Space Science: Atmospheres Part- 7b

Venus, Earth and Mars
Where is the H_2O on Venus?
Planetary Escape
Isotope Fractionation
Hydrodynamic Escape

Result of Simple Model

Mars

The Ice Planet

Water primarily in ice caps and regolith as a permafrost?

Earth

The Water Planet?

Venus

The Water Vapor Planet

Run away Greenhouse Effect?

Where is the water?

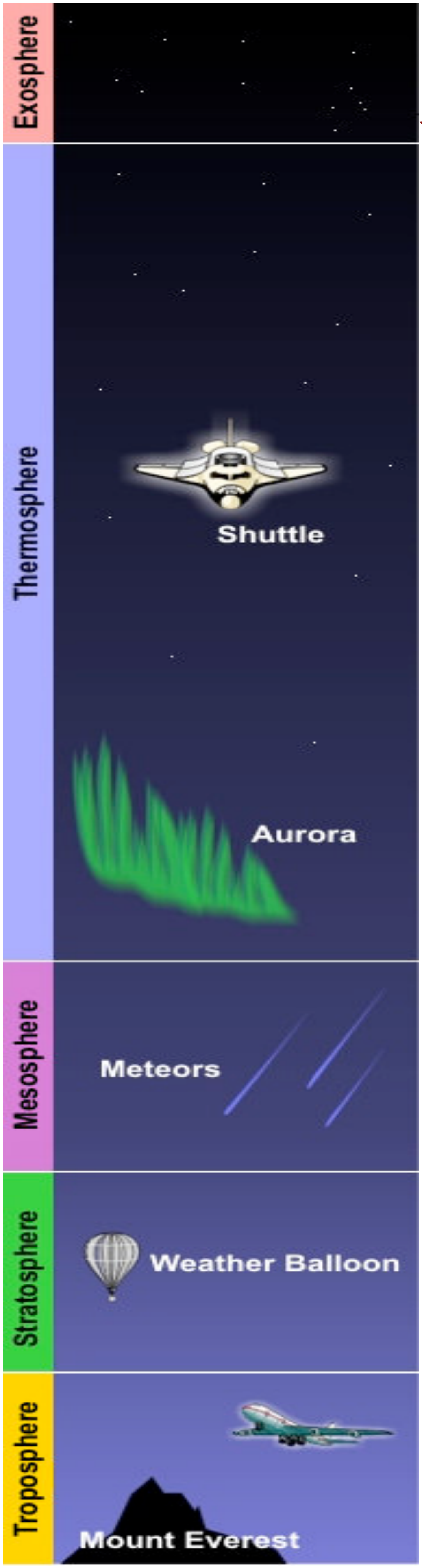
Since H_2O does not condense and is lighter than N_2 or CO_2 it can reach regions where UV can dissociate

