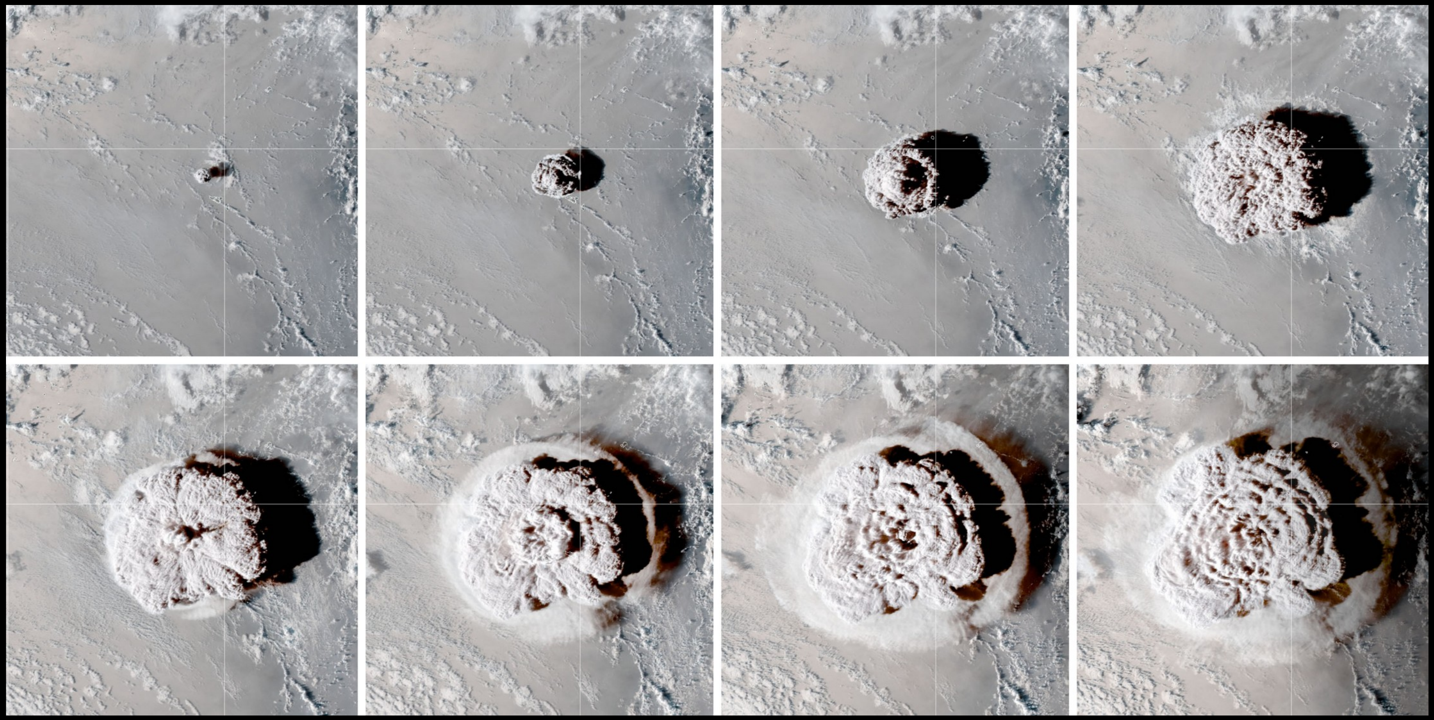
Terrestrial AGW / TID ducting



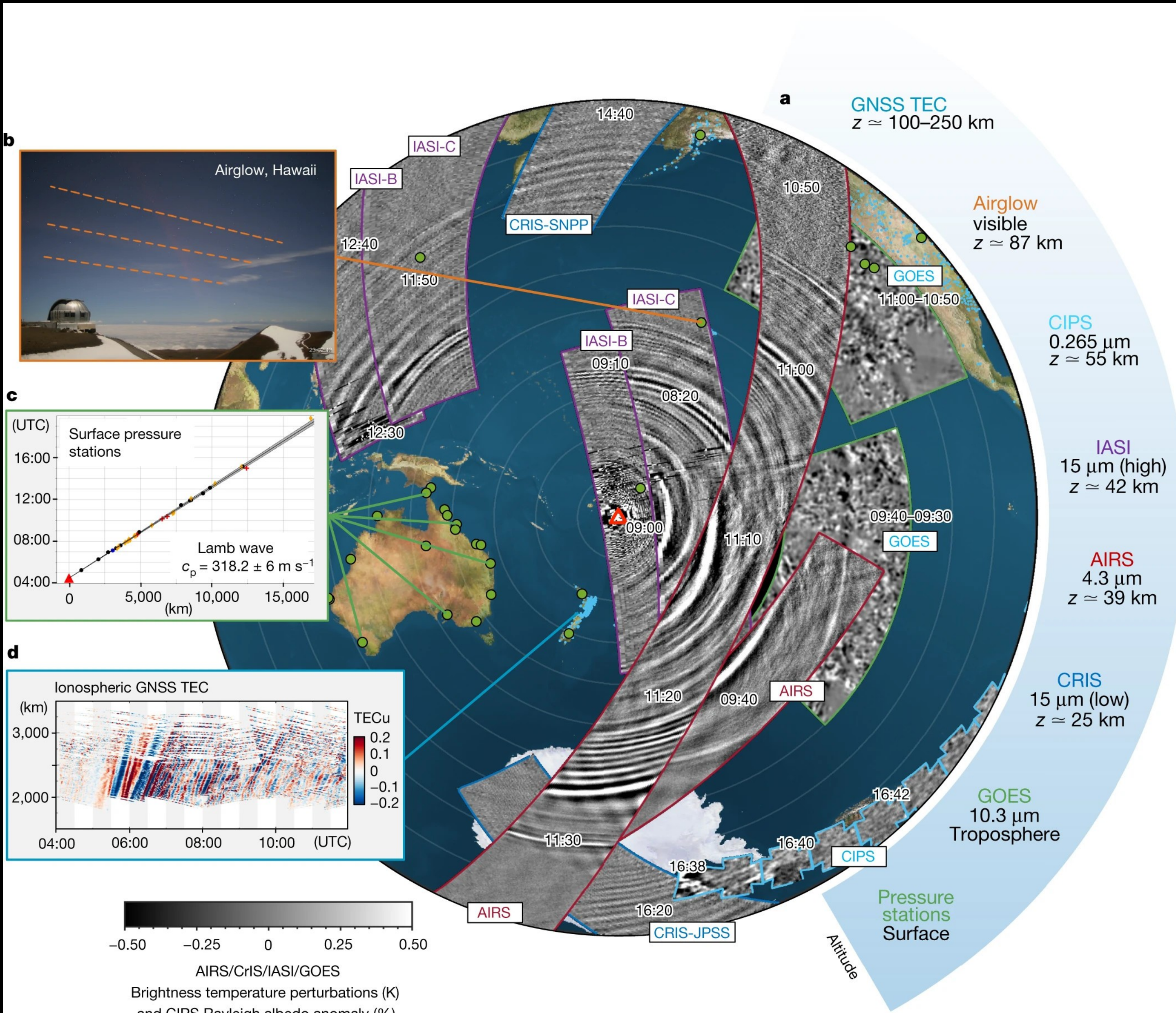
Tonga Eruption

- Tonga Eruption; largest volcanic eruption of 21st century
- 15th. January 2022, 0415 UT
- Eruption column reached mesosphere
- Distinct AGWs / Lamb Waves generated





