Atmospheric Structures of Ocean Planets:

a Study of Mechanisms to Determine Inner Edge of Habitable Zone

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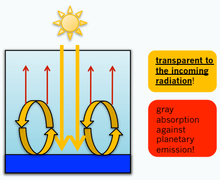
Introduction

The inner edge of the "Habitable Zone" is determined by "Radiation Limit" mechanisms!

Previous study 1: Nakajima et al. [1992]



One dimensional plane parallel atmospheric structure with **lower saturated moist-convective troposphere over ocean and upper stratosphere** was calculated. Planetary radiation flux was obtained against each structure. (Fig. 1)

RL 1: the KI-limit

A condition for a stratospheric structure line to connect a saturated troposphere structure line. (Fig. 2)

RL 2: the radiation limit of the troposphere

In the case of optically thick atmosphere, **the temperature structure around the photosphere in the moist-convective troposphere fixes planetary radiation.**

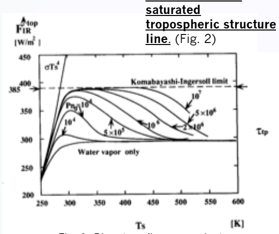


Fig. 1. Planetary flux F_{IR} against T_s

The structure of a radiative-convective atmosphere was calculated. F_{IR} was obtained as a result of a parameter T_s. Each line corresponds to different values of surface dry air pressure p_{air}.

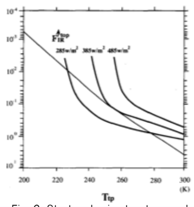


Fig. 2. Stratospheric structure and saturated water vapor line

Previous study 2: Nakajima [2006]

The RLs depend on planetary mass!

The study examined the effect of planetary mass, using the same model as Nakajima et al. [1992]

RL 1: the KI-limit

The KI limit becomes larger when planetary mass becomes larger (Fig. 3) because a saturated tropospheric structure line moves upward in τ-T diagram.

RL 2: the radiation limit of the troposphere

The radiation limit of the troposphere becomes larger when planetary mass becomes larger, too. It is because the photospheric pressure becomes higher and also the temperature, following the saturated water vapor pressure line.

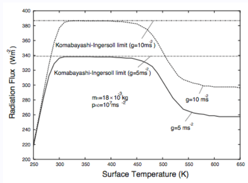


Fig. 3. Planetary flux against F_{IR} Ts (different values of g)

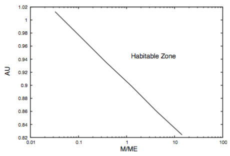


Fig. 4. The inner edge of the HZ against planetary mass (normalized by the Earth's mass)

By these studies, the machanisms to determine HZ were clarified.

But the assumption, "the atmosphere is transparent to incoming radiation", may affect the results.

Purpose

These studies ignore the absorption of incoming central star radiation in the planetary atmosphere!
But the atmospheric structure is influenced by that!
(e. g., ozone in the atmosphere of the Earth)

In this study

(1) **We clarify the effect of the absorption on the two kind of radiation limits!**

(2) **We suggest a new atmospheric structure of an ocean planet, and the condition for the structure to form is obtained!**

Method for Structure Calculation

We assumed **a plane parallel atmosphere** same as previous studies.
As a first step, we assumed the **atmospheric composition is pure water vapor and the mass is same as the Earth's one**.

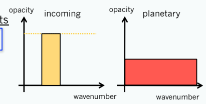
Method 1: simplified absorption model

Absorption of Incoming Radiation
Incoming radiation is divided into two parts

$$F_{in}(\tau) = (1-\gamma)F_{in}(0) + \gamma F_{in}(0)e^{-\alpha\tau}$$

non-absorbed / absorbed

here, γ is the ratio of flux at absorbed bands, α is the ratio of opacity for incoming radiation to opacity for planetary radiation.



Planetary Emission and Absorption
be calculated by using two-stream approximation with constant gray opacity κ (= 10^{-2} m² kg⁻¹)

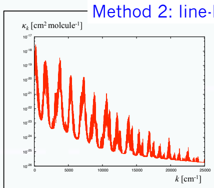
A stratospheric structure is given by an analytical solution (Weaver and Ramanathan [1995], Pujol and Fort [2002]),

$$\sigma T^4(\tau) = (1-\gamma)F_{in}(0)\frac{1+\frac{3}{2}\tau}{2} + \gamma F_{in}(0)\frac{2+\frac{3}{\alpha}+(\frac{4}{3}\alpha-\frac{3}{\alpha})e^{-\alpha\tau}}{4}$$

Changes of γ, α are corresponded to changes of atmospheric conditions (gas components, clouds ...) or spectral distribution of the incoming radiation.

This model is used **to clarify the effect of the absorption generally**.

Method 2: line-by-line calculation

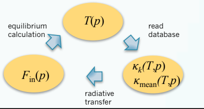


Absorption of Incoming Radiation
be calculated considering wavelength dependence

Planetary Emission and Absorption
be calculated by using two-stream approximation with Rosseland mean opacity $\kappa(T,p)$ table

・line absorption data from HITRAN + lorentz line shape (depend on T, p)

Here, This method is used only pure water vapor atmospheres with various,incoming fluxes and central star types **as the examples**.



