2026.03.23

Introduction to Planetary Sciences

Lecture Notes

Textbook errata

Lecture 2026.03.02

Lecture 2026.03.09

Lecture 2026.03.16

Assignments

Assignment 1 (due 11:59 pm, Mar 20, 2026)

Assignment 2 (due 11:59 pm, Apr 10, 2026)

Assignment 3

Assignment 4

选课指导

课程通知

教学大纲

课程教参

教学内容

课外拓展

在线课堂

课堂实录

课程作业

创建内容 评估 工具 合作伙伴内容

assignment 1

assignment 2

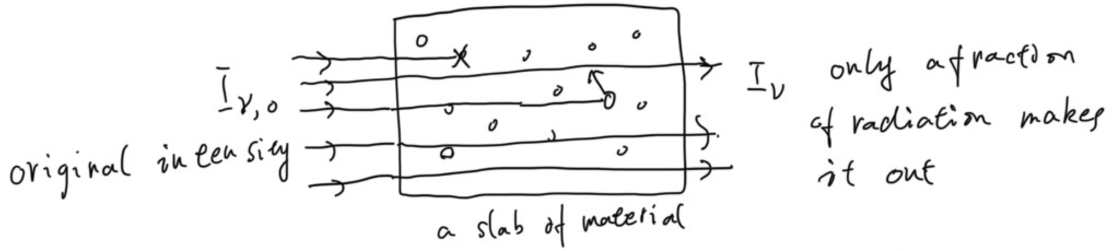
Absorption / Opacity / Optical Depth

(Loosely based on C.4.5)

Michael Richmond's lecture notes http://spiff.rit.edu/classes/phys440/lectures/optd/optd.html

Central question: The photons we see, where do they come from?

- Opacity κ_ν: the measure of impenetrability to radiation
  - It is a function of frequency ν
  - Note that the textbook uses α_ν (Eqn. 4.38)
- Optical depth
- Optically thin, optically thick
- Photosphere
- Additional reading
  - https://en.wikipedia.org/wiki/Photosphere
  - https://en.wikipedia.org/wiki/Opacity_(optics)
  - https://en.wikipedia.org/wiki/Optical_depth_(astrophysics)



e.g. 100 photons in ⟶ ⟶ 30 photons out

Q. what determines $I_\nu / I_{\nu,0}$? i.e., what fraction of light can go through?

when slab is thin. $dI_\nu = I_{\nu 0} - I_\nu = K_\nu \rho I_{\nu,0} ds$

the denser the material is (ρ)

the larger the distance the beam travels (ds)

the ability of absorbing light (K_ν)

K: opacity. Unit: L^2/m

$dI_\nu = -K_\nu \rho I_\nu ds$, $\frac{dI_\nu}{I_\nu} = -K_\nu \rho ds$, $\ln I_\nu \Big|_{I_{\nu,0}}^{I_\nu} = -\int K_\nu \rho ds$

$$I_\nu = I_{\nu 0} e^{-\int K_\nu \rho ds}$$

$\int K_\nu \rho ds = \tau_\nu$ optical depth

① when $\tau << 1$, $I_\nu = I_{\nu,0} e^{-\tau_\nu} = I_{\nu,0}(1-\tau_\nu)$ most photons make it

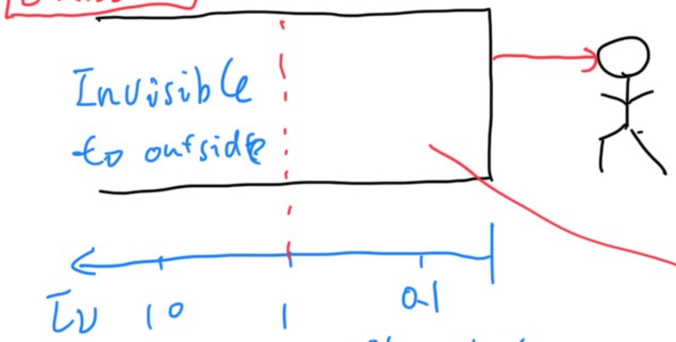
optically thin

② when $\tau >> 1$, $I_\nu = I_{\nu,0} e^{-\tau_0} << I_{\nu,0}$ almost no photons make it

optically thick

③ $\tau = 1$, $I_\nu = I_{\nu,0} e^{-1} = 0.37 I_{\nu,0}$

Emission



Q: where does this photon come from

most likely, this photon comes from the region $\tau_\nu \leq 1$

$e^{-0.1} = 90\%$ chance

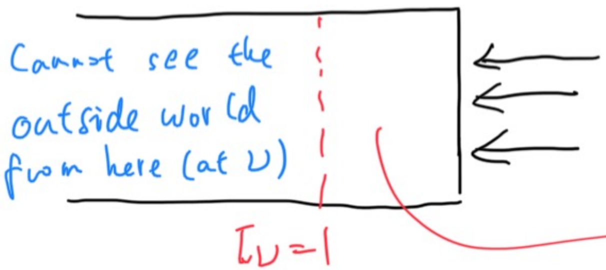
$e^{-1} = 37\%$

$e^{-10} < 0.01\%$

Photosphere: an object's outer shell from which light is radiated. $\tau_\nu(\text{photosphere}) = \frac{2}{3}$

$e^{-2/3} = 0.5$, 50% chance

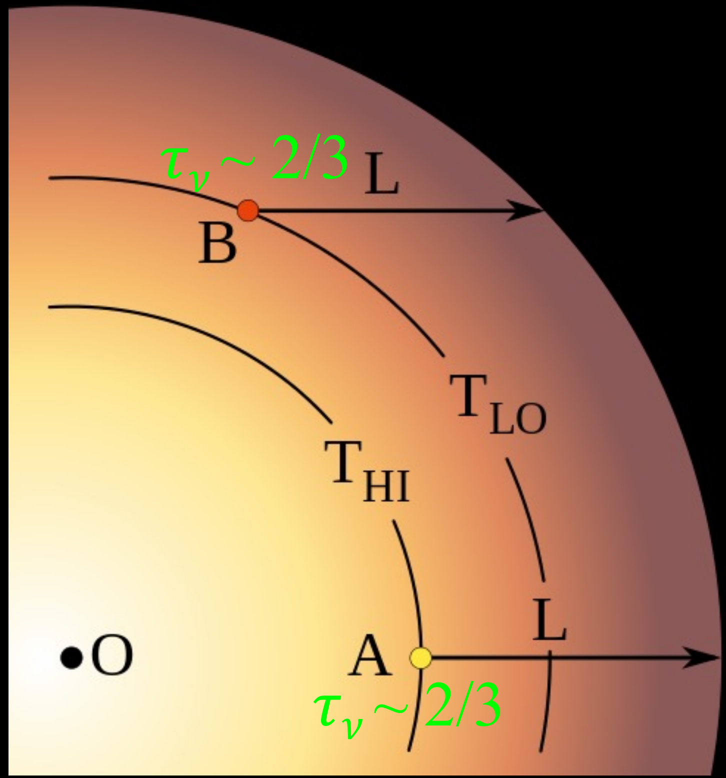
absorption



where is most radiation absorbed?

Similarly, most incident photons are stopped at $\tau_\nu \leq 1$

Limb Darkening



Temperature decreases outward in the solar atmosphere

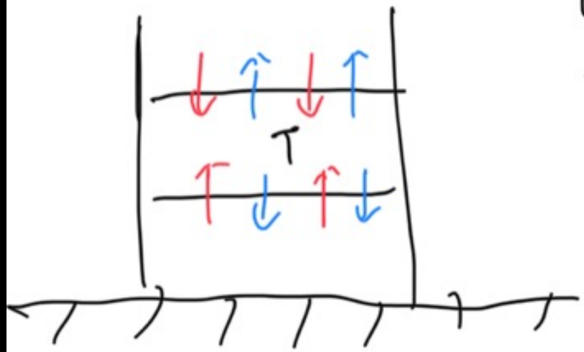
https://en.wikipedia.org/wiki/Limb_darkening

C.5 Planetary Atmosphere

- Goals: find the density, temperature, and composition at each location in the atmosphere.
- Two governing physical principles
  - Hydrostatic equilibrium $\frac{\partial p}{\partial z} + \rho g = 0.$ *# of equations? # of unknowns?*
    - Assuming g is known and independent of z *# of unknowns?*
    - Ideal gas law: $p = nkT$ *# of unknowns?*
    - ***Assuming*** composition is known and independent of z *# of unknowns?*
    - ***Assuming*** T is known and independent of z *# of unknowns?*
    - In reality, this is not always the case: composition and T can both be functions of z
  - Thermal equilibrium:

    [energy input per sec] + [energy output per sec] = 0

    - Primarily governed by the efficiency of energy transport.