Tonga Eruption



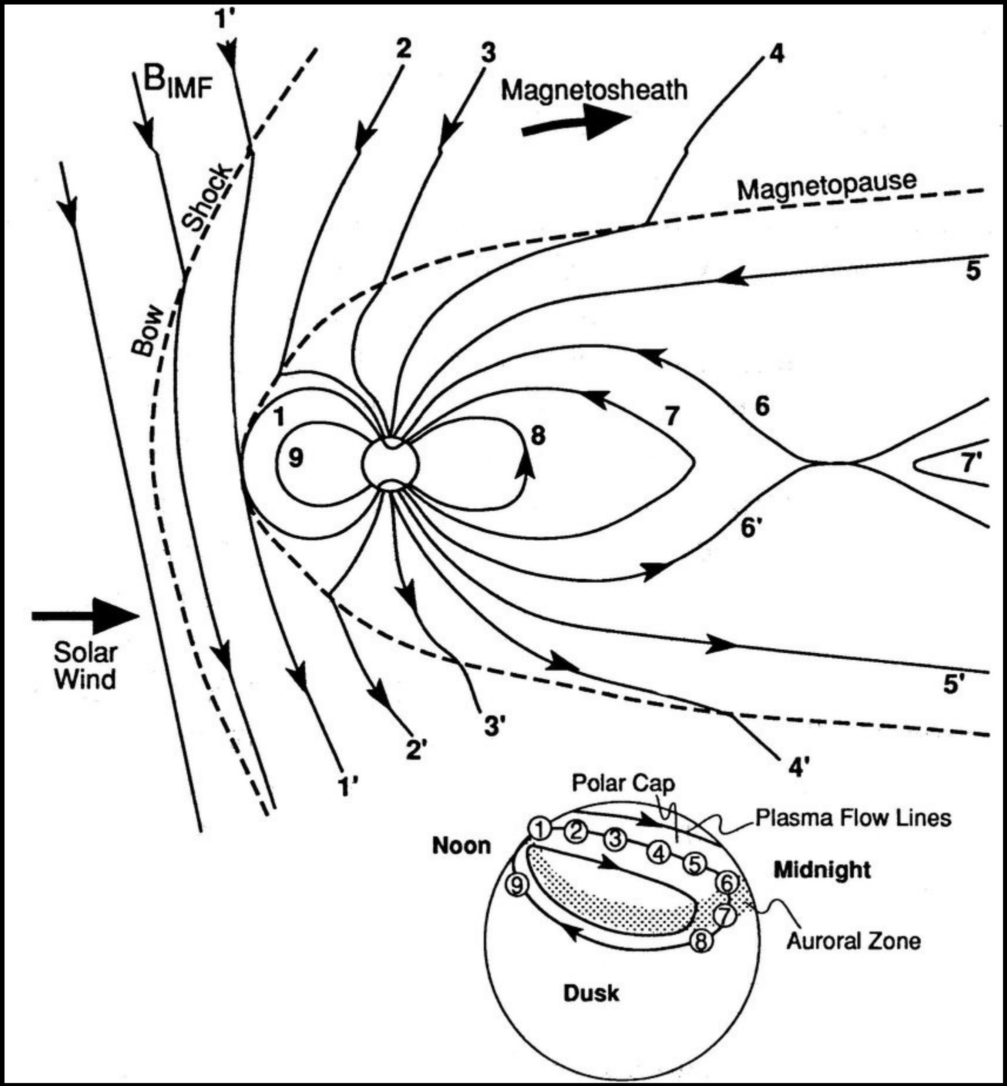
Wright et al., (2022)

Global reach of Tonga eruption atmospheric waves

Ionosphere regions : Auroral / High Latitude

- Seasonal extremes – solar illumination strongly varies throughout the year.
- In winter solar illumination is zero for many months; in summer it is constant.
- Significant extra source of plasma production here caused by *high energy particle precipitation*
- Major source of night side plasma production which is not present at other latitudes
- Auroral excitation requires particle energies of between 1 – 10 keV
- Most magnetospheric electrons cannot reach the ionosphere due to magnetic mirroring – those that do must have pitch angle within the loss cone.
- Electrons are accelerated by electric fields and Alfvén Waves in the magnetosphere-ionosphere transition region (~ 1000 km – 30 000 km altitude), which ‘widens’ the loss cone

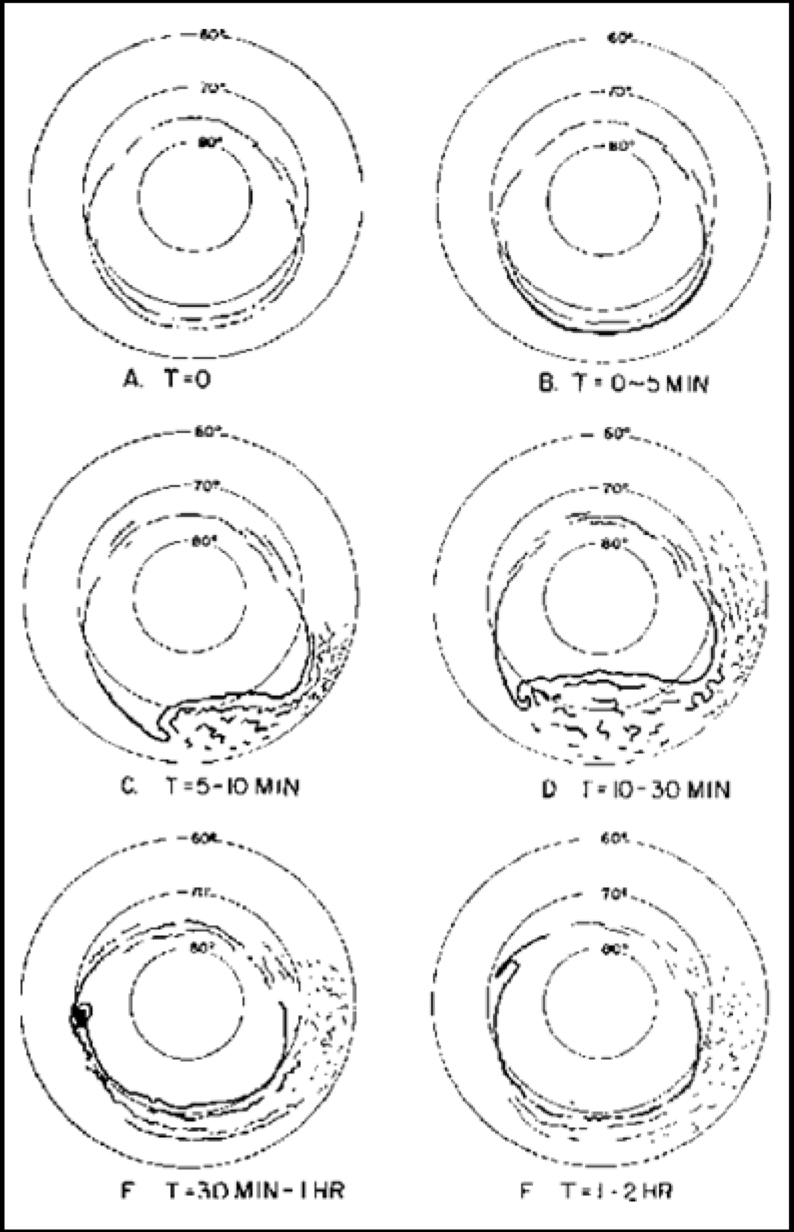
Ionosphere regions : Auroral / High Latitude



Adapted from Dungey (1961)

- Nightside aurora is a consequence of the *Dungey cycle*
- Solar / interplanetary magnetic field convected from dayside to nightside
- Magnetic reconnection occurs in magnetotail which releases large population of energetic electrons
- Electrons further accelerated in magnetosphere – ionosphere acceleration region above poles
- Auroral substorms – visible manifestation of the effects of the space weather environment on Earth environment
- High latitude field lines also connect to magnetosheath and solar wind

Ionosphere regions : Auroral / High Latitude



Auroral substorm, defined by Akasofu (1964), proceeds in several stages:

