Radiation Limits of Ocean Planets: Effects of the Atmospheric Absorption of the Incoming Radiation with One-Dimensional Radiative-Convective Equilibrium Model

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Introduction The upper limit of the planetary radiation of an ocean planet is given by some mechanisms called "Radiation Limits." The radiation limits are important when we consider the evolution of the climate of the terrestrial planets [1] and when we determine the Habitable Zone of exoplanets because the radiation limits are related to the inner edge of the habitable zone [2].

Nakajima et al. [3] clarified the mechanisms of the radiation limits with a simplified radiative-convective equilibrium atmospheric model. In their model, the atmosphere is assumed to be transparent against the incoming radiation, whereas it is gray against the planetary radiation. There are two limits which are determined by different mechanisms, the "Komabayashi-Ingersoll Limit" [4, 5](an upper limit, hereafter the KI limit) and the "Radiation Limit of the Troposphere" (an asymptotic limit). The KI limit is determined from the condition that the base of the stratosphere should be saturated, and the radiation limit of the troposphere is determined from the condition that the atmospheric structure around the photosphere is fixed by the tropospheric saturated water vapor pressure condition.

Effects of absorption of the incoming radiation against the KI limit were investigated by Pujol and Fort [6] with a radiative equilibrium model. In this study, we investigate effects of the absorption against the radiation limit of the troposphere with a radiative-convective equilibrium model.

Model The atmospheric model is based on the radiative-convective atmospheric model used by Nakajima et al. [3], and the absorption of the incoming radiation is parameterized in the same way as Weaver and Ramanathan [7] and Pujol and Fort [6]. The radiative-convective equilibrium atmospheric model adopted in this study assumes following features for the atmosphere. The atmosphere has one-dimensional plane-parallel structure. In the atmosphere, a moist-convective layer (troposphere) is present at the bottom and a radiative equilibrium layer (stratosphere) is present at the top. The atmospheric composition is water vapor and dry air. The planetary radiation is absorbed by water vapor with gray-absorption, while dry air is assumed to be transparent. The amount of water is sufficient and the amount of atmospheric gas is determined so that the equilibrium against the incoming radiation is achieved. Planet surface and the troposphere are saturated with water vapor. And the tropospheric structure is assumed to be a moist pseudoadiabatic lapse rate. Also, values of parameters associated with atmospheric gases are set equal to those in Nakajima et al. [3]. The absorption of the incoming radiation is expressed by the absorption parameters. The energy flux of the incoming radiation, $F_{\rm in}$, as a function of τ, is written as,

$$F_{\rm in}(\tau) = (1-\gamma)F_{\rm in}^{\rm top} \ + \ \gamma F_{\rm in}^{\rm top} e^{-\alpha\tau}, \qquad (1)$$

where $F_{\rm in}^{\rm top}$ is the energy flux at the top of the atmosphere, and τ is the optical depth for the planetary radiation. The effective absorption width is expressed by γ, and α is the ratio of the opacities against the incoming radiation to the planetary radiation. The model parameters are γ, α, the surface pressure of the dry air $p_{\rm n0}$, and the surface temperature $T_{\rm s}$. For one parameter set, the equilibrium structure is calculated, and we obtain the planetary radiation flux $F_{\rm pl}$.

Results When the absorption against some wavelength in the upper layer is effective ($1-\gamma = 0.7$ and $\alpha = 10^2$, Fig. 1a), the two limits are present. Fig. 1a shows that the radiation limit of the troposphere becomes larger than that of the no-absorption case. This is because the absorption heats the stratosphere (Fig. 2a). The planetary radiation from the troposphere is the same with that of the no-absorption case because the tropospheric structure does not change by the absorption. The additional planetary radiation from the heated stratosphere contributes to the total planetary radiation flux $F_{\rm pl}$.

On the other hand, when the atmospheric window against the incoming radiation is not present ($1-\gamma = 10^{-4}$ and $\alpha = 5\times10^{-2}$, Fig. 1b), the results show a completely different behavior. In Fig. 1b, the branch 1 shows the radiation limits. But the branch 2 shows neither the upper nor the asymptotic limit (here, the "KI limit" corresponds to the relative one, see Pujol and Fort [6]). The existence of the branch 2 is the result of the formation of the optically thick, isothermal stratosphere (Fig. 2b) caused by nonexistence of the atmospheric window against the incoming radiation. The atmospheric structures shown in Fig. 2b have supersaturated region for the lower surface temperatures (corresponding to lower $F_{\rm pl}^{\rm top}$, red and green curves) while do not have that for the higher surface temperature (corresponding to higher