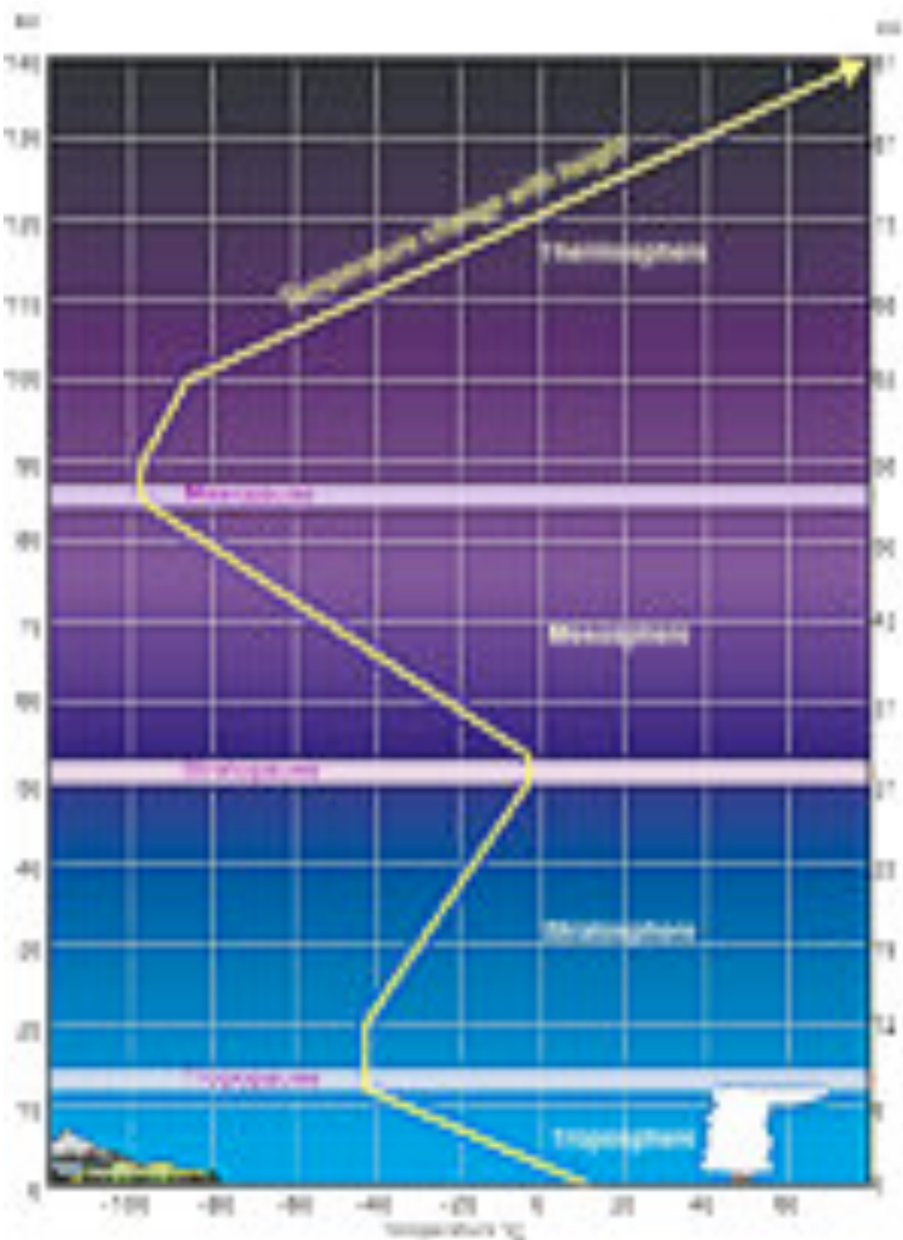
$$H_2O + h\nu \rightarrow OH + H + K.E.$$
$$\rightarrow O + H_2 + K.E.$$

Large scale heights

Vertical Structure

Exosphere??





Planetary Escape

Define Exobase : Top of Atmosphere

If an atom or molecule has an energy sufficient to escape + is moving upward it will have a high probability of escaping

Probability of escape is high if

collision probability is small;

