# Ionosphere and Thermosphere Basics

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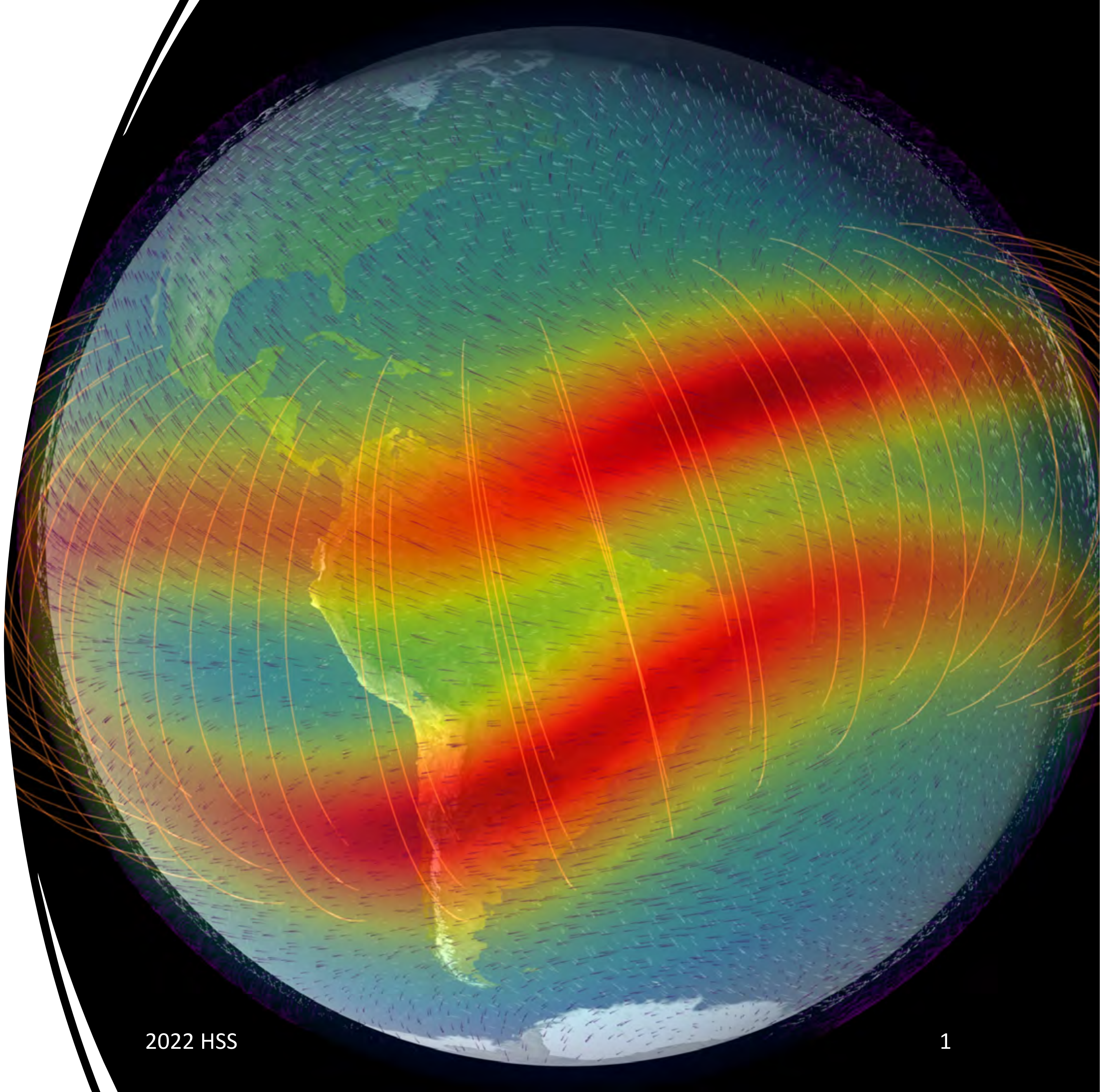
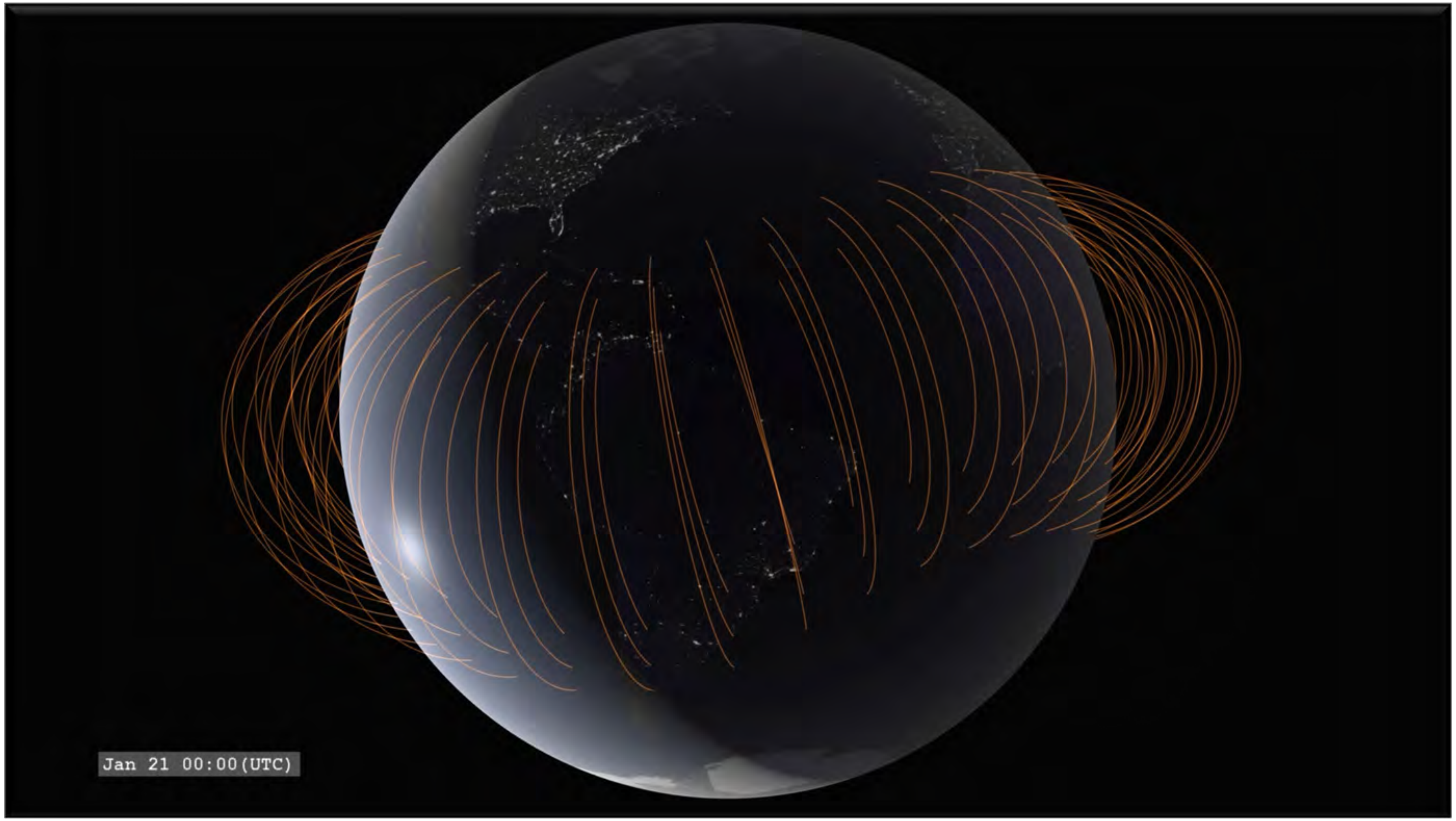


# Terrestrial Ionosphere




Credit: NASA's Scientific Visualization Studio

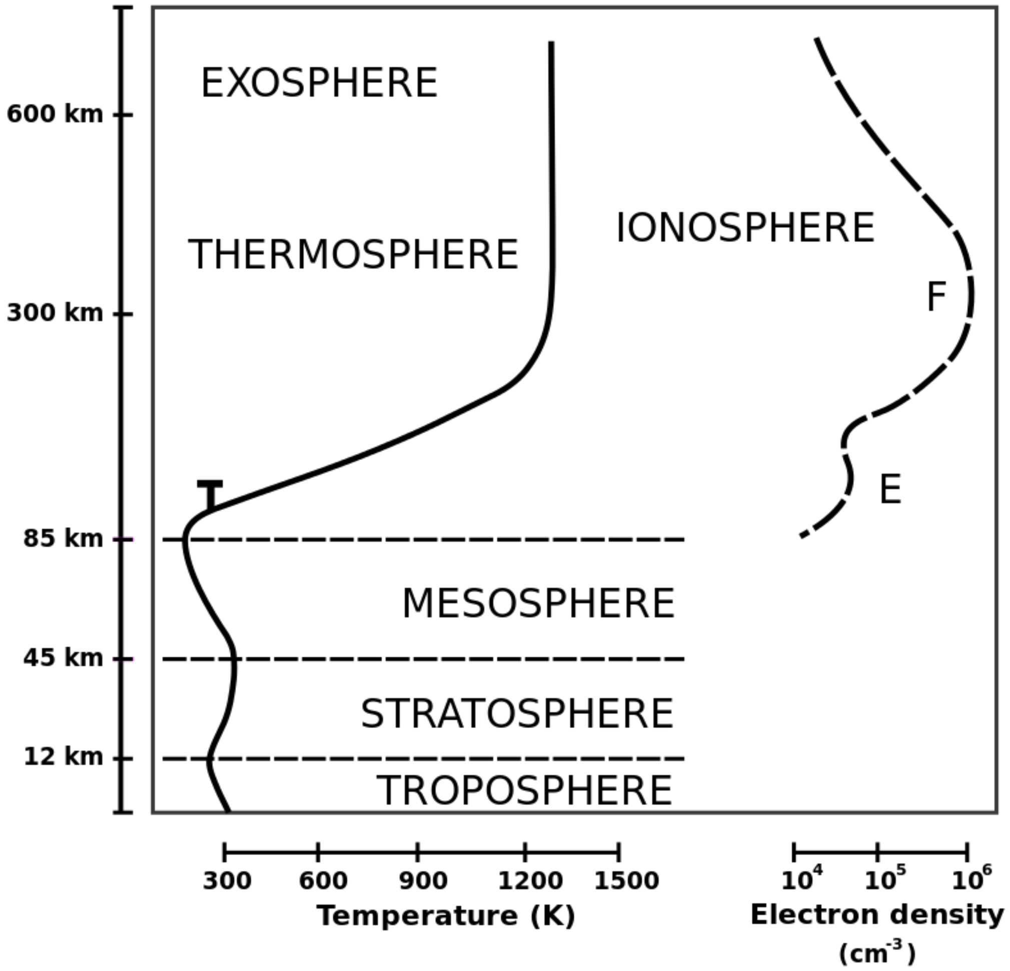
# Thermosphere and Ionosphere Definitions

