# Atmospheres in the solar system

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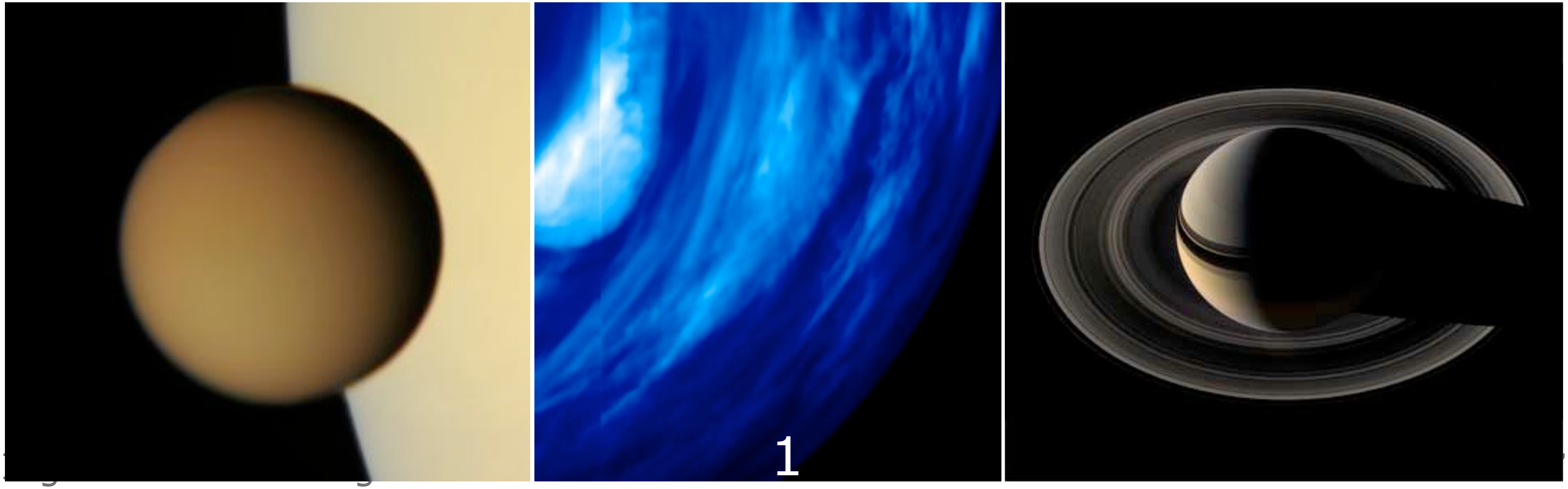
PG Lecture 13 Nov 2017



# What is an atmosphere?

- An atmosphere is a gas layer surrounding a planet
- Gravitational energy competes against escape processes

$$F_{esc} = \frac{n\,r}{2\sqrt{\pi}} \cdot \left(\frac{2\,k\,T}{m}\right)^{\frac{1}{2}} \cdot (\lambda + 1)\, e^{-\lambda}$$

Jeans escape flux

$$\lambda = \frac{\textit{gravitational potential energy}}{\textit{random kinetic energy}} = \frac{r_{exobase}}{H}$$

Lambda parameter indicates how transient an atmosphere is

Permanent atmospheres

| | Venus | Earth | Mars | Jupiter | Saturn | Titan | Uranus | Neptune | Triton | Pluto |
|---|---|---|---|---|---|---|---|---|---|---|
| λ | 1600 | 1100 | 490 | 2300 | 1300 | 68 | 200 | 450 | 84 | 21 |

Transient (non-permanent) atmospheres

| | Mercury | Moon | Callisto | Ganymede | Europa | Io | Comets |
|---|---|---|---|---|---|---|---|
| λ | <10 | <10 | <10 | <10 | 8 | 9 | <10 |

