How to make Habitable Planets

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I want to know How to make Habitable Planets

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1. Habitability and Water

Why water is important?
Habitable Condition

Real necessary and sufficient conditions for life are not well constrained yet. Terrestrial-life requires liquid water during at least some periods of their life. Consider existence of liquid water as a conventional necessary condition.
Importance of Liquid

Life using chemical energy (~ like terrestrial life) requires flow of energy and material.

Gas: highly mobile, but low material density. Solid: high density but very low mobility. Liquid: high density and high mobility

Liquid is important media for life.

Habitable environments are likely environments with some liquid.
H2O is composed of the most and 3rd most abundant elements

Cosmic abundance
H$_2$O as an abundant material
H₂O as a special liquid: high freezing and boiling T

H₂O has high F. and B. P. among small weight molecules.

Small weight ~ simple ~ easy to make ~ abundant
Habitability and Water

Water
  Highly abundant in cosmos.
  High freezing and boiling points
Water is in liquid phase at warm place near the central star
  warm ~ easy for chemical reactions
Good solvantan for ionized material

Probably, water is the 1st choice of life supporting liquid.
2. Water planets

One form of Habitable planets
Water Planets

Terrestrial planet with some amount of liquid water on its surface
ⅲsolid planets with wet atmosphere

〜 Generalized Earth
〜 One group of habitable planets.
Conditions required for the formation of a Water planet

1. Supply of H2O to the planet
   (or Supply of H and O)

2. H2O degasses from the planetary interior
   Planetary formation and evolution

3. H2O is kept at the surface
   (not lost into the space)
   Planetary evolution and climate

4. Some H2O is in the liquid phase
   Planetary climate
Stability field of liquid water

Temperature

- > 0.1 °C
- < 374.11 °C

Pressure

- > Saturation vapor pressure
Water planet

In 0 dimensional = globally averaged consideration

Bounded by
  complete vaporization ~ runaway greenhouse
  global freezing
2.1 Runaway greenhouse

Water vapor is a strong greenhouse gas. Large amount of water vapor in the atmosphere at high temperature.

High temperature yields strong greenhouse effect.

A typical positive feedback process.
The critical flux for the runaway greenhouse

A moist atmosphere (saturated by water vapor) has an upper limit of the outgoing infrared flux that can be emitted:

If insolation exceeds this limit, temperature increases until complete evaporation of liquid water from the surface.

Komabayashi-Ingersoll Limit

Nakajima, et al., 1992:
J. Atmos. Sci., 49, 2256.
Transfer of infrared radiation in a planetary atmosphere

Ignore the wavelength dependence of optical property: Gray approximation

\[
\frac{2}{3} \frac{dF_{\uparrow}}{d\tau} = F_{\uparrow} - \pi B \\
\frac{2}{3} \frac{dF_{\downarrow}}{d\tau} = -F_{\downarrow} + \pi B
\]

\[
\tau \equiv \int_{z}^{\infty} \kappa(z') \rho(z') \, dz' \quad \text{および} \quad \tau \equiv \int_{z}^{\infty} \kappa(z') \rho(z') \, dz' \\
\pi B = \sigma T^4
\]

Factor 2/3 arises from an assumption of zenith angle dependence of radiant flux.
Komabayashi-Ingersoll Limit

\[
\frac{1}{2} F \left( \frac{3}{2} \tau_t + 1 \right) = \sigma T_t^4
\]

\[
p^*(T) = p^*_0 \exp \left( -\frac{l}{RT} \right)
\]

\[
\tau_t = \kappa_v p^*_v \left( T \right) \frac{m_v}{g \bar{m}}
\]

\[
\tau_t = \frac{2}{3} \left( \frac{2\sigma T_t^4}{F} - 1 \right)
\]

\[
\tau_t = \frac{\kappa_v p^*_0 m_v}{g \bar{m}} \exp \left( -\frac{l}{RT_t} \right)
\]
Komabayashi-Ingersoll Limit

\[
\tau_t = \frac{2}{3} \left( \frac{2\sigma T_t^4}{F} - 1 \right)
\]

\[
\tau_t = \frac{\kappa_v p_0^* m_v}{g \bar{m}} \exp \left( - \frac{l}{RT_t} \right)
\]

Planetary Flux: outgoing infrared radiation

\[ F_{p\lambda} = \frac{3}{2} \int_0^{\tau_{\lambda s}} \pi B_\lambda(t) \exp\left[-\frac{3}{2} t\right] dt + \pi B_{\lambda s} \exp\left[-\frac{3}{2} \tau_{\lambda s}\right] - F_{\lambda 0} \]

\[ F_{\lambda s} \rightarrow \pi B_{\lambda s} \]

