Terrestrial Ionospheres

I

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Outline

This presentation will briefly describe the ionospheres of Earth, Venus, and Mars; explain how ions are produced and destroyed; and offer a hypothesis for why these terrestrial planet ionospheres differ in fundamental aspects.

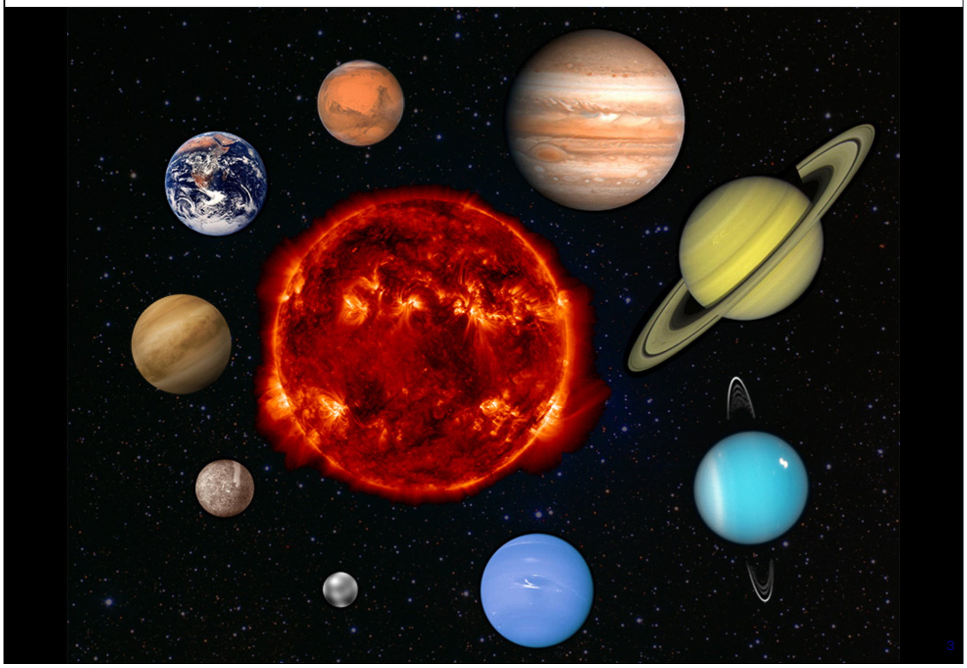
Part I:

- Introduction to Earth's ionosphere
- Overview of Earth's atmosphere
- Ionization processes
- Chemical processes

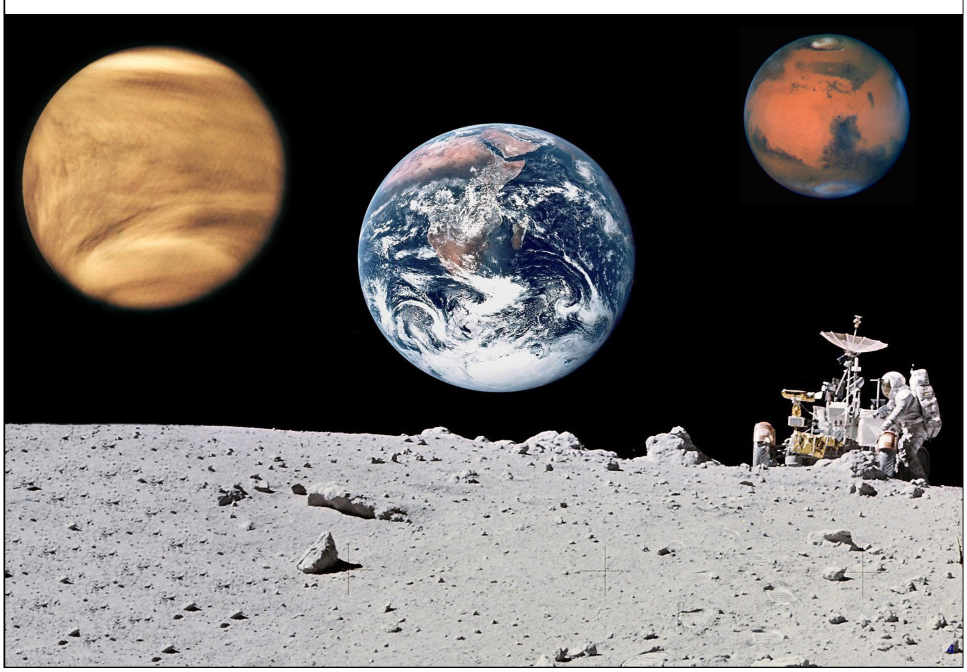
Part II:

- Ionospheres of Mars and Venus
- Atmospheres of Mars and Venus
- Why is Earth so different?

Planets that have Atmospheres Must Also Have Ionospheres



The Terrestrial Planets (that have atmospheres)



Motivating Questions

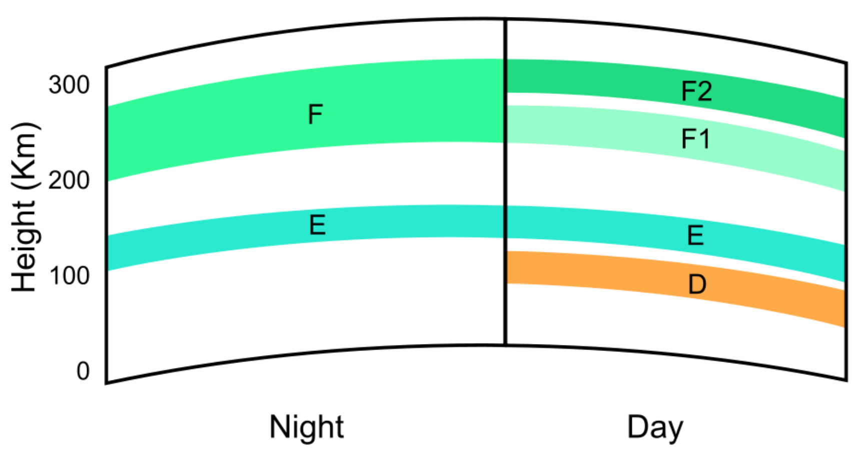
• Why does the ionosphere occur in “layers?”

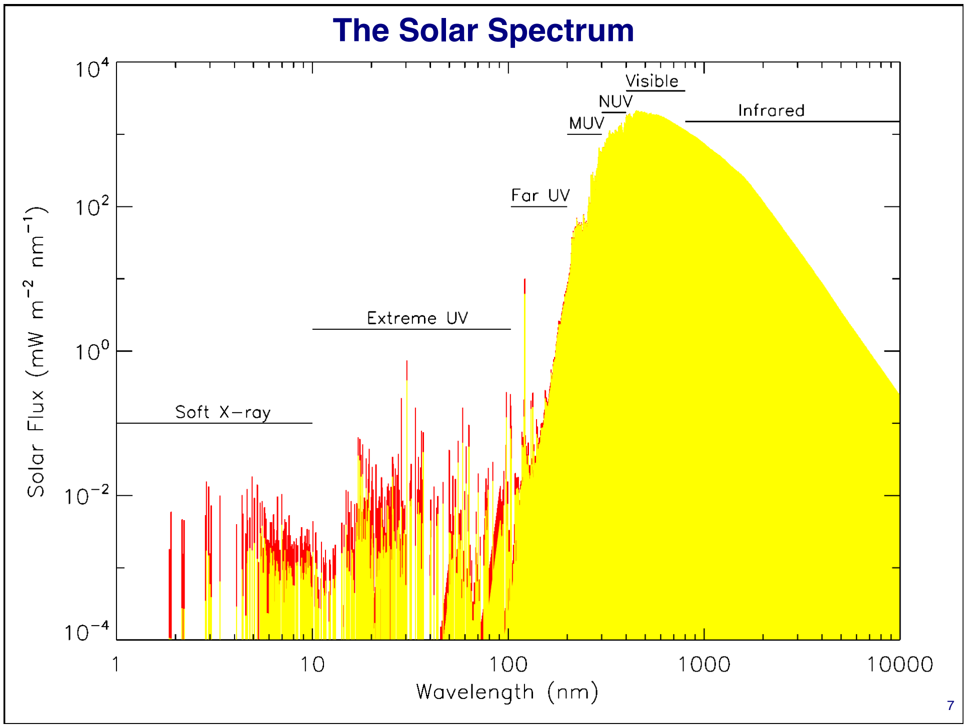
• Since the Earth’s ionosphere is produced mostly by solar radiation, why does it persist at night?