Hydrostatic E. $\frac{dp}{dz} = -\rho g$

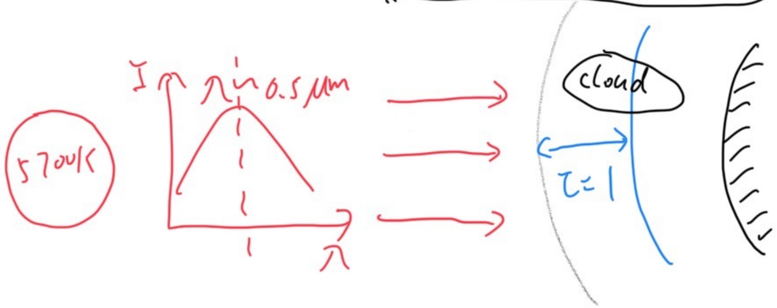
Thermal E $\rightarrow \frac{dT}{dt} = 0$

Heating = Cooling

Thermal Structure: Energy Sources and Possible Processes That may Affect Temperature

- Energy sources (C.5.1.1)
  - Solar radiation
    - Mainly optical , but EUV (100 – 10 nm) heating of the upper atmosphere is important
  - Re-radiation of sunlight by a planet's surface or atmospheric molecules, dust particles or cloud droplets (mainly IR)
  - Internal heat sources from below (e.g., volcanoes, geysers, release of gravitational energy, etc)
- Earth (P102):
  - nearly one-quarter of the solar radiation is absorbed by the atmosphere;
  - nearly half is absorbed at the surface;
  - nearly one third is reflected back to space
- Other processes
  - Chemical reactions in an atmosphere change its composition, which leads to changes in opacity and hence thermal structure.
  - Chemical interactions between the atmosphere and the crust or ocean.
  - Clouds and/or photochemically produced haze layers scatter incident light, affecting the energy balance.
  - Biochemical and anthropogenic processes.

Atmosphere absorption



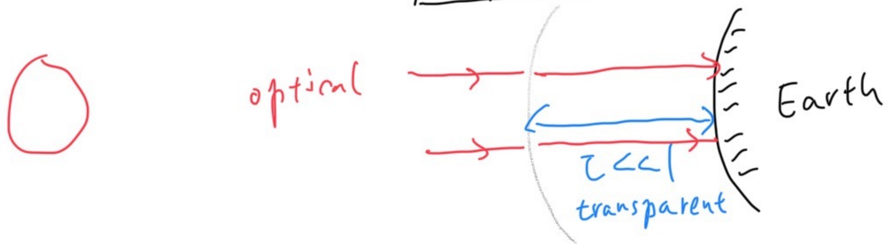
$I = I_0 e^{-\tau}$

$\tau = K \cdot l$

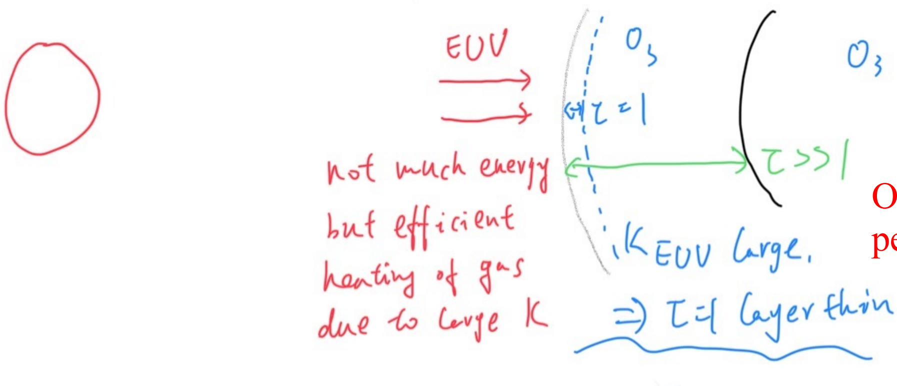
At $\tau = 1$, $I = 0.37 I_0$

63% energy absorbed

Surface absorption



EUV heating of the upper atmosphere



O_3 depletion

O3 depletion → EUV penetration & reach the ground

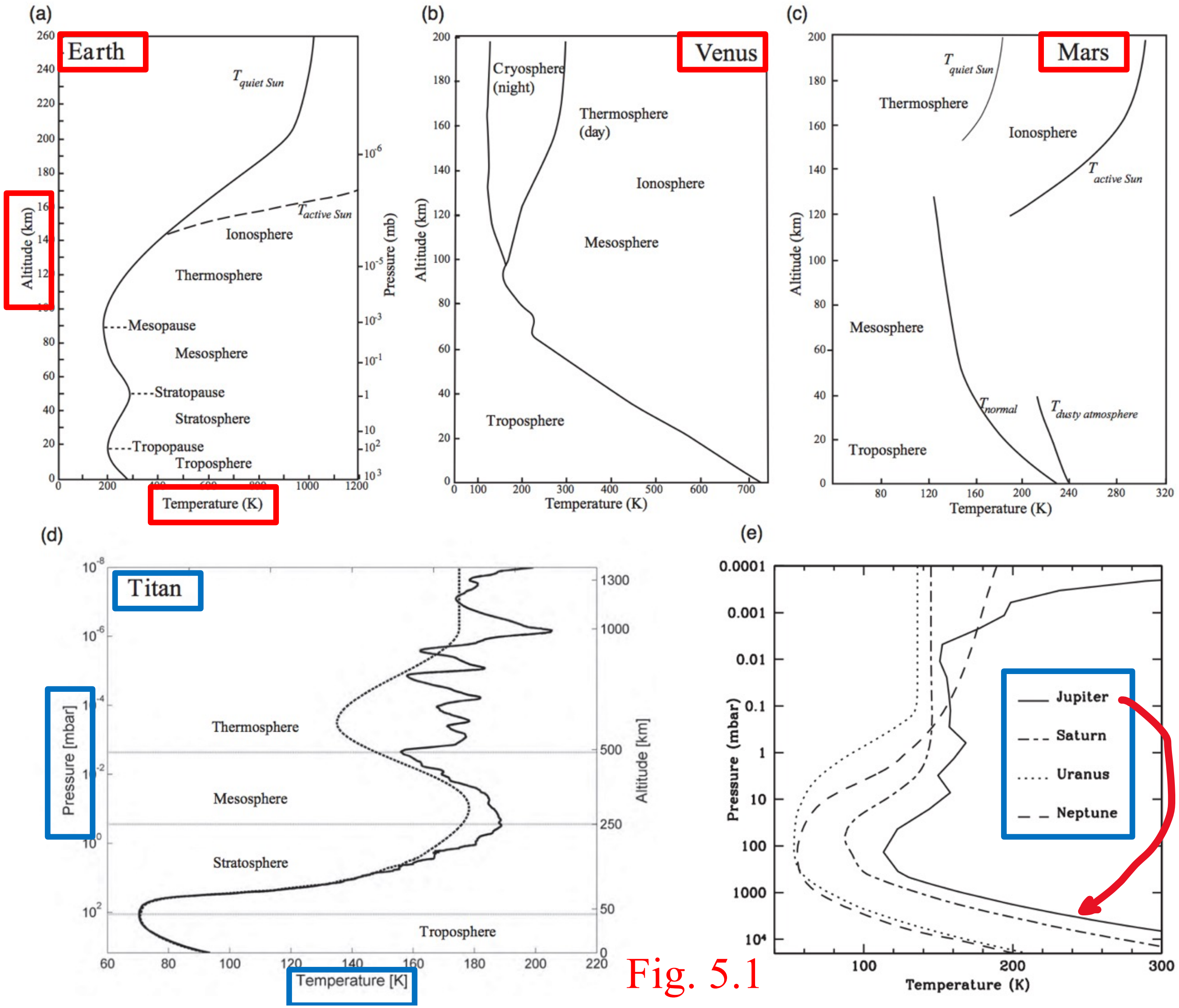
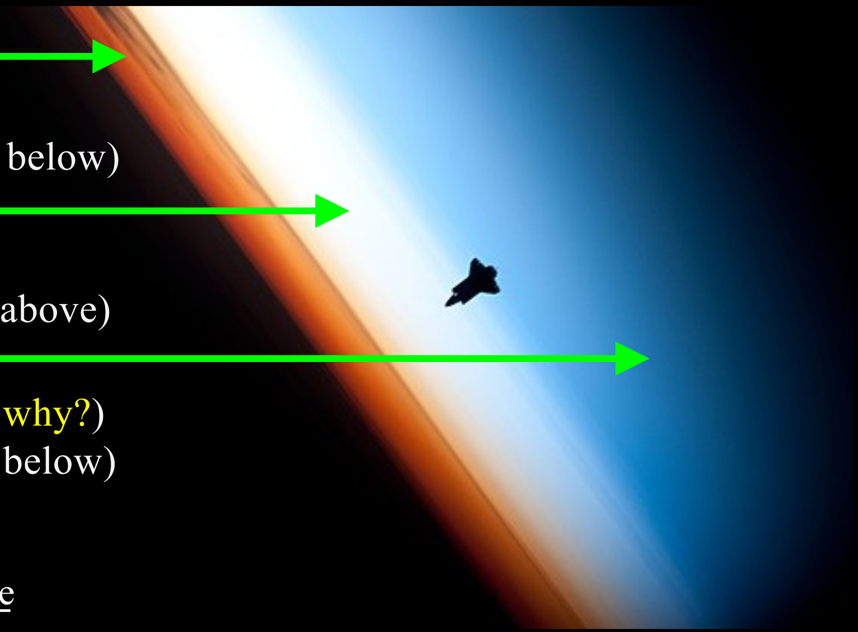