**Thermosphere:**

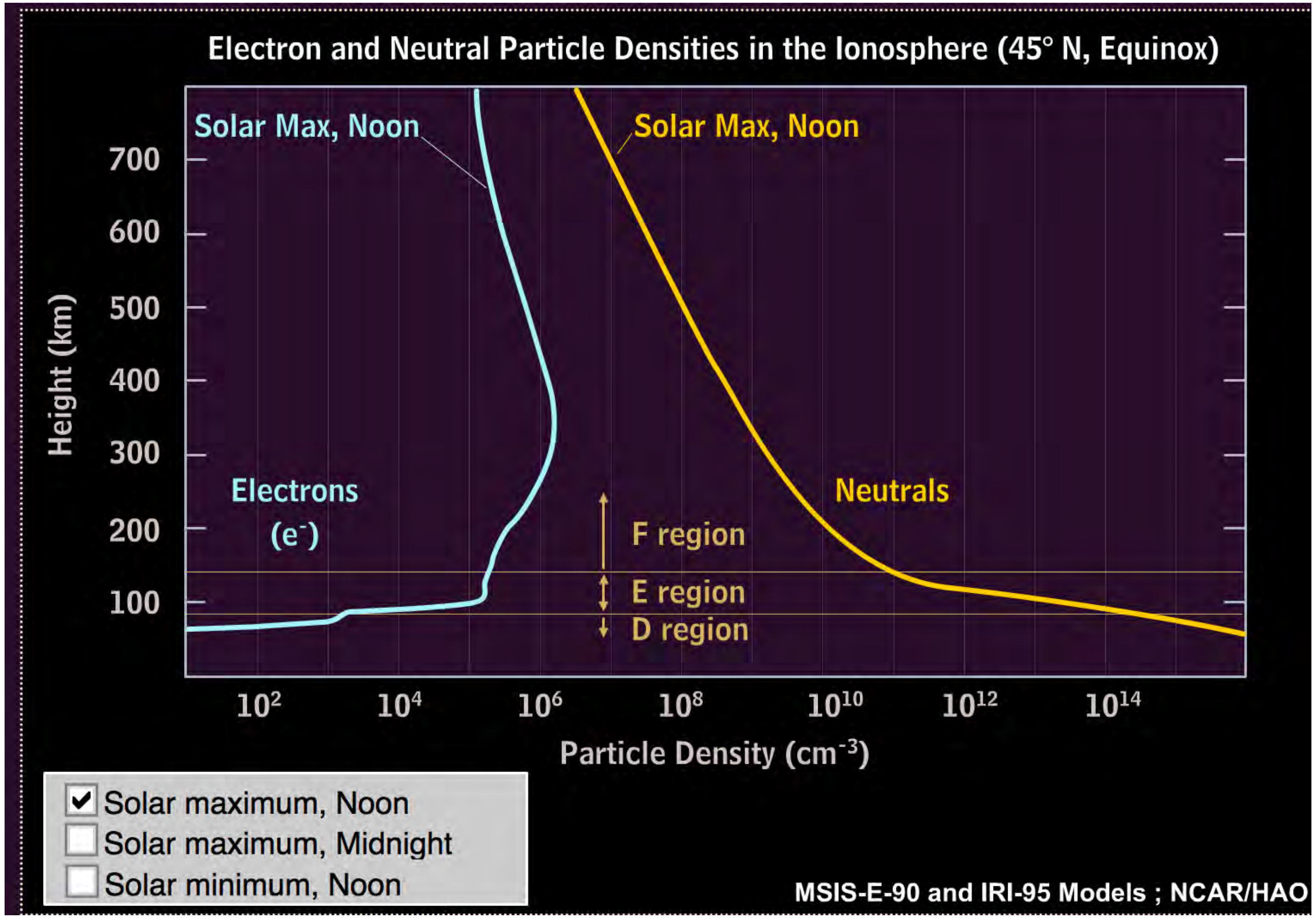
- neutrals
- Layers are divided based on **temperature gradient**
- Starting from the coldest region at mesopause to several hundred km.

**Ionosphere:**

- plasma
- Layers are divided based on **plasma density**
- Starting from about 80 km to several hundred km.

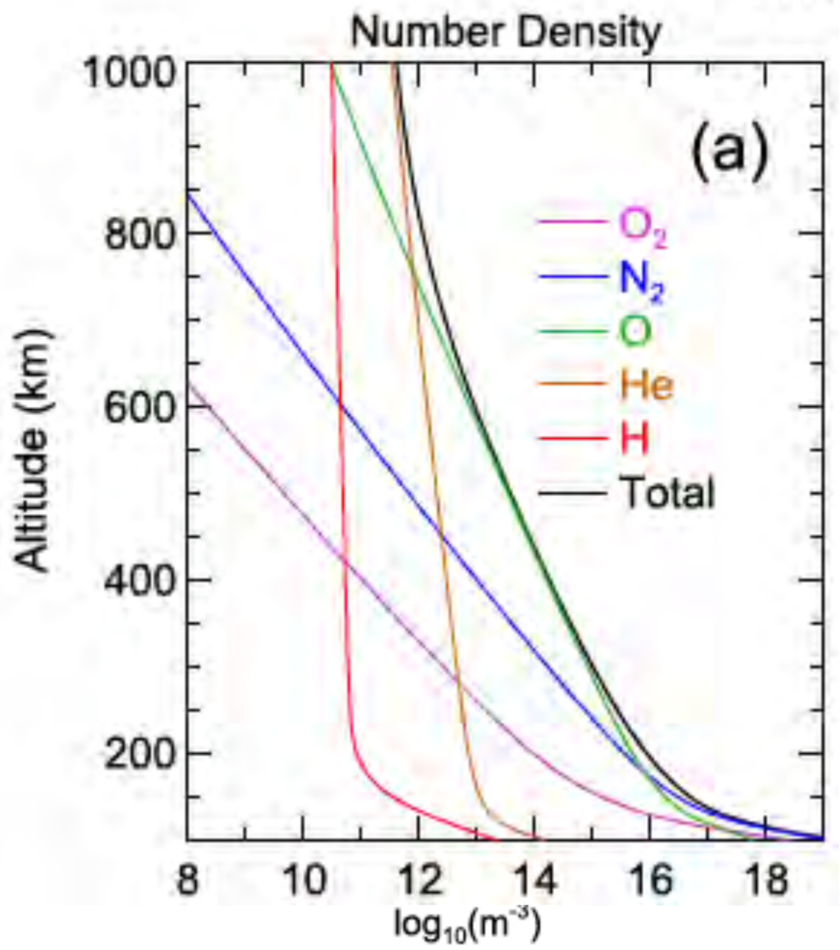


# Thermosphere and Ionosphere Density Profiles




- Ionosphere: weakly ionized plasma
- Ion-neutral collisional coupling strongly controls the IT dynamics.

# Thermosphere Composition




Global average number density profiles at solar max from the NRLMSISE-00 empirical model. From Emmert, 2015, Advances in Space Research.

- The most abundant neutrals in the lower atmosphere are $N_2$ and $O_2$.
- The most abundant neutrals in the thermosphere are O, $N_2$ and $O_2$.
- Lighter neutrals, such as H and $H_e$, become more and more important at higher altitudes.

- All neutral densities decrease exponentially with increasing altitude according to their **scale height (H, in m) above about 100 km**.

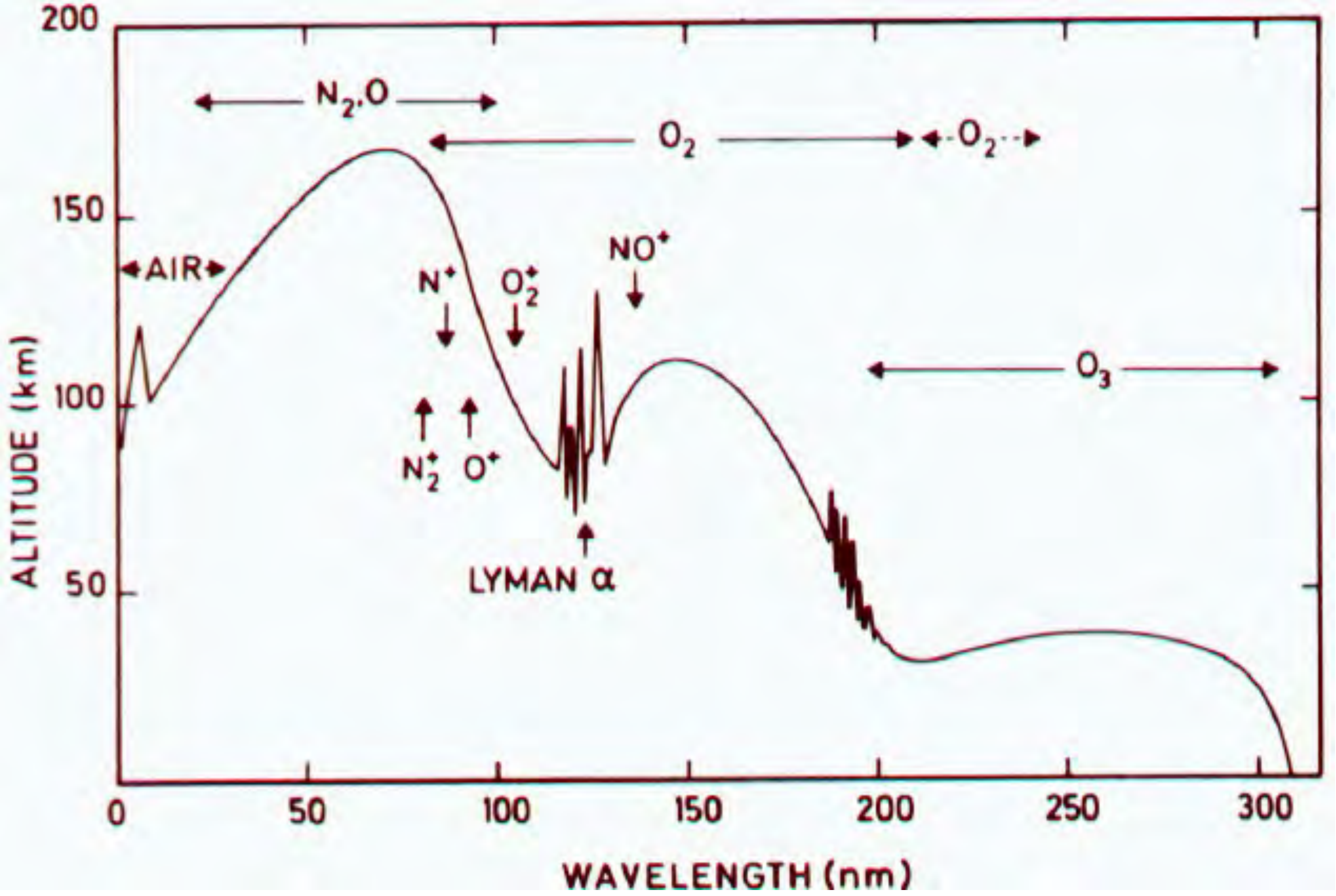
$$n(z) = n(z_0)e^{-\frac{z-z_0}{H}} \qquad H = \frac{kT}{mg}$$