Determined by the distribution of temperature and absorber
Integral of the Planck function weighed by optical depth.
Most sensitive to the temperature around: \( \tau_{\lambda} \); 1
Radiativ-convective equilibrium

\[ F_{p\lambda} = \frac{3}{2} \int_0^{\tau_{\lambda s}} \pi B_{\lambda}(t) \exp\left[ -\frac{3}{2} t \right] dt + \pi B_{\lambda s} \exp\left[ -\frac{3}{2} \tau_{\lambda s} \right] - F_{\lambda 0} \]
Dry Adiabat

\[
\left( \frac{\partial T}{\partial p} \right)_s = \frac{\alpha T}{\rho C_p} \\
\rho = \frac{wp}{RT} \\
\alpha = \frac{1}{T}
\]

\[
\left( \frac{\partial T}{\partial p} \right)_s = \frac{RT}{wpC_p} = \frac{RT}{pC_p'} = \frac{(C_p' - C_v')T}{pC_p'} = \frac{\gamma - 1}{\gamma} \frac{T}{p}
\]

\[
\left( \frac{T}{T_0} \right) = \left( \frac{p}{p_0} \right)^{\frac{\gamma - 1}{\gamma}}
\]

\[
\gamma = \frac{C_p}{C_v}
\]
Moist adiabat

\[ dS = \left( \frac{\partial S}{\partial p} \right)_{T,n_i} dp + \left( \frac{\partial S}{\partial T} \right)_{p,n_i} dT + \left( \frac{\partial S}{\partial n_v} \right)_{T,p,n_n} dn_v = 0 \]

\[ d\Delta G = \left( \frac{\partial \Delta G}{\partial p} \right)_{T,n_i} dp + \left( \frac{\partial \Delta G}{\partial T} \right)_{p,n_i} dT + \left( \frac{\partial \Delta G}{\partial n_v} \right)_{T,p,n_n} dn_v = 0 \]

\[ \Delta G = \mu_v (p, T, n_v, n_n) - \mu_c (p, T) = 0 \]
Moist adiabat

\[
\begin{bmatrix}
\left( \frac{\partial S}{\partial p} \right)_{T,n_i} & \left( \frac{\partial \Delta G}{\partial p} \right)_{T,n_i} \\
\left( \frac{\partial S}{\partial n_v} \right)_{T,p,n_n} & \left( \frac{\partial \Delta G}{\partial n_v} \right)_{T,p,n_n}
\end{bmatrix}
\left[ dp + \left[ \left( \frac{\partial S}{\partial T} \right)_{p,n_i} - \left( \frac{\partial \Delta G}{\partial T} \right)_{p,n_i} \right] \right]
\]

\[
\left( \frac{\partial T}{\partial p} \right)_s = - \frac{\left[ \left( \frac{\partial \Delta G}{\partial n_v} \right)_{T,p,n_n} \left( \frac{\partial S}{\partial p} \right)_{T,n_i} - \left( \frac{\partial S}{\partial n_v} \right)_{T,p,n_n} \left( \frac{\partial \Delta G}{\partial p} \right)_{T,n_i} \right]}{\left[ \left( \frac{\partial \Delta G}{\partial n_v} \right)_{T,p,n_n} \left( \frac{\partial S}{\partial T} \right)_{p,n_i} - \left( \frac{\partial S}{\partial n_v} \right)_{T,p,n_n} \left( \frac{\partial \Delta G}{\partial T} \right)_{p,n_i} \right]}
\]

\[ n_c = 0 \quad \text{moist pseudoadiabat} \]
moist pseudoadiabat

\[
\left( \frac{\partial T}{\partial p} \right)_{\text{moist pseudoadiabat}} = \frac{RT}{p \left( x_n c_{pn} + x_v^* c_{pv} \right)} \frac{1 + x_v^* \left( \frac{l}{RT} - 1 \right)}{\left[ \frac{l^2}{RT^2 \left( x_n c_{pn} + x_v^* c_{pv} \right) - 1} \right]}
\]

\[
\left( \frac{\partial T}{\partial p} \right)_{\text{moist pseudoadiabat}} \rightarrow \frac{RT}{pc_{pn}}
\]

Dry adiabat @ small water vapor fraction

\[
\left( \frac{\partial T}{\partial p} \right)_{\text{moist pseudoadiabat}} \rightarrow \frac{RT}{p \left( x_n c_{pn} + x_v^* c_{pv} \right)} \frac{\frac{RT}{l^2}}{RT^2 \left( x_n c_{pn} + x_v^* c_{pv} \right)} = \frac{1}{p} \frac{l}{l^2} = \frac{RT^2}{pl}
\]