# Atmospheres in the solar system

$N_2$ atmospheres

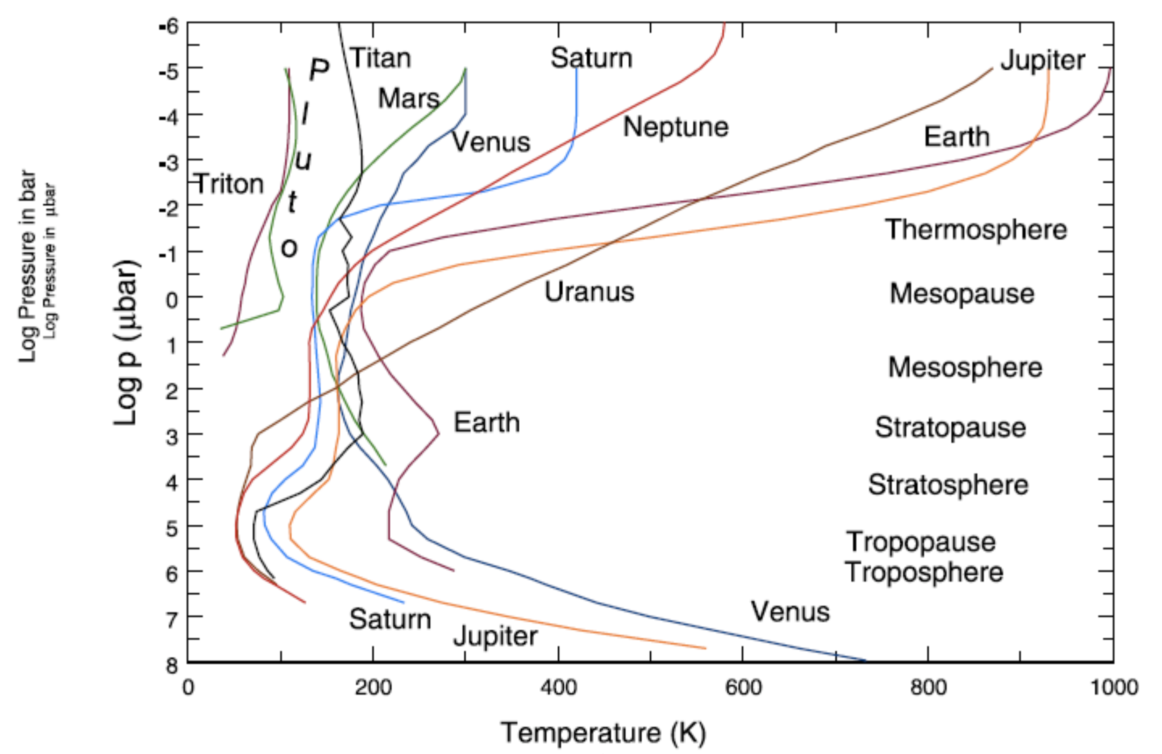
- Earth
- Titan
- Triton
- Pluto

$CO_2$ atmospheres

- Venus
- Mars

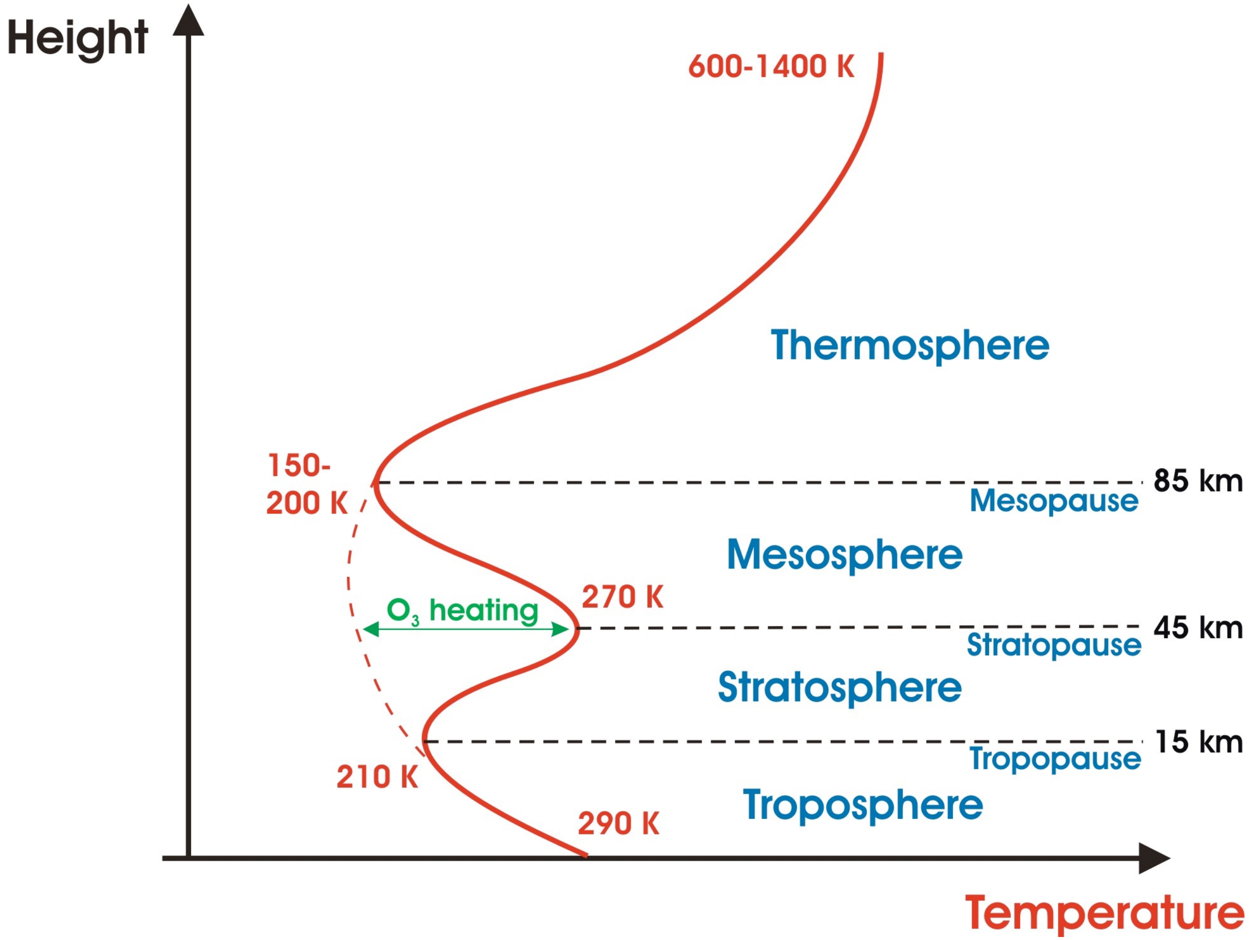
$He/H_2$ atmospheres

- Jupiter
- Saturn
- Uranus
- Neptune

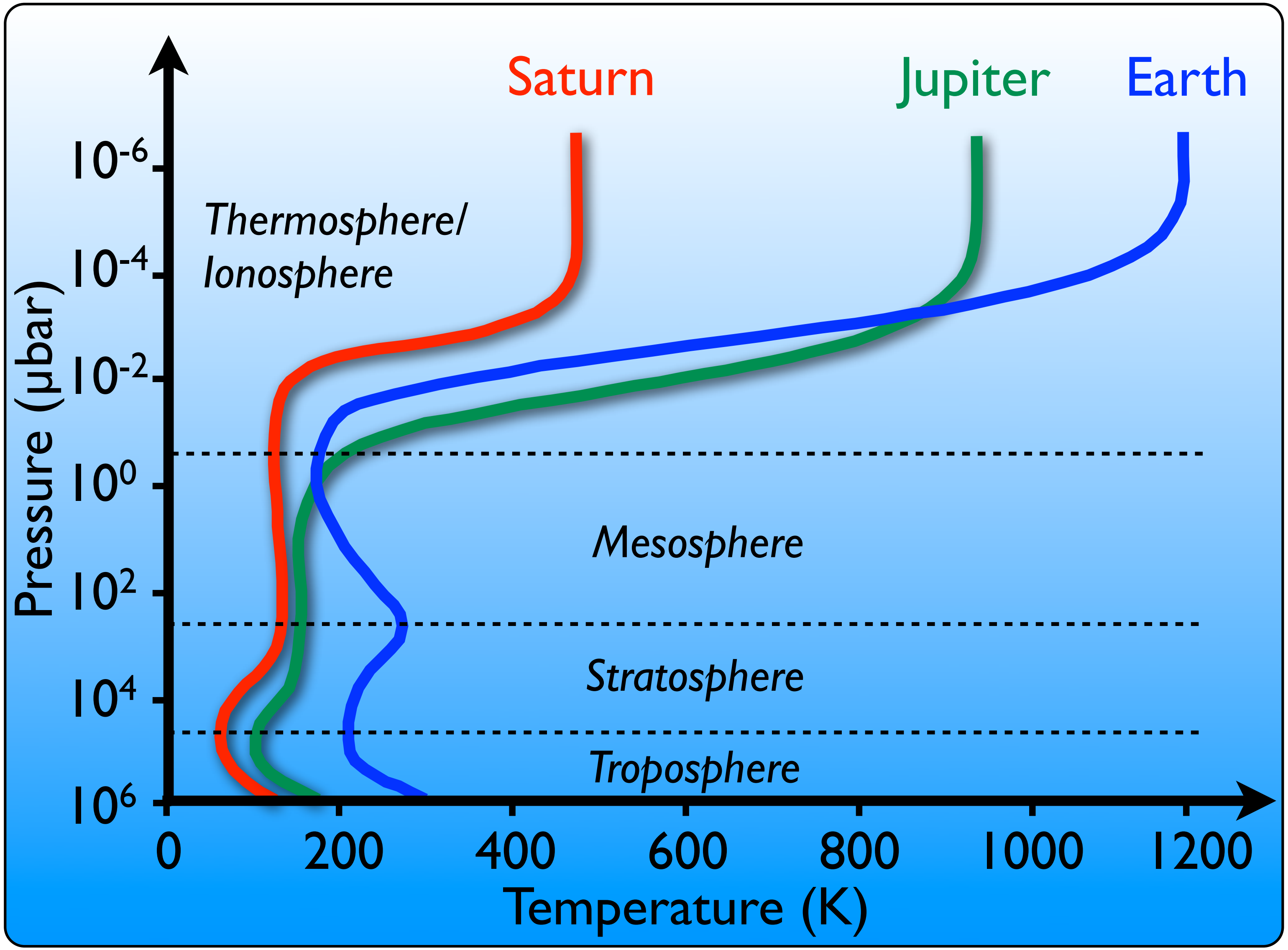


# Thermal structure

The Earth's atmosphere is vertically subdivided into different regions/layers:

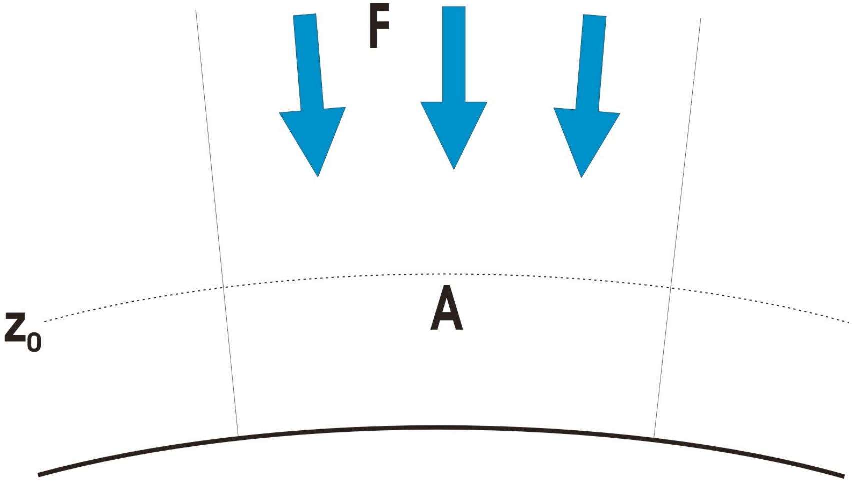


# Earth and other planets



# Hydrostatic behaviour

The pressure is defined as the weight (per surface area) of the atmosphere above:



$$p(z_0) = \frac{F}{A} = \int_{z=z_0}^{\infty} \rho(z) \cdot g(z) dz$$

and the change or pressure with height is given by:

$$dp = -\rho(z) \cdot g(z) dz$$

Hydrostatic equation

Pressure decreases with altitude since the weight of the atmosphere above becomes smaller for increasing height.

# Part 1: Composition of atmospheres

From the ideal gas law: $p = n\,k\,T$

k is Boltzmann's constant
n is total gas number density

and: $$\frac{dp}{dz} = -\rho \cdot g = -m \cdot n \cdot g$$

m is the mean molecular mass (in units of mass):
$m = \sum (n_i m_i)/n$
where $n_i, m_i$ are density, mass of gas i

we get: $$\frac{dp}{dz} = -\frac{m\,g}{k\,T} \cdot p = -\frac{1}{H} \cdot p$$

where: $$H = \frac{k\,T}{m\,g}$$

is the pressure scale height

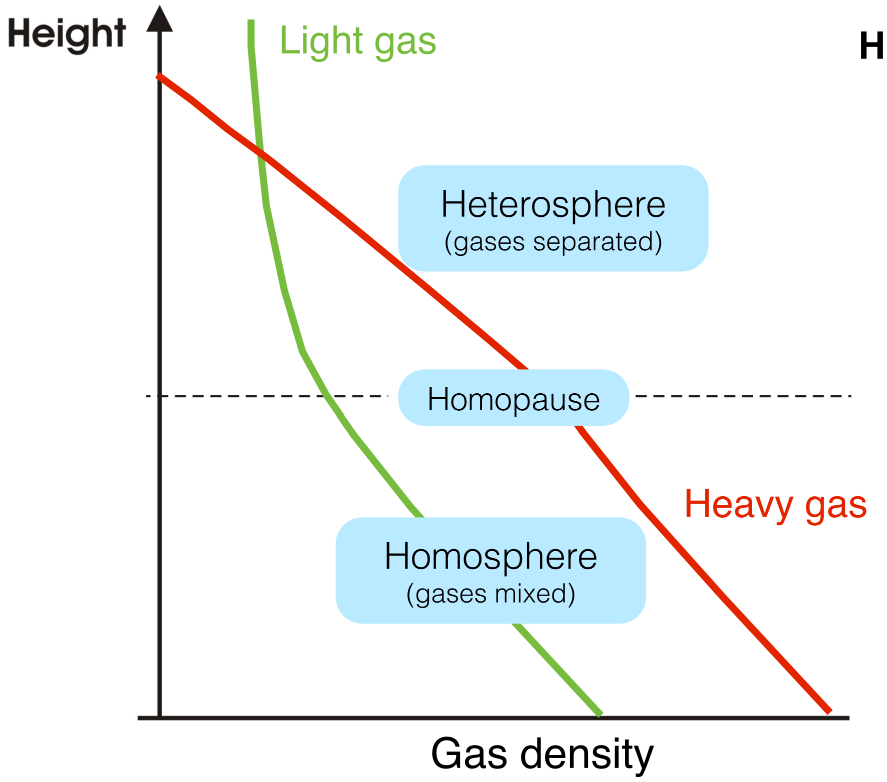
giving: $$p(z) = p(z_0)\, e^{-\int_{z_0}^{z} \frac{dz'}{H}}$$

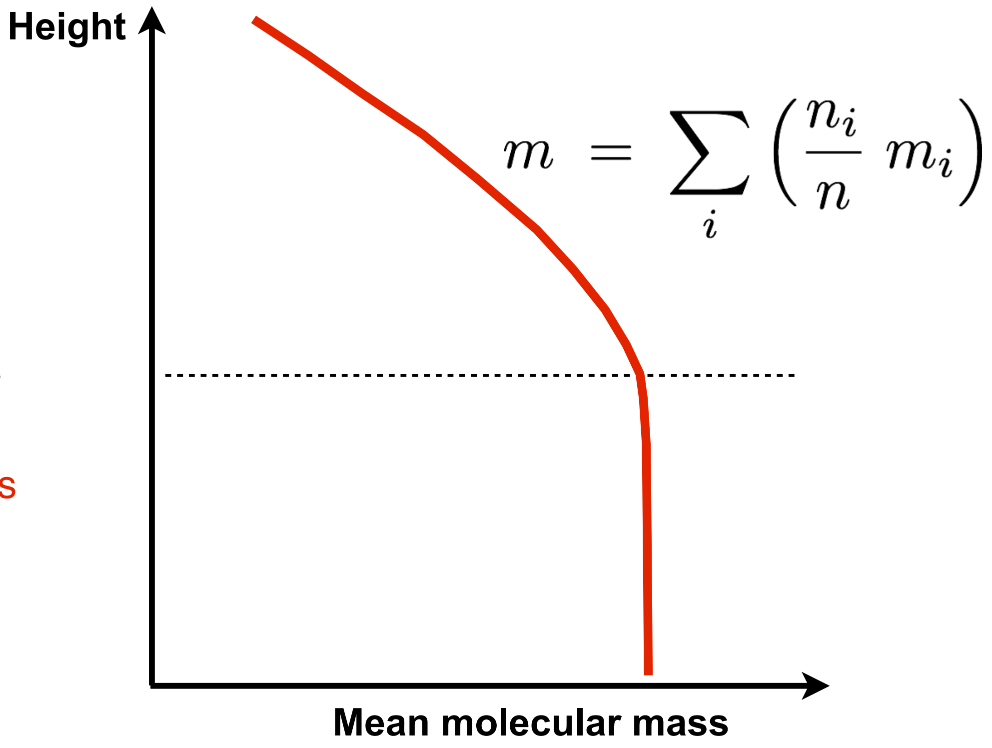
So, when moving up in altitude by one scale height, pressure decreases by a factor of 1/e ~ 0.37.

