Thermosphere
Part-3

EUV absorption
Thermal Conductivity
Mesopause
Thermospheric Structure
Temperature Structure on other planets
Thermosphere Absorbs EUV

Absorption: Solar Spectrum

The spectrum of solar radiation outside the Earth's atmosphere matches closely that of a blackbody at 5800 K.

Peaks at visible (0.4-0.7 μm), max @ 0.5 μm, about half in the IR and small fraction at UV

EUV--very little heat flux
But also very little atmosphere
But it is the region for escape
And diffusive separation
Thermosphere
(heating at short wavelengths)

1. EUV Heats (also: soft x-rays, charged particles)

\[
\begin{align*}
O_2 & + h\nu \rightarrow O + O \\
N_2 & + h\nu \rightarrow N + N \\
O & + h\nu \rightarrow O^+ + e \\
X & + h\nu \rightarrow X^+ + e
\end{align*}
\]

\[J_2 = \sigma_{abs}F_{EUV}(z)\] from before

greater smaller

also creates ionosphere

2. At Lower Altitudes: Cooling
(Recombine O, N etc.)

\[N_2, O_2 \text{ and } O \text{ Cannot Radiate IR}
\]

Homonuclear Diatomics and Atoms

Discuss briefly will return:

\[\text{no } CO_2 \text{ (diffusive separation)}\]

\[\text{Must Conduct Deposited Heat to a Region Containing}\]

\[CO_2 , H_2O , O_3 \text{ etc.}\]

Mesopause (Roughly)

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**Diagram**

- EUV heating
- IR cooling
- Thermal conduction
- Mesopause

**Rough picture**

Z

<table>
<thead>
<tr>
<th>130km</th>
<th>EUV heating</th>
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<tbody>
<tr>
<td>80km</td>
<td>Thermal conduction</td>
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Heat Source: Absorption of EUV Photons

\[ \rho \, c_p \, \frac{dT}{dt} = \mu \, \frac{dF_s}{dz} \]

: reduction in the energy flux

assumes unit efficiency of photon energy to heat

\[ \rho \, c_p \, \frac{dT}{dt} = \mu \, \frac{dF_s}{dz} = \sigma_{abs} \, n_{abs} \, F_s \]
Heat loss: Conduction

Considered the thermal heat flux: $\Phi_T$

Conductive flux is opposite to temperature difference

$\Phi_T \propto -\Delta T$

Negative sign - -flow of heat is from high $T$ to low $T$

(you may have called it Newton cooling law)

Write: (1D) $\Phi_T = -K \frac{dT}{dz}$ or (3D) $\vec{\Phi}_T = -K \nabla T$

$K$ is the thermal conductivity

Energy left in the volume gives the heating rate

- $d\Phi_T/dz >$ heating - -leaves heat in $dz$:

- $d\Phi_T/dz <$ cooling - -removes heat from, $dz$:

\[
\Delta z \quad \frac{\Phi_T + \Delta \Phi}{\Phi_T}
\]

Heating/ Cooling rate = $\rho c_p \frac{dT}{dt} = - \frac{d}{dz} \Phi_T$
Heat Flux: What is $K$

$$\Phi_T = -K \frac{dT}{dz}$$

$$K \approx \text{const} \left( \rho c_v \right) \bar{L}_d \bar{v}_d$$

$\bar{L}_d$ is a diffusion length
  (molecular or eddy)

$\bar{v}_d$ is a mean diffusion speed
  (molecules or parcels of air)

**Heat Eq. with thermal conduction (diffusion)**

$$\rho c_p \frac{dT}{dt} = - \frac{d}{dz} (K \frac{dT}{dz}) + S(z) - L(z)$$

(Source - Loss)

This is a region where diffusive separation dominates

Here conduction is by gas - phase collisions
Heat Eq. with thermal conduction (diffusion)

\[ \rho c_p \frac{dT}{dt} = - \frac{d}{dz} \left( -K \frac{dT}{dz} \right) + S(z) - L(z) \]

(Source - Loss)

Thermosphere:

Heating by absorption of sunlight (EUV):

\[ S(z) = \mu [dF_s/dz] \text{ (in 1D)} \]