Saturated vapor pressure curve @ large water vapor fraction

\[
\frac{dp^*}{dT} = \frac{l}{RT^2} p^*
\]
Assymptotic limit controlled by moist troposphere

Nakajima, et al., 1992:
J. Atmos. Sci., 49, 2256.
Runaway greenhouse
Earth

$S_0 = 960 \text{ Wm}^{-2}$

$F_0 = 300 \text{ Wm}^{-2}$

$S_0$ and $F_0$ represent the solar constant and the solar flux at Earth's distance, respectively. The graph shows the temperature as a function of pressure (in logarithmic scale). The different curves represent various values of the solar flux, with $S_0$ being the baseline. The graph illustrates how changes in solar flux affect the temperature at various pressures.

Abe & Matsui, 1988: JAS, 45, 3081-3101. Fig. 1
2.2 freezing limit

A simple global energy balance model with ice albedo feedback.

\[ \pi r^2 S (1 - A) = 4 \pi r^2 F \]

\[ F = \frac{2 \sigma T_s^4}{3 \tau_s + 2} \]

\[ A = \begin{cases} 0.3 & (T_s \geq 273) \\ 0.6 & (T_s < 273) \end{cases} \]
Multiple equilibrium state

\[ \tau_s = 0.834 \]
Multiple equilibrium state

\( \tau_s = 0.834 \)

critical flux for the runway greenhouse
2.3 stability of liquid water

Planetary flux

Abe, 1993: Lithos, 30, 223.
Amount of H2O necessary for formation of liquid water

Abe, 1993: Lithos, 30, 223.
Earth-sized planet @Mars, Venus, Earth orbit.

Abe, 1993: Lithos, 30, 223.
3. Water planet in geological time scale

Continuously Habitable Condition
Cause of change

1. Loss of H2O
   H2O is dissociated in the upper atmosphere.
   lost into space as H.
2. Evolution of the central star
   increase of the insolation about 30% in 4.5b.y.
3. Carbonate formation
   CO2 dissolves into liquid water
   fixed as carbonate
3.1 Loss of H2O

H loss from the present Earth is rather rapid.

UV dissociation of H2O into H is also rapid.

Limited by supply of H2O to the upper atmosphere.
Water content in the upper atmosphere

Water vapor condenses in the troposphere. Water content in the upper atmosphere limited by the P-T condition at the tropopause. Cold Trap

While water vapor mixing ratio \( < 10^{-3} \)

1 ocean mass water survives \( > 4.5 \) b. y. (Diffusion Limit)
Planetary flux

CO₂ amount

Critical flux
~280 W/m²
~115%
2. Evolution of the central star

Abe, 1993:
Lithos, 30, 223.
3.3 Carbonate formation

CaO + 2CO₂ + H₂O → Ca²⁺ + 2HCO₃⁻

HCO₃⁻ + H⁺ ↔ H₂CO₃

HCO₃⁻ ↔ CO₂⁻ + H⁺

H₂CO₃ ↔ CO₂ + H₂O

Ca²⁺ + CO₂⁻ ↔ CaCO₃

CaO + CO₂ → CaCO₃
Carbonate formation

\[ \text{CaO} + 2\text{CO}_2 + \text{H}_2\text{O} \overset{\text{(dep.)}}{\rightarrow} \text{Ca}^{2+} + 2\text{HCO}_3^- \]

\[ \text{HCO}_3^- + \text{H}^+ \leftrightarrow \text{H}_2\text{CO}_3 \]

\[ \text{HCO}_3^- \leftrightarrow \text{CO}_3^{2-} + \text{H}^+ \]

\[ \text{H}_2\text{CO}_3 \leftrightarrow \text{CO}_2 + \text{H}_2\text{O} \]

\[ \text{Ca}^{2+} + \text{CO}_3^{2-} \leftrightarrow \text{CaCO}_3 \]

The duration of carbonate formation is the time required for the transition from dissolution to precipitation:

\[ \tau_{\text{carb}} \sim 10^{5-6}\text{ y} \]
Effect of carbonate formation

Abe, 1993: Lithos, 30, 223.
Carbon Cycle


Carbon Cycle

Carbon Cycle

Carbon Cycle

Without continents
Without Continents

![Graph showing the amount of carbon (mol) over time (Ga) with different temperature (°C) for various components: Seafloor, Continent, Seafloor, Atmosphere, Ocean, and Temperature.](Tajika&Matsui, 1990; Tajika 1992)
Importance of planetary interior

Degassing from planetary interior is crucial.