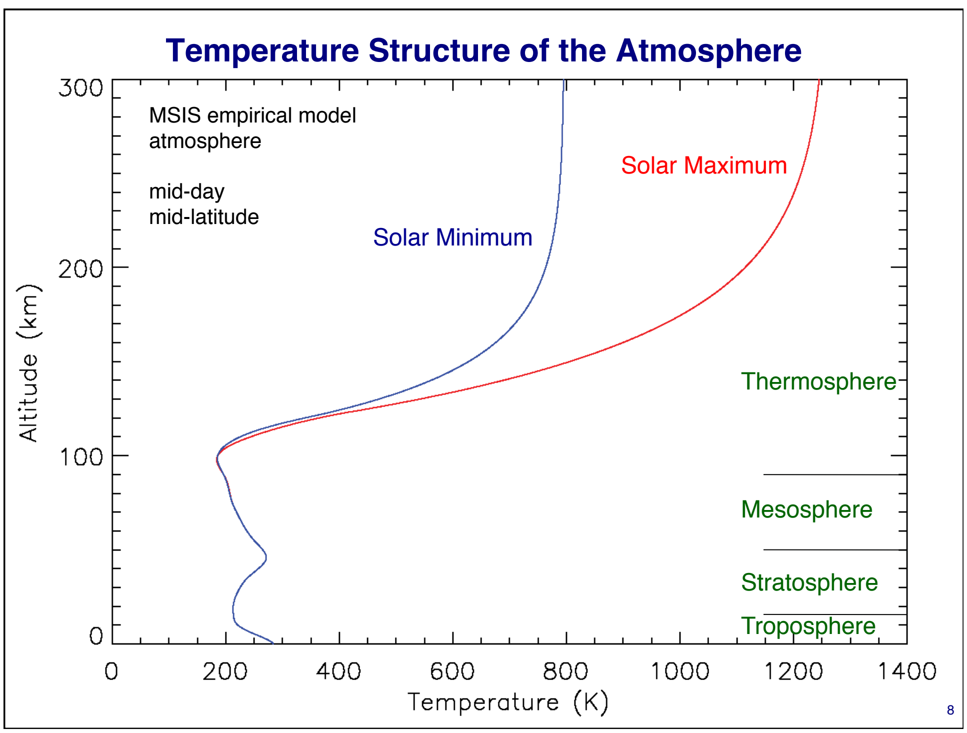
• Since most ionization occurs between 100 to 200 km in altitude, why is most of the ionosphere above 300 km altitude?

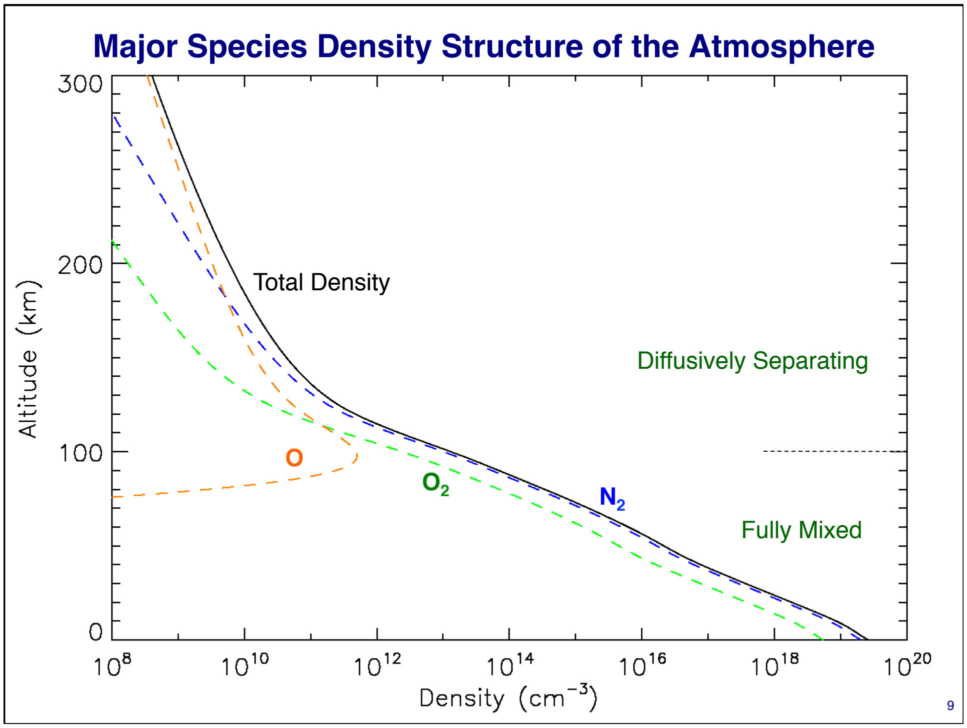
• Why are the ionospheres of Venus and Mars so different from Earth’s?

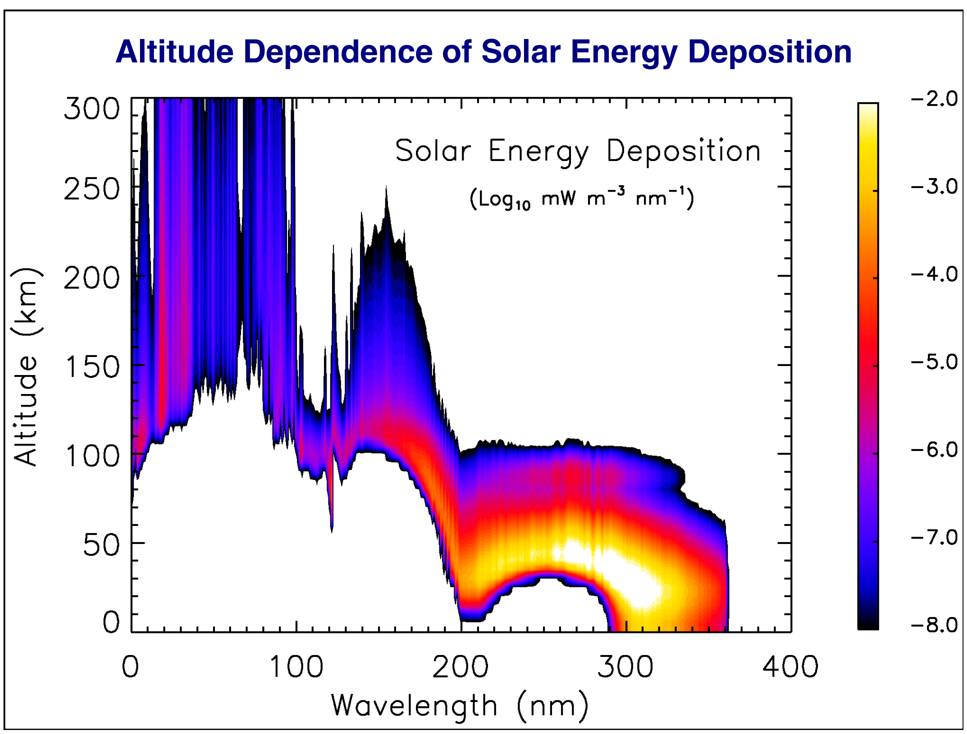
“Layers” in the Ionosphere



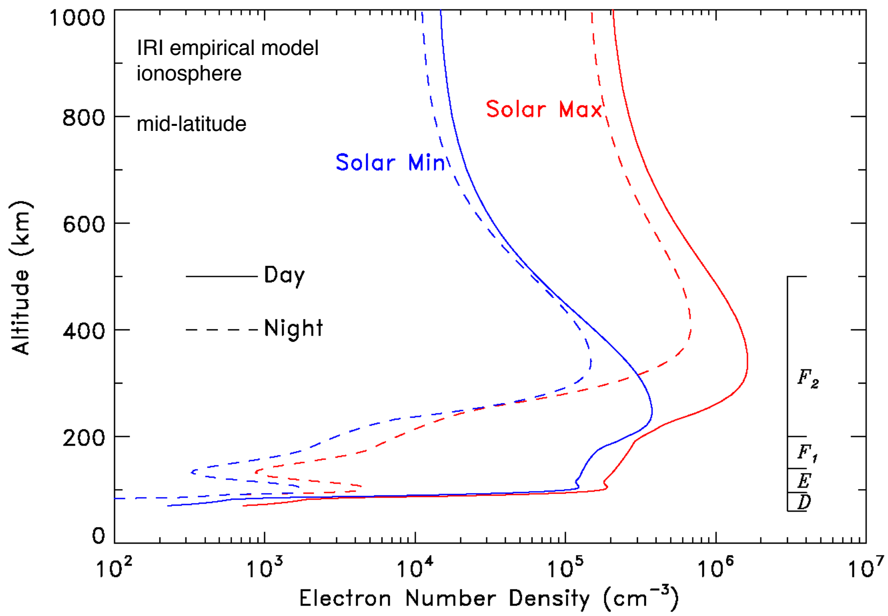

The Solar Spectrum
Solar Flux (mW m^-2 nm^-1)
Wavelength (nm)
Soft X-ray
Extreme UV
Far UV
MUV
NUV
Visible
Infrared
7


Temperature Structure of the Atmosphere
MSIS empirical model
atmosphere
mid-day
mid-latitude
Solar Minimum
Solar Maximum
Thermosphere
Mesosphere
Stratosphere
Troposphere
Altitude (km)
Temperature (K)
8


Major Species Density Structure of the Atmosphere
Altitude (km)
Density (cm^{-3})
Total Density
Diffusively Separating
Fully Mixed
O
O_2
N_2
9


Altitude Dependence of Solar Energy Deposition
Solar Energy Deposition
(Log_{10} mW m^{-3} nm^{-1})
Altitude (km)
Wavelength (nm)