The same applies to number densities:

$$n = \frac{p}{k\,T} \text{ , so: } n(z) = n(z_0)\left(\frac{T(z_0)}{T(z)}\right) e^{-\int_{z_0}^{z} \frac{dz'}{H}}$$

Gases below the homopause (near 105 km on Earth) are well mixed due to small scale turbulence and larger scale winds, while above the homopause they diffusively separate

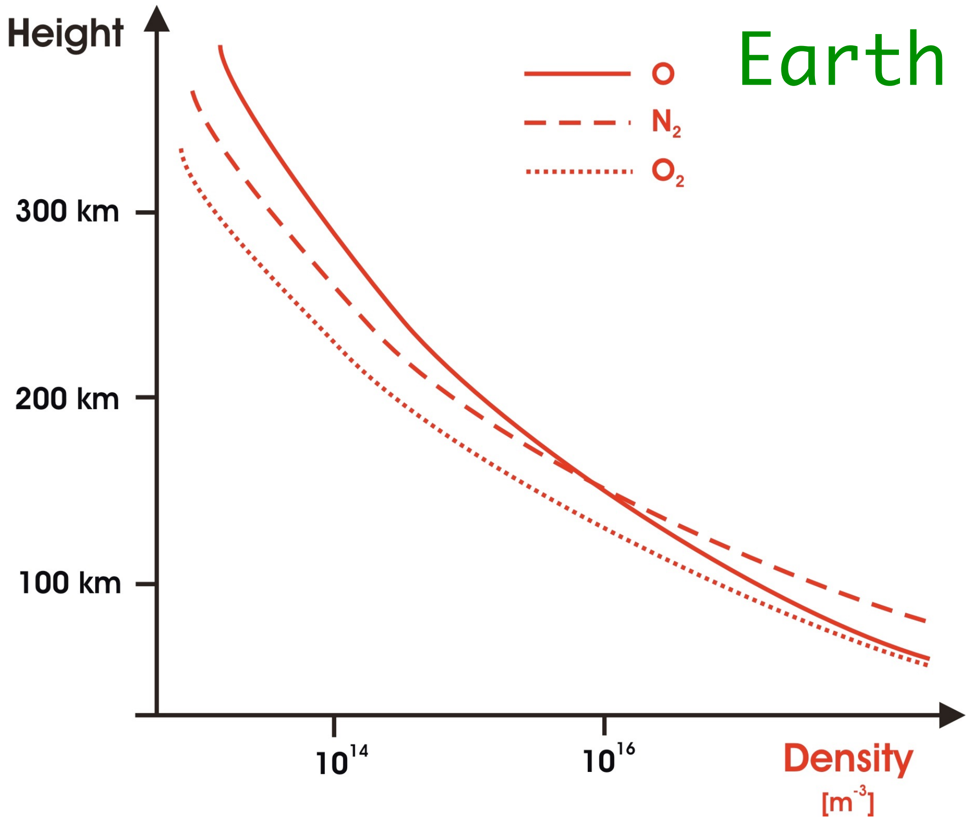




$$m = \sum_i \left(\frac{n_i}{n}\, m_i\right)$$

# In the heterosphere gases distribute vertically according to their individual scale heights

$$H_i(z) = \frac{k\,T(z)}{m_i\,g(z)}$$



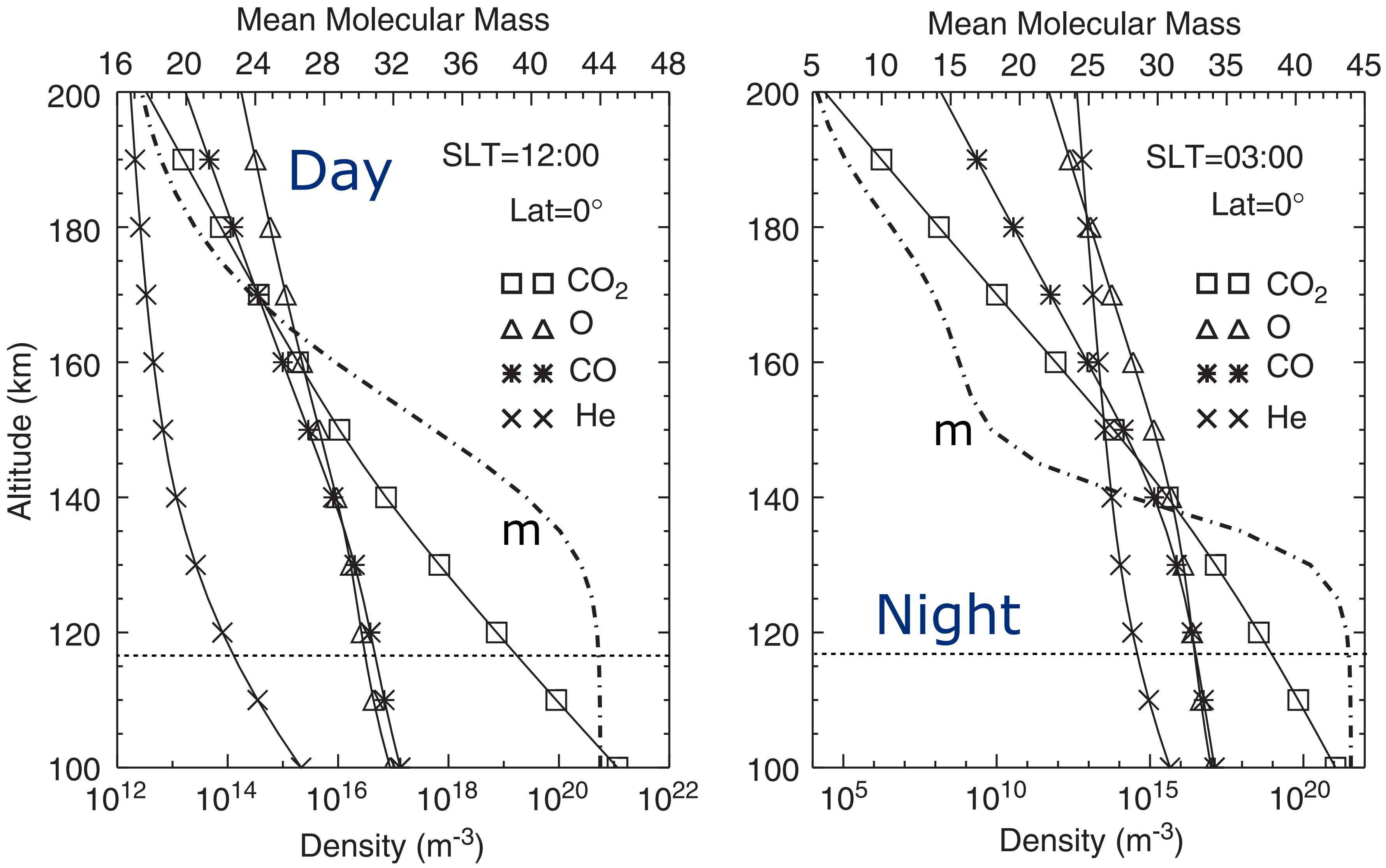
Earth

For T = 800 K on Earth:

