

The planetary environment - I

Lecture 4

W.K. Tobiska

Space Environment Technologies

Announcements

Resources

- ◆ **JB2008:** quicklink at <http://spacewx.com>
- ◆ **Comments solicited:**
 - 21348 (solar irradiances), 15390 (GCRs), 16457 (ionosphere), 14222 (neutral atmosphere), **16709 (real-time space weather)**
 - See Standards link at <http://spacewx.com> for reviewing the standards to help improve them [note: these are not the official versions – those must be purchased from ISO]

Announcements

Miscellaneous

- ◆ Interplanetary dust -
<http://stardust.jpl.nasa.gov/news/news19.html>
- ◆ JPL ephemeris generator for the Solar System at
<http://astronautics.usc.edu/utility/>
- ◆ Goddard Space Flight Center website indicates there is typically 100 billion kg (10^{11} kg = 10^8 metric tons) of material released during a CME.
(<http://helios.gsfc.nasa.gov/cme.html>)
- ◆ SDO AIA witnesses a double eclipse
<http://www.nasa.gov/feature/goddard/2016/nasa-s-sdo-witnesses-a-double-eclipse>

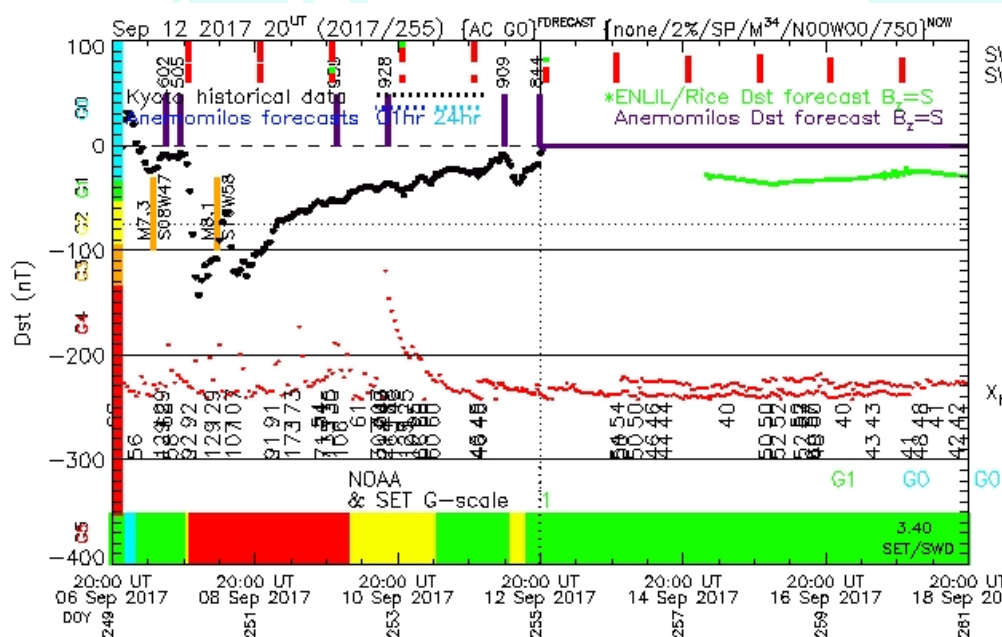


Visible from the ISS, a smoke plume rises from the Manhattan area after two planes crashed into the towers of the World Trade Center on September 11, 2001.

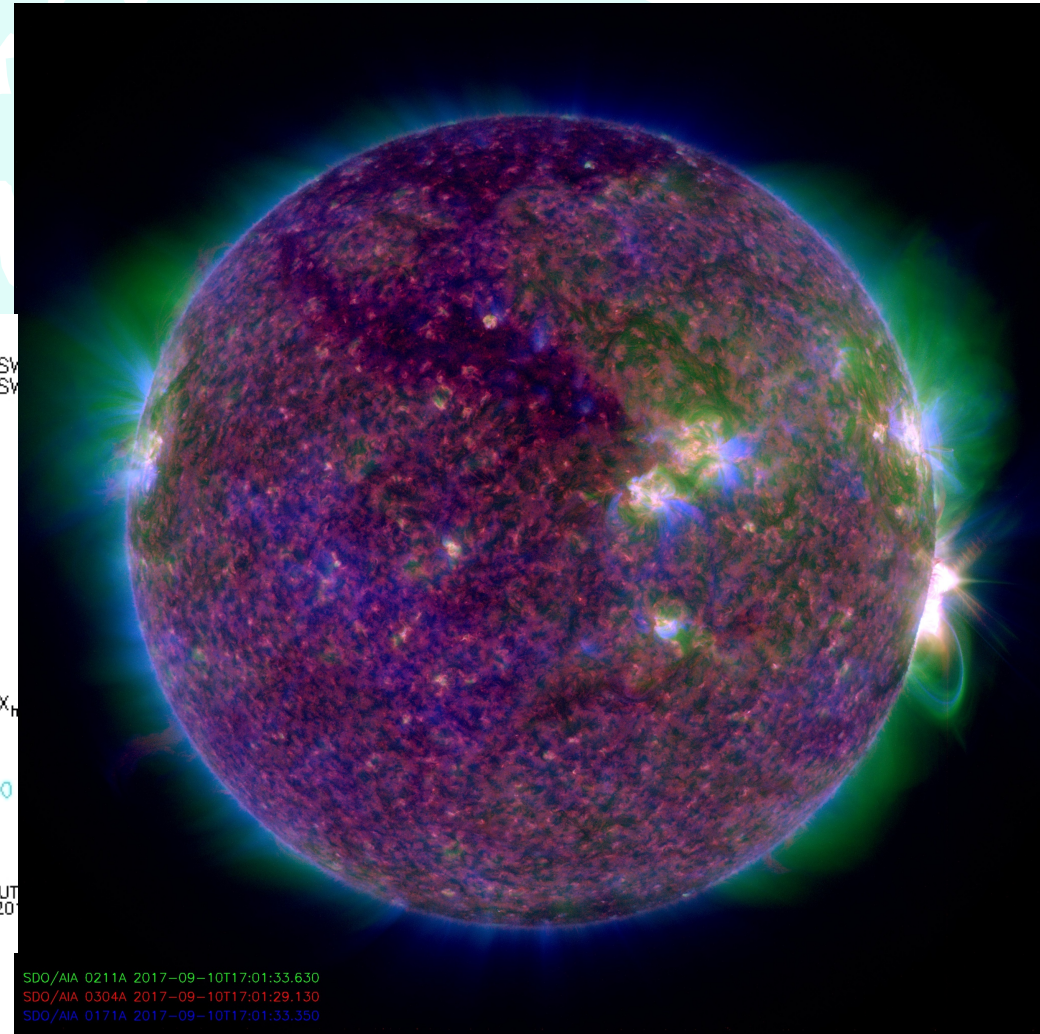
Announcements

Miscellaneous

- ◆ Sep 10, 2017 large CME misses Earth



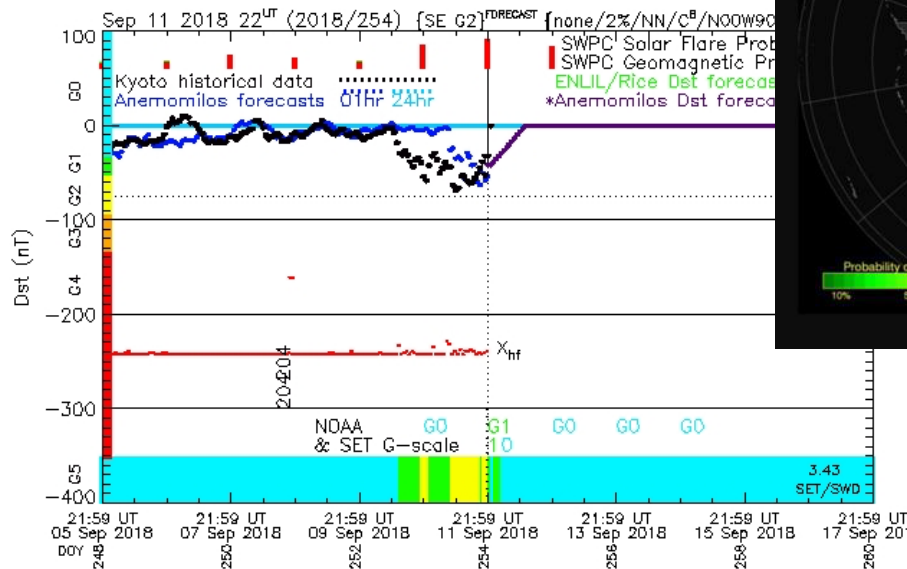
http://sol.spacenvironment.net/~sam_ops/index.html?



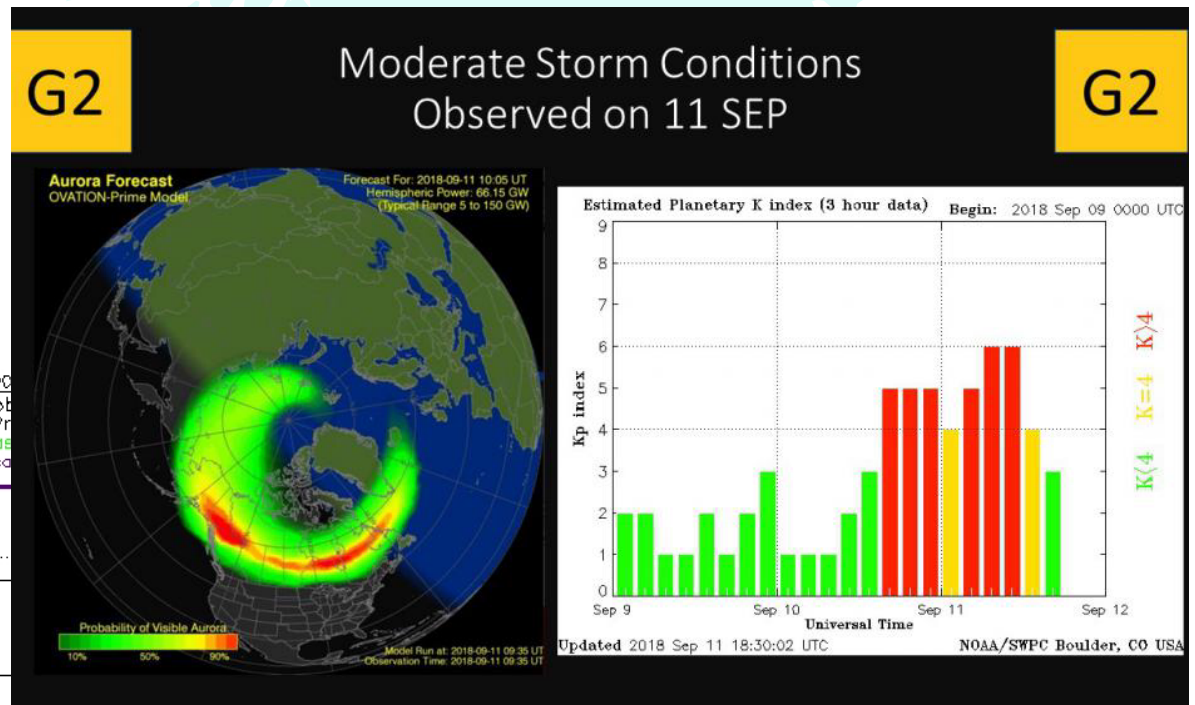
Announcements

Miscellaneous

- ◆ Sep 11, 2018 high speed stream geomagnetic storm



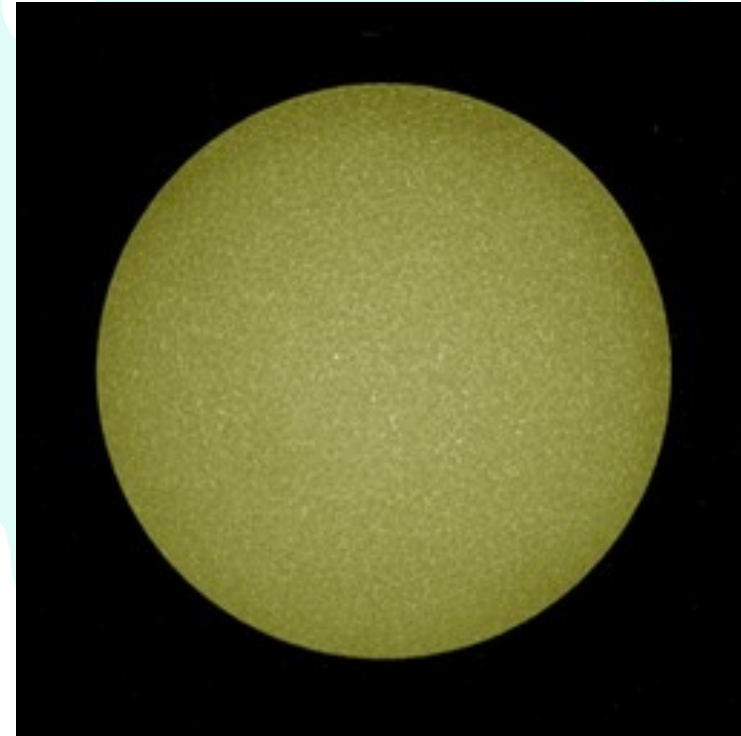
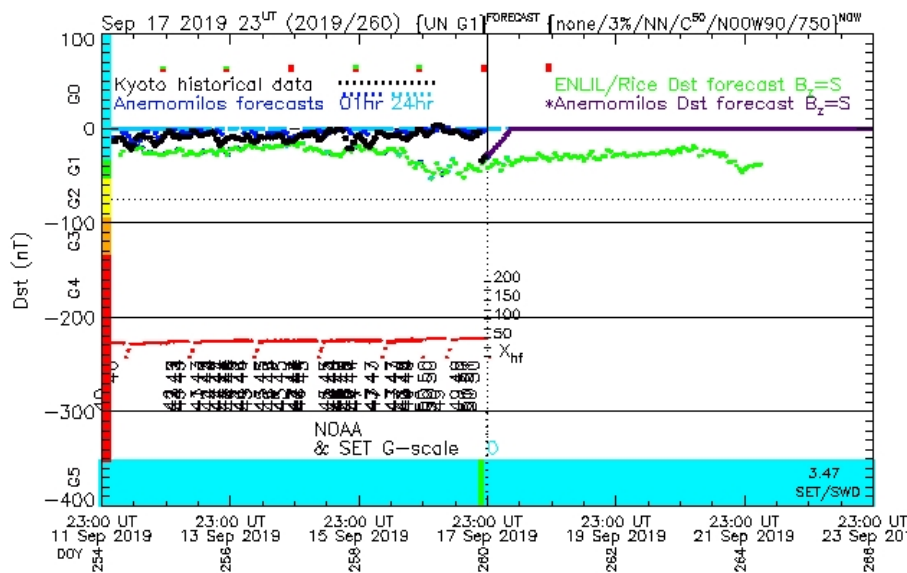
http://sol.spacenvironment.net/~sam_ops/index.html?



Announcements

Miscellaneous

- ◆ Sep 17, 2019 solar minimum



http://sol.spacenvironment.net/~sam_ops/index.html?

Announcements

Miscellaneous

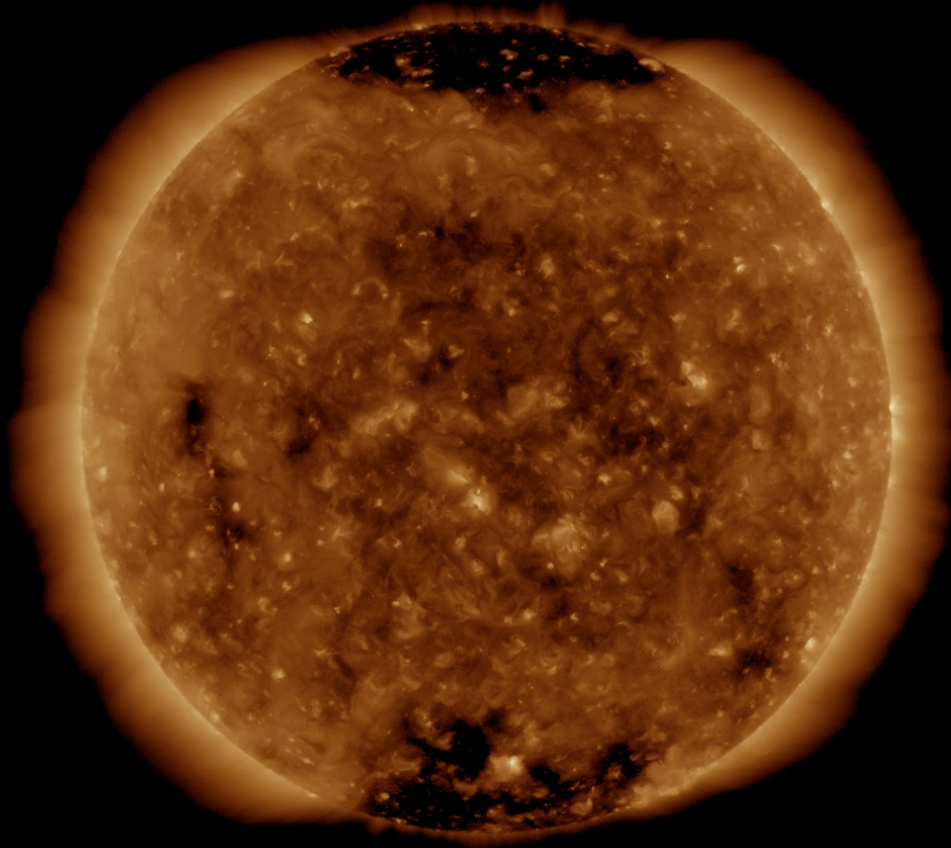
- ◆ Satellite failures: <http://www.sat-index.co.uk/failures/>
- ◆ Orbital debris video:
http://www.space.com/common/media/video/player.php?videoRef=SP_090218_space_debris
- ◆ STS waste dump causes airglow
<http://www.space.com/missionlaunches/090911-space-water-dump.html>
- ◆ Why future astronauts may be sent to 'gravity holes'
<http://www.newscientist.com/article/dn17713-why-future-astronauts-may-be-sent-to-gravity-holes.html>
- ◆ Solar wind from MSFC website
<http://solarscience.msfc.nasa.gov/SolarWind.shtml>
- ◆ Solar wind coupled to Earth's atmosphere
http://www.spacedaily.com/reports/Scientists_Discover_Surprise_In_Earth_Upper_Atmosphere_999.html
- ◆ Voyager 1 officially crossed into interstellar space in August 2012

Announcements

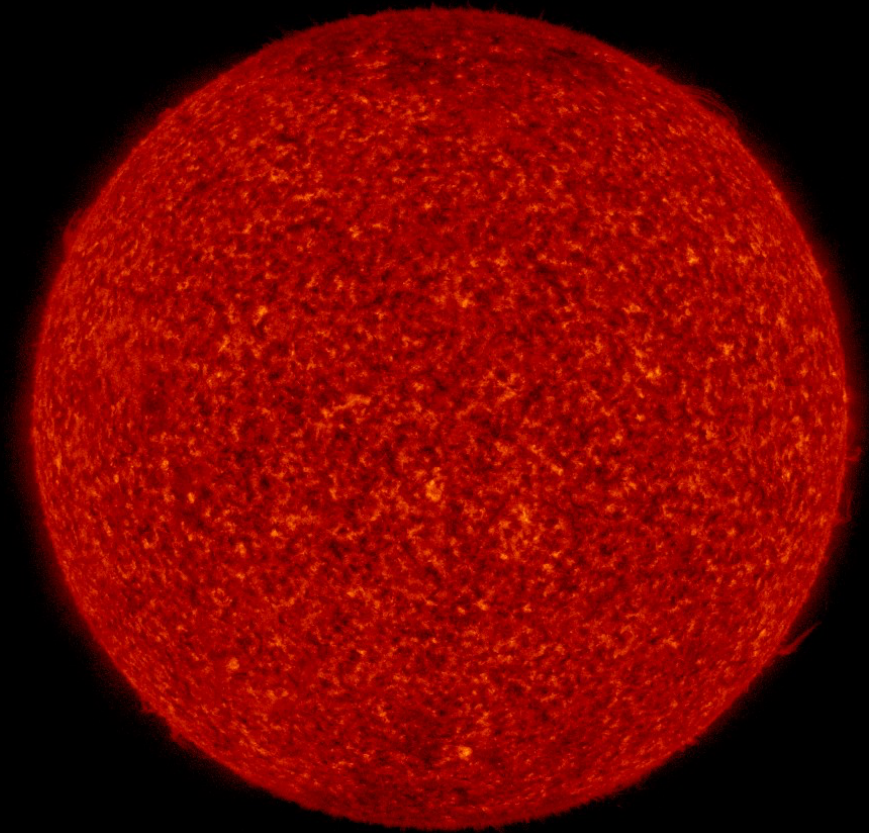
Miscellaneous

- ◆ images from the STEREO probes are separated in their solar orbits and provide stereoscopic views of the sun.
 - STEREO Homepage: <http://stereo.gsfc.nasa.gov/>
 - 3D Image Gallery:
<http://stereo.gsfc.nasa.gov/gallery/3dimages.shtml>
 - An animated "wiggle stereogram":
http://upload.wikimedia.org/wikipedia/commons/8/8b/BLUE_STEREO_3D_Time_for_Space_Wiggle.gif

Extremely quiet solar minimum



SDO/AIA 193 2019-09-17 17:55:41 UT



SDO/AIA 304 2019-09-17 17:57:30 UT

Lecture Overview

The planetary space environment - I

- Gas kinetic theory

 - Ideal Gas Law

 - Molecular and atomic collisions

- Earth

 - Atmospheric physics

 - Surface and lower atmosphere

 - Upper atmosphere

 - Heating (Solar, auroral, conduction, mixing)

 - Cooling (conduction, mixing)

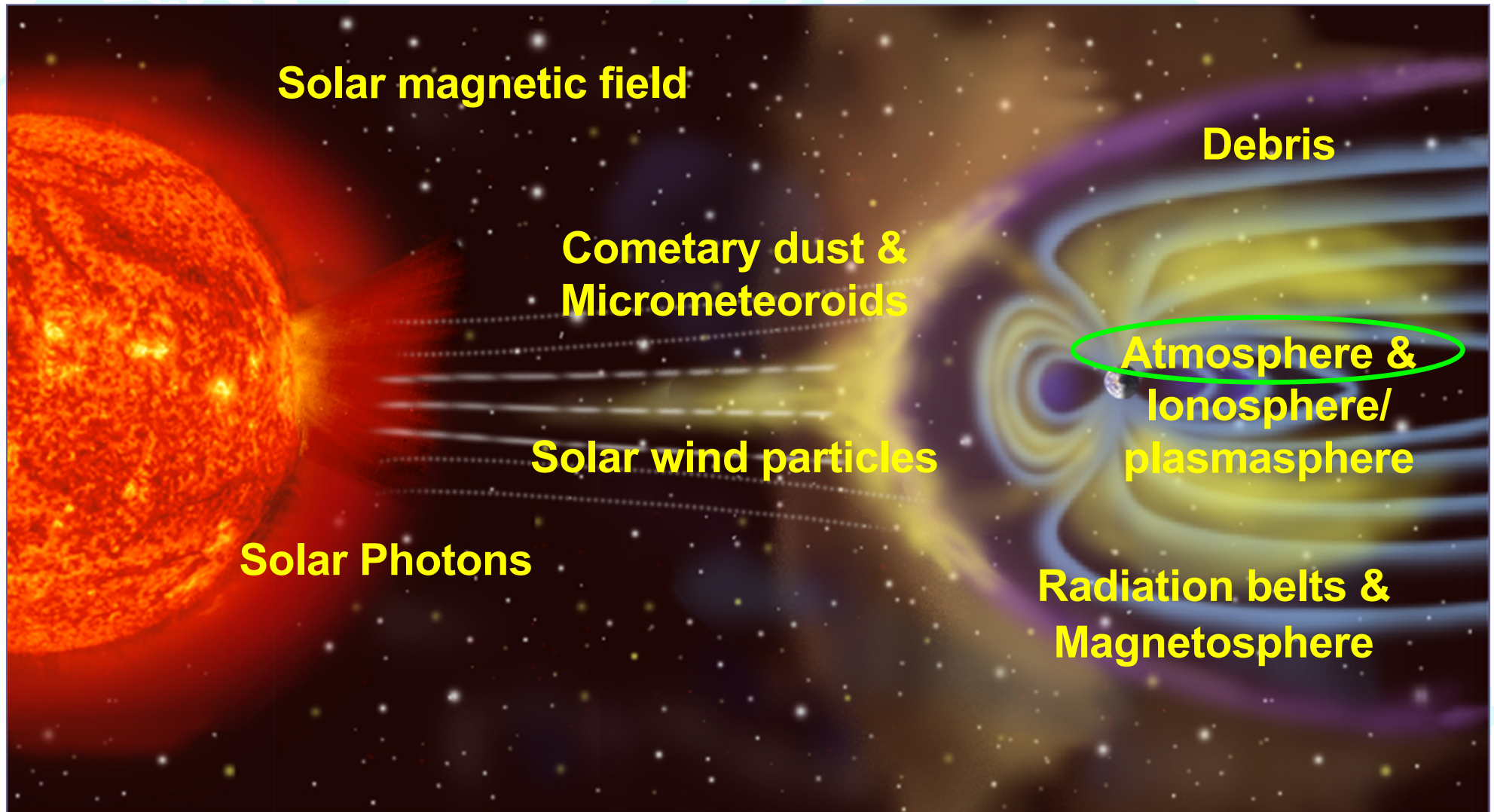
 - Dynamics

Homework

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The planetary space environment

The space environment



A light blue silhouette of a world map serves as a background for the title text.