Ionosphere Basic Altitude Structure



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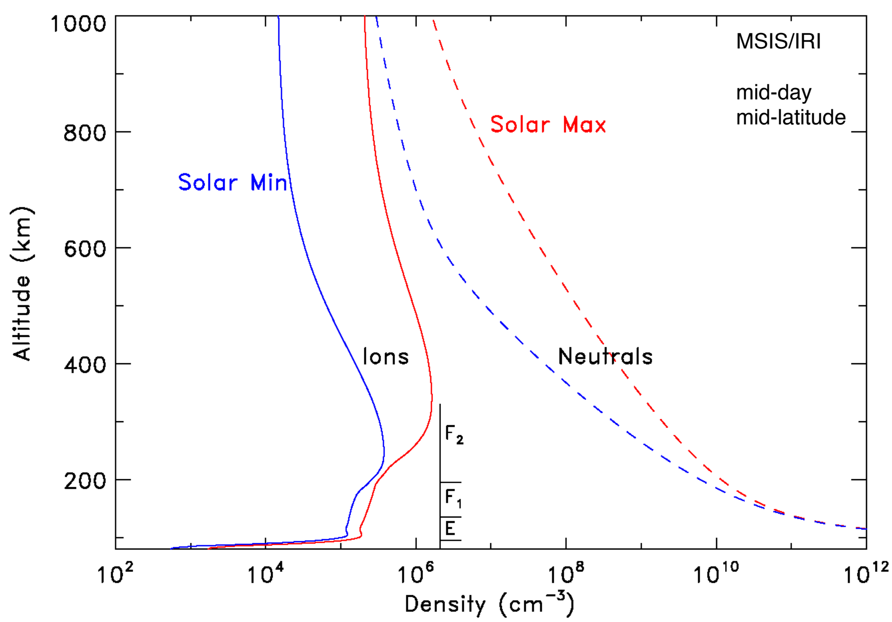
Thermosphere-Ionosphere Variability



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Atmospheric Distribution in Hydrostatic Equilibrium

Pressure gradient: $$\frac{dp}{dz} = -g(z)\rho$$ (height derivative of pressure equals acceleration of gravity times density)

Perfect gas law: $$p = nkT = \frac{\rho}{M}kT$$ *M* is the mean molecular mass

If *g* and *T* are not functions of *z*, then: $$\frac{dp}{dz} = -p\frac{Mg}{kT} = -\frac{p}{H}$$ where *scale height* $H = \frac{kT}{Mg}$

$$\frac{dp}{p} = -\frac{dz}{H}$$

"law of atmospheres": $$p(z) = p(z_0)\exp\left[-\frac{z-z_0}{H}\right]$$

In diffusive separation: $$n_j(z) = n_j(z_0)\exp\left[-\frac{z-z_0}{H_j}\right]$$ where $H_j = \frac{kT}{M_j g}$

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At what Altitude is Energy Deposited in an Atmosphere?

Controlled by *cross sections* of atmospheric gases for absorption (σ) or ionization (σ_i).

Which are in general a function of wavelength (λ).

For a single-species, plane-parallel atmosphere, at any particular λ:

Ionization Rate = (radiation intensity) x (ionization cross section) x (density)

$$q(z) = q_z = I_z \sigma_i n_z$$

Beer's law: $I_z = I_\infty \exp(-\tau_z)$

where $\boldsymbol{\tau_z}$ is the *optical depth*: $$\tau_z = \frac{\sigma N_z}{\mu} = \frac{\sigma n_0 H}{\mu}\exp\left[-\frac{z-z_0}{H}\right]$$

and $\boldsymbol{\mu}$ = cos (*solar zenith angle*)

$$q_z = I_\infty \exp(-\tau_z)\sigma_i n_0 \exp\left[-\frac{z-z_0}{H}\right]$$

$$q_z = I_\infty \sigma_i n_0 \exp\left[-\frac{z-z_0}{H} - \tau_z\right]$$

This expression (due to Sidney Chapman) is known as the ***Chapman Function***.

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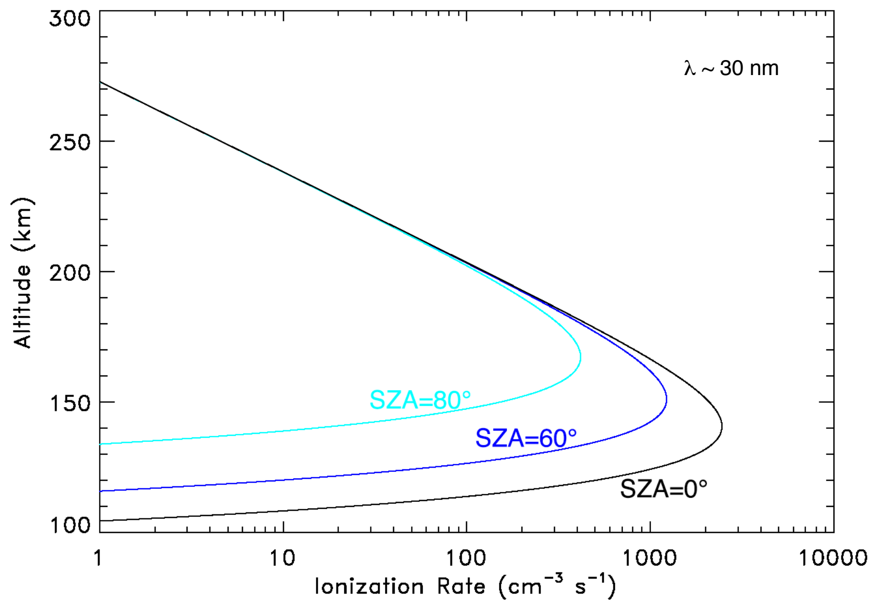
Typical Chapman Function



Deposition of energy by a Chapman Function causes a Chapman "Layer."

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Where is the Peak of a Chapman Function?

$$q_z = I_\infty \sigma_i n_0 \exp\left[-\frac{z - z_0}{H} - \tau_z\right]$$

$$\frac{dq_z}{dz} = I_\infty \sigma_i n_0 \left[-\frac{1}{H} + \frac{\tau_z}{H}\right] \exp\left[-\frac{z - z_0}{H} - \tau_z\right] = 0$$

$$-\frac{1}{H} + \frac{\tau_z}{H} = 0$$

$$\tau_z = 1$$

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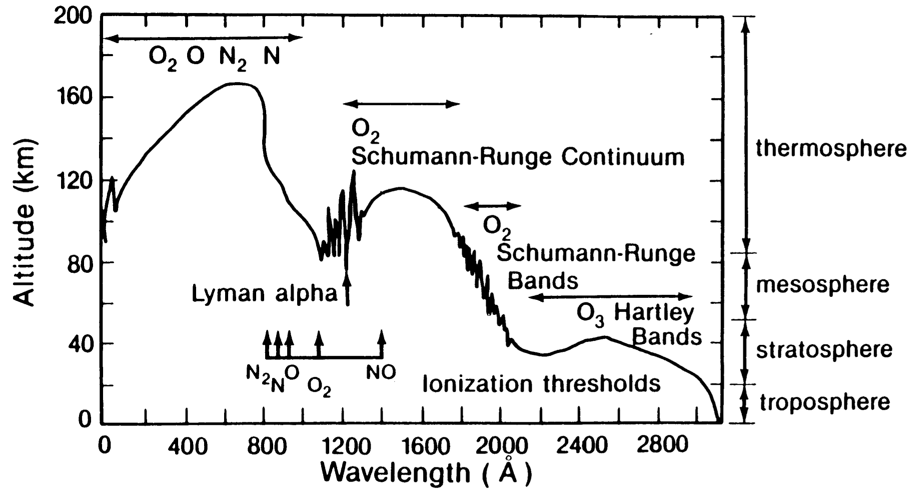
Plot of the Altitude at which Solar Photon Optical Depth = 1



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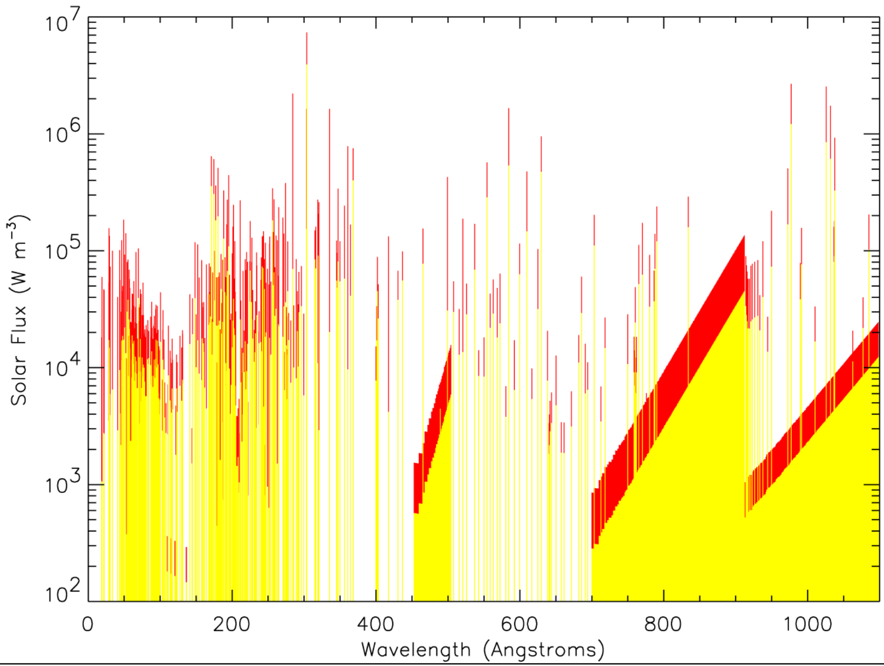
Solar Extreme-Ultraviolet and Soft X-ray Spectrum