Assume:

\[ \rho c_p \frac{dT}{dt} = 0; \text{ steady state} \]

Assume \( L(z) = \text{Radiative Loss} = 0 \)

except at the bottom 'boundary'

Treat as a boundary value problem

Below mesopause: we will do radiative transfer soon
Thermosphere T Structure

Heat equation for the thermosphere

\[ 0 = \frac{d}{dz} \left[ K \frac{dT}{dz} \right] + S(z) \quad [S(z): \text{Chapman Layer}] \]

Solve: First - - - Integrate from \( z \) to infinity

\[ 0 = K \left( \frac{dT}{dz} \right)_z^\infty + \int_z^\infty S(z')dz' \]

No Heat Loss to Space (\( \frac{dT}{dz} = 0 \) at top of atmosphere)

\[ K \frac{dT}{dz} = \int_z^\infty S(z')dz' \]

A realistic \( K: K(T) \approx K_o T^{4/3} \)

Integrate again: from Mesopause (\( z_m \)) to \( z \) gives \( T(z) \)

\[ T^{7/4}(z) \approx T_m^{7/4} + \frac{7}{4K_o} \int_{z_m}^z dz' \int_{z'}^\infty S(z'')dz'' \]

\( T_m \) is the boundary: where heat conducted downward is radiated to space

Relationship to our old \( T_e \)?
HEAT FLUX DOWN = HEAT DEPOSITED ABOVE

\[ K \frac{dT}{dz} = \int_{z}^{\infty} S(z') dz' \]

\[ \approx \int_{z}^{\infty} \left[ \mu \frac{dF_s}{dz'} \right] dz' \]

\[ \approx \int_{z}^{\infty} \mu \ dF_s \]

\[ \approx F_s^0 \mu \left[ 1 - \exp\left( -\frac{\tau}{\mu} \right) \right] \]

This says that the downward heat flux at any altitude must be equal to all the energy deposited above by the absorption of EUV photons.
\[ K \frac{dT}{dz} \approx F_s^0 \mu \left[ 1 - \exp\left(\frac{-\tau}{\mu}\right) \right] \]

For simplicity let \( K = K_o \) a constant; \( \mu = 1 \).

\[ T(z) \approx T_m + \frac{F_s^0}{K_o} \int_{z_m}^{z} dz' \left[ 1 - \exp\left(\frac{-\tau'}{\mu}\right) \right] \]

If absorption maximum is high (\( z_{\text{max}} > \sim 130 \text{km} \))
then, below maximum variation is nearly linear

\[ T(z) \approx T_m + \frac{F_s^0}{K_o} [z - z_m] \quad \text{for} \quad z_m < z < z_{\text{max}} \]
Thermosphere Structure (Cont)

For $K = K_o; \mu = 1$.

$$T(z) \approx T_m + \frac{F_s}{K_o} \int_{z_m}^z dz' \left[ 1 - \exp(-\tau') \right]$$

Change variable:

Optical depth $- - \tau = \int_{z}^{\infty} \sigma_{\text{abs}} n_{\text{abs}}(z') dz' \approx \sigma_{\text{abs}} H n_{\text{abs}}(z)$

$$\frac{d\tau}{dz} \approx -\frac{\tau}{H}$$

$$T(z) \approx T_m + \frac{F_s H}{K_o} \int_{\tau}^{\tau_m} \left[ \frac{d\tau'}{\tau'} \right] \left[ 1 - \exp(-\tau') \right]$$
\[ \tau(z) \propto x \]

\[ \tau = 0 \quad z \rightarrow \infty \]

\[ x \propto \tau(z) ; \quad [T(z) - T_m] = [F_0/K_0][Hy] \]

\[ y(x) = \int_x^{x_m} \left\{ \frac{1 - \exp(-x')}{x'} \right\} dx' \]

Over how many scale hieght does heat have to be conducted
Thermospheric Temperature

$Z_m = 80\text{km}$

Mesopause

$220\text{ K}$

$1000\text{ K}$
Temperature vs. Altitude
Earth’s Atmosphere
Rise in T in Thermosphere
due to EUV Absorption
and Thermal Conduction
to Mesopause

