The planetary environment - II (Earth's ionosphere)

Lecture 6

W.K. Tobiska

Space Environment Technologies

Announcements

Contributions

daily space news and events from JPL

– http://www2.jpl.nasa.gov/calendar/

tutorial on solar wind and interplanetary magnetic field

– http://www-ssc.igpp.ucla.edu/ssc/tutorial/solwind_magsphere_tutorial.pdf

"Solar Wind Flows From Magnetic Funnels on the Sun"

– http://www.universetoday.com/am/publish/solar_wind_source.html?2242005

Bastille Day event

An article on theBastille Day 2000 Event we covered in class. http://science.nasa.gov/headlines/y2000/ast14jul_2m.htm The article brings together solar flares, sun's rotation, and auroras

Contributions

Contributions

CME and comet collision from STEREO

a "collision" between a CME and a comet

http://www.nasa.gov/mission_pages/stereo/news/encke.html

Mars Exploration Rover video clip

mission of the Mars Exploration Rover

http://www.youtube.com/watch?v=eKGAvtRgzTw

Aurora over Canada

aurora in British Columbia, Canada, 2006

http://www.youtube.com/watch?v=qIXs6Sh0DKs

Solar neutrinos and flares affect radioactive decay rates?

http://www.symmetrymagazine.org/breaking/2010/08/23/the-strange-case-of-solar-flares-and-radioactive-elements/

Contributions

CME can change direction

http://science.nasa.gov/science-news/science-at-nasa/2010/21sep_zigzag

Analysis of April 2002 storm event

http://cires.colorado.edu/events/rendezvous/2007/posters/I18I.pdf2

Collapse of thermosphere

http://hubpages.com/hub/The-Thermosphere-Layer-of-Earths-Atmosphere-is-Collapsing

Air Force satellite to monitor space debris:

http://bigthink.com/ideas/24204

Solar probe has 2018 launch

http://www.spaceflightnow.com/news/n1009/03solarprobe/

Solar wind interaction with airless Solar System bodies

http://www.sciencedaily.com/releases/2010/09/100923190805.htm

Contributions

Contributions- GCRs affect servers

– Sun Microsystems Enterprise flagship servers were experiencing mysterious crashes in 2000. Turns out their L2 caches had defective error protection and neutron strikes (due to GCRs) in these areas would cause the servers to crash. This affected Bell systems, America Online, Ebay, etc. Turns out Verisign moved to IBM Unix servers because of it. So space weather is not only an Astro issue!

Contributions

Contributions- Quantas flight SEE

- Quantas flight in 2006 had air data inertial reference unit single event effect failure traced most likely due to GCR radiation
- Sudden drop in altitude; 122 injured, 12 serious, 39 hospitalized

Contributions

Contributions

Photos from the stratosphere for less than $2000

- Article: http://www.newscientist.com/blog/technology/2006/09/spaceflight-on-cheap.html
- Photos: http://www.srcf.ucam.org/%7Ecuspaceflight/nova1selected/index.html

Miscellaneous

- **Book on "Space Weather & Telecommunications" by John M. Goodman (see syllabus on DEN site)**

ISS from STS 115 and Earth

Credit: NASA

Lecture Overview

The planetary space environment - II

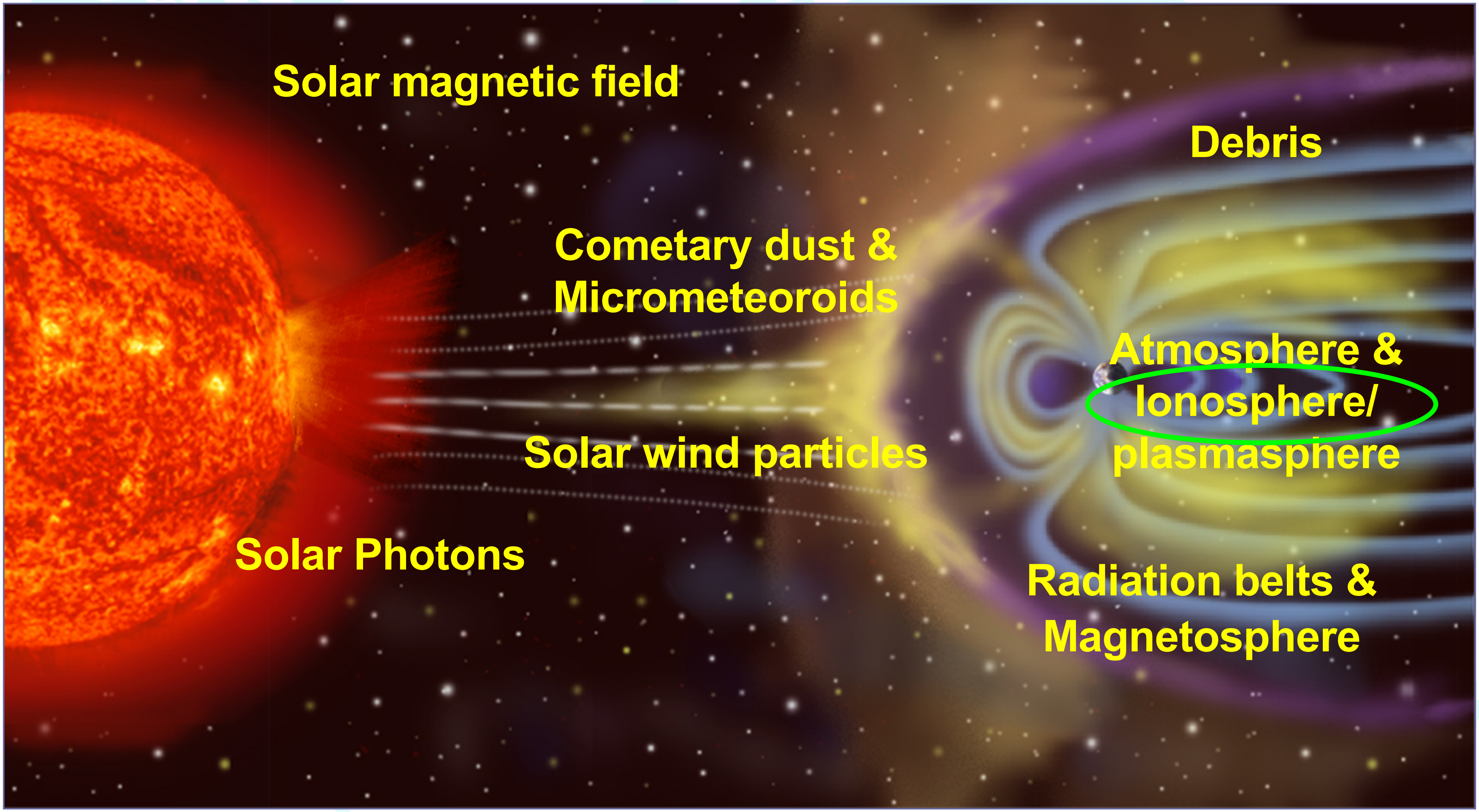
Earth

- Ionospheric physics
  - Thermospheric coupling
  - Electron-ion production and loss processes (solar EUV photoionization, charged particle precipitation, Joule heating, waves, winds)
  - Ionospheric Structure and Dynamics
  - Ionospheric features

Homework

The planetary space environment

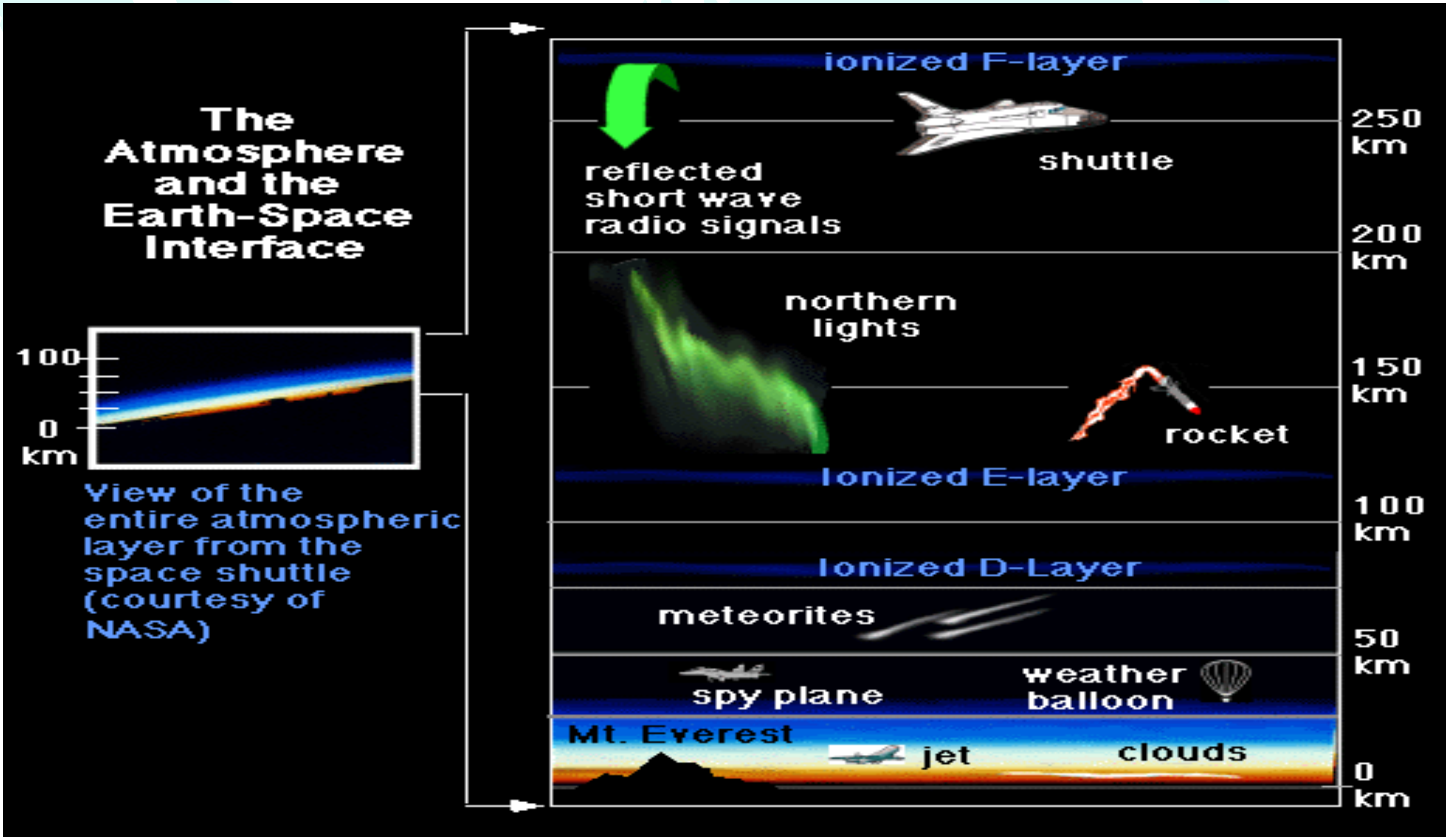
The space environment



Credit: Steele Hill/NASA

Ionospheric physics

The Ionosphere

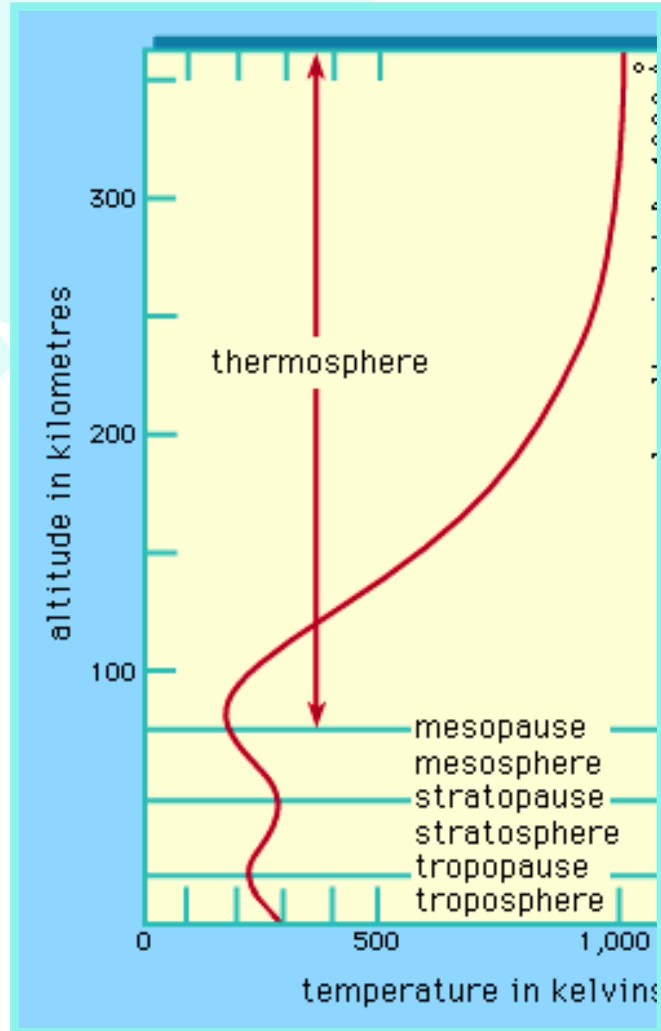


Credit: Tobiska

Thermosphere coupling

The thermosphere

- Atmosphere heated by solar EUV
- Temperature increases with altitude to exobase (~ 500 km)
- Below 120 km (turbopause), atmosphere is turbulently mixed
- Above 120 km, atmosphere is stratified into layers of atomic species by molecular diffusion
- Thermosphere is electrically NEUTRAL



First Principles

1. Equation of Energy (Conservation of Energy):

Heat Production + Heat Loss + Heat Transport = 0

$$\frac{\partial n\varepsilon}{\partial t} + \nabla \bullet (n\varepsilon \mathbf{v}_0) + \nabla \bullet \mathbf{E} + p\nabla \bullet \mathbf{v}_0 - \sum_i n_i \mathbf{X}_i \mathbf{V}_i = \mathrm{P} - \mathrm{L} \quad \textbf{(6-1a)}$$

$$\mathbf{E} = -\lambda \nabla T + T \sum_i c_{p_i} \rho_i \mathbf{V}_i \quad \textbf{(6-1b)}$$

for n=particle concentration, **E** = heat flux, ε = total translational energy, and $\mathbf{X}_i$ is any external force acting upon the particles

2. Equation of Continuity (Conservation of Mass):

Particle Production + Particle Loss + Particle Transport = 0

$$\frac{\partial \mathrm{n}}{\partial \mathrm{t}} + \nabla \bullet (n\mathbf{v}_0) + \nabla \bullet (\sum_i n_i \mathbf{V_i}) = 0 \quad \textbf{(6-2)}$$

for $\mathbf{V}_i$ = diffusion velocity and v_0 = mass average velocity

Credit: Tobiska

First Principles (con't.)

3. Equation of Motion (Newton's 2nd Law):

Force = mass × acceleration

$$F = ma = m\frac{dU}{dt} \qquad \textbf{(6-3)}$$

4. Equation of State (Ideal Gas Law):

pressure ≈ concentration × temperature

$$p = nkT \qquad \textbf{(6-4)}$$

Credit: Tobiska

Equation of Energy

Rate of change of energy in single packet of gas is given by

$\partial\varepsilon/\partial t$ = Heat production rate +

Heat loss rate +

Heat transport rate

Credit: Balthazor

Equation of Energy

We take a single packet of gas and examine its energy density which can be written as

$$\varepsilon = \underbrace{\overbrace{c_P}^{\text{specific heat at constant pressure}} T}_{\text{internal energy}} + \underbrace{\frac{V^2}{2}}_{\text{kinetic energy}} \qquad (6\text{-}5)$$

Credit: Balthazor

Equation of Energy

Heat production: solar irradiances

- **primary global heating** from absorption of solar UV/EUV/XUV radiation on the dayside - 2 processes
  - photodissociation: e.g. $O_2 + h\nu \rightarrow O + O$
  - ionization: e.g. $NO + h\nu \rightarrow NO^+ + e^-$
- **secondary local heating** from excess energy (kinetic energy)
  - Joule heating, electron precipitation, thermal conduction and vibrational, rotational, elastic collisions via eddies and turbulence

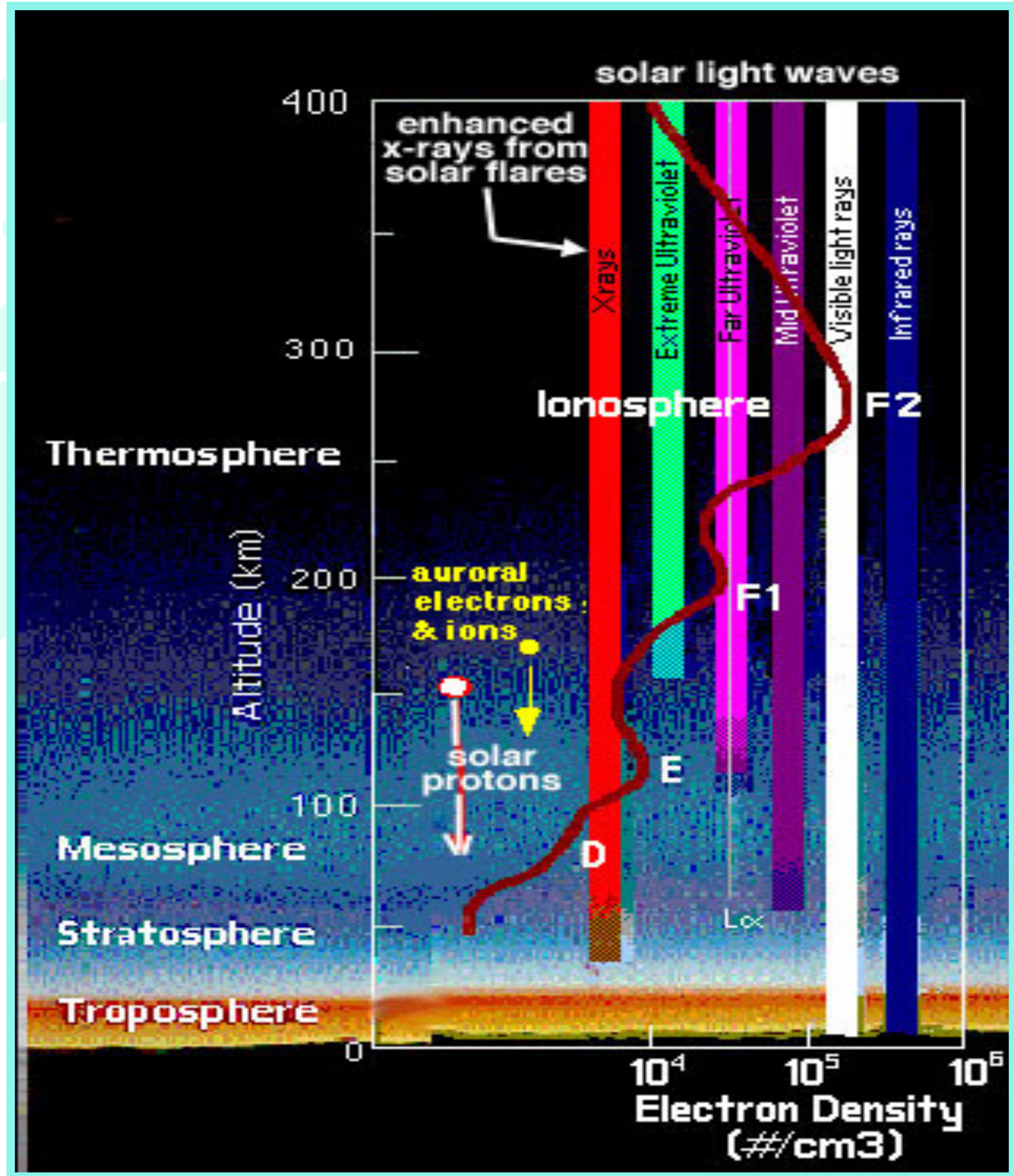
Credit: Tobiska

Ionizing radiation sources

- **Solar radiation - primary global ionization source**
- **Joule heating and precipitating electrons coupled with Earth magnetosphere - important only at high latitudes and are a secondary global ionization source**
- Bremsstrahlung X-rays from braking electrons constrained by the Earth magnetosphere can penetrate to the mesosphere or below
- Precipitating protons and α-particles from solar wind - penetrate to the mesosphere or below