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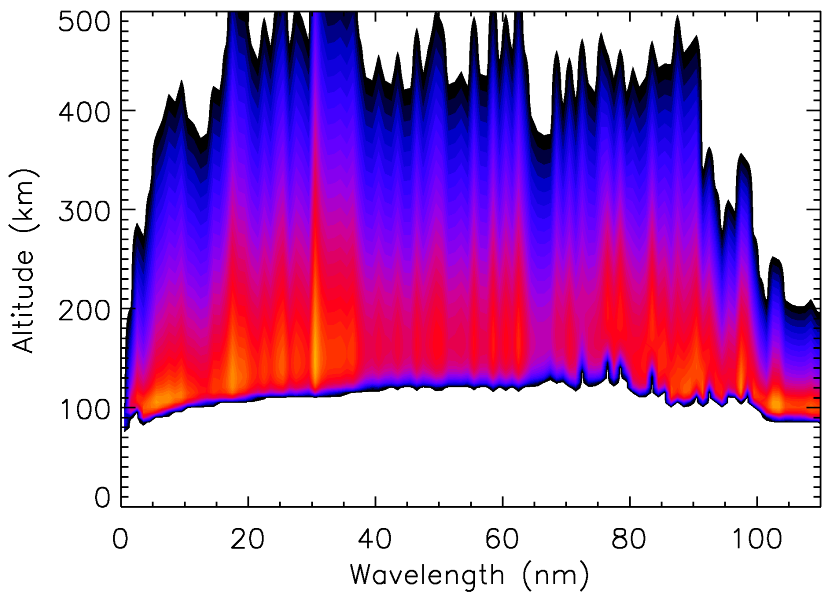
Wavelength-Dependence of Ionization Rates (solar min)



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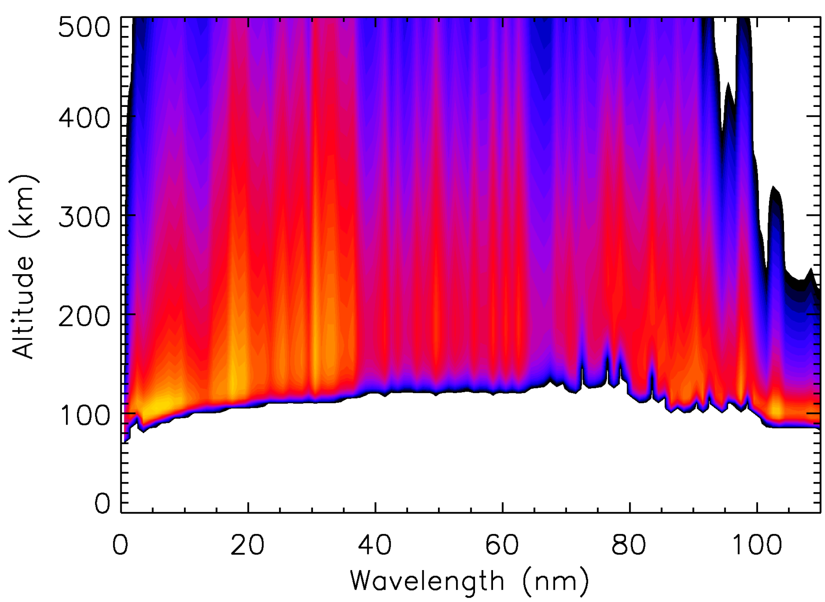
Wavelength-Dependence of Ionization Rates (solar max)



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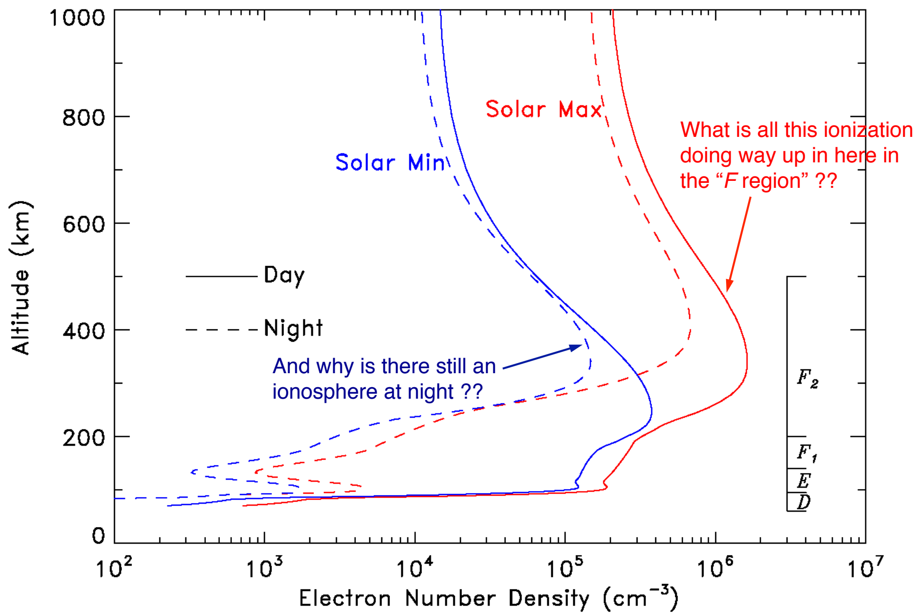
Ionosphere Basic Altitude Structure



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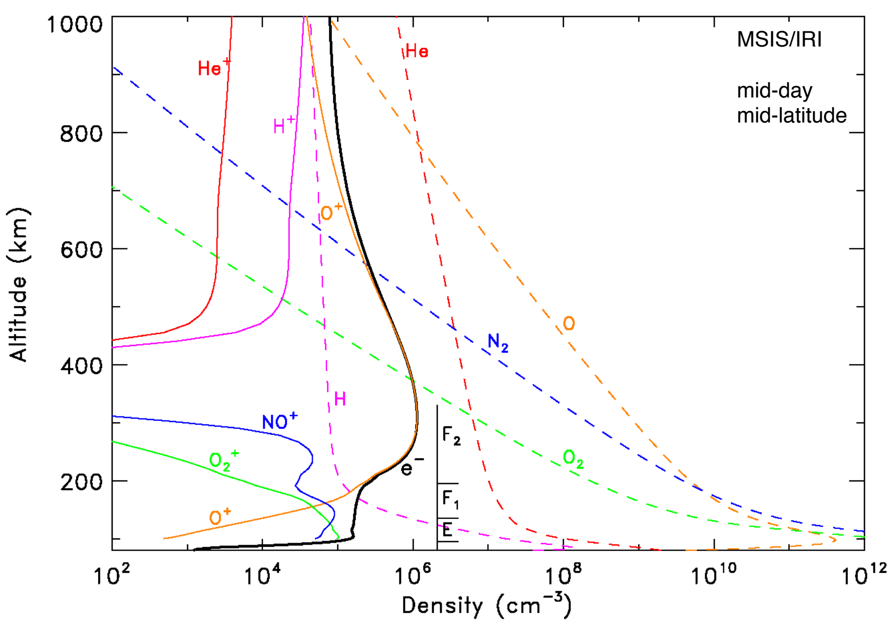
Thermosphere/Ionosphere Composition



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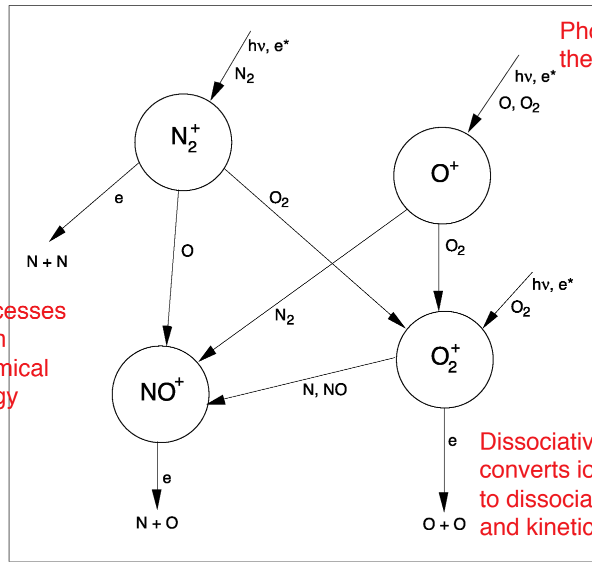
Ionization Processes and Thermospheric Heating



Photon flux enters the atmosphere

Ionization processes convert photon energy to chemical potential energy

Dissociative recombination converts ionization energy to dissociation products and kinetic energy

i.e., heat

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Types of Ionospheric Chemical Reactions