Auroral oval undergoes initial brightening

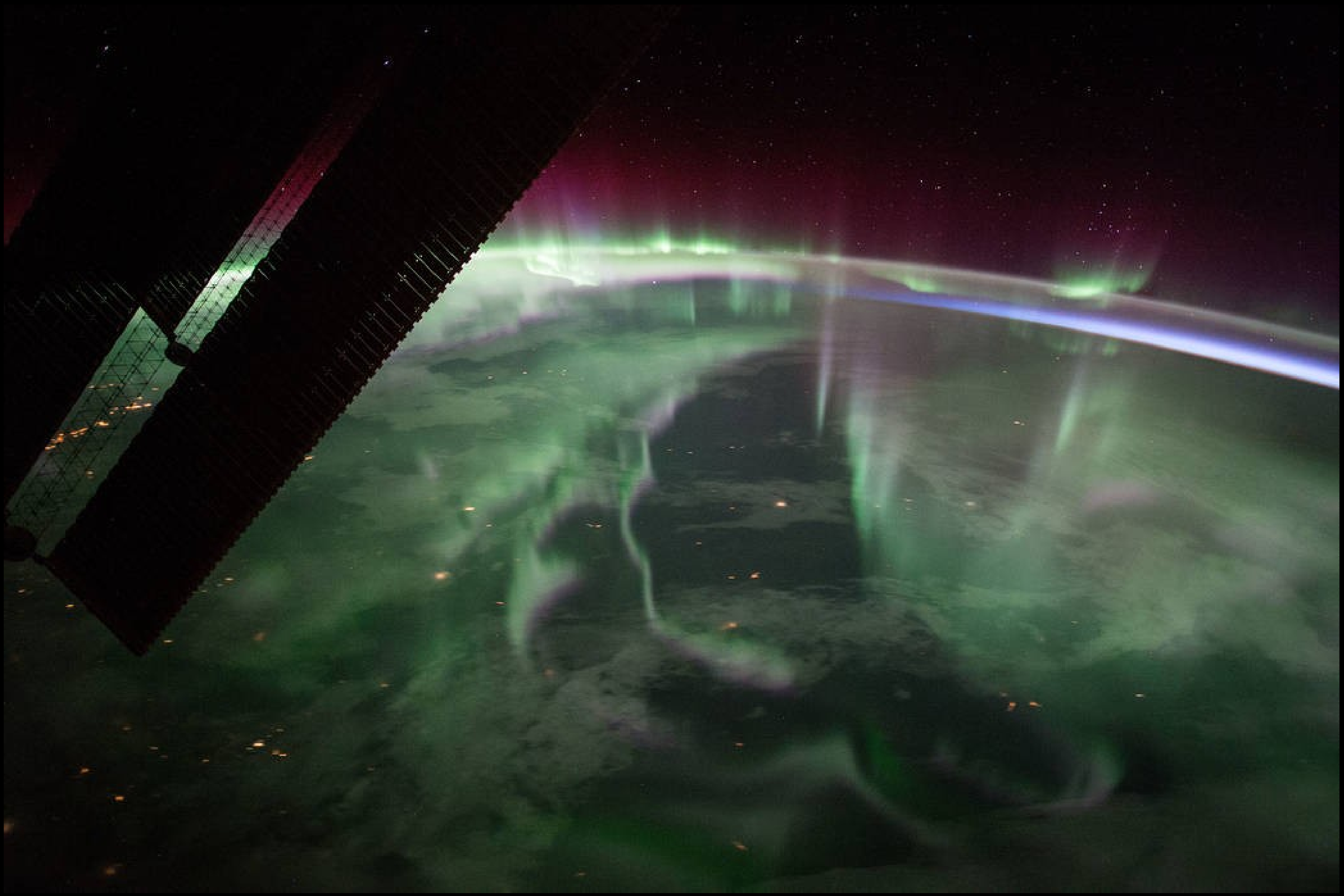
Expands equatorwards and oval thickness broadens in latitude

Becomes more filamentary

Recovery phase – arc gradually retreats polewards again and returns to initial conditions