mean free path for a collision

$\lambda_{col} \approx 1 / n_x \sigma_{col}$

σ_{col} = collision cross section

n_x = density at exobase

Exobase altitude occurs when

scale height ~ mean free path

$H_x \sim \lambda_{col}$

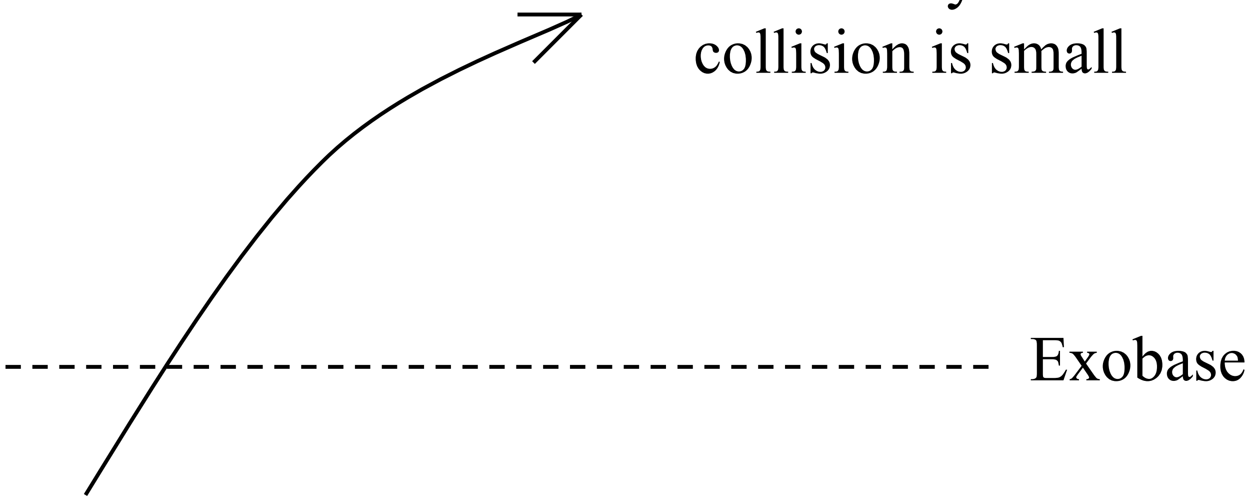
$H_x \sim 1 / n_x \sigma_{col}$

since $n_x H = N_x$ column density

$N_x \sigma_{col} \sim 1$

$$\boxed{N_x \approx 1 / \sigma_{col}}$$

Exobase



Exobase: $N_x \, \sigma_{col} \sim 1$

N_x = column of atmosphere

$\sigma_{col} \sim$ molecular size $\sim 10^{-15}$ cm^2

Therefore,

$N_x \approx \sigma_{col}^{-1} \approx 10^{15}$ atom / cm^2

or,

$n_x \approx [H_x \, \sigma_{col}]^{-1}$

Earth: ~1000K, O : g_x ~850cm/s^2;

$H_x \sim 1000$km

$n_x \sim 10^7$ O/cm^3 ; $z_x \sim 550$km

Escape (continued)

Escape Energy = E_{es} = ½ m v_{es}^2
= mg_xR_x

g_x = acceleration of gravity at exobase
R_x = distance of exobase from *center of planet*
[**surface v_{es} : V 10.4; E 11.2, M 4.8 km/s**]

At Earth $T_x \approx$ 1000 K, v=1km/s!! ***(no escape???)***

BUT, for a given T_x there is a distribution of v

For a given T_x there is a distribution of v

$$f(\vec{v}) = \frac{1}{[2\pi\, kT/m]^{3/2}} \exp\left[-\frac{mv^2}{2kT} \right]$$

$$= f(v_x)\, f(v_y)\, f(v_z) \;\; ;$$

$$\iiint f(\vec{v})\, d^3v = 1$$

Can Focus on the z component only!

$$f(v_z) = \frac{1}{[2\pi\, KT/m]^{1/2}} \exp\left[-\frac{mv_z^2}{2kT} \right] \; ;$$

$$\int_{-\infty}^{+\infty} f(v_z)\, dv_z = 1$$

Need: Flux of molecules across exobase in the $+z$ direction

$$\Phi_{es} = \int\int\int [n_x\, v_z]\, f(\vec{v})\, d^3v \; ; \qquad v_z > 0, \quad v > v_{es}$$

Escape (continued)

Things are often written
in terms of the mean speed

$$\bar{v} \equiv \int\int\int v\, f(\vec{v})\, d^3v$$

* Problem: Verify that the mean speed is

$$\bar{v} = \sqrt{\frac{8\,K\,T}{\pi\, m}}$$

Flux across a surface $v_z > 0$, (all v)

$$\Phi_+ = \int\int\int n_x\, v_z\, f(\vec{v})\, d^3v$$

$$= n_x \int_0^\infty \frac{v_z}{[2\,\pi\, kT/m]^{1/2}} \exp\left[-\frac{mv_z^{\,2}}{2KT}\right] dv_z$$

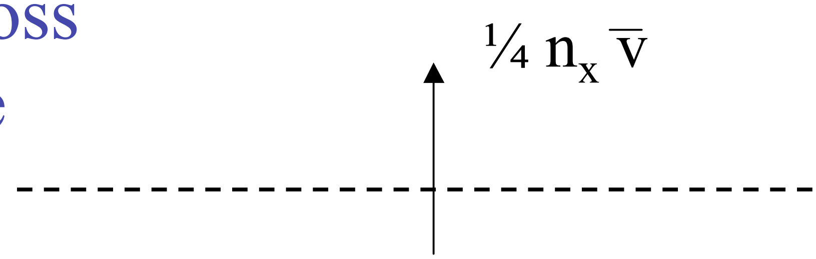
$$= n_x (kT/m)/[2\,\pi\;\; kT/m]^{1/2} = n_x \left[\frac{kT}{2\pi m}\right]^{1/2}$$

$$\underline{\Phi_+ = \frac{1}{4}\; n_x\; \bar{v}}\;\; ; \; 1/4 \text{ due to isotropic assumption}$$

This is in the absence of gravity

Escape Flux (cont.)