Radiative Recombination

$X^+ + e^- \rightarrow X + h\nu$

slow, rate coefficients of the order of 10^{-12} $cm^3\, s^{-1}$

Dissociative Recombination

$XY^+ + e^- \rightarrow X + Y$ + kinetic energy

fast, rate coefficients of the order of 10^{-7} $cm^3\, s^{-1}$

Charge Exchange

$WX^+ + YZ \rightarrow WX + YZ^+$

moderately fast, rate coefficients of the order of 10^{-10} $cm^3\, s^{-1}$

Atom-Ion Interchange

$X^+ + YZ \rightarrow XY^+ + Z$

rate depends on the strength of the YZ bond

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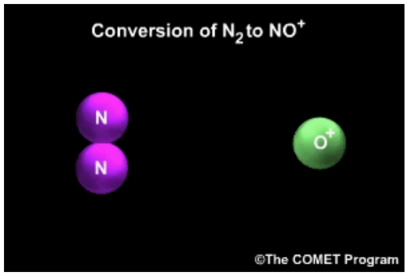
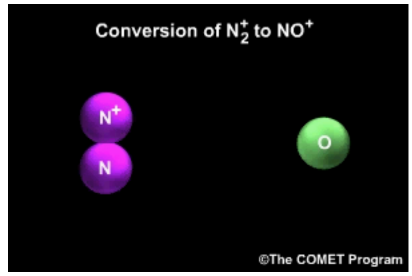
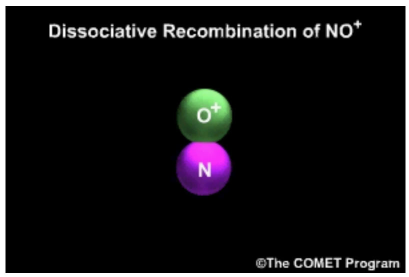
Idealized Illustration of Some Ion Chemical Reactions







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Simple Case – Single Species Molecular Atmosphere

$M_2 + h\nu \rightarrow M_2^+$ ionization rate q

$M_2^+ + e^- \rightarrow M + M$ rate coefficient α

Assuming photochemical equilibrium: $q = \alpha\,[M_2^+]\,[e^-]$

Assuming charge neutrality: $[e^-] = (q/\alpha)^{1/2}$

The *E* region ionosphere, ~100~150 km, contains mostly molecular ions, photochemical equilibrium applies, and most dissociative recombination rates are similar (i.e., very fast).

This formula approximates ion densities in the "*E* region" of Earth's ionosphere, which is, roughly speaking, a "Chapman Layer."

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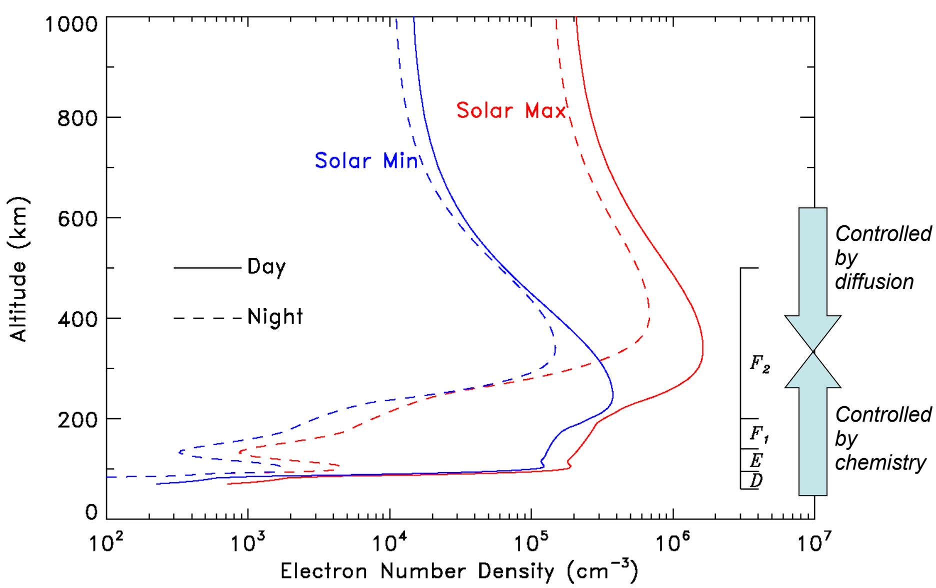
Complicated Case – Earth's *F* Region Ionosphere

Because of the decrease in molecular densities, the photochemical lifetime of O^+ becomes longer than the diffusion lifetime (the time it takes to move by a scale height in the vertical direction) above ~200 km.

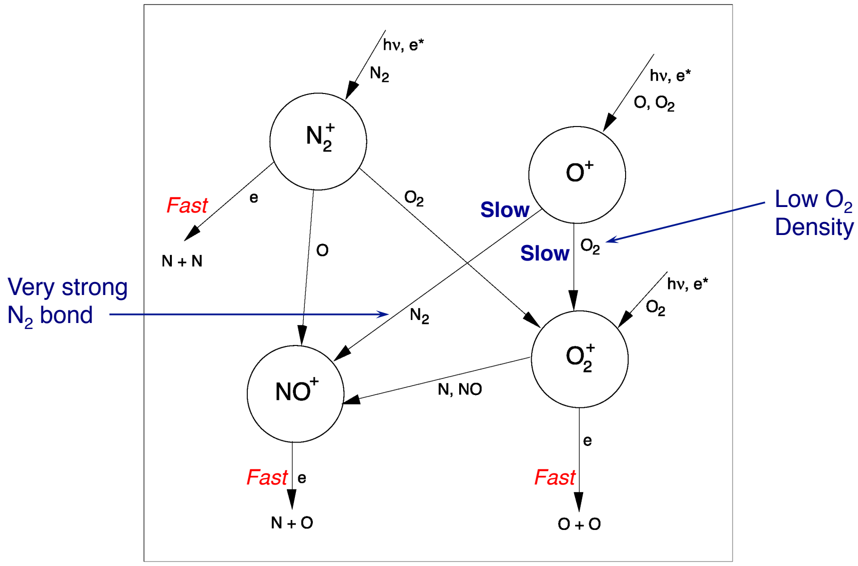
Thus, the *F* region is *not* a simple Chapman layer caused by the absorption of radiation, but rather a balance between chemical reactions at lower altitude and ambipolar diffusion at higher altitude.

The long lifetime of O^+ at high altitude is also why the F_2 region persists at night.

Ionosphere Basic Altitude Structure



Ion Chemistry Explains Why O^+ is the Primary *F*-region Ion



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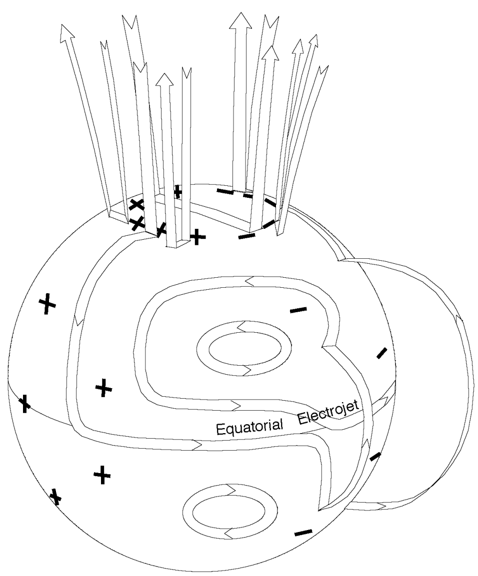
Ionospheric Electrodynamics



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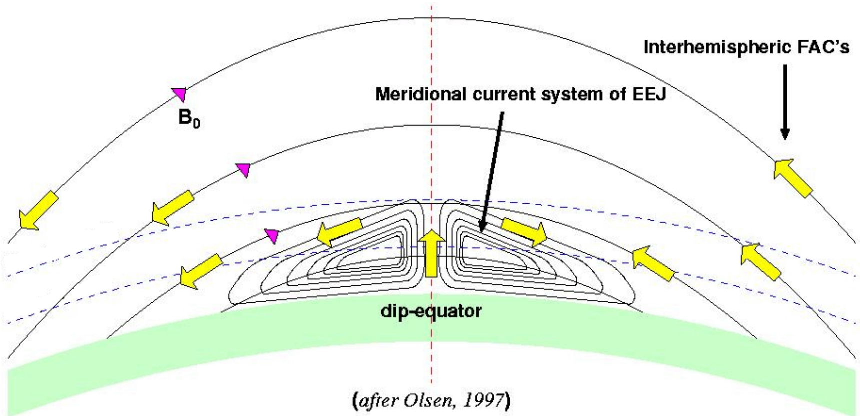
The Low-Latitude Dynamo Creates the Appleton Anomaly



a.k.a., equatorial ionization anomaly, intertropical arcs, tropical nightglow, etc.

