APRIM 2017, July 4th, 14:45-15:00, Room 201 A, 2F

Luminosities of ice giants with condensate in early atmosphere

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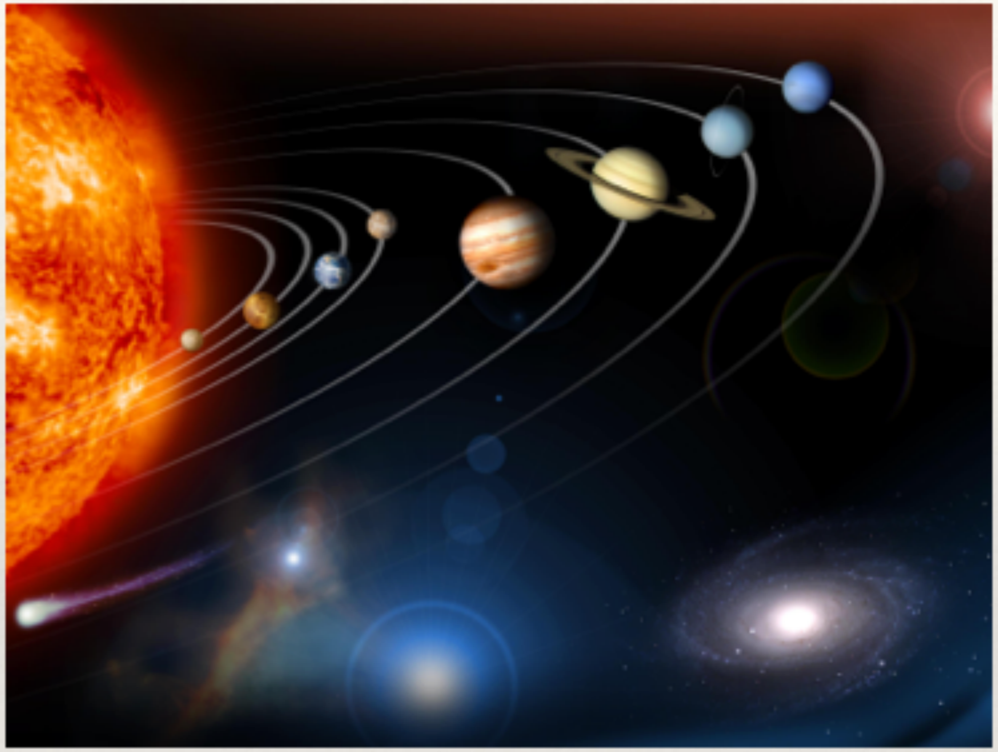
Kurosaki & Ikoma (2017)

Ice Giants



Ice giants in solar system
Uranus & Neptune

Both planets are in distant region

Uranus: 30,588 days

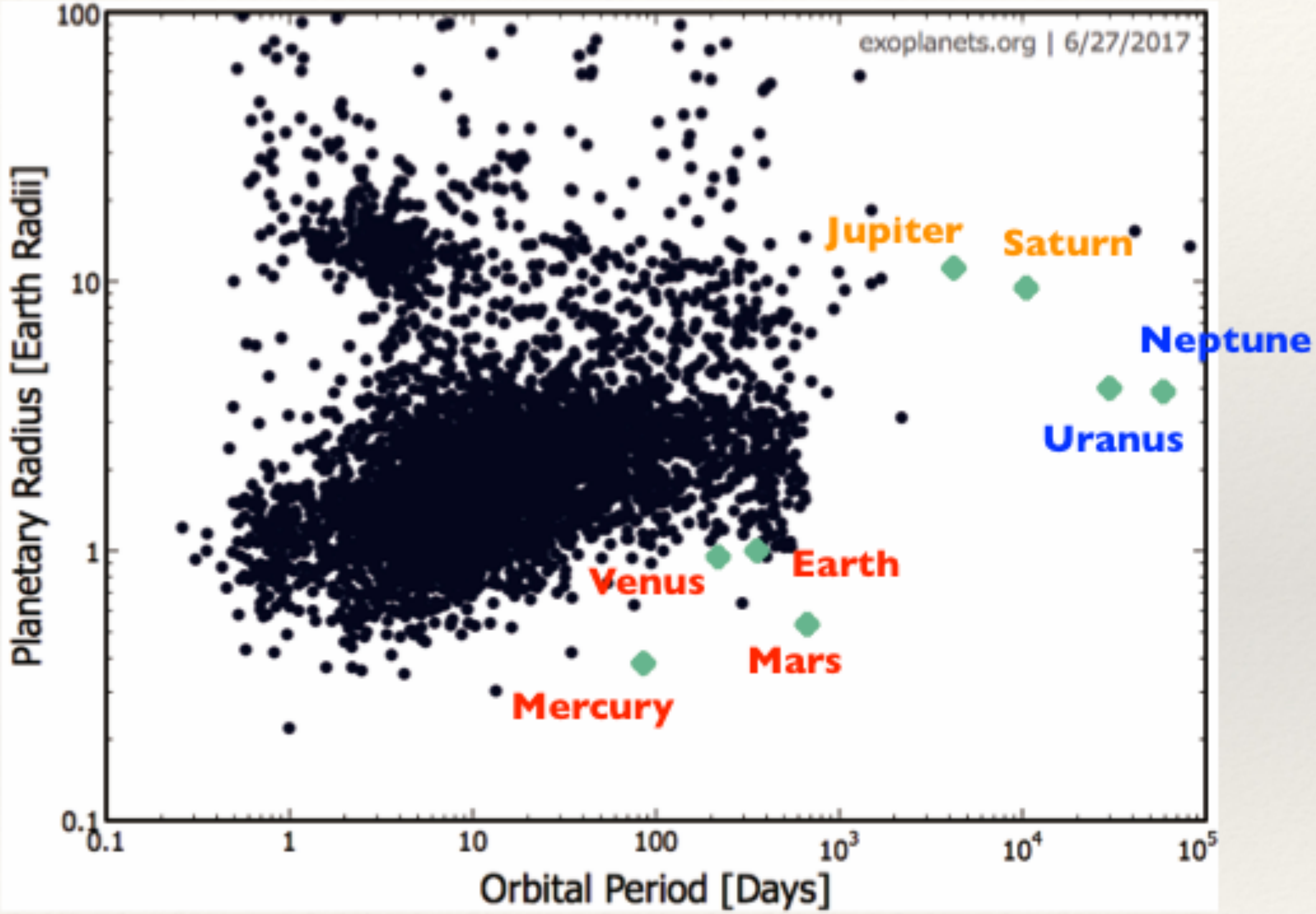
Neptune: 59,799 days

The atmosphere is enriched in heavy elements.