(a)
Earth
$T_{quiet\ Sun}$
$T_{active\ Sun}$
Ionosphere
Thermosphere
Mesopause
Mesosphere
Stratopause
Stratosphere
Tropopause
Troposphere
Altitude (km)
Pressure (mb)
Temperature (K)
(b)
Venus
Cryosphere
(night)
Thermosphere
(day)
Ionosphere
Mesosphere
Troposphere
Altitude (km)
Temperature (K)
(c)
Mars
$T_{quiet\ Sun}$
Thermosphere
Ionosphere
$T_{active\ Sun}$
Mesosphere
T_{normal}
$T_{dusty\ atmosphere}$
Troposphere
Altitude (km)
Temperature (K)
(d)
Titan
Thermosphere
Mesosphere
Stratosphere
Troposphere
Pressure [mbar]
Altitude [km]
Temperature [K]
(e)
Jupiter
Saturn
Uranus
Neptune
Pressure (mbar)
Temperature (K)

Fig. 5.1

Layers in the Earth's Atmosphere

- Troposphere: 0 – 10 km
  - Convection
  - T decreases with z (heating from below)
- Stratosphere: ~ 10 – 50 km
  - Ozone layer
  - T increases with z (heating from above)
- Mesosphere: ~ 50 – 100 km
  - Least understood (inaccessible – why?)
  - T decreases with z (heating from below)



- https://en.wikipedia.org/wiki/Troposphere
- https://en.wikipedia.org/wiki/Tropopause
- https://en.wikipedia.org/wiki/Stratosphere
- https://en.wikipedia.org/wiki/Mesosphere
- https://en.wikipedia.org/wiki/Thermosphere

Space Shuttle Endeavour / NASA

Table E.9 Basic Atmospheric Parameters for the Giant Planets[a]

Parameter	Jupiter	Saturn	Uranus	Neptune
Mean heliocentric distance (AU)	5.203	9.543	19.19	30.07
Geometric albedo (A_0)	0.52	0.47	0.51	0.41
Bond albedo	0.343 ± 0.032	0.342 ± 0.030	0.290 ± 0.051	0.31 ± 0.04
Effective temperature (K)	124.4 ± 0.3	95.0 ± 0.4	59.1 ± 0.3	59.3 ± 0.8
Equilibrium temperature (K)	110	81	58	46
Temperature ($P = 1$ bar) (K)	165.0	134.8	76.4	71.5
Tropopause temperature (K)	111	82	53	52
Mesosphere temperature (K)	160–170	150	140–150	140–150
Exobase temperature (K)	900–1300	800	750	750
Tropopause pressure (mbar)	140	65	110	140
Scale height (at 1 bar) (km)	24	47	25	23
Adiabatic lapse rate (K/km)	2.1	0.9	1.0	1.3
Energy balance[b]	1.63 ± 0.08	1.87 ± 0.09	1.05 ± 0.07	2.68 ± 0.21

?

Table E.10 Basic Atmospheric Parameters for Venus, Earth, Mars and Titan[a]

Parameter	Venus	Earth	Mars	Titan
Mean heliocentric distance (AU)	0.723	1.000	1.524	9.543
Geometric albedo A_0	0.84	0.367	0.15	0.21
Bond albedo	0.75	0.306	0.25	0.20
Surface temperature (K)	737	288	215	93.7
Equilibrium temperature (K)	232	255	210	85
Exobase temperature (K)	270–320	800–1250	200–300	149
Surface pressure (bar)	92	1.013	0.00636	1.47
Scale height at surface (km)	16	8.5	11	20
Adiabatic lapse rate (K/km)	10.4	9.8	4.4	1.4

Atmosphere Composition (C.5.2)

- How to measure the composition of a planetary atmosphere?
  - Remote sensing / spectrum
  - Mars & Venus: 95-97% CO_2

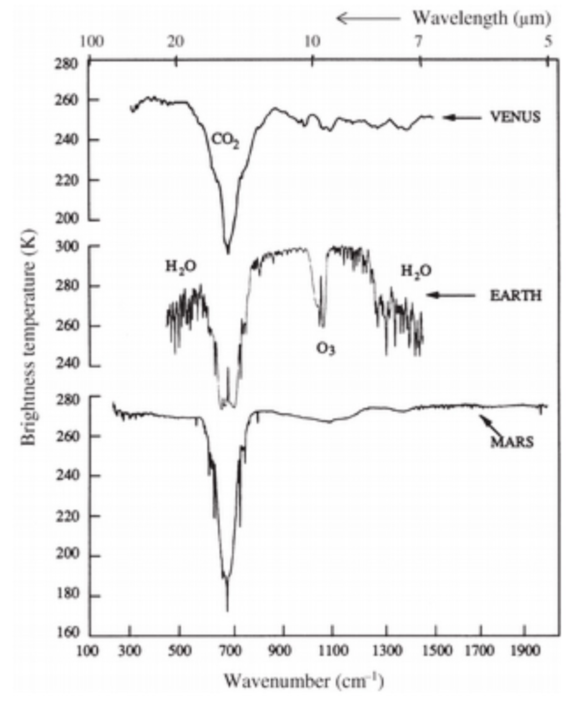
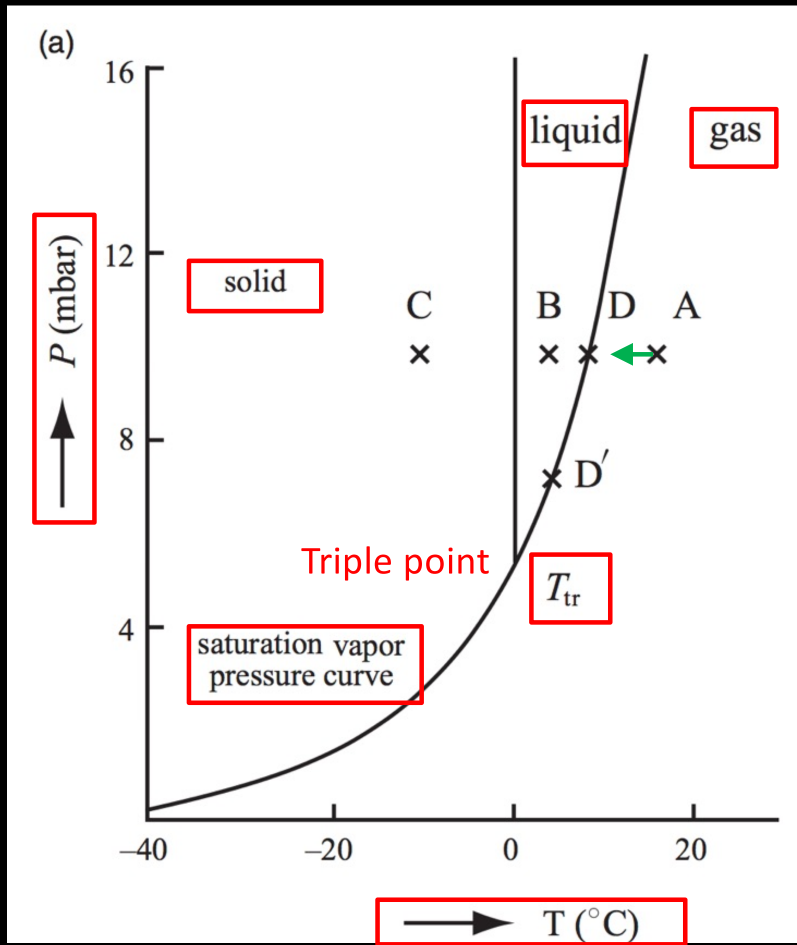