- K is the Boltzmann constant: $1.38 \times 10^{-23}$ J/K
- g is the gravitational acceleration: 9.8 m/s$^2$
- T is the neutral temperature in Kelvin and m is the neutral mass in Kg.

# Absorption of Solar Radiation

- Dissociates molecular gases into atomic gases
- Heats the atmospheric gases
- Ionizes atmospheric gases to produce the ionosphere

Photodissociation due to absorption of solar photons gives different neutral constituents in the upper atmosphere than those in the lower atmosphere.



# Photodissociation

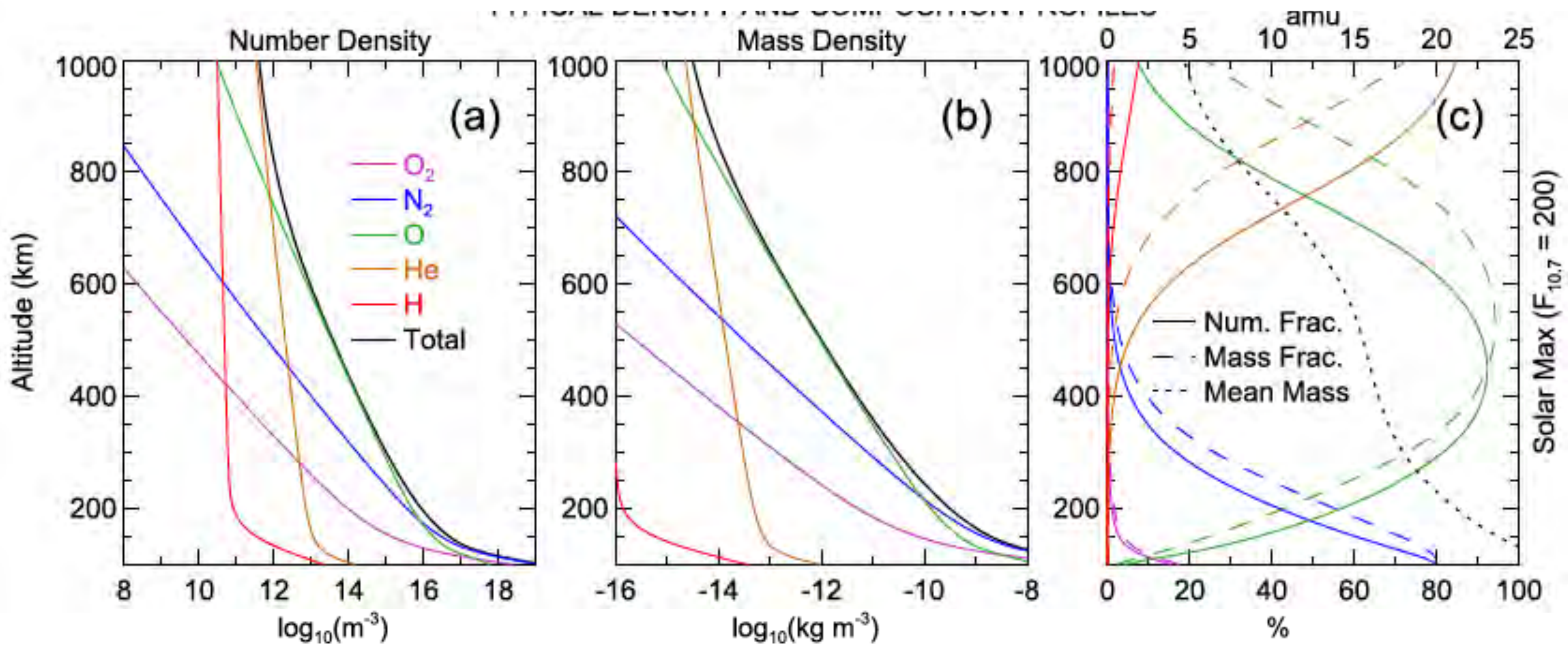
- Photodissociation is a chemical reaction in which a chemical compound is broken down by photons.
- The radiation dissociates the molecular species of $O_2$ and $N_2$ into atomic species of O and N, thus changing the composition of the thermosphere from a molecular atmosphere near the mesopause around 85 km to an atomic atmosphere.
- O, N, H in the thermosphere are created due to photodissociation.

$$O_2 + h\nu \rightarrow O + O$$
~5.12 eV

$$N_2 + h\upsilon \rightarrow N + N$$
~9.8 eV

$$H_2O + h\upsilon \rightarrow H + OH$$
$$OH + h\upsilon \rightarrow O + H$$
~4.77 eV for each bond between O-H

# Typical Thermosphere Density and Composition Profiles



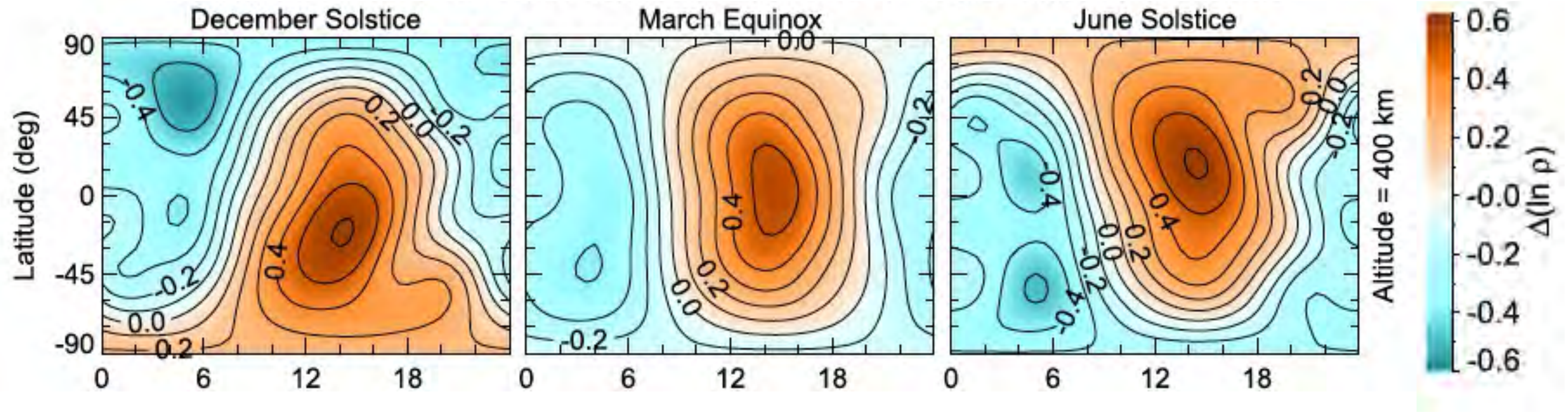

(a) Global average number density profiles at solar maximum (F10.7 = 200 solar flux units from the NRLMSISE-00 empirical model.

(b) Corresponding mass density profiles for each species.

(c) Number mixing ratios (solid lines) and mass mixing ratios (dashed lines) for each species.

From Emmert, 2015, Advances in Space Research.