Change of KI-limit

Method 1

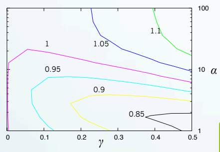


Fig. 6. Values of the KI limit (normalized by the value of the no-absorption case)

The result shown in Fig. 6 can roughly be separated In two regions:
α > 10 The KI limit becomes larger.
α < 10 The KI limit becomes smaller,
than the value of the no-absorption case.

Fig. 7 shows changes of structures by the absorption. The temperature of the absorption region becomes higher by its heating. The temperature below the region becomes lower by shadowing.

The KI-limit becomes smaller when the heating by the absorption occurs at $\tau \sim 0.1$.
The KI-limits becomes larger when the absorption occurs $\tau < 0.1$.

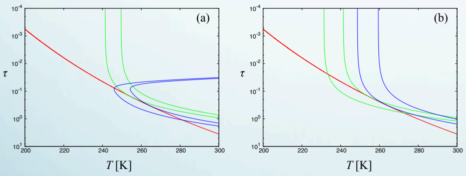


Fig. 7. Comparison of atmospheric structures with and without the absorption

without the absorption
with the absorption

(a) γ=0.5 α=100
$F_{in}(0)$=385, 440Wm⁻²

(b) γ=0.5 α=1
$F_{in}(0)$=325, 385Wm⁻²

Method 2

Table 1. Ki-limit calculated with method 2

T_{sun}	KI-limit
3000 [K]	600 [W m⁻²]
4500 [K]	575 [W m⁻²]
6000 [K]	570 [W m⁻²]
without absorption	610 [W m⁻²]

Values of the KI-limit calculated with method 2 are shown in table 1.
In table 1, the cases of T_{sun} = 3000,4500,6000K are considered.
The change of T_{sun} corresponds to the change of γ and α.

Reference List

[1] Nakajima, S., Hayashi, Y., and Abe, Y., J. Atmos. Sci., Vol. 49, 2256-2266, 1992
[2] Nakajima, M., Titech Graduation Thesis, 2006
[3] Pujol, T., and Fort, J., J. Geophys. Res., 107, D21, 4566-4572, 2002
[4] Weaver, C. P., and Ramanathan, V., J. Geophys. Res., 100, 11585-11591, 1995

Change of Radiation Limit of Troposphere

Method 1

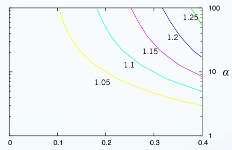


Fig. 8. Values of the radiation limit (normalized by the value of the no-absorption case)

Fig. 8 shows the change of the radiation limit.

The absorption makes the radiation limit of the troposphere larger.

This is because the absorption reduces the incoming radiation reaching photosphere.

Fig. 9 shows the absorption does not change the photospheric F_{IR} value!

By using method 1, we calculated radiative-convective atmospheric structure which corresponds to each value of T_s, regarding γ and α as parameters.

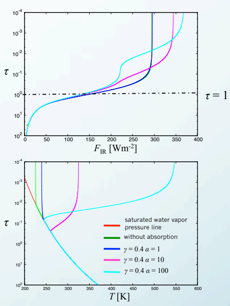
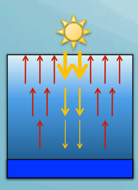


Fig. 9. Examples of calculated atmospheric structure

Method 2 is under calculation...

Another Radiation Limit

When the incoming radiation is larger than the KI-limit, the atmosphere can not have moist-convective troposphere.
In such a case, "dry atmosphere" without moist-convection forms.



without moist-convection!

Method 2

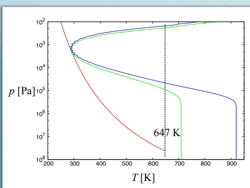


Fig. 10. radiative equilibrium atmospheric structure corresponds to incoming flux larger than the KI-limit

F_{in} = 600 Wm⁻², T_{sun} = 4500 K
F_{in} = 600 Wm⁻², T_{sun} = 3000 K

The atmospheric structures shown in Fig. 10 become isothermal at lower layer. This is because the incoming radiation does not reach the layer. This phenomenon can be modeled as γ=1 and α<1 case in method 1.

$$\sigma T_{iso}^4 \sim F_{in}(0)\frac{3}{\alpha}$$

If α is sufficiently large, T_{iso} becomes < 647K (critical temperature of water).
In such a case, **the planet can have ocean against the incoming radiation over the KI-limit!**

Here, an important fact is recognized.
Incoming flux over the "KI-limit" only mean, "The atmosphere can not have moist-convective troposphere", not "a planet cannot have ocean on its surface".

Conclusion

We studied the effect of the absorption of incoming central star radiation, using, (method 1) "Simplified absorption model" and "(method 2) line-by-line calculation".
As a result,

(1) The KI-limit becomes smaller when the heating by the absorption occurs at $\tau \sim 0.1$.
The KI-limits becomes larger when the absorption occurs $\tau < 0.1$.
The absorption makes the radiation limit of the troposphere larger.

(2) The possibility of a new atmospheric structure of a ocean planet, "dry atmosphere", was obtained.

As a future work,
・We consider dry- and moist-convection in line-by-line structure calculation.
・We include the effect of "continuum absorption" of water vapor in the calculation.