Credit: Tobiska

Solar radiation absorption compared to auroral and solar particles

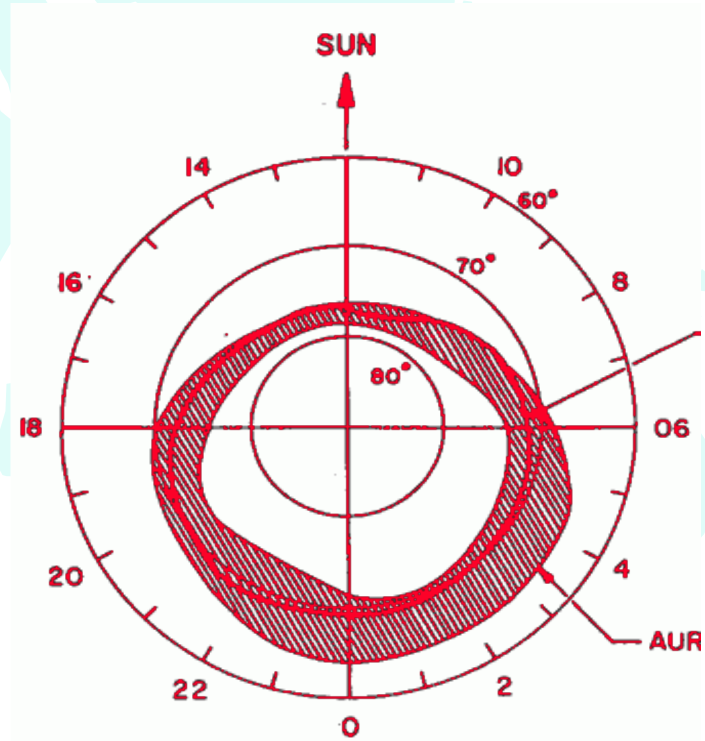


Credit: Balthazor

Equation of Energy

Heat production: energetic charged particles are injected (precipitated) from the magnetosphere

Electrons spiral down ‘open’ magnetic field lines around auroral oval and impact neutral oxygen and nitrogen



Credit: Balthazor

Equation of Energy

Heat production: Joule Heating and Lorentz Forcing

- Ions accelerated by crossed **E** and **B** fields (left hand rule)
- **Joule heating**: macroscopic motions of ions and neutrals do not coincide $\rightarrow$ frictional heating
- **Lorentz Forcing**: microscopic motions of ions and neutrals do not coincide $\rightarrow$ collisional momentum transfer

Credit: Balthazor

Joule Heating

The macroscopic frictional heating of the thermosphere due to a bulk motion difference between the thermosphere and the ionosphere is Joule heating where E' is the perturbed electric field, V_N is the particle velocity (normal or perpendicular direction) B is the magnetic field, J is the electric current, and J•E is the ion heating

$$\mathbf{J} \bullet \mathbf{E}' = \mathbf{J} \bullet \left(\mathbf{E} + \left(\mathbf{V}_{\mathrm{N}} \times \mathbf{B}\right)\right) \qquad \textbf{(6-6)}$$

Credit: Balthazor

Lorentz forcing

Microscopic collisional momentum (hence energy) is transferred between **high speed ions and low speed neutrals**

(or 'ion drag', when momentum is transferred from **high speed neutrals to low speed ions**)

$$-\rho\, \upsilon_{n_i}\left(\mathbf{V_n} - \mathbf{V_i}\right) = \mathbf{V_n} \bullet \left(\mathbf{J} \times \mathbf{B}\right) \quad \textbf{(6-7)}$$

Credit: Balthazor

Joule vs Lorentz

At high altitudes and/or large electric fields Joule heating is dominant over Lorentz by approximately an order of magnitude

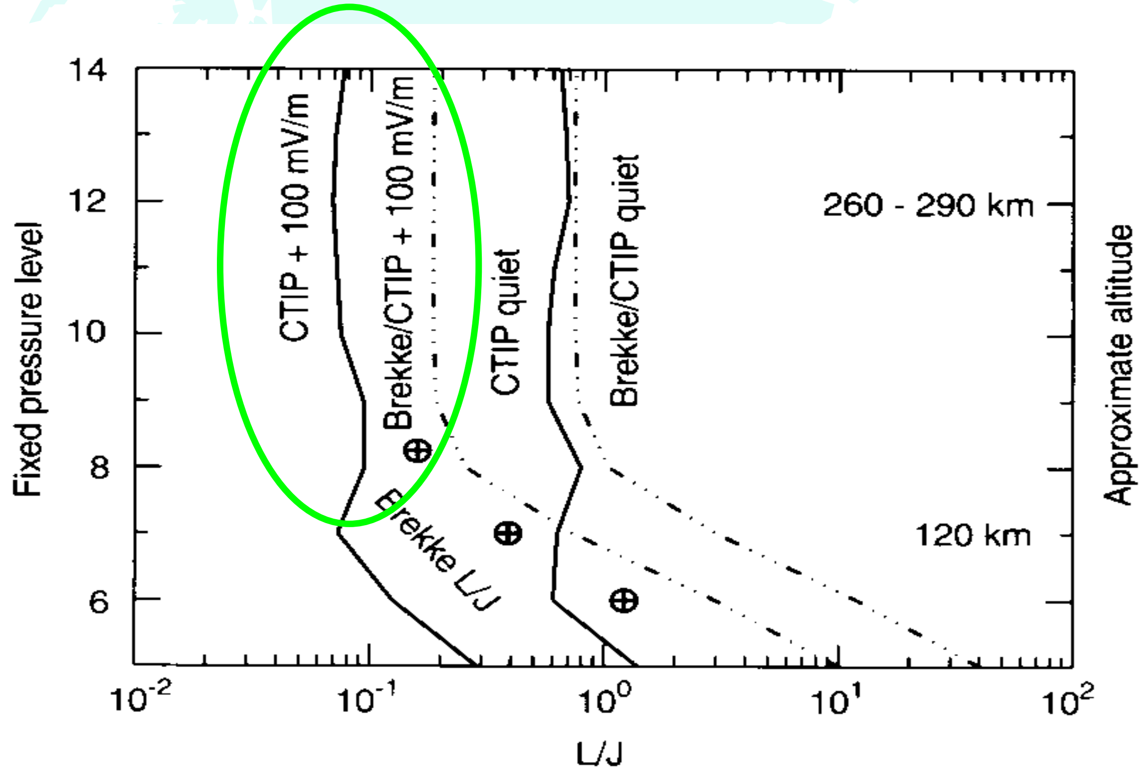
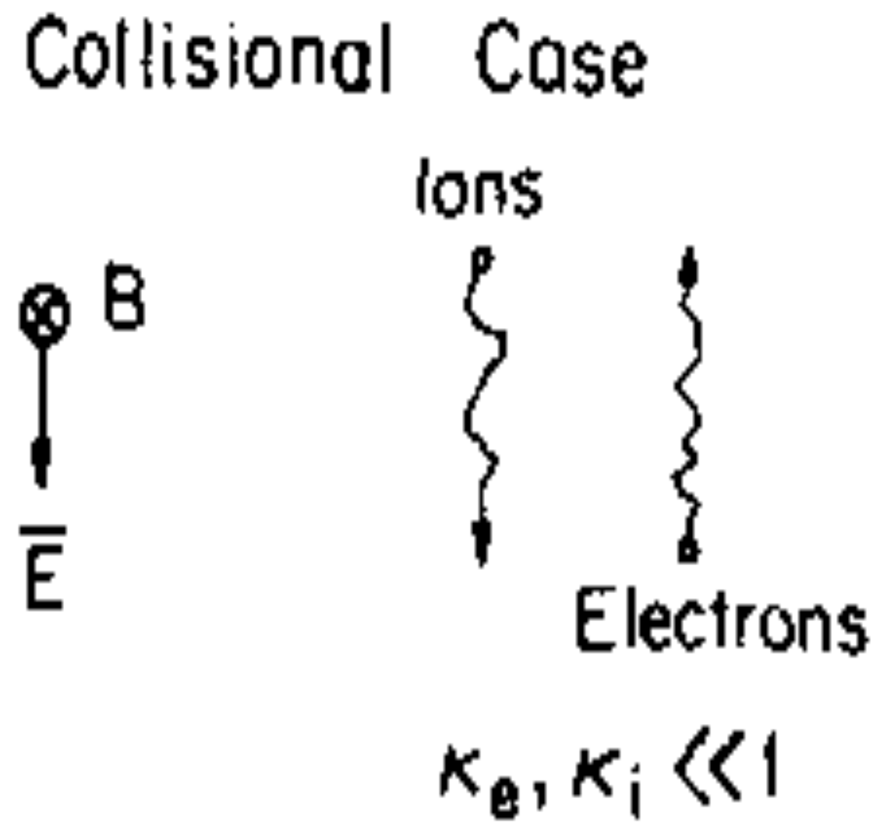


Fig. 3. Plot of the ratio of Lorentz forcing to Joule heating against height at latitude 70°N, longitude 162°E, Day 1. The *two solid lines* show the coupled model results for (a) quiet atmosphere, and (b) during the 100 mV/m enhanced electric field. The *broken lines* show results from the extrapolation of the Brekke formula, Eq. (4), for both quiet and enhanced atmospheres, whilst the *three discrete points* are the Brekke results

Credit: Balthazor

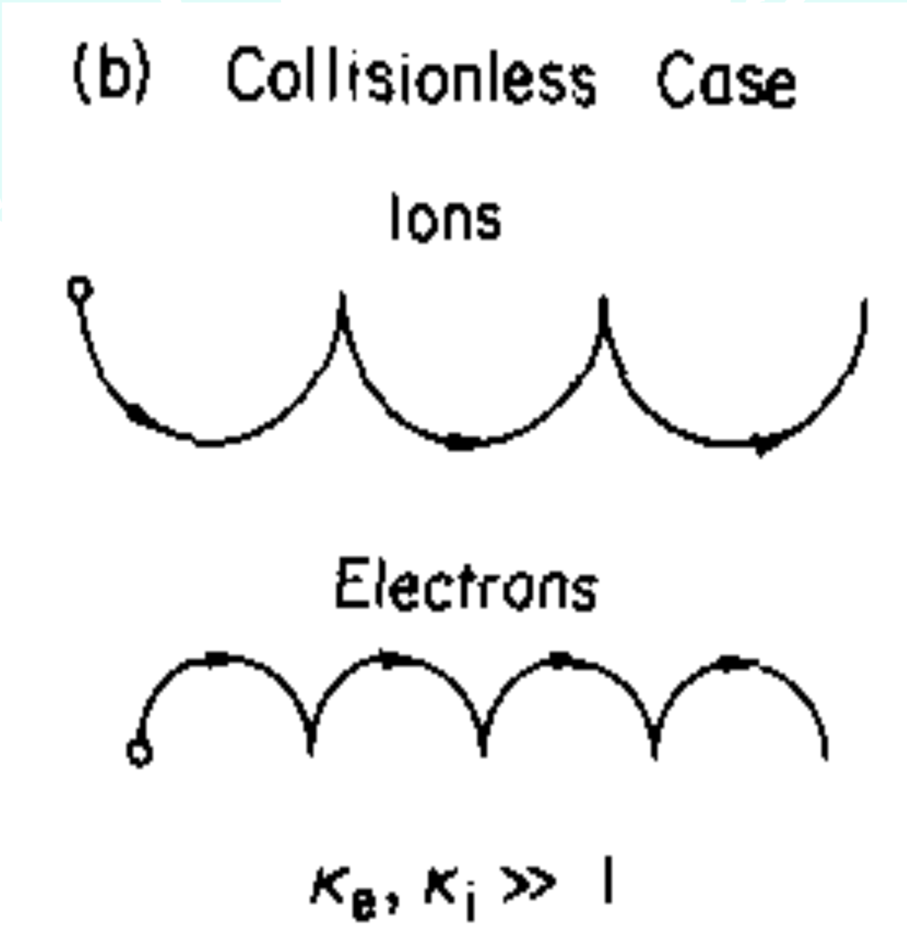
Why do ions drag?

In a collision-dominated atmosphere, e.g., below ~ 120 km, the trajectory is continually being re-established along the potential (gravity) gradient



Credit: Balthazor

Why do ions drag?

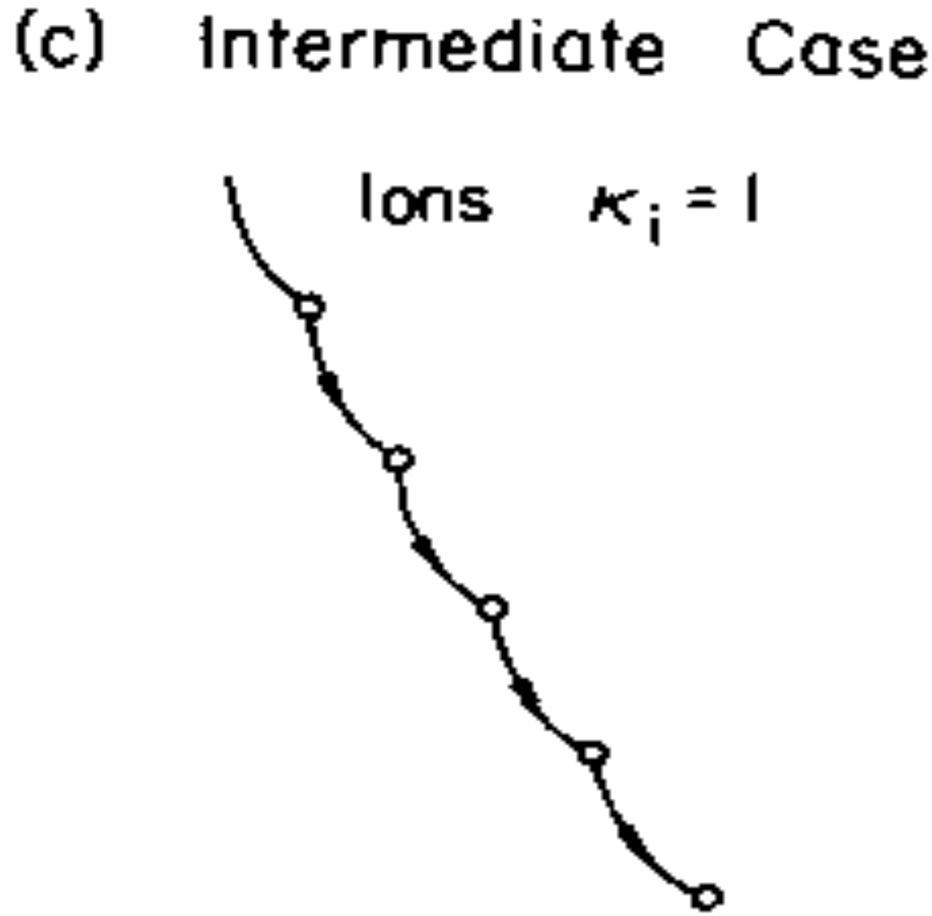


But in a collisionless atmosphere, above ~ 150 km, they are forced to spiral around electric field lines (left hand or motor rule)

Credit: Balthazor

Why do ions drag?

And, of course, there is a transition region - in the lower thermosphere near the 120-150 km altitude



Credit: Balthazor

Equation of Energy

Heat production: winds (advection)

- Advection - non-cyclical motion of gas particles (as opposed to convection)
- Neutral winds transport energy
- Chemical transport by neutral winds allows species to be created by dissociation, for example, and be moved elsewhere before recombination

Credit: Balthazor

Equation of Energy

Heat production: wave dissipation

- Waves from a variety of sources will dissipate through turbulence, viscosity, resonance
- Possible sources of wave dissipation are

  Thermospheric tides

  Gravity waves aka atmospheric gravity waves aka Travelling Atmospheric Disturbances

  MHD waves

Credit: Balthazor

Equation of Energy

Heat production: molecular conduction

- Thermospheric temperature becomes asymptotic > 400-500 km due to rapid thermal conductivity
- Heat flux $\propto$ temperature gradient, i.e., $\Phi \propto \nabla T$

Credit: Balthazor

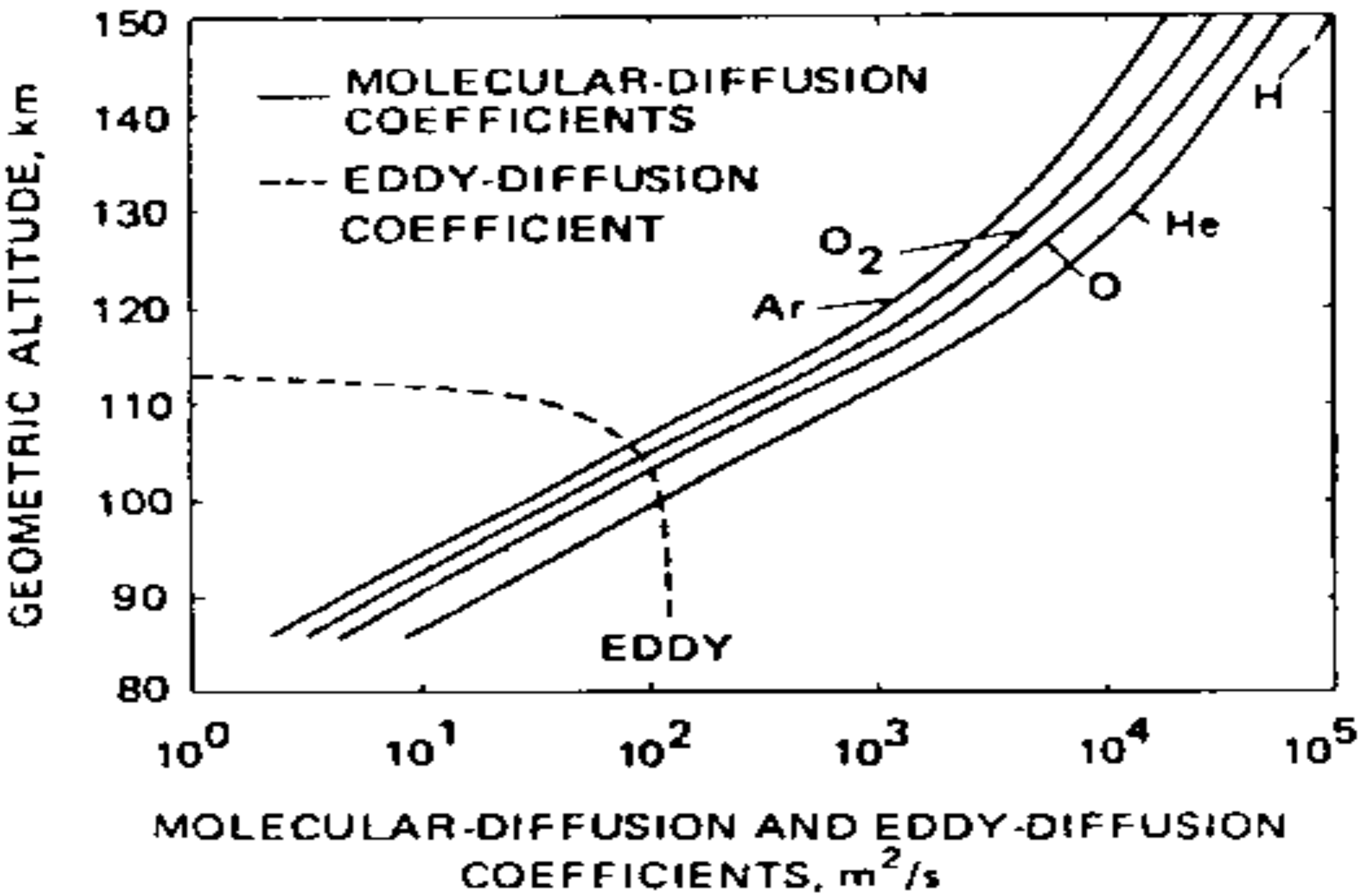
Equation of Energy

Heat production: eddy transport

- This is an important process below the turbopause (~120 km) and dominates below ~100 km
- Eddy mixing transports heat down to into the mesosphere (around 50 km)