e.g.) Marley & McKay (1999) Fortney et al. (2011)

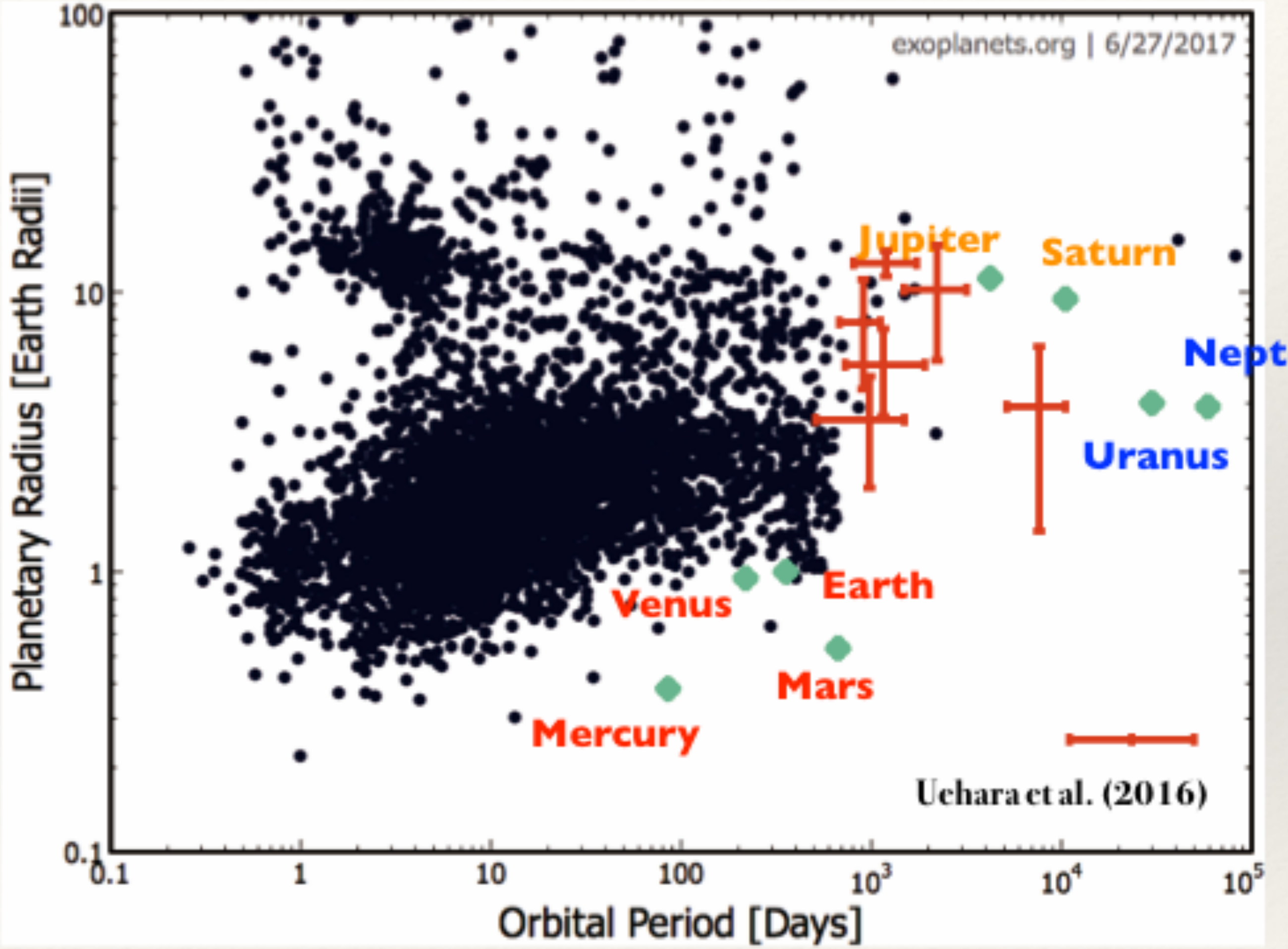
Extra-solar system: Many Neptune-size planets are detected.

Neptune-size Planets



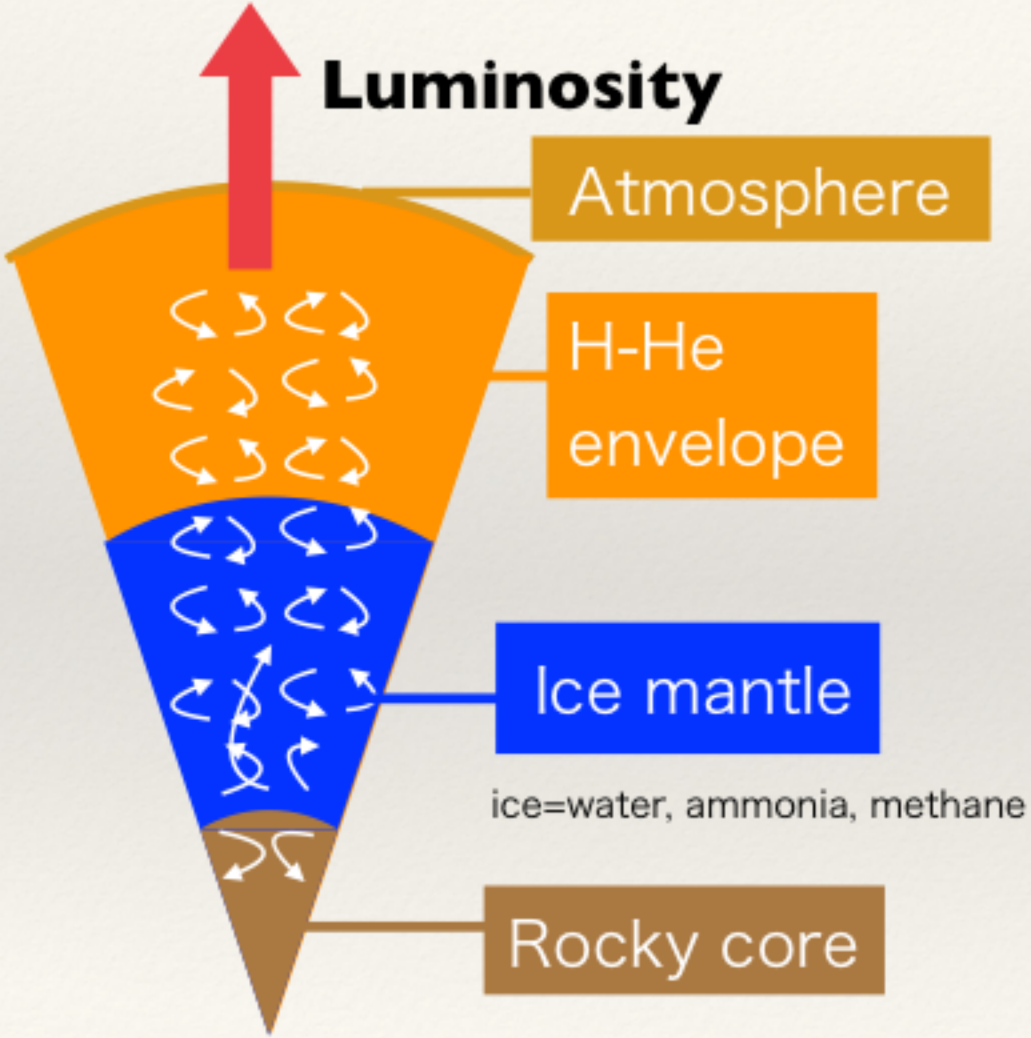
Most of all Neptune-size planets are in hot-region