Gas kinetic theory

Knudsen number

Assumptions

Neutral atomic or molecular flows

Molecular attractive and repulsive forces are negligible

Steady state flow (simple case of the more complex Boltzmann equation)

Knudsen number - indicator of gas flow rarefaction (or decompression)

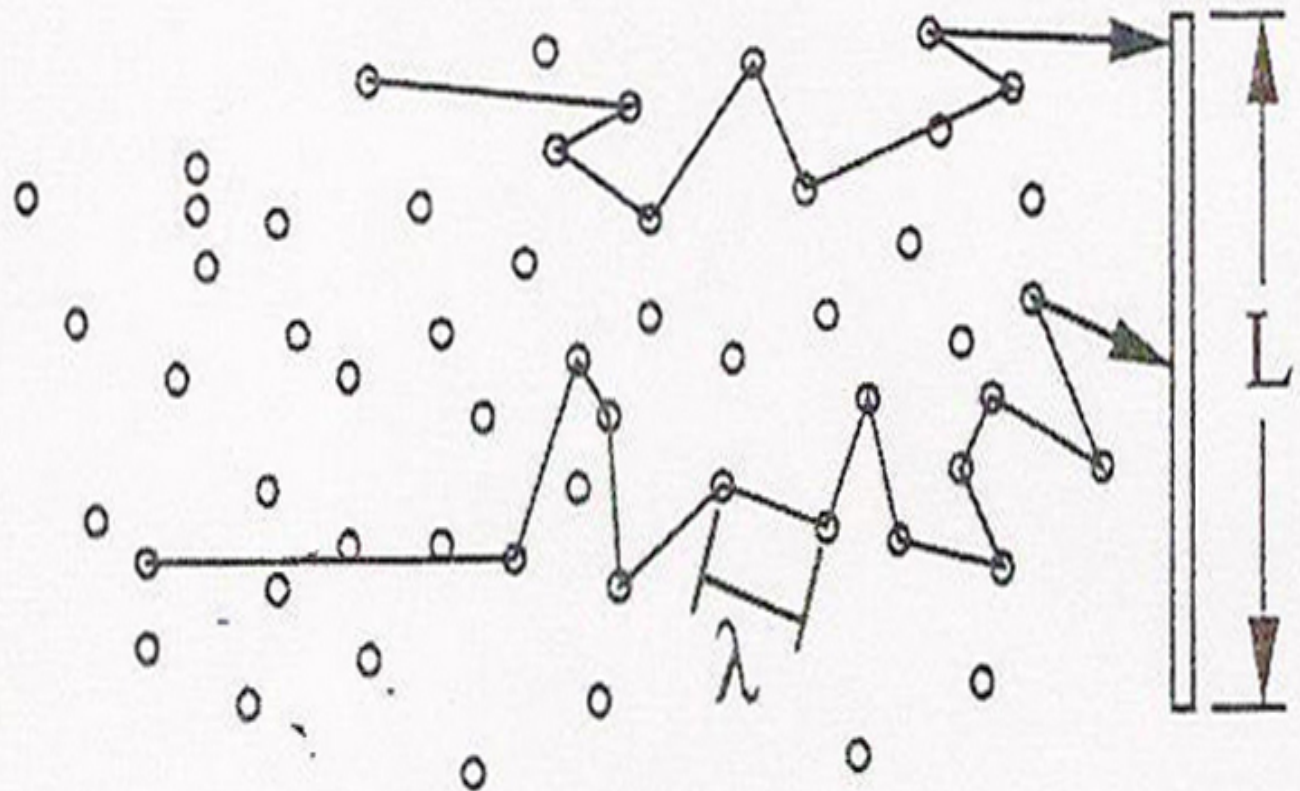
$$Kn = \frac{\lambda}{L} \quad (4-1)$$

where λ is mean free path of a molecule and L is the characteristic length of the object stationed in the flow

Continuum flow

Continuum Flows:

Navier-Stokes
Equations Apply

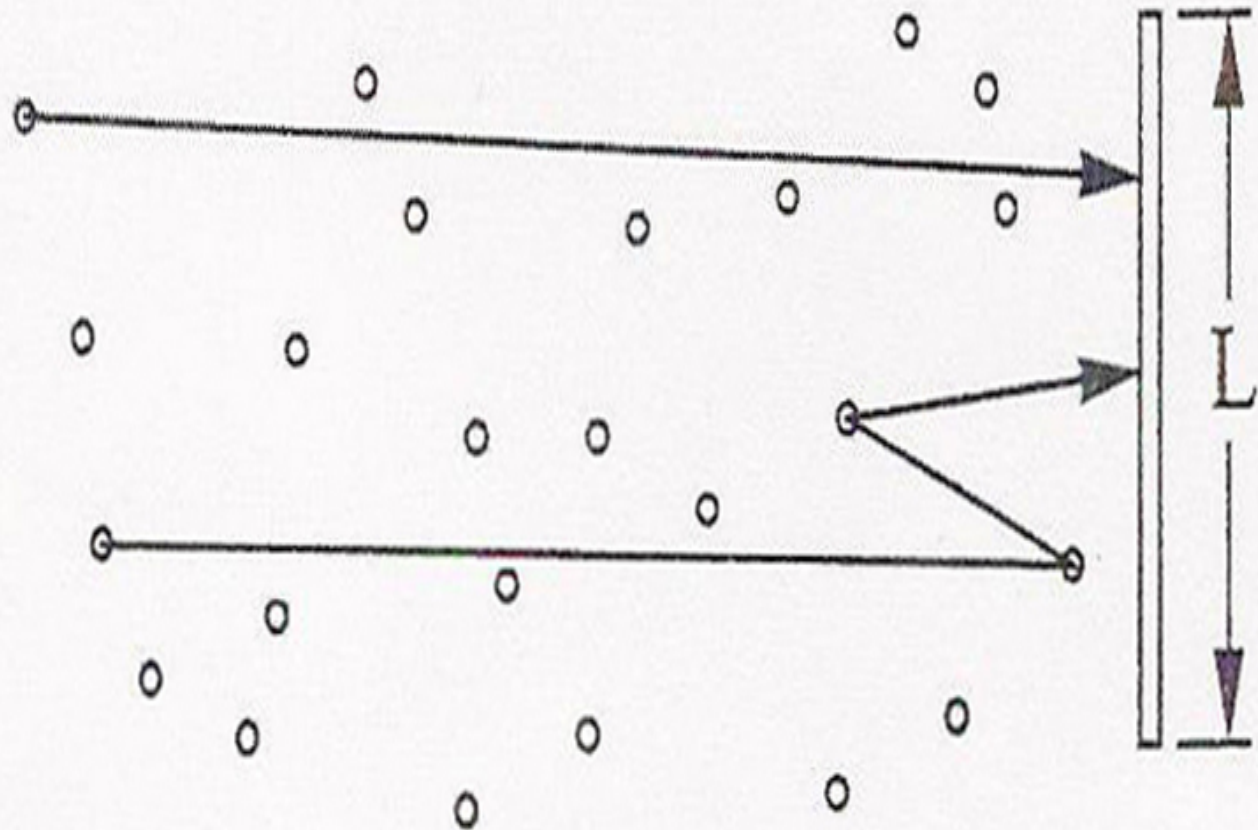


Rarefied/transitional flow

Rarefied Flows:

Navier-Stokes
Equations Fail

Boltzmann
Equation Applies



Flow regimes

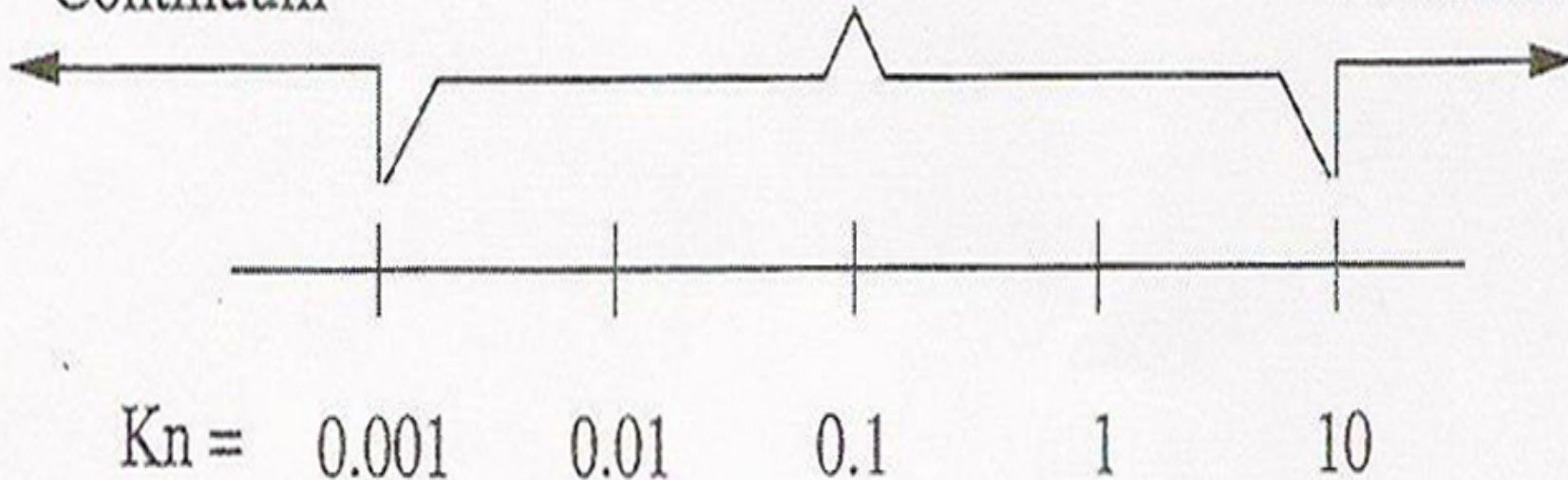
Knudsen Number: $Kn = \frac{\lambda}{L}$

(transitional)

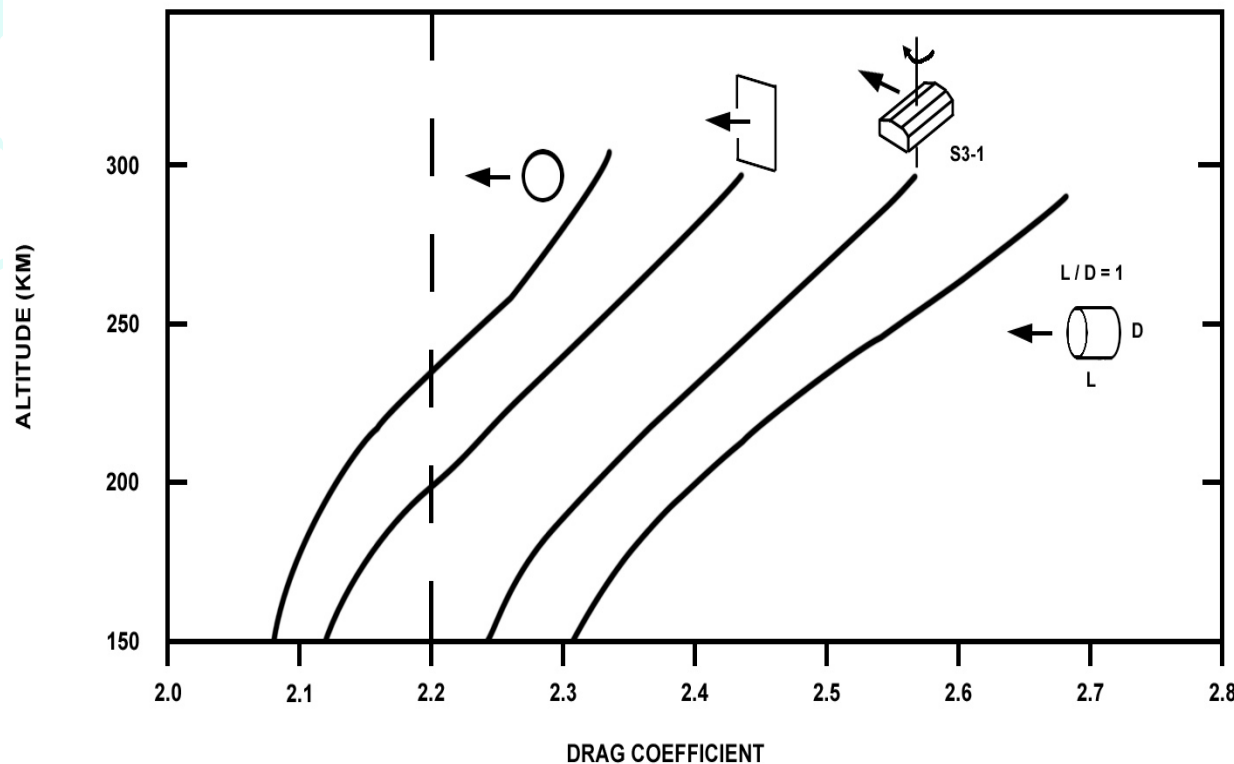
Rarefied

Free Molecule

Continuum

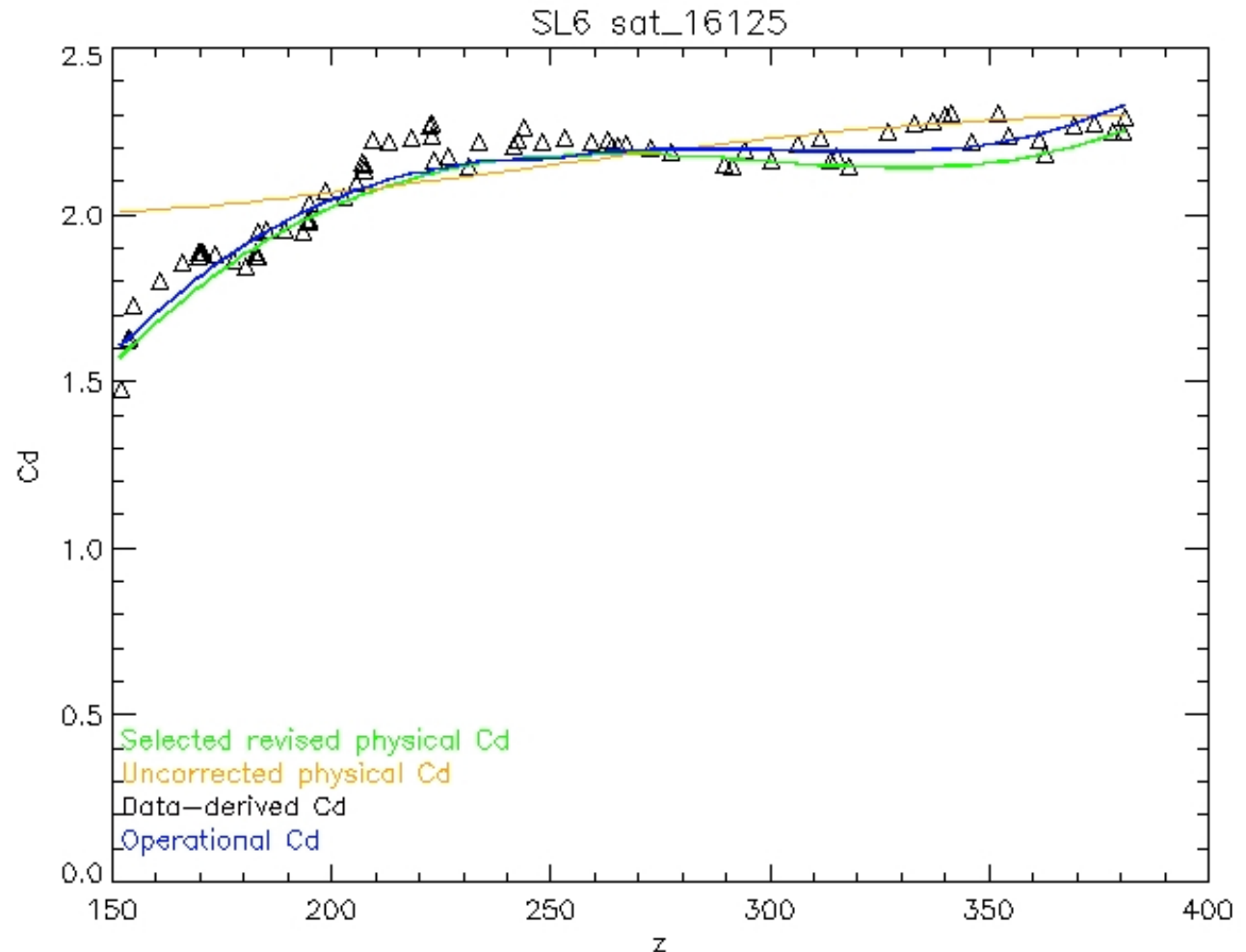


Example Physical Drag Coefficients of Compact Satellites

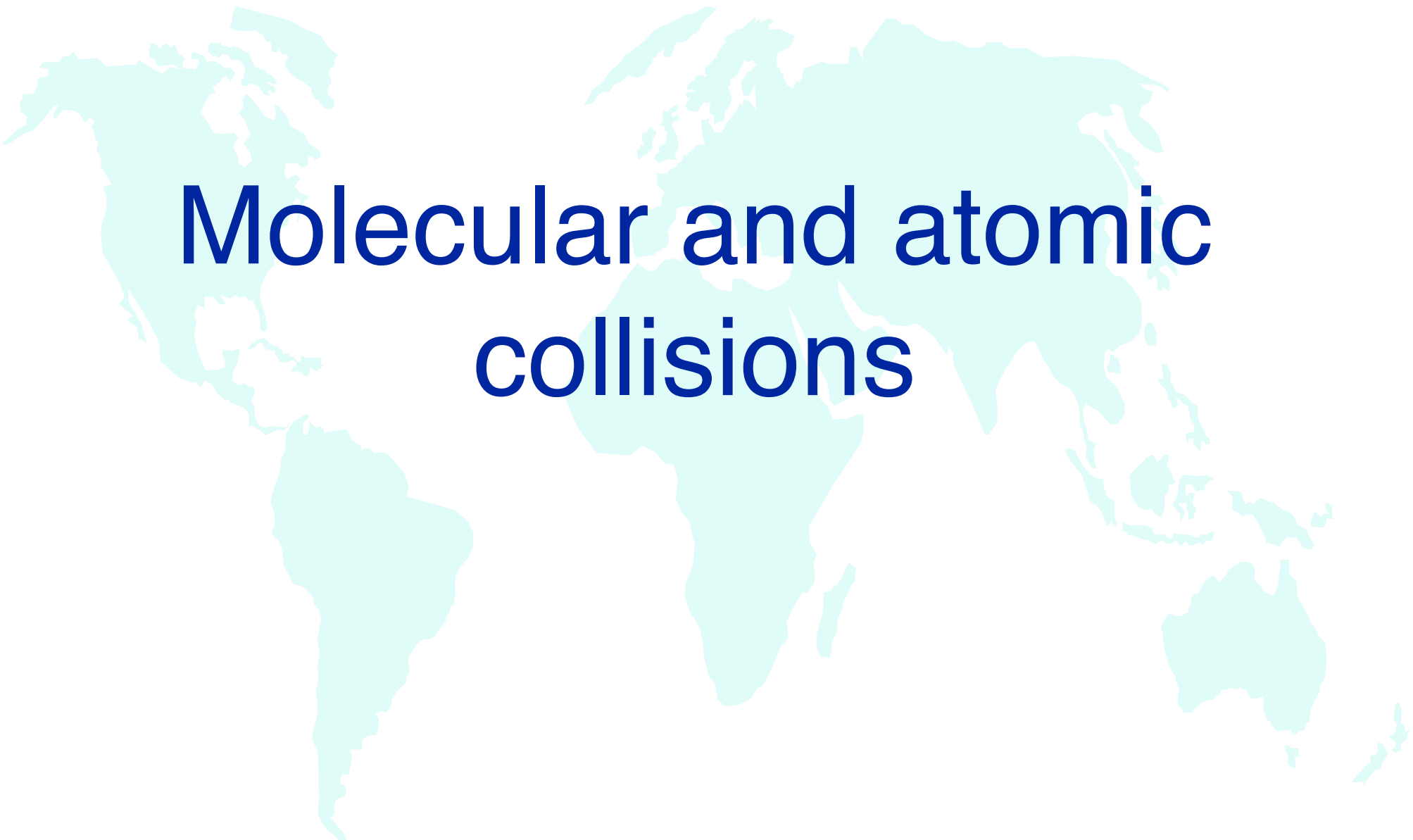


Example Drag Coefficients' Change

Ballistic coefficient (β)
 definition:
 $1/\beta = C_D A/m$ where C_D is
 the drag coefficient
 modulated by geometry and
 local atmosphere conditions
 (atomic oxygen
 concentration); A is the
 effective area of the object
 and m is the mass of the
 object.

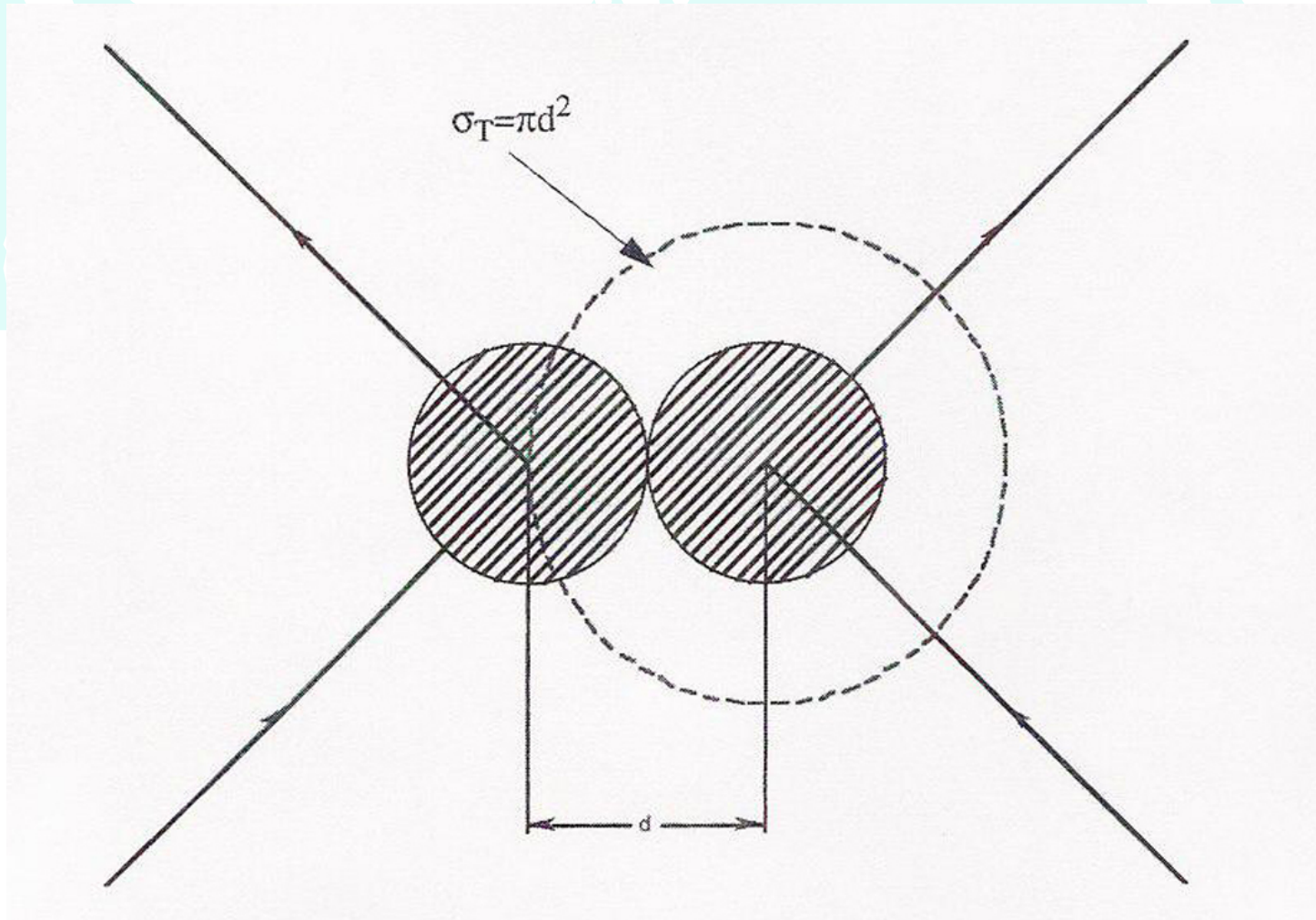


Credit: Tobiska

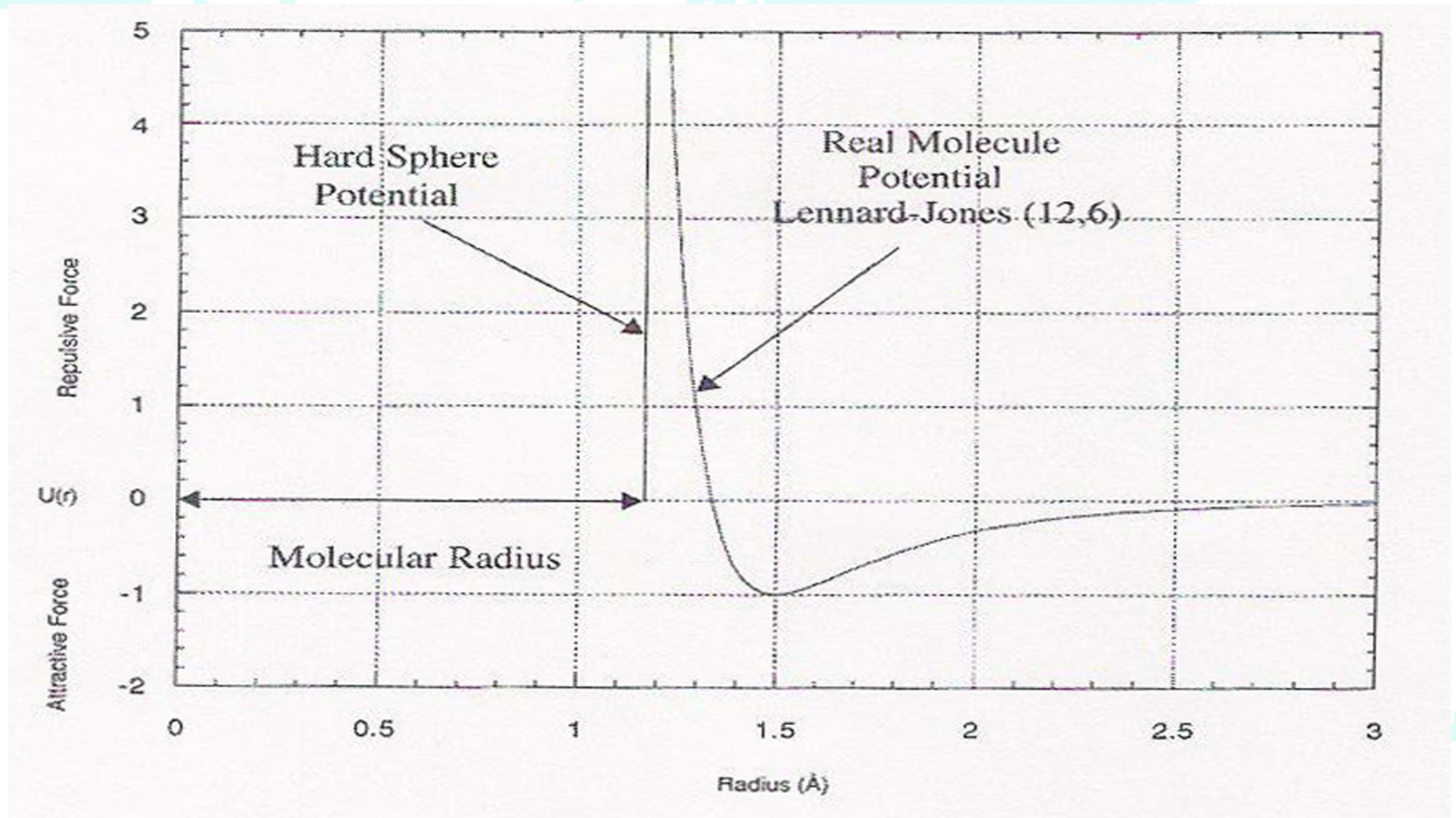
A light blue world map is centered in the background of the slide, showing the outlines of the continents.

Molecular and atomic collisions

Collisional cross section



Energy potential diagram



Atomic and molecular size

O	0.66 Å (charge distribution radius)
O ₂	3.62 Å (diameter)
N ₂	3.29 Å (diameter)
H	0.7 Å (charge distribution radius)
He	1.2 Å (charge distribution radius)
Ar	1.6 Å (charge distribution radius)
CO ₂	3.8 Å (diameter)
NO	3.45 Å (diameter)

$$1\text{Å} = 0.1\text{nm} = 1 \times 10^{-10} \text{ m}$$

Collisional cross section

Two molecule (or atom) collision

$$\sigma_T = \pi d^2 \quad (4-7)$$

where distance between their two centers is d and the total collisional cross section is σ with a mean molecular spacing, related to number density, n , of

$$\delta = n^{-1/3} \quad (4-8)$$

and the relative velocity of a collision between two molecules is

$$\mathbf{V}_r = \mathbf{V}_1 - \mathbf{V}_2 \quad (4-9)$$

Mean collision rate

The probability of collision is given by

$$P = n(\sigma_T V_r \Delta t) \quad (4-10)$$

where n is the number density and, in some small time (Δt), a molecule will collide with any other molecule in a **cylinder of volume** given by

$$\vartheta = \sigma_T V_r \Delta t \quad (4-11)$$

Therefore the **mean collision rate** (averaged over all molecules in the gas) is

$$\nu = n \overline{\sigma_T} \overline{V_r} \quad (4-12)$$

Mean free path

The hard sphere approximation for mean collision rate is given by

$$\nu = n\pi d^2 \overline{V}_r \quad (4-13)$$

and the total number of collisions per unit time per unit volume is (1/2 signifies two molecules required for a collision)

$$N_c = \frac{1}{2} n \nu = \frac{1}{2} n^2 \sigma_T \overline{V}_r \quad (4-14)$$

and the mean free path relative to collision rates is

$$\lambda = \frac{\overline{V}_r}{\nu} \quad (4-15)$$

Mean free path

Note that the mean thermal, peculiar or random speed of a molecule in a gas is $\overline{v'}$ therefore mean free path can be rewritten as

$$\lambda = \frac{1}{\frac{\overline{V_r}}{\overline{v'}} n \pi d^2} \quad (4-16)$$

or simplified as

$$\lambda = \frac{1}{\sqrt{2} n \pi d^2} \quad (4-17)$$

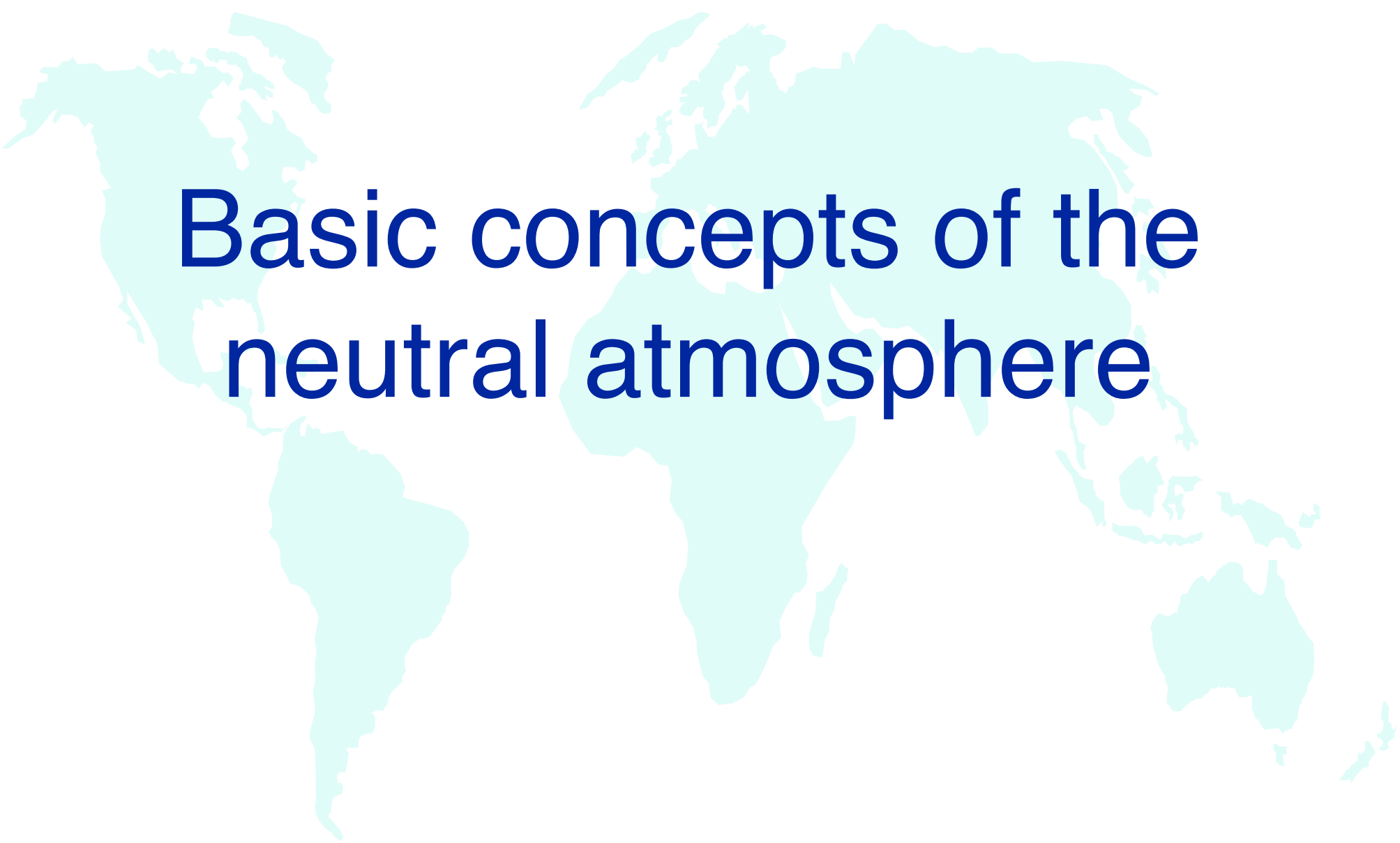
Loschmidt number

A useful quantity is the Loschmidt number for the number density at standard temperature and pressure; for example, using molecular nitrogen gas in a room is a perfect gas (Ideal Gas Law); N₂ is 78% and O₂ is 21% (at sea level) with 1% minor constituents; sea level is 1 atmosphere (1 atm); therefore, from equation (4-5), consider for lower atmosphere only

$$n_0 = \frac{p_0}{kT_0} \quad (4-18)$$

$$n_{0\text{ N}_2} = (0.78) \frac{1.01325 \times 10^6}{1.3805 \times 10^{-16} \cdot 273} = 2.097 \times 10^{19} \text{ cm}^{-3} \quad (4-19)$$

where $p_0 = 1 \text{ atm} = 760 \text{ Torr} = 1.01325 \text{E}6 \text{ dyn cm}^{-2}$ and $T_0 = 0^\circ\text{C} \approx 273.15 \text{ K}$ while k (*Boltzmann's constant*) is expressed in erg K^{-1}

A light blue world map is centered in the background of the slide, showing the continents of North America, South America, Europe, Africa, Asia, and Australia. The map is semi-transparent, allowing the title text to be clearly visible over it.