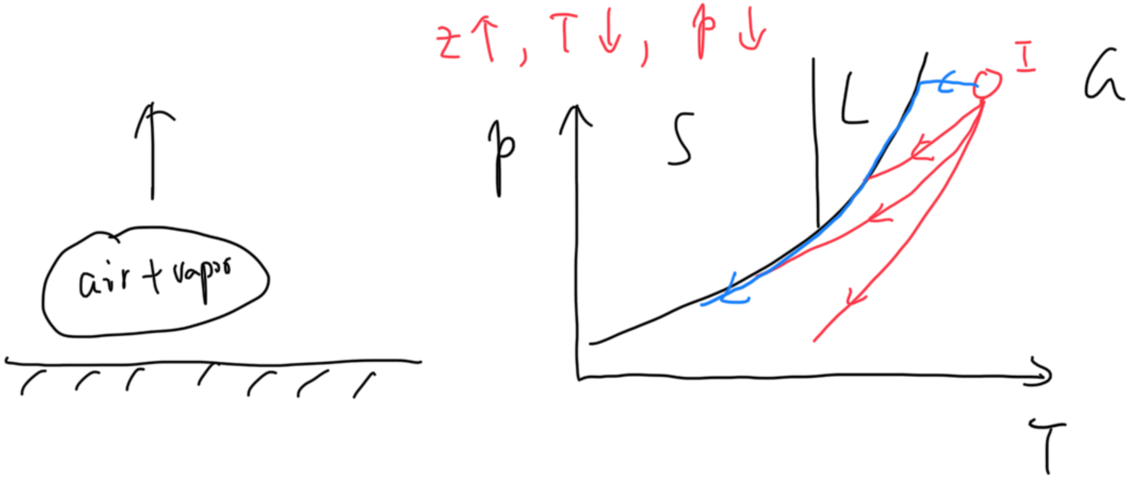
Figure 5.2 Thermal infrared emission spectra of Venus, Earth and Mars. The Venus spectrum was recorded by *Venera 15*, the spectrum of the Earth by *Nimbus 4* and that of Mars by *Mariner 9*. (Adapted from Hanel et al. 1992)

  - In situ probe
    - Venus, Mars, Jupiter, Moon, Titan, Mercury, Enceladus

Cloud Formation (C.5.3)

Figure 5.4
Discussion on P119





cloud formation

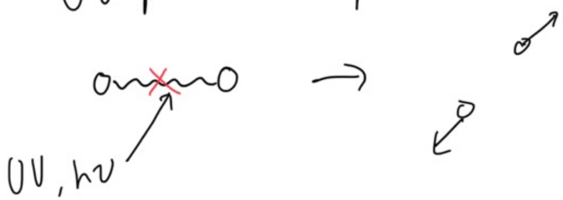
C.5.4 Meteorology (skip)

C.5.5 Photochemistry

C.5.6 Molecular and Eddy Diffusion (skip)

Ozone (C.5.5.1)

UV photons can photo dissociate molecule



$O_2 + h\nu \to O + O$, $\lambda < 175$ μm ①

$O + O \to O_2 + h\nu$ ②

$O + O + M \to O_2 + M$ ③

$O + O_2 + M \to O_3 + M$ ozone ④

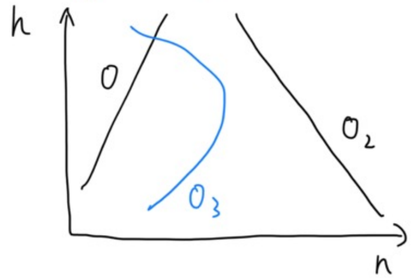
$O_3 + h\nu \to O_2 + O$, $\lambda \leq 310$ μm ⑤ why ozone is important

$O_3 + O \to 2O_2$ ⑥

④ generates O_3
⑤, ⑥ destroys O_3
} chemical equilibrim, net changes = 0

$$\frac{d\,n(O_3)}{dt} = 0 \Rightarrow n(O_3)$$

④ : $O + O_2$



O_2: $h\uparrow$, $n(O_2)\downarrow$

O: $h\uparrow$, $UV\uparrow$, $O\uparrow$

④ $\to O_3$, need both O and O_2

h too high, bad; h too low, bad

$n(O_3)$ peaks at intermediate h

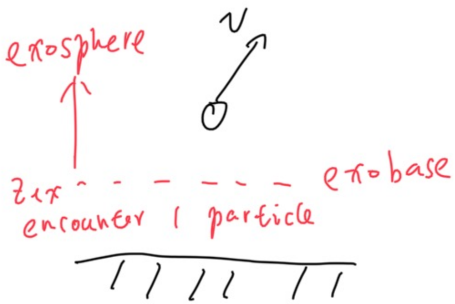
Atmospheric Escape (5.7)

- Thermal (Jeans) Escape
  - Mean free path: the average distance travelled by a moving particle between successive collisions
  - https://en.wikipedia.org/wiki/Mean_free_path

Q: Could this particle escape the planet?

A: ① $v > v_{escape}$

② no collision



Mean free path in uniform medium

$$l_{fp} \cdot \sigma \cdot n = 1$$

molecular cross section (σ)

particle density (n)

Ununiform medium: $\int_0^{l_{fp}} \sigma\, n(l)\, dl = 1$

$$\int_{z_{ex}}^{\infty} \sigma\, n(z)\, dz = \sigma \int_{z_{ex}}^{\infty} n(z)\, dz, \quad n(z) = n(z_{ex})\, e^{-\frac{z - z_{ex}}{H}}$$

$\int_{z_{ex}}^{\infty} \sigma\, n(z)\, dz$ ||| 1

$$= \sigma \int_{z_{ex}}^{\infty} n(z_{ex})\, e^{-\frac{z - z_{ex}}{H}} dz$$

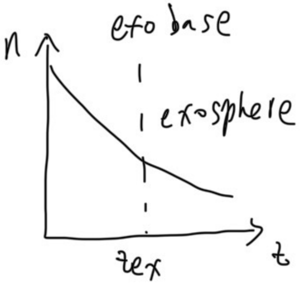
$$(5.11) \cdots = \sigma\, n(z_{ex}) \int_{z_{ex}}^{\infty} e^{-\frac{z - z_{ex}}{H}} dz = \boxed{\sigma\, n(z_{ex}) H = 1}$$

$$-H e^{-\frac{z}{H}} \Big|_0^{\infty} = H$$

⇓ z_{ex}

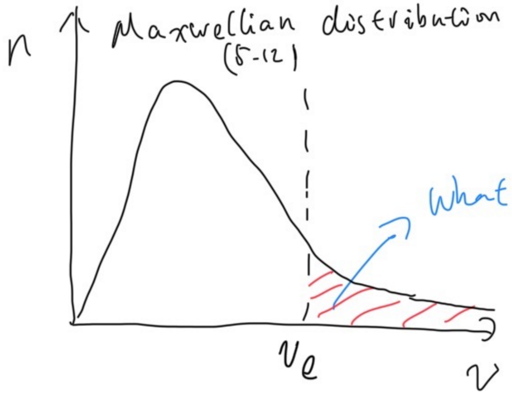
Earth: a few 100 km

$$f(v)dv = N\left(\frac{2}{\pi}\right)^{1/2}\left(\frac{m}{kT}\right)^{3/2} v^2 e^{-mv^2/(2kT)}dv. \tag{5.12}$$



OK, this is about the location of exobase

What's the rate of mass loss from the exosphere?