Credit: Balthazor

Diffusion Coefficients



Credit: Balthazor

Vandenberg launch Sep 2005

Credit: LA Times

Vandenberg launch

Credit: LA Times

Vandenberg launch

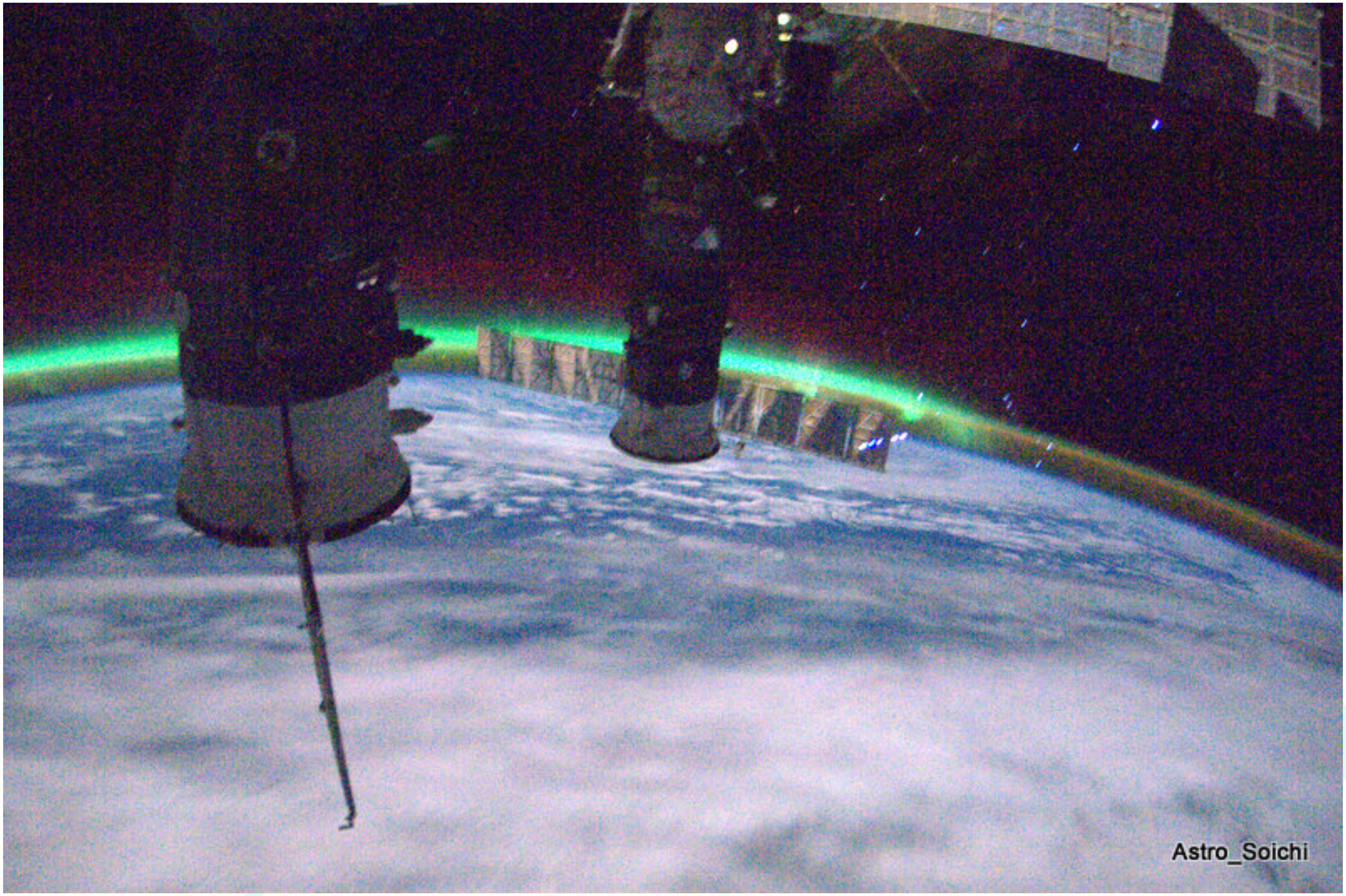
Credit: LA Times

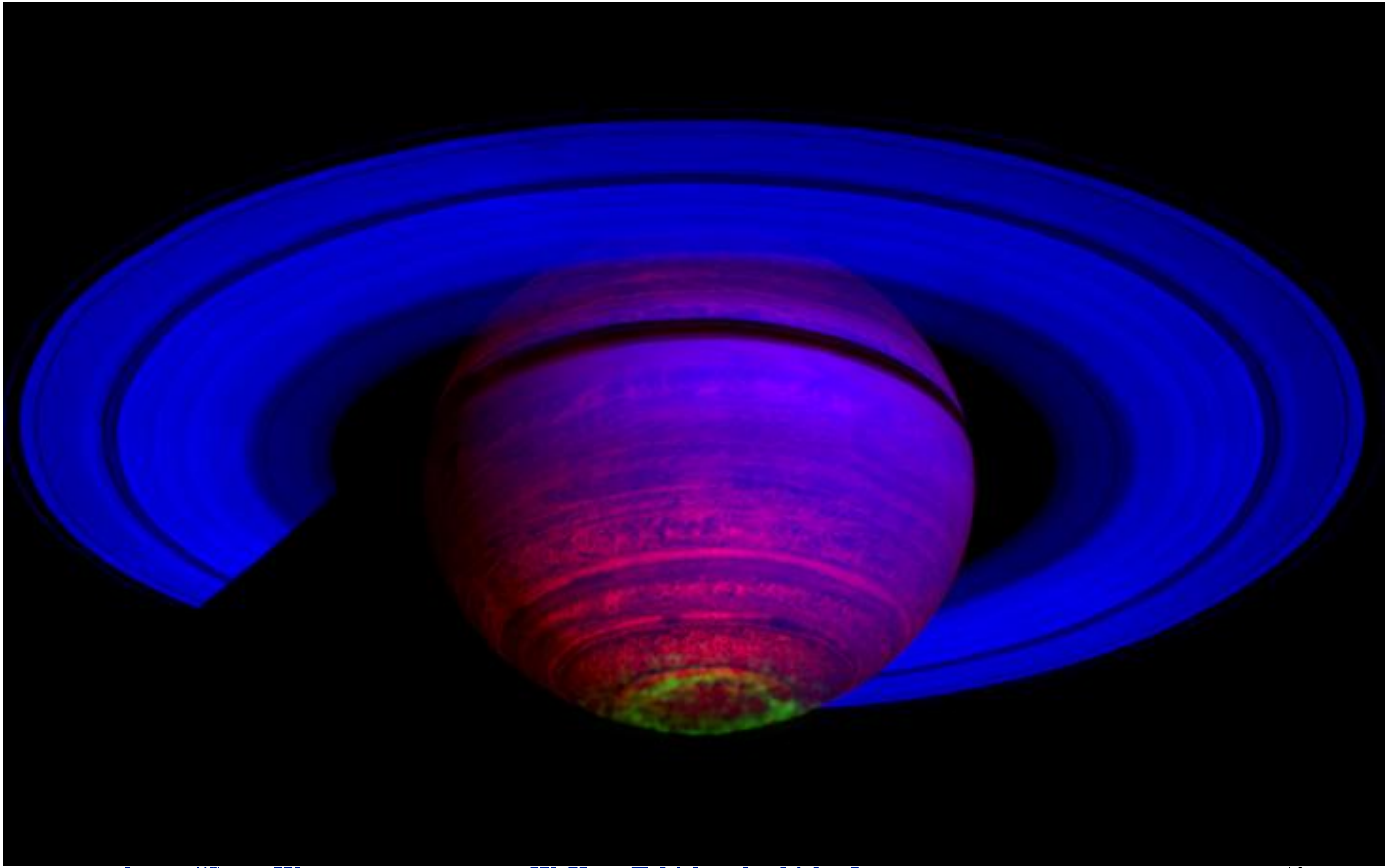
Equation of Energy

Heat loss: radiation

- This is the principal mechanism of thermospheric heat loss (CO_2 and NO)
- Auroral emission (spectral, e.g. OH lines and Oxygen line @ 630 nm red line and 557 nm green line)
- Airglow emission (e.g. O, N)

Credit: Balthazor


Astro_Soichi



The Continuity Equation

Ion Production

Ions and electrons, once formed, will tend to recombine unless they are prevented from doing so and we can rewrite the continuity equation so that

$$M + \text{energy} \leftrightarrow M^{+} + e^{-}$$

$$\frac{\partial n}{\partial t} = P - L - \nabla(n\mathbf{V}) \qquad \textbf{(6-8)}$$

Credit: Balthazor

Ion Production

Ion Transport

$$\frac{\partial n}{\partial t} = P - L - \nabla(n\mathbf{V}) \qquad \textbf{(6-9)}$$

Ions and electrons will be influenced by the vertical pressure gradient and the heavier ions will tend to 'settle'

The resultant separation will form an electric field which will tend to restore the particles

Credit: Balthazor

Thermospheric chemistry

- The dominant neutral species are atomic oxygen, molecular nitrogen, molecular oxygen, helium, and hydrogen, respectively
- The dominant ion species is atomic oxygen
- Much of the chemistry involves O and N in one form or another although nitrogen has a very small photodissociation cross-section

Credit: Tobiska

Ionization potentials

Atom or molecule	H	He	C	N	O	Ar	Ne	NO	O_2	CO_2	N_2
Ionization Potential (eV)	13.60	24.59	11.26	14.53	13.62	15.76	21.56	9.25	12.08	13.79	15.58
Max wavelength (nm)	91.2	50.4	110.1	85.3	91.0	78.7	57.5	134.0	102.7	89.9	79.6

Neutral-Neutral Chemistry (photodissociative reactions)

$$O_2 + h\nu \rightarrow O + O$$
$$O + O + M \rightarrow O_2 + M$$
$$O + OH \rightarrow O_2 + H$$
$$O + HO_2 \rightarrow O_2 + OH$$
$$O + O \rightarrow O_2 + h\nu$$
$$N(^2D) + O_2 \rightarrow NO + O$$
$$N(^4S) + O_2 \rightarrow NO + O$$
$$N(^2D) + O \rightarrow N(^4S) + O$$
$$N(^4S) + NO \rightarrow N_2 + O$$
$$N(^2D) + e^- \rightarrow N(^4S) + e^-$$
$$N(^2D) + NO \rightarrow N_2 + O$$
$$N(^2D) \rightarrow N(^4S) + h\nu$$
$$NO + h\nu \rightarrow N(^4S) + O$$
$$NO + h\nu_{Lyman\alpha} \rightarrow NO^+ + e^-$$

Credit: Balthazor

Neutral-Ion Chemistry

$$N_2^+ + O \rightarrow N(^2D) + NO^+$$

$$NO^+ + e^- \rightarrow N(^2D) + O \ (80\%)$$
$$\rightarrow N(^4S) + O \ (20\%)$$

$$N_2^+ + e^- \rightarrow N(^4S) + N(^4S) \ (10\%)$$
$$\rightarrow N(^4S) + N(^2D) \ (90\%)$$

$$N^+ + O_2 \rightarrow NO^+ + O$$

$$N^+ + O_2 \rightarrow O_2^+ + N(^4S)$$

$$N^+ + O \rightarrow O^+ + N$$

Dissociative recombination (fast reactions)

Credit: Balthazor

Neutral-Ion Chemistry

$$O_2^+ + e^- \rightarrow O + O$$

Dissociative recombination (fast reactions)

$$O_2^+ + N(^4S) \rightarrow NO + O$$

$$O_2^+ + NO \rightarrow NO^+ + O_2$$

$$O^+ + O_2 \rightarrow O_2^+ + O$$

$$O^+ + N_2 \rightarrow NO^+ + N(^4S)$$

Charge Exchange

$$NO^+ + O_2 \rightarrow O_2^+ + N_2$$

$$NO + h\nu_{\text{Lyman}\alpha} \rightarrow NO^+ + e^-$$

$T_1 = 0.667\ T_i + 0.333\ T_n$; T_i is ion temperat
and $T_R = (T_i + T_n)/2$.

Credit: Balthazor

F2 Region Chemistry

For the dominant ionospheric layer, the F2 region, there is a two-stage recombination process

1) $O^+ + N_2 \rightarrow NO^+ + N$

where the rate is $\propto \beta\ [O^+]$ which controls the rate at high altitudes (reaction between most predominant species)

2) $NO^+ + e \rightarrow N + O$

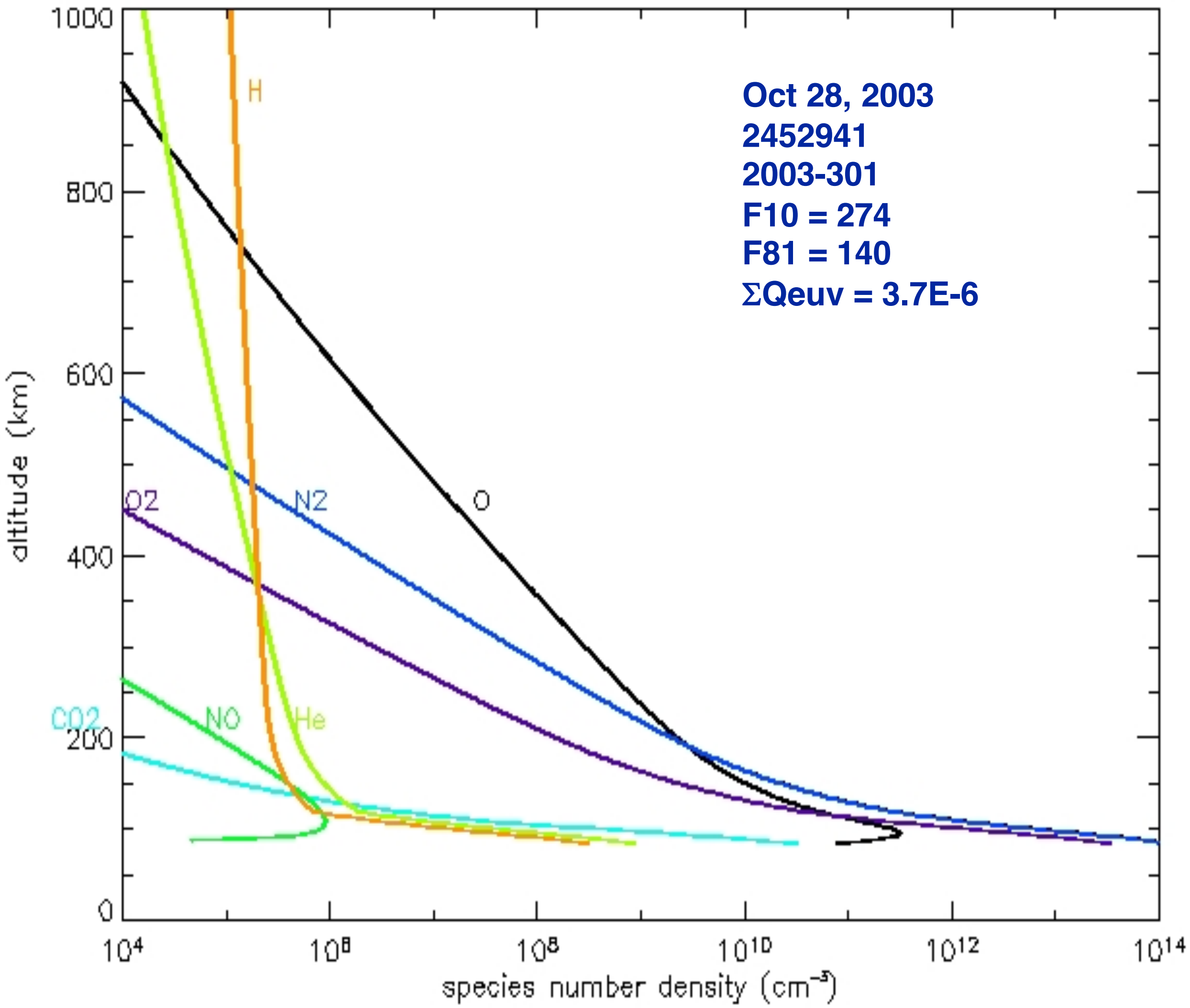
where the rate is $\propto \alpha\ [NO^+][n_e]$ which controls the rate at low altitudes where α is large (more NO available)

Credit: Balthazor

BREAK

Ionospheric structure

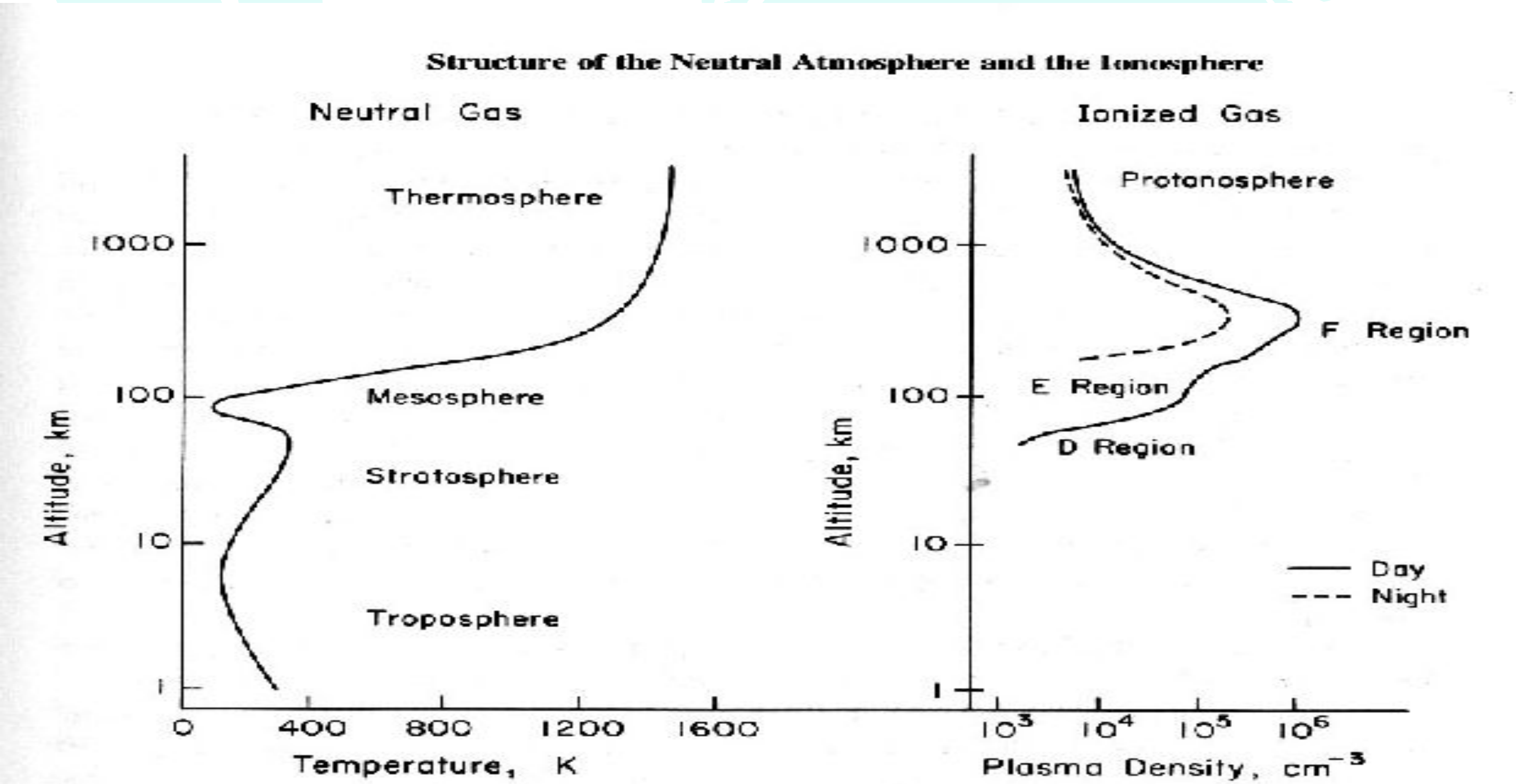
Thermosphere species



- Major species
  - O, O_2, N_2
- Minor species
  - NO, CO_2 are significant for cooling
  - He, H useful for aeronautical applications
  - Ar