Basic concepts of the neutral atmosphere

Ideal gas law

Pressure

Gas exerts a pressure on its container walls which is a result of the atom and molecule impact on walls

If no energy loss exists, then particles change direction only (conservation of energy)

Total impulse (rate change of momentum) per unit area is the pressure and is written as

$$P = 2m\phi v \quad (4-2)$$

where ϕ is the number of molecules (also designated n) of mass m and the average normal velocity is v

Ideal gas law

Kinetic energy

Average kinetic energy of a molecule or atom in a gas depends on the temperature

If n is the number of molecules (or atoms) in a given volume then $nv/6$ molecules will cross a unit area in a unit time (6 directions: $\pm x, y, z$) and

$$p = \frac{1}{3} mnv^2 \quad (4-3)$$

The average kinetic energy, KE, and temperature, T is

$$KE = \frac{1}{2} mv^2 = \frac{3}{2} kT \quad (4-4)$$

where k is Boltzmann's constant ($1.380658 \text{ E-23 J/K}$)

Ideal gas law

Ideal Gas Law

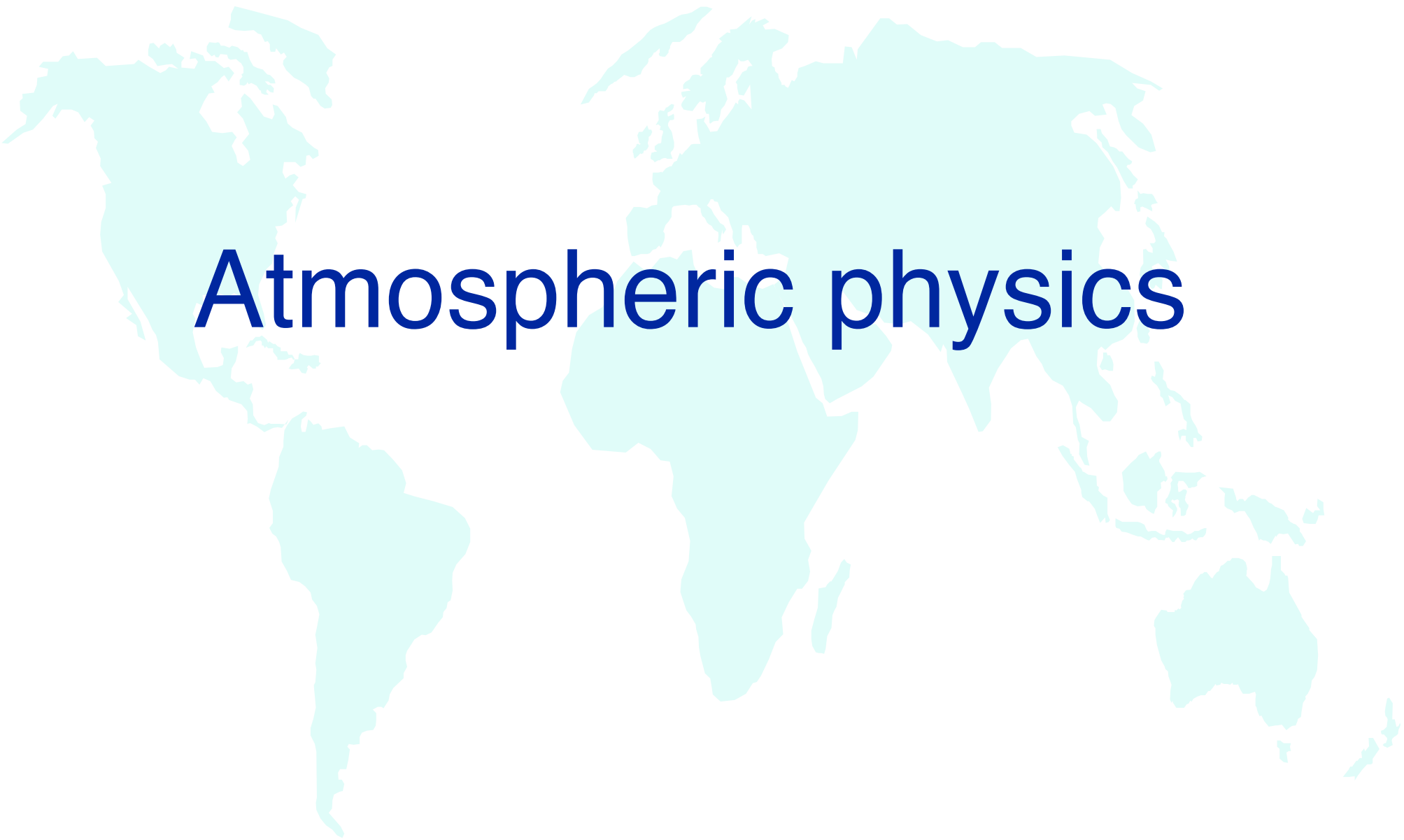
The equation of state for a perfect gas is the combination of equations (4-3) and (4-4)

$$p = nkT \quad (4-5)$$

Guy-Lussac Law

If the density of a gas is $\rho = nm$ then equation (4-5) can be rewritten as

$$\frac{p}{\rho} = \frac{kT}{m} \quad (4-6)$$

A light blue world map is centered in the background of the slide.

Atmospheric physics

Hydrostatic equation

In a real atmosphere, each molecule feels gravity. For the thermosphere, we assume the Ideal Gas Law is effective for a gas in diffusive equilibrium for each i^{th} species

$p_i = n_i k T$ for Ideal Gas Law pressure-temperature

$\rho_i = n_i m_i$ in kg for density of a species or $\rho = \sum \rho_i$ and n is the number density (atoms cm^{-3}) while m is the atom's mass (e.g. atomic oxygen, O, in kg = $16 \text{ AMU} / (\text{Avogadro's Number} \times 1000)$ where $\text{Av \#} = 6.022137\text{E}23$ molecules (or atoms) per mole

Therefore, the hydrostatic equation can be written

$$\Delta p = -nmg \Delta z \quad (4-20)$$

for describing pressure change per unit area that is dependent upon the gravitational force on a gas particle, g , and upon the height above the surface, z .

Credit: Tobiska

Barometric Law

The hydrostatic equation and Ideal Gas Laws can be combined such that

$$\frac{dp}{p} = \frac{-nmg \, dz}{nkT} \quad (4-21)$$

and

$$\int_{p_0}^p \frac{dp}{p} = - \int_{z_0}^z \frac{dz}{kT/mg} \quad (4-22)$$

or solved and rewritten as the Barometric Law where additional relationships are shown in the notes below

$$p(z) = p_0 e^{-\left(\frac{z-z_0}{kT(z)/mg(z)}\right)} \quad (4-23)$$

Credit: Tobiska

Density scale height

The density scale height is defined as the term

$$H(z) = \frac{kT(z)}{mg(z)} \quad (4-24)$$

and gravity at an altitude z above the surface is

$$g(z) = g_0 \left(\frac{R_e^2}{(R_e + z)^2} \right) \quad (4-25)$$

for R_e as the Earth radius (6378.14 km), $T = T(z)$, and $g_0 = 9.80665 \text{ m s}^{-2}$

Credit: Tobiska

Temperature solution

We note that temperature at an altitude can be written from equation (4-23)

$$T(z) = \frac{p}{n(z)k} e^{-\left(\frac{z-z_0}{kT/mg}\right)} \quad (4-26)$$

for $z_0 = 120$ km and, in general, consider that the change of temperature with altitude can be written as

$$\frac{dT}{dz} = \sigma T(z) + A \quad (4-27)$$

where σ is a scaling factor and A is an arbitrary constant.
 $dT/dz \approx 15\text{K}/1\text{km}$ near 120 km (turbopause)

Credit: Tobiska

Temperature solution

Equation (4-27) just happens to be a first order nonhomogenous differential equation; its solution is known and gives us $T(z)$

$$T(z) = -Ce^{-\sigma(z-z_0)} + A \quad (4-28)$$

If we evaluate the solution at $T = T_0$ for $z = z_0$ and $T = T_\infty$ at $z = \infty$ then

$$T(z) = T_\infty - (T_\infty - T_0)e^{-\sigma(z-z_0)} \quad (4-29)$$

and where $T_0 = 386$ K then σ is

$$\sigma(z) = \frac{\frac{dT}{dz}}{T_\infty - T_0} \quad (4-30)$$

Credit: Tobiska

Thermospheric temperature

The thermospheric temperature, $T(z)$, is a function of altitude combined with energy input and loss of the region

A physics-based solution requires solving for energy and momentum conservation as well as mass continuity at all altitudes (examples later)

An empirical method of calculating T_{∞} is the Jacchia 1971 (J71 = CIRA 72) nighttime minimum exospheric temperature equation which is then used in equation (4-29) with $T_0 = 386$ K at 120 km

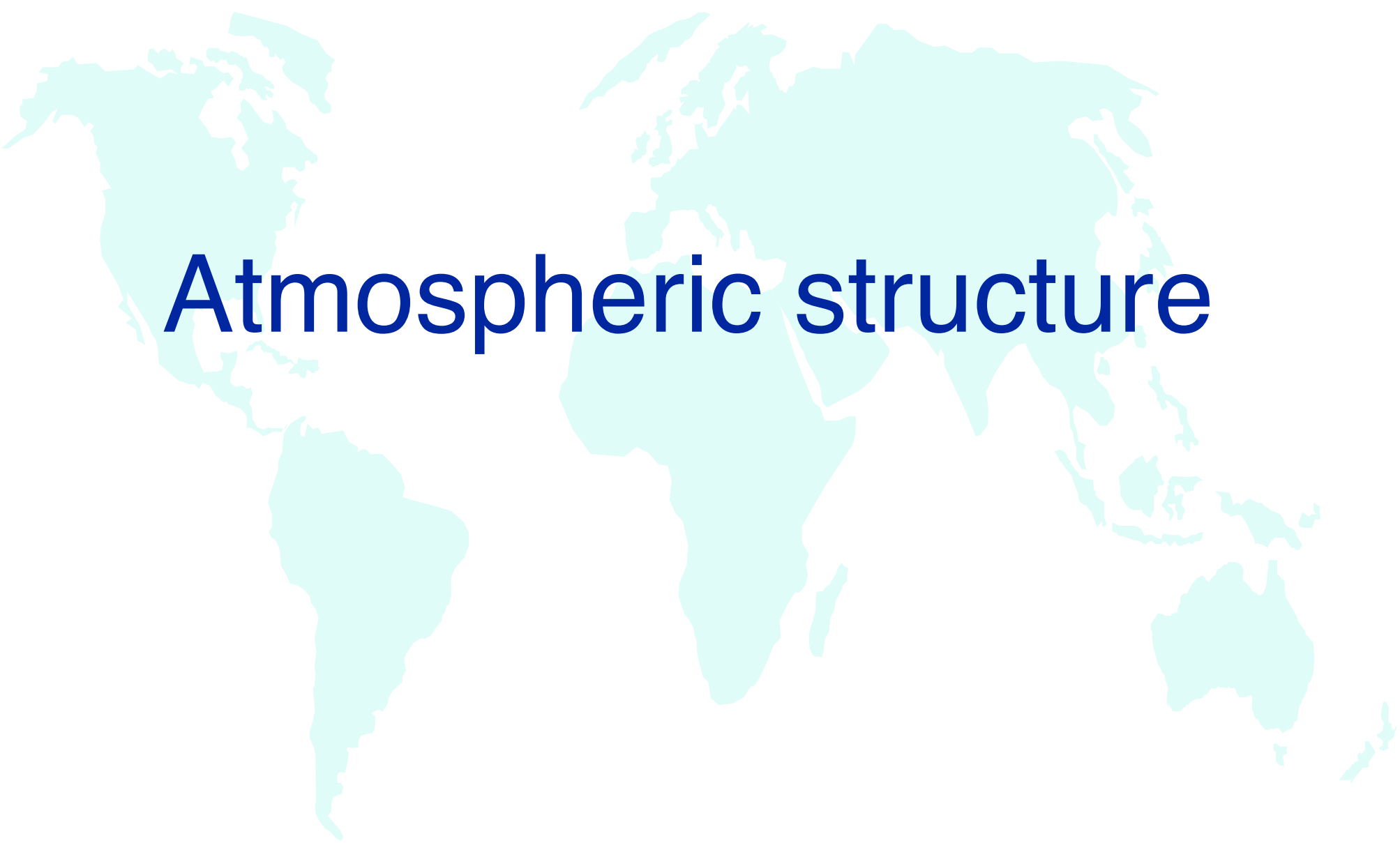
$$T_{\infty} = 379 + 3.24\overline{F_{10.7}} + 1.3(F_{10.7} - \overline{F_{10.7}}) \quad (4-31)$$

where $F_{10.7}$ is the 10.7-cm solar flux and $\overline{F_{10.7}}$ is the 81-day average of $F_{10.7}$ (see *s2k_output.txt* file)

Credit: Tobiska

A light blue silhouette of a world map is centered in the background of the slide.

BREAK

A light blue silhouette of a world map is centered in the background of the slide.

Atmospheric structure

Temperature regions

Troposphere

0-15 km; temperature decreases with altitude; turbulent mixing is primary kinetic process; convection is primary thermal process

Stratosphere

15-50 km; temperature increases with altitude; turbulent mixing is primary kinetic process; convection is primary thermal process

Mesosphere

50-85 km; temperature decreases with altitude; turbulent mixing is primary kinetic process; radiation is primary thermal process

Thermosphere

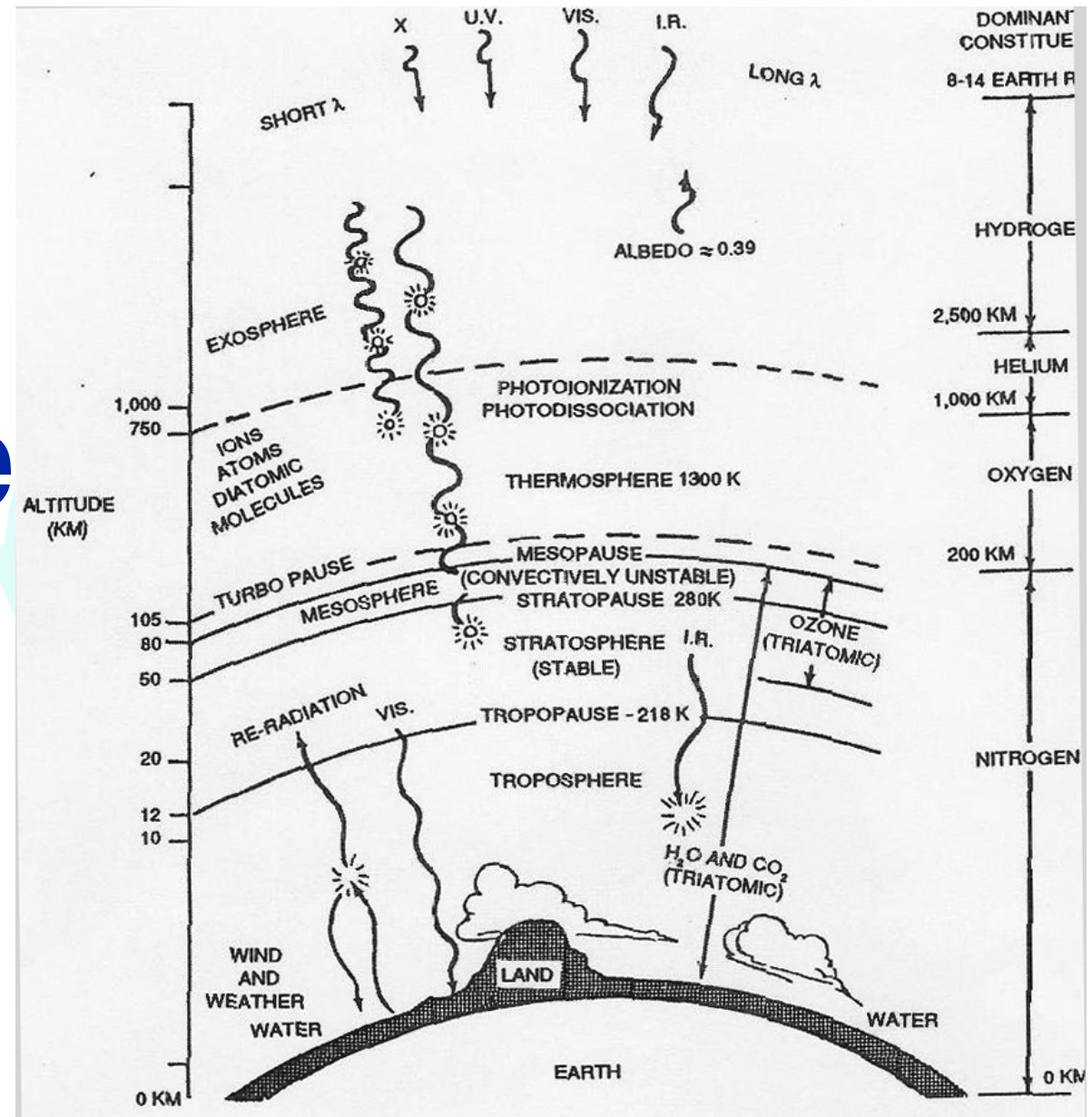
85-500 km; temperature increases with altitude; eddy mixing and molecular diffusion are primary kinetic processes; eddy and molecular conduction are primary thermal processes

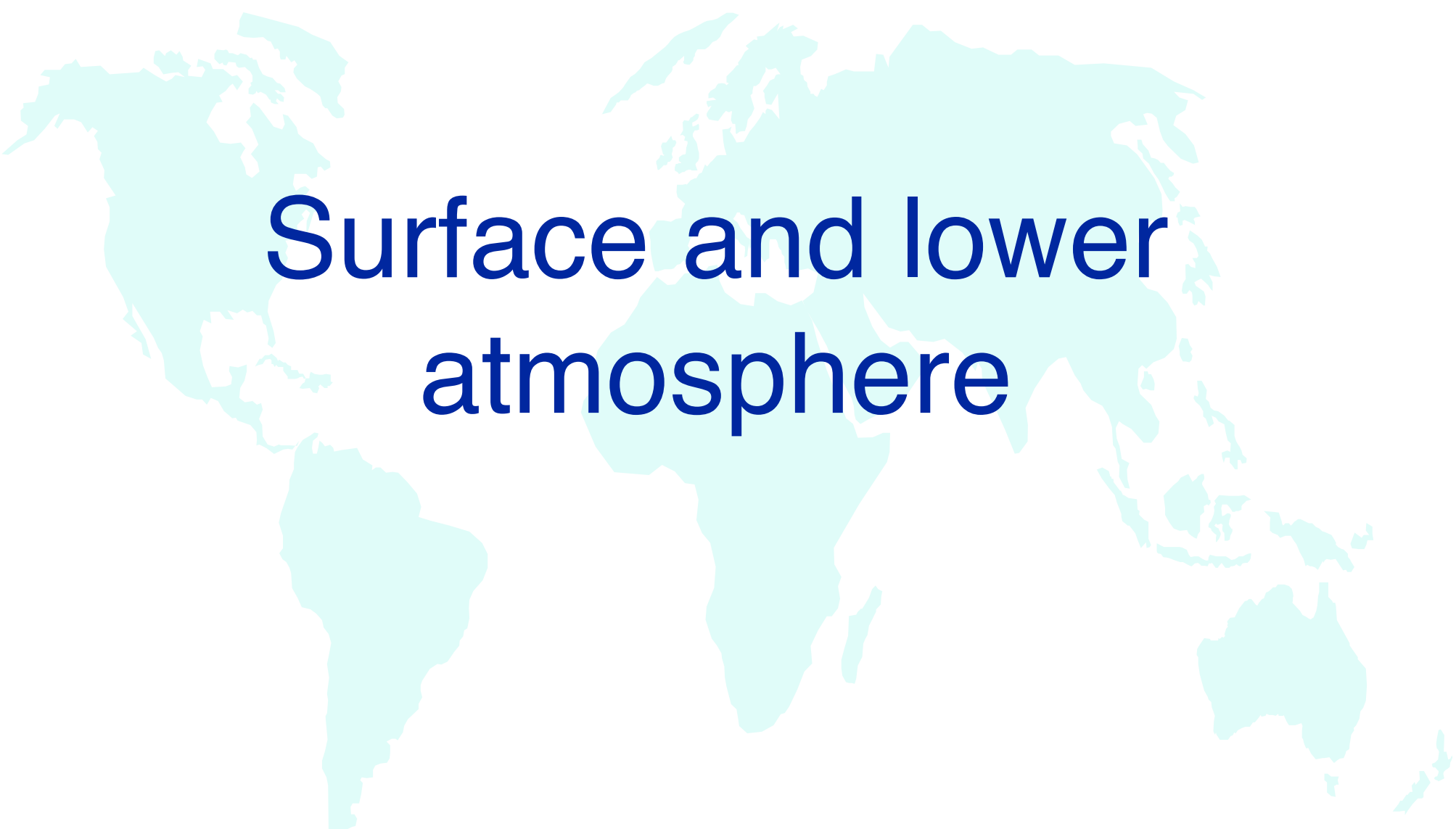
Exosphere

>500 km; temperature is constant with altitude; atom escape is primary kinetic process; no thermal process

Credit: Tobiska

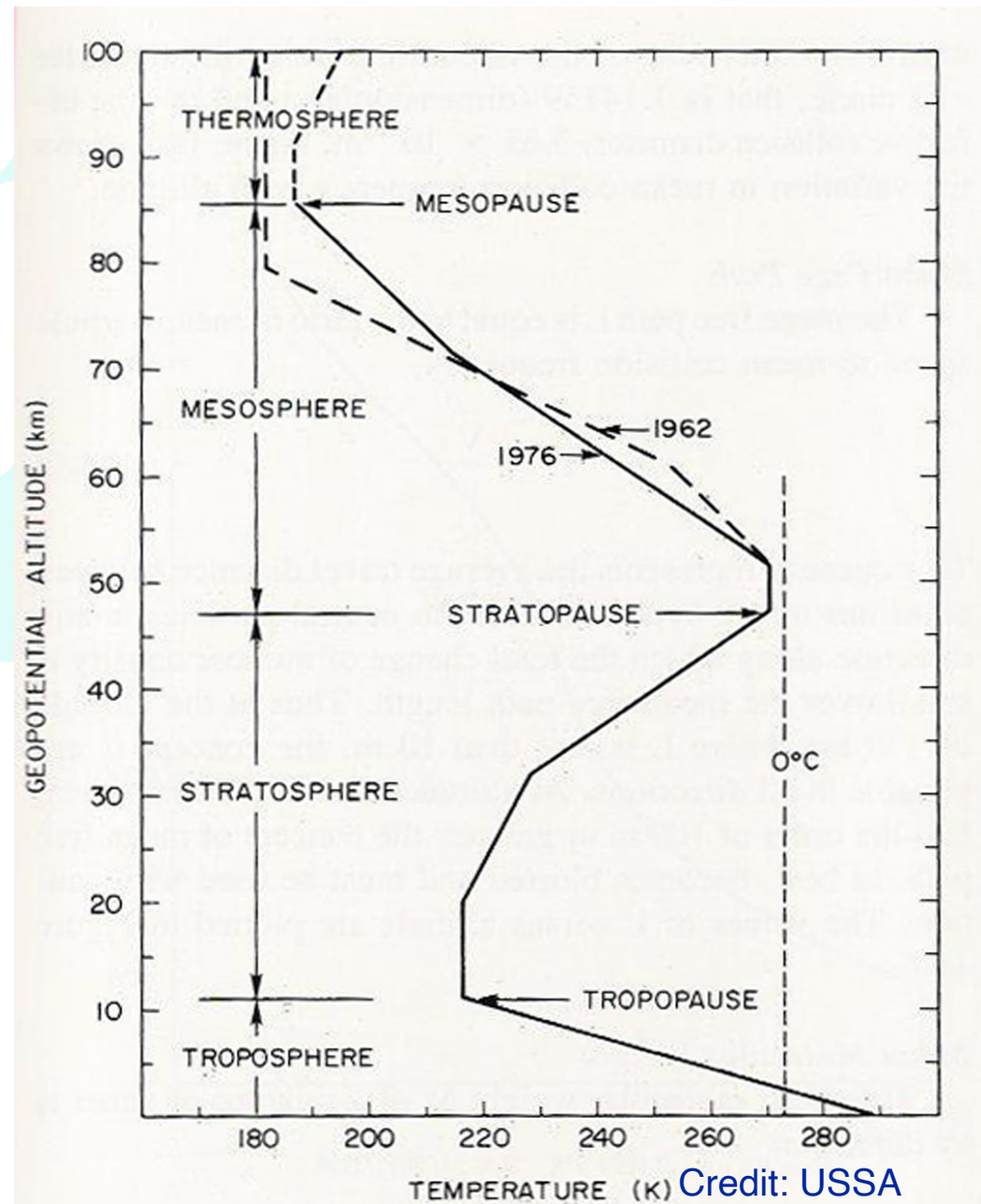
Atmosphere processes



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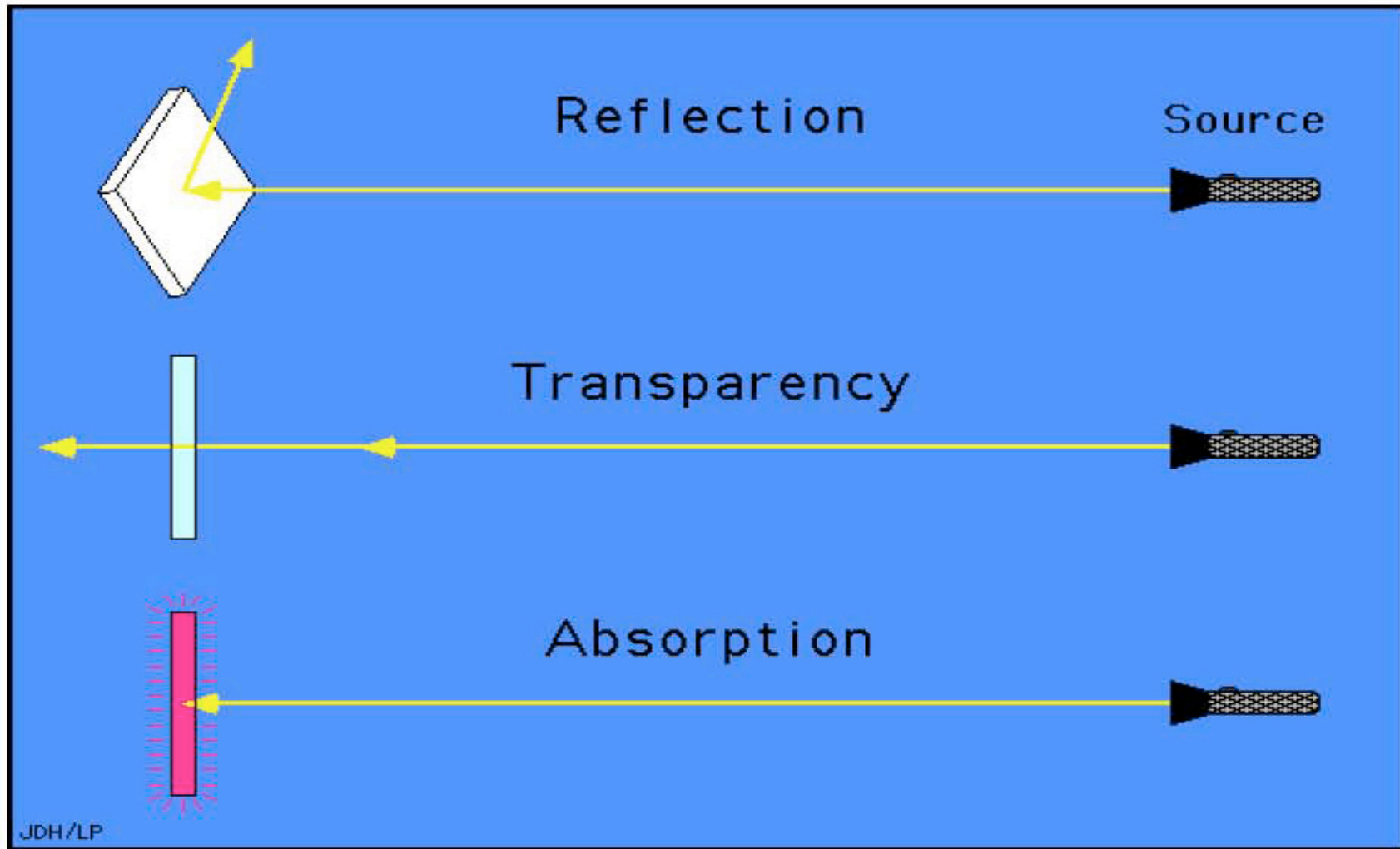
Surface and lower atmosphere