$v \uparrow,\ n \downarrow$

What fraction of particles have a velocity $v > v_e$?

integration $\int_{v_e}^{\infty} \cdots$

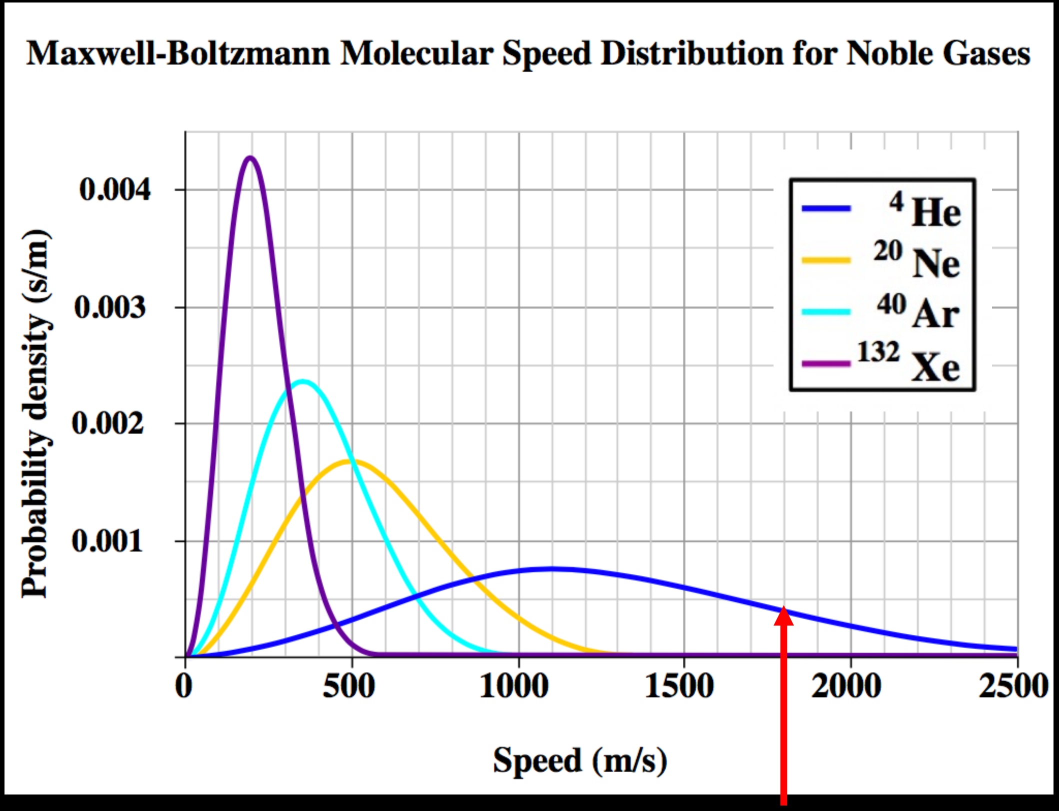
$$\phi_J = \frac{N_{ex} v_0}{2\sqrt{\pi}}(1+\lambda_{esc})e^{-\lambda_{esc}}, \quad \lambda_{esc} = \left(\frac{v_e}{v_0}\right)^2 \text{ escape para}$$

Jeans formula (5.14), atoms/s/cm^2 $\quad v_0 = \sqrt{2kT/m}$

Atmospheric Escape (5.7)

- Thermal (Jeans) Escape
  - Mean free path: the average distance travelled by a moving particle between successive collisions
  - https://en.wikipedia.org/wiki/Mean_free_path
- Helium is a non-renewable resource
  - He is easy to escape, for two reasons
    - He atoms can reach high velocities
    - He makes up a good fraction of the atmosphere in the exosphere

Reason I



The probability density functions of the speeds of a few noble gases at a temperature of 298.15 K (25 °C).

He atoms can reach very high velocities!

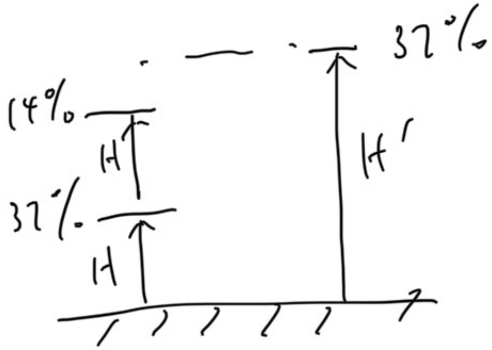
Wiki
https://en.wikipedia.org/wiki/Maxwell–Boltzmann_distribution

$$\rho = \rho_0 e^{-\frac{z}{h}}$$

$$h = \frac{kT}{mg}$$

molecular weight

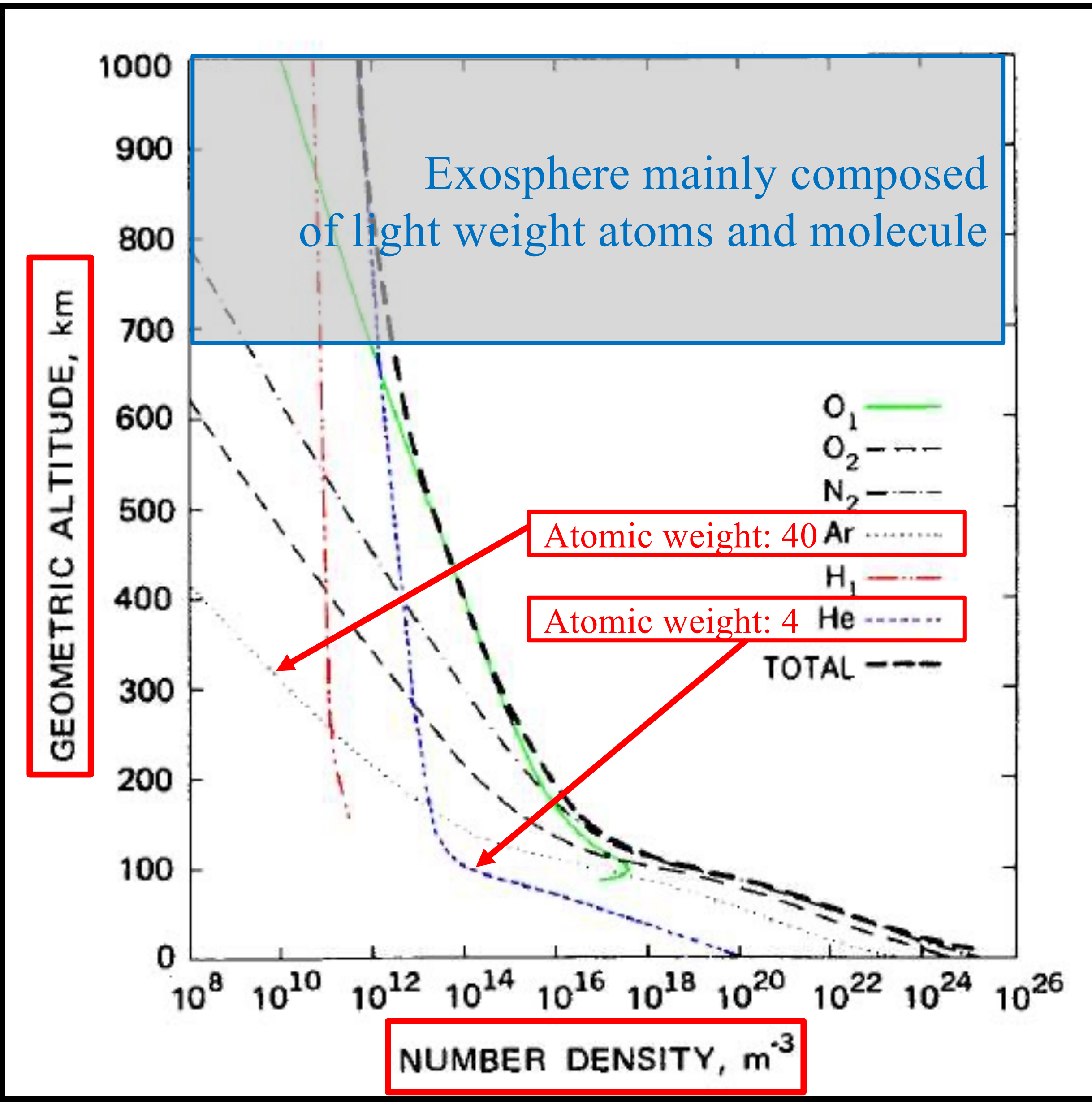
Have ppl thought about, why use "mean" molecular weight?