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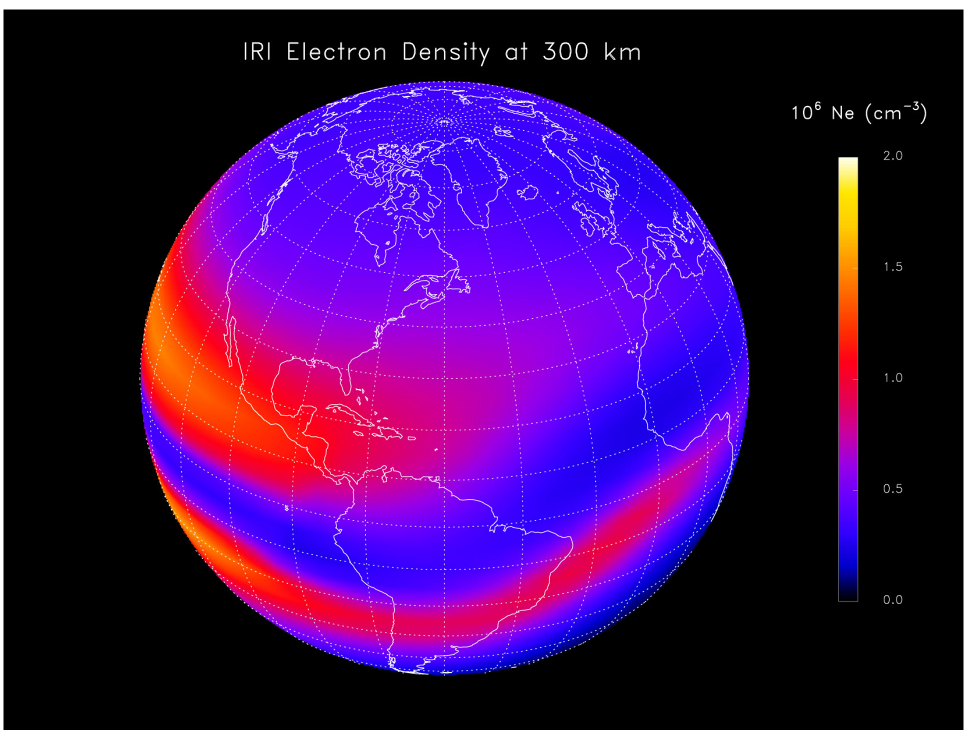
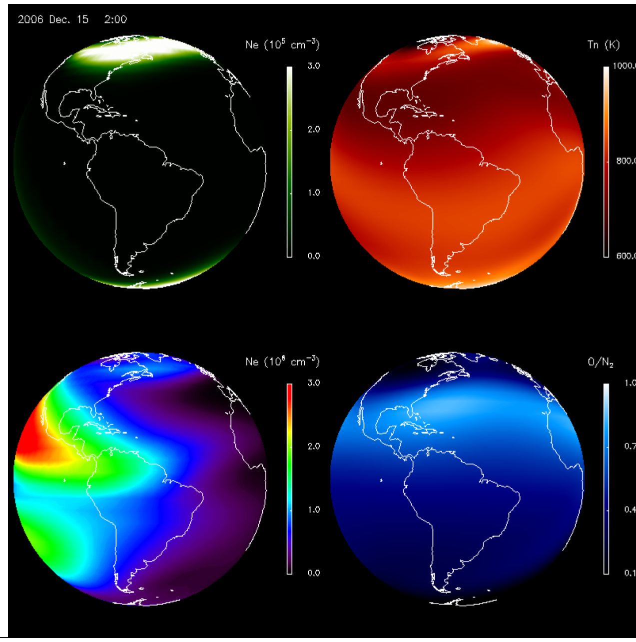


Thermosphere-Ionosphere Modeling during Storms

E-region Electron Density (~110 km)

Neutral Temperature (~160 km)



F-region Electron Density (~300 km)

O/N_2 Ratio (~160 km)

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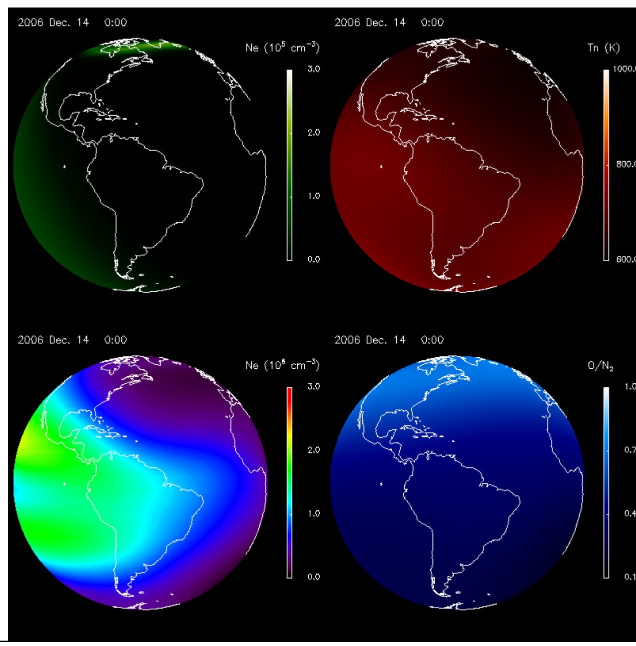
Thermosphere-Ionosphere Modeling during Storms

E-region Electron Density (~110 km)

Neutral Temperature (~160 km)



F-region Electron Density (~300 km)

O/N_2 Ratio (~160 km)

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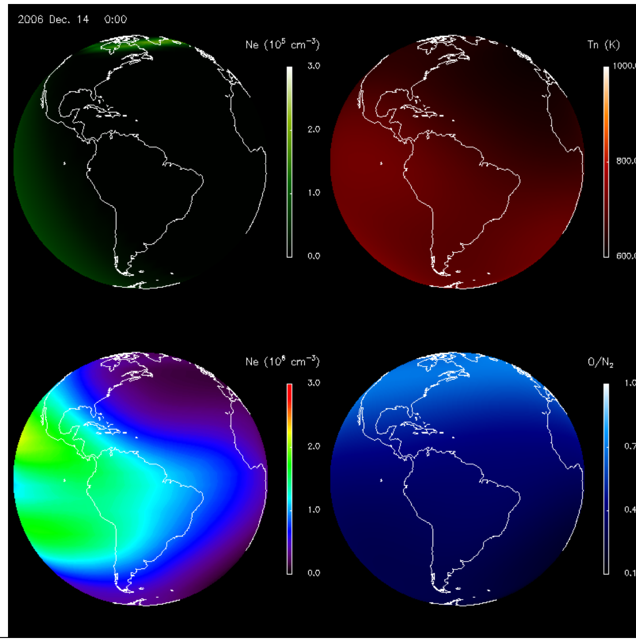
Thermosphere-Ionosphere Modeling during Storms

E-region Electron Density (~110 km)

Neutral Temperature (~160 km)



F-region Electron Density (~300 km)

O/N_2 Ratio (~160 km)

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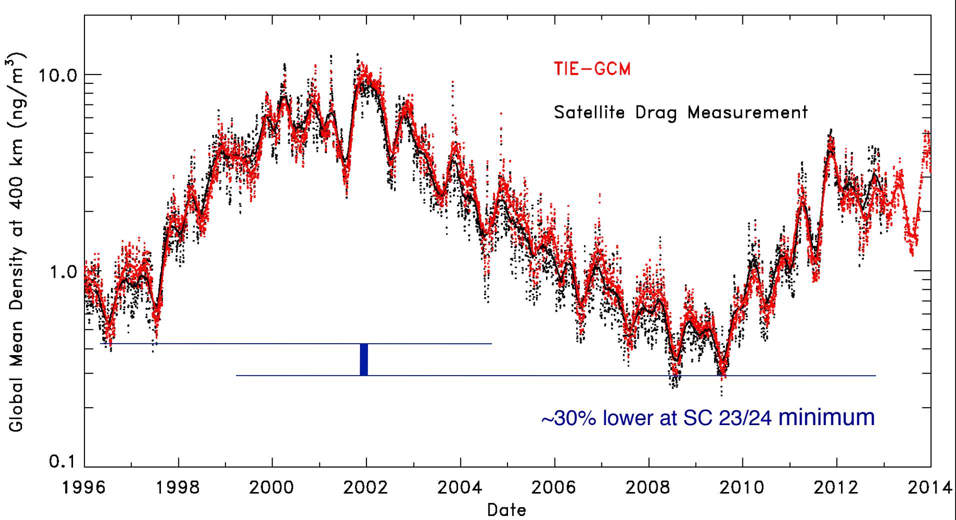
Comparison of Density Simulation to Satellite Drag Data



The $F_{10.7}$ solar radio flux index does not describe this difference between the solar minima. To accurately simulate the upper atmosphere density, we need to use actual solar measurements, or indices derived from them.

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Terrestrial Ionospheres

II

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Part II:

- Ionospheres of Mars and Venus
- Atmospheres of Mars and Venus
- Why is Earth so different?

Motivating Questions

- Why does the ionosphere occur in "layers?"
  - — It doesn't, really, but there is such a thing as a Chapman function.
- Since the Earth's ionosphere is produced mostly by solar radiation, why does it persist at night?
  - — Because of the long lifetime of O^+, which is due its slow reaction with N_2.
- Since most ionization occurs between 100 to 200 km in altitude, why is most of the ionosphere above 300 km altitude?
  - — Also because of the long lifetime of O^+.
- Why are the ionospheres of Venus and Mars so different from Earth's?