Lower atmosphere from US Standard Atmosphere (USSA)

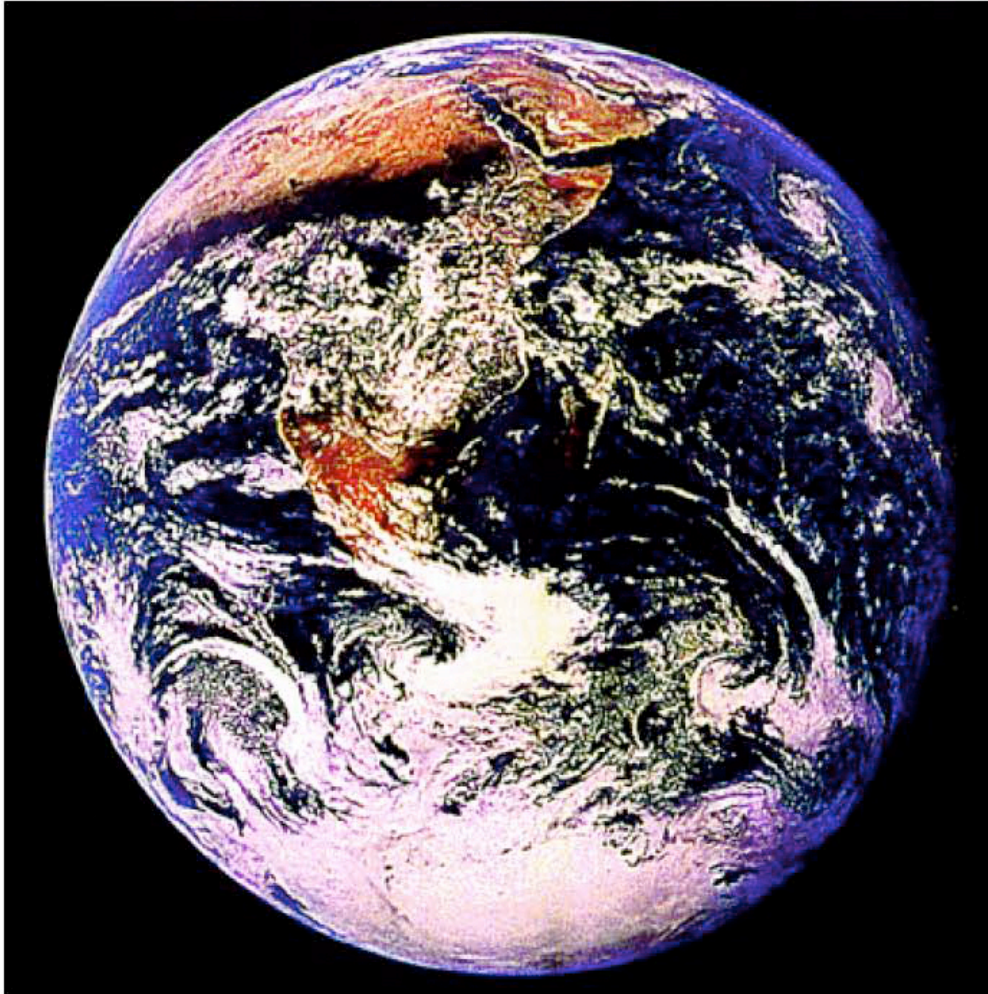


Credit: USSA

Photon interactions with matter



Earth's reflectivity

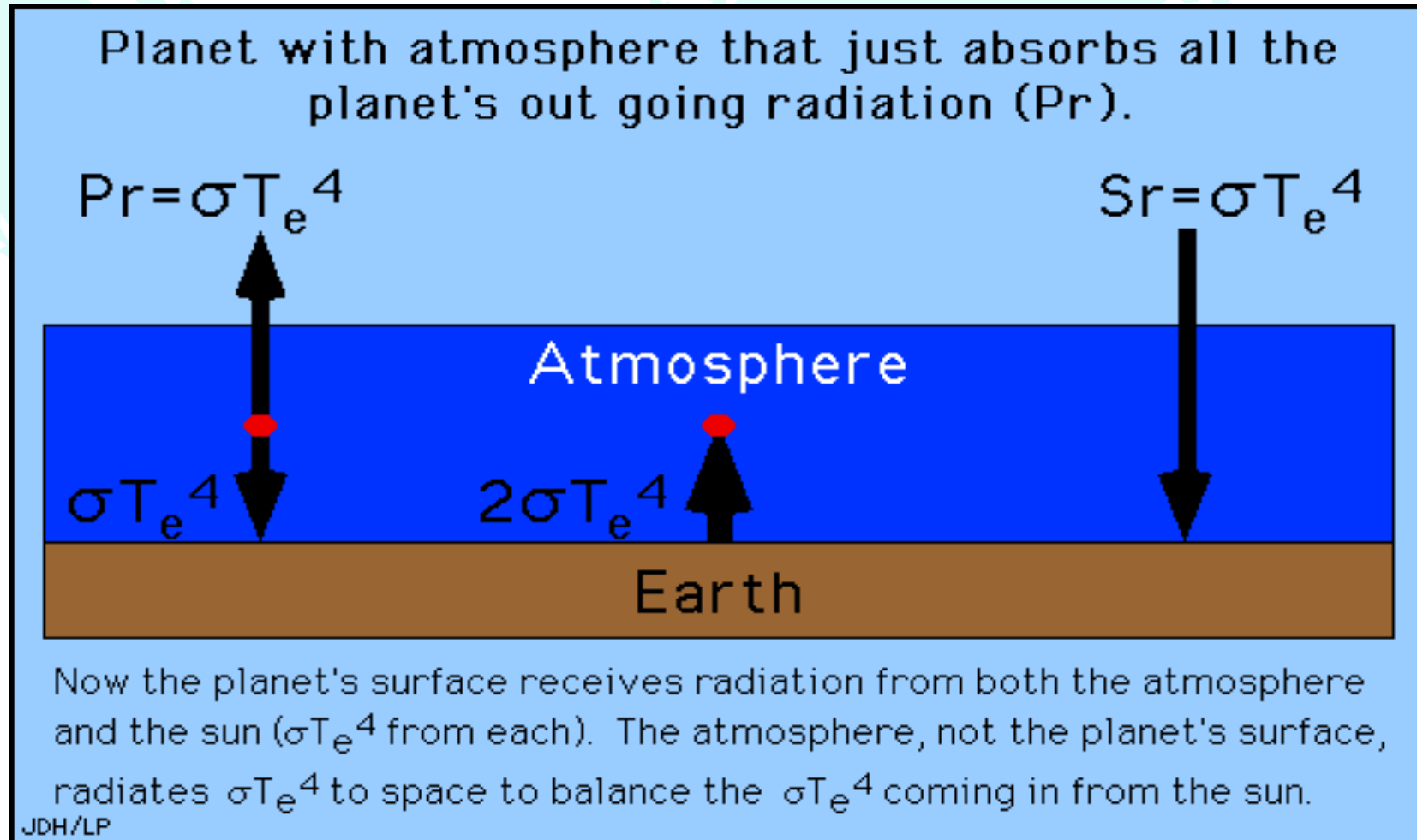


- ◆ Effects of Earth's atmosphere on incoming radiation
 - Clouds reflect [24%]
 - Atmosphere scatters [7%]
 - Earth's surface reflects [4%]
 - Snow
 - Vegetation
 - Ocean
 - Desert

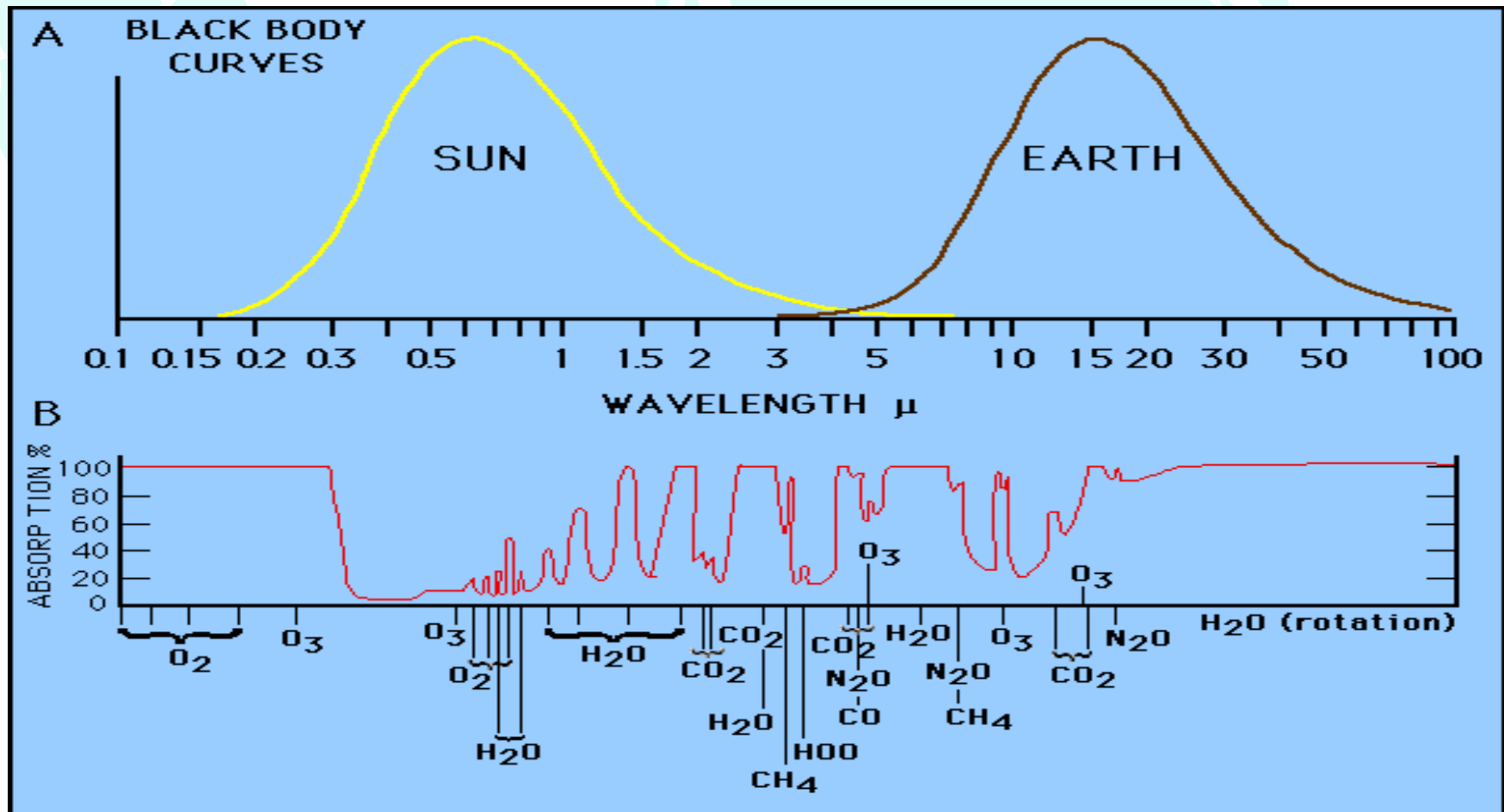
Atmosphere transparency



Atmosphere absorption



Earth's absorption



Radiation transfer

A planet and it's atmosphere can radiate back to space only as much energy as it absorbs from incoming solar radiation

The amount of radiation a rotating planet radiates back to space is determined by its effective temperature

$$4\pi R^2 \sigma T_e^4 = (1 - \Lambda) \pi R^2 (\pi F_{solar}) \quad (4-33)$$

where Λ is the Earth's albedo (0.29), R is radius of Earth, F_{solar} is the incident solar flux, and σ is the mass scattering coefficient, T_e = effective temperature

Radiation transfer

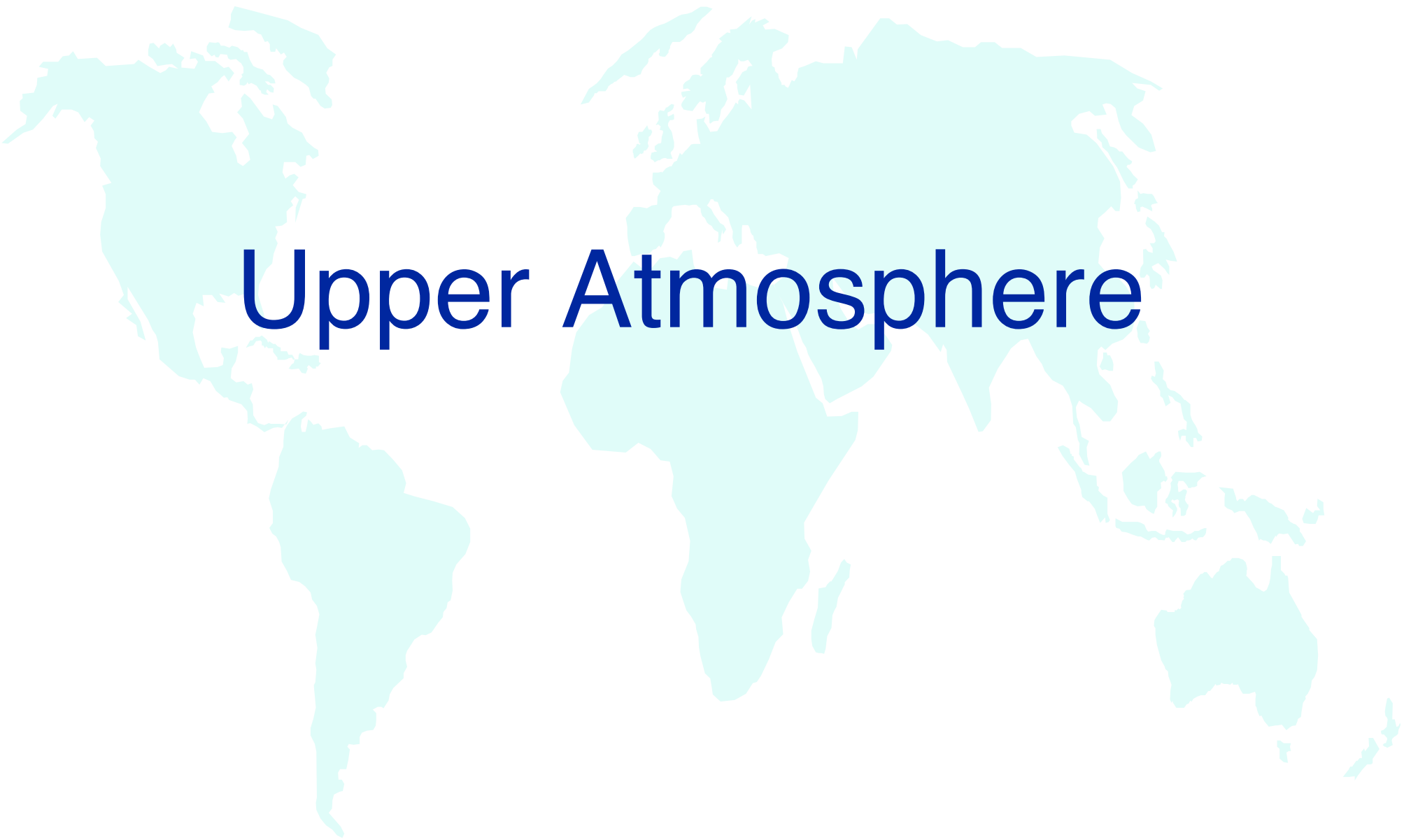
The wavelength of planetary radiation is determined by the planet's effective temperature (Wien's Law)

$$\lambda = \frac{2898}{T} \quad (4-34)$$

How strongly a planet's atmosphere absorbs the planet's radiation depends on the optical properties of its atmosphere and the nature of a planet's radiation

A planet's atmosphere can be considered to have a bottom and a top; it radiates both upward and downward

Earth albedo temperature currently is about 15 deg C

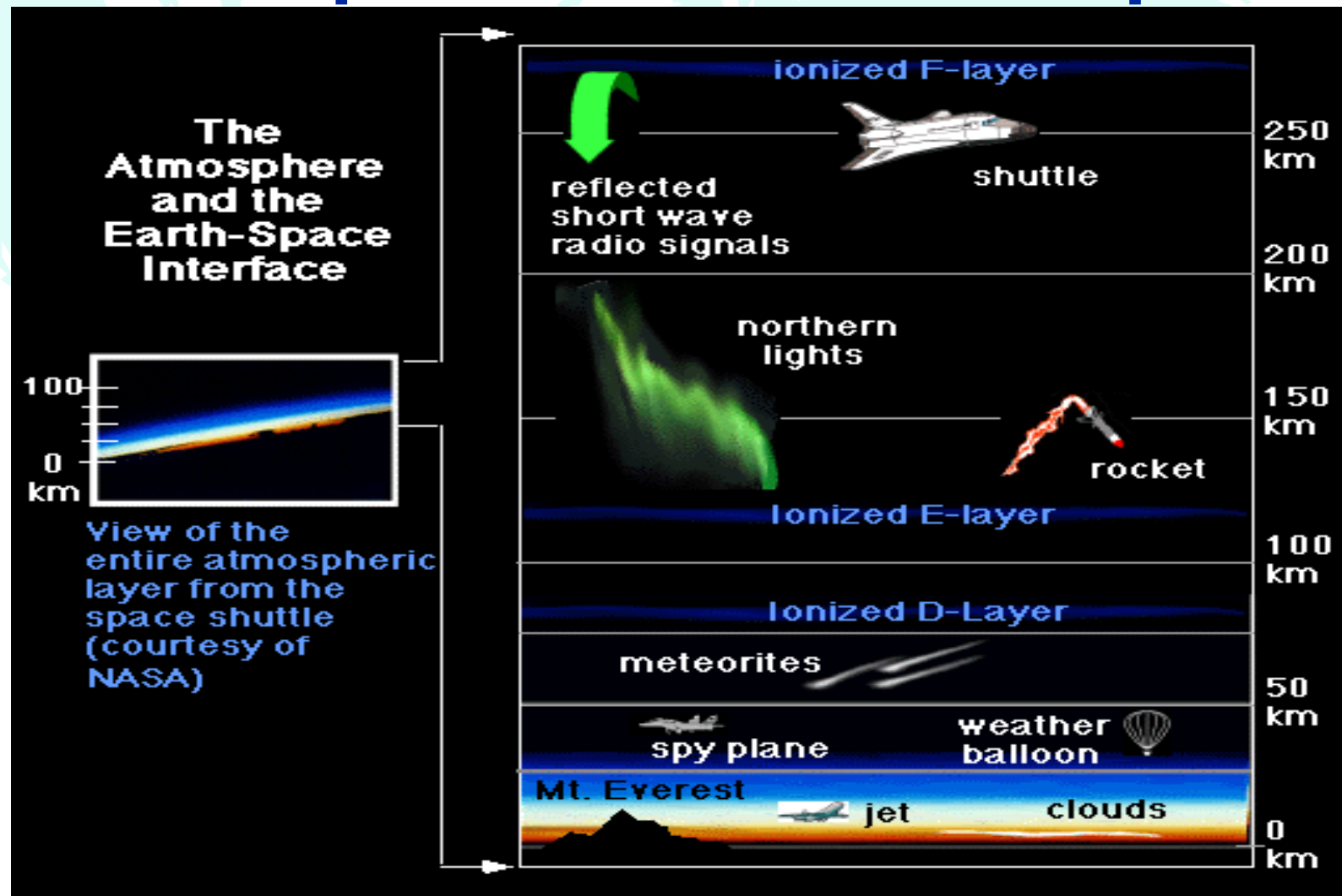
A light blue silhouette of a world map is centered in the background of the slide.