Credit: Tobiska

Thermosphere-Ionosphere structure



Credit: Balthazor

Thermosphere vs Ionosphere

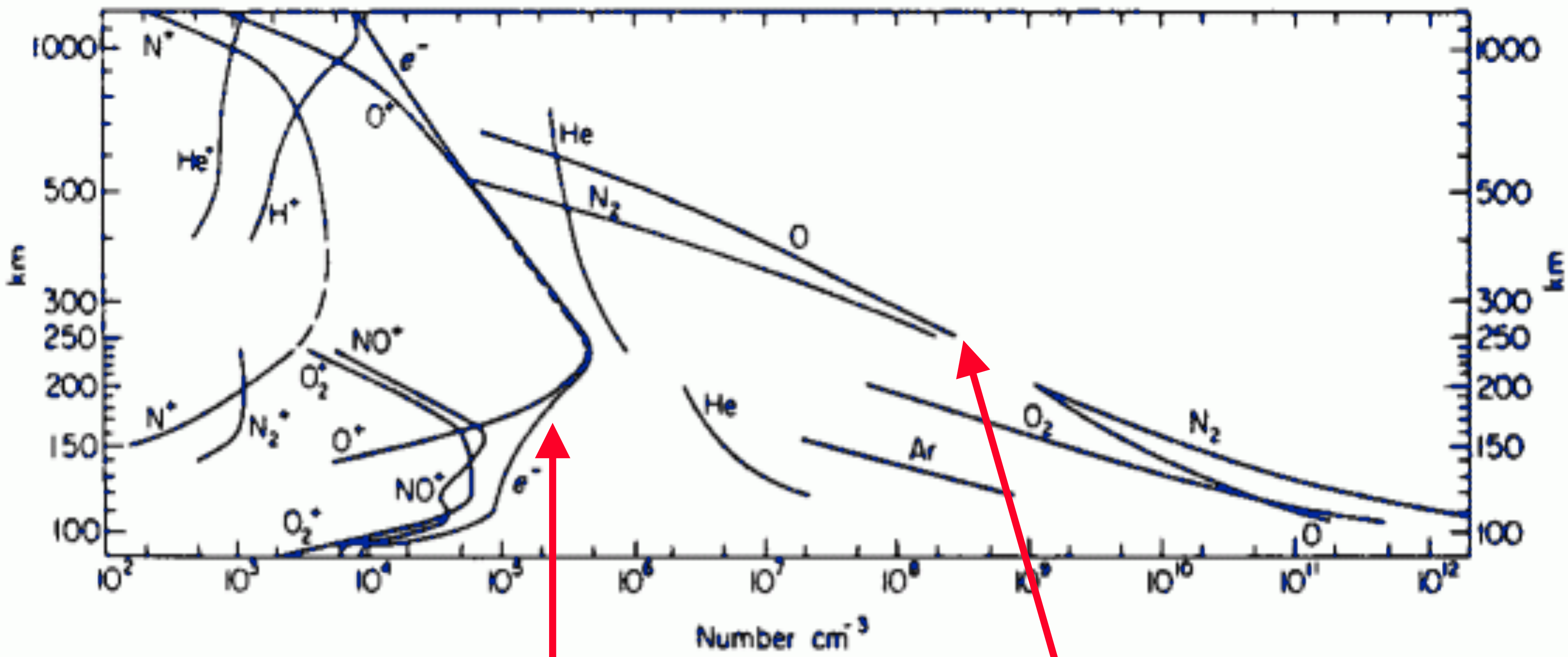


Fig. 1.2. International Quiet Solar Year (IQSY) daytime atmospheric composition, based on

Ionospheric density << Thermospheric density by ~ 1E5

Credit: Balthazor

Ionospheric Layers

- D-region:
  - 50-85 km
  - dominated by H_2O^+
  - $\lambda < 1$ nm (Xray) or Lyman-alpha (121.6 nm)
- E-region:
  - 85-140 km
  - dominated by O_2^+
  - $1 < \lambda < 10$ nm (XUV) or Lyman-beta (102.6 nm or CIII (97.7 nm)
  - E-F1 valley is the cross-over between the two regions

Credit: Tobiska

Ionospheric Layers

- F1-region:
  - 140-250 km
  - dominated by NO^+
  - $10 < \lambda < 91$ nm & 121 nm (EUV and Lyman-alpha)
  - F1 maximum electron density ~200 km
- F2-region:
  - 250-500 km
  - dominated by O^+
  - $10 < \lambda < 91$ nm (EUV)
  - F2 maximum electron density ~300 km (F2max)

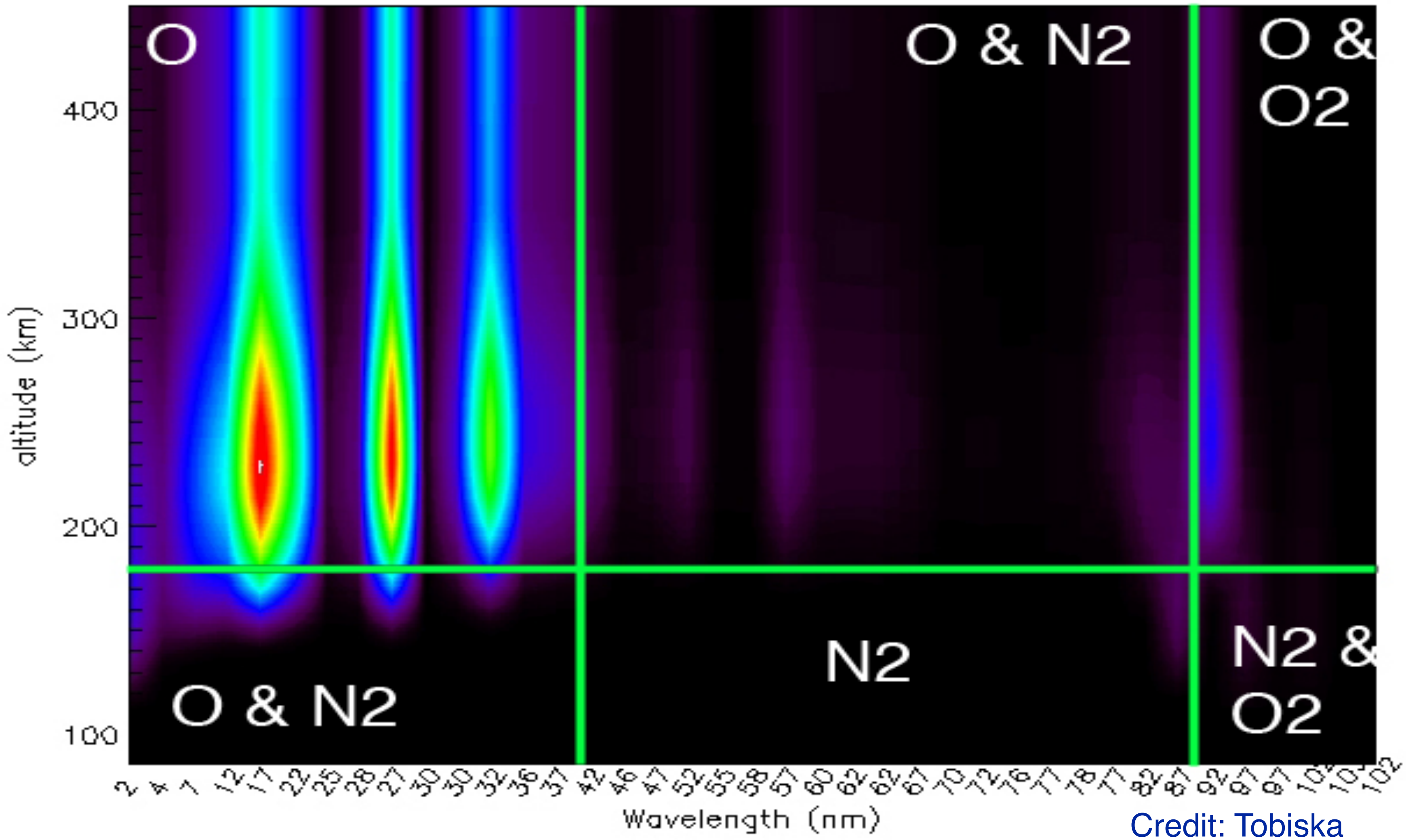
Credit: Tobiska

Ionospheric Layers

- Topside ionosphere:
  - >500 km
  - dominated by O^+
  - $\lambda < 102.6$ nm (EUV < Lyman-beta)
- Total Electron Content (TEC):
  - integrated ionosphere from top to bottom

Credit: Tobiska

Photoionization regions



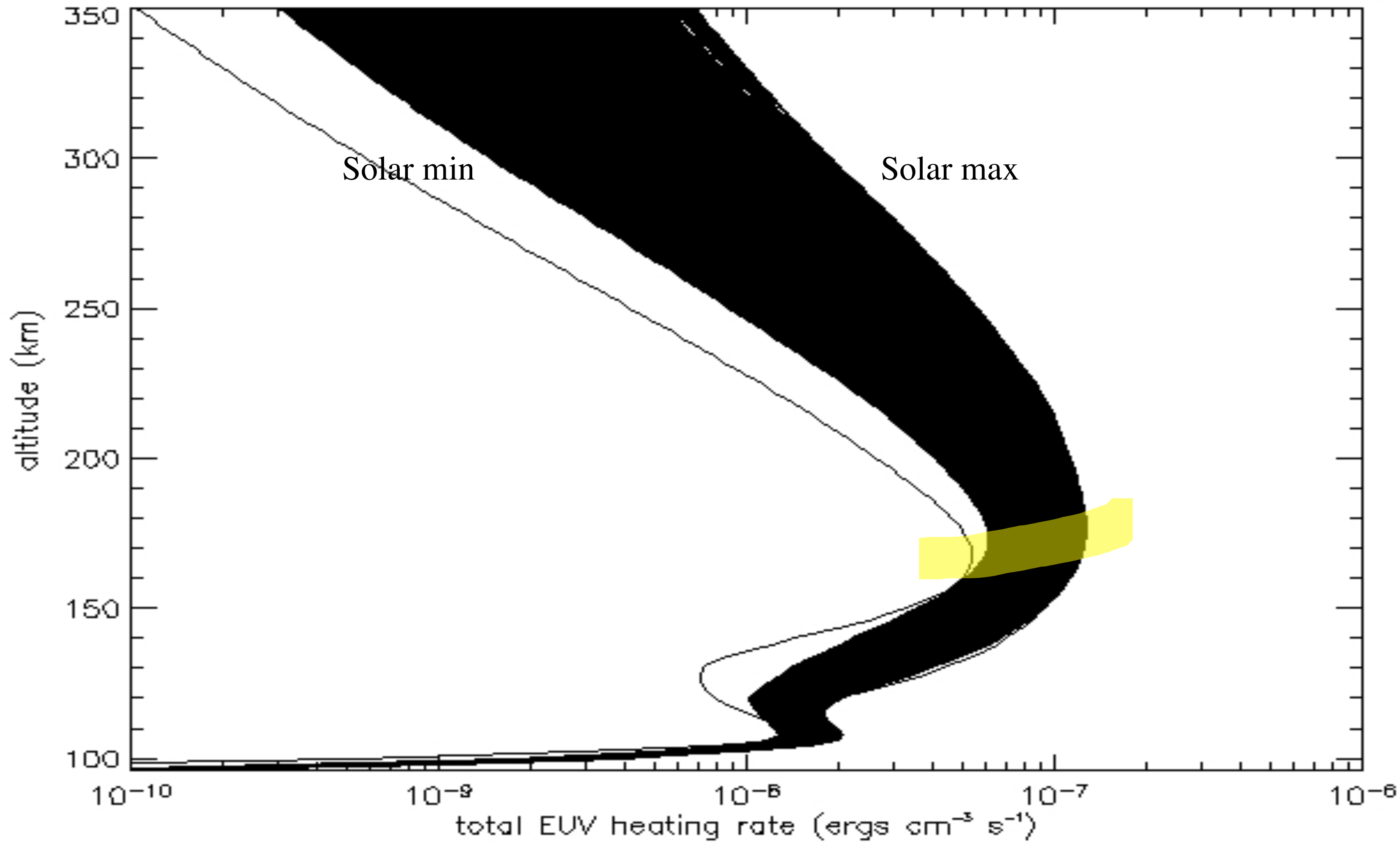
Credit: Tobiska

Ionospheric Layers

- Additional concepts:
  - Relatively little N_2^+ because fast recombinations tend to form NO^+
  - Hotter thermosphere (during higher solar activity) tends to raise peak layers of ionization because there is a denser atmosphere at a given altitude and the unit optical depth is higher.

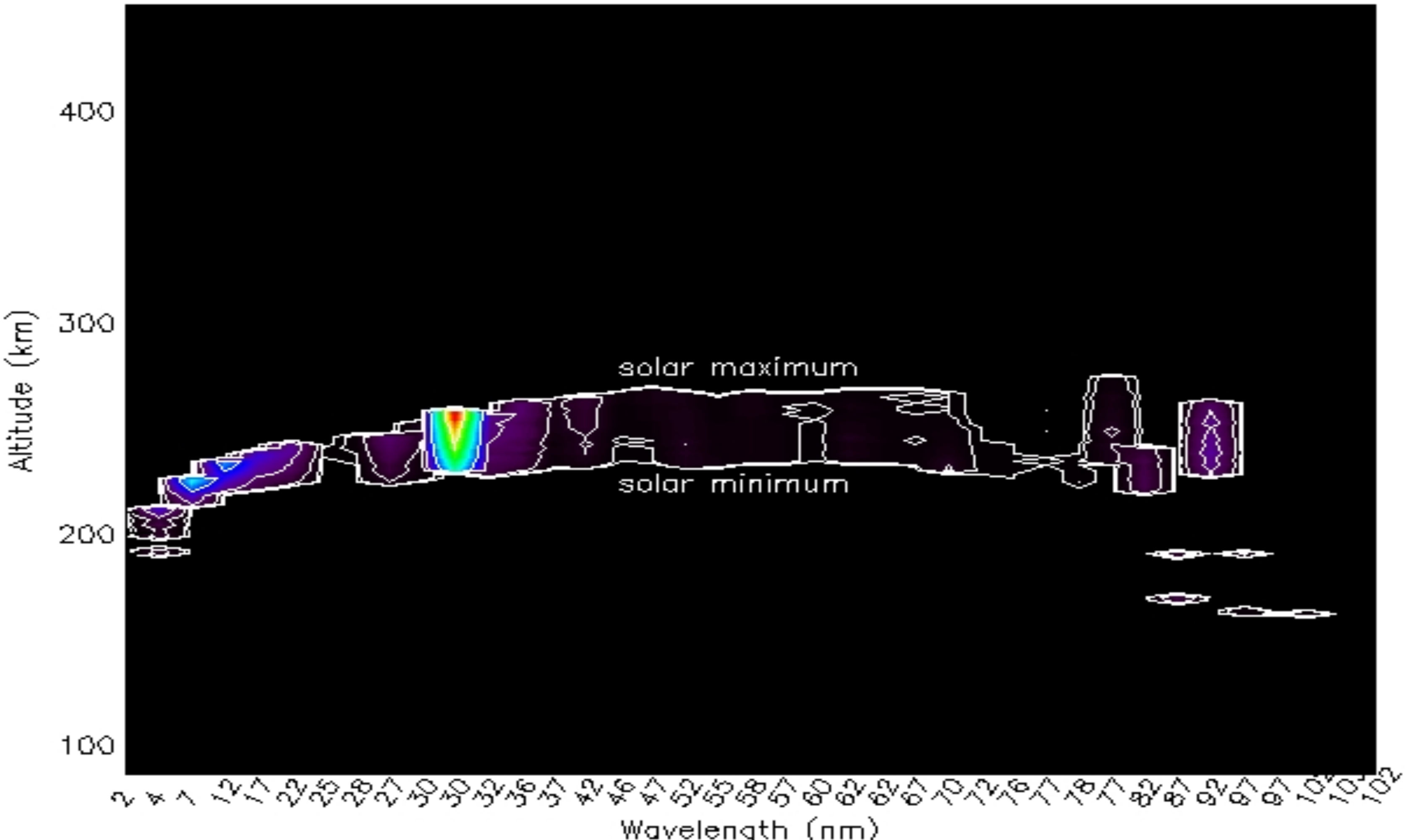
Credit: Tobiska

Solar max-min heating



Credit: Tobiska

Solar max-min optical depth



Credit: Tobiska

Scale Height

In equilibrium and considering only gravity and the pressure gradient

$$dp = -nmg\, dh \quad (6\text{-}13)$$

$$\frac{dp}{dh} = -nmg \quad (6\text{-}14)$$

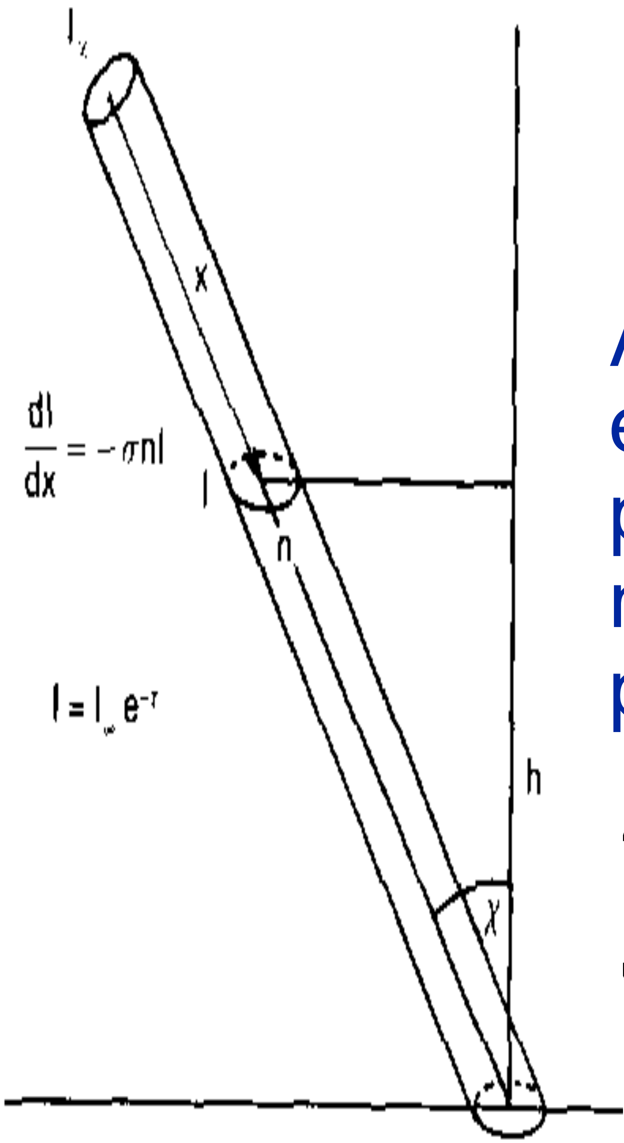
but p = nkT

$$\frac{1}{p}\frac{dp}{dh} = -\frac{mg}{kT} = -\frac{1}{H} \quad (6\text{-}15)$$

where H = kT/mg is the scale height

Credit: Balthazor

Chapman Layer Production



Assume single species gas with exponential N(h), constant H, plane stratified, and monochromatic radiation for ion production rate, P

$$P = P_{m_0} \exp\left(1 - z - \exp(-z)\sec\chi\right) \quad \textbf{(6-17)}$$

$$\text{where } z = \frac{\text{h - h}_0}{\text{H}}, \chi = \text{SZA},$$

m_0 denotes maximum ion production

Credit: Balthazor

Chapman Function

Pedersen (1927) and Chapman (1931) provided a mathematical form for relating ion production with ionizing radiation

$$P = \eta \sigma \mathrm{nI} \quad (6\text{-}16)$$

P = Production rate, I = intensity of ionizing radiation, n = number density (concentration) of neutral particles, σ = absorption cross-section, η = ionization efficiency