$$\frac{1}{2}mv^2 \simeq kT \Longrightarrow m\downarrow, \ v\uparrow$$

same for all particles

Reason II



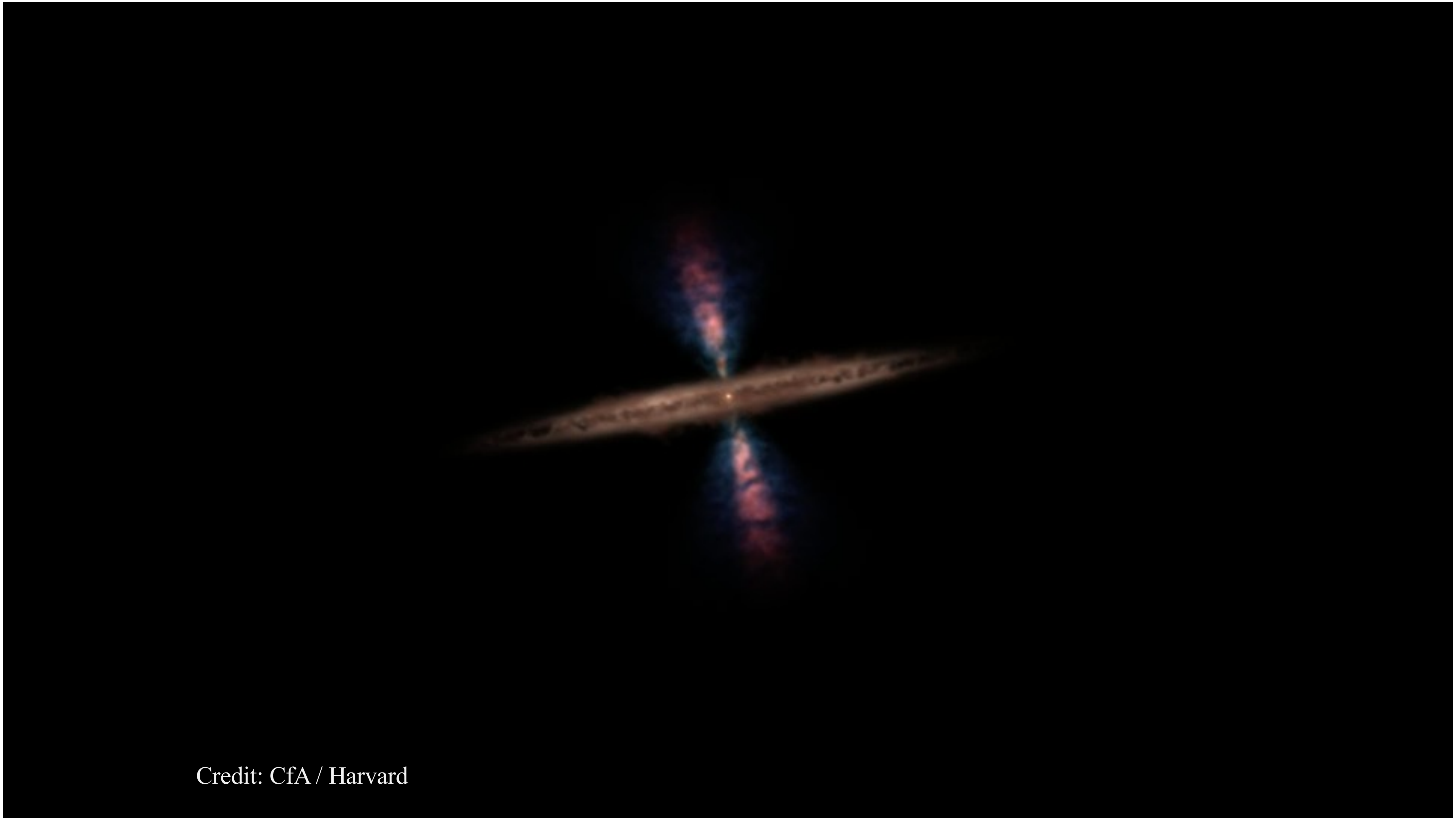
U.S. Standard Atmosphere

Atmospheric Escape (5.7)

- Thermal (Jeans) Escape
  - Mean free path: the mean free path is the average distance travelled by a moving particle between successive collisions
  - https://en.wikipedia.org/wiki/Mean_free_path
- Helium is a non-renewable resource
- Hydrodynamic Escape
  - https://en.wikipedia.org/wiki/Hydrodynamic_escape
- Hot Jupiter

Origin of atmosphere (C.5.8)

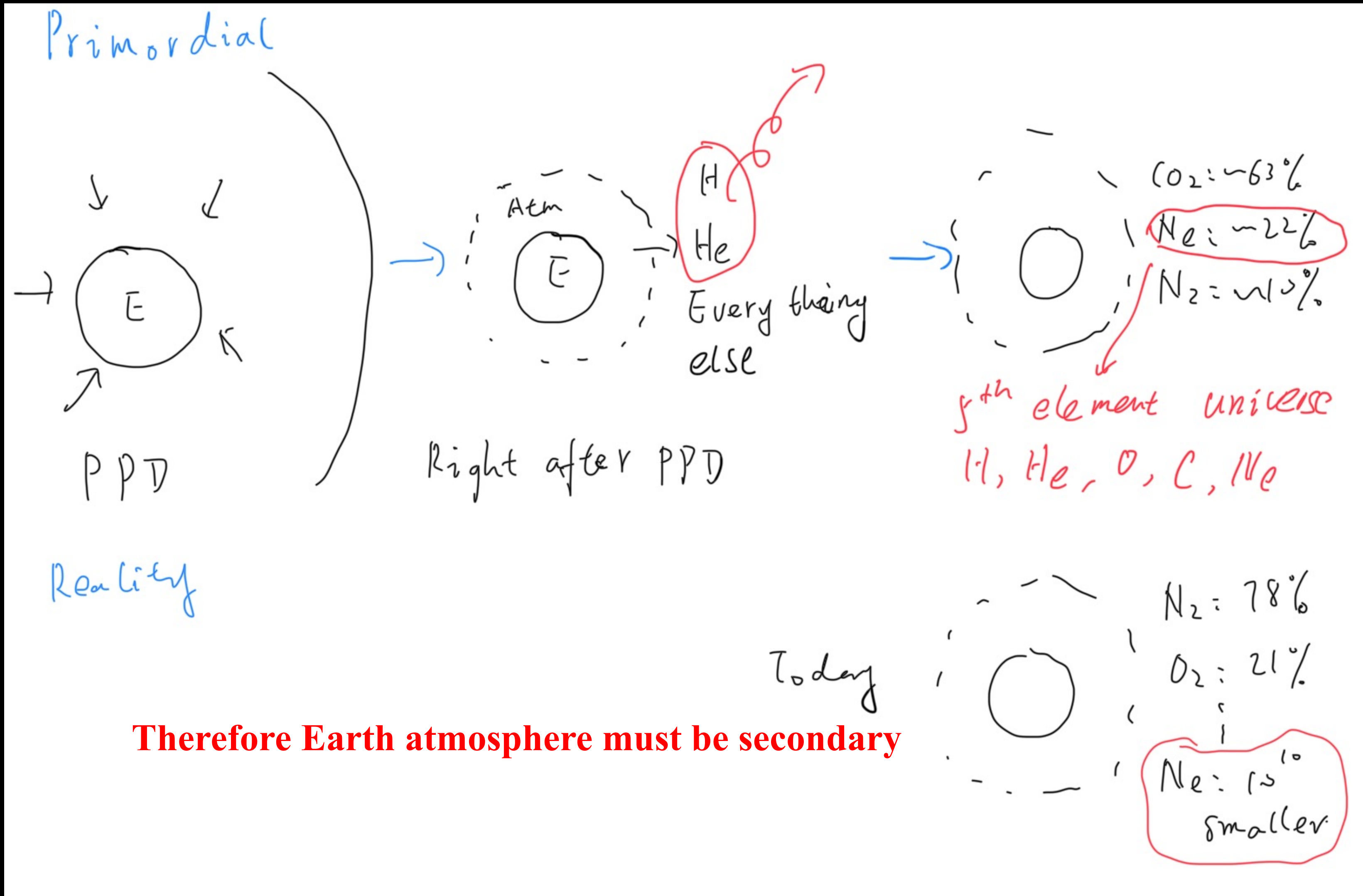
- Source of the atmosphere
  - Primordial
    - Accretion from a gaseous disk during formation