Upper Atmosphere

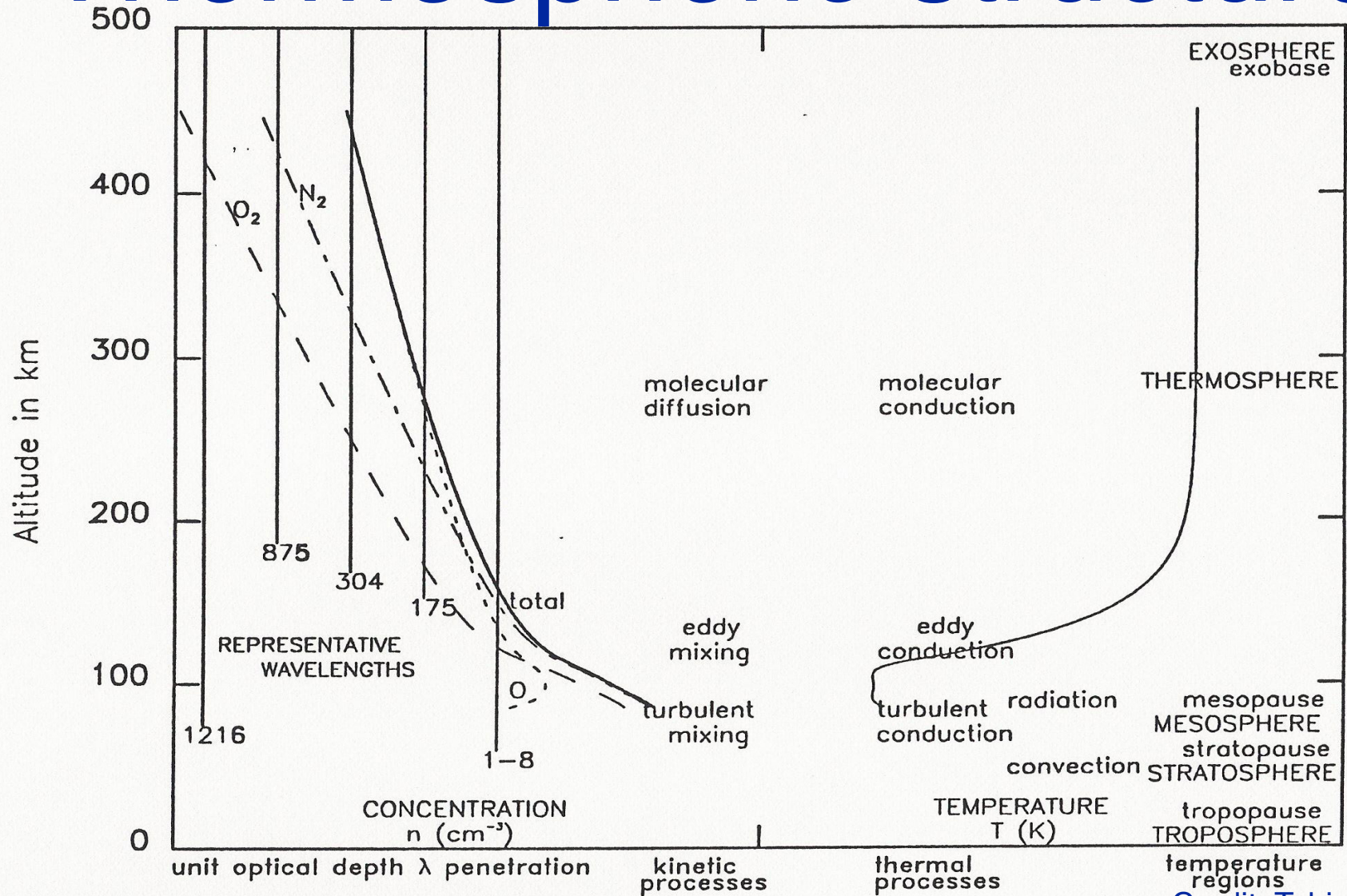
Shuttle view of limb



Atmosphere-Earth space

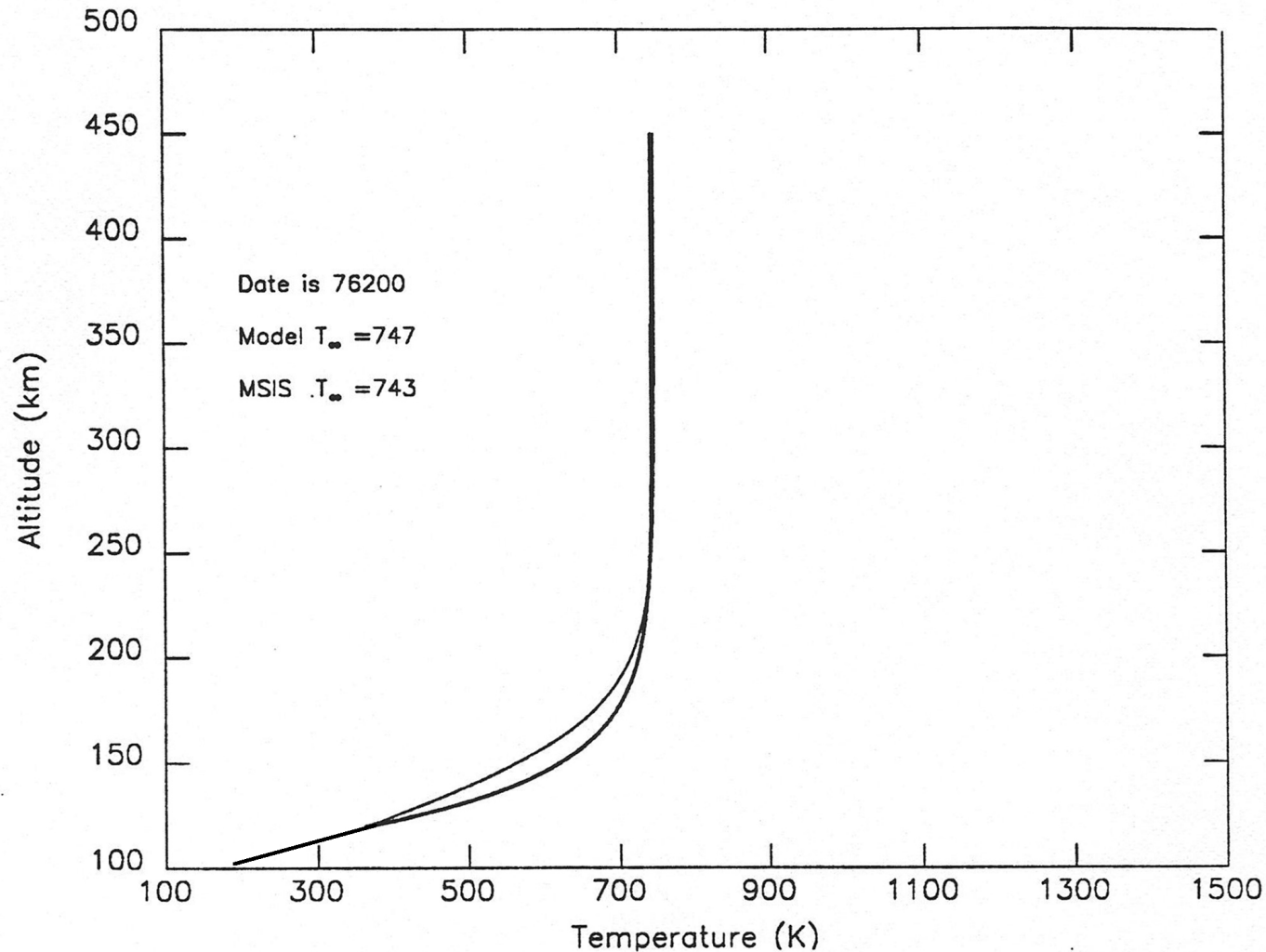


Thermospheric structure



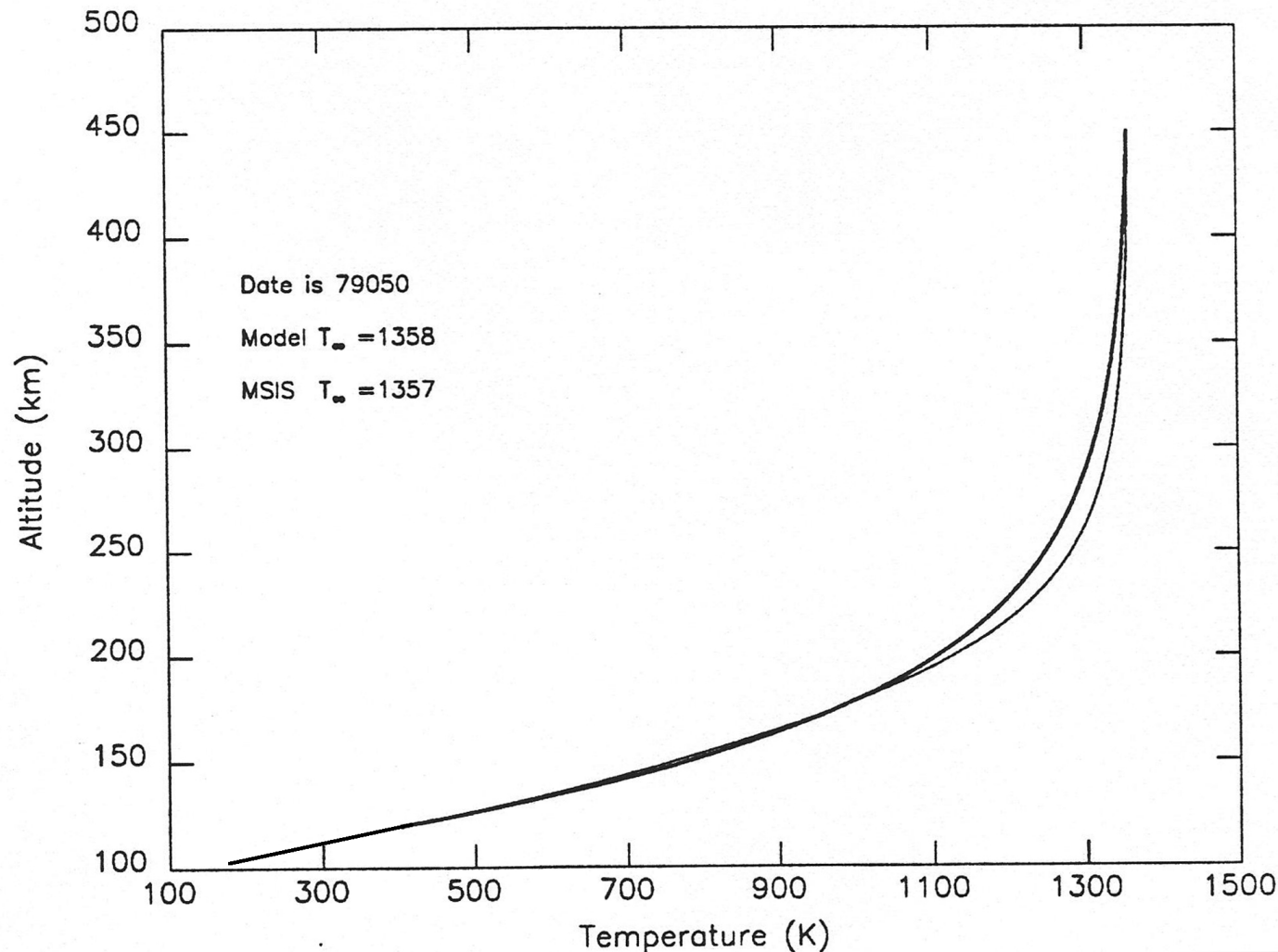
Credit: Tobiska

Thermosphere - solar min

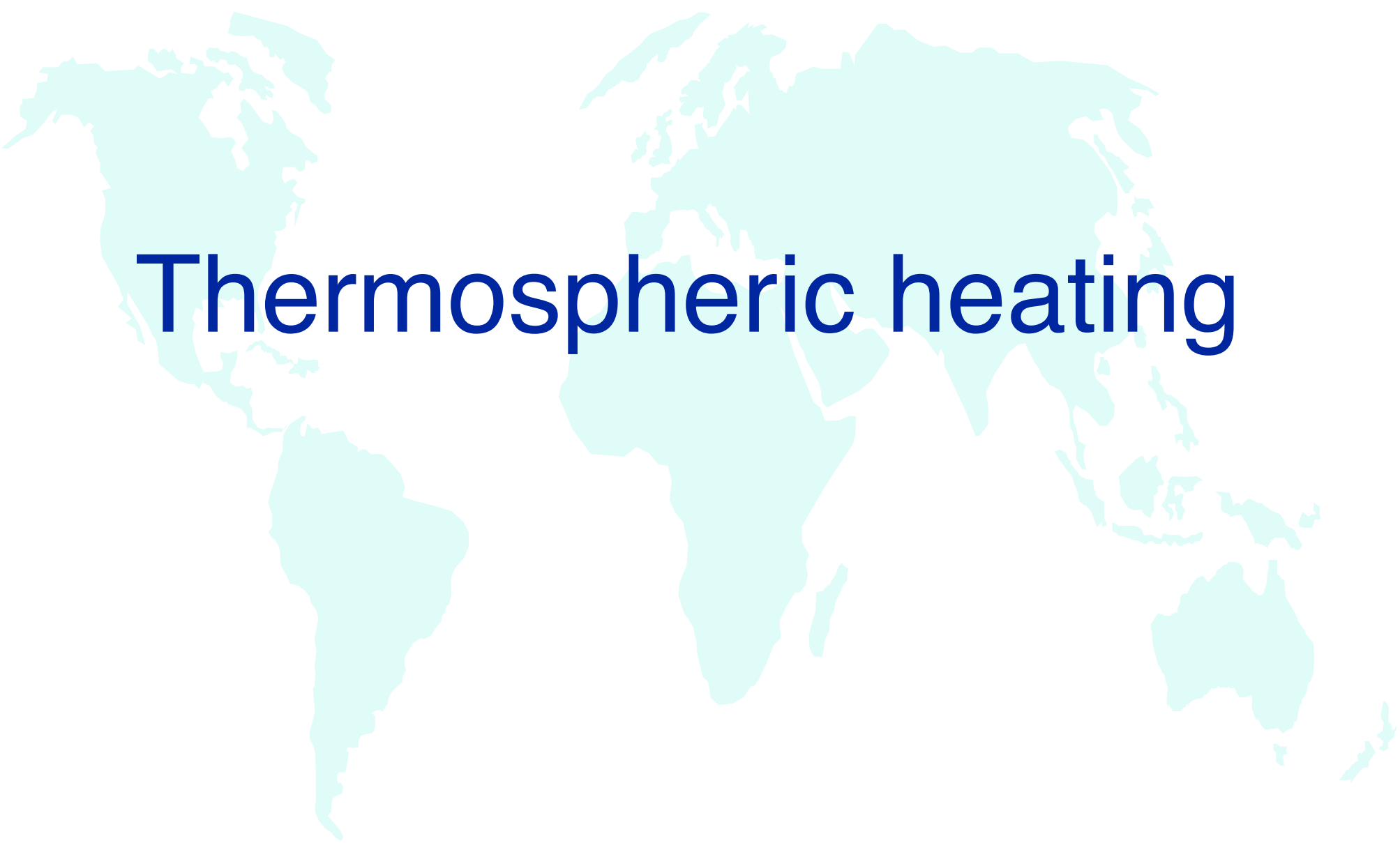


Credit: Tobiska

Thermosphere - solar max

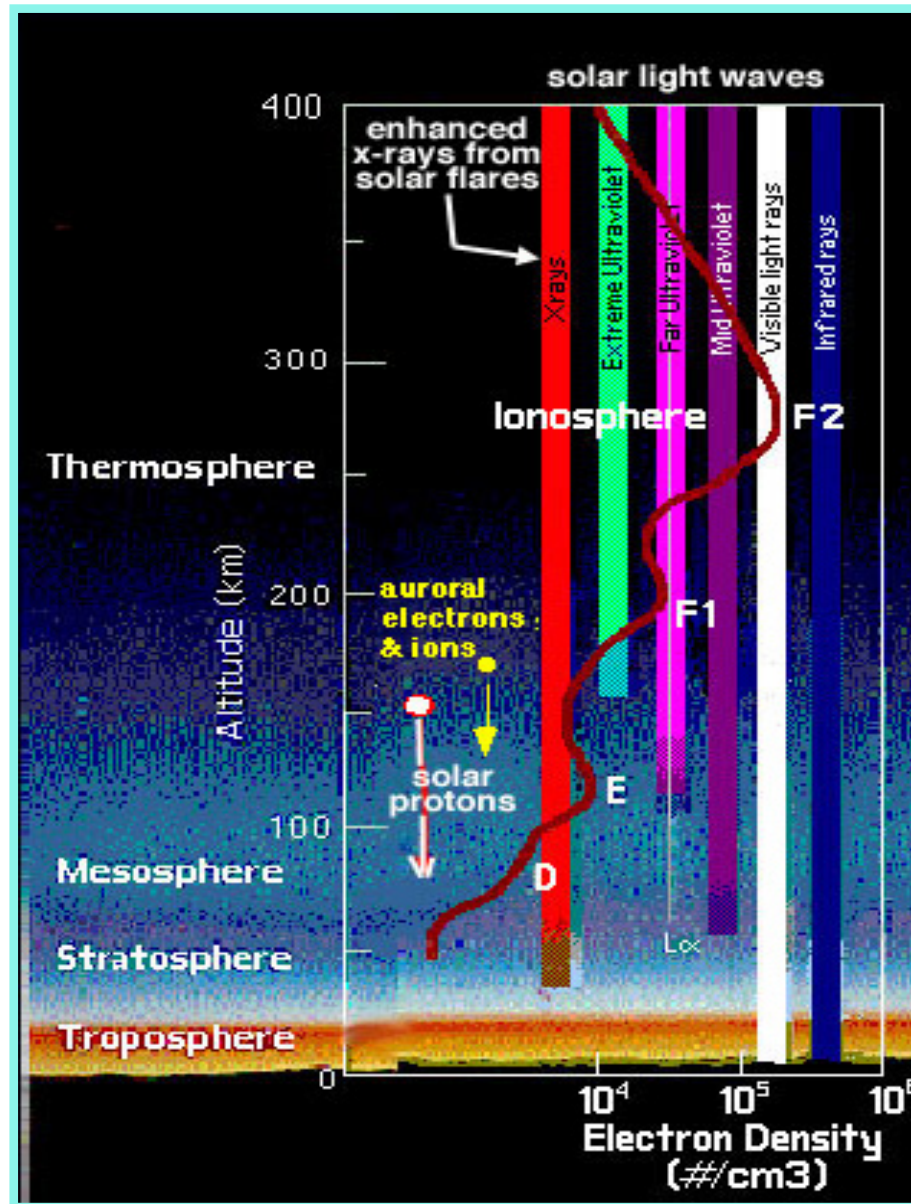


Credit: Tobiska

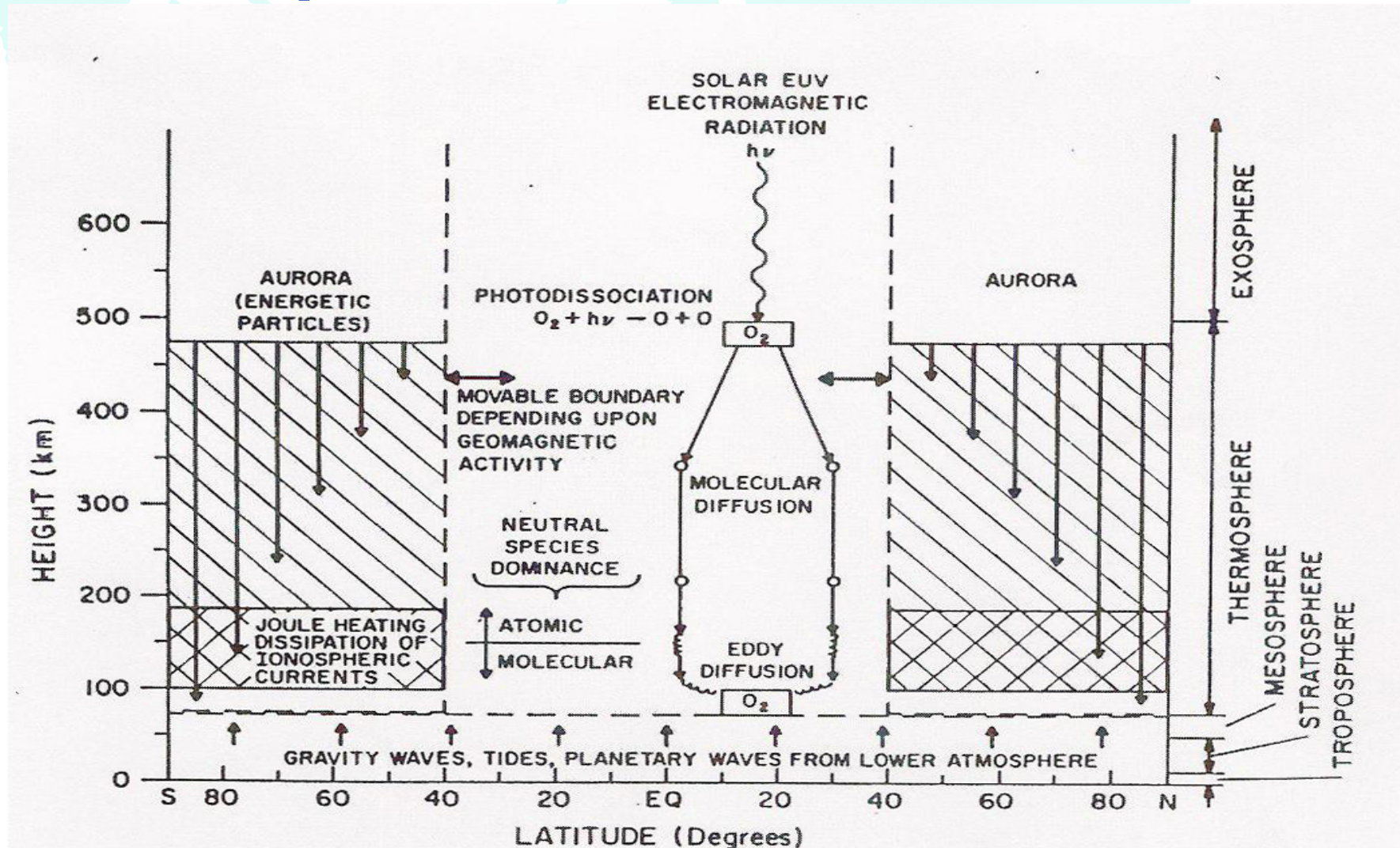
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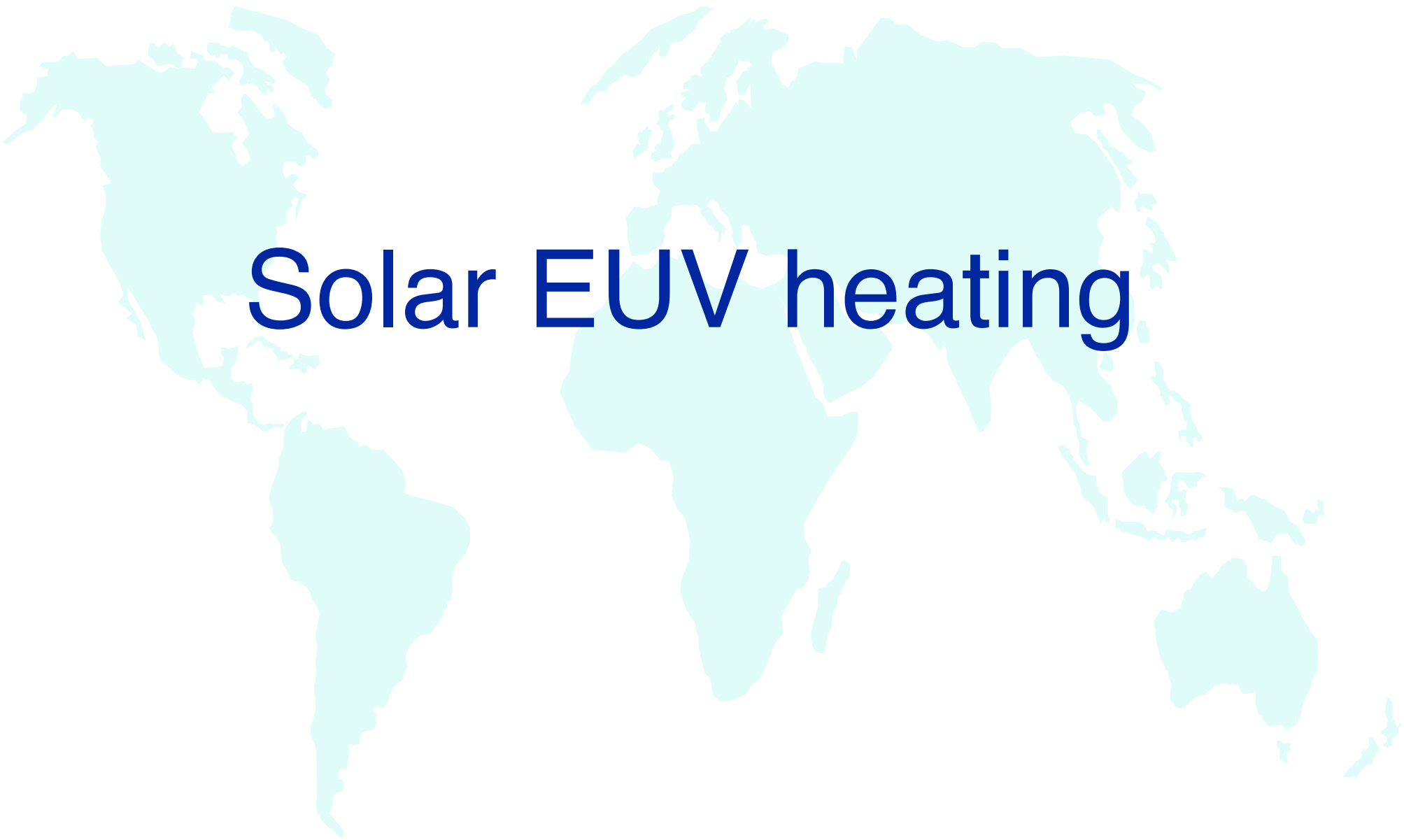
Thermospheric heating

Heat production processes



Heat production and loss



A light blue silhouette of a world map serves as a background for the title text.

Solar EUV heating

Solar EUV heating

Solar extreme ultraviolet (EUV) photons heat the thermosphere and provide the primary energy input into it (enhanced by FUV heating)

they have enough energy to be absorbed by atoms and molecules in the thermosphere

photoabsorption processes - photons are absorbed by gas particles and are raised to a higher energy state thus giving them additional energy that appears as kinetic energy, hence temperature

photoionization processes - photons are absorbed and have enough energy to eject one or more electrons from an outer shell and thus create the ionosphere

a first step is to know the flux of solar EUV flux (photons $\text{cm}^{-2} \text{s}^{-1}$ or ergs $\text{cm}^{-2} \text{s}^{-1}$) at the “top” of the atmosphere

Credit: Tobiska

Solar EUV heating

For solar EUV/FUV heating, one must know

Photon or energy flux at each wavelength ($\# \text{ cm}^{-2} \text{ s}^{-1}$)

Species' densities by altitude ($\# \text{ cm}^{-3}$)

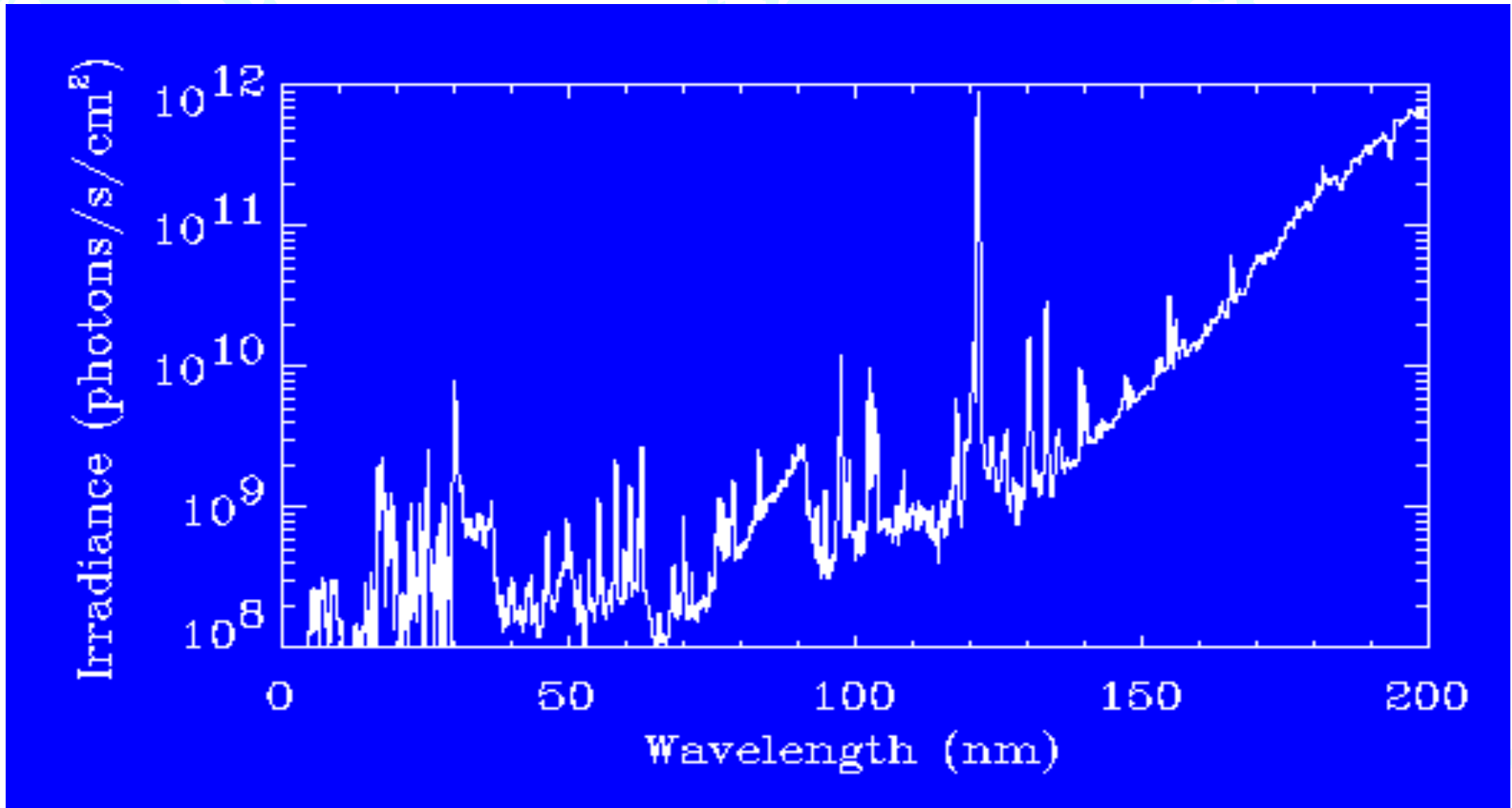
Species' cross sections at each wavelength in the solar spectrum for either photoionization or photoabsorption (the area of a particle “seen” by a photon of a particular wavelength) (cm^2)

Efficiency of photon absorption/ionization processes by altitude (unitless)

Unit optical depth for each species by altitude and wavelength, i.e., the altitude where a photon is most likely absorbed (sometimes unitless or a length, i.e., altitude)

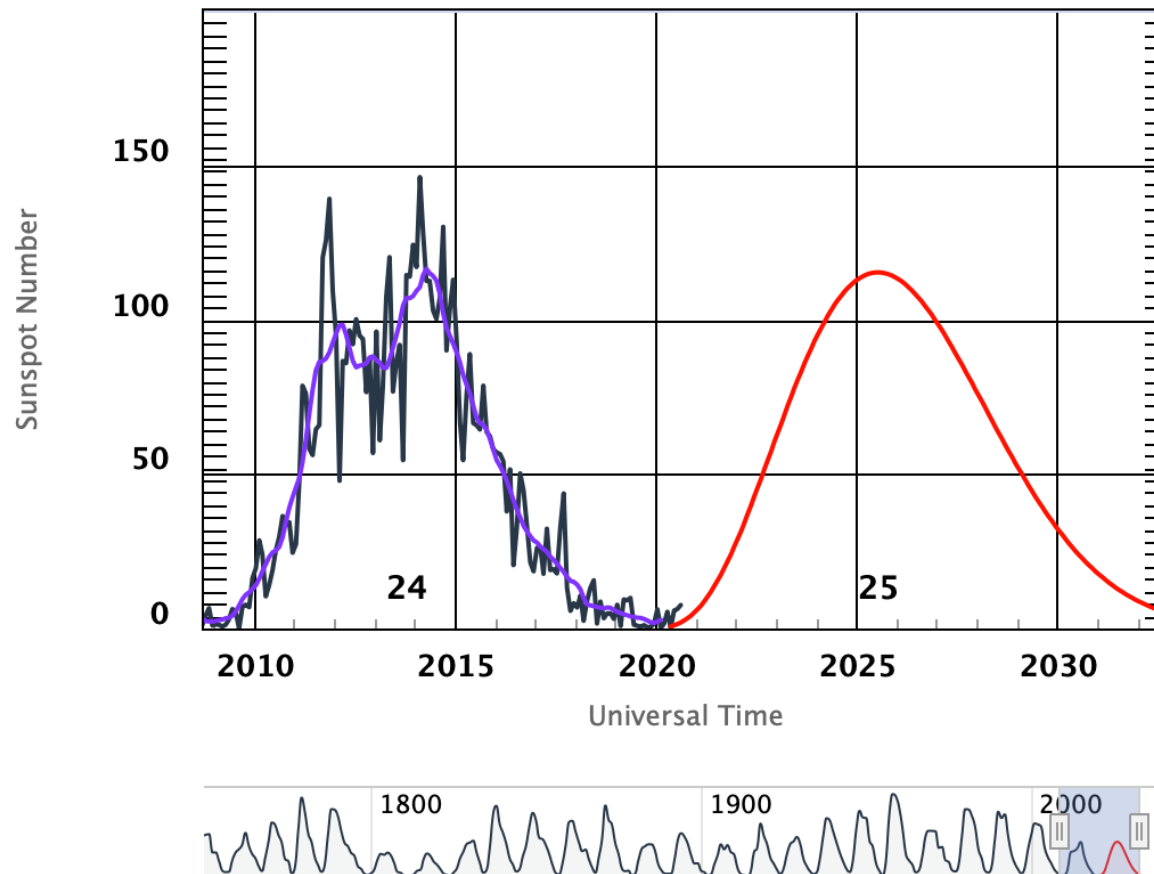
Credit: Tobiska

Solar EUV photons



Sunspot proxy for solar activity

ISES Solar Cycle Sunspot Number Progression

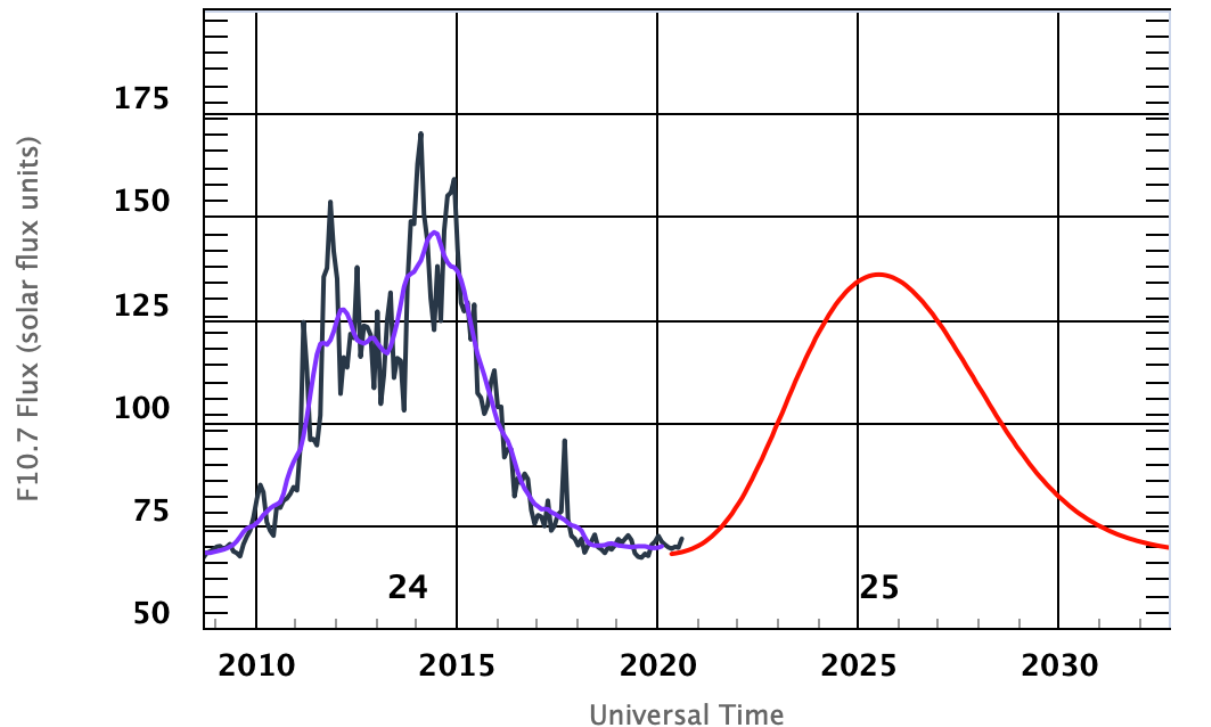


◆ Monthly Values — Smoothed Monthly Values — Predicted Values

Space Weather Prediction Center

F10.7 proxy for EUV

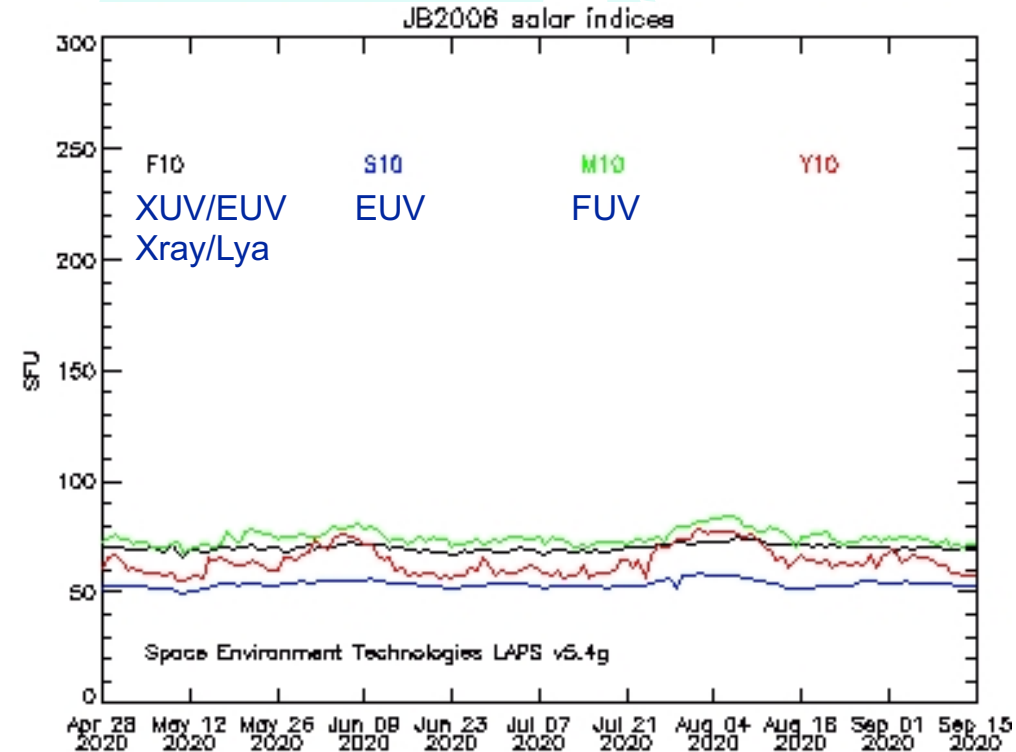
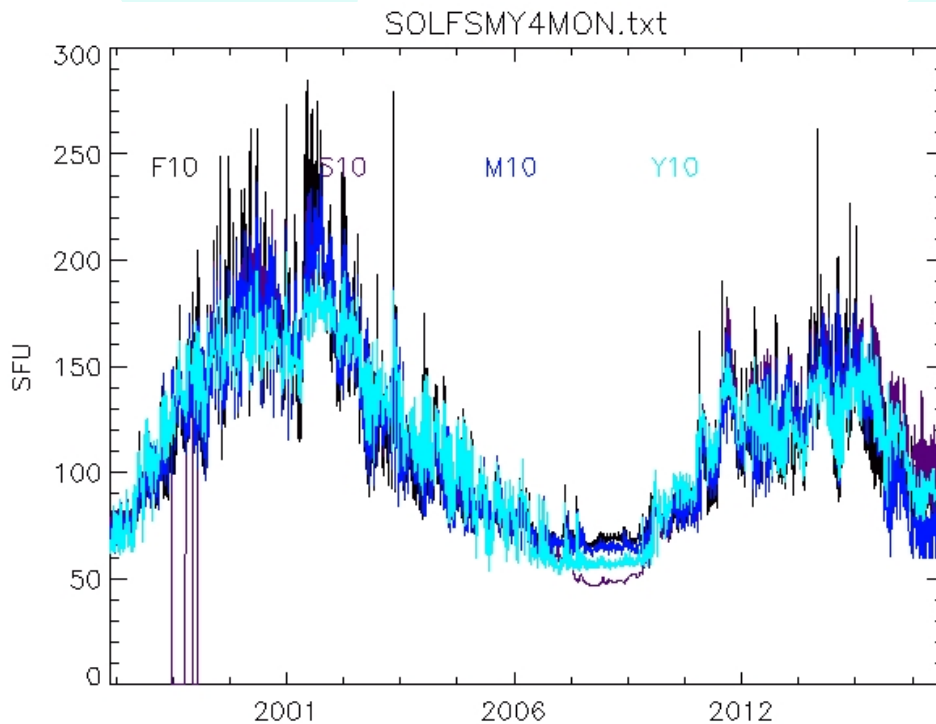
ISES Solar Cycle F10.7cm Radio Flux Progression