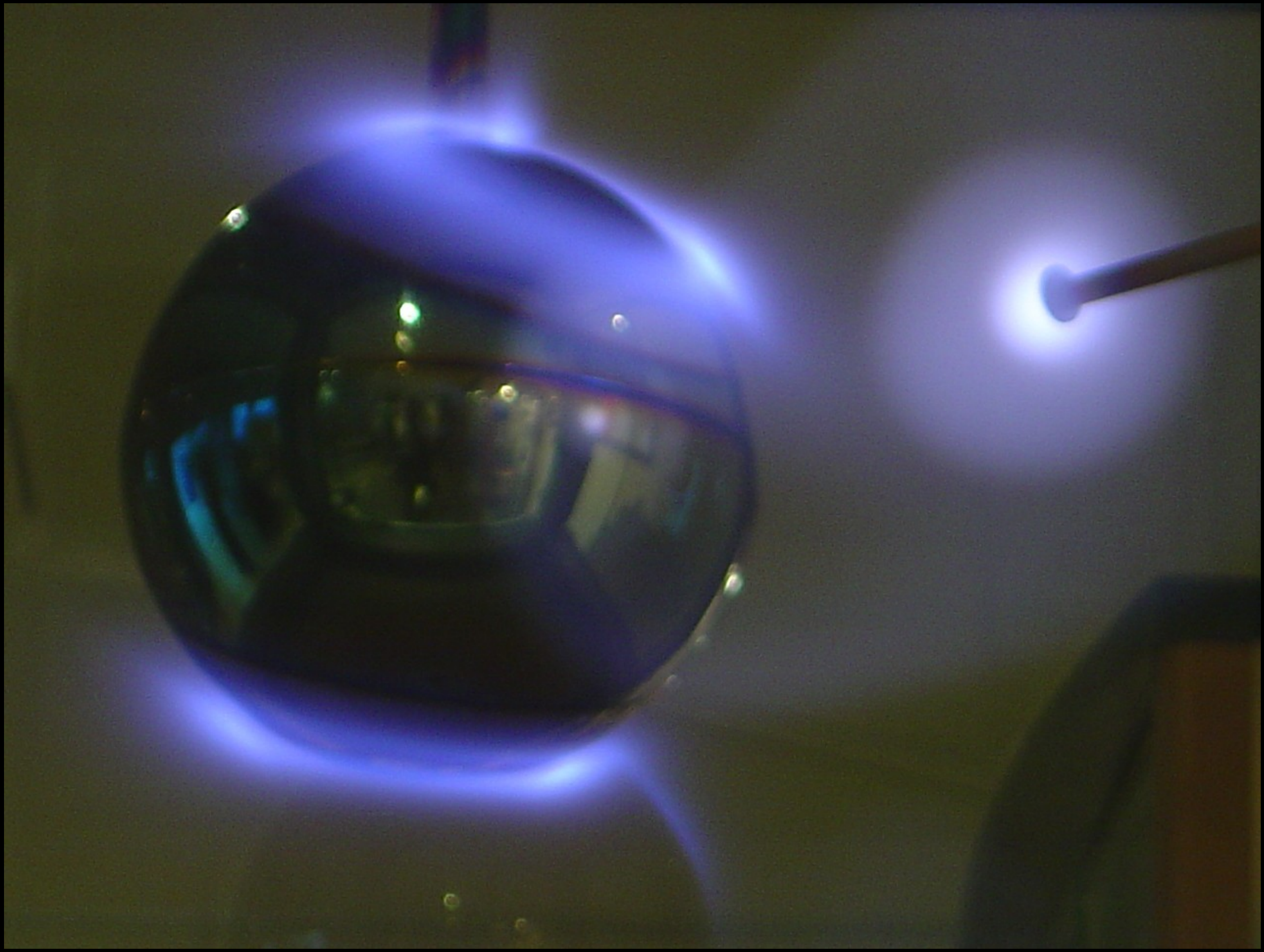
Syun-Ichi Akasofu in 2011

Ionosphere regions : Auroral / High Latitude



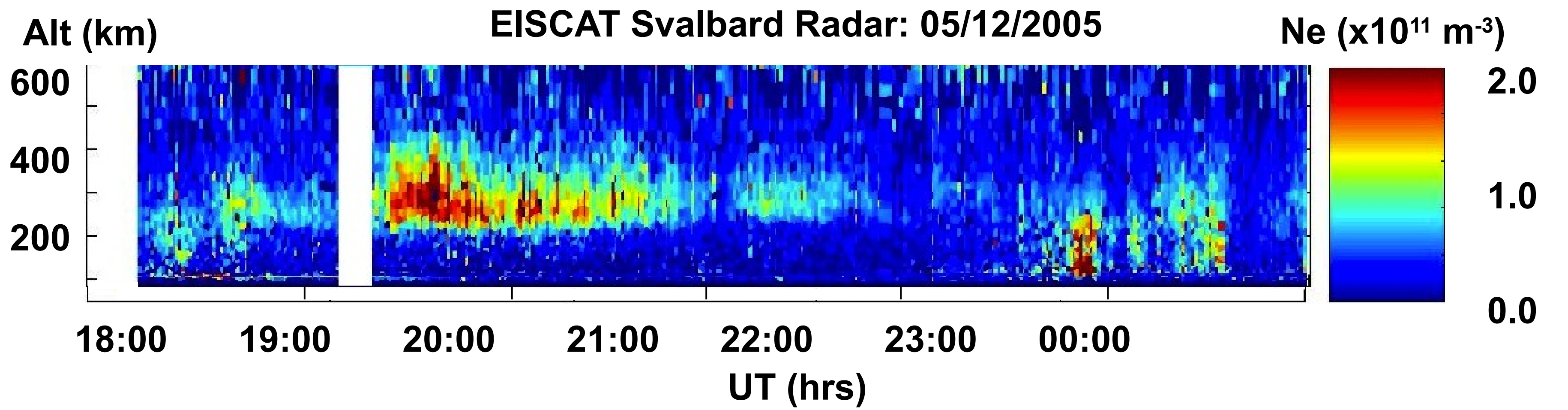
Aurora over Canada as seen from ISS during substorm. Credit: NASA

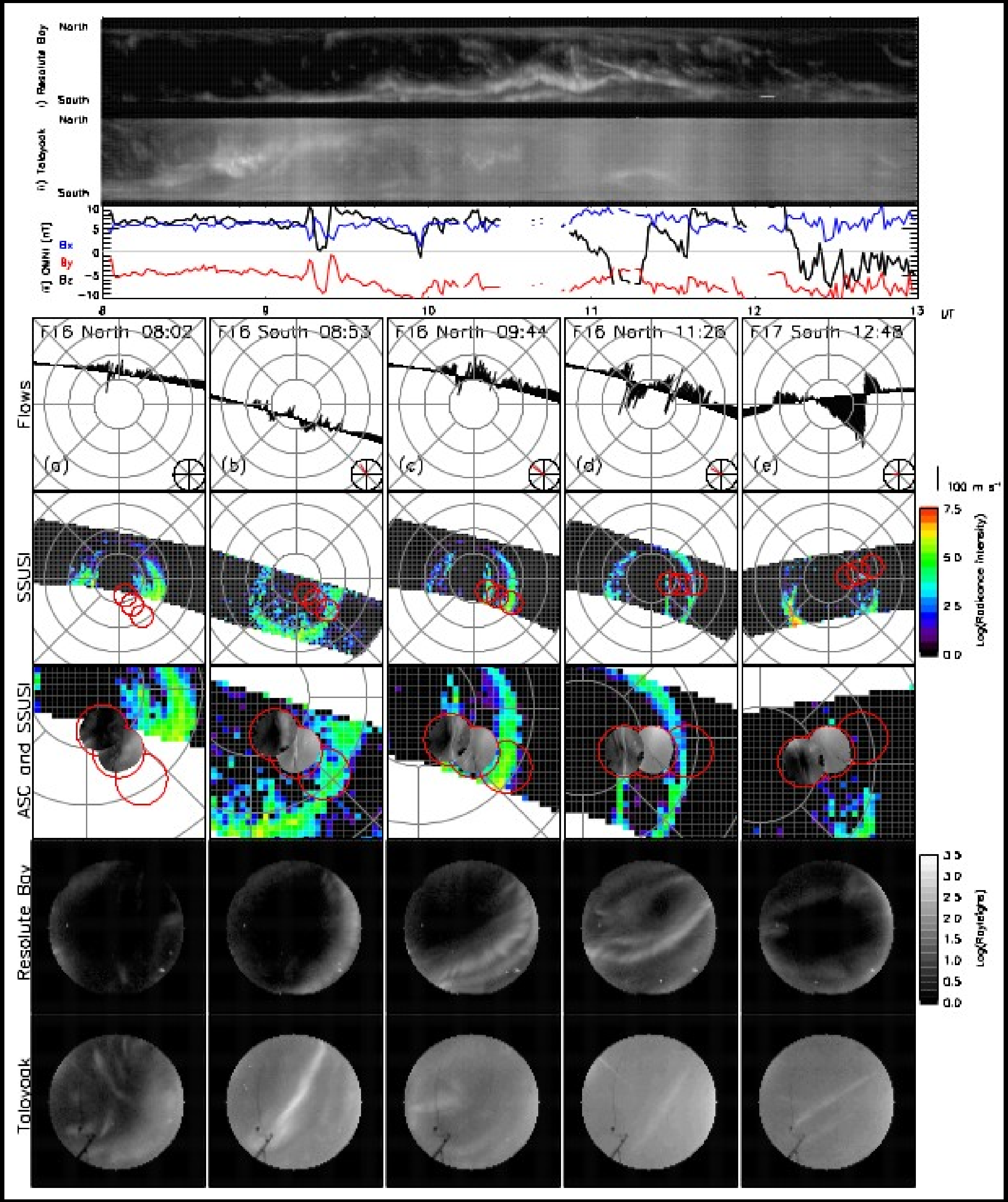
Ionosphere regions : Auroral / High Latitude



Ionospheric regions : Auroral / High Latitude

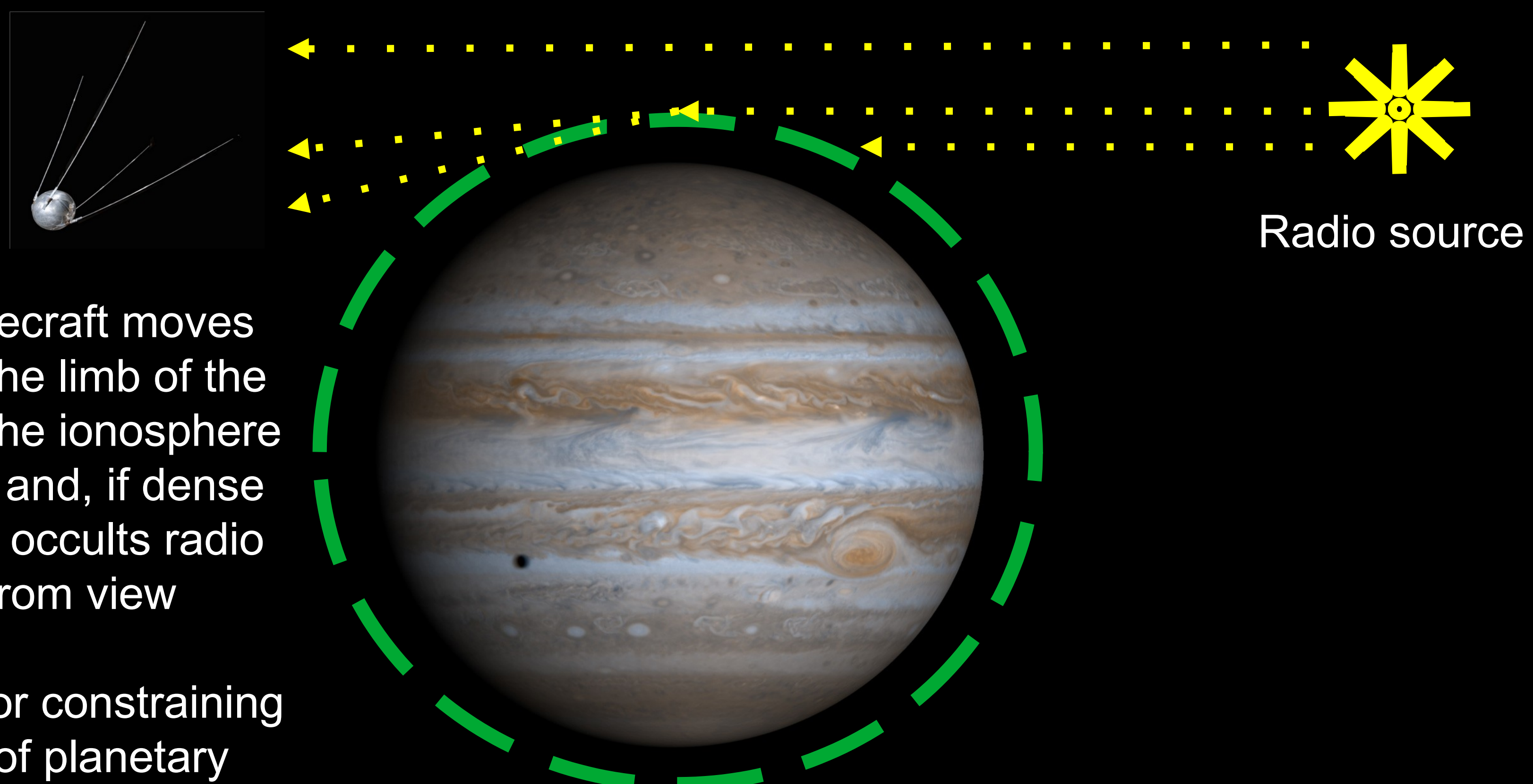
- High latitude ionosphere studied by a variety of ground based facilities such as :
  - EISCAT Svalbard Radar (left, example data below)
  - Ground based magnetometers
  - All sky cameras
  - Sounding rockets
- Also studied from space:
  - In situ particle and magnetic field measurements by polar orbiting satellites
  - Observations of UV-auroral emission