Credit: Balthazor

Chapman Layer Loss

$$L = \alpha[X^+]n = \alpha n^2 \qquad (6\text{-}18)$$

Loss rate   Ion density   Recombination coefficient

for ion X at a number density (concentration), *n*, with a recombination coefficient, α

At equilibrium,   Production = Loss

Credit: Balthazor

Chapman Layers

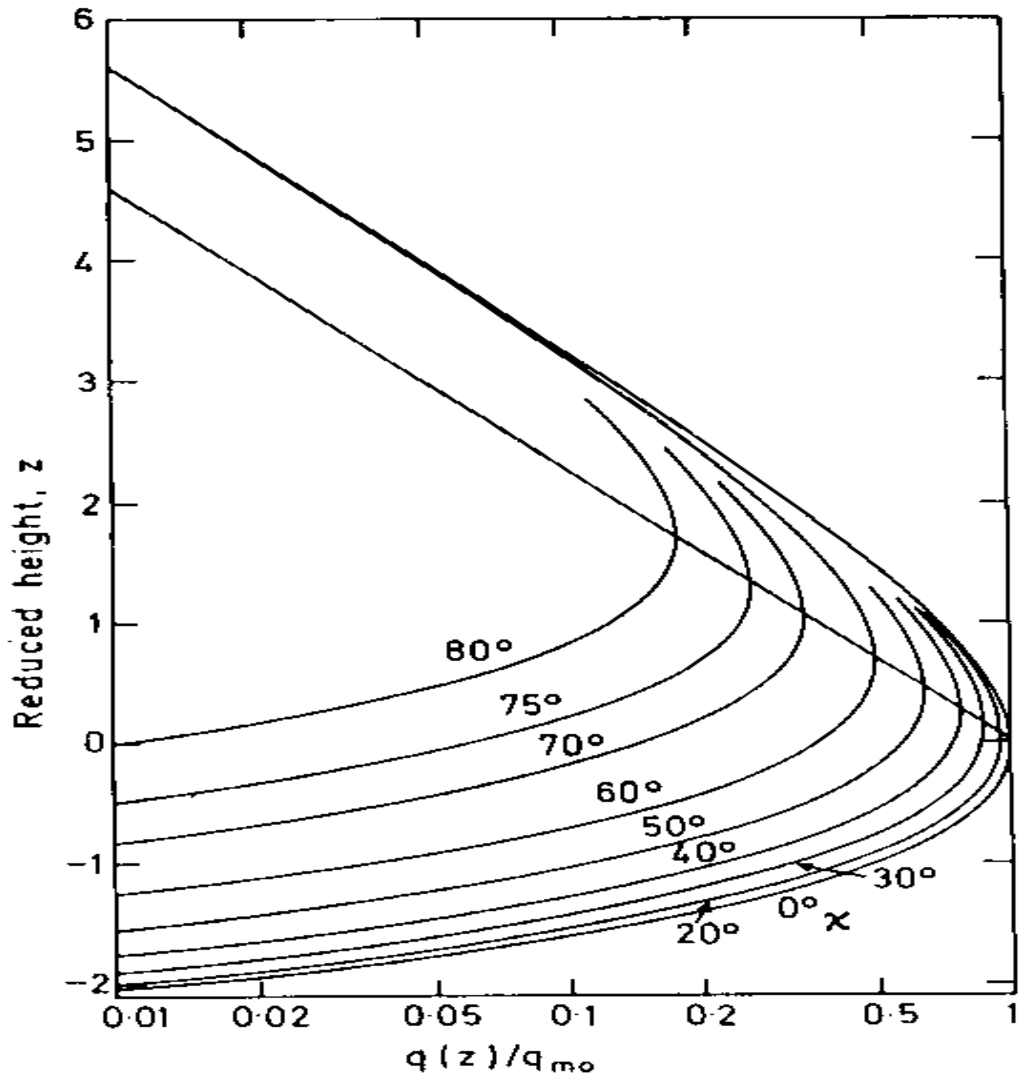
If P $\propto$ In and as h (altitude) increases, ionizing photons, I, increase and concentration, n, decreases, we expect that *at some particular height,* there is a maximum production rate and hence a maximum ion density.

Credit: Balthazor

Chapman Profile

(q = P in this figure)

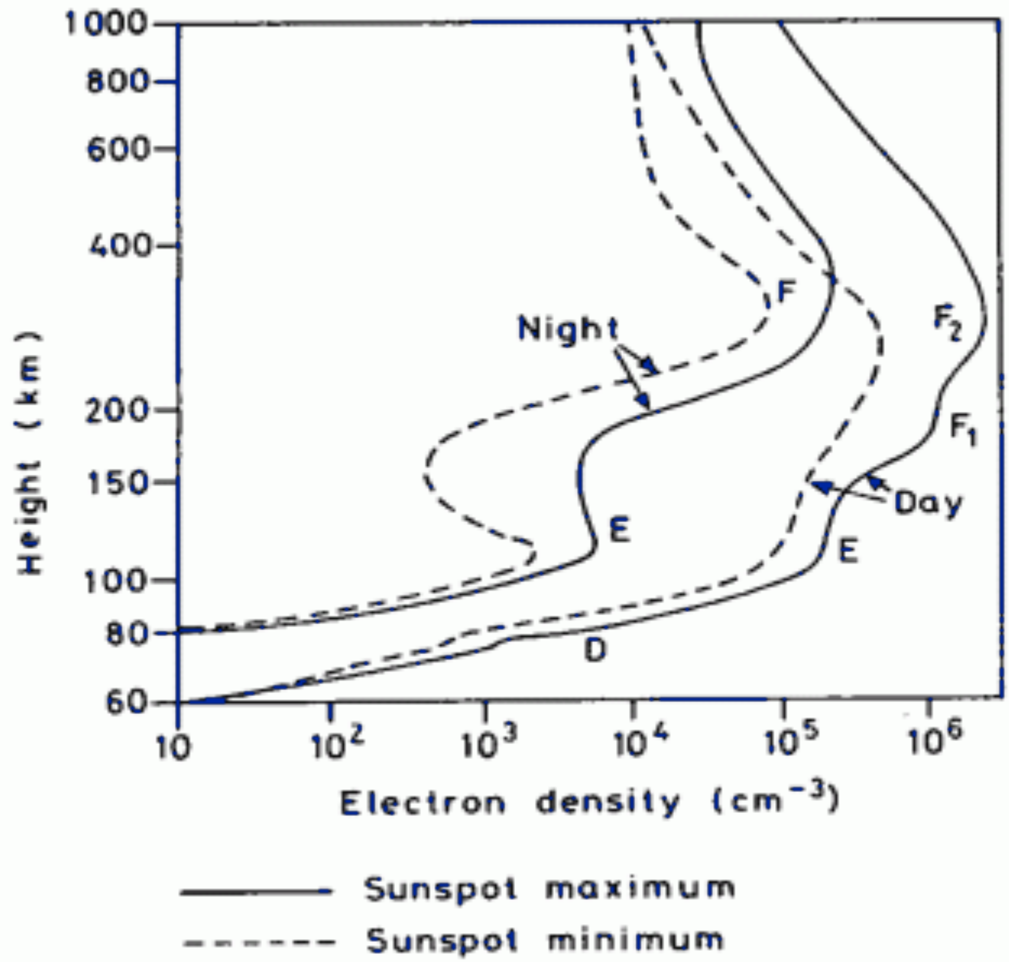
X is the angle of incidence of the solar photons where 90 degrees is the limb and 0 degrees is overhead



Credit: Balthazor

Ionosphere structure

- Exists inside (and above) the thermosphere, made up of free electrons and positive ions (and a few negative ions)
- Ionosphere is electrically NEUTRAL overall (but not necessarily neutral locally)



Credit: Balthazor

Ionosphere structure

- Atomic Ions: O^+, N^+, H^+, He^+
- Molecular Ions: O_2^+, N_2^+, NO^+

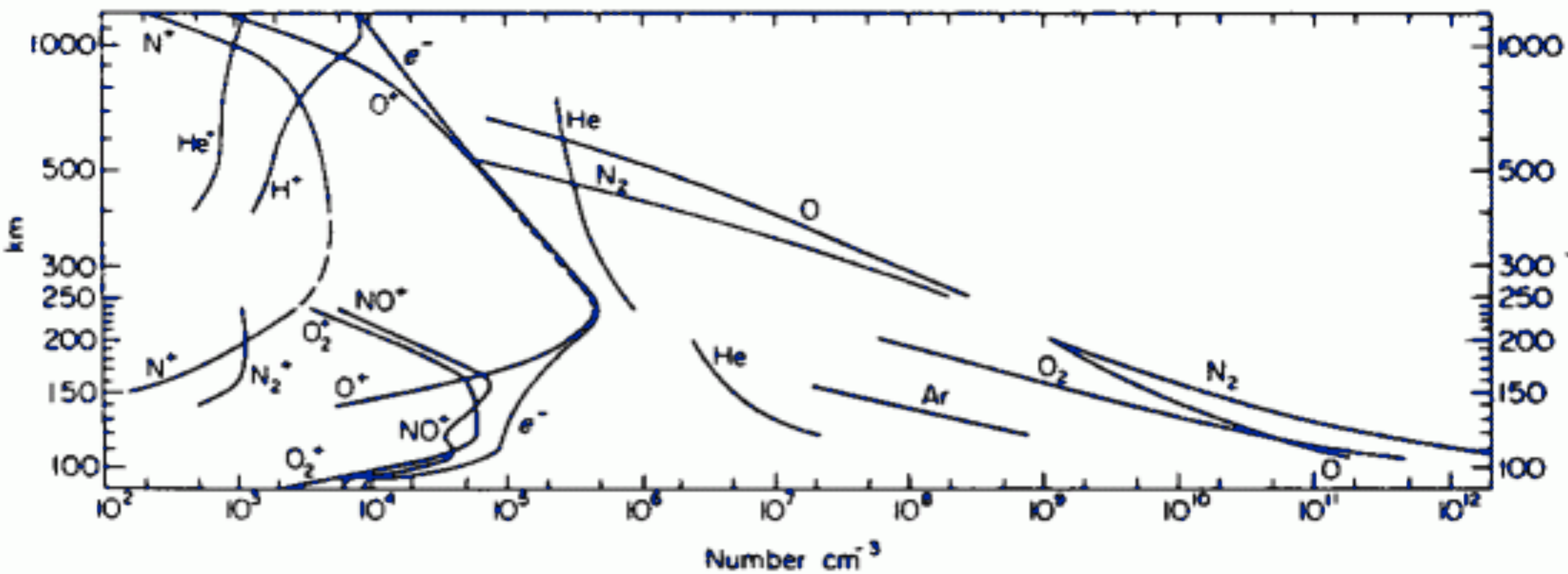


Fig. 1.2. International Quiet Solar Year (IQSY) daytime atmospheric composition, based on

Credit: Balthazor

Chapman Layers

- The production rate is greatest at the level where the optical depth is unity.
- We expect an 'α-Chapman layer' at ~ 180 km – the F1 layer.

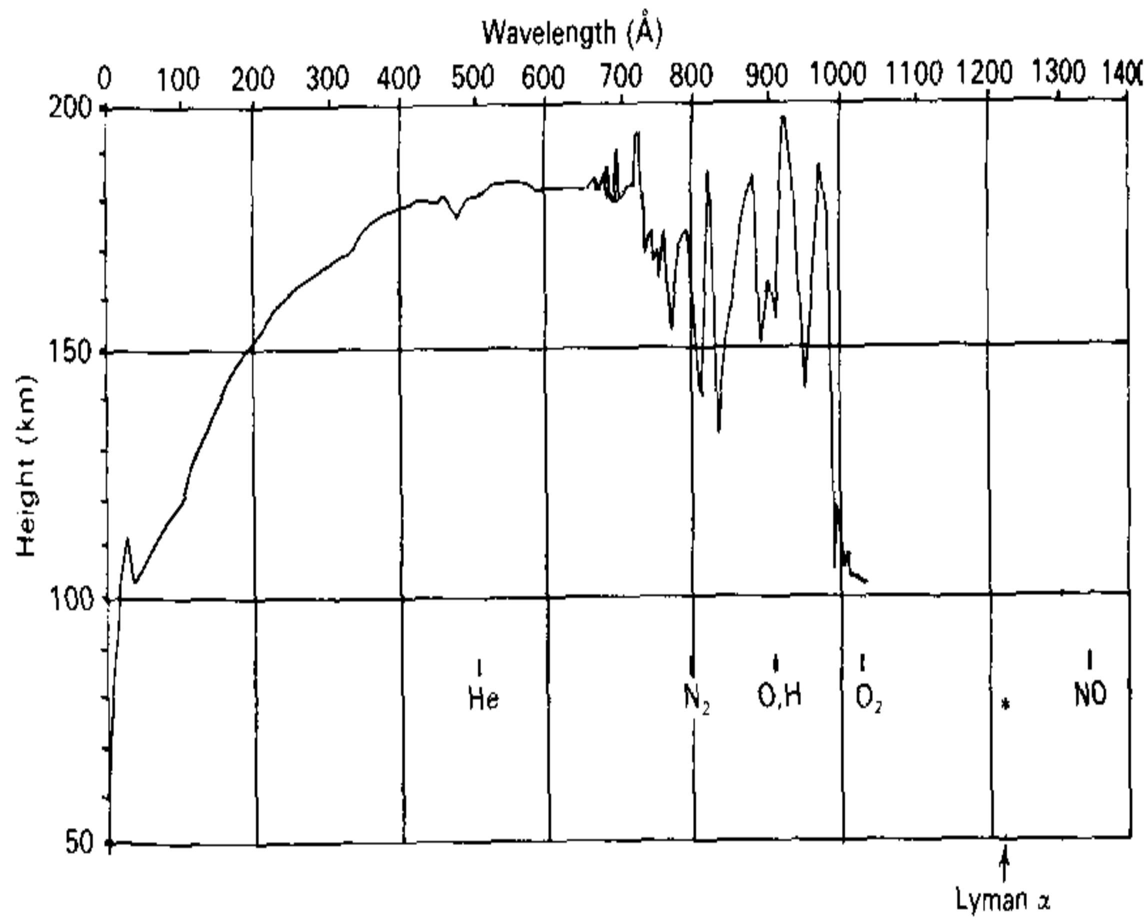


Fig. 6.11 Height where the optical depth reaches unity for radiation vertically incident on a

Credit: Balthazor

Complications with the ionosphere loss processes

Electrons may combine with neutrals to form negative ions

Positive ions may also combine with negative ions as well as with electrons

$$N_m = N_{m0} \cos \chi \qquad \textbf{(6-19)}$$

This is a β–Chapman layer (modified recombination coefficient β) for N_m = to the maximum concentration of ions

Credit: Balthazor

Equation of Motion

- The lower thermosphere is collision-dominated
- Basic equations of fluid dynamics may be used, e.g. Navier-Stokes
- We resort to Newtonian mechanics,

$F = ma$

to describe the forces acting upon a *packet of neutral gas* and its rate of change of velocity

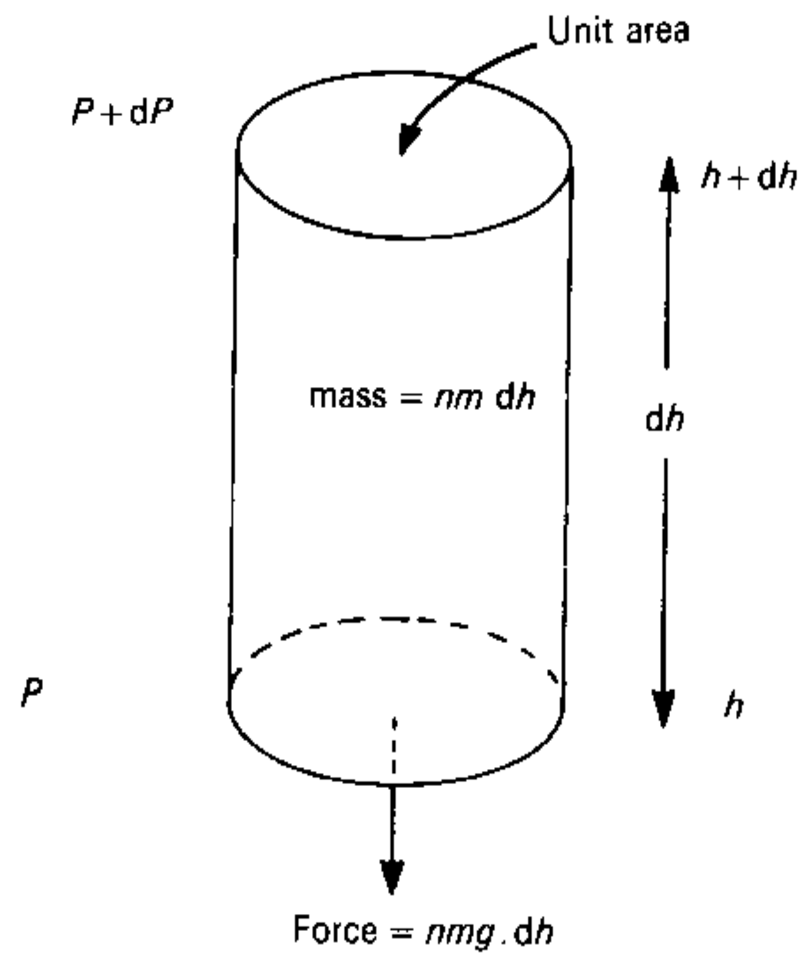
Credit: Balthazor

Equation of Motion

Take a single packet of gas and draw a force diagram in the Lagrangian frame i.e., moving with the gas packet

Acting upon the gas packet:

- Gravity & Pressure Gradient
- Coriolis effects
- Ion Drag
- Viscosity



Credit: Balthazor

Equation of Motion

acceleration = force ÷ unit mass

a = dU/dt = F/m

$$\frac{dU}{dt} = g \underbrace{- \frac{1}{\rho}\nabla p}_{\text{pressure gradient}} \underbrace{-2\Omega \wedge U}_{\text{Coriolis forcing}} \underbrace{-\upsilon_{ni}(U - V)}_{\text{ion drag}} \underbrace{+ \frac{1}{\rho}\nabla(\mu \nabla U)}_{\text{viscosity}} \qquad \textbf{(6-10)}$$

U, ρ, p, υ_{ni} = neutral gas velocity, mass density, pressure, neutral-ion collision frequency; Ω= Earth's angular rotation; V = ion velocity; m = viscosity coefficient, g=gravity

How important are each of these terms? Depends on location in thermosphere.