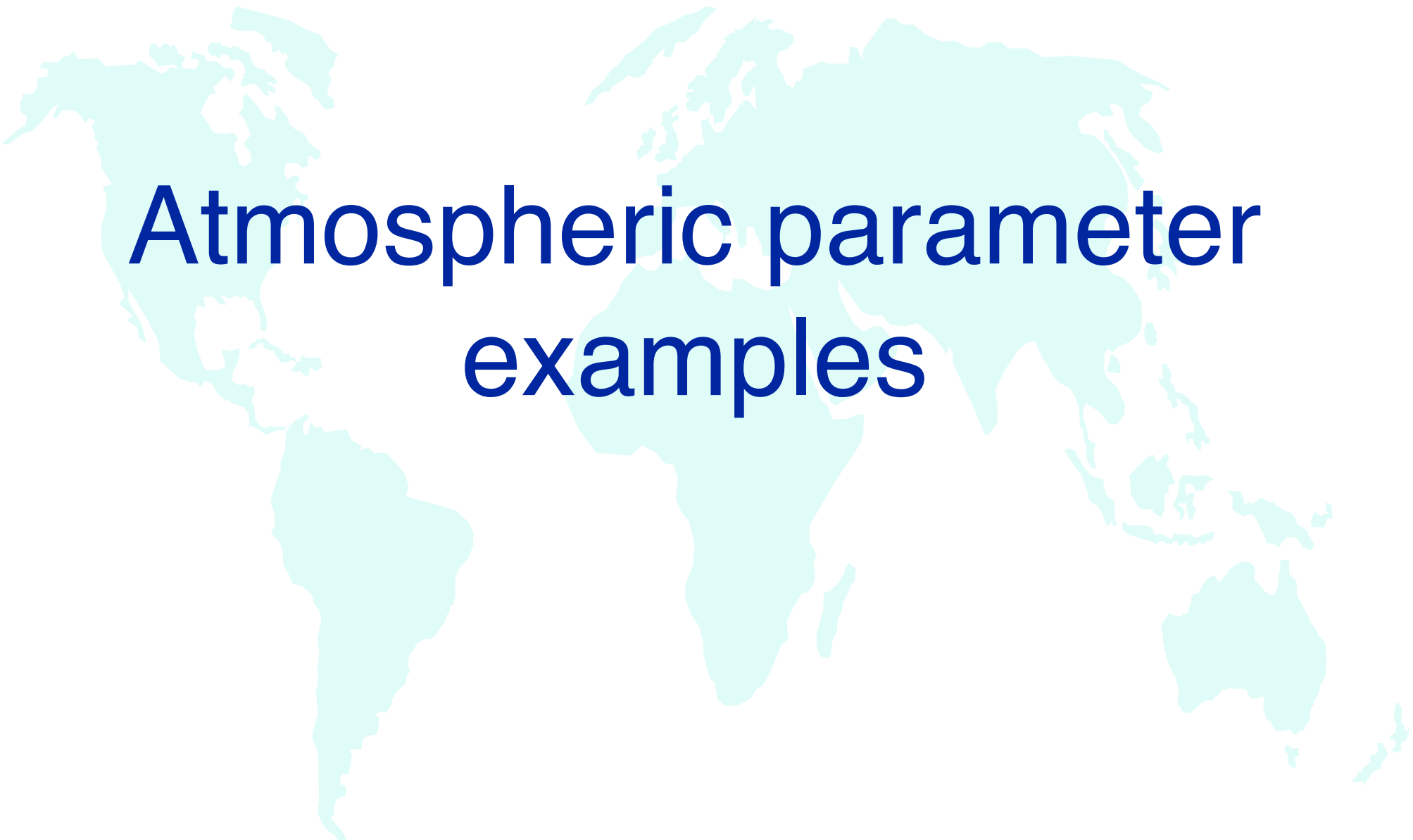
◆ Monthly Values — Smoothed Monthly Values — Predicted Values

Space Weather Prediction Center

Xray, XUV, EUV, Ly- α , FUV JB2008 indices

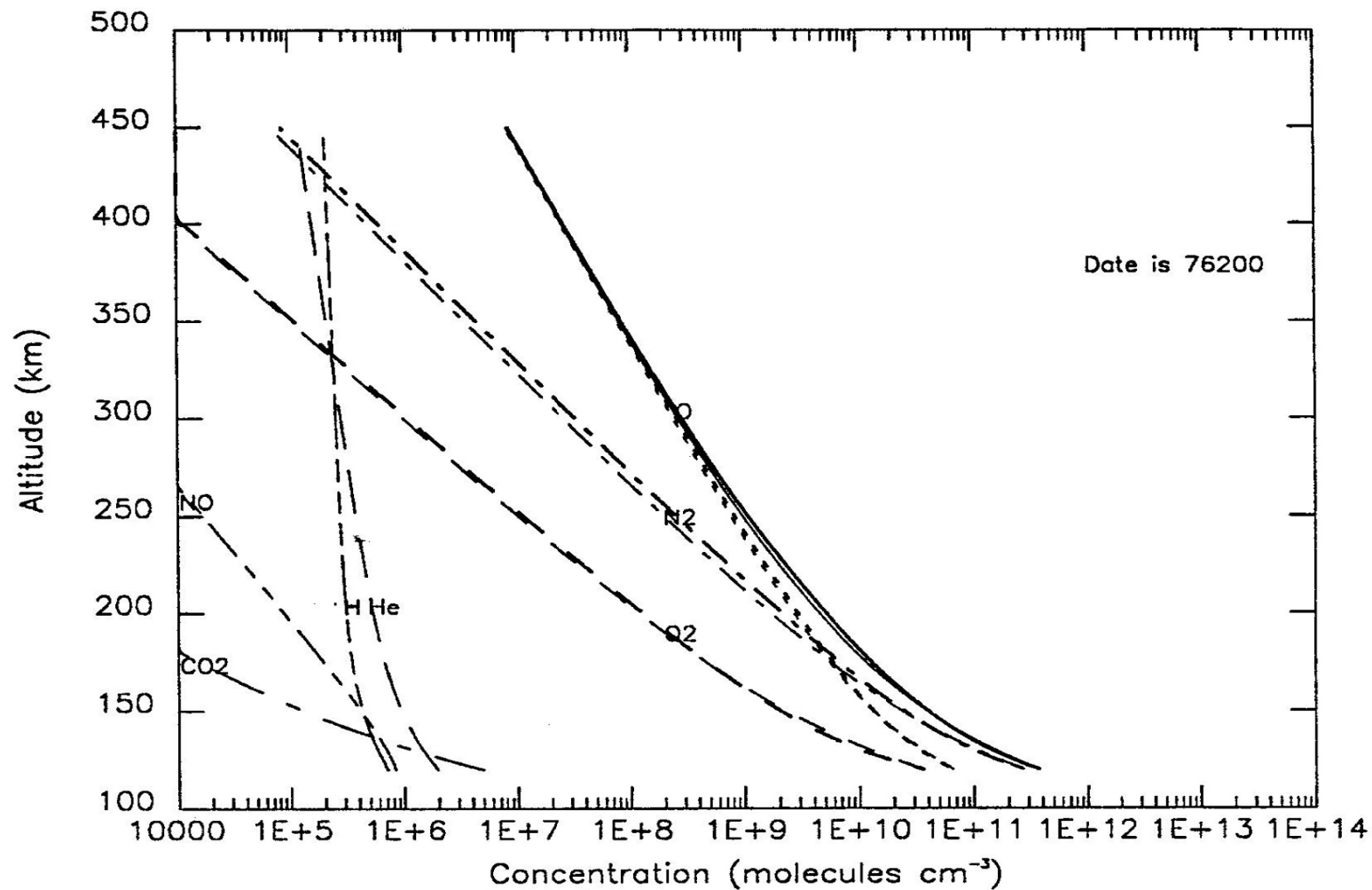


Credit: Tobiska

A light blue world map serves as a background for the title text.

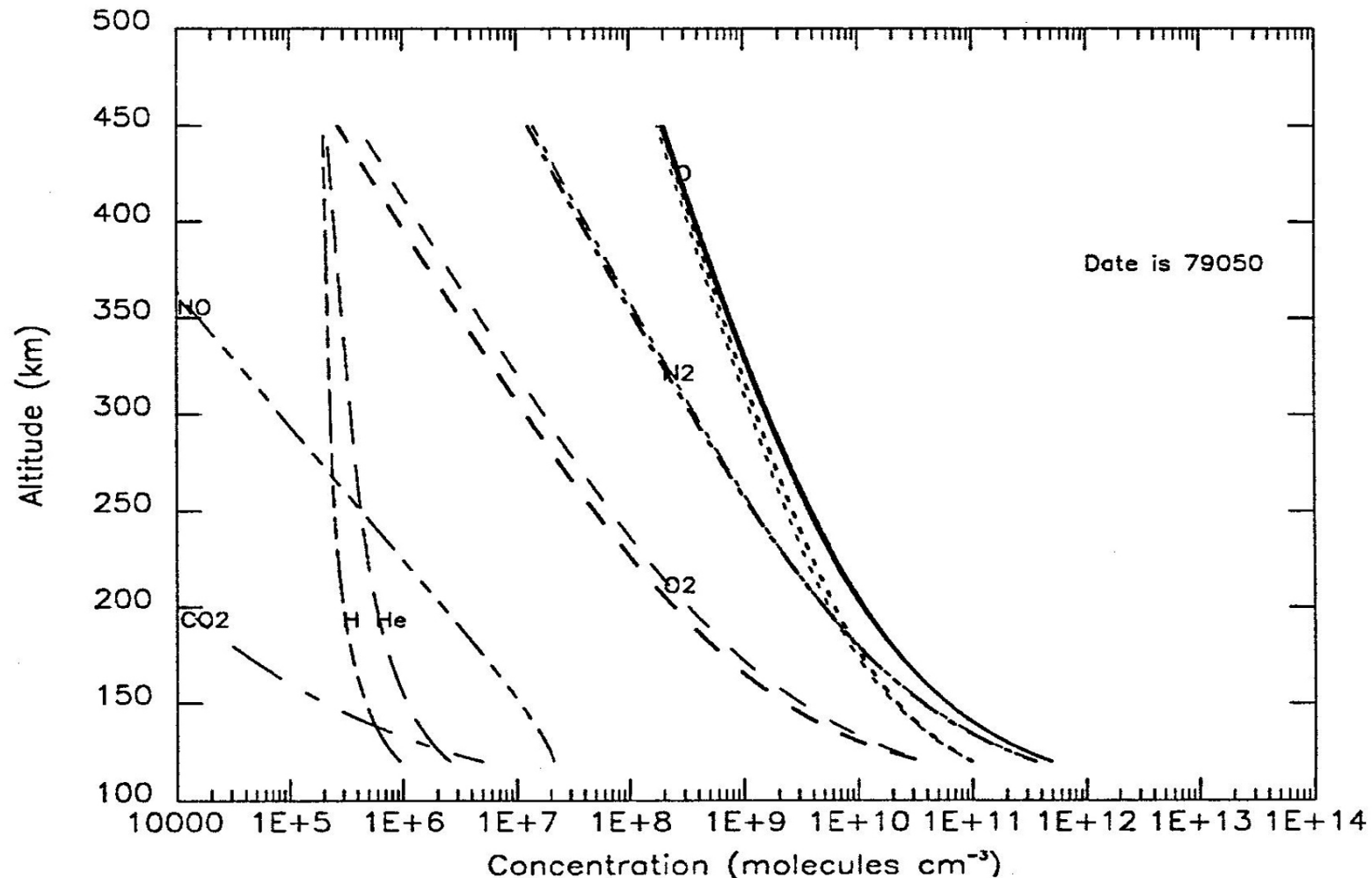
Atmospheric parameter examples

Composition - solar min



Credit: Tobiska

Composition - solar max



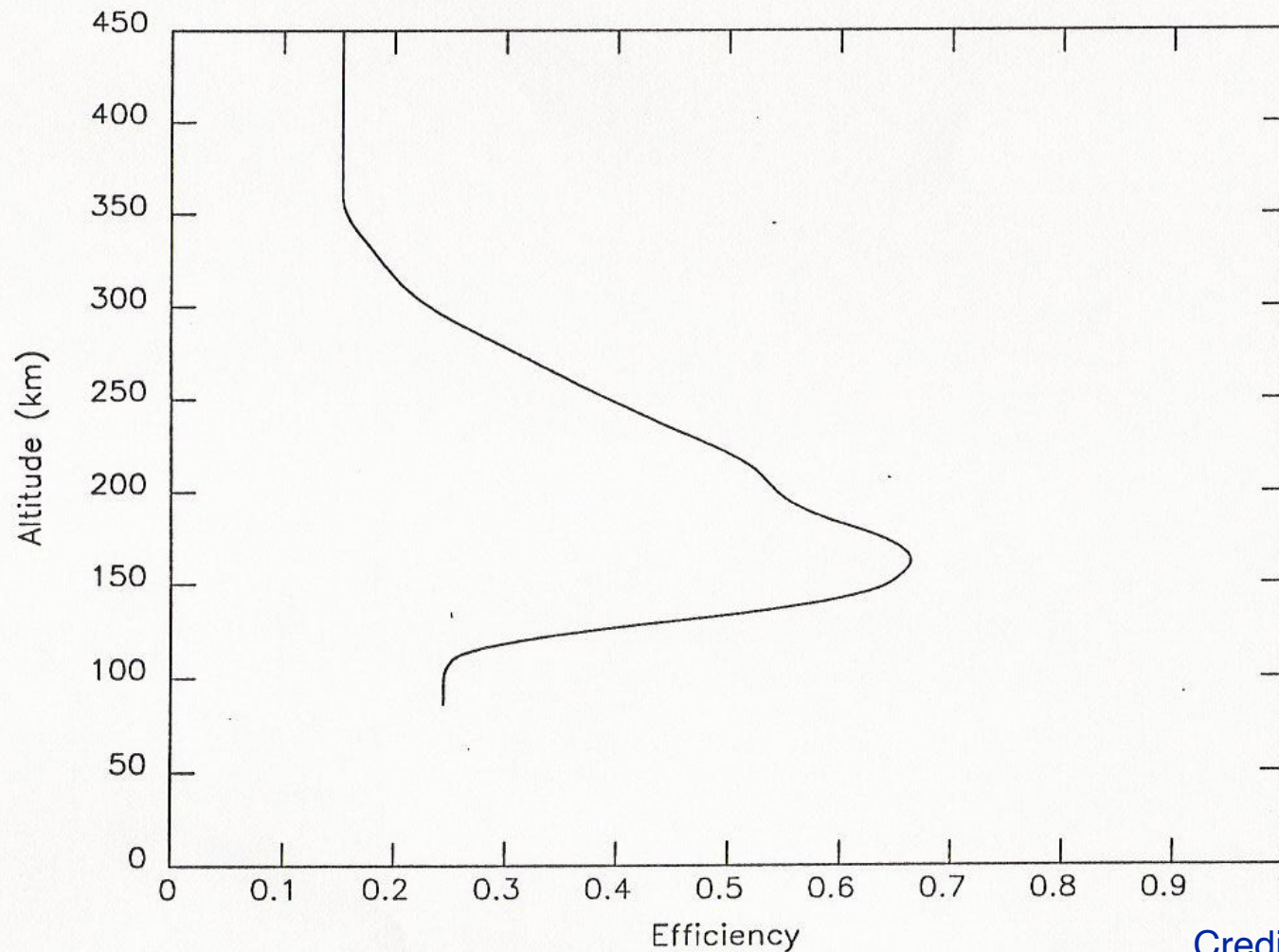
Credit: Tobiska

The graph displays the cross section (in units of $\times 10^{-17} \text{ cm}^2$) as a function of 37 wavelength intervals. The y-axis is logarithmic, ranging from 0.1 to 5. The x-axis represents wavelength intervals from 75 to 1025. Two data series are plotted: absorption (solid line) and ionization (dashed line). The absorption curve shows a broad peak around 550 nm and several sharp peaks at higher wavelengths, particularly around 850 nm and 1000 nm. The ionization curve shows a broad peak around 600 nm and several sharp peaks at higher wavelengths, particularly around 850 nm and 1000 nm. The legend indicates that the solid line represents absorption and the dashed line represents ionization. The graph is labeled with O_2^+ , N_2^+ , and O at various points along the curves.

<https://SpaceWx.com>

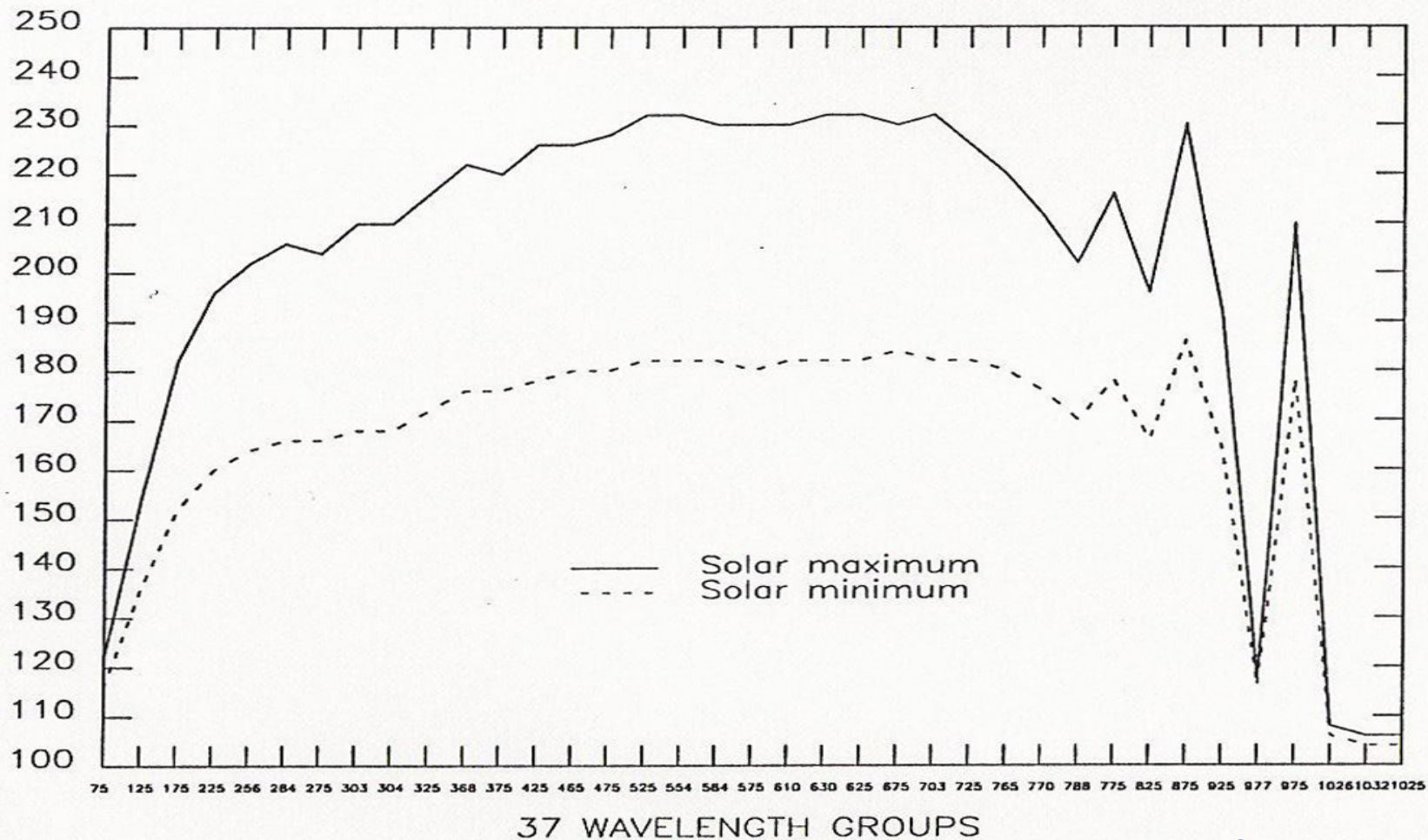
W. Kent Tobiska <ktobiska@spacewx.com>

EUV heating efficiency



Credit: Tobiska

EUV Unit optical depth



Credit: Tobiska

Physics-based temperature

Energy input (P = energy production term)

1. Solar photons (XUV, EUV, and FUV heating)
2. Charged particles (electron precipitation and Joule heating)
3. Mechanical energy from dynamics (winds, waves, circulation, tides)
4. Cosmic rays
5. Thermal (molecular conduction) and kinetic (molecular diffusion) transport from other layers

Energy loss (L = energy loss term)

1. Radiation to space
2. Mechanical energy dissipation (turbulence and eddies)
3. Thermal (molecular conduction) and kinetic (molecular diffusion) transport from other layers

Credit: Tobiska

Conservation of energy

1-D Time-dependent (1DTD) equation for the thermospheric temperature uses conservation of energy and is written

$$\rho c_v \frac{\partial T}{\partial t} + \nabla \cdot \mathbf{E} = P - L \quad (4-32)$$

where $\mathbf{E} = -\lambda \nabla T$ is the conductive heat flow resulting from the temperature gradient and assumes no diffusion velocities in the gas; λ is the thermal conductivity coefficient and ∇T is the temperature gradient; c_v is the specific heat at constant volume and ρ is mass density; P and L are energy production and loss terms; use Crank-Nicolson technique to derive solution to $T(z)$

EUV heating

Putting it all together for the heat production example due to solar EUV photons, Q_{euv} , where

$$P = q_{euv} + q_{particle} + q_{Joule} + q_{dynamics} \quad (4-35)$$

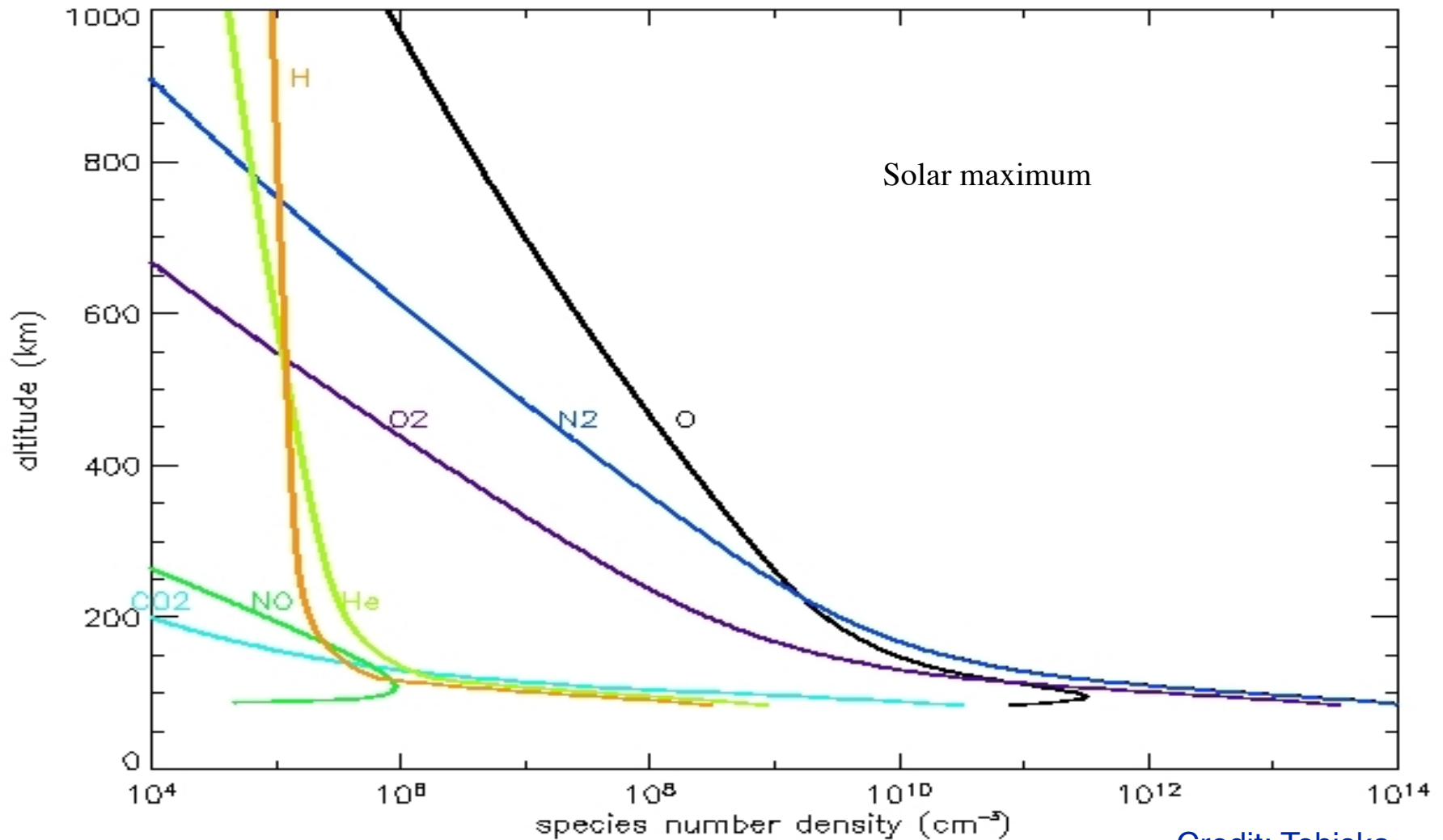
where

$$q_{euv}(z) = \sum_i \sum_{\lambda} n_i(z) \sigma_i(\lambda) E(\lambda, z) \varepsilon_i(z) \quad (4-36)$$

with variables' examples in the next slides

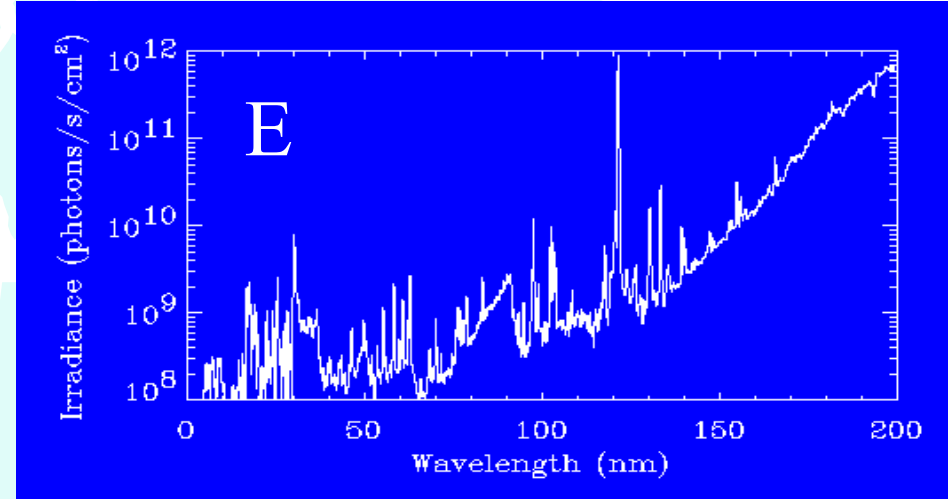
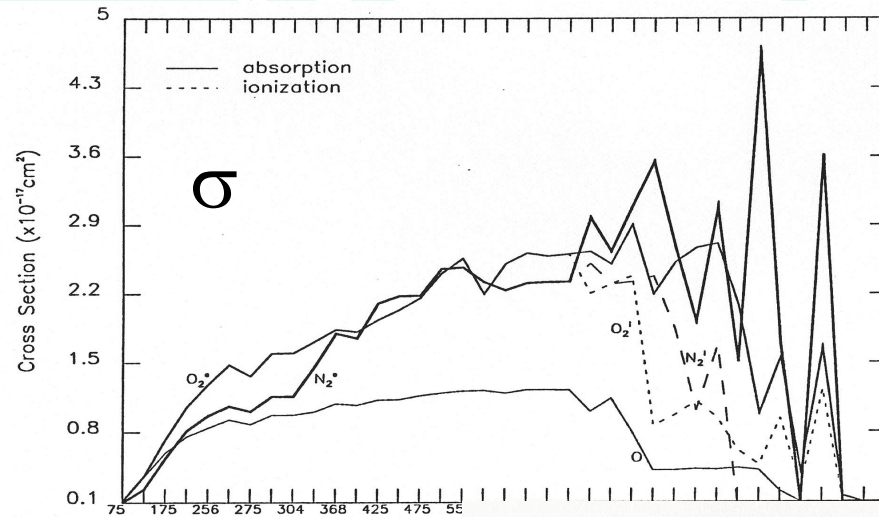
Credit: Tobiska