These are averages
Tropopause is higher and hotter
Near equator ~16-18km and ~ 10km near poles
Drives high altitude horizontal flow
Jets planes ~10km:e close to stratosphere
to avoid turbulence
Earth's Thermal Structure

Thermosphere T depends on Solar Activity
Photo-chemistry Venus + Mars

Simpler

$$\text{CO}_2 + h\nu \rightarrow \text{CO} + \text{O} \quad (1)$$

$$\text{CO} + \text{O} + \text{M} \rightarrow \text{CO}_2 + \text{M} \quad (2)$$

On Venus  CO $\rightarrow$ CO$_2$
may be aided by sulfur + chlorine species

On Mars: (2) is very slow
(density Is very small):

Expect considerable CO, especially so
as free O oxidize surface (iron oxide)

**BUT** there is a small amount of H$_2$O

$$\text{H}_2\text{O} + h\nu \rightarrow \text{OH} + \text{H} \quad (3)$$

$$\text{CO} + \text{OH} \rightarrow \text{CO}_2 + \text{H} \quad (4)$$

Recycles CO$_2$ but
Can lose the H--hence loss the H$_2$O
Venus Atmosphere

Cloud Tops $\rightarrow T_e$

$\text{CO}_2$ even at high altitudes $\rightarrow$ cooling

Slow Rotation

1 year $= 2$ days

(retrograde due to thick atmosphere and tidal forces?)
Mars Atmosphere

Te at Surface
Dust absorbs $h\nu$ and changes the lapse rate
Thermosphere strongly dependent on solar activity
Titan’s Atmosphere

Stratosphere/ mesosphere due to absorption in hydrocarbon haze

\[ \text{CH}_4 + h\nu \rightarrow \text{CH}_3 + \text{H} \ (\text{CH}_f + \text{H}_2) \]

React to form \( C_nH_m \) and \( \text{H}_2 \) escapes.

Thermosphere subject to particles from Saturn’s magnetosphere
Giant Planets

Internal heat sources
Adiabatic lapse rate down to liquid metal hydrogen
Jupiter has evidence of a stratosphere and a mesosphere
Atmosphere Thermal Structure: Summary

**Typically**
- Troposphere (Lower, Convective)
- Mesosphere [Stratosphere] (Middle, Radiative)
- Thermosphere (Upper, Conductive)
- Exosphere (Escape)

**Venus**
- Temperature Lapse, $\gamma \leq \Gamma_d$
- Tropopause at cloud layer (~ 70 km)
- $T_e \sim$ Top of cloud layer
- Thermosphere (Cryosphere)
  - $T_d \sim$ 300 km ($CO_2$ at high altitudes)
  - $T_n \sim$ 100 km (Slow rotation 1yr $\approx$ 2 days)

**Mars**
- Temperature Lapse $\gamma \leq \Gamma_d$
  - (Strong Day / Night Variations: Dust $\gamma << \Gamma_d$
- Mesosphere $T < T_e$ ($CO_2$ cooling)
- Thermosphere like Mesosphere
  - (Strongly affect by solar activity)

**Titan**
- Temperature Lapse $\gamma \sim \Gamma_d$
- Stratosphere (Haze Layer)
- Mesosphere (Cooler to space)
- Thermosphere (Solar UV + Energetic Particles
  from Magnetosphere Cooled by HCN, Slow Rotations)

**Grant Planets**
- Internal heat source comparable to solar
- Tropopause $\sim$ 0.1 bar, $\gamma \sim \Gamma_d$
- Temperature + pressure increase to about 2M bar so phase change to a liquid (metallic) state ($4 \times 10^4$ km) and a metallic core ($3 \times 10^4$ K) ($1 \times 10^4$ km) (Jupiter)
- Mesosphere (stratosphere) $\leq$ 0.001 bar Hydrocarbon coolants
- Thermosphere (Solar EUV)
#3 Summary

Things you should know

EUV absorption
Mesopause
Thermosphere
Thermal conductivity
Heat flux
General picture of the vertical structure