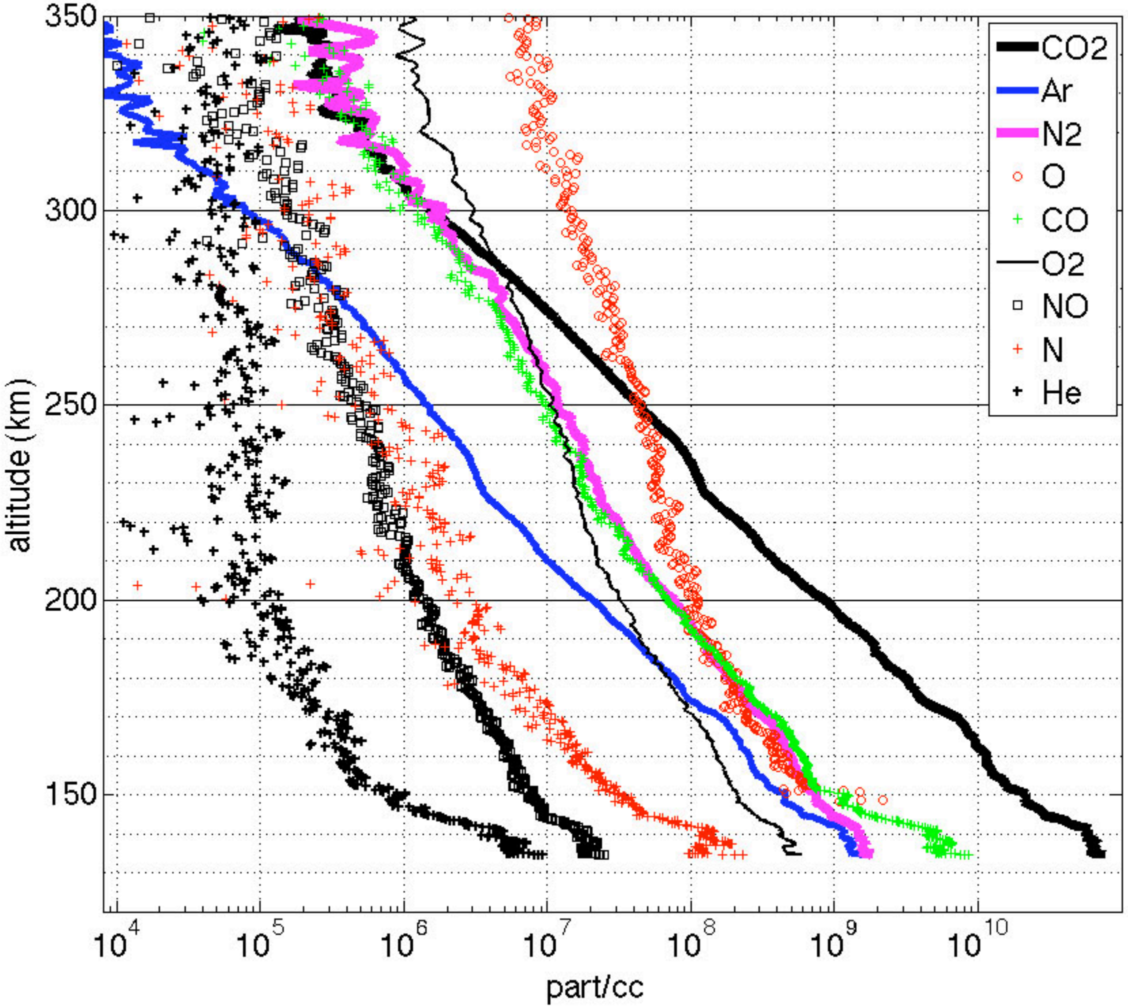
$O_2$: m=32 amu - H ≈ 24 km
O: m=16 amu - H ≈ 48 km
$N_2$: m=28 amu - H ≈ 27 km

| Earth | O | $O_2$ | $N_2$ |
|---|---|---|---|
| 100 km | 4% | 18% | 78% |
| 200 km | 58% | 2% | 40% |
| 300 km | 89% | 0.5% | 10.5% |

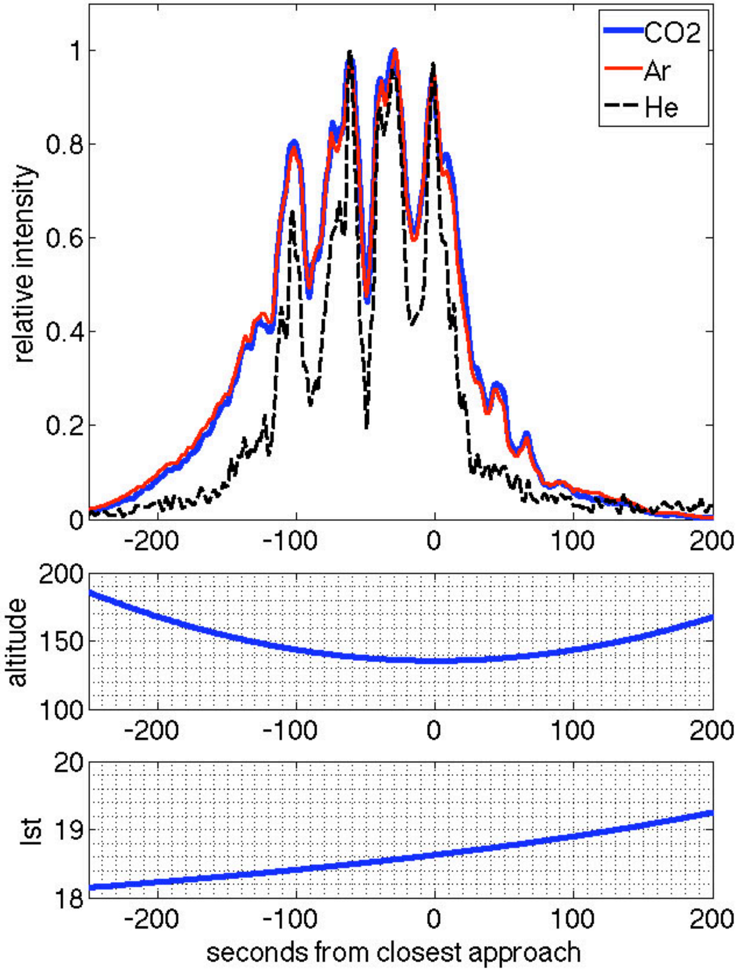
# Venus


Mean Molecular Mass
16
20
24
28
32
36
40
44
48
200
180
160
140
120
100
Altitude (km)
Day
SLT=12:00
Lat=0°
CO$_2$
O
CO
He
m
$10^{12}$
$10^{14}$
$10^{16}$
$10^{18}$
$10^{20}$
$10^{22}$
Density (m$^{-3}$)
Mean Molecular Mass
5
10
15
20
25
30
35
40
45
200
180
160
140
120
100
SLT=03:00
Lat=0°
CO$_2$
O
CO
He
m
Night
$10^{5}$
$10^{10}$
$10^{15}$
$10^{20}$
Density (m$^{-3}$)

# Mars

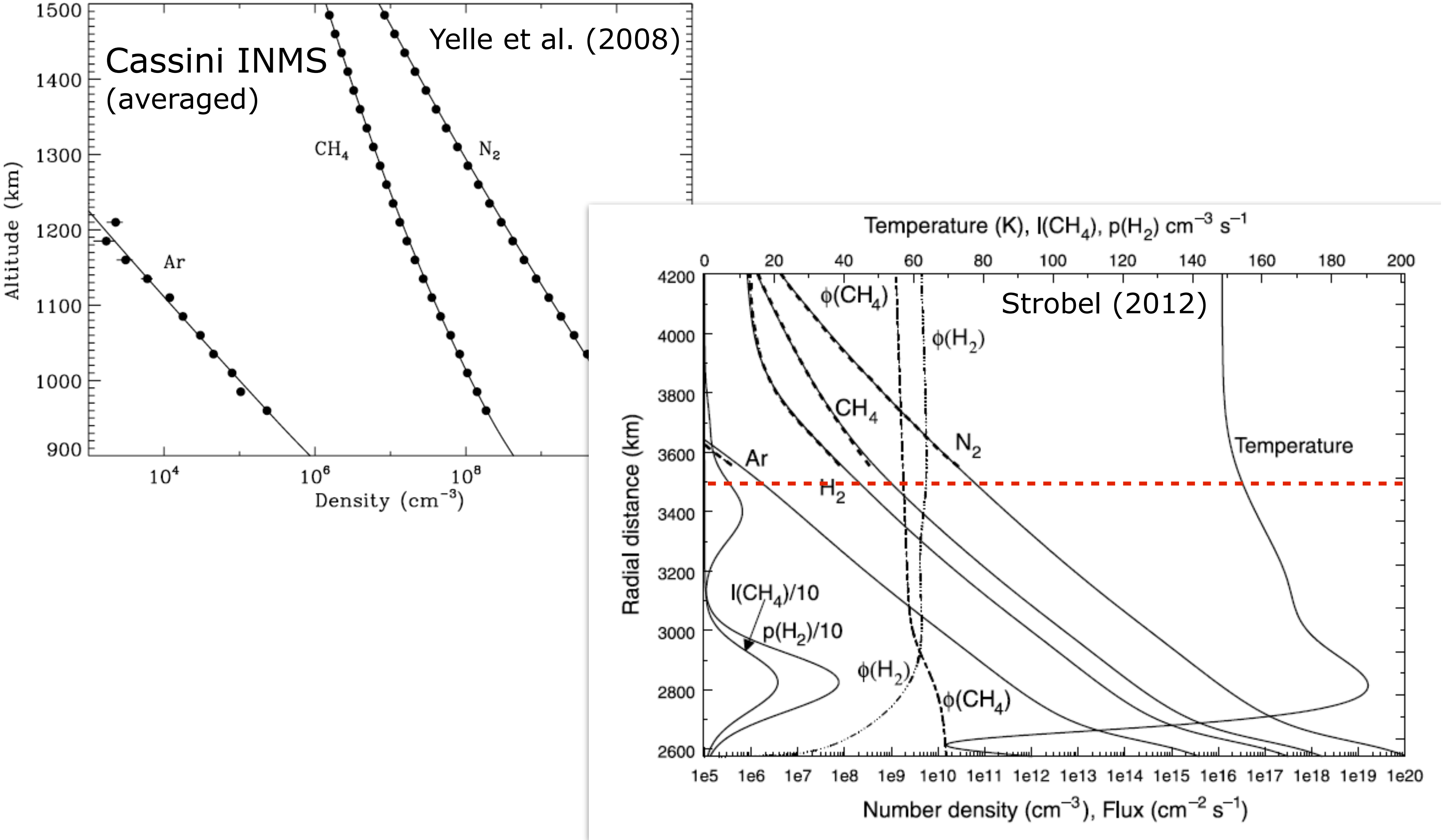


large waves!