Continents play important role in determining the environment.
Continuously Habitable Zone

Zone の内側限界 : H2Oの散逸
暴走限界
Zone の外側限界 : CO2の凝縮
デクトニックな活動が活発で大きな脱ガスが維持される場合
現在の太陽系 : 0.95－1.37AU
46億年間 : 0.95-1.15AU
4. Various Water Planets

Habitable Zone Limits for Dry Planets
Y. Abe, A. Abe-Ouchi, N. H. Sleep, and K. J. Zahnle
Submitted to J. Astrobiology
Problem of global average

Discussion using global average implicitly assumes an ocean-covered ‘aqua’ planet that has a large amount of liquid water like the present Earth.

However, there is a possibility of a habitable ‘land’ planet that is covered by vast dry desert but has locally abundant water. Ancient Mars might be in such a state.
Liquid water: limited by itself

The conditions for the existence of liquid water can be different for a less water land planet from that of an aqua planet, because both the ice-albedo feedback, which causes the complete freezing, and the runaway greenhouse, which causes the complete evaporation, are caused by the phase change of water.
Ocean planet and Land planet

![Graphs showing precipitation patterns over latitude for Ocean and Land planets.](image-url)
Ocean planet and Land planet

図 3.20 (a)年平均でみた降雨量 (P) と蒸発量 (E) と P-E の南北分布、(b)水蒸気の南北輸送量、実線は(a)図の P-E の分布を維持するのに必要な輸送量を求めたもの、破線は Sellers (1965) による同様な見積もり、一点鎖線は Starr et al. (1969) による輸送量の計算値 (Newton, 1972)
Ocean planet and Land planet

Ocean planet and Land planet

Dune planet (Herbert, F. (1965) *Dune,*
Example of A Land Planet

Surface Temperature

Precipitation

Zonal Wind (sigma=0.81)

Meridional Wind (sigma=0.81)
Runaway greenhouse of an ocean planet

Global average insolation below the critical flux

Even if the insolation at the low latitude is above the critical, High latitude emits the excess

Present Earth is in this state
Runaway greenhouse of an ocean planet

Global average insolation above the critical flux

Planetary radiation cannot exceed the critical
Energy balance cannot be achieved

Runaway
Runaway greenhouse of a land planet

Global average insolation above the critical flux

Dry low latitude can emit above the critical, High latitude is below the critical

Water can exist at high latitude
GCM result:
Ground water vs net insolation
Surface temperature vs relative insolation
Water content in the upper atmosphere

成層圏上部の水蒸気量は極端に小さい：非常にわずかな水の量(平均1mm)でも長期間安定に存在できる

The water content in the upper atmosphere is extremely small.
The lifetime of water on the surface of the land planet is longer than that of the aqua planet.
The freezing limit (of solar flux) is smaller on land planet than on aqua planet.
Land Planet vs Aqua Planet

Stability region of Liquid water

阿部, 1993:
惑星の科学, 朝倉書店, pp. 227.
Various Water Planets

(1) Aqua Planet
   1-1 Ocean (only) Planet:
       Without continents, surface can be very hot
   1-2 Ocean-Land Planet:
       Earth-like
(2) Land Planet:
       *Dune Planet*, ancient Mars?

The abundance of water is important!
Ocean-Land Planets: $x0.1 \sim x10$ earth ocean mass water
5. Supply of water
Water amount and Water Planet

$\text{H}_2\text{O}$ itself is very abundant
water is more abundant than rock
If we collect all water,
--> the planet should be like Uranus or Neptune.

Water planets
Only small amount of water is captured
Earth Ocean: only 0.027% of the Earth mass
$10 \times \text{ocean mass} \rightarrow \text{Ocean (only) planet}$
$0.1 \times \text{ocean mass} \rightarrow \text{Land Planet}$
Supply of water to planetary material

Supply of water to planets
---contained in the solid material
Solar nebula: low pressure, $\text{H}_2\text{O}$ cannot be liquid
----> $\text{H}_2\text{O}$ is taken in as ice at first
( Maybe reacted with rock later ----> Hydrous mineral )
This occurs beyond 2.7AU.
‘Snow line’ ~ 2.7AU
Stability of liquid water on planets

The region where H\textsubscript{2}O is taken in the solid planet material (>2.7AU) is beyond the region where liquid water is stable on planets.

--- Transport mechanism determines water abundance on planets. However, the mechanism is not clarified yet.

阿部, 2009, 日本惑星科学会誌 遊星人.
Candidates of Water source

Not well constrained

1. Nebula Gas
2. Comets
3. Material of Asteroid belt
4. Planetesimal of earth orbit

In our solar system, 3 or 4 is likely. However, in extra solar systems, any source will be possible. ---> Variety of water planets.
How to make a habitable planet

Unresolved

--- Major issues:
- Habitable planets other than water planets
- Variety of water planets
- Cause of Variety
references