- Example study of auroral zone ionosphere using many different data sources
- Space based UV-imaging, ASI, magnetic field measurements
- Bowen et al., (2023)

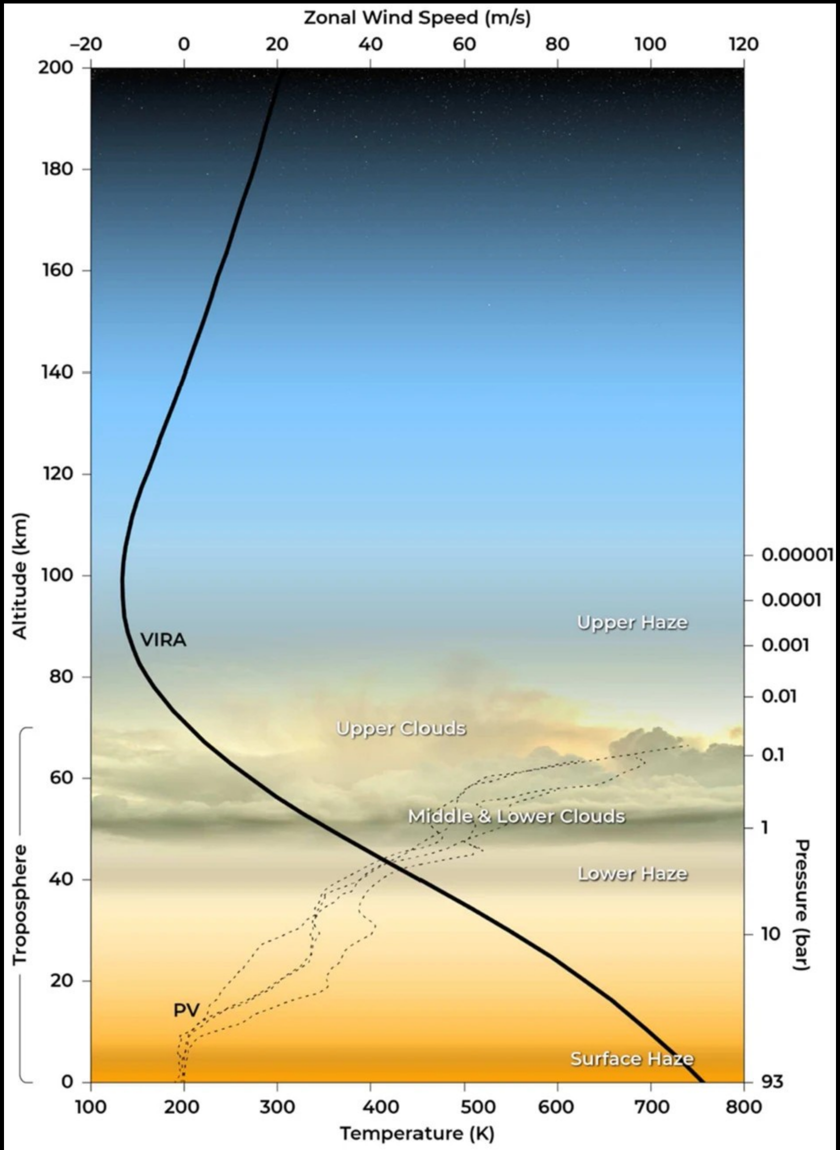
Remote detection of planetary ionospheres by radio occultation

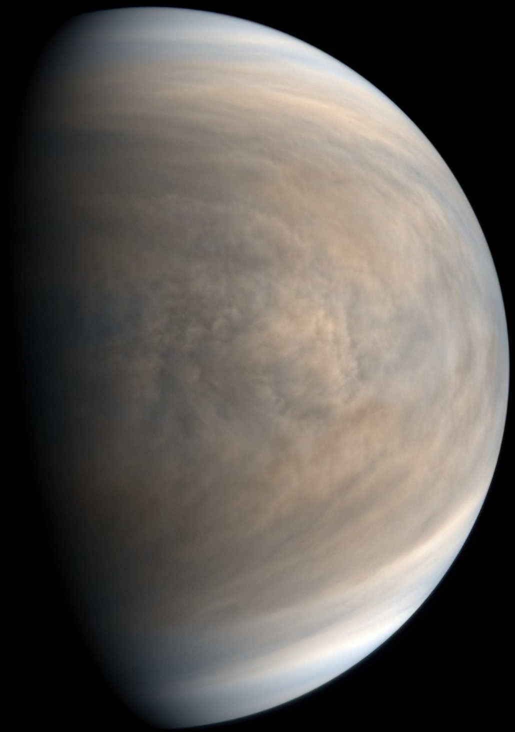


As spacecraft moves behind the limb of the planet, the ionosphere scatters and, if dense enough, occults radio source from view

Useful for constraining models of planetary ionospheres which are otherwise hard to sample