Neptune-size Planets at Distant Region



Can we detect those distant planets by direct imaging ?

How to estimate the Luminosity



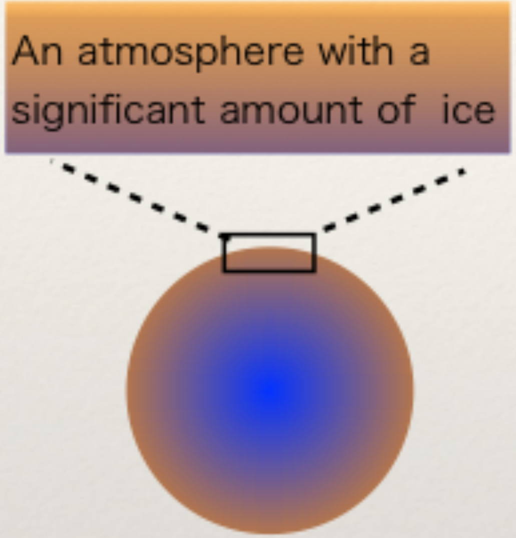
The thermal evolution model constructed by Hubbard (1977)

→ The model explains the present luminosity of Jupiter

Assumptions

1. Fully convective interior
2. The compositional distribution is unchanged through the evolution
3. Condensation is ignored
4. The planet possesses a high luminosity immediately after the formation

Atmosphere: Enriched in Heavy Elements



An atmosphere with a significant amount of ice

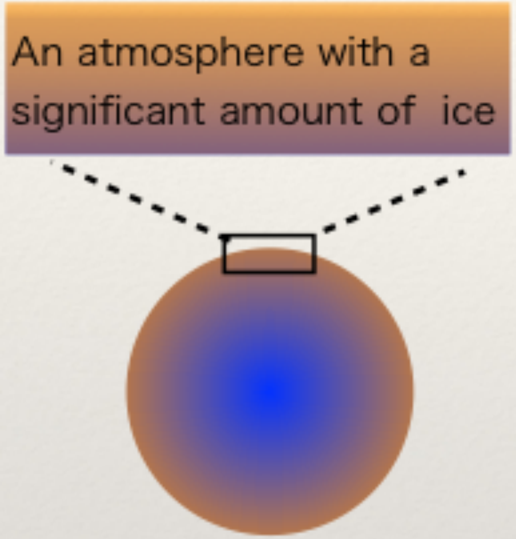
What will happen if the planet has
an atmosphere enriched in icy materials

- Opacity will increase
- Heat capacity will become smaller
- Condensation will occur

The planetary flux will be

Increased? Decreased?

Atmosphere: Enriched in Heavy Elements



What will happen if the planet has
an atmosphere enriched in icy materials

- Opacity will increase
- Heat capacity will become smaller
- Condensation will occur

The planetary flux will be

Increased? Decreased?

Latent heat due to the condensation heats up the atmosphere

The planetary flux should be *increased*

Demonstrate the effect by solving the interior & atmosphere

Purpose of this Study

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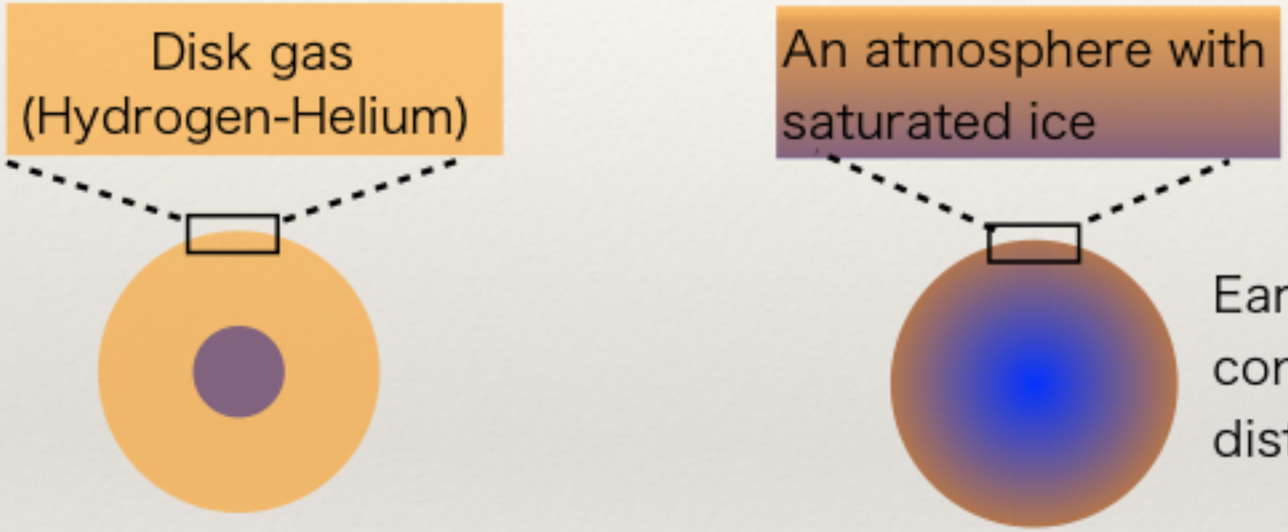
We investigate the thermal evolution of the ice giant with a significant amount of ice constituents (water, ammonia, and methane) in the atmosphere



Disk gas (Hydrogen-Helium)

An atmosphere with saturated ice

Early in the stage, condensable constituents distribute upper atmosphere.