# Typical Thermosphere Density Variation

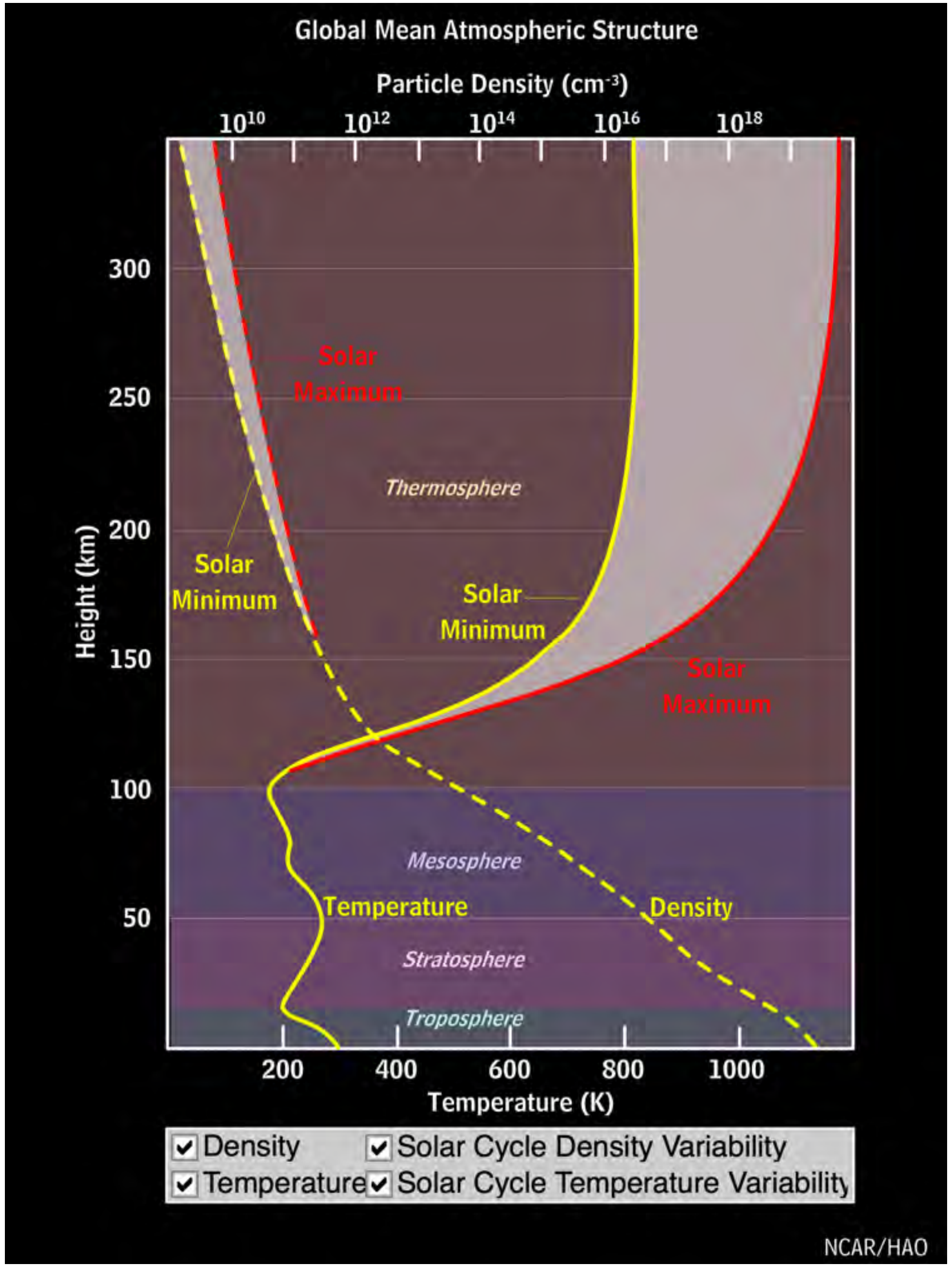



- Solar EUV and FUV irradiance is the primary heating source for the thermosphere (Roble, 1995 ), and its variation with local time and latitude (including its absence on Earth's night side) produces large variations in thermospheric density at fixed altitudes according to NRLMSISE-00.
- At 400 km the density variation shows a predominately diurnal character, with peak density at 14–15 local time (LT) at the subsolar latitude. Minimum density occurs near 05 LT in the winter hemisphere.

- From Emmert, 2015, Advances in Space Research.

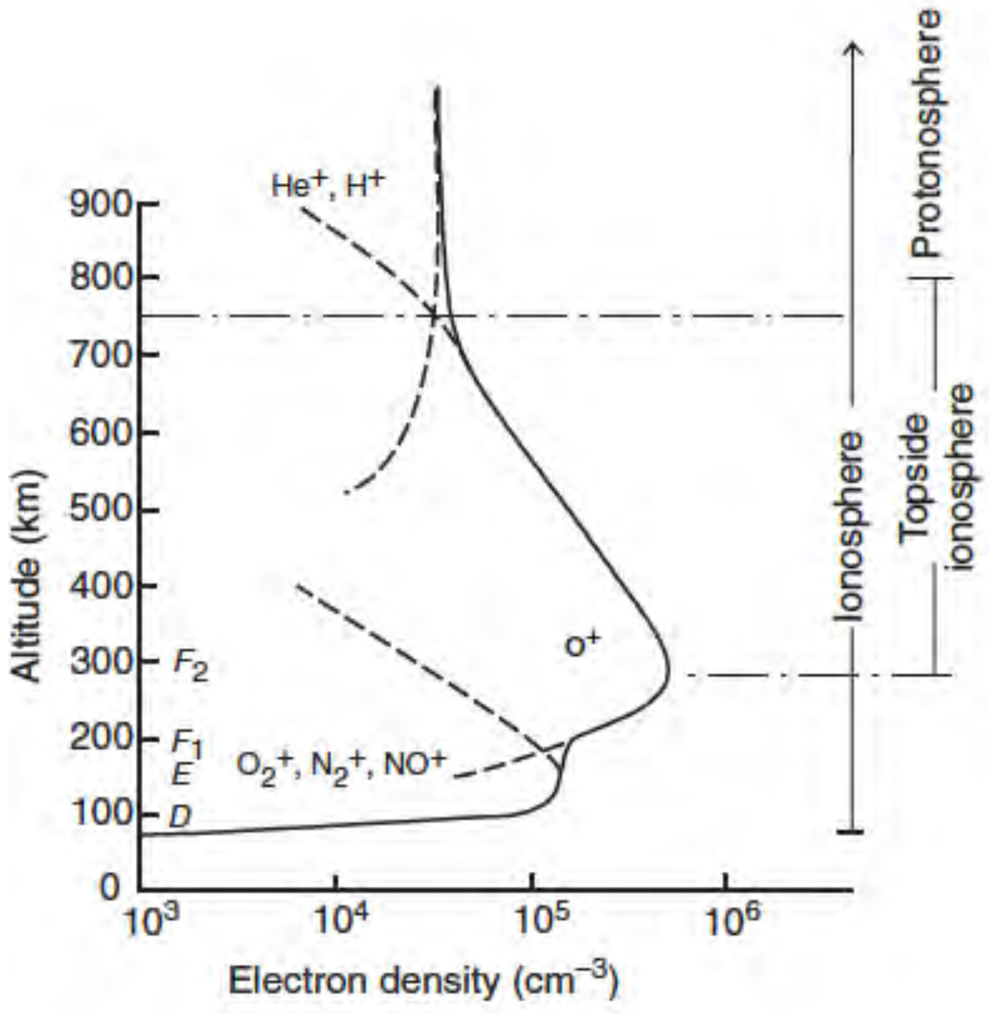
# Solar Cycle Variability of Thermosphere

- Near the bottom of the thermosphere (~100 km), the neutrals are well mixed and have the same rate of decreasing.
- Above this height, the neutral densities decrease according to their own scale height.
- During solar maximum, the solar radiation is higher than that during solar minimum. So the thermosphere temperature is higher and the scale height is larger, and then the neutral density is higher.



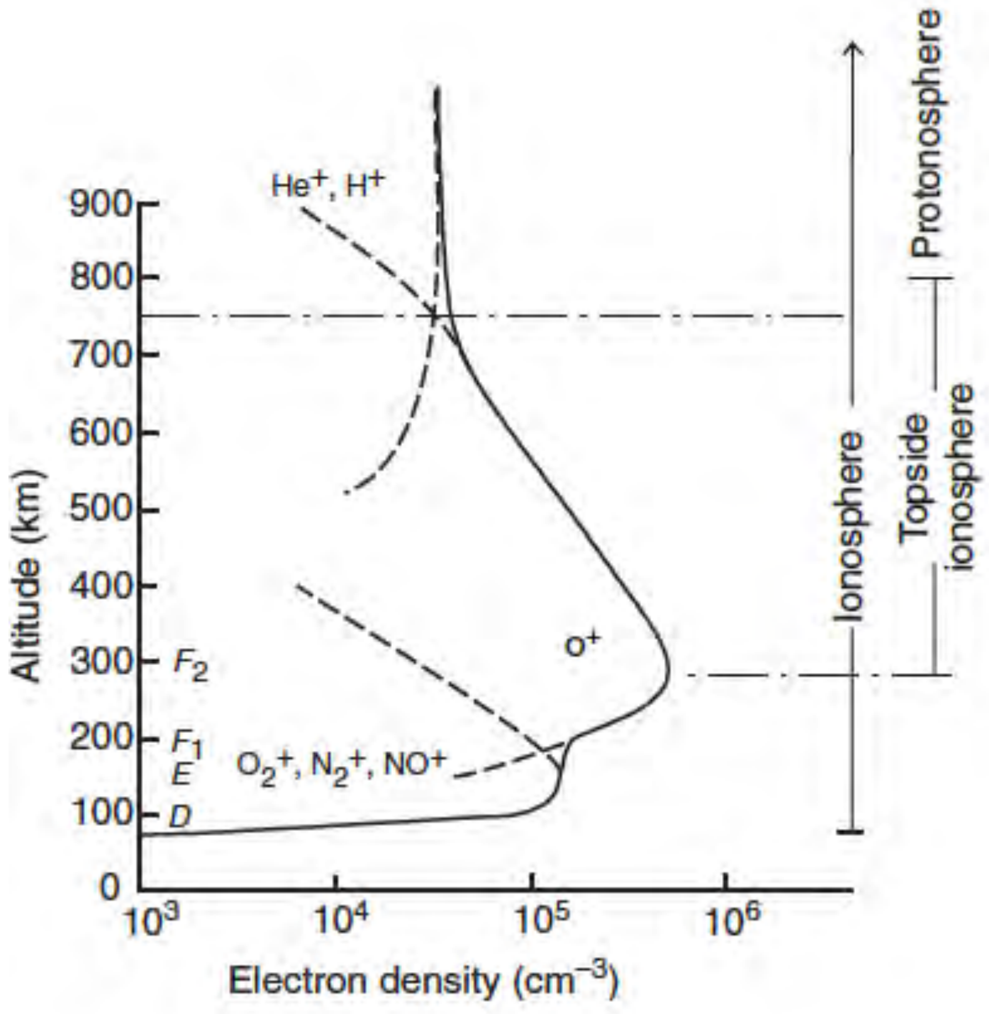
# The Earth's Ionosphere

- The ionosphere is the ionized portion of the upper atmosphere and horizontally stratified into different layers.
- It extends from about 60 to beyond 1000 km and completely encircles the Earth but with considerable spatial/temporal variations.
- Most important processes in different layers:
  - Topside/plasmasphere: plasma transport
  - F layer: plasma transport/chemical loss processes
  - D-E layer: chemical processes



# The Earth's Ionosphere

- The F2 layer possess the largest plasma density and is the most important layer for radio wave propagation.
  - **NmF2**: peak density of the F2 layer
  - **hmF2**: peak height of the F2 layer
- **Total electron content (TEC)**: integral of the electron density within a column of unit area between the receiver and the transmitter, such as GPS receiver and the GPS satellite. Important parameters to characterize the ionosphere plasma content.
- The most abundant ion in terrestrial ionosphere is $O^+$ in the F2 layer and molecular ions ($O_2^+$ and $NO^+$) in the E layer.