Flux Across Exobase



$$\bar{v} = \sqrt{\frac{8\,kT}{\pi\, m}} \quad ; \qquad n_x = \text{density}$$

Probablity of Escape

$$P_{es} = \int_{mgR}^{\infty} f_+(E)\, dE$$

$f_+(E)$ = energy distribution of *flux* at exobase

Escape (continued)

For Escape Use: $E > E_{es}$

where E_{es} is the escape energy

The escape flux is

$$\Phi_{es} = \iiint_{E>E_{es}} (n_x \, v_z) \, f(\vec{v}) \, d^3v$$

Rewrite as the flux across the exobase

times a probability of escape

$$\Phi_{es} = \frac{1}{4} (n_x \bar{v}) \, P_{es}$$

Obtain P_{es}

problem

Jeans (thermal) Escape

$$P_{es} = \left[1 + \frac{E_{es}}{kT}\right] e^{-E_{es}/kT}$$

E_{es}/kT : compares thermal energy to escape energy

OR: using, $E_{es} = mg_x R_x$,

$$E_{es}/kT \equiv mg_x R_x/kT = R_x/H_x$$

In this form: Compares Radius at the top of the atmosphere to the scale height!

Total Loss by Jeans Escape

$Flux_+$ x P_{es} x Area x Time

or

N_{es} = Column Lost = $Flux_+$ x P_{es} x Time

(Pressure change = N_{es} m g)

Example:

H from the earth

Present escape flux ~ 10^7 H/cm^2/s

If constant:

t ~ (3×10^7 s/yr) x 4.5 $\times10^9$yr ~ 1.4 $\times10^{17}$ s

N_{es} ~ 1.4 x 10^{24} H/cm^2

Δp ~ 2×10^3 dynes/cm^2 ~ 2 $\times10^{-3}$bar

or

Total column at Earth

N ~ 2 $\times10^{25}$ mol.(N_2,O_2)/ cm^2

(~10 meters frozen)

Equivalent water loss: ~0.5 m!

Escape (cont.)

* Problem: Jeans escape

	Escape Energy
Venus	0.56 eV / u
Earth	0.65 eV / u
Mars	0.13 eV / u
Jupiter	18 eV / u
Titan	0.036 (0.024*) eV/u *(at exobase)

Assume $T_x = 1000$ K (not true on present Venus)

Use a time $t = 4.5$ byr $\approx 4.5 \times 10^9 \times 3 \times 10^7$ sec

Assume $N_x = 10^{15}$ atoms / cm^2

Calculate the net column loss, N_{es},

of H, H_2(or D), N from

each planet assuming $H = k T_x / m g_x$

and the exobase is either all H, H_2, or N.

Approx. Present Values
z_x: V 200km; E 500km, M 250km, T1500km
T_x: V 275K, E 1000K, M 300K, T 160K
Jupiter: no surface, use T_x =1000K

Isotope Fractionation

(preferential loss of lighter species)

Relative loss rate is determined by

1. **Masses of the escaping species**

   therefore, $(P_{es})_D \ll (P_{es})_H$!!

2. **But they must be present at the exobase!**

   hence, depend on differences in diffusive separation !!

Compare loss of H to D:

H = lighter; D = heavier to learn about

Loss of water

Isotope Fractionation

(preferential loss of lighter species)

Relative loss rate depend on
differences in diffusive separation !!

Compare loss of H to D: H = lighter; D = heavier

$N_H(z_h)$, $N_D(z_h)$: col densitiesbelow homopause (turbopause)

determined by atmospheric concentrations,
same H--mixed

At homopause

Ratio: $\mathbf{R_{D/H}(z_h) = N_D(z_h)/ N_H(z_h) = n_D(z_h)/ n_H(z_h)}$

At exobase

$n_H(z_x)$, $n_D(z_x)$ densities at exobase: $\Delta z = z_x - z_h$
Different H =kT/mg

$n_H(z_x) = n_A(z_h) \exp[-\Delta z/H_H]$; $n_D(z_x) = n_B(z_h) \exp[-\Delta z/H_D]$

Ratio: $\mathbf{R_{D/H}(z_x) = R_{D/H}(z_h) \exp[-\Delta z(1/H_B-1/H_A)]}$
$\mathbf{= R_{D/H}(z_h) \exp[-\Delta z\, \Delta m\, g_x/kT_x]}$

Rel. concentration.
Height of exobase, **Δz** , + mass dif., **Δm.**

Isotope Fractionation (cont.)

Loss rate of a column of atmosphere

$$\frac{dN_A}{dt} = -\ \Phi_{es}^{A}$$

For Jeans (thermal) Escape:

$$\Phi_{es}^{A} = -\frac{n_A \bar{v}_A}{4} P_{es}^{A}$$

$$\text{with } P_{es}^{A} = \left[1 + \frac{E_{es}}{kT}\right] e^{-E_{es}/kT}$$

Calculate

The fraction of species A still in the atmosphere is

$$f_A(t) \approx N_A / N_A^{o} = \exp(-t/t_A)$$

$$(t_A)^{-1} \approx \frac{[(\bar{v}_A/4)P_{es}^{A}]}{H} \exp(-\Delta z / H_A)$$

Depends only on mass of A and

the temperature at the exobase

Isotope Fractionation (cont.)