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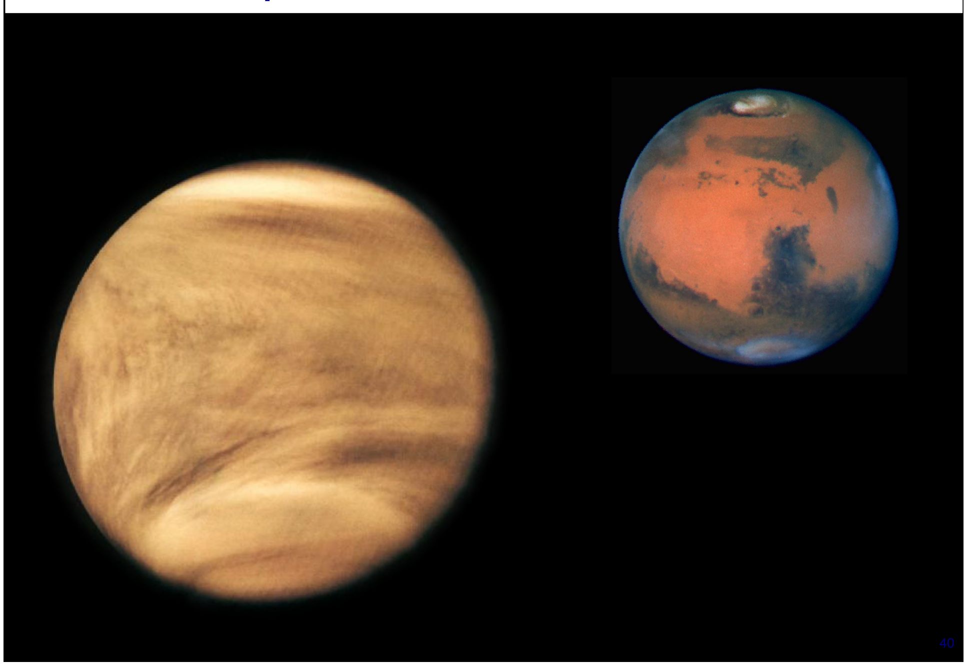
Ionospheres of Other Terrestrial Planets



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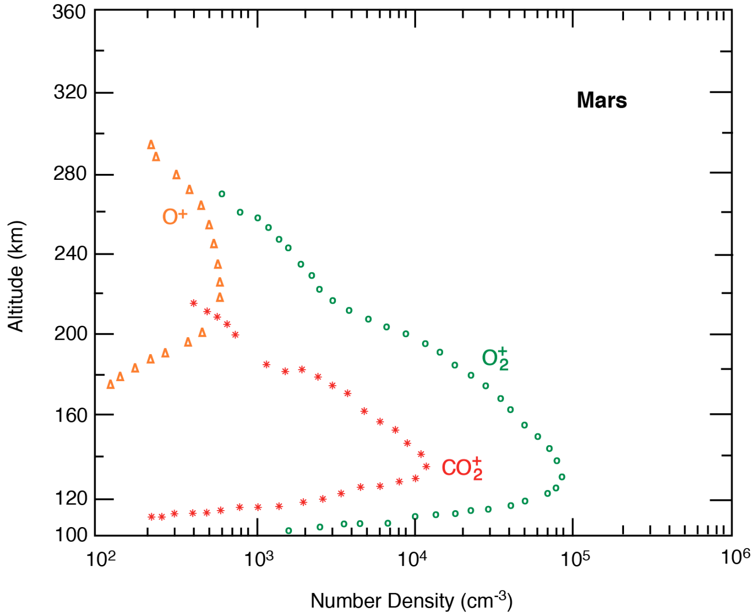
Ionosphere of Mars



Ion composition measurements from the Viking 1 mission

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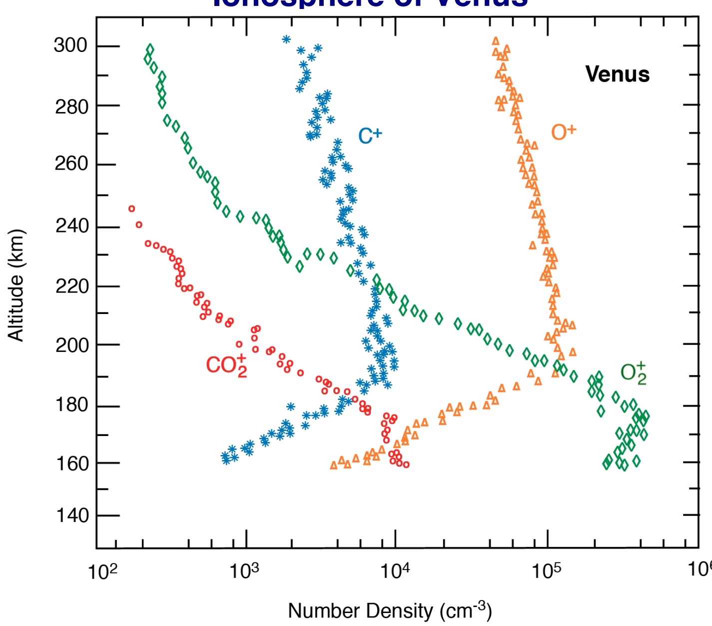
Ionosphere of Venus



Ion composition measurements from the Pioneer Venus mission

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Why are the ionospheres of Mars and Venus, although similar to each other, so different from Earth?

On Mars and Venus the most abundant ion is O_2^+, and also O^+ at high altitude. Unlike Earth, there is no "*F* layer", and very little ionosphere at night.

— Why doesn't O^+ have a longer lifetime on Mars and Venus?

— Why is there so much O_2^+ when they have so little O_2 in their atmospheres?

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Primary Atmospheric Composition of the Terrestrial Planets

The atmospheres of Venus, Earth and Mars contain many of the same gases, but in very different absolute and relative abundances.

Planet	Molecule	Abundance (bars)	% of Total
Venus	CO_2	87	96.5%
	N_2	3.2	3.5%
	SO_2	~0.01	~0.01%
Earth	N_2	0.78	77%
	O_2	0.21	21%
	H_2O	~0.01	~1.0%
	CO_2	0.0004	0.04%
Mars	CO_2	0.0062	95%
	N_2	0.0002	3%
	Ar	0.0001	2%
	H_2O	~10^{-6}	~0.01%

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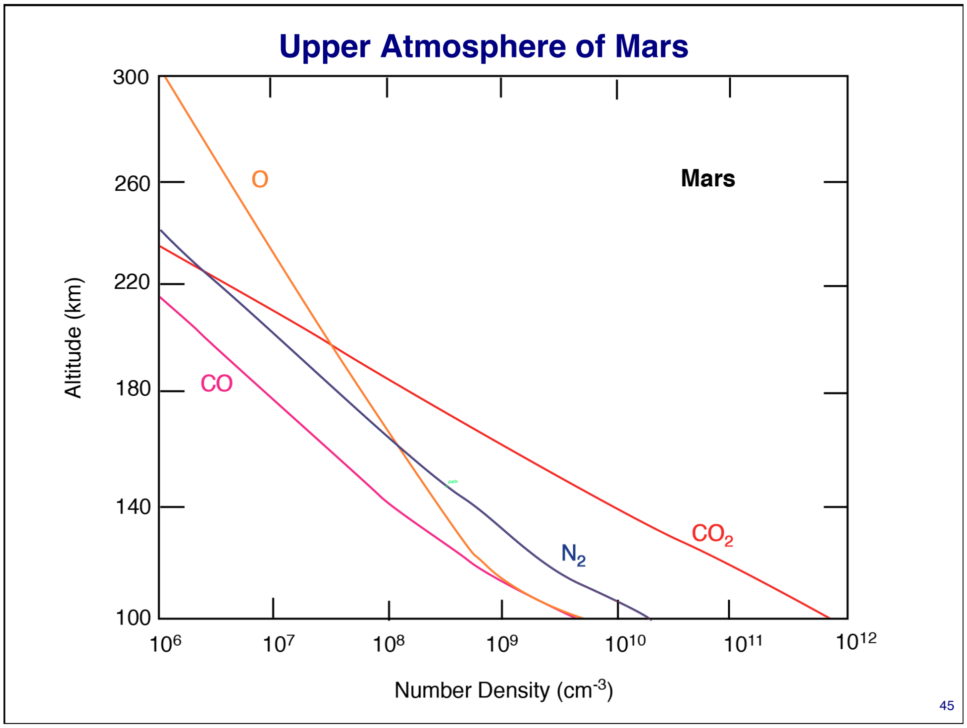
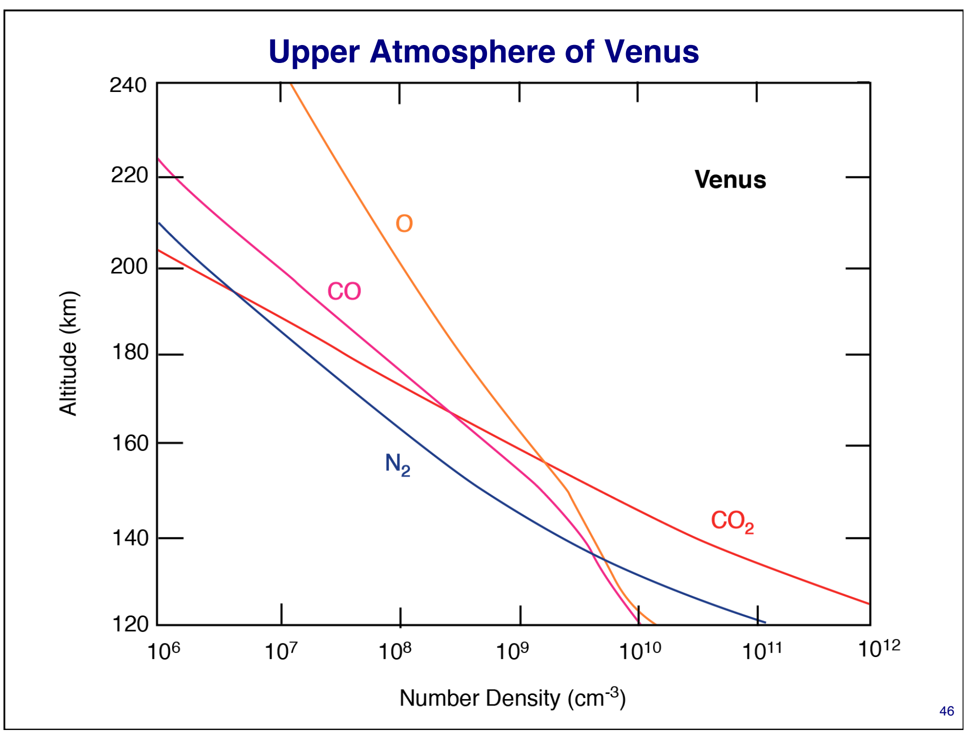