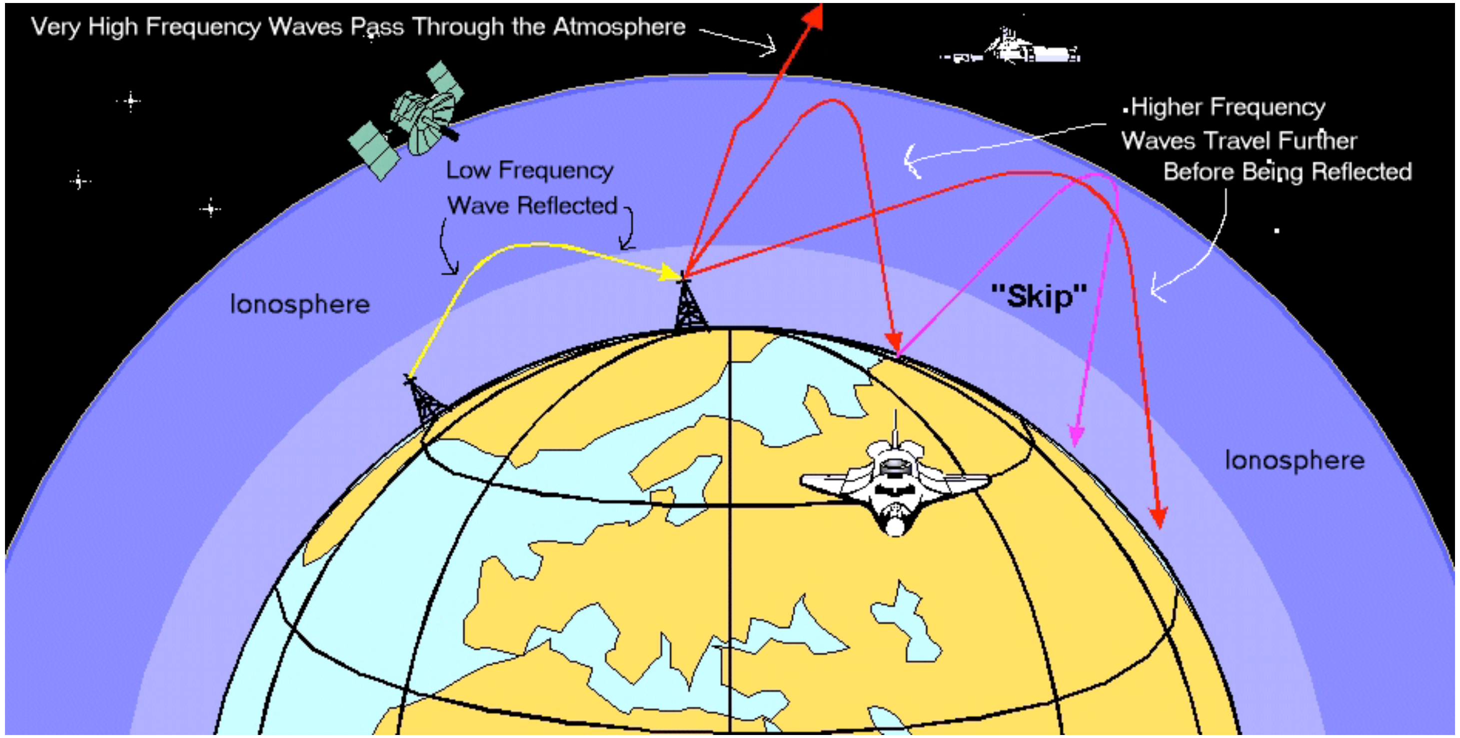


# The ionosphere and Radio Wave Propagation

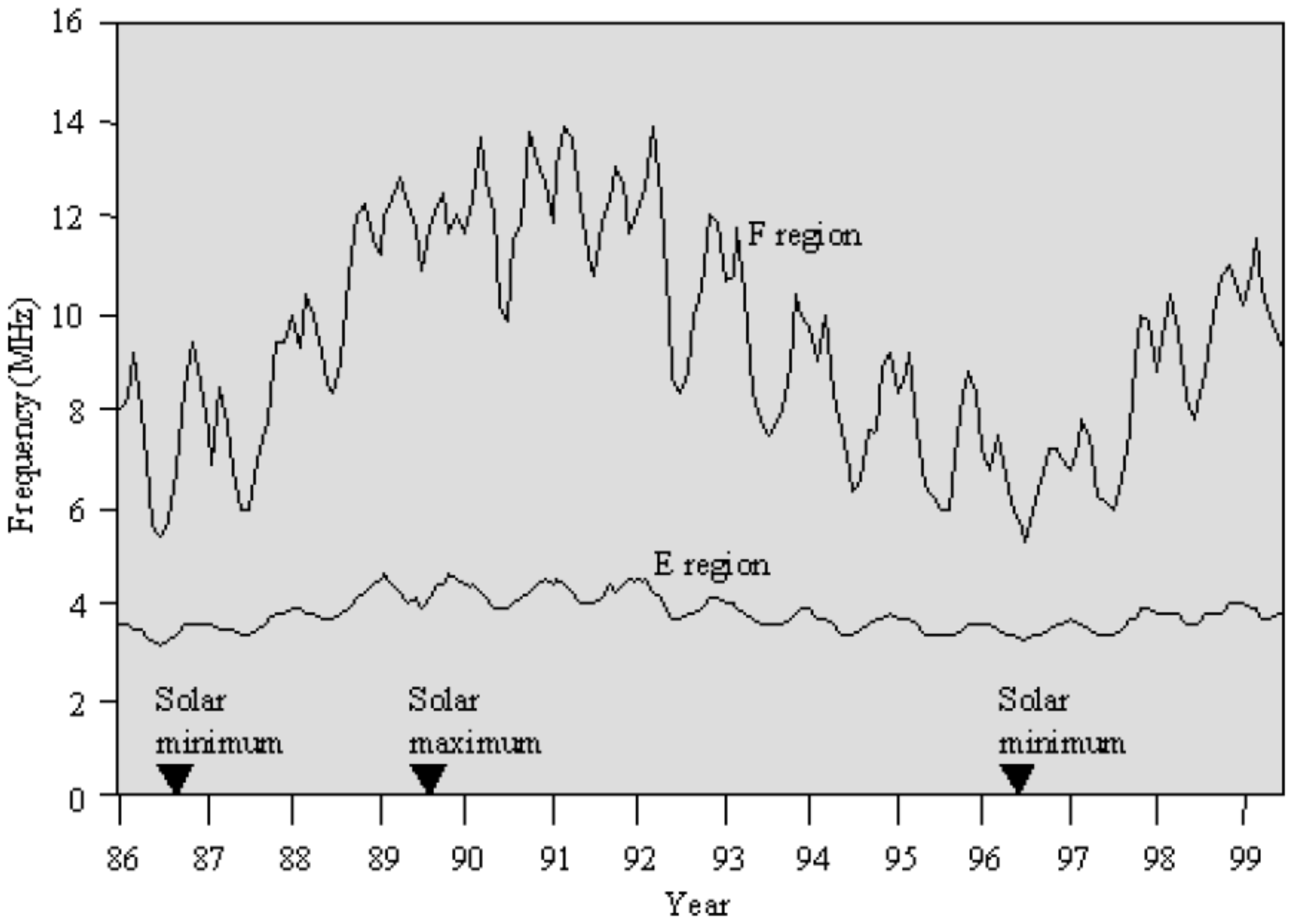
- **Plasma frequency $f_0$**: The natural resonant frequency of a plasma oscillation, equal to the minimum frequency of electromagnetic waves that can travel through the plasma without attenuation.
- EM waves reflect at the location where the plasma frequency equals the wave frequency.
- This is usually referred to as critical frequency.

$$f_0 = 9\sqrt{10^{-6} n_e}$$

($f_0$ in megahertz, $n_e$ in cm$^{-3}$)



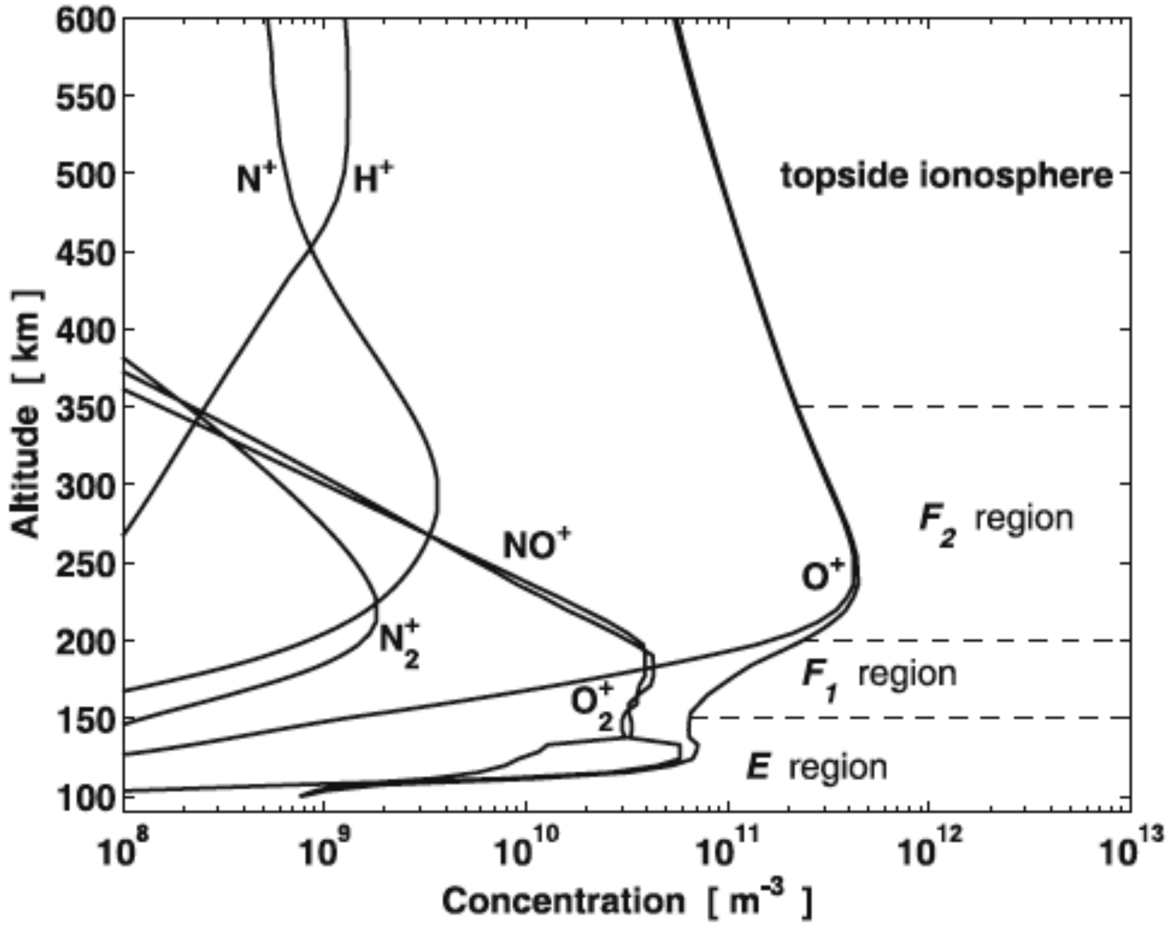
# A time series of critical frequency




- Time series of ionosphere E and F region critical frequencies measured by ionosonde are shown above.
- What trends can you see?