Credit: CfA / Harvard

Origin of atmosphere (C.5.8)

- Source of the atmosphere
  - Primordial
    - Accretion from a gaseous disk during formation
  - Secondary
    - Volcanic activity
    - Sublimation of ices (e.g., brought to Earth by comets, etc)
      - *What would happen if a comet strikes the Earth?*
      - *What if we move the Earth to Pluto's orbit?*
    - Sputtering (microscopic particles of a solid material are ejected from its surface, after the material is bombarded by energetic particles of a plasma or gas)
- Earth's atmosphere: secondary

Z	Element	Mass fraction
1	Hydrogen	73.97%
2	Helium	24.02%
8	Oxygen	1.04%
6	Carbon	0.46%
10	Neon	0.134%
26	Iron	0.109%
7	Nitrogen	0.096%
14	Silicon	0.065%
12	Magnesium	0.058%
16	Sulfur	0.044%



Primordial
E
PPD
Atm
E
H
He
Every thing else
Right after PPD
CO2: ~63%
Ne: ~22%
N2: ~10%
5th element universe
H, He, O, C, Ne
Reality
Today
N2: 78%
O2: 21%
Ne: 10^10 smaller
Therefore Earth atmosphere must be secondary

Climate Evolution (C.5.8.2)

- Two positive feedback loops on the Earth

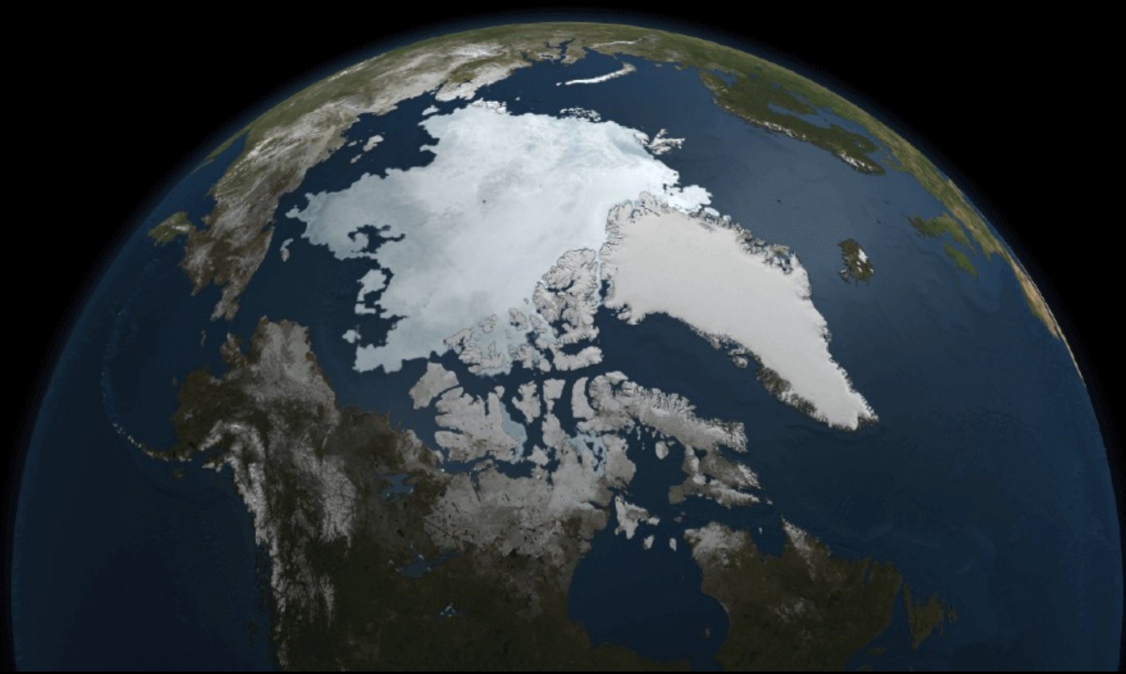
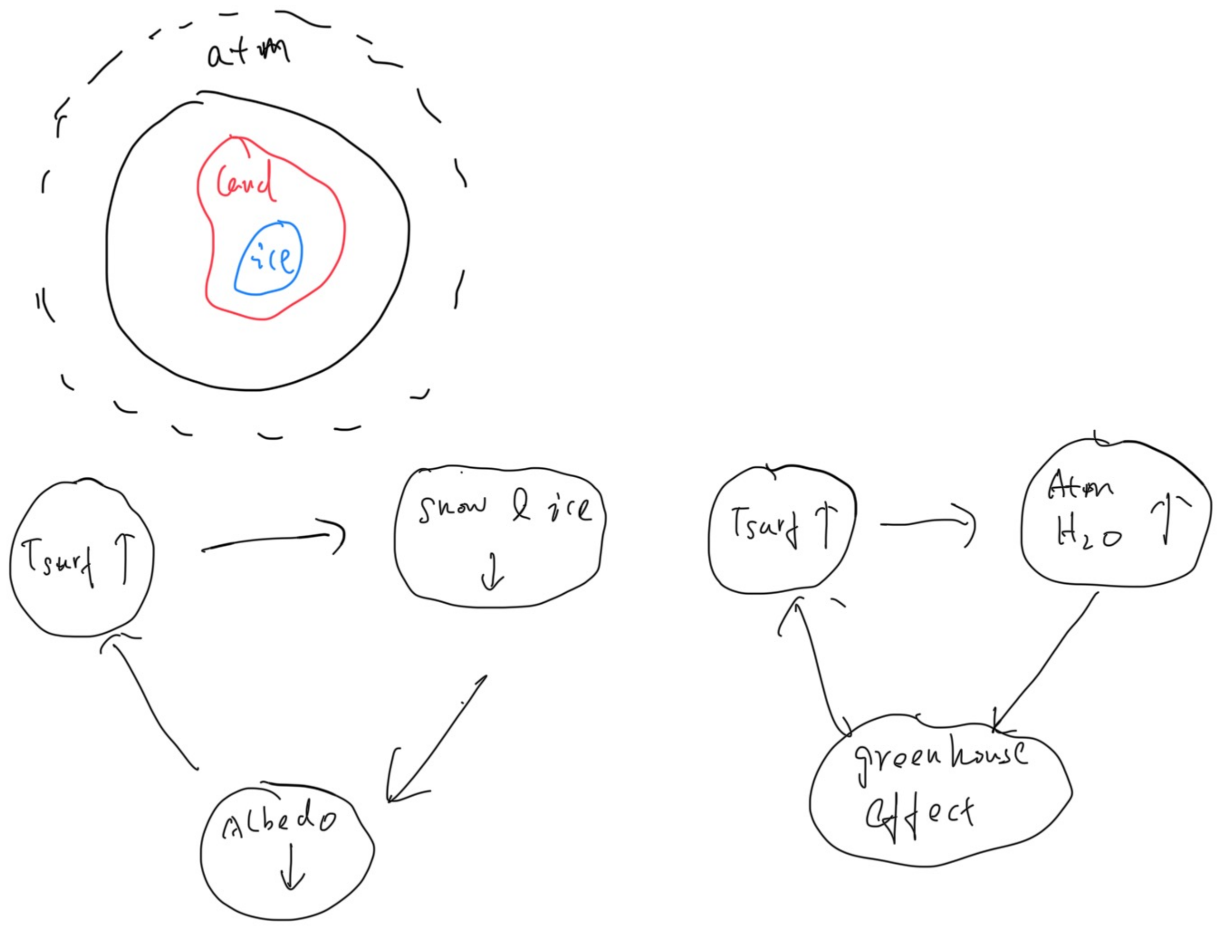