Mahaffy et al. (2015)

# Titan



Cassini INMS (averaged)

Yelle et al. (2008)

Strobel (2012)

# Part 2: Energetics of atmospheres

# Possible energy sources

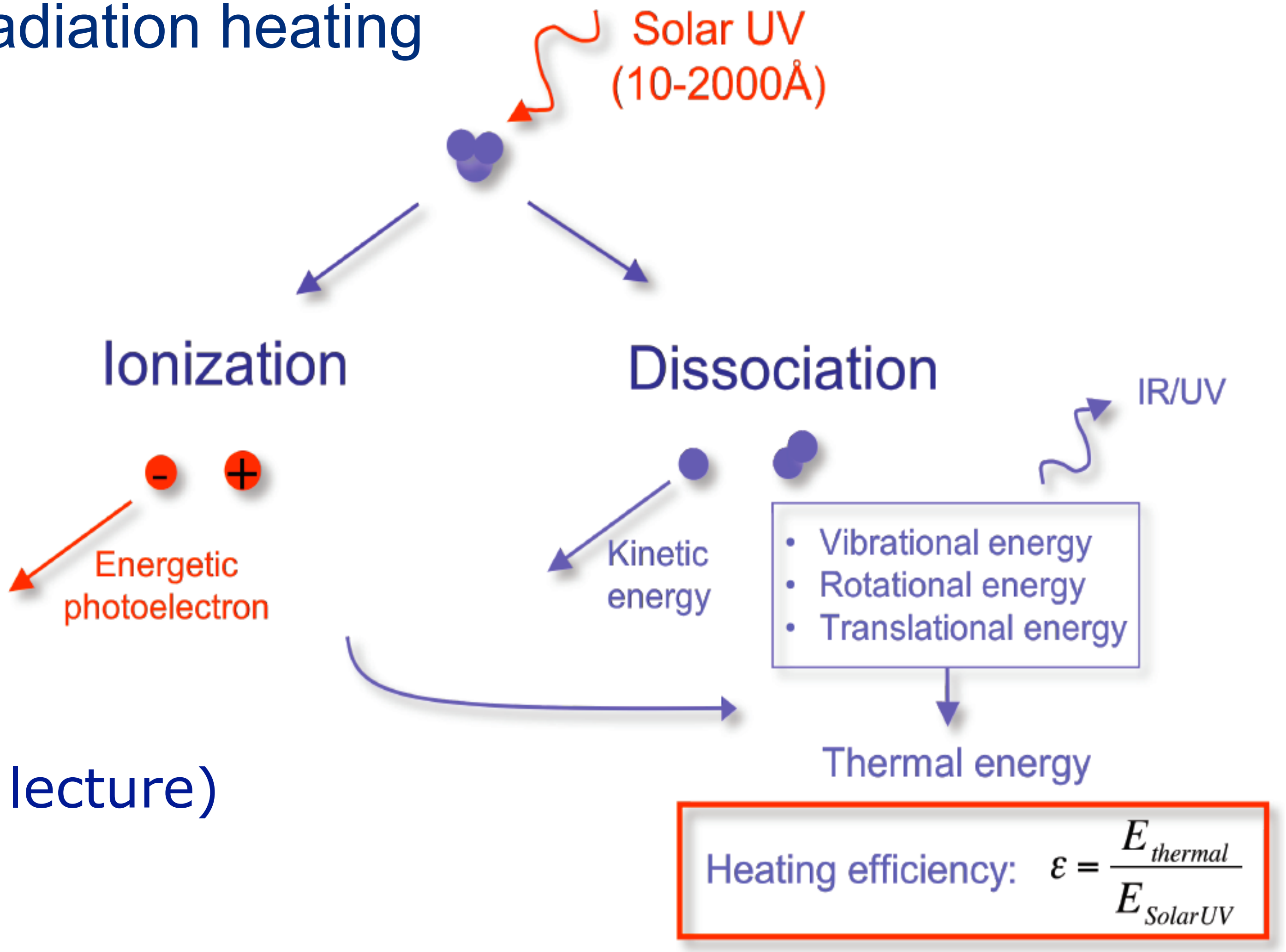
- Solar radiation heating

- Magnetosphere - atmosphere coupling: Joule heating & particle precipitation heating

- Upward propagating waves from below

# Possible energy sources (1)

- Solar radiation heating



Solar UV (10-2000Å)

Ionization

Dissociation

IR/UV

Energetic photoelectron

Kinetic energy

- Vibrational energy
- Rotational energy
- Translational energy

Thermal energy

Heating efficiency: $\varepsilon = \frac{E_{thermal}}{E_{SolarUV}}$

(Marina's lecture)

# Key chemistry in Earth's thermosphere

$O_2 + h\nu \rightarrow O(^3D) + O(^1D)$

$O_3 + h\nu \rightarrow O_2 + O$

$H_2O + h\nu \rightarrow H + OH$

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

$O + O + M \rightarrow O_2 + M + 5.12\ \mathrm{eV}$

$O + O_3 \rightarrow O_2 + O + 4.06\ \mathrm{eV}$

$O + OH \rightarrow O_2 + H + 0.72\ \mathrm{eV}$

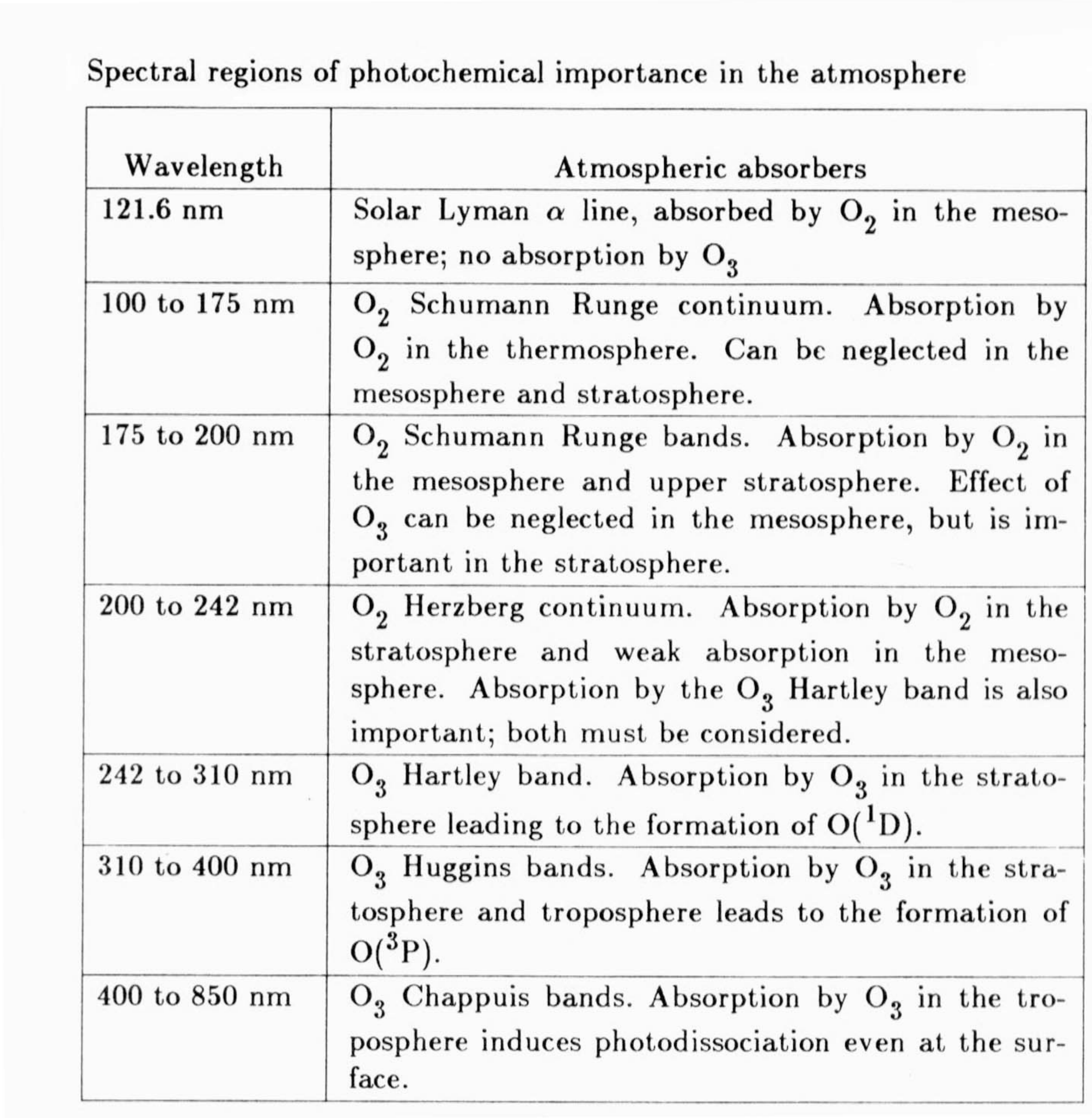
$N(^2D) + O_2 \rightarrow NO + O + 1.84\ \mathrm{eV}$

$N(^4S) + O_2 \rightarrow NO + O + 1.4\ \mathrm{eV}$

$N(^4S) + NO \rightarrow N_2 + O + 2.68\ \mathrm{eV}$

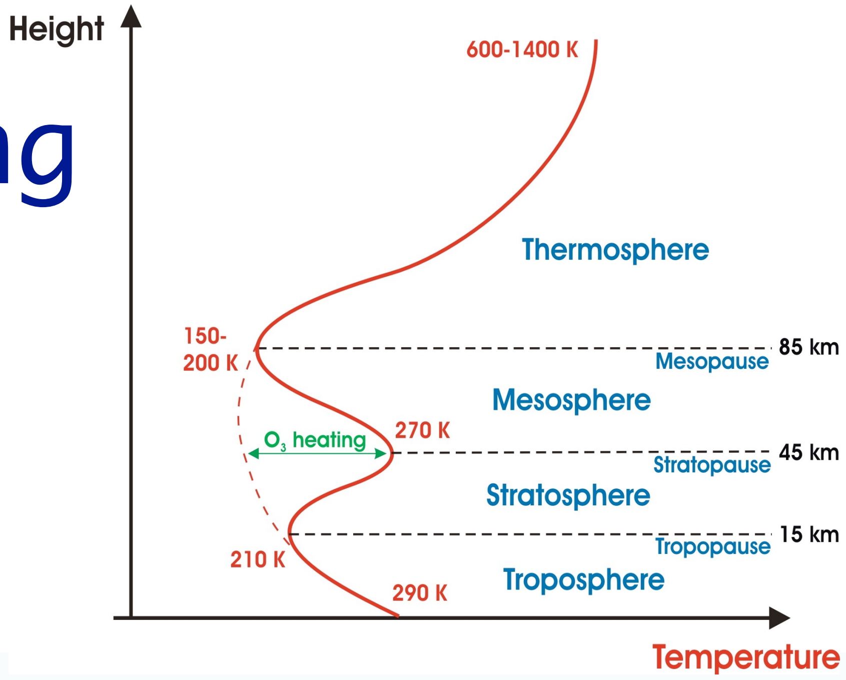
In essence, photon energy from the Sun is transformed into thermal energy via chemical reactions.