Upper Atmosphere of Mars
Mars
O
CO
N2
CO2
Altitude (km)
300
260
220
180
140
100
10^6
10^7
10^8
10^9
10^10
10^11
10^12
Number Density (cm^-3)
45


Upper Atmosphere of Venus
Venus
O
CO
N2
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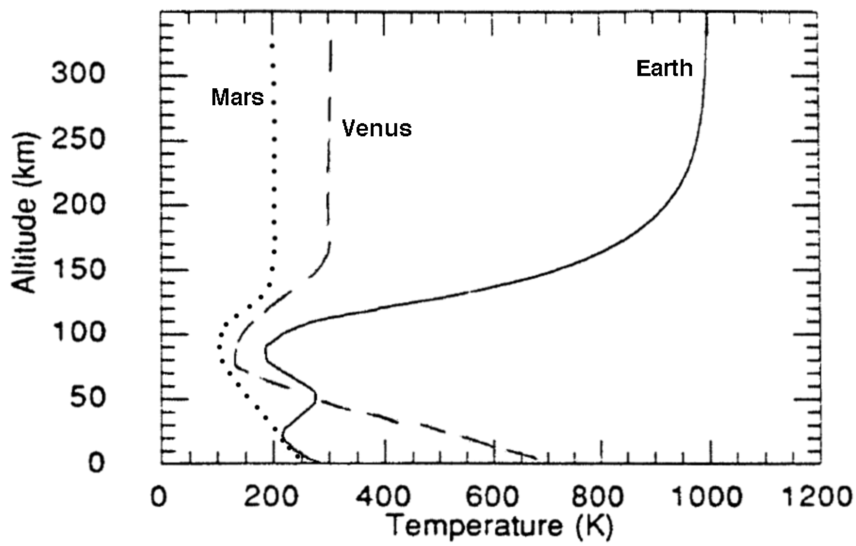
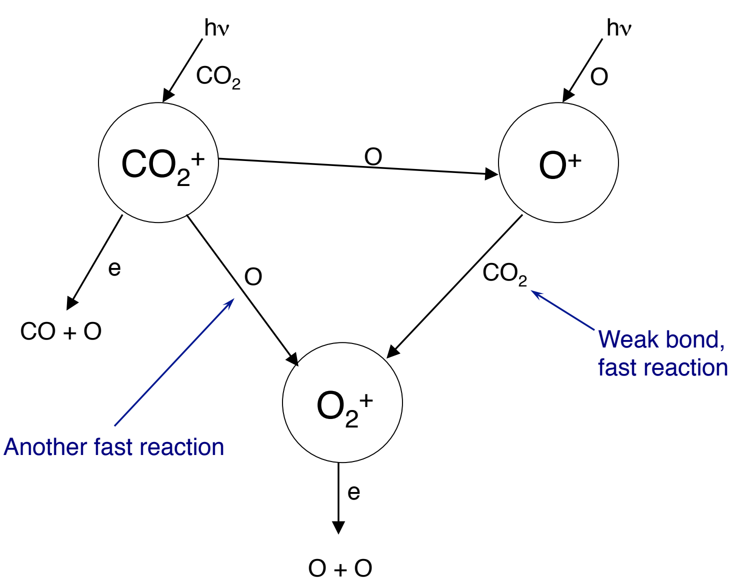
Altitude (km)
240
220
200
180
160
140
120
10^6
10^7
10^8
10^9
10^10
10^11
10^12
Number Density (cm^-3)
46

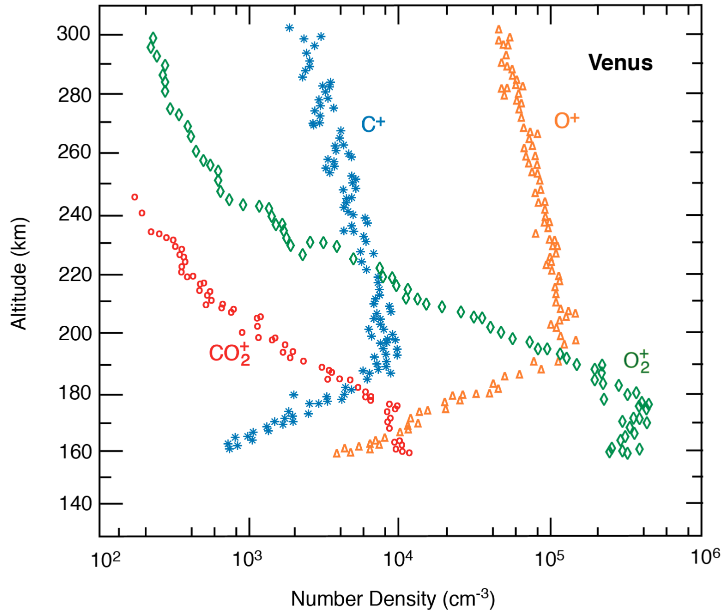
Average Temperature Profiles of the Terrestrial Planets



Principal Ionization Processes on Venus & Mars



A High-Carbon, Low-Density, Low-Altitude Ionosphere



Ion-interchange reactions convert O^+ and CO_2^+ to O_2^+, which has a short lifetime.

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Venus and Mars are "Normal", *Earth* is Anomalous

On Venus and Mars, O^+ reacts rapidly with CO_2 and CO_2^+ reacts rapidly with O because these atom-ion interchange reactions have fast rate coefficients.

This is because CO_2 is not very strongly bonded, compared to N_2.

Therefore, Venus and Mars ionospheres are "*E* region" types, controlled mostly by photochemical equilibrium at their peaks.

Earth lacks sufficient carbon in its atmosphere, and doesn't have enough O_2 at high altitude, for this to happen. Atom-ion interchange of O^+ with N_2 is very slow, due to the strength of the N_2 bond. This creates the high, dense, persistent "*F* region" and a lot of interesting ionospheric variability.

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So…

Where's the Carbon?

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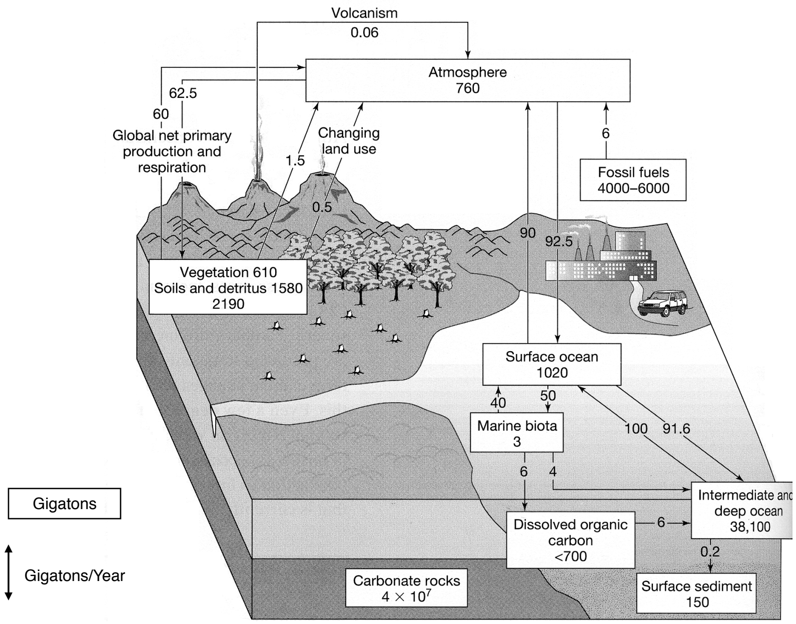
The Earth's Carbon Cycle



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Summary

• Why does the ionosphere occur in "layers?"

— It doesn't, really, but there is such a thing as a Chapman function.

• Since the Earth's ionosphere is produced mostly by solar radiation, why does it persist at night?

— Because of the long lifetime of O^+, which is due its slow reaction with N_2.

• Since most ionization occurs between 100 to 200 km in altitude, why is most of the ionosphere above 300 km altitude?

— Also because of the long lifetime of O^+.

• Why are the ionospheres of Venus and Mars so different from Earth's?

— Because they have CO_2 in their atmospheres, which rapidly reacts with O^+.

The F-region ionosphere is unique to Earth among the known planets. This is due to its peculiar atmosphere, lacking in CO_2, dominated by N_2, and carrying its oxygen in unusual and reactive states. Earth has a significant carbon budget, and once had much higher levels of CO_2 in its atmosphere, but most of its carbon is currently locked up in the crust in the form of carbonate rocks. Thus, the F-region ionosphere may be a recent event in the history of Earth, an artifact of geology and biology.

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Question for Discussion

A high, dense, "*F*-layer" ionosphere observed on a terrestrial-type planet would be a sign of life on that planet.

1. True
2. False