Two species A and B (e.g., H and D)

The ratio of total atmospheric concentrations vs. t is

$$r_{AB}(t) = \left[\frac{N_A(t)}{N_B(t)}\right] / \left[\frac{N_A^o}{N_B^o}\right] \approx \exp[-t\,(\frac{1}{t_A} - \frac{1}{t_B})]$$

One can re write

$$\mathbf{r_{AB}(t) \approx [f_A(t)]^x} \quad \text{with} \quad x = (1 - t_A/t_B)$$

and $f_A(t)$ the fraction of A remaining at time t.

Enrichment of Heavy Isotope Indicates Atmospheric Loss

D / H

SUN	1.5×10^{-5}
COMETS	$\sim 3 \times 10^{-4}$
EARTH'S WATER	$\sim 1.6 \times 10^{-4}$
VENUS Atmosphere	$\sim 2 \times 10^{-2}$

D enriched relative to Sun

So not only Venus
--but earth has also lost water!!

(unless you think comet pasting on of water is the starting point!)

Note: this does NOT depend on how much water we started with!!

D/H Ratio Earth and Venus

$t_H << t_D$ (your problem)

$$(r_{HD})_{now} = \left(\frac{N_H}{N_D}\right)_{now} \Big/ \left(\frac{N_H}{N_D}\right)_{solar} \approx [f_H(t)]^x$$

Earth : D / H 1.6×10^{-4}

$r_{HD} = 1.5 \times 10^{-5} / 1.6 \times 10^{-4} \approx 0.09$

$x \sim 1$; $f_H(t) = 0.09$

That is, only ~ 10% of original water released is still in the atmosphere and oceans (assuming well mixed);

Disagrees with present loss rate must have been an earlier epoch of rapid loss

Venus : D / H 2×10^{-2}

$f_H(t) \approx 0.0008$!

or – -assuming the same original water budget as the Earth

≈ 0.008 of Earth's present water budget

present value of loss rate (~ 10^7 /s) too small

Need wet hot early atmosphere with H_2O well mixed

(to hot to condense ar all altitudes inspite of lapse rate)

For both V and E :

did hotter (EUV) early Sun and/or T - Tauri caused blow - off

Enrichment of Heavy Isotope Indicates Atmospheric Loss

Other species

	V	E	M	S
$^{36}Ar / ^{38}Ar$	5.1	5.3	4	5.5
$^{40}Ar / ^{36}Ar$	1	296	3000	---

($^{40}K \rightarrow {}^{40}Ar + e^{+} + e^{-}$ $\sim 10^{8}$ years)

Xe , N, O and C are also fractionated

Need escape processes other than Jeans escape for heavy species

ESCAPE PROCESSES

1. Jeans Escape
2. Hydrodynamic Escape (Blow Off)
3. Photo Dissociation
4. Dissociative Recombination
5. Interaction with the Local Plasma
6. T – Tauri Sweeping

Very heavy species 2?

When molecules are at the exobase
3 and 4 are important

Venus

$$H_2O + h\nu \rightarrow OH + H + KE$$
$$\rightarrow O + H_2 + KE$$

Present Mars

$$CO_2^{+} + e \rightarrow CO + O + KE$$
$$O_2^{+} + e \rightarrow O + O + KE$$

In the absence of a protecting magnetic field
5 and 6 are important

Fractionation:
nonthermal escape processes

Diffusive separation gives an
exobase ratio between a
lighter (A) and heavier (B) species

If the *loss mechanism* is not strongly
affected by the mass difference then:

Only their relative abundance at the exobase is
important: Rayleigh fractionation law !

Applies to Mars for processes 3, 4, 5

Result (Ar and N arew fractionated)
^{36}Ar / ^{35}Ar no need for hydrodynamic episode
^{14}N / ^{15}N models give too mach loss (buffered by CO_2?)

BUT!
non-fractionation of ^{18}O / ^{16}O, ^{13}C / ^{12}C
means there are large reservoirs!!
carbonatcs and permafrost?

#7b Summary

Things you should know

Greenhouse Model for Terrestrial Planets
Venus vs. Earth vs. Mars
Water Loss from Venus
Planetary Escape
Energy Flux Distribution
Jeans Escape
Isotopic Fractionation
Other Escape Processes