No studies focused on the thermal evolution of the ice giant with a significant amount of ice constituents in the atmosphere

We discuss the difference of the planetary luminosity with/without the effect of the condensation of water, ammonia, and methane.

Method: Model Summary

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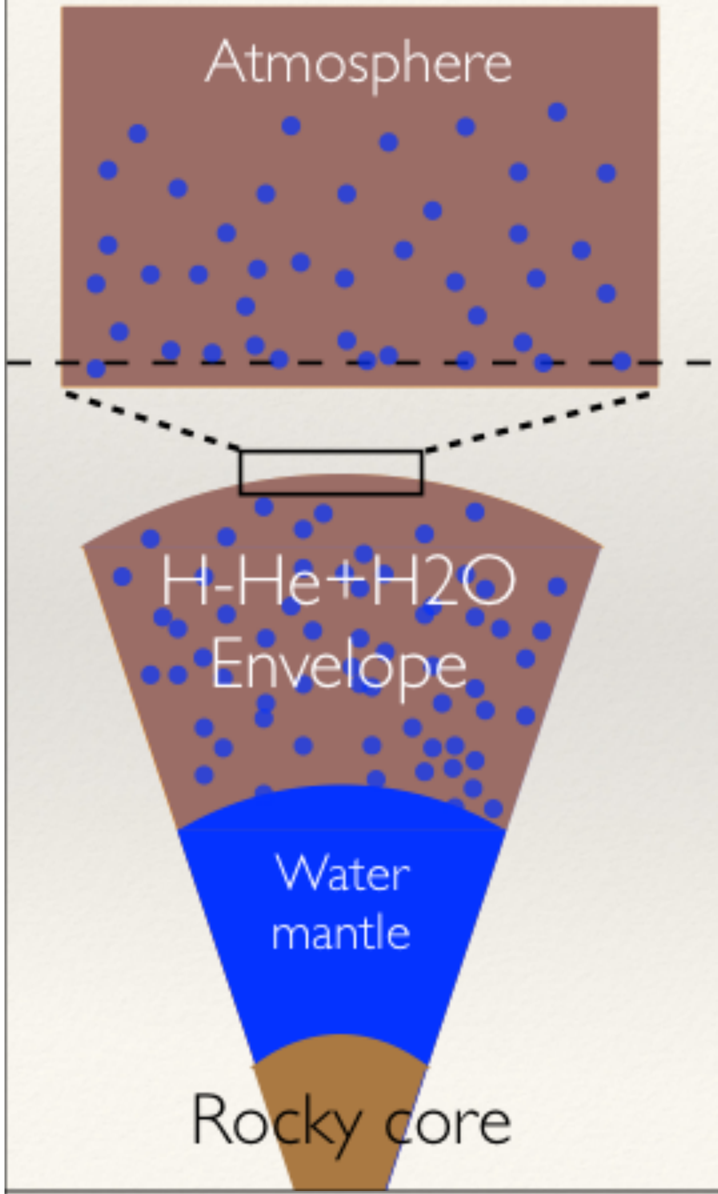


Boundary between the interior and atmosphere=100 bar

Atmosphere

Radiative-convective equilibrium

Constituents: H_2, He, H_2O, NH_3, CH_4

Condensates: H_2O, NH_3, CH_4

Envelope → Hydrogen, Helium, Water

Mantle → Water

Core → Rock ($MgSiO_3$)

Convective equilibrium (Isentropic)

Parameters:

Initial ice mole fraction in the atmosphere

$NH_3/H_2O=0.135$ (solar value of N/O)

$CH_4/H_2O=0.056$ (smaller than solar value of C/O)

Methods: Thermal Evolution

Fully convective interior → Constant entropy in each layer

$$\frac{\partial L_r}{\partial M_r} = -T\frac{\mathrm{d}S}{\mathrm{d}t}$$

=> integrate by mass

$$\int_0^{M_p} \frac{\partial L_r}{\partial M_r} dM_r = L_p = 4\pi R_p^2 F_p$$

The thermal evolution timescale is calculated by this equation

$$\boxed{4\pi R_p^2 F_{\mathrm{top}}} = \boxed{-\left[\frac{\mathrm{d}S_{\mathrm{env}}}{\mathrm{d}t}\int_{M_c}^{M_p} T dM_r + \frac{\mathrm{d}S_{\mathrm{c}}}{\mathrm{d}t}\int_0^{M_c} T dM_r\right]}$$