Credit: Balthazor

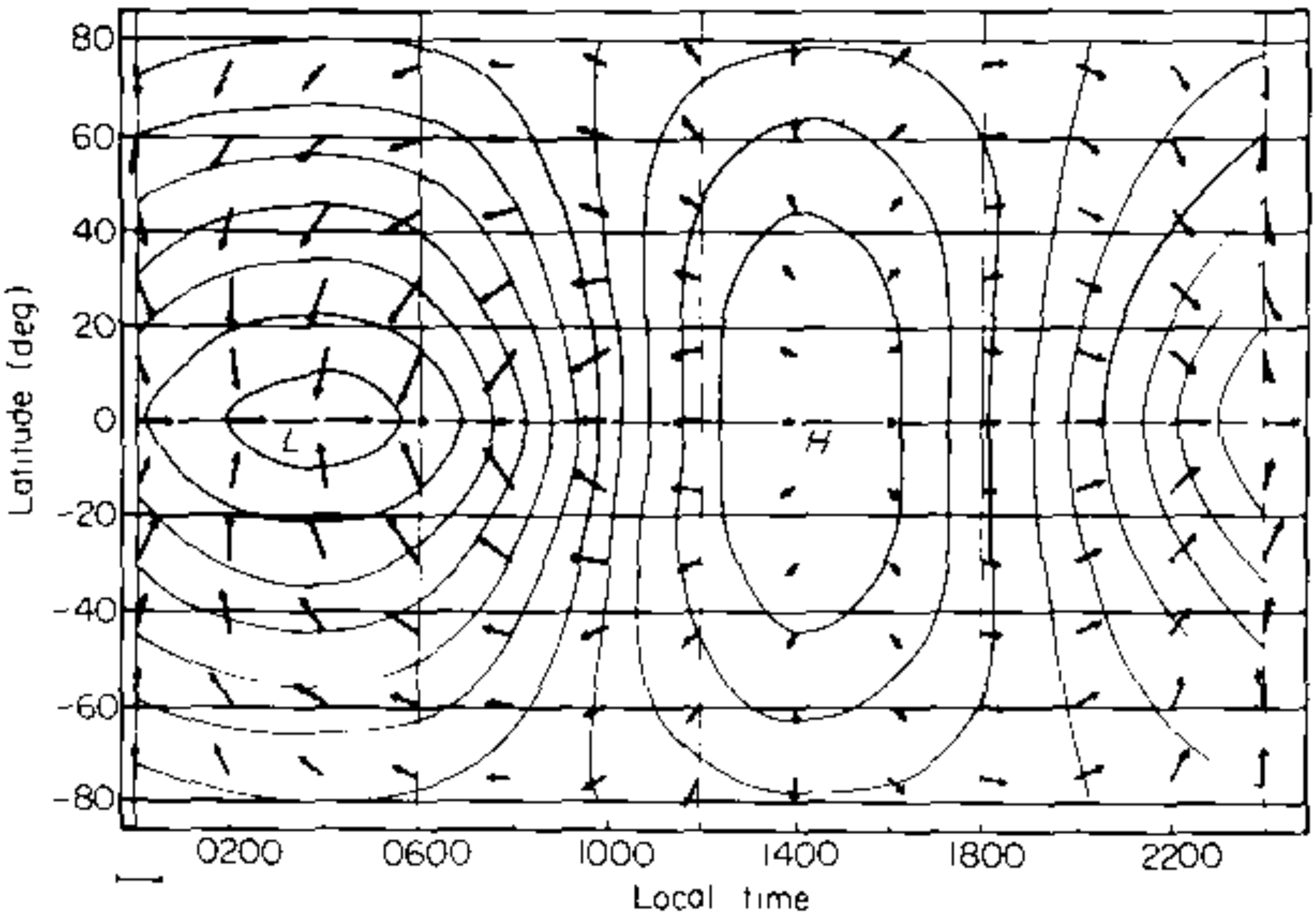
Equation of Motion

- Convert to Eulerian frame, i.e. in the frame of the Earth, by means of a canonical transform

$$\underbrace{\frac{dX}{dt}}_{\substack{\text{rate of change of X}\\ \text{(a gas parameter)}\\ \text{in the packet of gas}}} = \underbrace{\frac{\partial X}{\partial t}}_{\substack{\text{rate of change of X}\\ \text{at a fixed point on}\\ \text{the Earth's surface}}} + \underbrace{(V \bullet \nabla)X}_{\substack{\text{advection}\\ \text{term}}} \quad \textbf{(6-11)}$$

Credit: Balthazor

Thermal Winds



Credit: Balthazor

Tides and Winds Terminology

In the upper thermosphere, solar heating of the thermosphere itself instigates horizontal winds flowing from the dayside to the nightside

The Earth's rotation implies that these are 'tidal' – however we refer to them as 'winds', since in the lower thermosphere (< ~ 120 km), vertical winds propagate upwards from the mesosphere

These are referred to as (thermospheric) 'tides'

Credit: Balthazor

Tides and Winds

- The sun (and moon) will cause tidal effects that propagate westwards, due to heat and gravity
- The solar forcing and natural modes (Hough modes) of oscillation (cf. guitar string) will combine to give tidal modes
- Hough function (n,m): n cycles per day, m-n nodes between the poles
- The dominant tidal modes (in order) are solar-diurnal, solar-semidiurnal (heating-drive), and lunar-diurnal (gravity-driven)

Credit: Balthazor

Thermal Winds

We would expect an eastward wind across the sunset terminator

At the equator, Coriolis terms $\rightarrow 0$

To a first approximation, the neutral atmosphere is slowed by viscosity and we ignore ion drag

Below the turbopause, it is eddy viscosity

Above the turbopause, it is molecular viscosity

Credit: Balthazor

Thermospheric Waves

Waves propagate from any disturbance.

The restoring forces are both gravity vertically (e.g. ocean waves) and compression horizontally (e.g. sound wave): hence '**acoustic gravity waves**' or '**atmospheric gravity waves**' (AGWs), or more generally, '**travelling atmospheric disturbances**' (TADs).

Credit: Balthazor

Thermosphere Waves

Wave propagation tends to be along 'wave guides'

An obvious wave guide is the pressure gradient of the atmosphere (c.f. ocean waves)

Phase propagation is upwards.

Credit: Balthazor

Thermosphere Waves

- A disturbance will generally create a 'family' of TADs
  - Large Scale (LS)
  - Medium Scale (MS)
- LS-TADs originate from magnetically conjugate auroral disturbances in the thermosphere
  - λ (wavelength) ~ 1000s km, τ (period) ~ 10s min, v (velocity) ~ 100s m/s, particle motion $\leftrightarrow$
- MS-TADs originate from the middle atmosphere
  - λ ~ 10s km, τ ~ mins, v ~ 10s m/s, wavefront ~ 45^o

Credit: Balthazor

Large Scale TADs

What is the triggering disturbance?

Large electric fields in the polar regions drive the ionosphere through ExB forcing (left hand or motor rule)

The ionosphere 'rubs against' the pseudo-stationary thermosphere

Credit: Balthazor

Observing TAD/TIDs

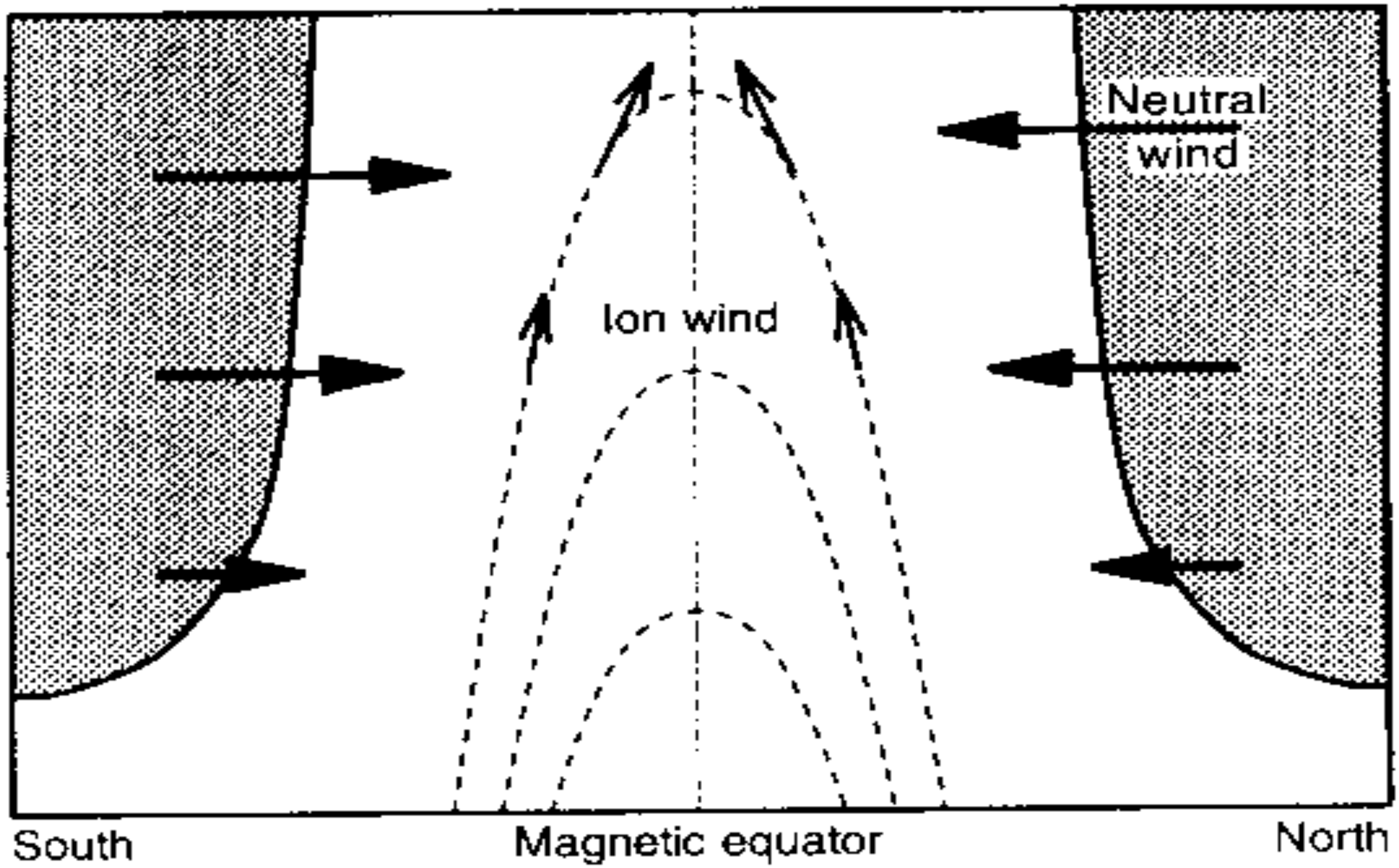
Motion of the thermosphere is notoriously difficult to image.

We rely on a proxy: the movement of the embedded ionosphere, which reflects and refracts radio waves. However…

…ions are constrained to spiral about field lines. Thus, horizontal motion of the thermosphere will result in a vertical component to the motion of the ionosphere (in the general case where 0 < dip angle < 90)

Credit: Balthazor

TAD/TID coupling



Credit: Balthazor

hmF2 signature of TAD

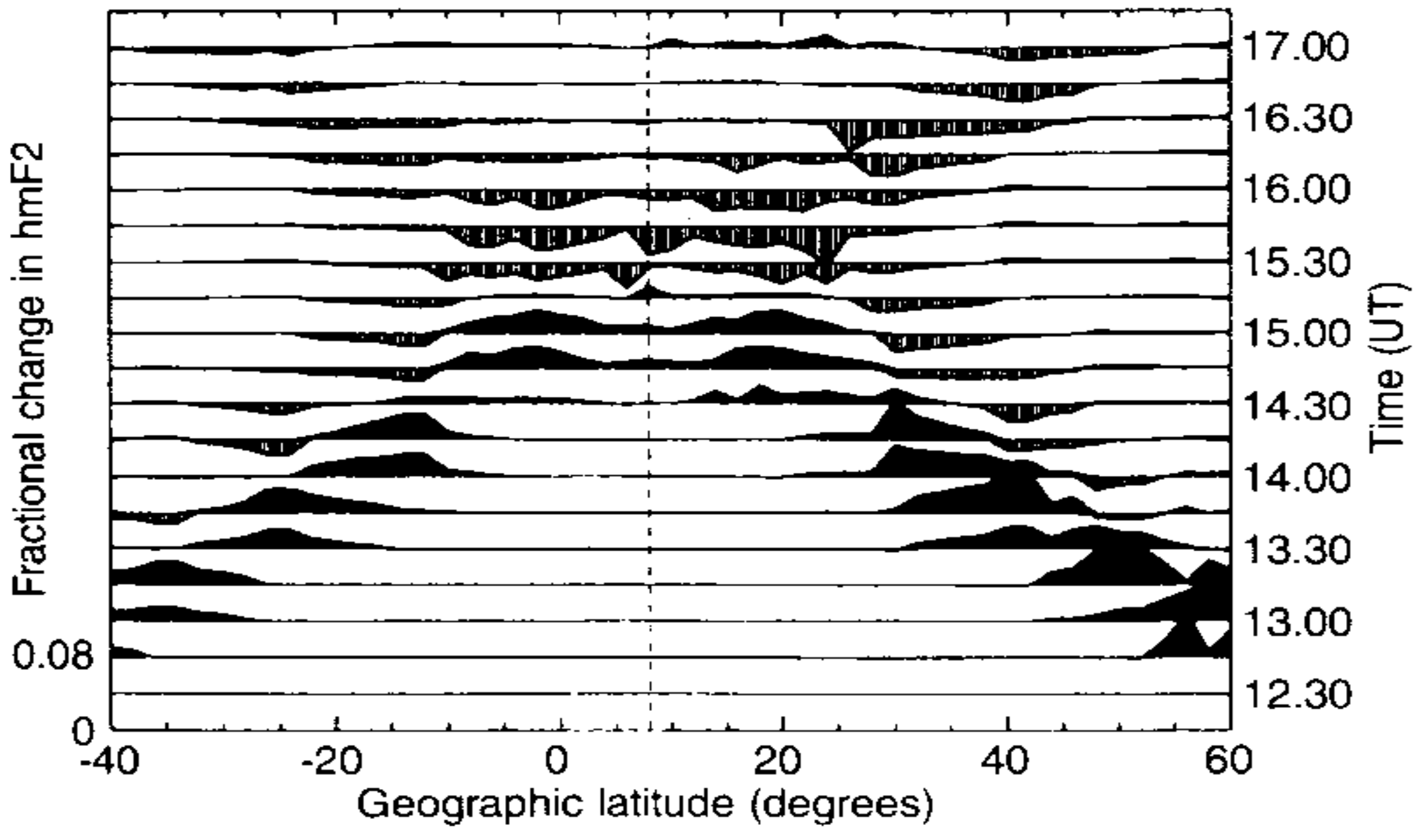


Fig. 4. Change in hmF2 (the height of the F2 peak), relative to steady-state conditions. The format of the plots is identical to that of Fig. 1

Credit: Balthazor

NmF2 signature of TAD

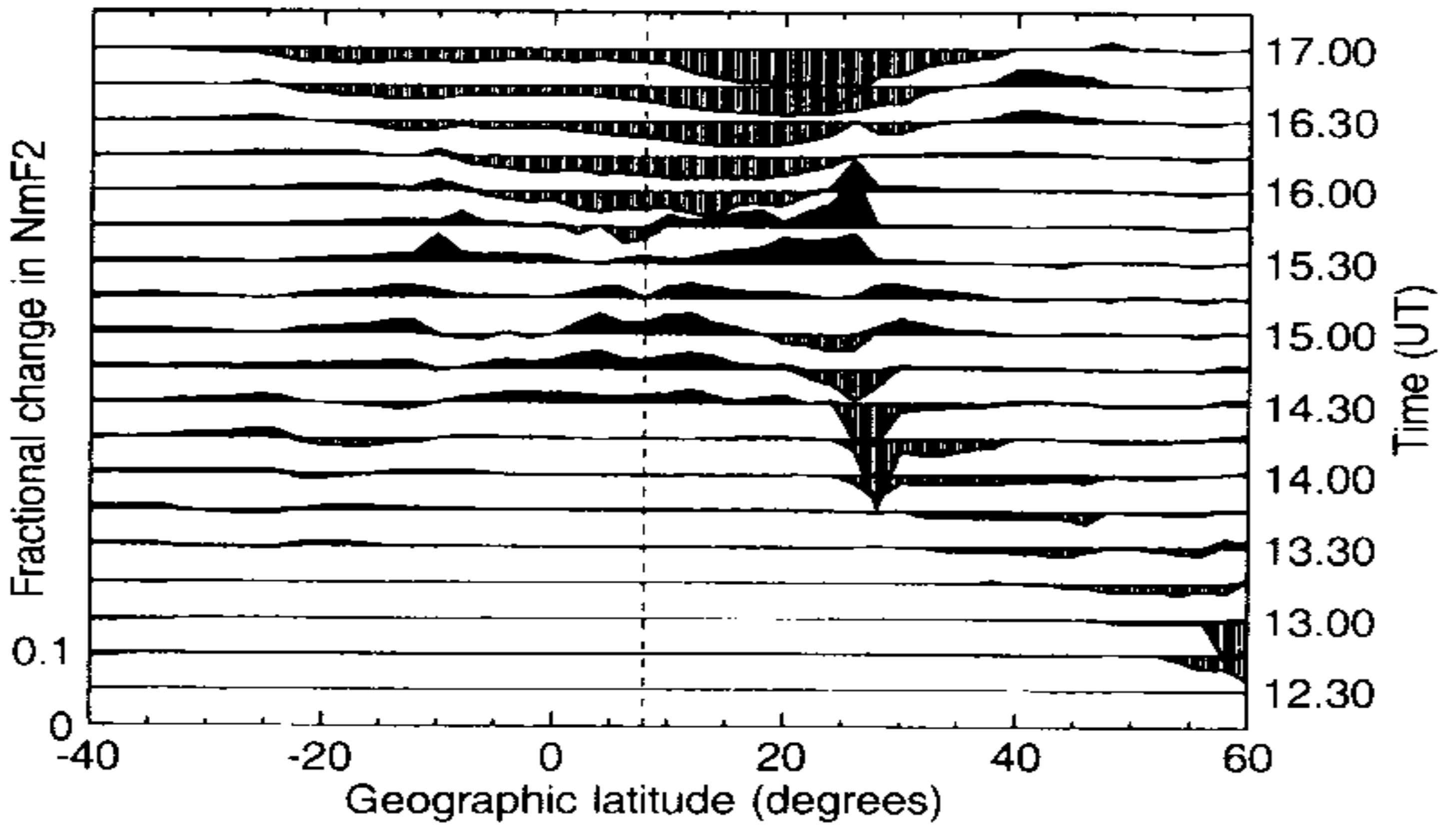
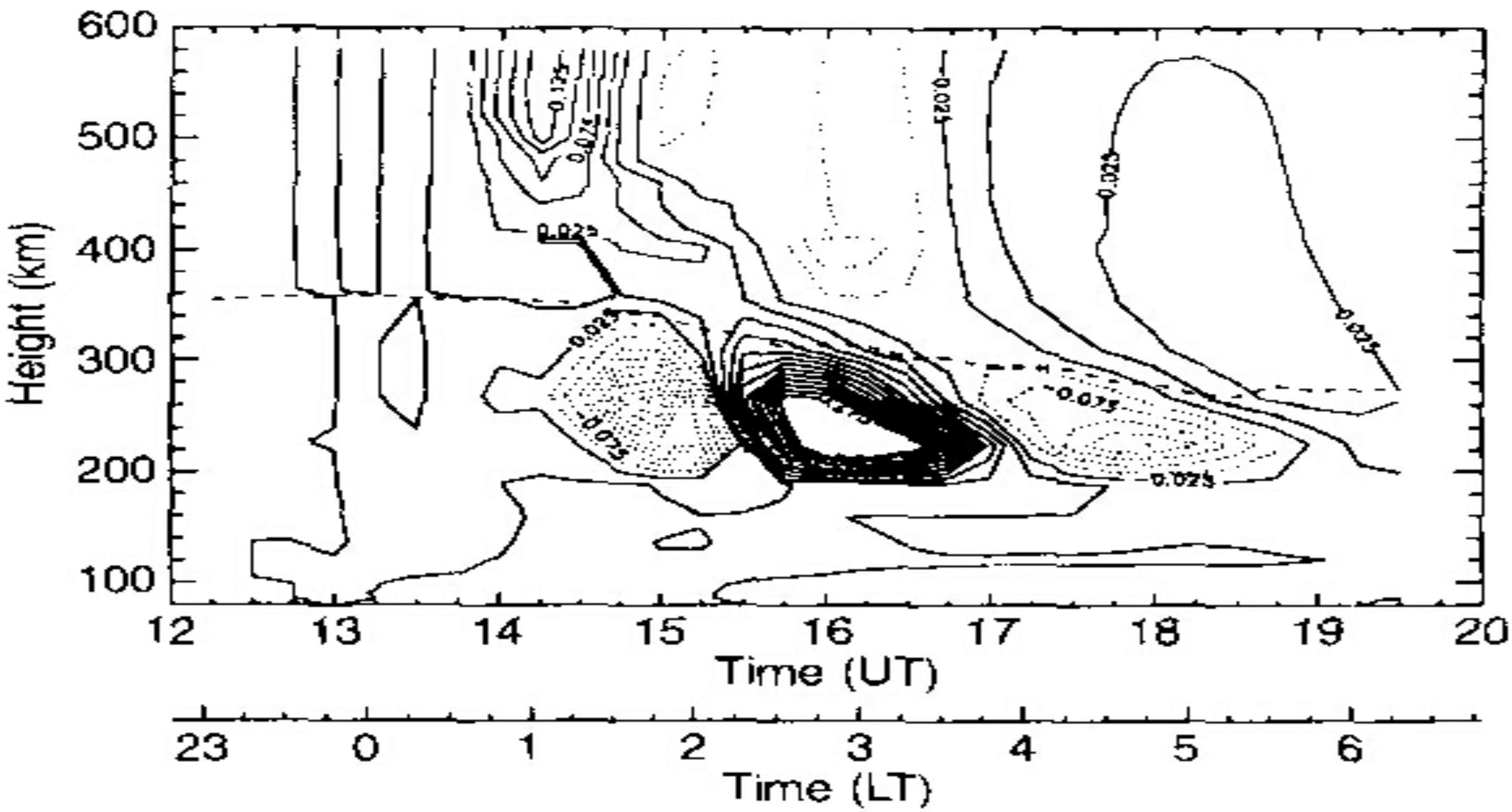


Fig. 5. Change in NmF2 (the density of the F2 peak), relative to steady-state conditions. The format of the plots is identical to that of Fig. 1

Credit: Balthazor

Ionospheric signature of TAD



Credit: Balthazor

Polar Vortices / Flywheel

Ions driven by a large electric field can accelerate to ~ km/s

Lorentz forcing will impart momentum to the neutral gas

The polar thermosphere can thus ‘spin up’ into a flywheel, retaining its momentum, and driving the ionosphere long (~hours) after the strong electric field conditions have vanished.