# Ionosphere Composition

- The E layer is from 90 km to 150 km and is due to soft X-ray (1–10 nm) and far ultraviolet (UV) solar radiation ionization of molecular species. In the auroral zone, particle precipitations also can ionize neutrals here.
- The $F_1$ layer is the lower sector of the F layer and exists from about 150 to 220 km. It is composed of a mixture of molecular ions $O_2$+ and NO+, and atomic ions O+.
- In $F_2$ layer, the O+ atomic ions become the most abundant species.



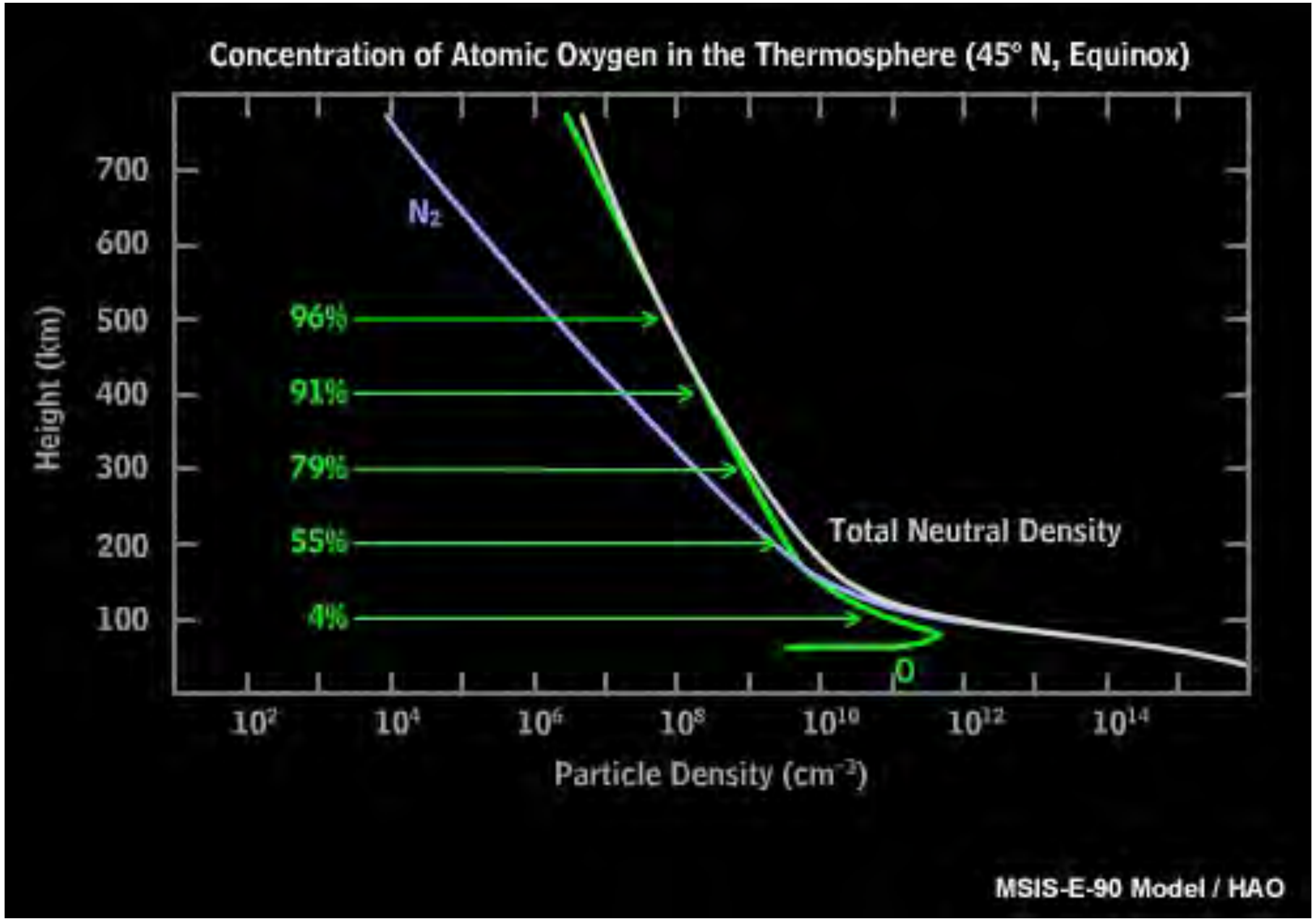
# Chemistry in different ionosphere layers

| | Major source | Major loss | |
|---|---|---|---|
| E and F1 layer | $N_2 + h\nu \rightarrow N_2^+ + e$ | $N_2^+ + O \rightarrow NO^+ + N$<br>$e + N_2^+ \rightarrow N + N$<br>$NO^+ + e \rightarrow N + O$ | Equilibrium determined by photoproduction and chemical loss |
| | $O_2 + h\nu \rightarrow O_2^+ + e$ | $e + O_2^+ \rightarrow O + O$ | Equilibrium determined by photoproduction and chemical loss |
| F2 layer | $O + h\nu \rightarrow O^+ + e$ | $O^+ + N_2 \rightarrow NO^+ + N$<br>$NO^+ + e \rightarrow N + O$ | Equilibrium determined by photoproduction and diffusion |

**Why O/$N_2$ ratio important?**

The production of ionization depends largely on the [O] density, while chemical loss is determined by the abundance of $N_2$ and, to lesser degree, $O_2$.

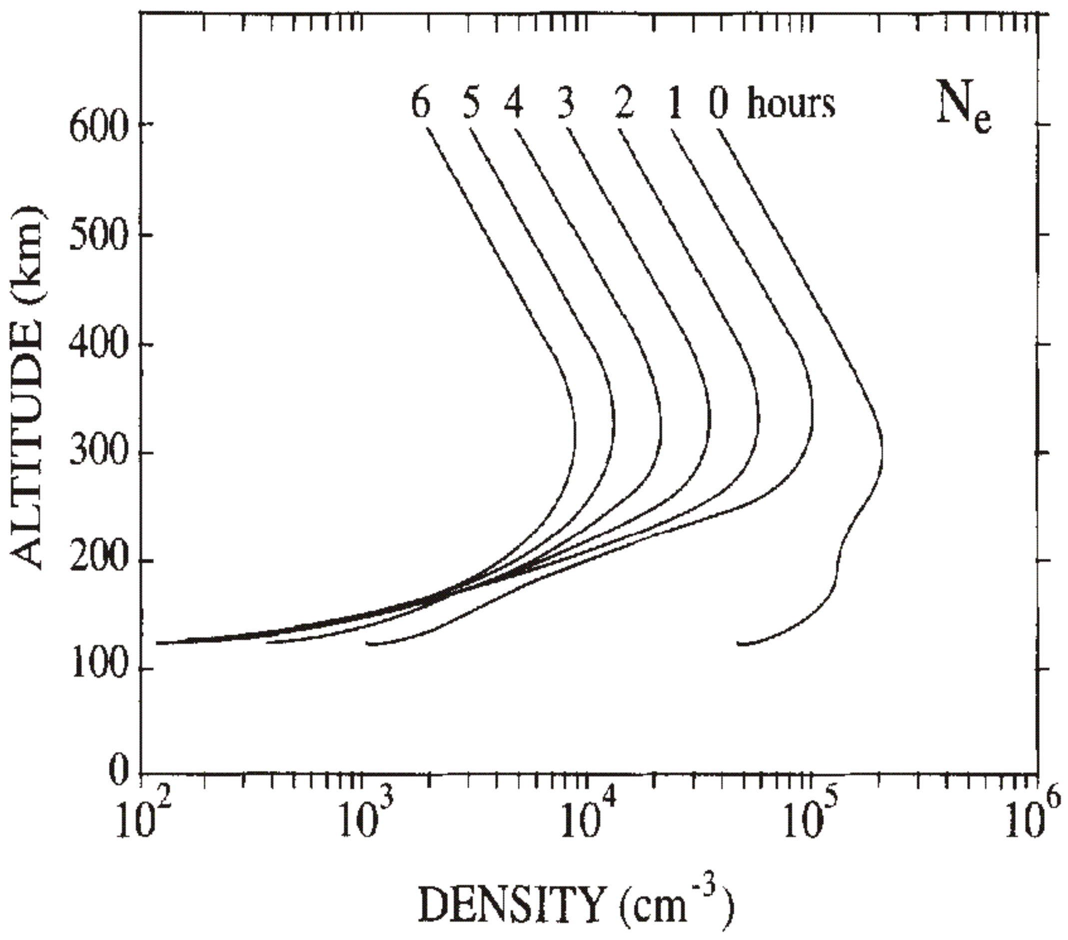
# Ratio of atomic oxygen in the thermosphere