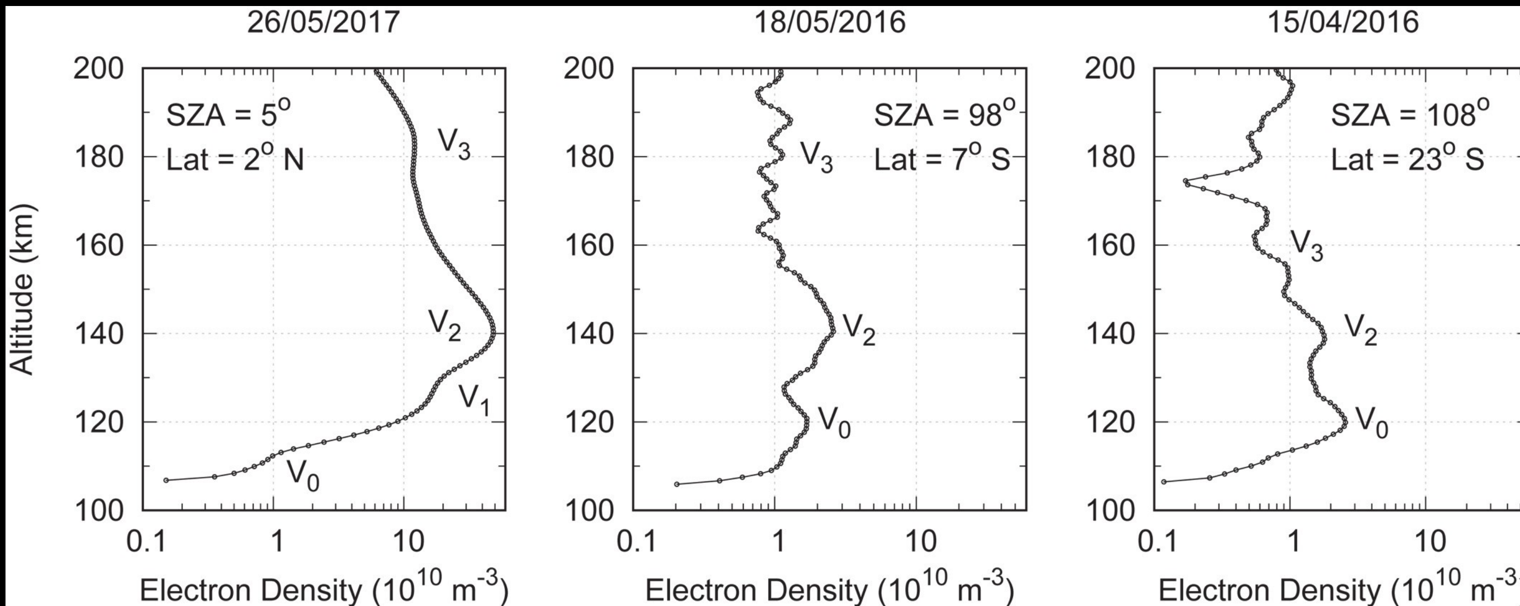
Planetary ionospheres : Venus





- Main atmospheric constituent gas is CO_2
- Closer to the Sun so higher solar-UV flux
- Much thicker atmosphere than Earth

Planetary ionospheres : Venus



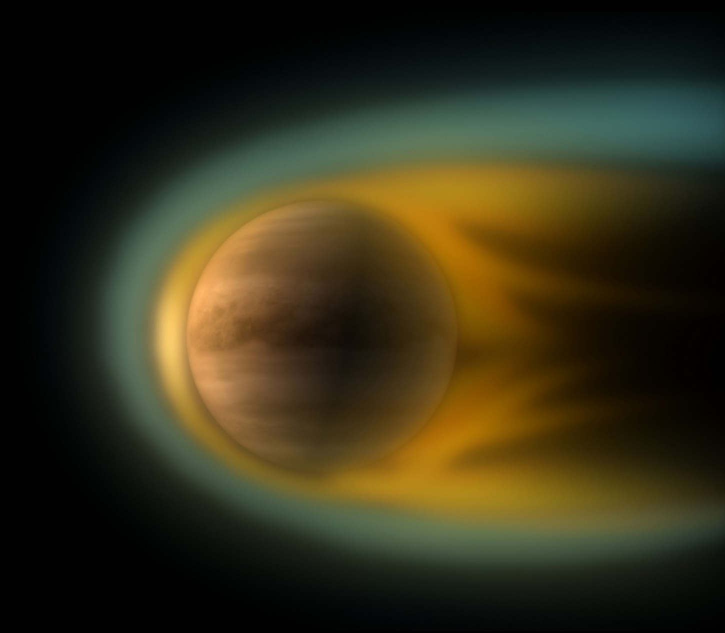
Tripathi et al. (2022)

Venus lacks a global magnetic field unlike the Earth

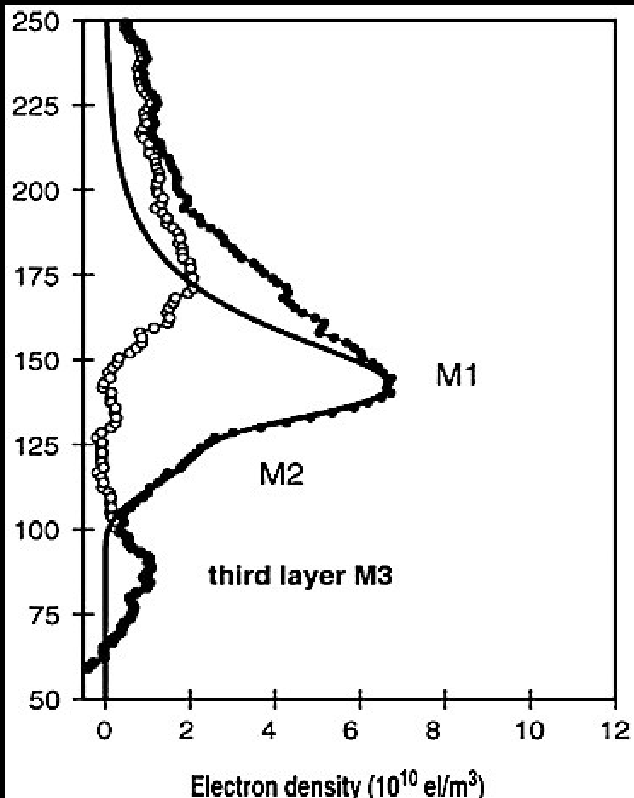
Solar wind interacts directly with upper atmosphere

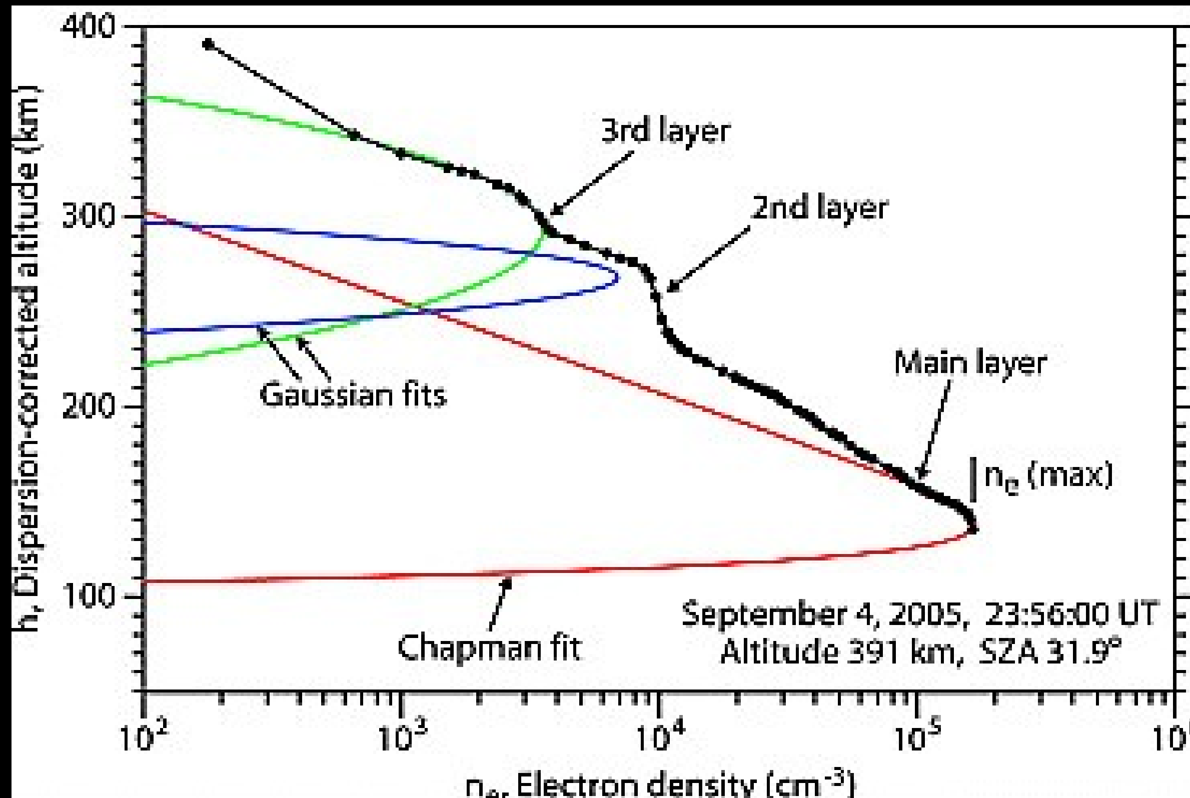
Solar wind particles are source of ionization and loss of atmospheric gas to space