Credit: Balthazor

Super-rotation

- Early satellite data showed that the equatorial thermosphere super-rotates in the evening sector
- Average eastward zonal flow ~ 150 m/s @ 350 km, 50 m/s @ 200 km, most pronounced @ 2100-2400 LT
- Associated with solar heating

Credit: Balthazor

Ionospheric features

Conductivities

- **Hall conductivity**: due to currents flowing perpendicular to the electric field
- **Pedersen conductivity**: due to currents flowing parallel to the electric field

Credit: Balthazor

F-region Motor

- During the daytime, the conductivity along the field lines is high
- The F-region plasma will thus be exposed to ~ the same electric field which will tend to drive the F-region plasma like a motor with a velocity

$$\mathbf{v} = \frac{\mathbf{E} \times \mathbf{B}}{|\mathbf{B}|^2} \quad (6\text{-}20)$$

Credit: Balthazor

F-region dynamo

- In the F-region we have a conducting ‘slab’, defined at low altitudes by recombination erosion, and at high altitudes by the decreasing density gradient
- The vertical wind is always small
- The horizontal neutral wind, in equatorial regions, blows zonally (i.e., east-west)

Credit: Balthazor

F-region dynamo

Assume that the magnetic field lines are infinitely long and horizontal

In the reference frame of the neutral gas the **perturbed electric current** is

$$\mathbf{J}' = \sigma \bullet \mathbf{E}' \qquad \textbf{(6-21)}$$

with conductivity, σ

In the Earth's reference frame, current is

$$\mathbf{J} = \sigma \bullet (\mathbf{E} + \mathbf{U} \times \mathbf{B}) \qquad \textbf{(6-22)}$$

Credit: Balthazor

F-region dynamo

Therefore an electric current ~ 10 nA/m^2 will flow upwards[1] due to the dynamo effect:

$$|\mathbf{J}| = \sigma_P u |\mathbf{B}| \quad \textbf{(6-23)}$$

[1] i.e., the electric field is down and positive ions move up while electrons move down

Credit: Balthazor

F-region dynamo

An electric field ~ mV m^{-1} must build up in the vertical direction as a result of the charge separation to oppose the current flow.

$$\left|\mathbf{J_z}\right| = \sigma_P E_z + \sigma_P u \mathrm{B} = 0 \qquad \textbf{(6-24)}$$

Plasma drift speed = zonal neutral wind speed

Night-time approximation of insulating slabs at ends (top and bottom of ionosphere)

Credit: Balthazor

E-region dynamo

- During the day, the 'insulating ends' approximation is not valid, and the current flow into the conducting E-region must be taken into account.
- Daytime E-region conductivity > F-region conductivity (integrated up the field line), so the E-region 'controls' the dynamo process…

Credit: Balthazor

E-region dynamo (1)

- In the E-region between ~ 85 km and ~ 140 km, the collision frequency is greater than the ion gyro frequency but less than the electron gyro frequency.
- Thus, ions move with the neutral wind while electrons move perpendicular to the neutral wind.
- An electric field is produced.

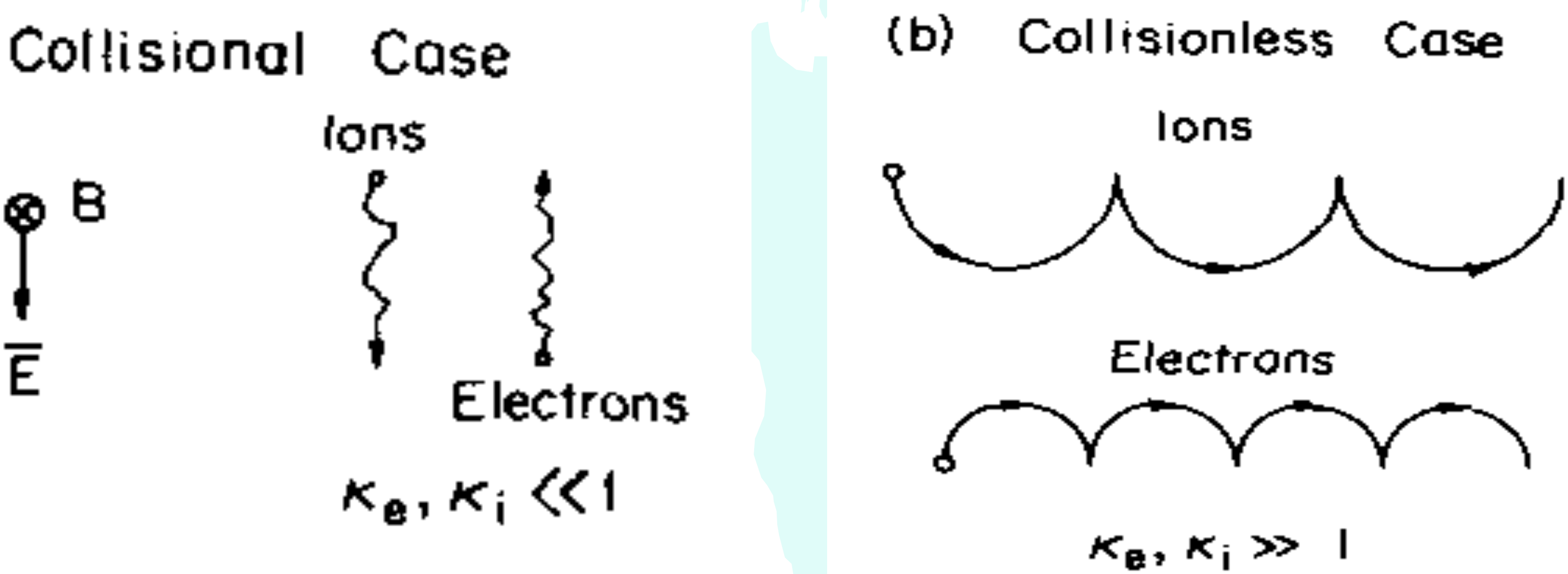
Credit: Balthazor

E-region dynamo (2)

- There will be an additional contribution to the electric current from the Hall conductivity (perpendicular to the winds)
- But no current can flow vertically, since the E-region is bounded above and below by ‘insulators’
- So the vertical Pedersen current must cancel the vertical Hall current.

Credit: Balthazor

Ion Gyrofrequency (ω) vs Collision Frequency (ν)



$\nu \gg \omega$

Collision freq >> ion gyrofrequency

$\nu \ll \omega$

Collision freq << ion gyrofrequency

Credit: Balthazor

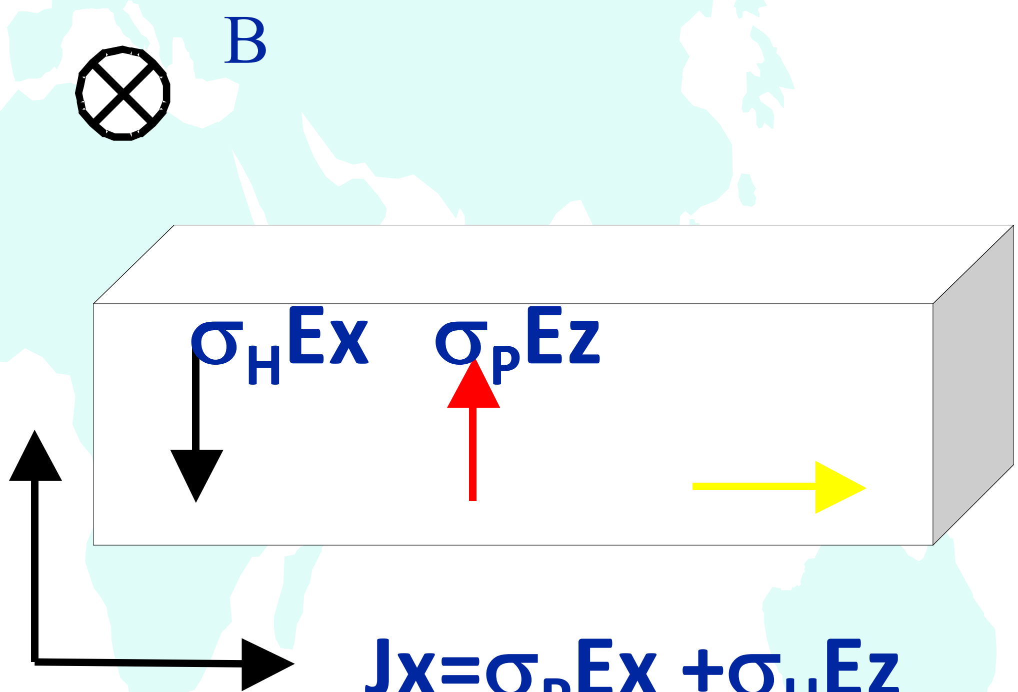
Conductivities help create the equatorial electrojet

$$\sigma_H E_x = \sigma_P E_z$$

$$E_z = \left(\frac{\sigma_H}{\sigma_P}\right) E_x$$

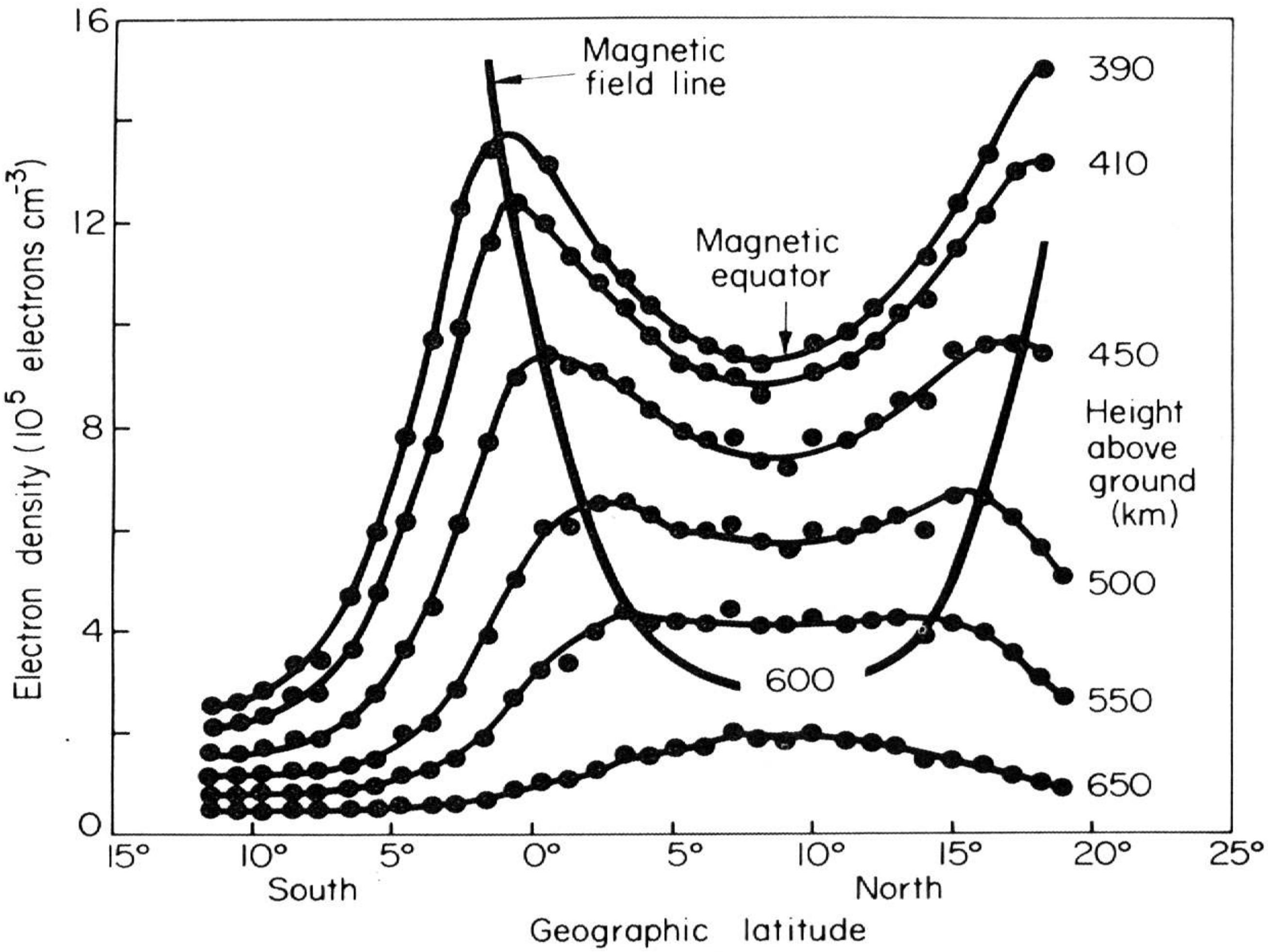
$$J_x = \sigma_H E_z + \sigma_P E_x$$

$$J_x = \underbrace{\left(\frac{\sigma_H^{\,2}}{\sigma_P^{\,2}} + 1\right)\sigma_P}_{\text{Cowling conductivity}} E_x$$



$J_x = \sigma_P E_x + \sigma_H E_z$

… and the Equatorial Anomaly



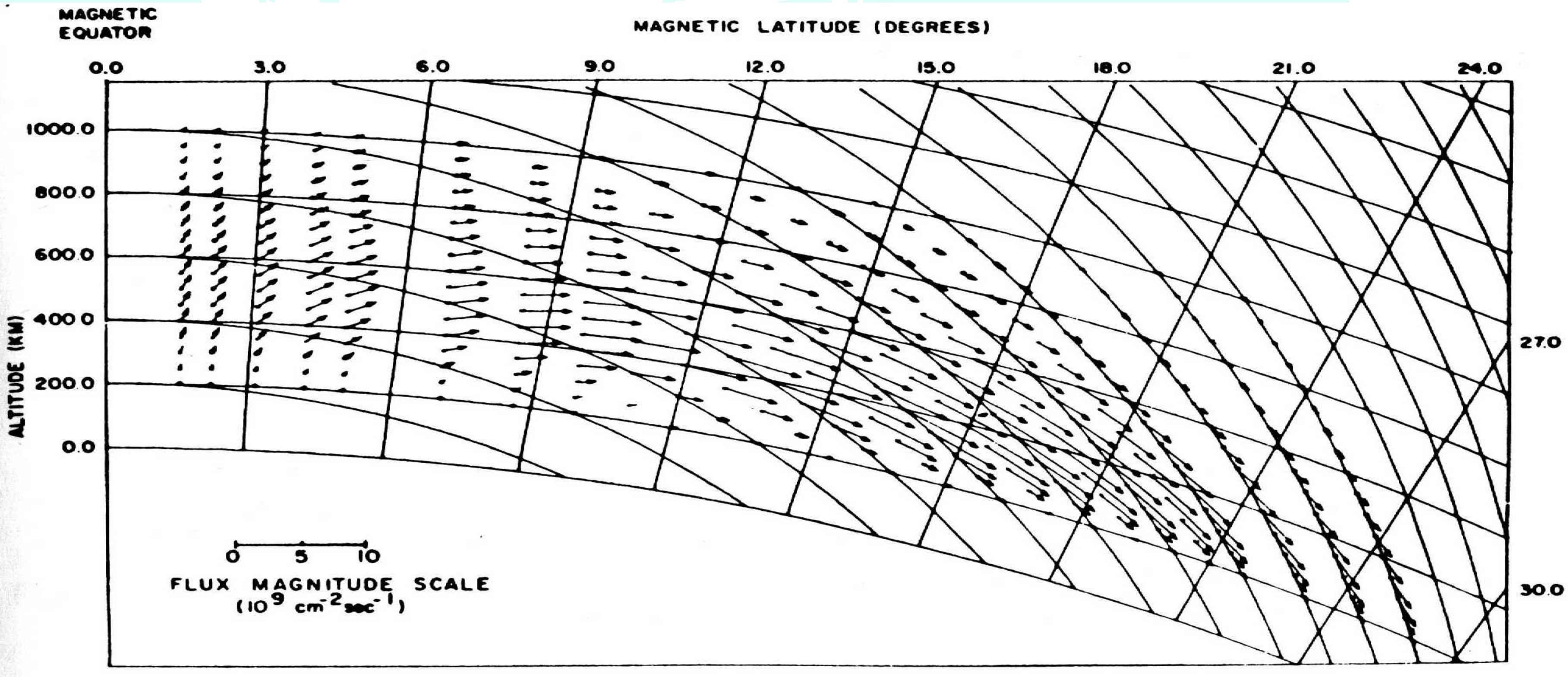
Credit: Balthazor

Equatorial Anomaly

- aka Appleton Anomaly
- We might expect the electron density to maximize over the equator at equinox. However, it actually maximizes ~ 10-20 degrees N and S, with a small minima at the equator.
- To explain this, we invoke the ‘fountain effect’.