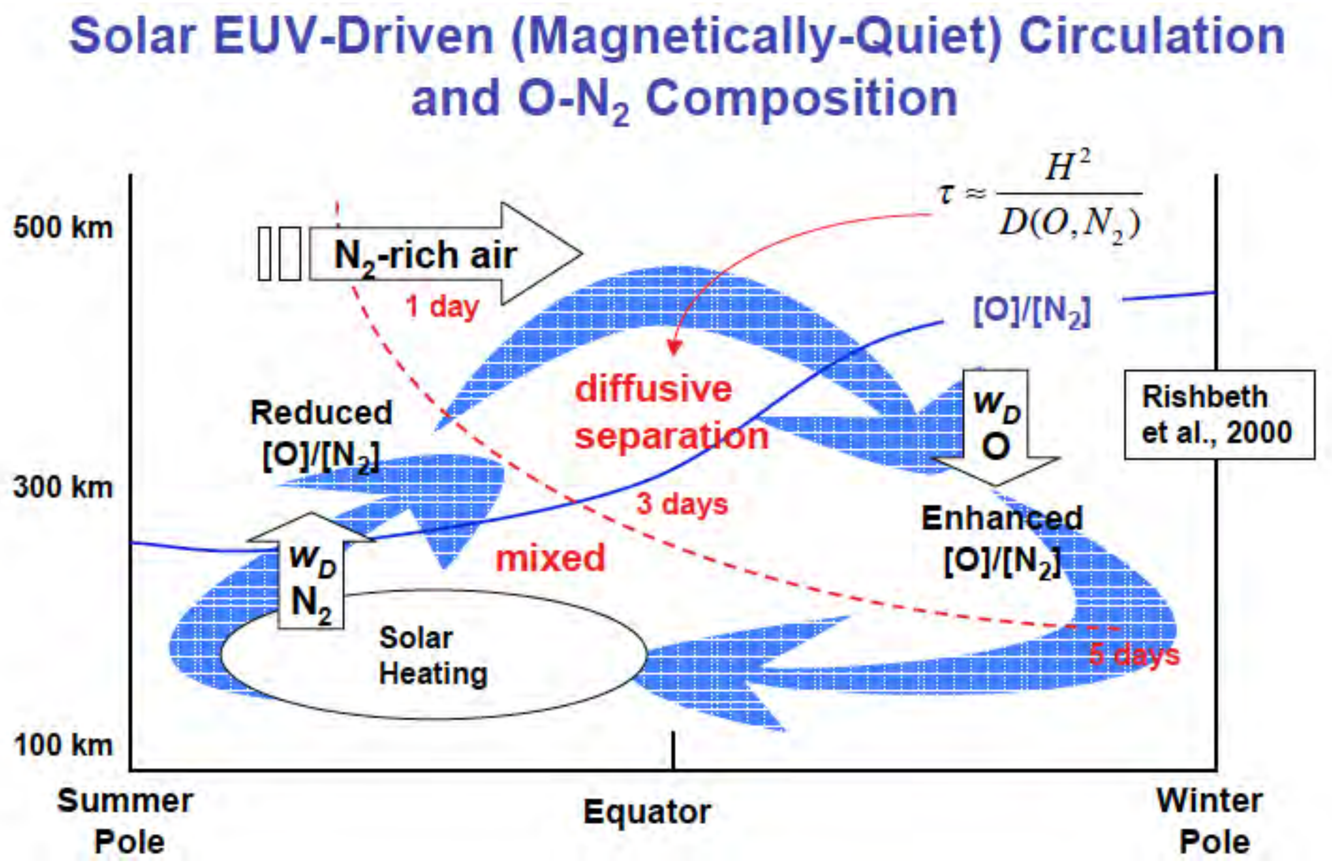
# Evolution of electron density due to chemical loss

- This figure shows calculated electron density profiles (Ne) at selected times after photoionization is set to zero.

- It shows the different time scales of evolution due to chemical losses at different altitudes.



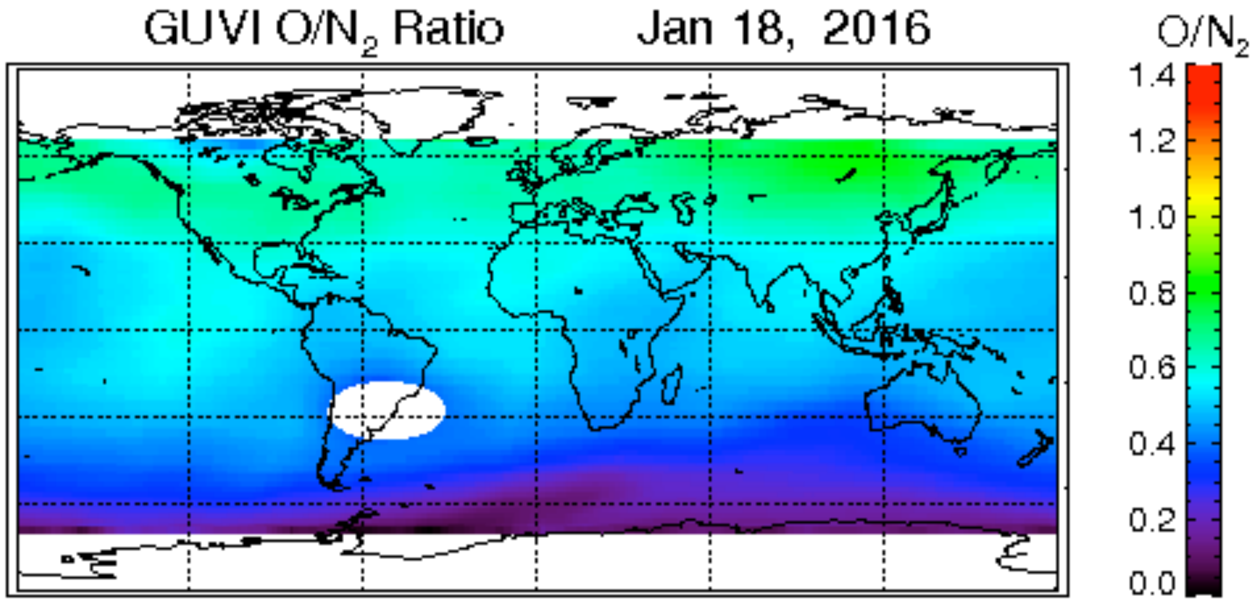
# Solar EUV-Driven Circulation during Magnetically Quiet Times



# Quiet day $O/N_2$ ratio

- The thermospheric column number density ratio of O and $N_2$ referenced at $N_2$ column number density level of $10^{17}$ $cm^{-2}$

- Seasonal thermosphere composition changes can be seen



# Plasma thermal structure

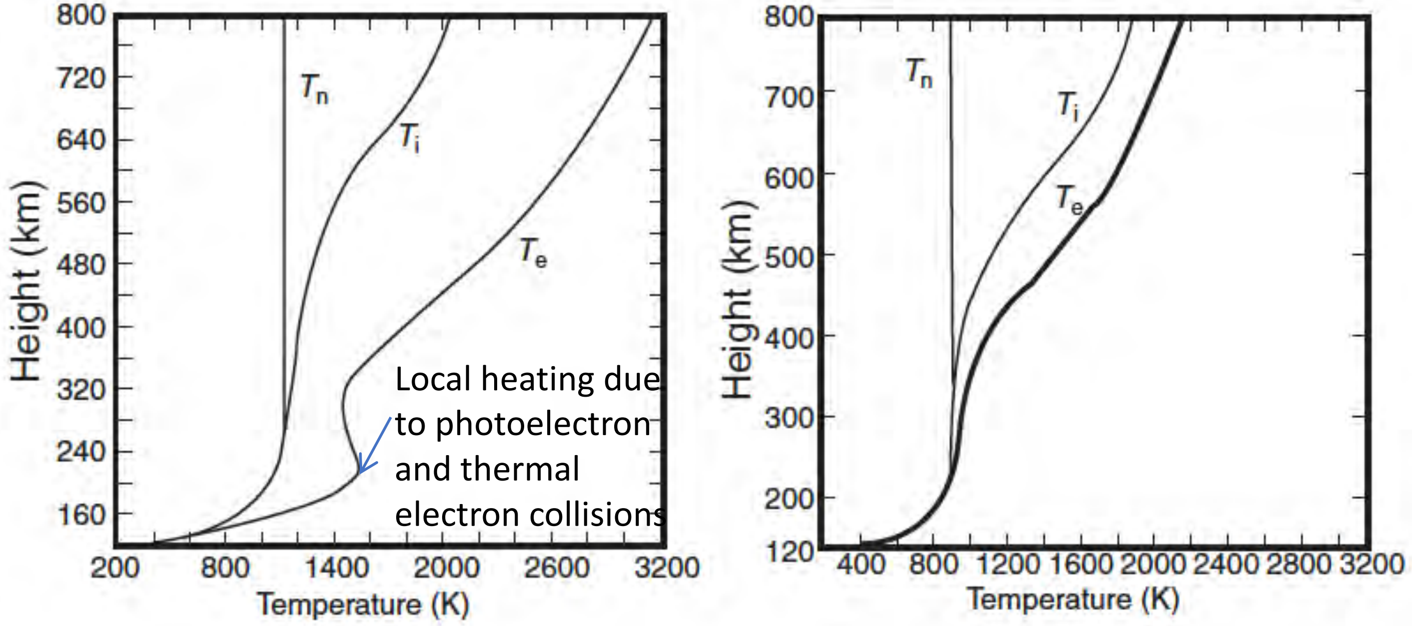



**Figure 11.17** Calculated electron, ion, and neutral temperature profiles for the ionosphere over Millstone Hill on March 23–24, 1970. The left panel is for 1422 LT and the right panel for 0222 LT.[22]