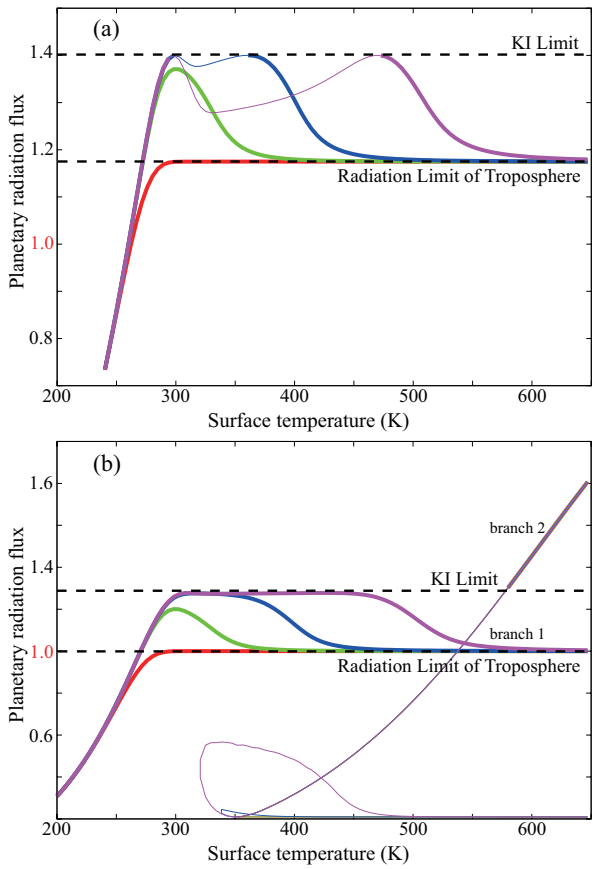

Fig. 1: The planetary radiation flux at the top of the atmosphere $F_{\rm pl}^{\rm top}$ (normalized by the radiation limit of the troposphere of the no-absorption case) against the surface temperature $T_{\rm s}$. Panels display results (a) $1-\gamma = 0.7$ and $\alpha = 10^2$, and (b) $1-\gamma = 10^{-4}$ and $\alpha = 5\times10^{-2}$. Each curve corresponds to $p_{n0} = 0$ Pa (red), $p_{n0} = 10^5$ Pa (green), $p_{n0} = 10^6$ Pa (blue), and $p_{n0} = 10^7$ Pa (purple), respectively. The fine parts of the curves corresponds to the atmospheres which have the supersaturated stratosphere.

$F_{\rm pl}^{\rm top}$, blue curve). The critical $F_{\rm pl}^{\rm top}$ is the relative KI limit.

Summary We investigate the effects of the atmospheric absorption of the incoming radiation on the radiation limit of the troposphere of ocean planets. To clarify the effects, we use a simple parameterization of the absorption. We have found two important cases. In the case 1, the radiation limit becomes larger than the no-absorption case when the absorption in the upper atmosphere is effective. On the other hand, in the case 2, the radiation limit disappears when the window against the incoming radiation is not present.

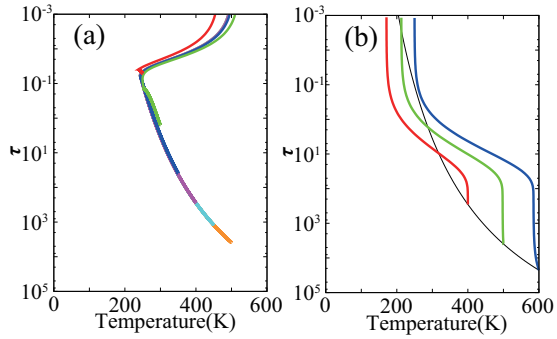

Fig. 2: Atmospheric temperature against the optical depth τ. (a) Curves correspond to the atmospheres of $T_{\rm s} = 250$K (red), $T_{\rm s} = 300$K (green), $T_{\rm s} = 350$K (blue), $T_{\rm s} = 400$K (purple), $T_{\rm s} = 450$K (light blue), and $T_{\rm s} = 500$K (orange) of the green curve of Fig. 1a. (b) Curves correspond to the atmospheres of $T_{\rm s} = 400$K (red), $T_{\rm s} = 500$K (green), and $T_{\rm s} = 600$K (blue) of the branch 2 of the green curve of Fig. 1b. Black curve shows the saturated water vapor pressure condition for the stratosphere.

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