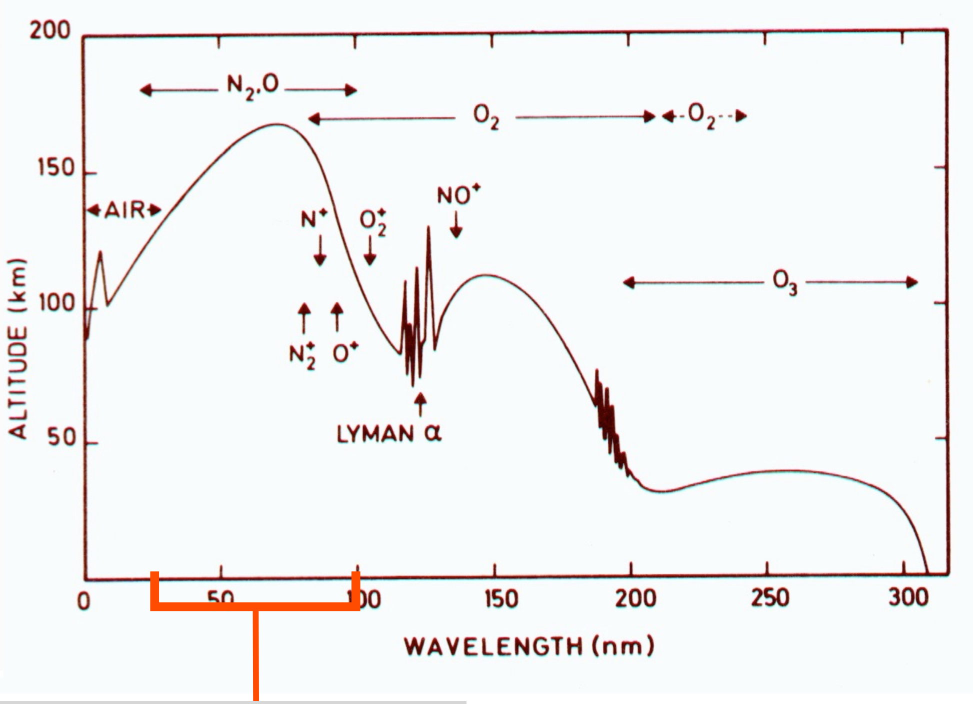
# Atmospheric heating



Spectral regions of photochemical importance in the atmosphere

| Wavelength | Atmospheric absorbers |
|---|---|
| 121.6 nm | Solar Lyman α line, absorbed by $O_2$ in the mesosphere; no absorption by $O_3$ |
| 100 to 175 nm | $O_2$ Schumann Runge continuum. Absorption by $O_2$ in the thermosphere. Can be neglected in the mesosphere and stratosphere. |
| 175 to 200 nm | $O_2$ Schumann Runge bands. Absorption by $O_2$ in the mesosphere and upper stratosphere. Effect of $O_3$ can be neglected in the mesosphere, but is important in the stratosphere. |
| 200 to 242 nm | $O_2$ Herzberg continuum. Absorption by $O_2$ in the stratosphere and weak absorption in the mesosphere. Absorption by the $O_3$ Hartley band is also important; both must be considered. |
| 242 to 310 nm | $O_3$ Hartley band. Absorption by $O_3$ in the stratosphere leading to the formation of $O(^1D)$. |
| 310 to 400 nm | $O_3$ Huggins bands. Absorption by $O_3$ in the stratosphere and troposphere leads to the formation of $O(^3P)$. |
| 400 to 850 nm | $O_3$ Chappuis bands. Absorption by $O_3$ in the troposphere induces photodissociation even at the surface. |

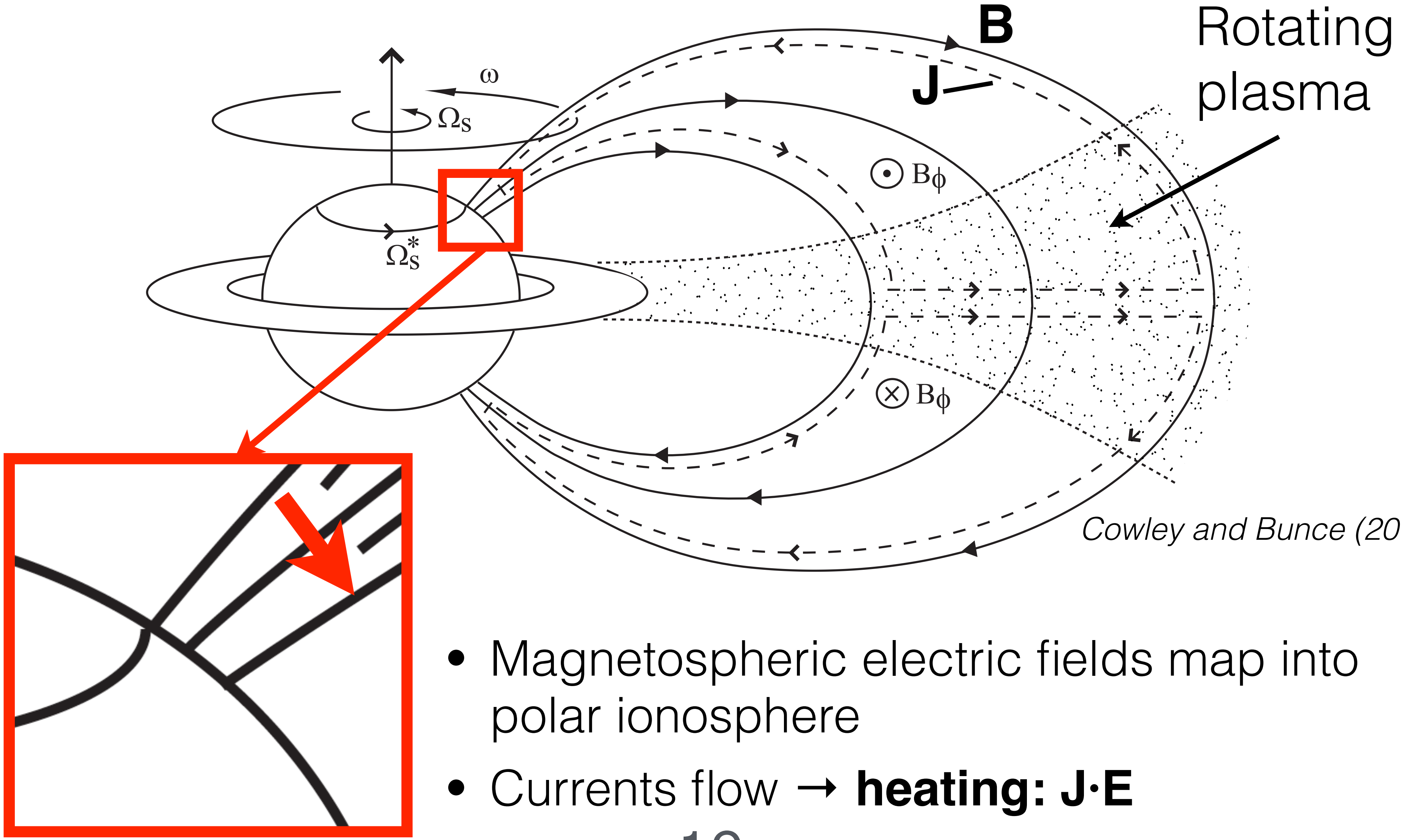




Ionization of O, $O_2$ , $N_2$

# Possible energy sources (2)

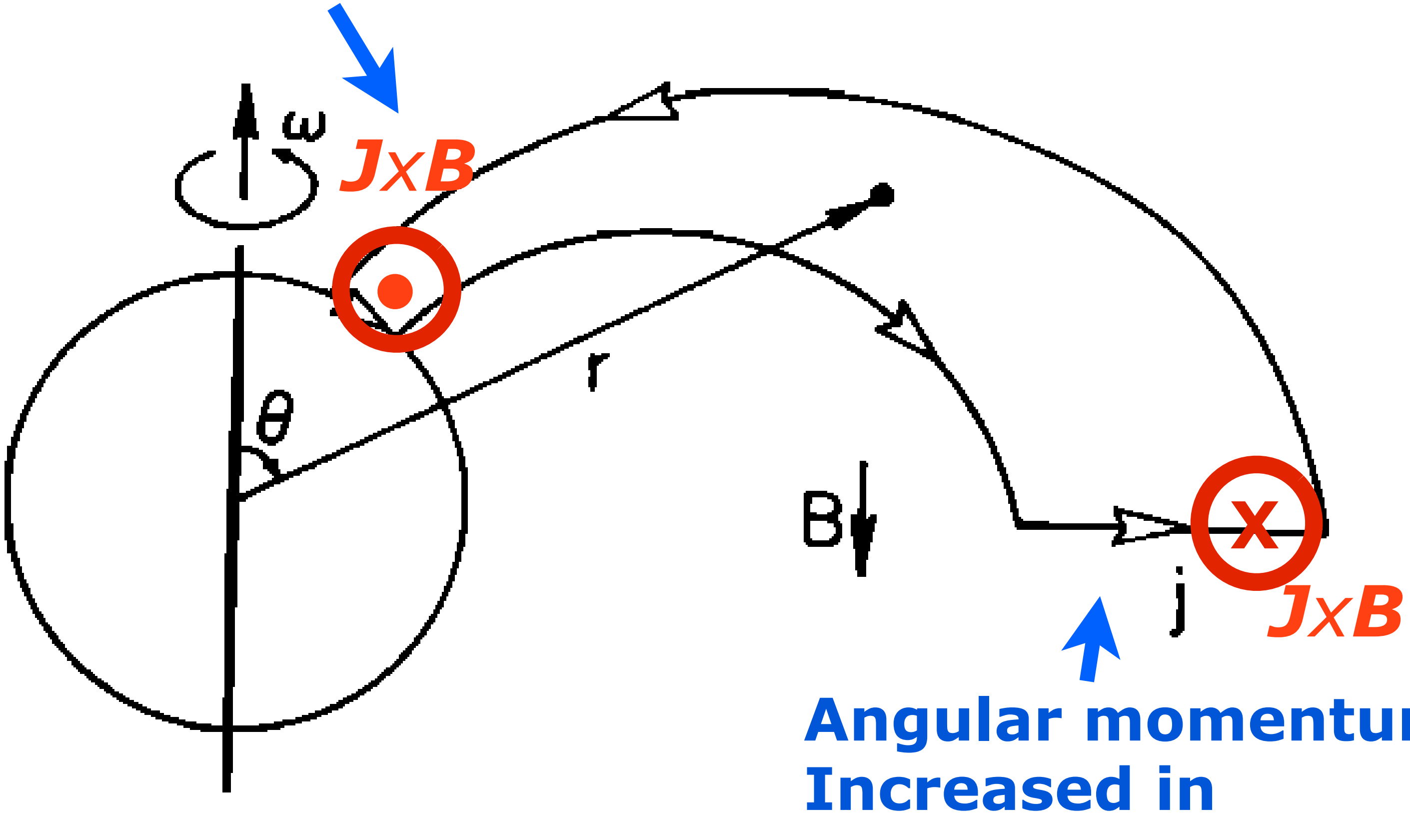
- Magnetosphere - atmosphere coupling: Joule heating