# Diurnal variation at mid-latitudes

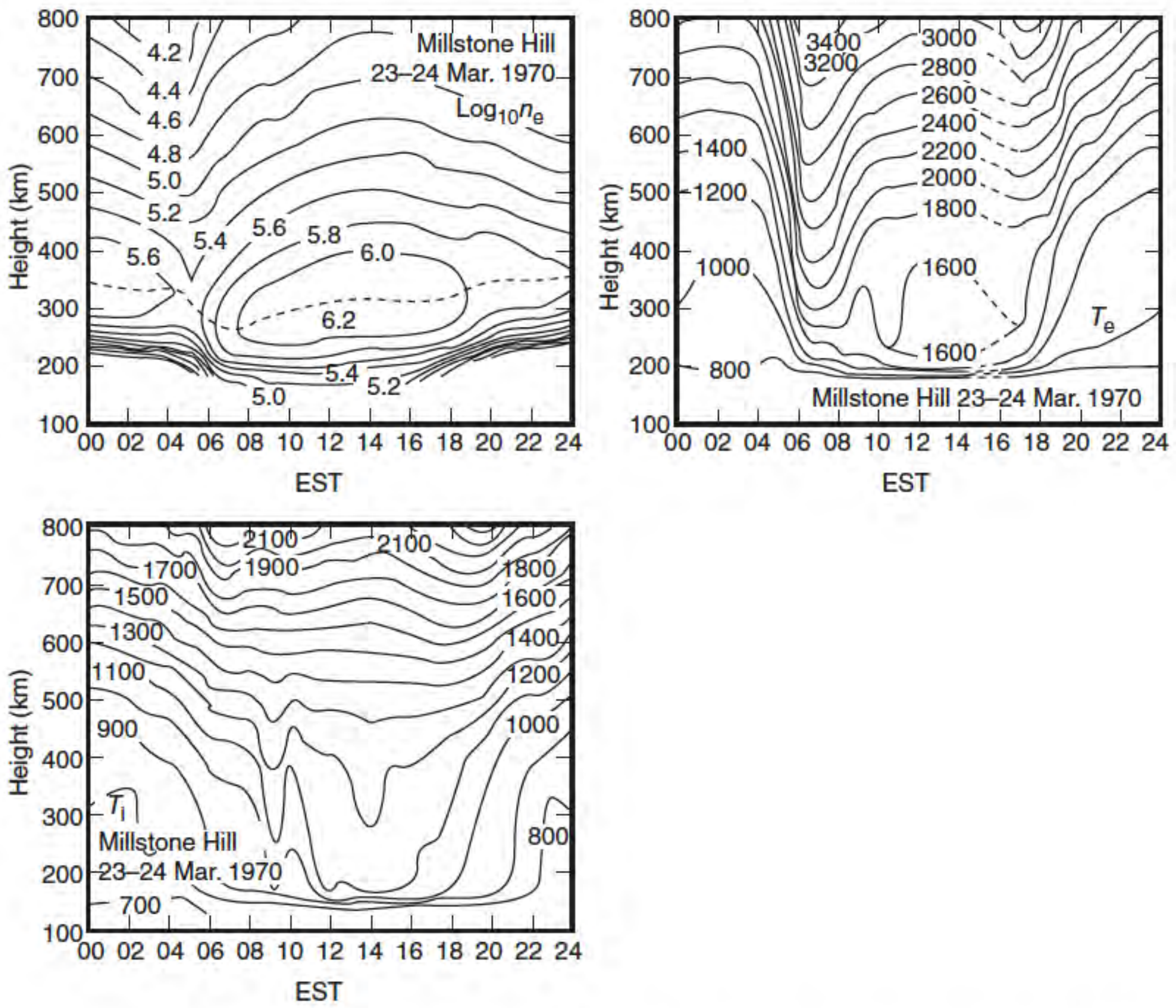



**Figure 11.20** Contours of electron density (top left), electron temperature (top right), and ion temperature (bottom) measured by the Millstone Hill incoherent scatter radar on 23–24 March 1970.[28] $n_e$ is in $\mathrm{cm}^{-3}$ and the temperatures are in K.

# Seasonal variation at mid-latitudes

- The ionosphere's seasonal variation is related to a solar zenith angle change and thermospheric wind pattern change.
- The O/N2 ratio in the winter hemisphere is higher than that in the summer hemisphere.
- The O+ densities in winter are therefore larger than those in summer at F region altitudes. In turn, the higher electron densities in winter result in lower electron temperatures owing to the inverse relationship between the electron density and temperature. This is called **winter anomaly**.

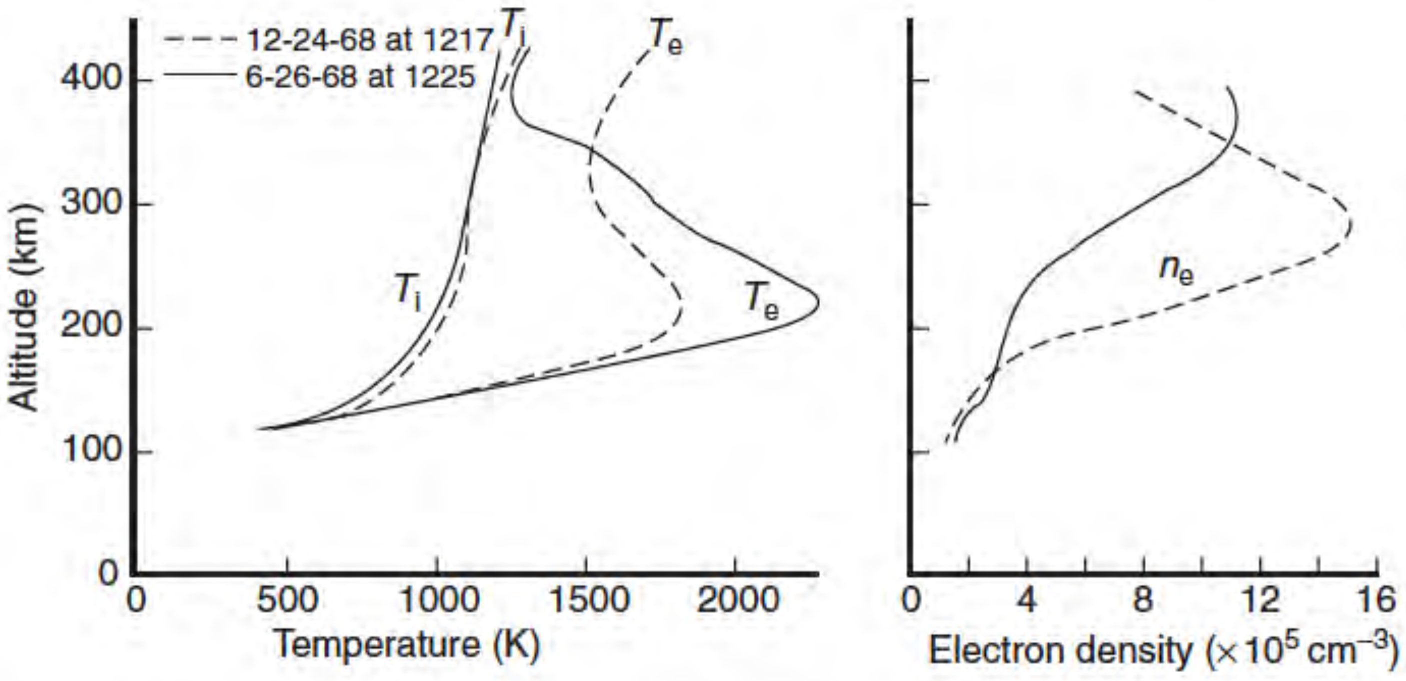



**Figure 11.21** Summer (solid curves) and winter (dashed curves) profiles of $T_e$, $T_i$, and $n_e$ measured by the Arecibo incoherent scatter radar during the daytime.[29]

# Solar cycle variation at mid-latitudes

- At solar maximum, the solar EUV fluxes and the O densities are greater than those at solar minimum, and these conditions lead to higher electron densities and lower electron temperatures.
- The lower electron temperatures are a result of the inverse relationship between the electron density and temperature.

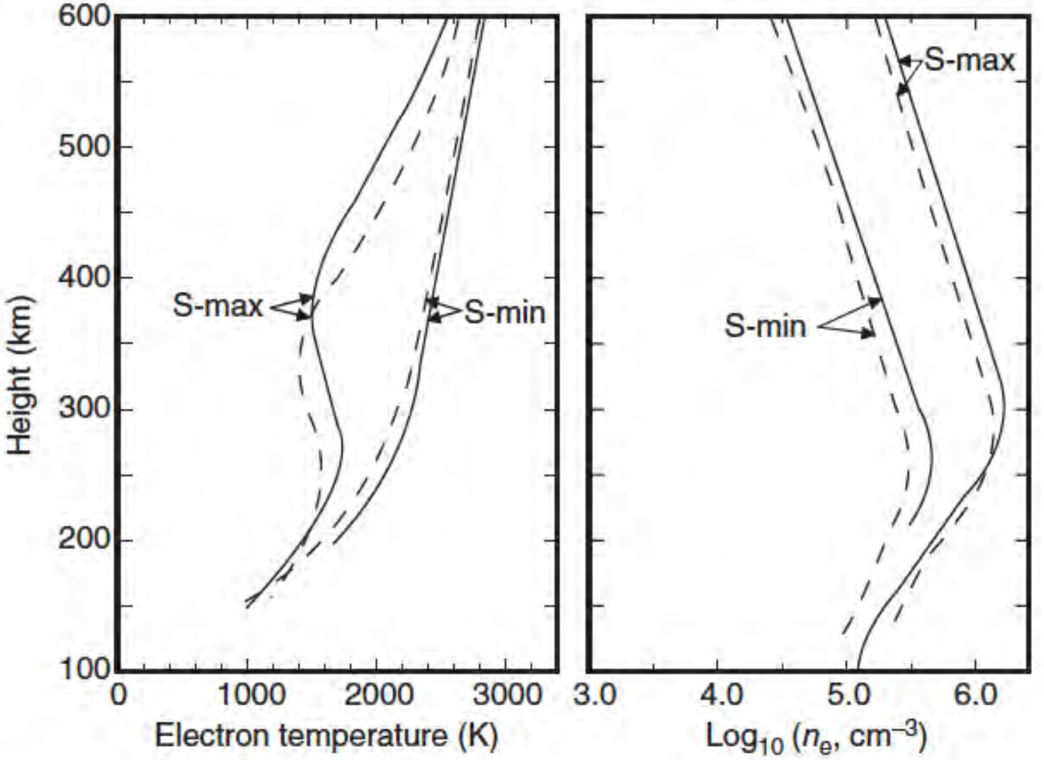



**Figure 11.22** Electron temperature and density profiles for the daytime mid-latitude ionosphere at equinox for both solar minimum and maximum conditions. The solid curves are profiles measured by the Millstone Hill incoherent scatter radar, while the dashed curves are calculated.[30]