Space Science: Atmospheres
Part- 9

Review
CO$_2$ Cycle
O$_2$ Cycle
Out-Gassing Bodies
Review

Composition
Solar, Giant Planets, Terrestrial Planets

Vertical Structure
Hydrostatic (scale height)
Diffusion/ homopause

Thermal Structure
Solar (Albedo)/ Internal Heating
Adiabatic Lapse (troposphere; potential temp.)
Thermal Conduction(thermosphere)
Radiation to Space (strato and mesospheres)

Chemistry
Absorption (optical pathlength)
Reaction rates
Ozone (EUV/UV: Chapman layers)
Ionospheres (ambipolar diffusion)

Radiation Transport
Greenhouse (IR vs. Visible)

Circulation/ Winds
Momentum Eq. (Rossby/Ekman numbers)
Boundary Layer (eddy viscosity)
Hadley Cells (bouyancy)
Geostrophic/ Cyclostrophic Flow
Zonal Winds/ Belts
Planetary/ Gravity Waves

Evolution / Escape
Escape (Jeans, Hydro., non-thermal)
Isotope ratios (heavy isotopes enhanced)
Fate of water and CO₂
Atmospheres / Evolution

Heat Sources
- Compressional Energy
- Trapped Radioactive Material
- Tidal Interactions

Initial Species
- Solar abundance
  - Solar wind composition?
  - Carbonaceous chondrites?

Variables
- Early sun fainter
- Earth’s Orbit -- eccentricity,
  - axial tilt, precession (~ 20 ka
    - 400 ka)
- Ice coverage, etc.
Atmospheric Sources

Volcanoes/ Outgassing

\( \text{H}_2, \text{H}_2\text{O, CO}_2, \text{H}_2, \text{S, SO}_2 \ldots \)

Impacts

Comets, meteors, micrometeorite

LOSSES

Surface

Condensation/ Reactions

Escape

Jeans

Hydrodynamic/ Blow off

Photo-Dissociation

Solar Wind + Solar Fields
EVOLUTION OF H₂O

Greenhouse: Triple Point of H₂O

Venus --- gas
Earth --- water
Mars --- ice

We discussed the lack of H₂O on Venus and Mars

Evolution of CO₂

Earth:
Atmosphere ~2.4x10^{18}gm
Ocean ~1.3 x10^{20}gm
Biosphere ~1 x10^{19}gm
Buried ~3.6x10^{23}gm

Venus:
Atmosphere ~4.4x10^{23}gm!
Surface ?

Mars:
Atmosphere ~ 3.0 x10^{20}gm
(scaled by mass to Venus ~0.005)
Surface?
**CO₂ Cycle on Earth**

- **Atmosphere**
  - CO₂
  - 2.4x10^{18} gm

- **Biosphere**
  - carbohydrates
  - 10^{19} gm
  - Photosynthesis
  - 10^{17} gm/yr
  - Burial
  - 3x10^{14} gm/yr

- **Ocean**
  - CO₃⁻
  - 1.3x10^{20} gm
  - Volcanoes
  - Weathering
  - 3x10^{14} gm/yr

- **Rocks**
  - Organics
  - 6x10^{22} gm
  - Carbonates
  - 3x10^{23} gm
  - Weathering
  - 3x10^{14} gm/yr

- **Evaporation**
  - 4x10^{17} gm/yr

- **Dissolve**
  - 4x10^{17} gm/yr

- **Respiration + Decay**
  - 10^{17} gm/yr

- **Photosynthesis**
  - 10^{17} gm/yr

- **Volcanoes + Weathering**
  - 10^{15} gm/yr

- **Evaporation**
  - 10^{15} gm/yr

- **Dissolve**
  - 4x10^{17} gm/yr

- **Burial**
  - 3x10^{14} gm/yr

- **Respiration + Decay**
  - 10^{17} gm/yr

- **Photosynthesis**
  - 10^{17} gm/yr

- **Volcanoes + Weathering**
  - 10^{15} gm/yr

- **Evaporation**
  - 10^{15} gm/yr

- **Dissolve**
  - 4x10^{17} gm/yr

**CO₂ ~ 3.6x10^{23} gm**
**H₂O ~ 1.6x10^{24} gm**
Photo synthesis + Respiration

Plants: \[ \text{CO}_2 \xrightarrow{h^v} \text{O}_2 + \text{C} \]
Respiration: \[ \text{O}_2 + \text{C} \rightarrow \text{CO}_2 \]