Credit: Balthazor

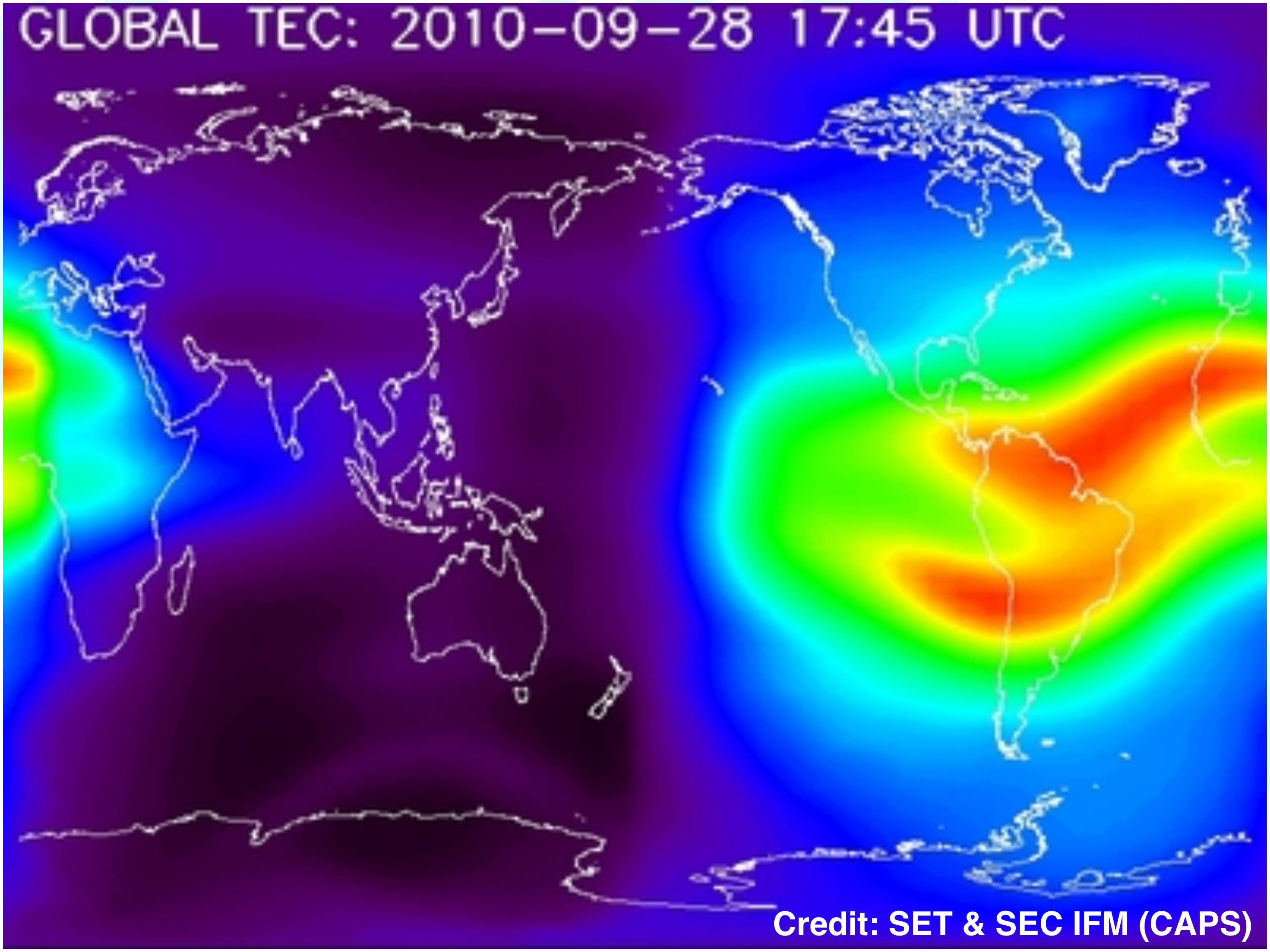
Fountain Effect



Equatorial Electrojet drives the F-region motor. E-field is zonal, magnetic field is meridional, so plasma drift is vertically upwards. Plasma then descends down the magnetic field lines either side.

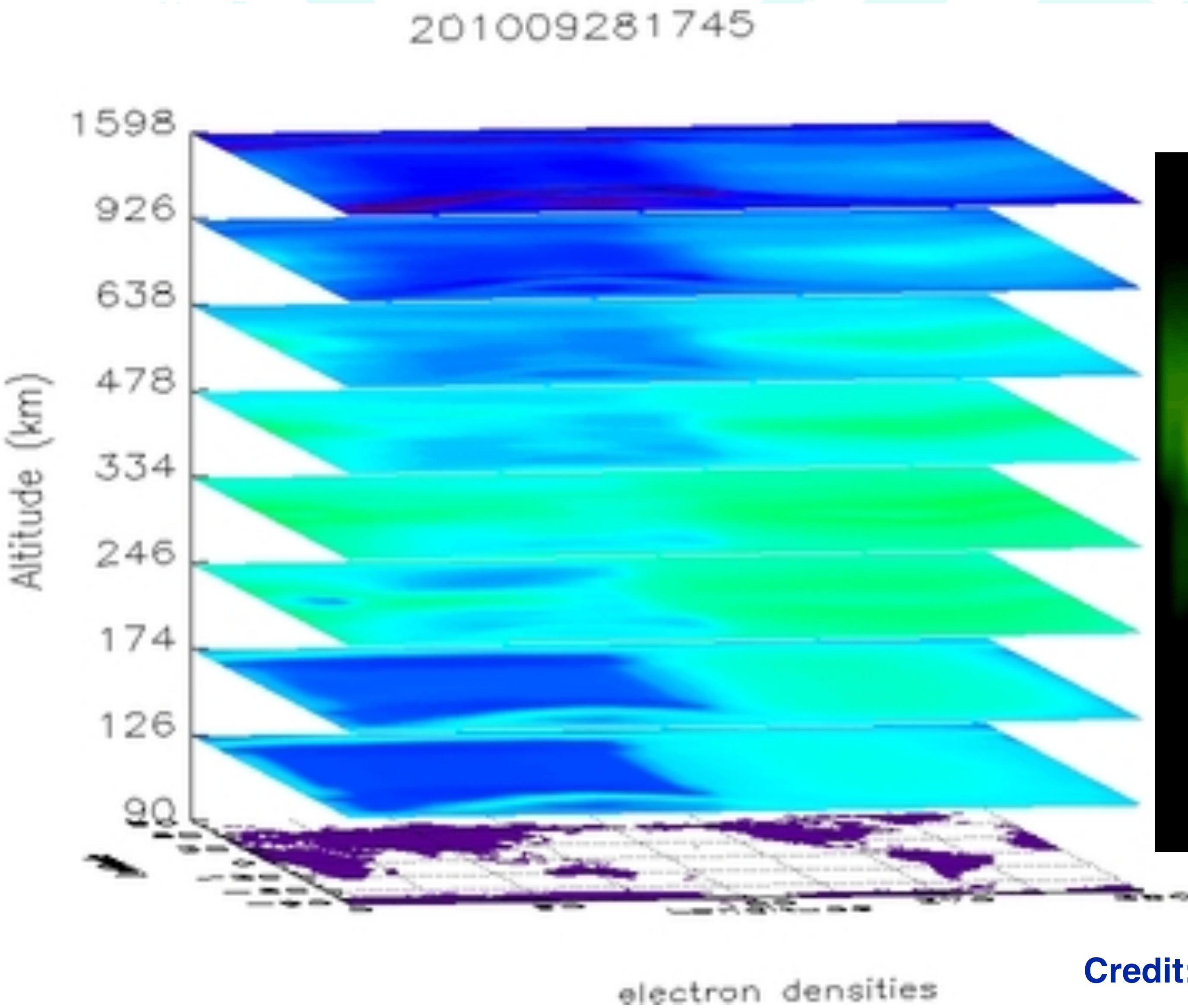
Credit: Balthazor

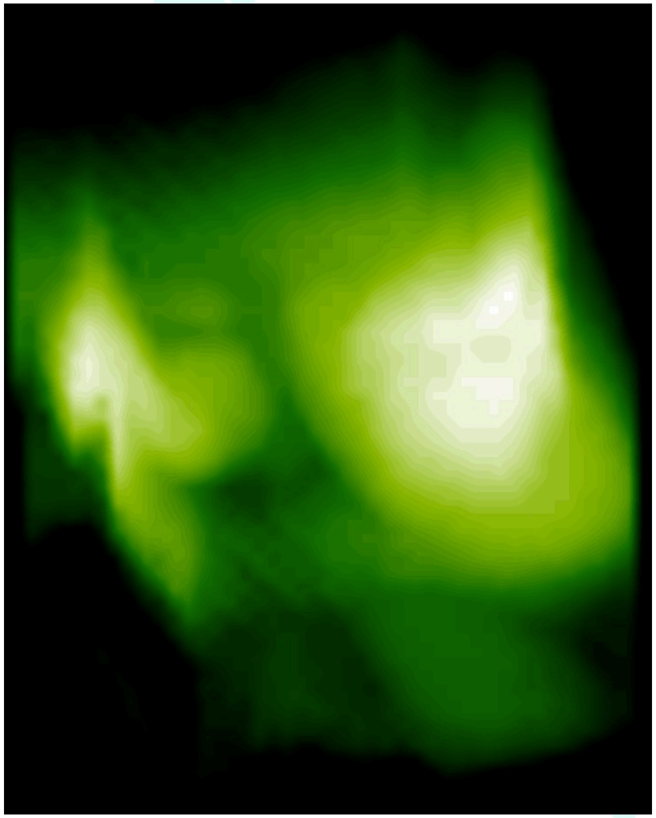
Equatorial Anomaly



Credit: SEC, SET

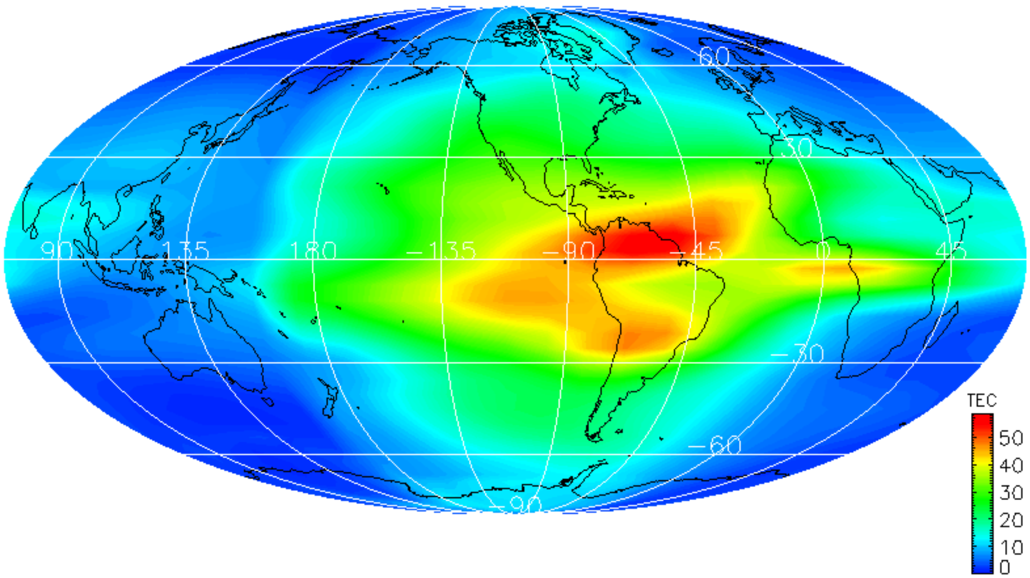
Equatorial Anomaly

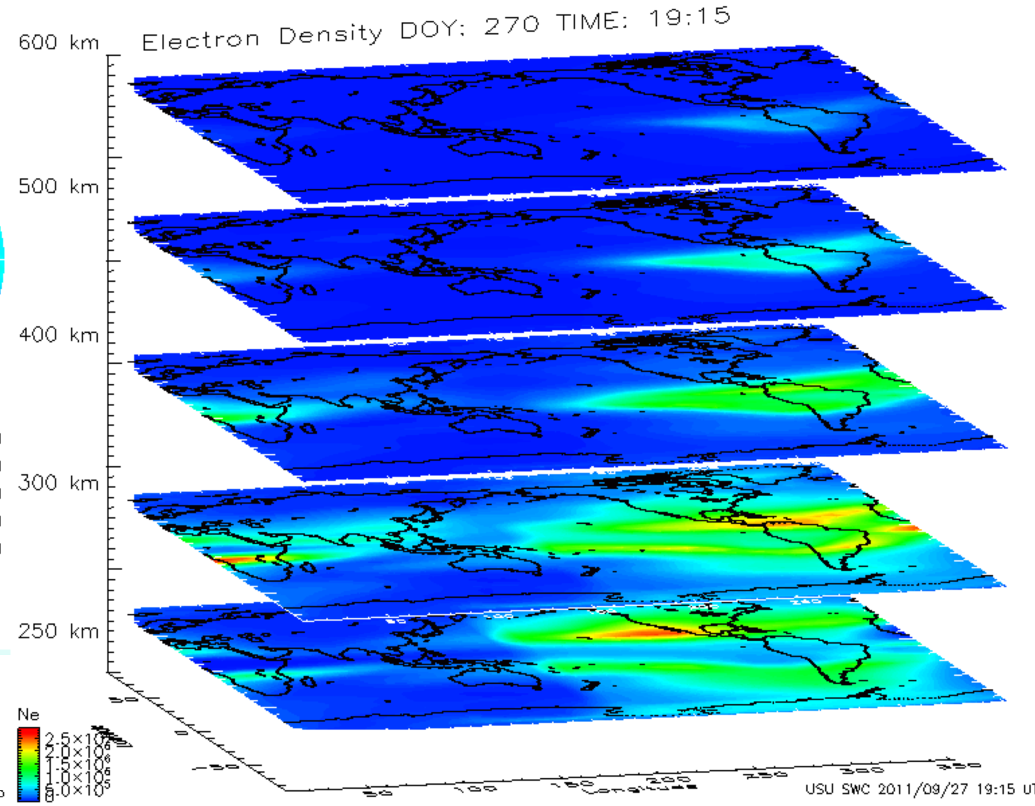


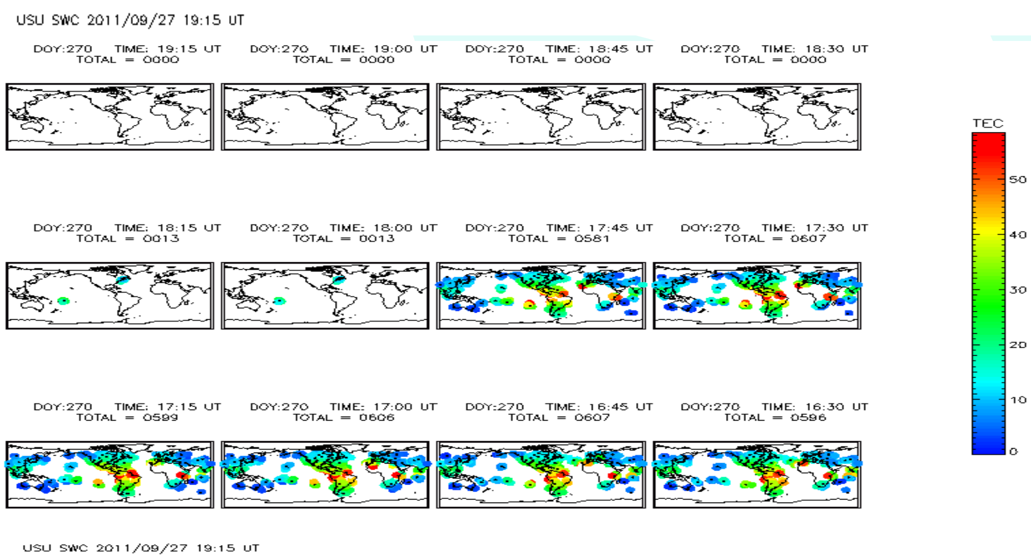


Credit: SET & SEC IFM (CAPS)

Equatorial Anomaly

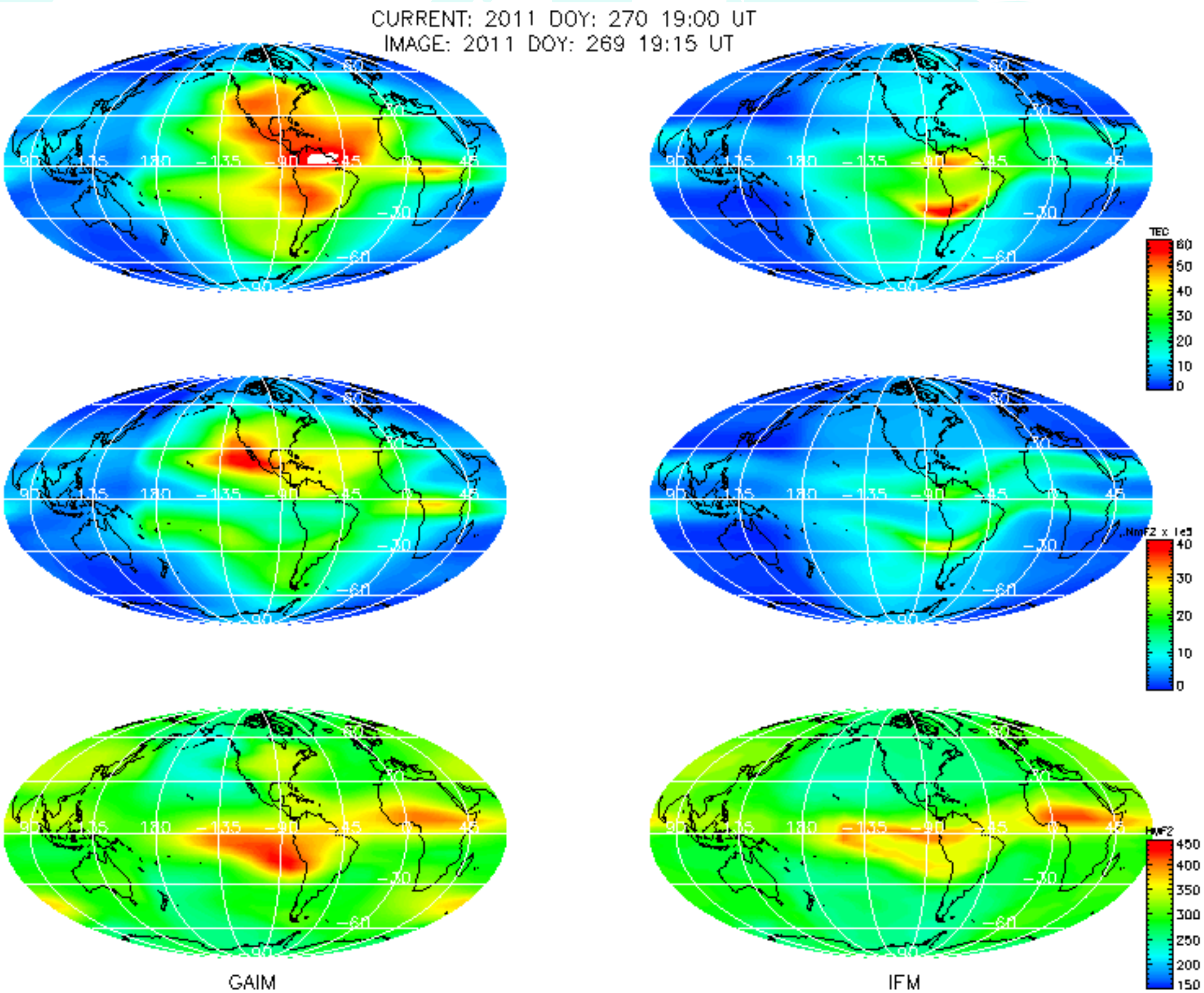






Credit: USU SWC

Equatorial Anomaly



Credit: USU SWC

Resources

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ISBN 0124040136, Academic Press
(may be out of print)

The Solar-Terrestrial Environment, Hargreaves,
ISBN 0521427371, Cambridge University Press

STEP Handbook of Ionospheric Models, ed. Robert Schunk, Utah State University

Space Weather & Telecommunications, John M. Goodman, ISBN 0-387-23670-8 (hc), Springer, 2005

Credit: Tobiska

Summary

- The planetary space environment - II
  - Earth
    - Ionospheric physics
      - Thermospheric coupling
      - Electron-ion production and loss processes (solar EUV photoionization, charged particle precipitation, Joule heating, waves, winds)
      - Ionospheric Structure and Dynamics
      - Ionospheric features