Atmospheric structure

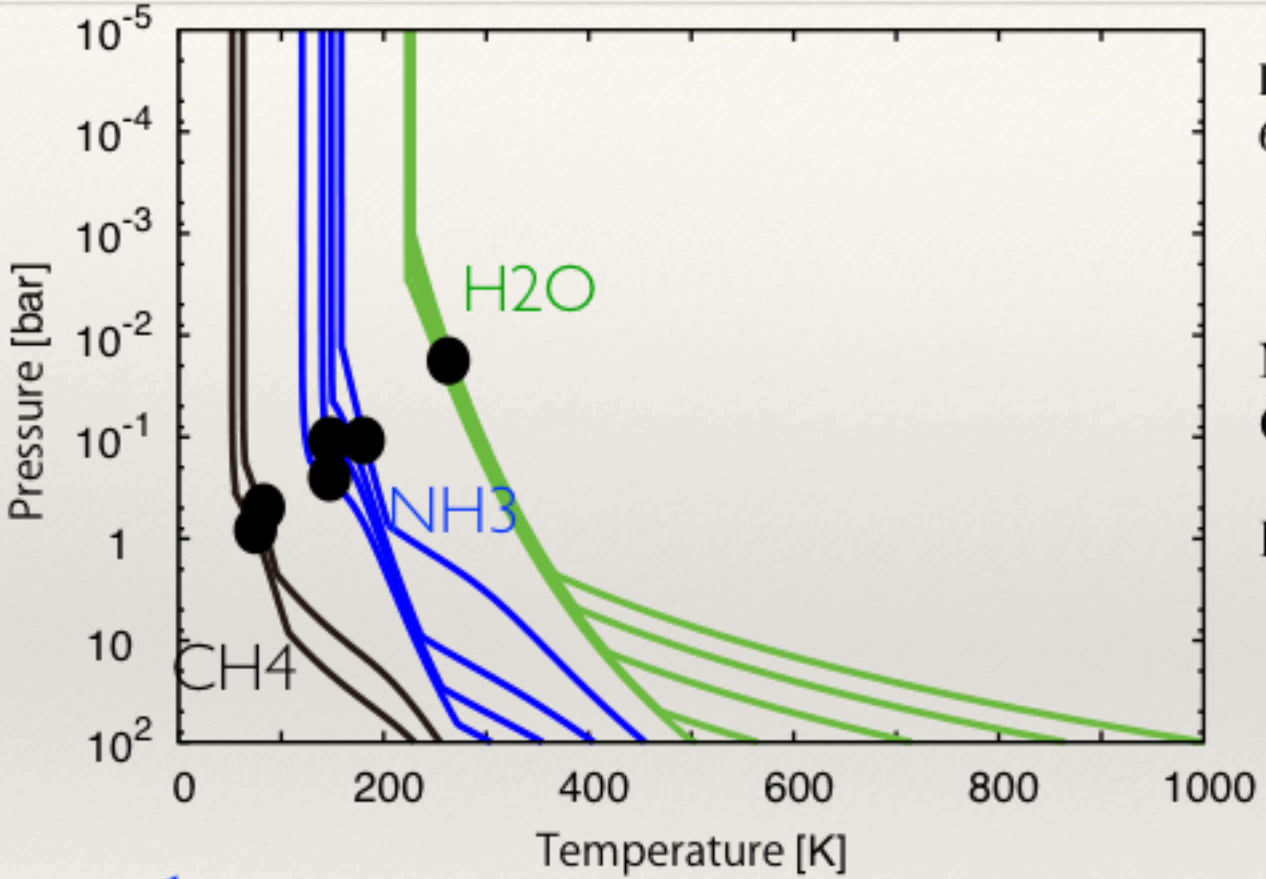
Cooling efficiency

Interior structure

Heat capacity

Calculate the atmospheric structure and interior structure simultaneously.

Atmospheric Structure Enriched in Ices



Ice constituents:
65 mol % in the atmosphere

● Optical depth = 1

NH_3/H_2O=0.135
CH_4/H_2O=0.056

Equilibrium temperature =58.2K

← **Time evolution**

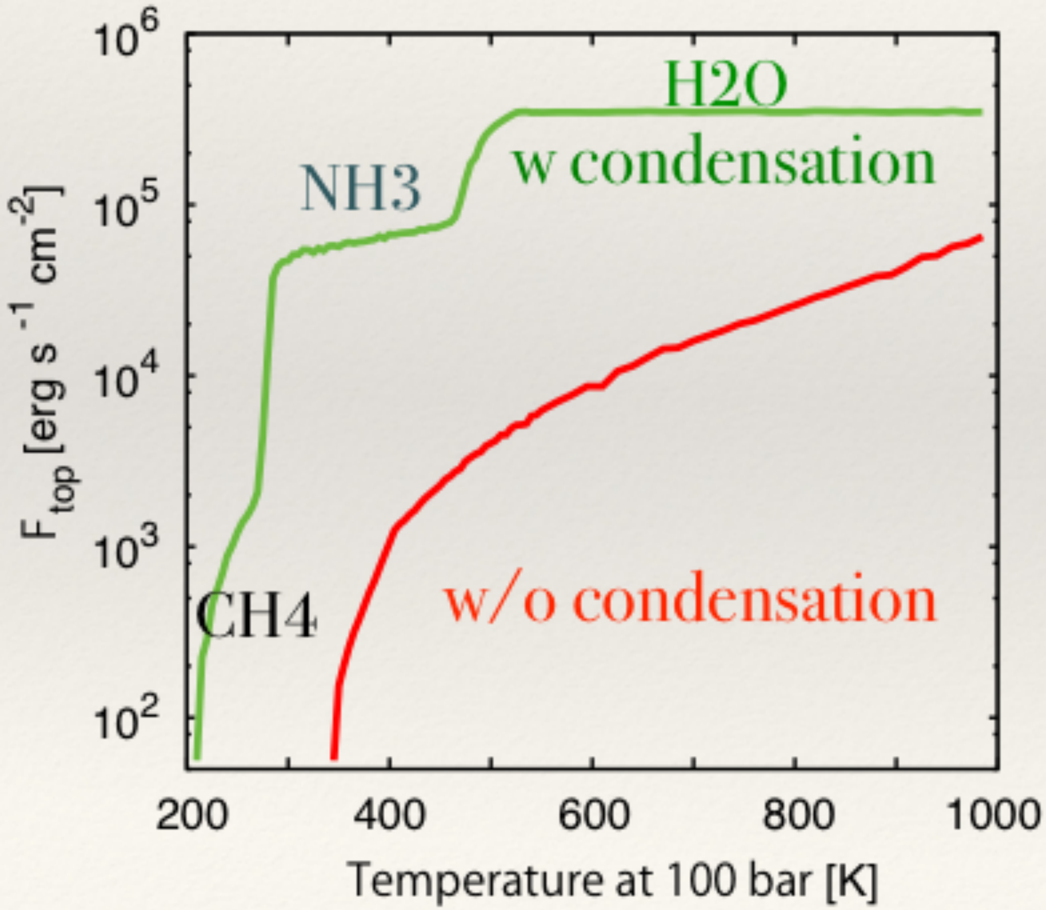
As the time passes, the bottom temperature decreases.