Image credit: NASA


atm
land
ice
Tsurf ↑
snow & ice ↓
albedo ↓
Tsurf ↑
Atm H_2O ↑
greenhouse effect

Chapter 6: Surface & Interior

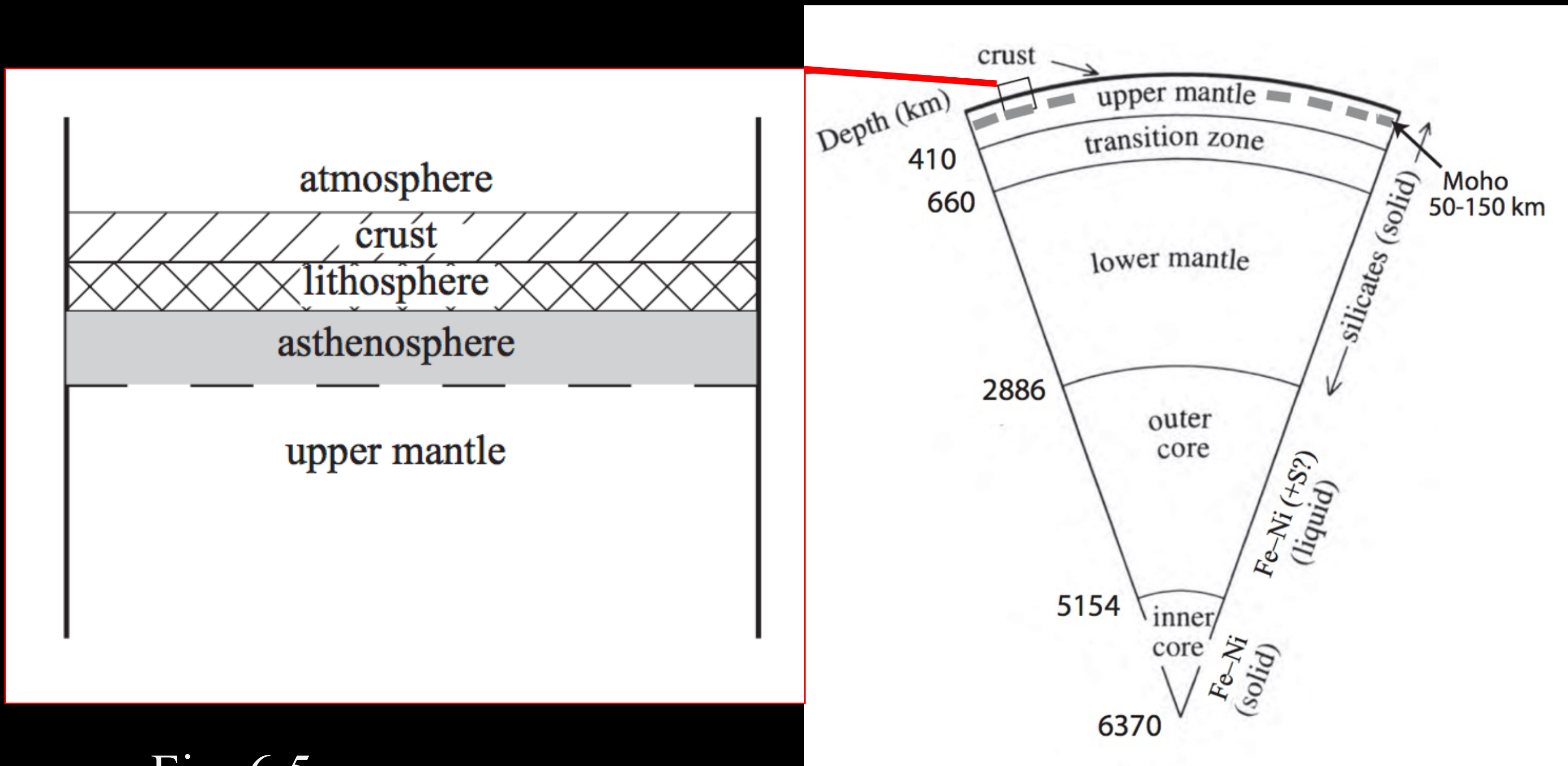
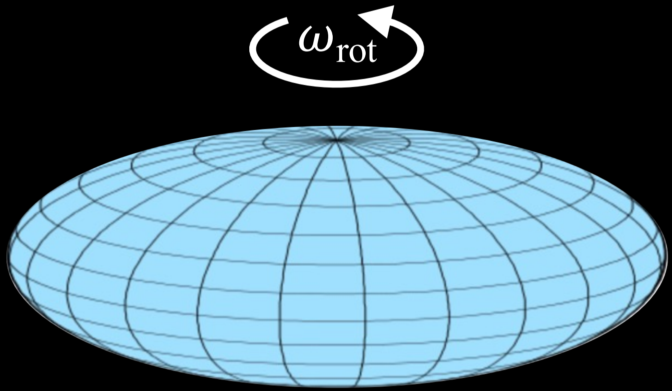


Fig. 6.5

Equipotential Surface (S.6.2.2)

The shape of a planetary object



Rotating Frame

An object sits still in a frame co-rotating with the planet. What is its total energy?

$E_{total} = E_g + E_k$
E_g = gravitational energy = $-GM/r$
E_k = kinetic energy = $-0.5r^2\ \omega_{rot}^2\ \sin^2(\theta)$

Equipotential surface: surface on which E_{total} is a constant

Objects can freely move along the surface of equipotential surface.

Equipotential surface defines the shape of a planet (***why?***)

Additional reading
https://en.wikipedia.org/wiki/Equipotential

Moment of inertia

$$I_P = \iiint_Q \rho(x,y,z)\,\|\mathbf{r}\|^2 \mathrm{d}V$$

- ***r*** is a vector perpendicular to the axis of rotation and extending from a point on the rotation axis to a point in the body
- $E_K = \frac{1}{2} I \omega^2.$
- For a uniform sphere, $I = 0.4\ MR^2$
- As mass becomes more concentrated towards the center, how would I_P change?

The relatively small $I/(MR^2)$ values for the giant planets, bodies that are rapid rotators in hydrostatic equilibrium, suggest a pronounced increase in density towards their centers.

Table E.15 **Gravitational Moments and Moment of Inertia Ratios**

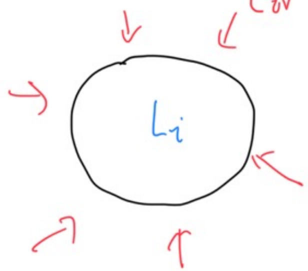
Body	J_2 ($\times 10^{-6}$)	J_3 ($\times 10^{-6}$)	J_4 ($\times 10^{-6}$)	J_6 ($\times 10^{-6}$)	I/MR^2	References
Sun					0.059	
Mercury	22.5 ± 0.1		6.5 ± 0.8		0.353	5
Venus	4.46 ± 0.03	-1.93 ± 0.02	-2.38 ± 0.02		0.33	1
Earth	1 082.627	-2.532 ± 0.002	-1.620 ± 0.003	-0.21	0.331	1
Moon	203.43 ± 0.09				0.393	1, 2
Mars	1960.5 ± 0.2	31.5 ± 0.5	-15.5 ± 0.7		0.365	1
Jupiter	14696.4 ± 0.2		-587 ± 2	34 ± 5	0.254	1
Saturn	16290.7 ± 0.3		-936 ± 3	86 ± 9	0.210	4
Uranus	3343.5 ± 0.1		-28.9 ± 0.2		0.23	1
Neptune	3410 ± 9		-35 ± 10		0.23	1
Io	1860 ± 3				0.378	3
Europa	436 ± 8				0.346	3
Ganymede	128 ± 3				0.312	3
Callisto	33 ± 1				0.355	3

1: Yoder (1995) and http://ssd.jpl.nasa.gov/. 2: Konopliv et al. (1998). 3: Schubert et al. (2004). 4: Anderson and Schubert (2007). 5: Smith et al. (2012).

S.6.2.3

- Additional heating sources of planets and moons
  - Heat left from accreting material during formation
  - Gravitational contraction
  - Differentiation of He from H.
  - Radiative decay
  - Temporal variation in tidal forces

Heat Sources



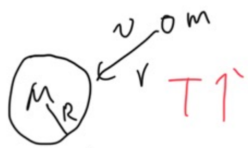
L_{ir} (not just incident energy, but absorbed)

L_i: intrinsic luminosity

$L_{tot} = L_{ir} + L_i$,

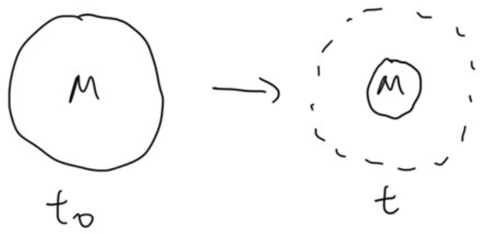
L_i { ① ② ③ ④ ⑤ :

① Heat generation:

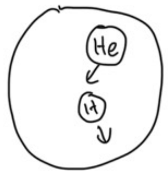


Formation

②



③



④

⑤ tides

Volcanism (C.6.3.2)

- Problem 7, Assignment 2

Impact Cratering (C.6.4)

Meteor Crater in Arizona (Fig. 6.23)