Process called *scavenging*



Planetary ionospheres: Mars



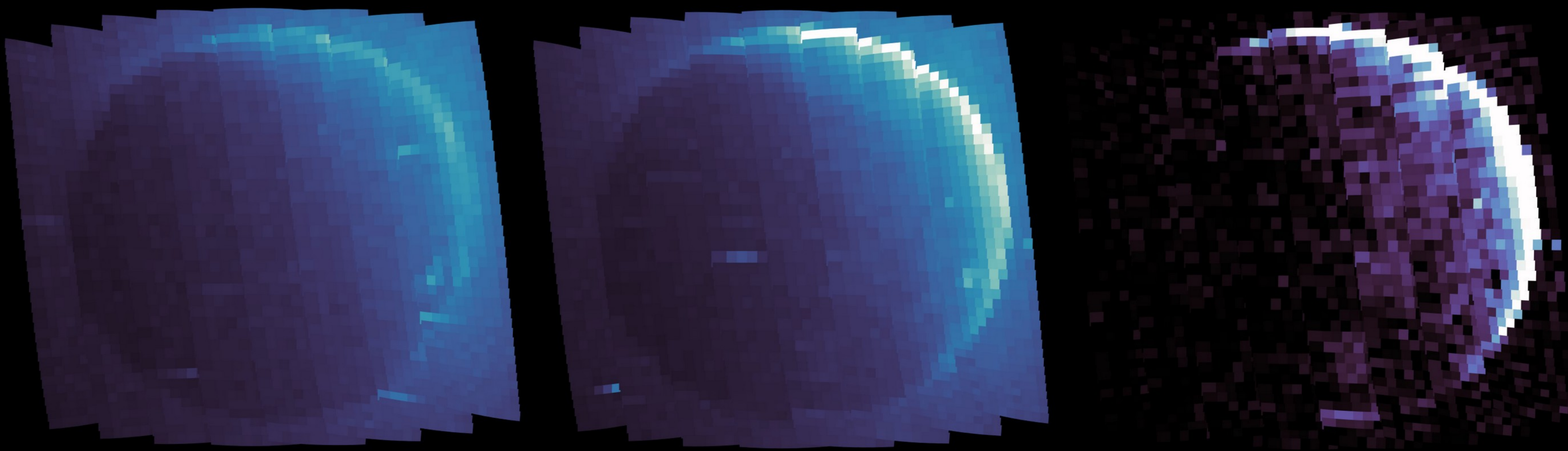


Reviews of Geophysics, Volume: 49, Issue: 4, 2011, DOI: (10.1029/2011RG000357)

- Thinner, more rarefied atmosphere than Earth. Primary constituent CO_2
- No global magnetic field. Atmosphere ionised by solar-UV, cosmic rays, and direct interaction with solar wind
- Arguably most ‘Chapman like’ of planetary ionospheres

Planetary ionospheres: Mars

Proton Aurora



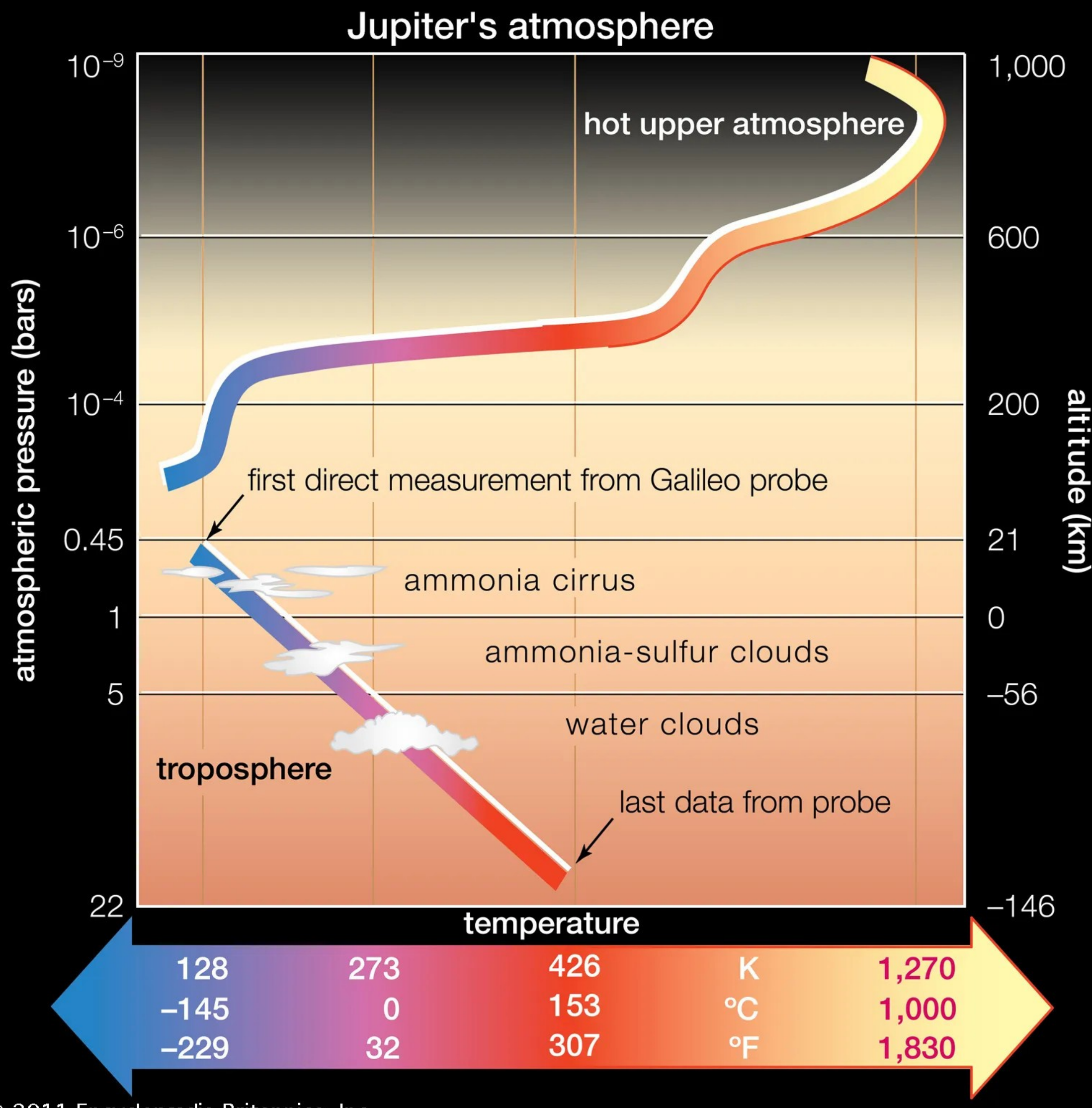
Neutral hydrogen and proton aurora simultaneously.

Proton aurora is visible as a significant brightening on the limb and disk.

Contribution of neutral hydrogen is subtracted revealing the distribution of proton aurora, showing that it peaks in brightness just off the Martian disk as energetic neutrals slam into the atmosphere.