*Cowley and Bunce (2003)*

- Magnetospheric electric fields map into polar ionosphere
- Currents flow → **heating: J·E**

# Angular momentum transfer from atmosphere to magnetosphere

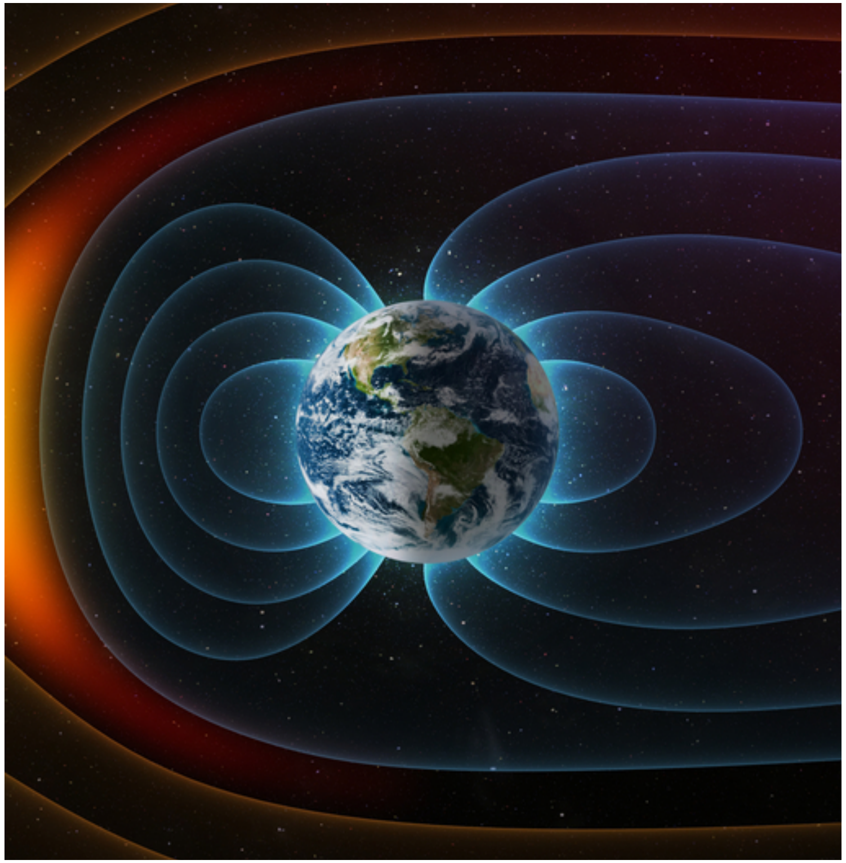


**Angular momentum Reduced in atmosphere**

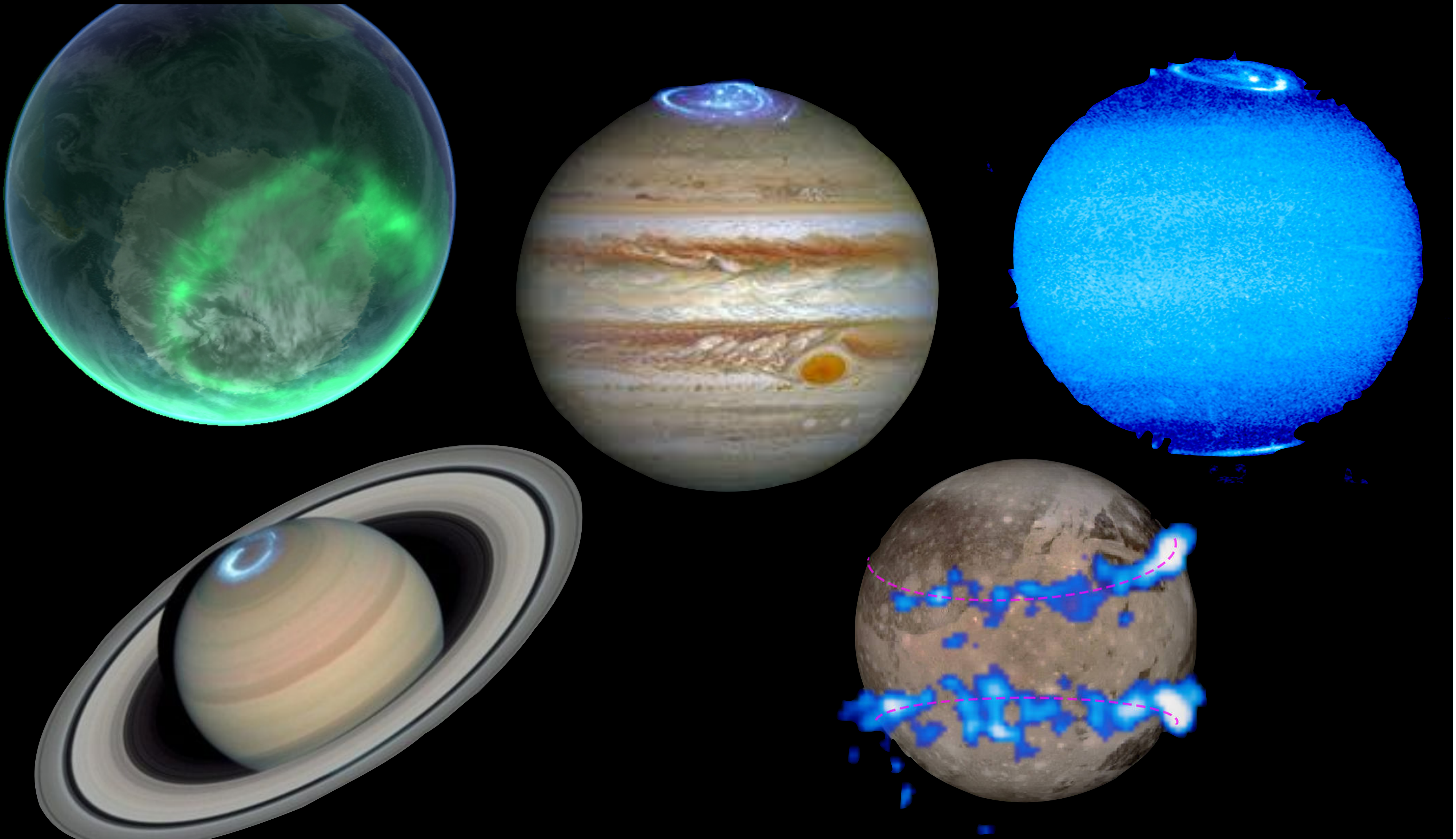
**Angular momentum Increased in magnetosphere**

# Energetic particle precipitation

- Magnetosphere processes also accelerate plasma, causing suprathermal electrons & protons to enter the upper atmosphere
- Since these travel along magnetic field lines, they enter the atmosphere at polar latitudes
- This excites atmospheric molecules and causes auroral emissions