→ **The main condensate changes as the time passes.**

The Outgoing Flux from the Atmosphere

Ice constituents: 65 mol % in the atmosphere

Ftop : the outgoing flux from the top of the atmosphere



Main Condensate

H2O → NH3 → CH4

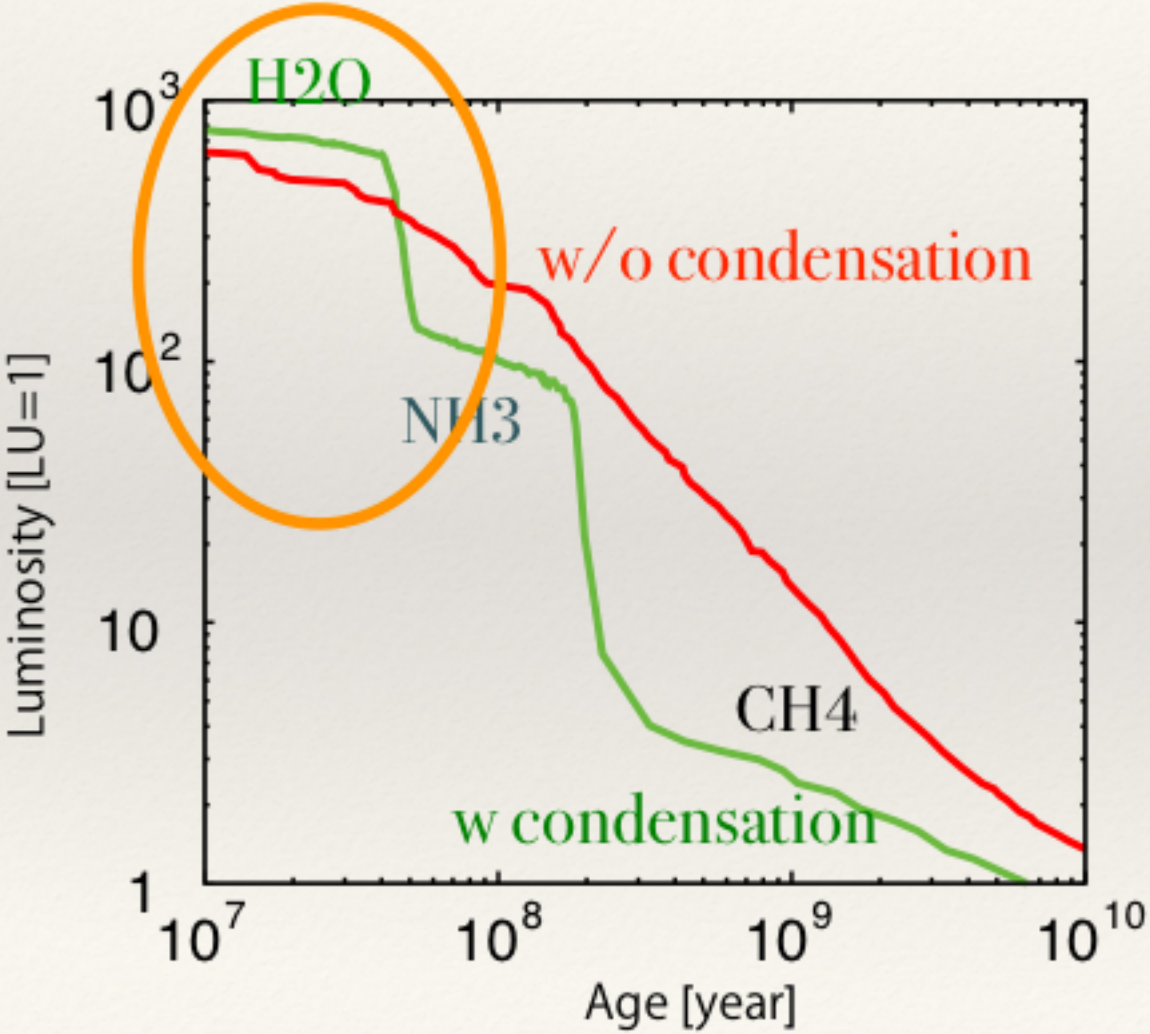
The temperature structure is changed by the condensation