$n_i(z)$: Neutral species

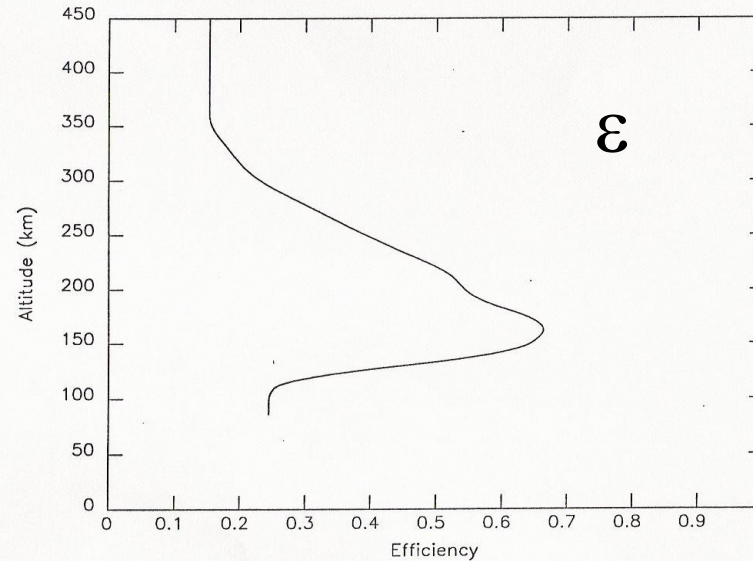


Credit: Tobiska

$$\sigma_i(\lambda), E(\lambda, z), \varepsilon_i(z)$$

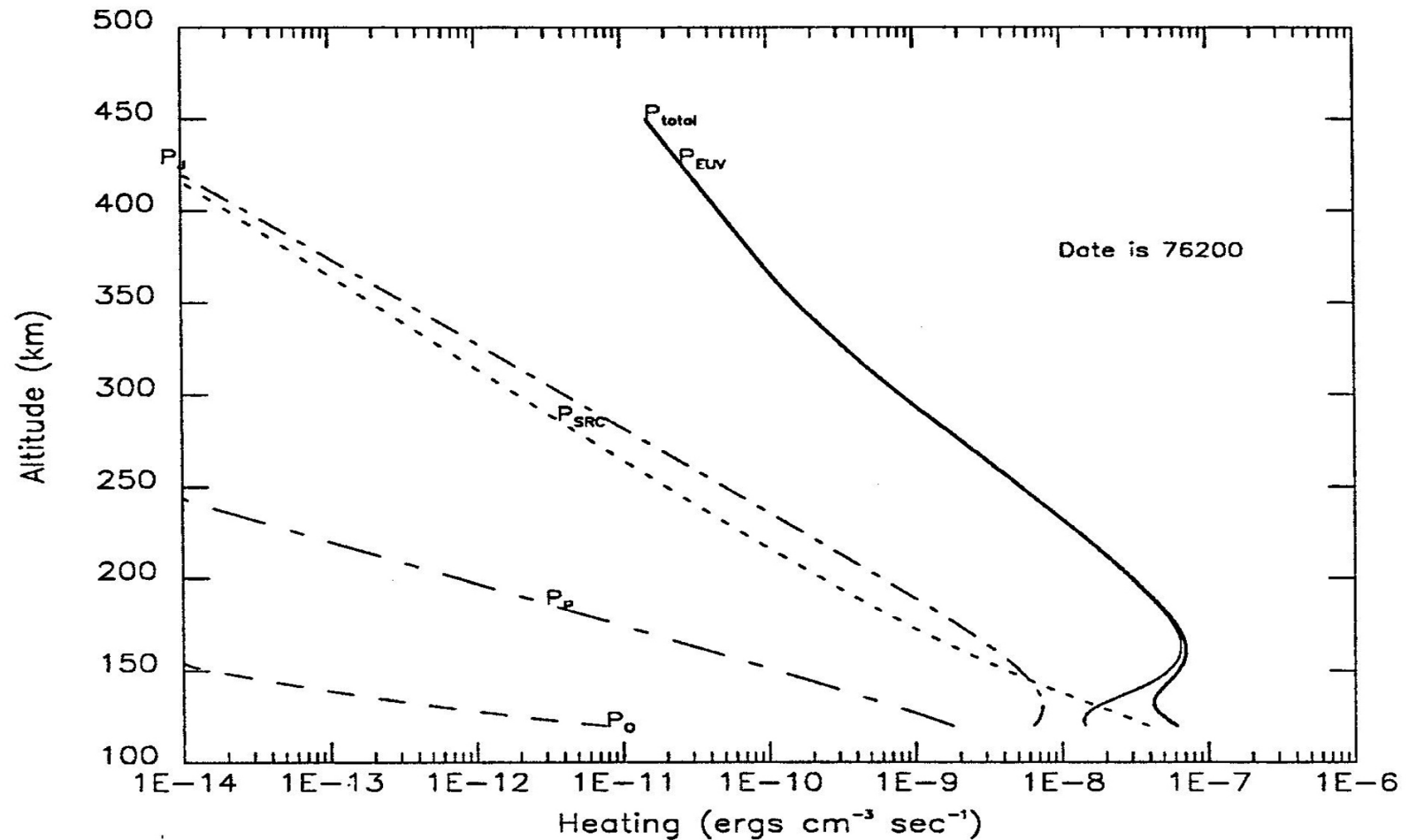


37 Wave



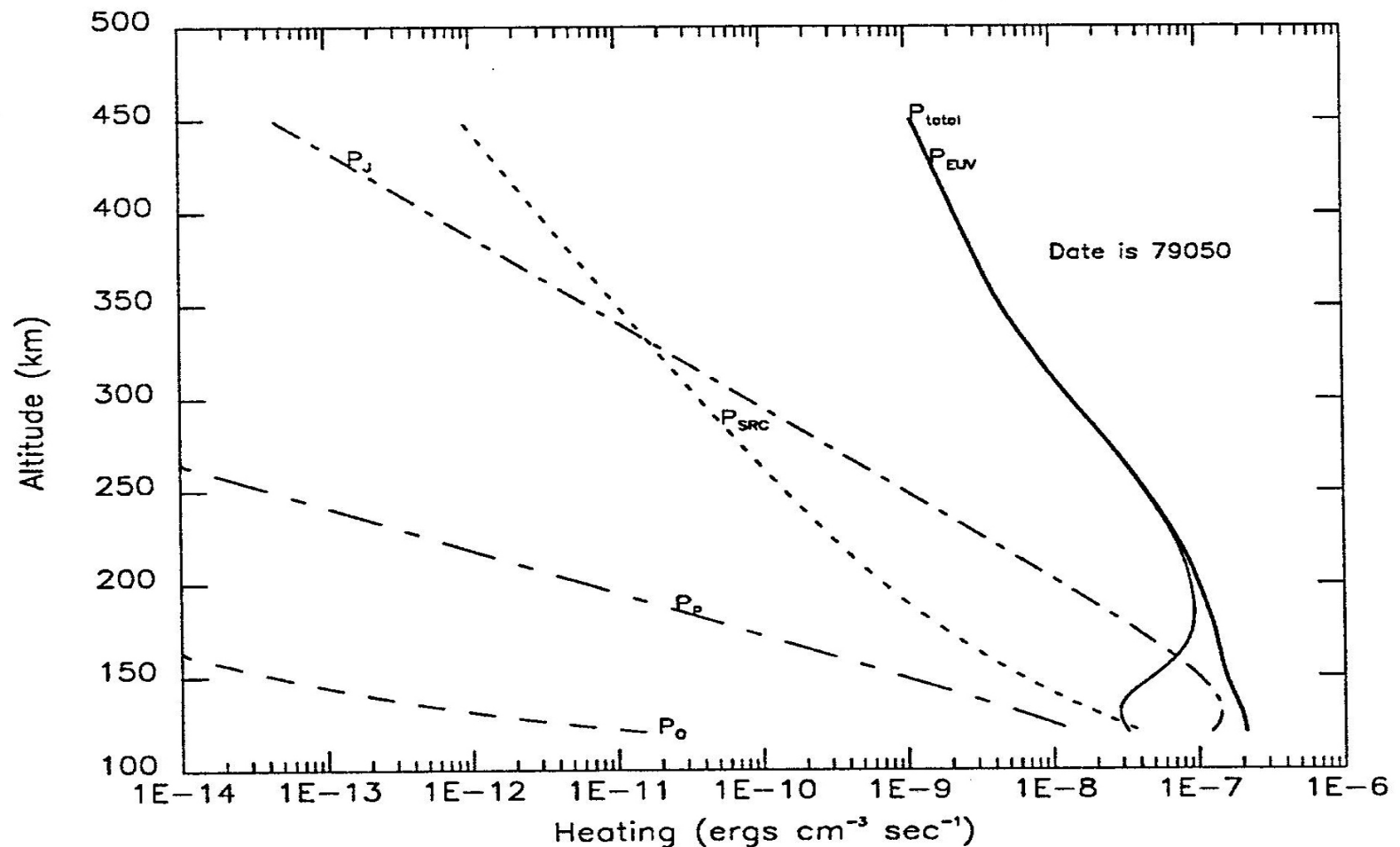
Credit: Tobiska

Heating - solar min



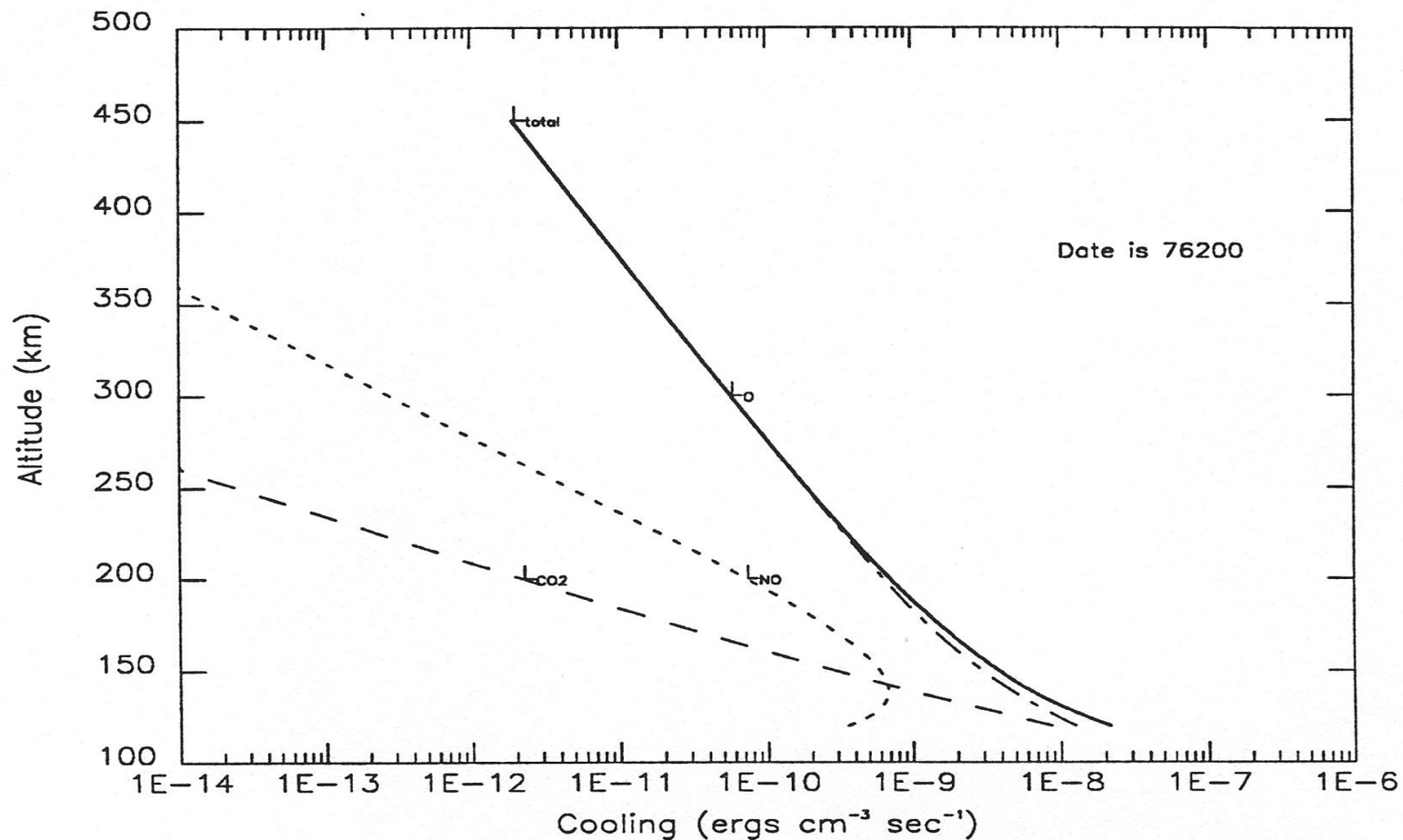
Credit: Tobiska

Heating - solar max



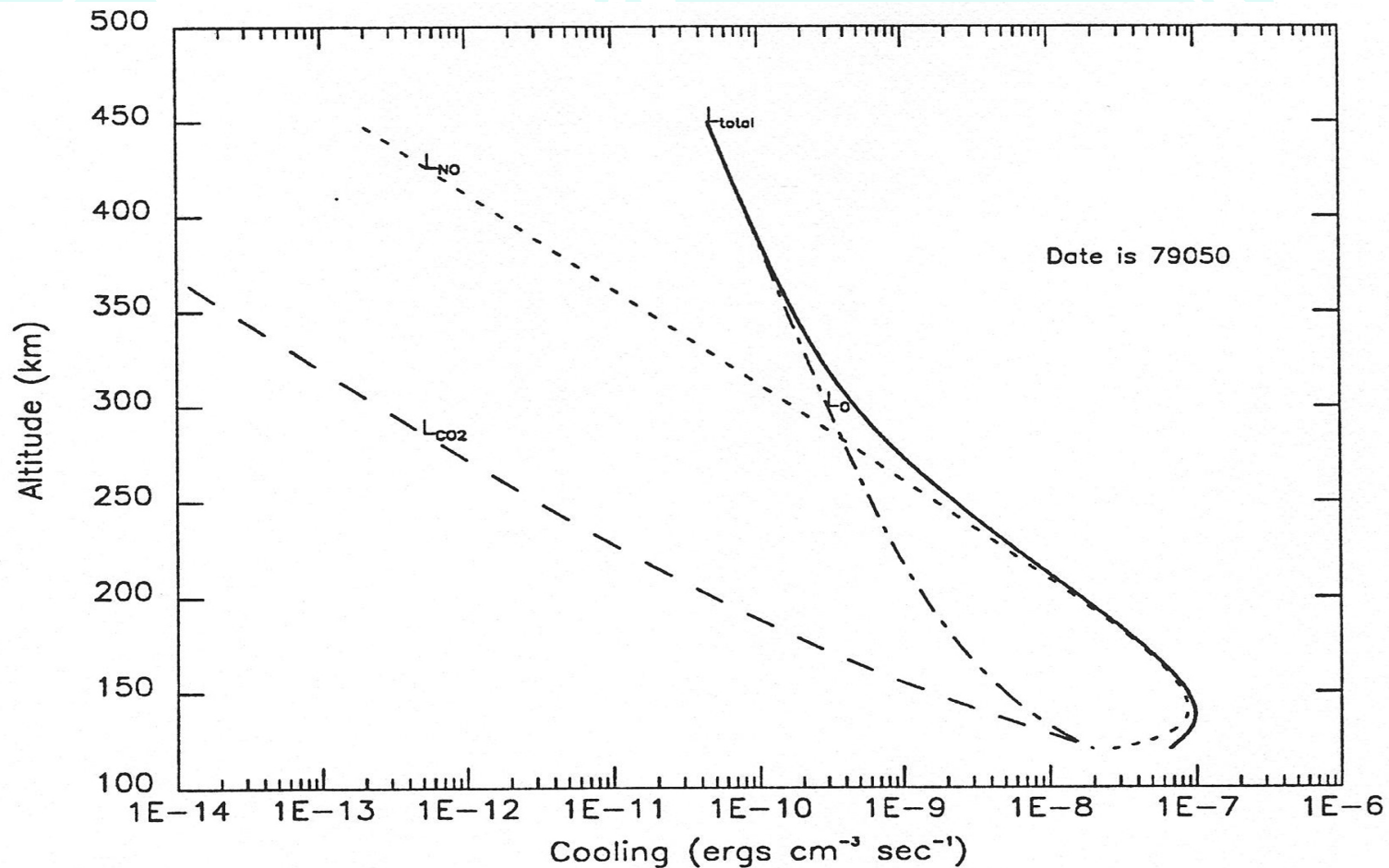
Credit: Tobiska

Cooling - solar min



Credit: Tobiska

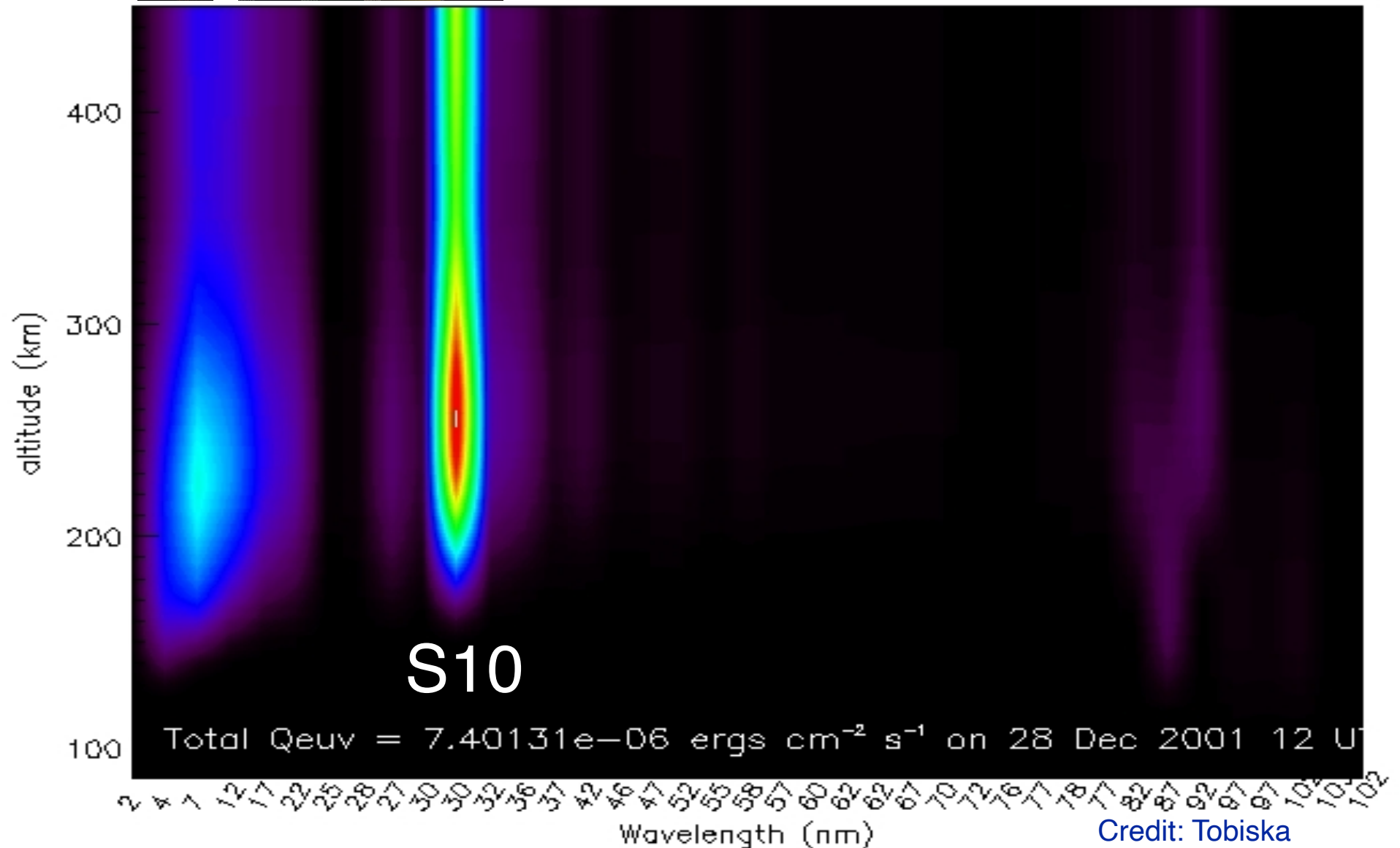
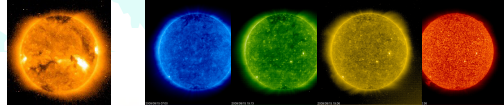
Cooling - solar max



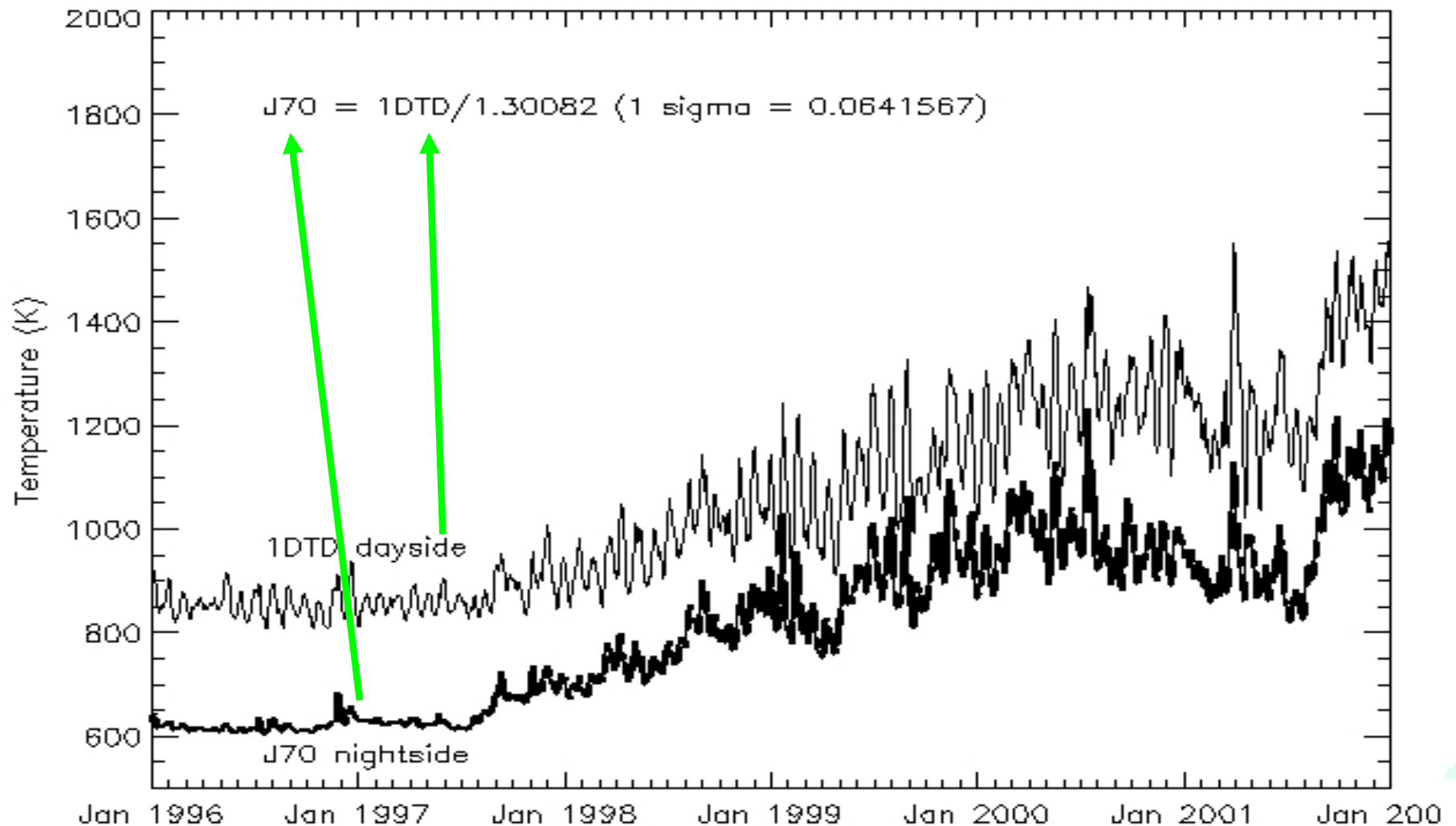
Credit: Tobiska



Q_{euV} : solar EUV heating (eq 4-36)

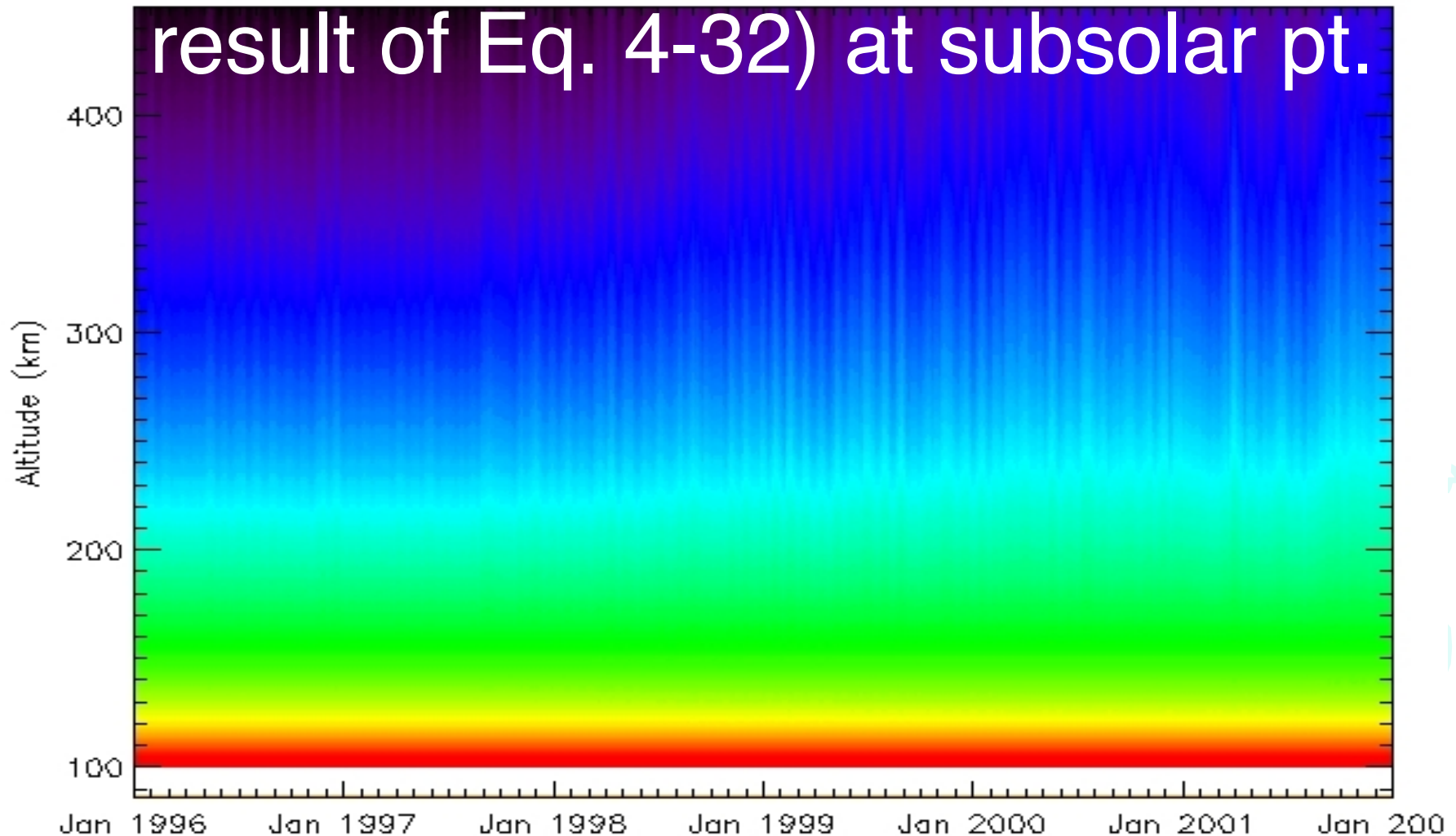


Exospheric temperature, T_{∞}



Credit: Tobiska

Thermospheric mass density, $\rho(z,t)$ result of Eq. 4-32) at subsolar pt.