Another Near Equilibrium

Ocean: dissolves \( \text{CO}_2 \rightarrow \text{bicarbonate} \)
bicarbonate \( \rightarrow \text{CO}_2 \) release
Near Equilibrium

Burial --- land + Sea

Plus

Weathering
Carbon in ‘rocks’ is oxidized \( \rightarrow \text{CO}_2 \)
Limestone (Ca CO\(_3\)) dissolves in water \( \rightarrow \)
bicarbonate
Double Atmosphere CO$_2$

Add $2.4 \times 10^{18}$ gm CO$_2$

Vapor pressure of CO$_2$ up

Dissolves More $\rightarrow$ find new equilibrium

Experiment is being done

Since 1980 $\sim 5 \times 10^{17}$ gm CO$_2$, added by fossil fuel burning

Look at Fastest part only

![Diagram of Atmosphere and Ocean with rate equation]

Rate Equation

$$\frac{dn_A}{dt} = -\frac{n_A}{\tau_{\text{dis}}} + \frac{n_0}{\tau_{\text{evap}}} = -\frac{dn_0}{dt}$$

In Equilibrium:

$$\frac{n_A^o}{\tau_{\text{dis}}} = \frac{n_0^o}{\tau_{\text{evap}}}$$
Estimate Time Constants and New Equilibrium

\[ \tau_{\text{evap}} \approx 1.3 \times 10^{20} \text{ gm} / 4 \times 10^{17} \text{ gm/yr} = 325 \text{ yr} \]
\[ \tau_{\text{dis}} \approx 2.4 \times 10^{18} \text{ gm} / 4 \times 10^{17} \text{ gm/yr} = 6 \text{ yr} \]
Fraction in Ocean \( \approx 97\% \)
Fraction in atmosphere \( \approx 3\% \)

Now Double

\[ \eta_A(\infty) + \eta_O(\infty) = 2 \eta_A^o + n_O^o \]

New Equilibrium

\[ \frac{\eta_A(\infty)}{\tau_{\text{dis}}} = \frac{\eta_O(\infty)}{\tau_{\text{evap}}} \]

Size of Increase

\[ \Delta = \frac{n_A(\infty) - n_A^o}{n_A^o} = 1/[1 + \tau_{\text{evap}} / \tau_{\text{dis}}] \approx 3\% \]
Double $\Rightarrow \sim 3\%$ increase

Find Effective Time Constant

\[ n_T = 2 n_A^o + n_o^o \]

\[ \frac{dn_A}{dt} = -\left( \frac{1}{\tau_{\text{dis}}} + \frac{1}{\tau_{\text{evap}}} \right)n_A + \frac{n_T}{t_{\text{evap}}} \]

\[ \tau_{\text{eff}} = \left( \frac{1}{\tau_{\text{dis}}} + \frac{1}{\tau_{\text{evap}}} \right)^{-1} \]

$\approx \tau_{\text{dis}} \approx 6$ years

Actual: 10% in 6 years

As ocean circulates slowly.
VENUS

Run away Greenhouse

\[ \text{H}_2\text{O} \text{ does not condense} \]
\[ \text{H}_2\text{O} + \text{hv} \rightarrow \text{OH} + \text{H} \]
\[ \rightarrow \text{O} + \text{H}_2 \]
\[ \text{H}_2 + \text{hv(} \text{or SW plasma) } \rightarrow \text{H} + \text{H} \]
\[ \text{H} (\text{and, possibly, } \text{H}_2) \text{ Lost} \]

Total \( \text{CO}_2 = 4.4 \times 10^{23} \text{g} \)

Atmosphere – Surface: Equilibrium?