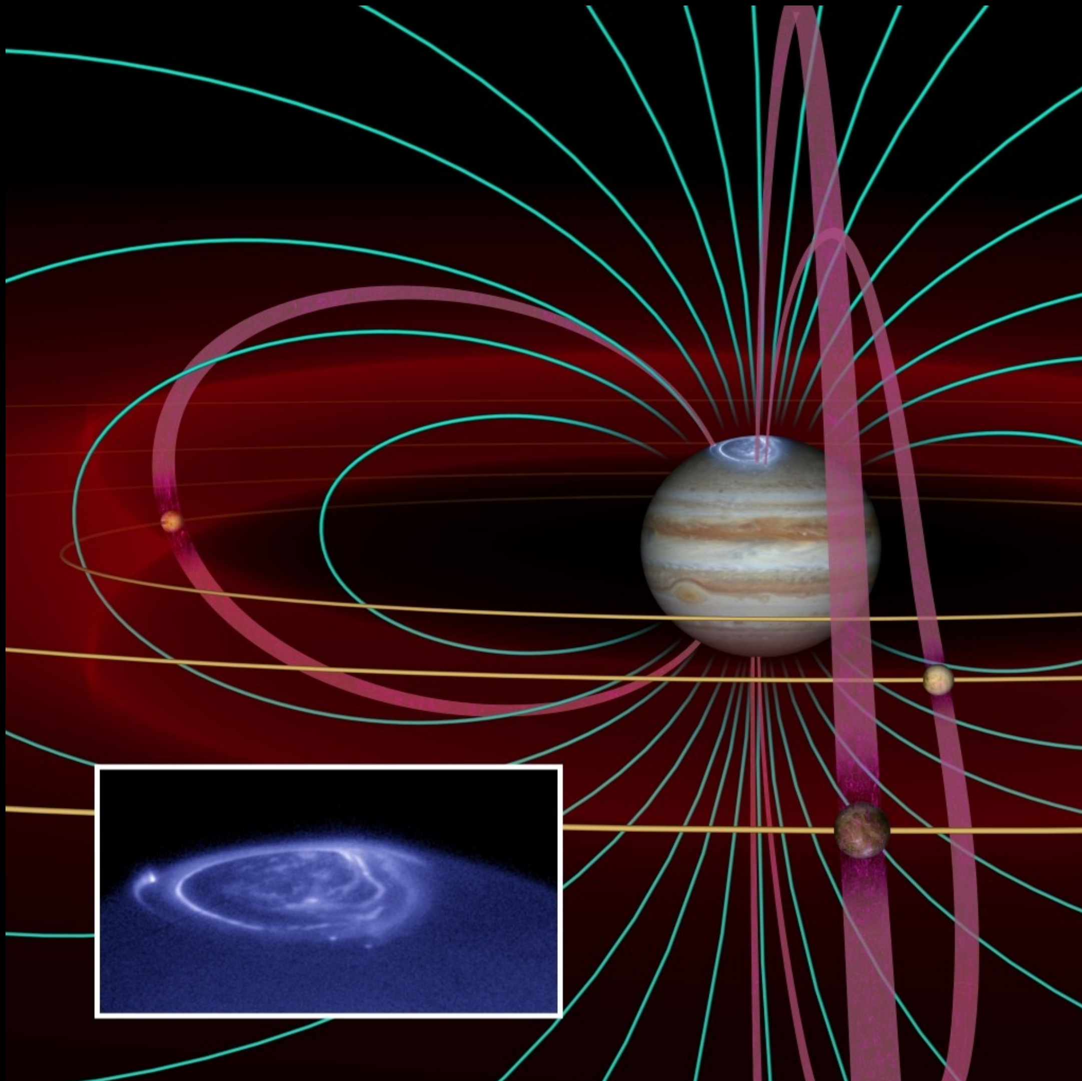
Credits: Embry-Riddle Aeronautical University/LASP, U. of Colorado

Planetary ionospheres : Jupiter



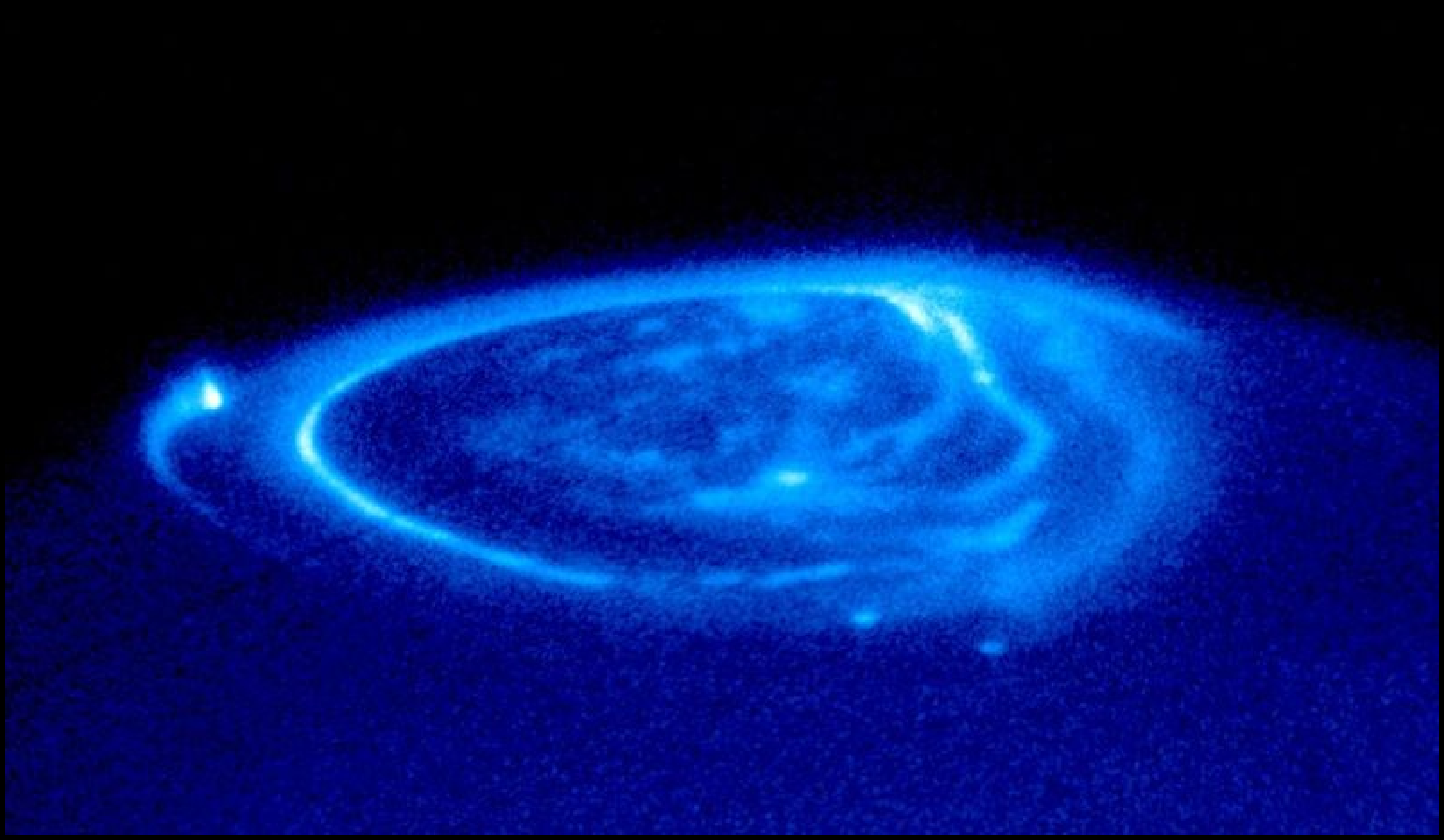
- Gas giant; main atmospheric constituents are H_2 and He. Also traces of NH_3, H_2O, CH_4, H_2S
- Sources of ionisation include solar-UV, high energy particle precipitation, powerful lightning, meteor

Planetary ionospheres : Jupiter



- *Very* strong planetary magnetic (strongest in the Solar System)
- Fast rotation energises particles trapped in field
- Direct current flow along magnetic field lines connecting Galilean moons and Jovian atmosphere
- Particle precipitation from both magnetosphere and moons causes powerful aurora

Planetary ionospheres : Jupiter



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