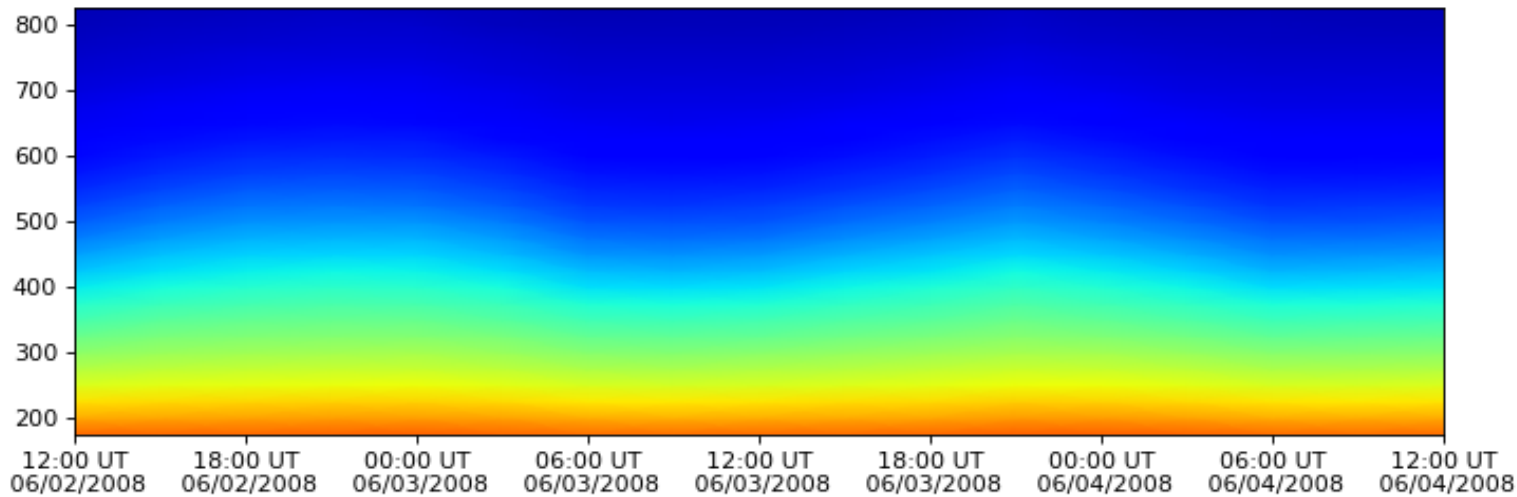


Credit: Tobiska

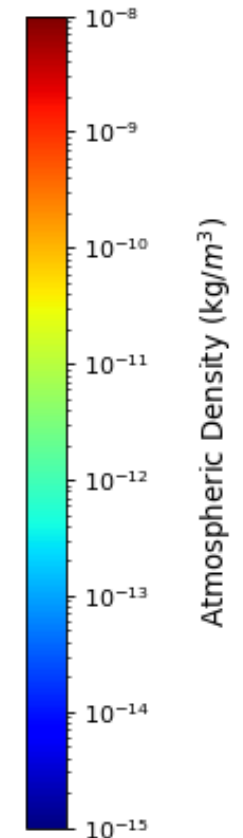
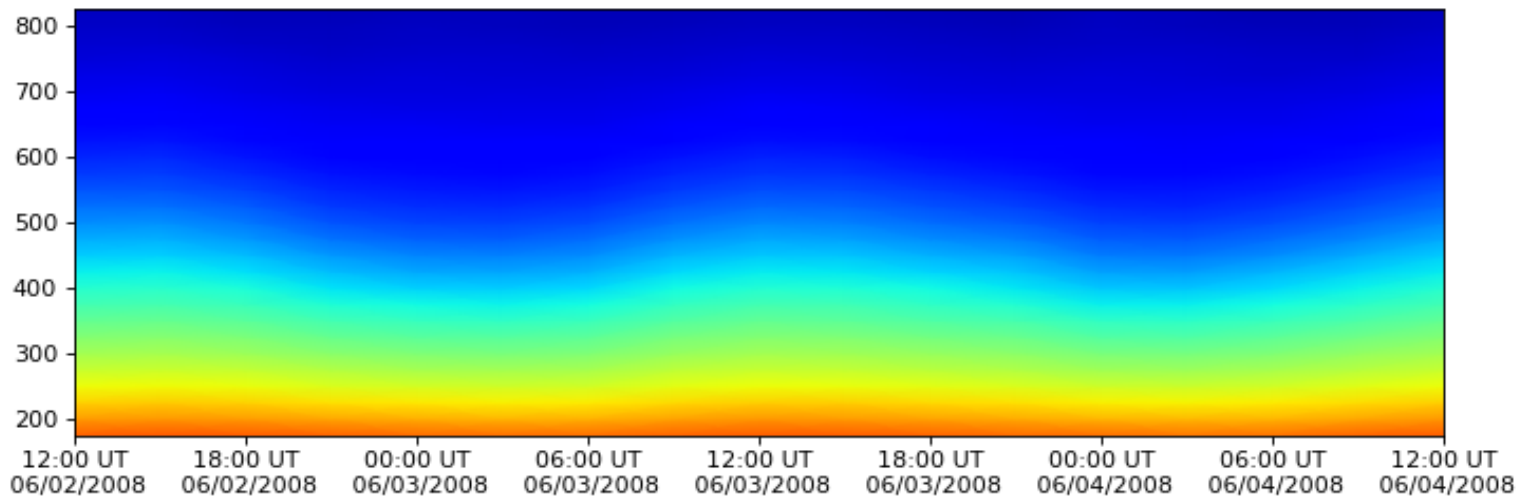


SET HASDM database

HASDM DataBase: Boulder, CO



HASDM DataBase: Null Island

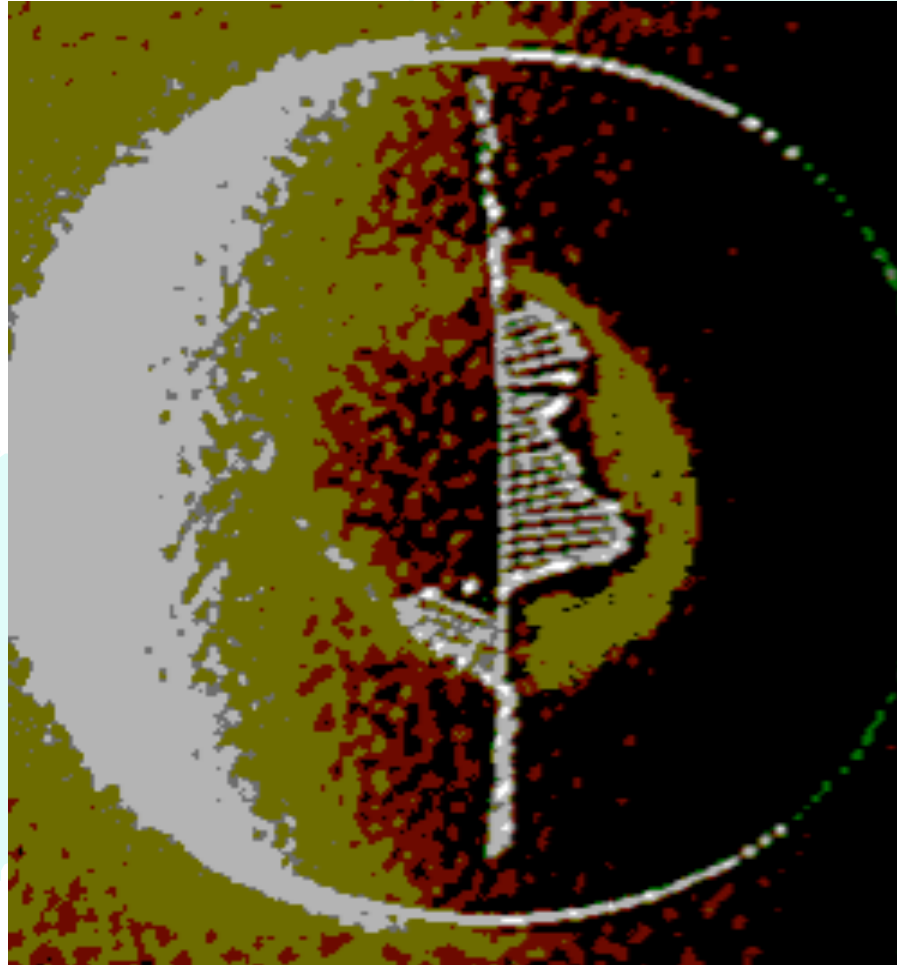


Credit: Tobiska

A light blue silhouette of a world map is centered in the background of the slide.

Auroral heating

Auroral heating processes

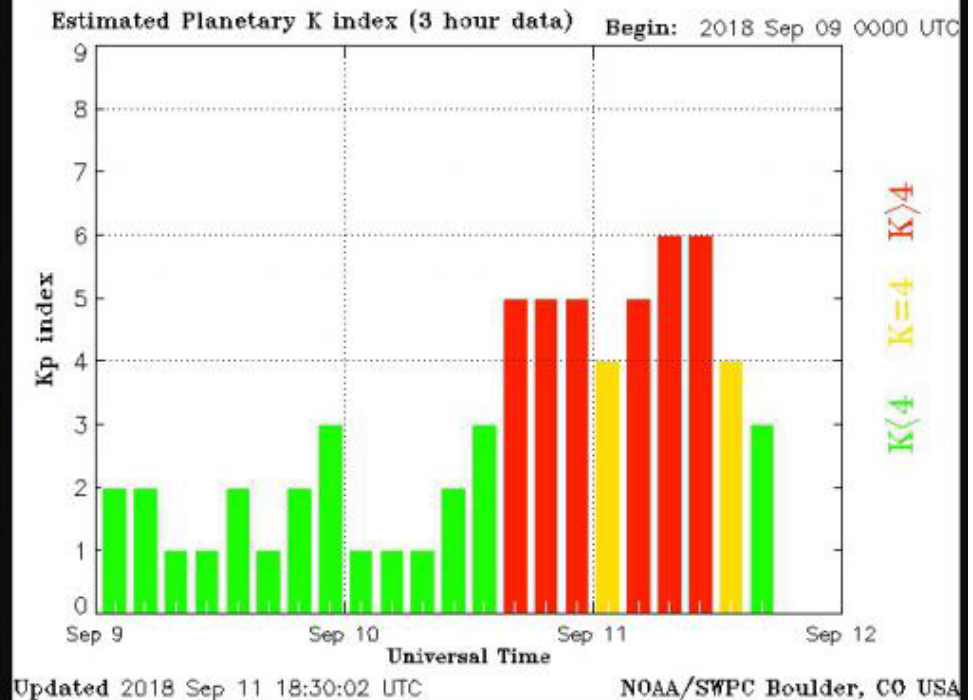
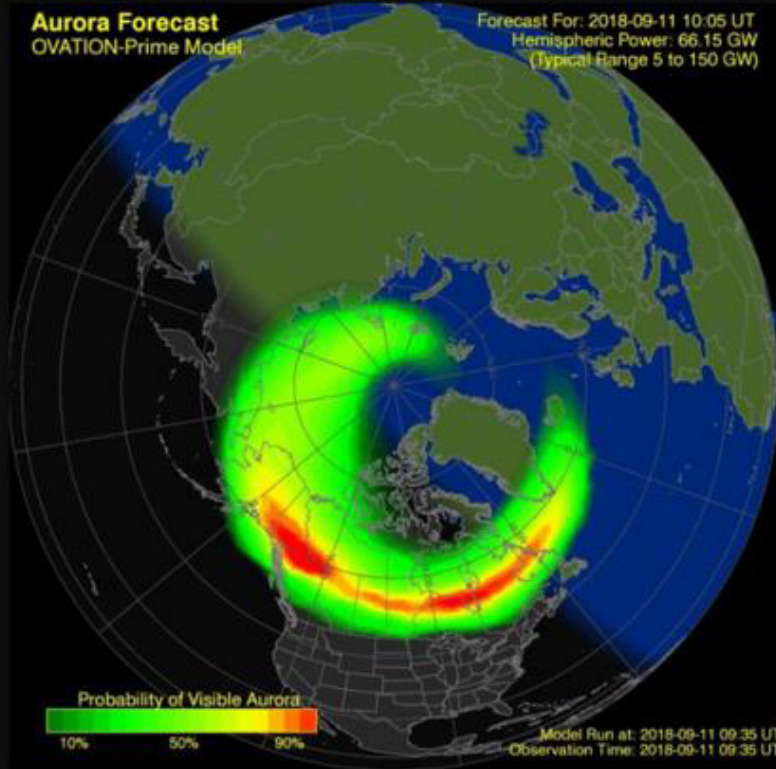


Hemispheric power input

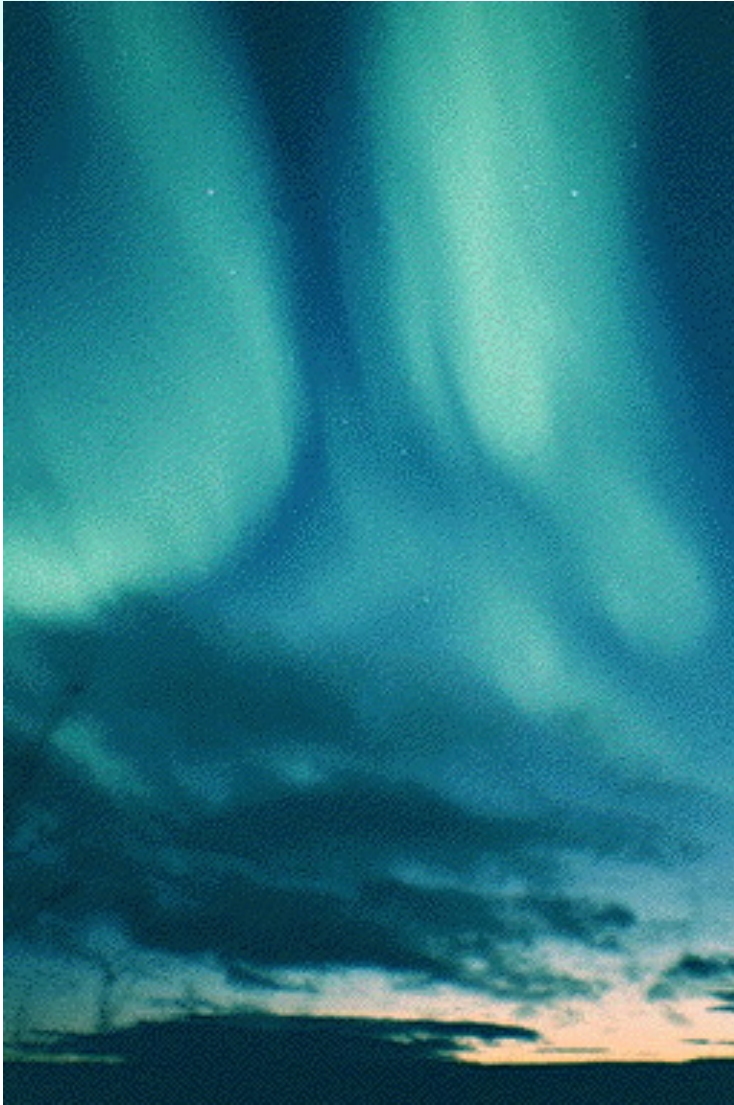
G2

Moderate Storm Conditions
Observed on 11 SEP

G2

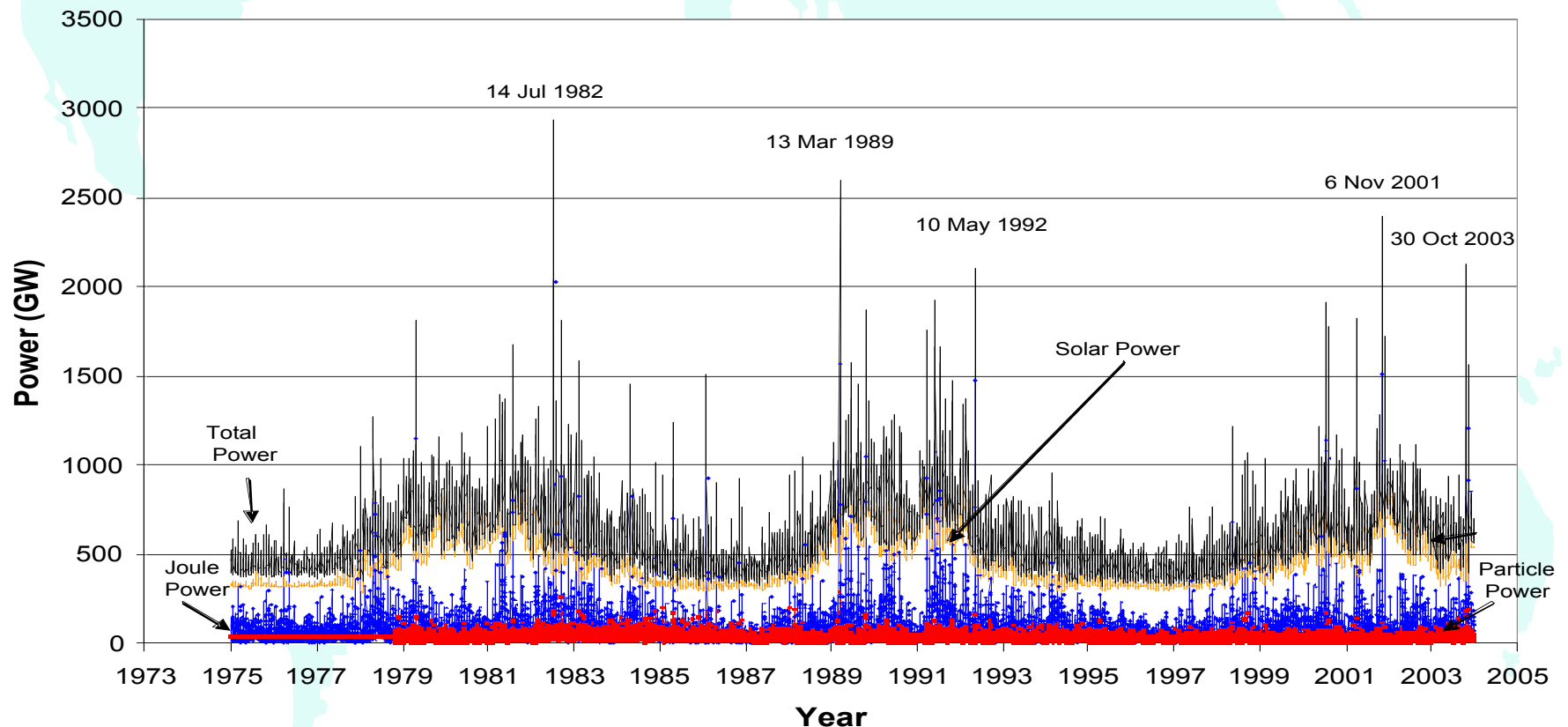


Auroral electron precipitation



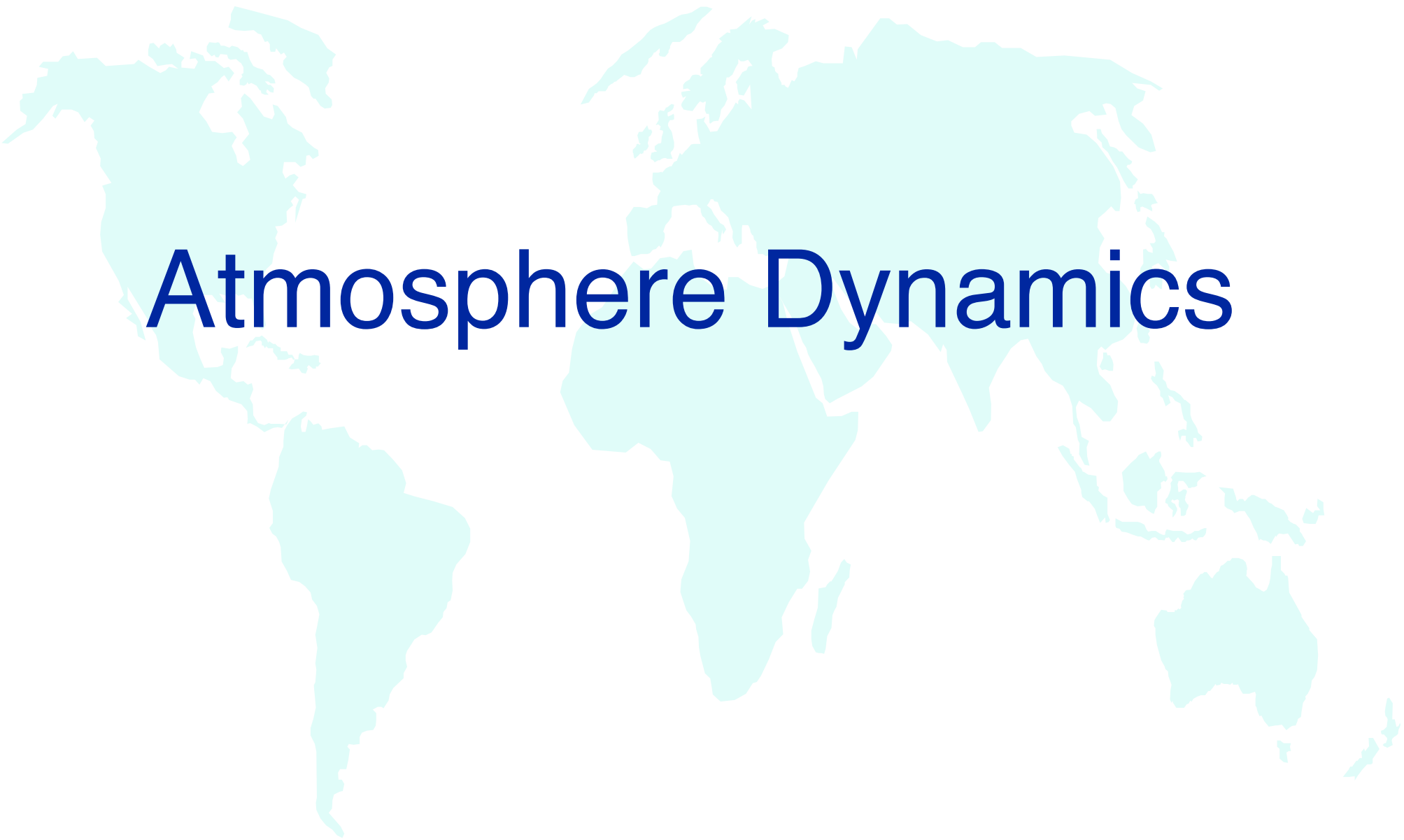
Power input comparison

Daily Average Power Values for Solar Cycles 21-23



A light blue silhouette of a world map serves as a background for the title text. The map shows the outlines of all continents and major islands.

Heating and cooling by conduction and mixing

A light blue silhouette of a world map serves as a background for the title text.

Atmosphere Dynamics

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 ($< \sim 120$ km), vertical winds propagate upwards from the mesosphere, which are referred to as (thermospheric) '**tides**'

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).

Thermal Winds

We would expect an eastward wind across the sunset terminator.

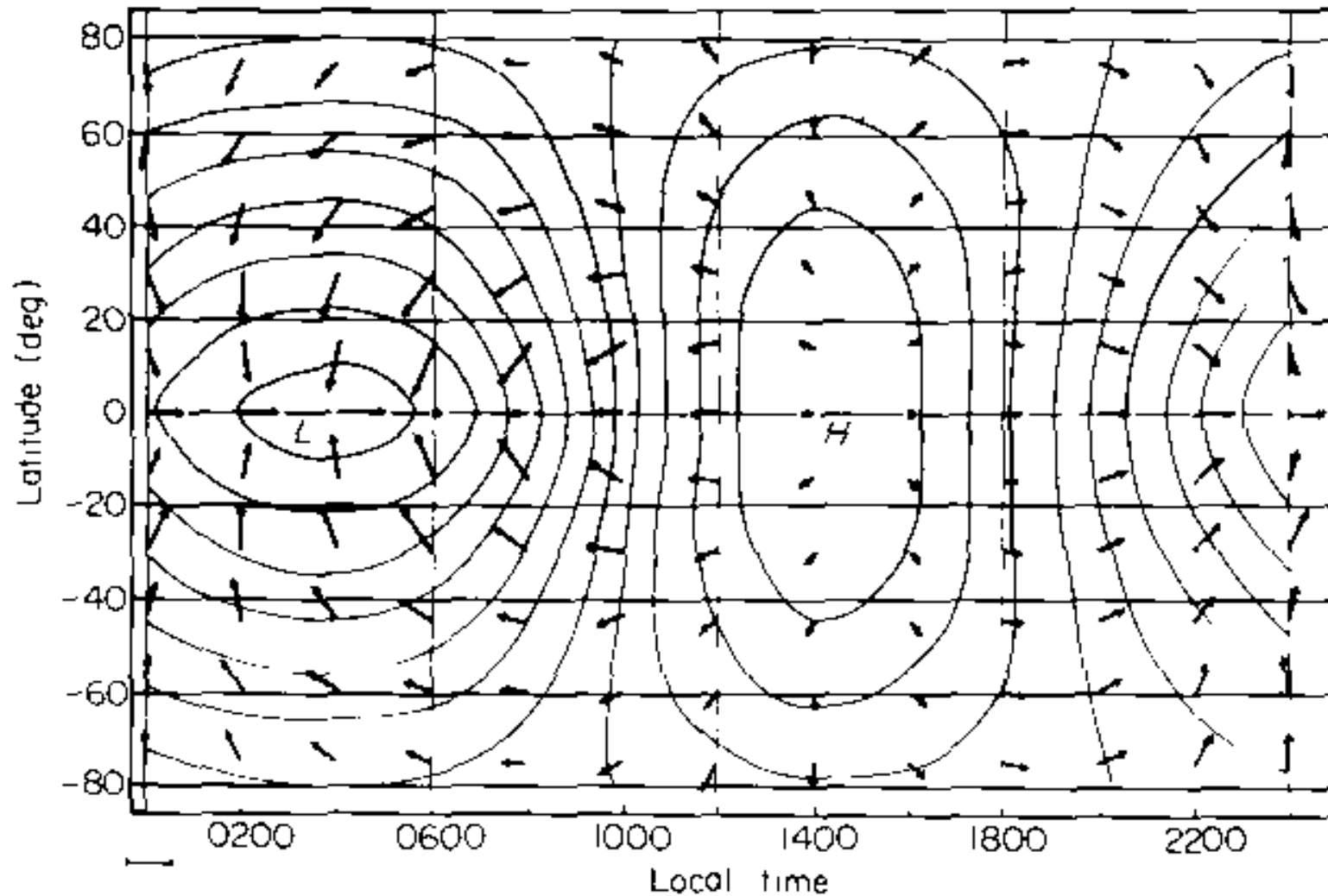
At the equator, Coriolis terms $\rightarrow 0$

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

*

Below the turbopause (~ 120 km), eddy viscosity. Above the turbopause, molecular viscosity.

Thermal Winds



Atomic Properties of the Elements

Physical Measurement Laboratory www.nist.gov/pml
Standard Reference Data www.nist.gov/srd

1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of ^{133}Cs

\$ For the most accurate values of these and other constants, visit pml.nist.gov/constants.

-  Solids
-  Liquids
-  Gases
-  Artificially Prepared

[†]Based upon ¹²C. () indicates the mass number of the longest-lived isotope.

For the most precise values and uncertainties visit ciaaw.org and pml.nist.gov/data.
NIST SP 966 (July 2019)

Summary

- ✓ **The planetary space environment**
 - ✓ Gas kinetic theory
 - ✓ Ideal Gas Law
 - ✓ Molecular and atomic collisions
 - ✓ **Earth**
 - ✓ Atmospheric physics
 - ✓ Surface and lower atmosphere
 - ✓ Upper atmosphere
 - ✓ Heating (Solar, auroral, conduction, mixing)
 - ✓ Cooling (conduction, mixing)
 - ✓ Dynamics