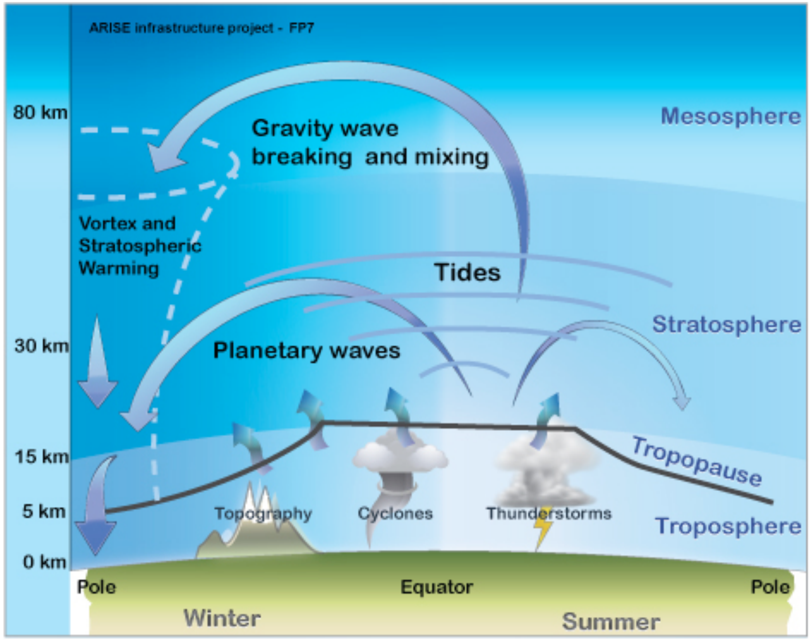
# Aurora: a TV screen of magnetosphere



# Possible energy sources (3)

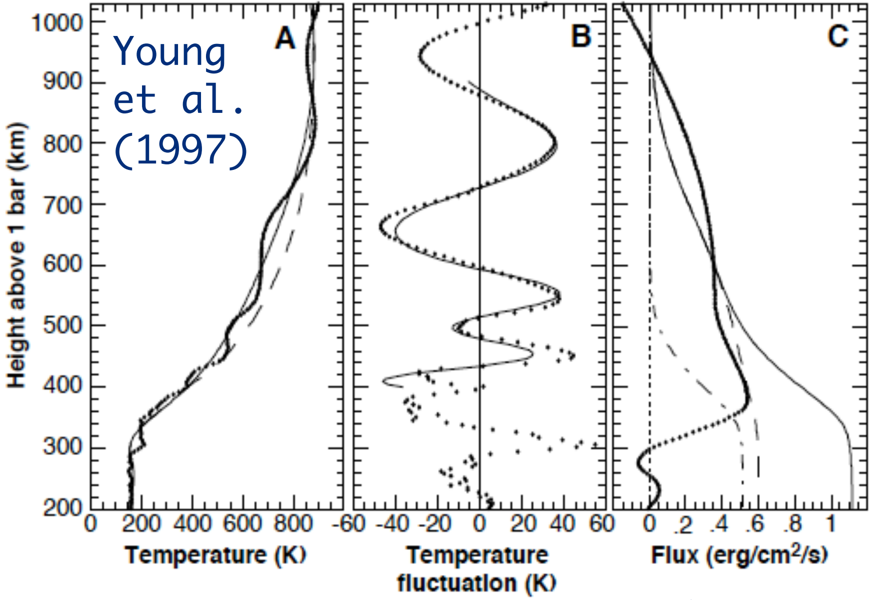
- Upward propagating waves from below

Earth



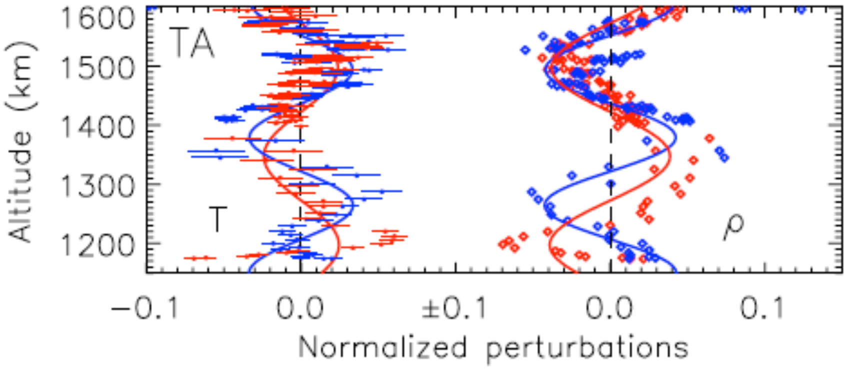
Upward propagating waves break and dissipate, releasing energy and momentum

Jupiter



Young et al. (1997)

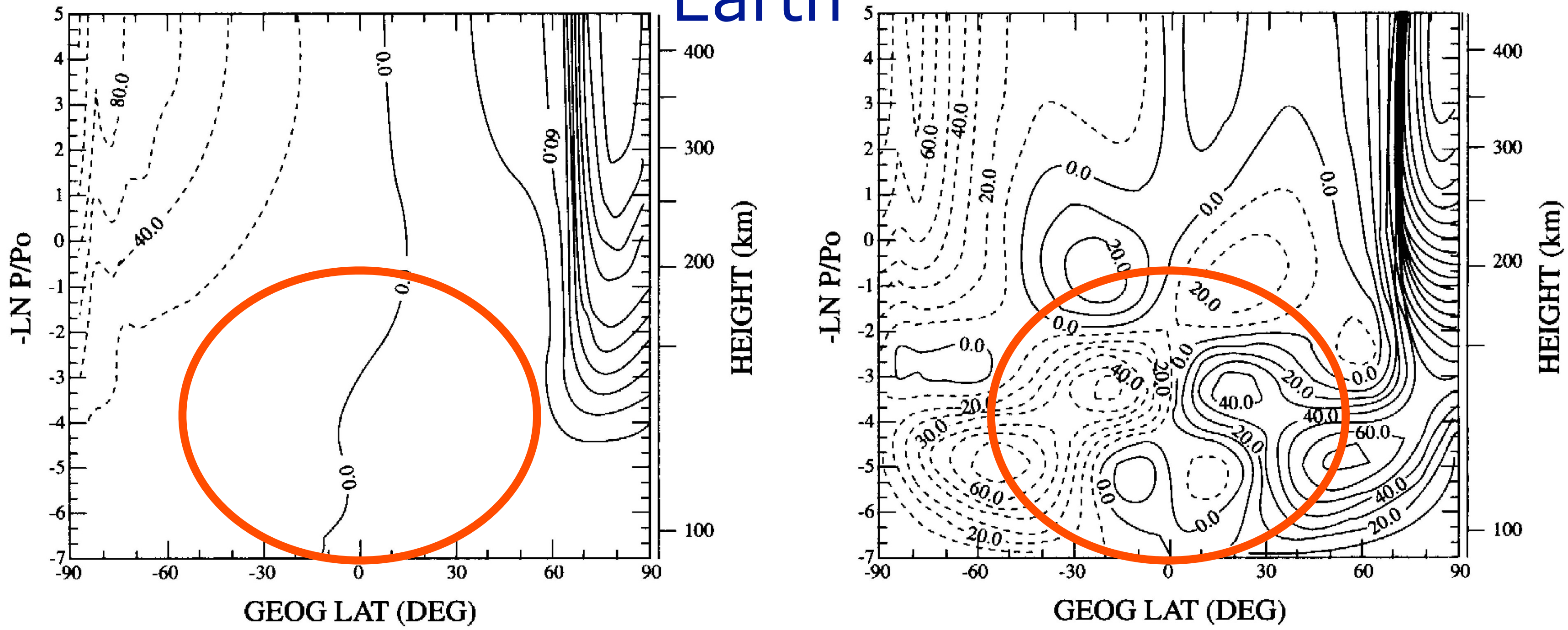
Titan



Mueller-Wodarg et al. (2006)

# Atmospheric waves also accelerate the background winds in the atmosphere

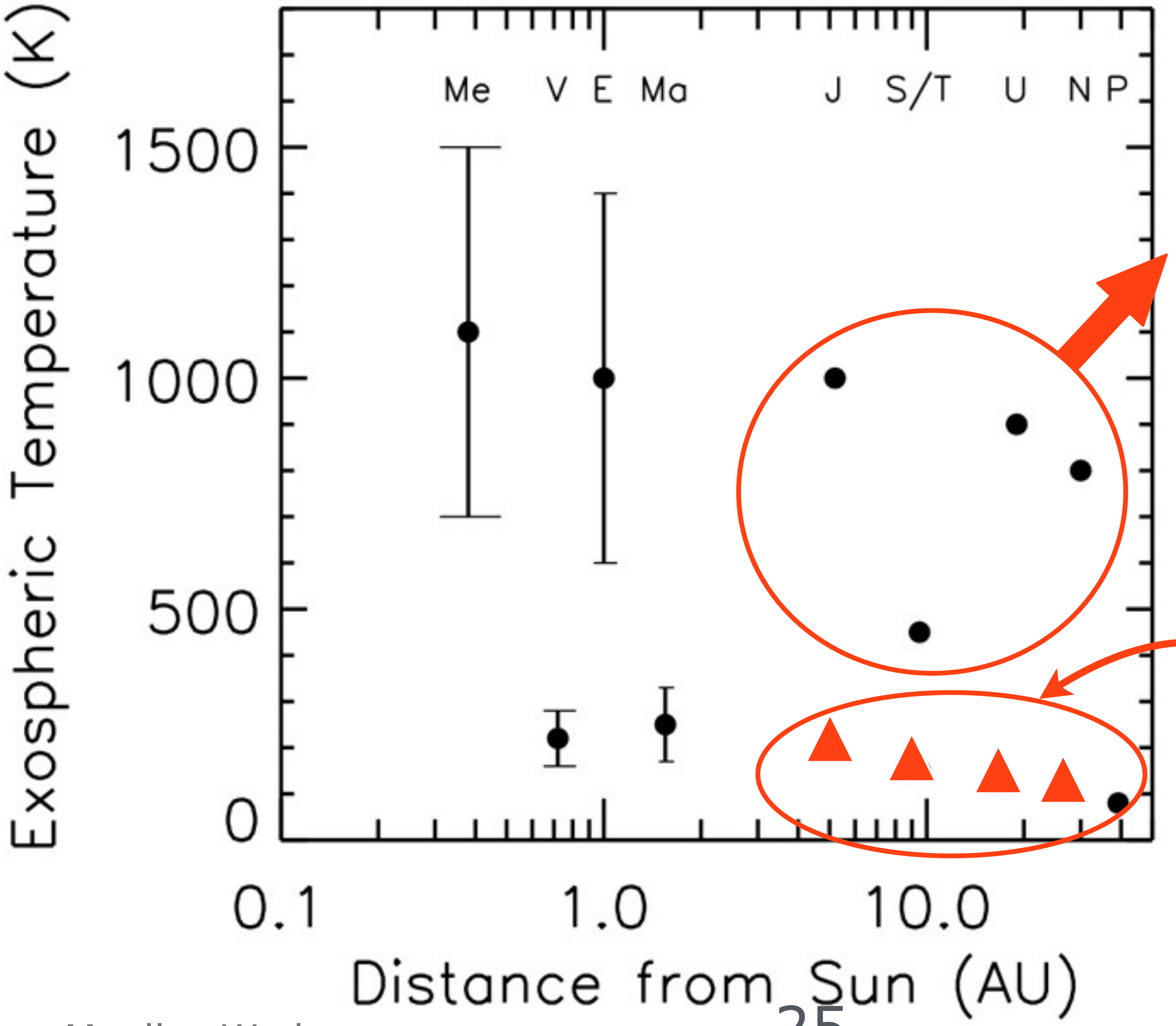
Earth



Zonally averaged meridional winds at 70°W and 18:00 UT for quiet-time conditions with (right) and without (left) tidal oscillations. Contours are positive southward.

Note how dissipating atmospheric waves dominate the low- to mid latitude thermosphere!

# Temperatures in solar system



Actual values:

Too hot!

→ "energy crisis"

Where does the missing energy come from?

Solar heating alone would give these temperatures

# Temperatures in solar system

| Planet | Solar EUV heating rate | Joule heating rate |
|---|---|---|
| Earth | 500 x $10^9$ W | 80 x $10^9$ W |
| Jupiter | 800 x $10^9$ W | 100,000 x $10^9$ W |
| Saturn | 200 x $10^9$ W | 2,000 x $10^9$ W |

So, is Joule heating our “missing energy” on Jupiter and Saturn?

And/or to atmospheric waves play a role?
(remember that they are one of 3 possible energy sources!)

# Take-home messages

- Exploring atmospheres on different planets helps us determine the universality of physical processes, improving our understanding of  Earth as well
- A basic understanding of terrestrial planets has evolved
- The outer solar system poses difficulties: Sun is no longer the elephant in the room and energetics become more messy.