Silicate Rocks + \( \text{CO}_2 \)

e.g., \( \text{CaSiO}_3 + \text{CO}_2 \)

Gives

\( \text{Carbonate} + \text{Quartz} \)
\( \text{CaCO}_3 + \text{SiO}_2 \)

Old idea? Magellan: Surface Looks Active
**Mars CO₂**

- **Poles**
  - Permanent Ice Caps
  - Seasonal CO₂ Caps
  - Runoff to ground water

**Atmosphere**

**Carbonates?**

**Runoff**

**Vapor Pressure**
- Determined by temperature
- Winter Pole
- Orbital cycles are very important

**Loss**
- \( \text{O}_2^+ + e \rightarrow O + O + \text{energy} \)
- Europa / Mars

[Diagram showing the cycle between Poles, Atmosphere, and Carbonates with runoff and weathering connections.]
Atmospheric $O_2$

In beginning

$$H_2O \xrightarrow{hv} O + H_2$$

carbonates in rocks (oxidized)

Little $O_2$, no $O_3 \Rightarrow UV \Rightarrow$ no organisms

$O_2$ Cycle

Source of $O_2$?

$$H_2O \text{ ultimately}$$

But $H_2O \rightarrow O + H_2 \rightarrow H + H \text{ to space}$

small $O$ loss as $H_2$ carries most of energy

$O_2$ eventually produced by organisms

Note: $CO_2$ stabilized by oceans

$O_2$ not so.
Oxygen Cycle

Oceans
1.4x10^{24} gm

Atmosphere
O_2
1.2x10^{21} gm

Photo dissociation
4x10^{11} gm/yr

Photo synthesis
10^{17} gm/yr

Respiration
Decay
10^{17} gm/yr

Weathering
3x10^{14} gm/yr

Biosphere
Carbon hydrates
10^{19} gm

Sediment Rock
Organic
6x10^{22} gm

Burial Of carbon
3x10^{14} gm/yr

Remove CO_2

Produce CO_2
Do Gases evolve from interior? Yes
H$_2$O, CO$_2$, SO$_2$, etc.
+ silicates

Note: Oxidized
Initially:
H$_2$O, CH$_4$, NH$_3$, H$_2$S, etc.
+ dust
Io: Dehydrated Volcanoes
SO₂, Sₓ, + silicates

Tidal Heating
Io’s Interaction with Jovian Plasma Emissions seen by Galileo

Escaping Na seen in Resonance Scattering
Global mosaic from Voyager 2. Triton (1,350km) one of only 4 objects with a nitrogen-dominated atmosphere. Cold surface (38 K) so most of the nitrogen is condensed as a frost. Pinkish deposits at south pole contain methane ice which has been irradiated. Dark streaks are an icy/carbonaceous dust deposited from geyser-like plumes, some of which were active during the Voyager 2 flyby. The bluish-green band around the equator is fresh nitrogen frost. The 'cryovolcanic' landscapes may be produced by icy-cold liquids that erupted from Triton's interior.
Enceladus
Outgassing $\text{H}_2\text{O}, \text{CO}_2, \text{N}_2$?
Did $\text{N}_2$ come from $\text{NH}_3$??
Saturn’s Giant Toroidal OH Atmosphere
Seen by HST
Produced by Enceladus

Can we detect these tori on extrasolar planets?
Titan’s Escaping Atmosphere
Seen Using Energetic Neutrals

Cassini: MIMI-INCA

$H = 8000$ km $\quad 20 \text{ keV} < E < 50 \text{ keV}$
$t_{\text{expo}} = 8 \text{ minutes}$
Even Mercury??

Na Atmosphere In Absorption

Why the poles?

How is Na resupplied?
There is lots to do and we had better be adaptable because the system is evolving.

The End