↓

Increase the planetary flux

The Effect on the Luminosity at Early Stage

Ice constituents: 65 mol % in the atmosphere



Increase the flux

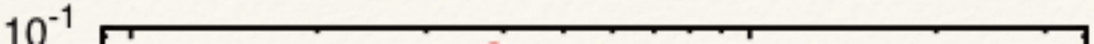
↓

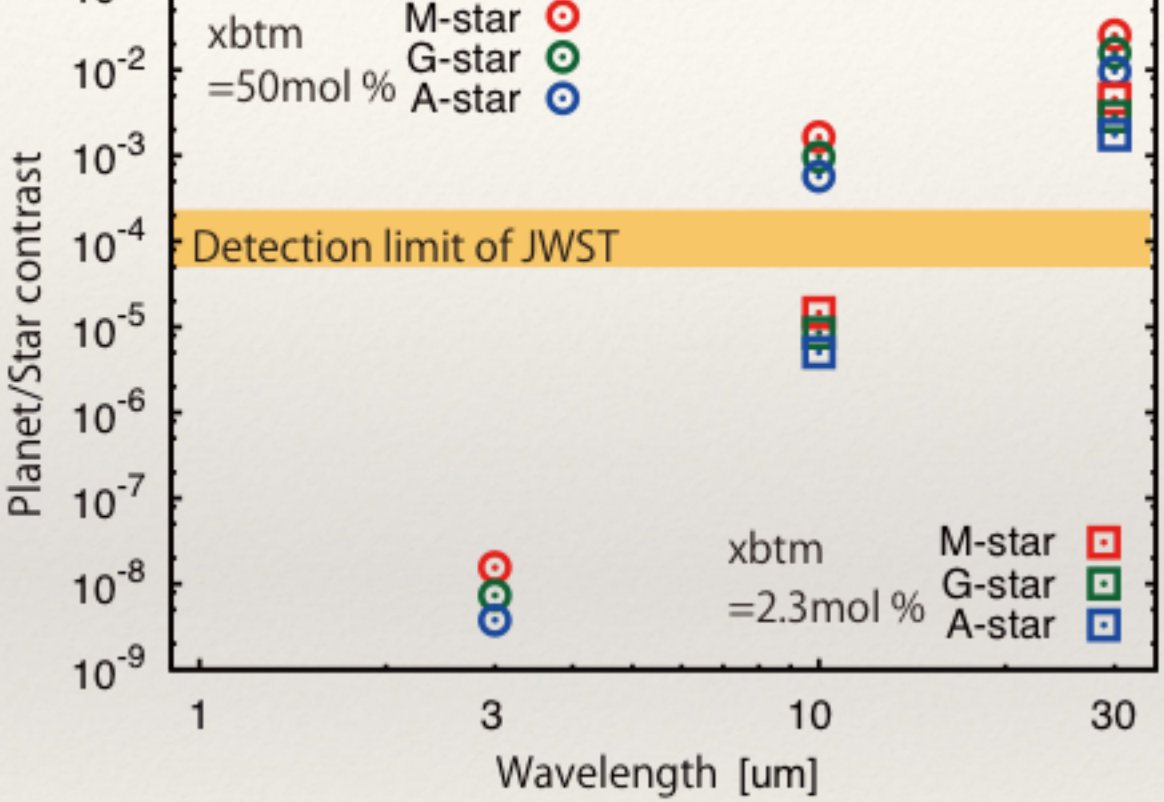
The luminosity become large

↓

In early age, the planet can be easier to detect

Self-luminous Extrasolar Ice giants at Early Age



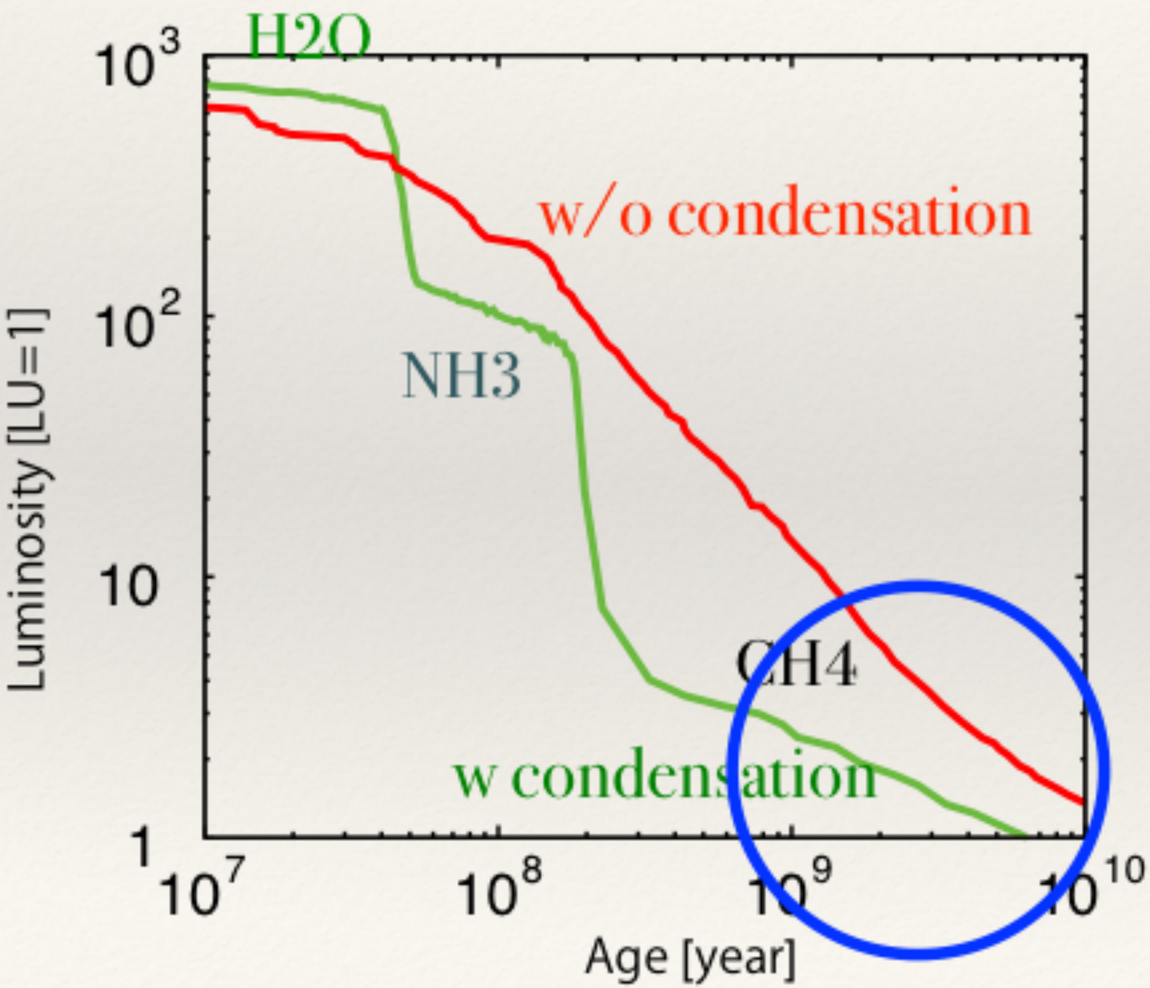


Wavelength longer than 10 µm

→ **Self-luminous ice giant with ice-rich atmosphere can be detected by JWST**

The Effect on the Luminosity at Late Stage

Ice constituents: 65 mol % in the atmosphere



Increase the flux

↓

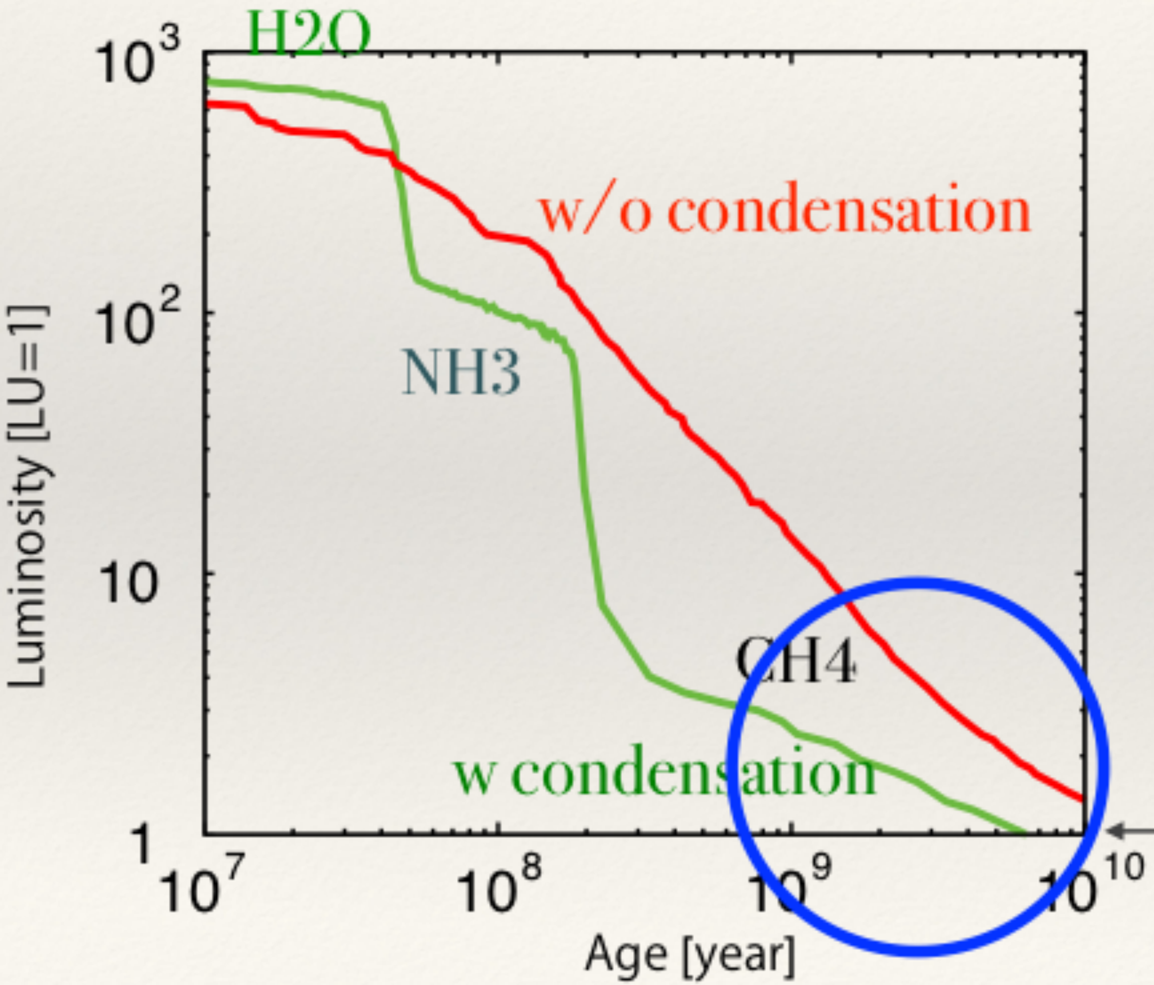
Shorten the evolutionary timescale of the planet

↓

The planet will cool faster

The Effect on the Luminosity at Late Stage

Ice constituents: 65 mol % in the atmosphere



Increase the flux

Shorten the evolutionary timescale of the planet

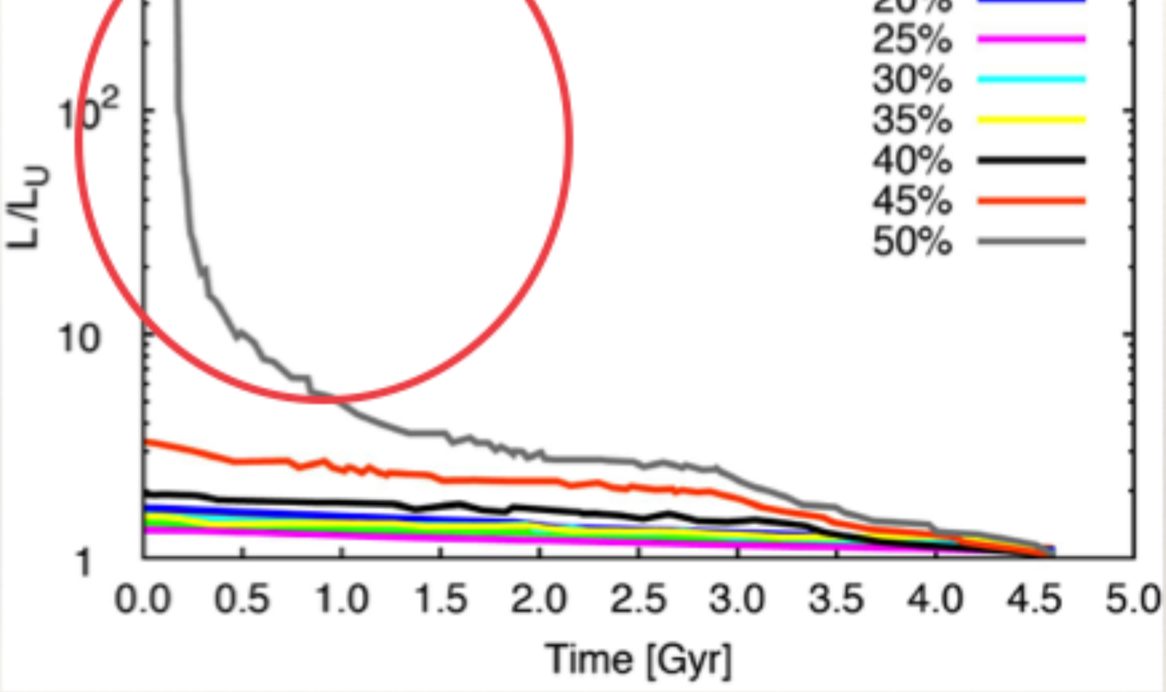
The planet will cool faster

This effect will important to explain the Uranian L

Pearl et al. (1980), Fortney et al. (2011)

Implication for Uranus

The small mol fraction of ice cannot shorten the timescale



cannot shorten the timescale

↓

A significant amount of ice constituents is required

↓

Global event is needed to mix the ice constituents in the atmosphere

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Summary

The thermal evolution of the ice giant with the effect of the condensations of water, ammonia, and methane is investigated.

Results

- Condensation of ices causes large outgoing flux.
- The cooling of the ice giant with the condensation is accelerated due to keeping the high temperature in the atmosphere.

Implication For Exoplanets

If the planetary atmosphere is rich in ice constituent at early age, the planetary luminosity is large enough to detect by JWST.

Implication For solar system planets

To explain the present luminosity of Uranus, a significant amount of ice constituents is required immediately after the formation.

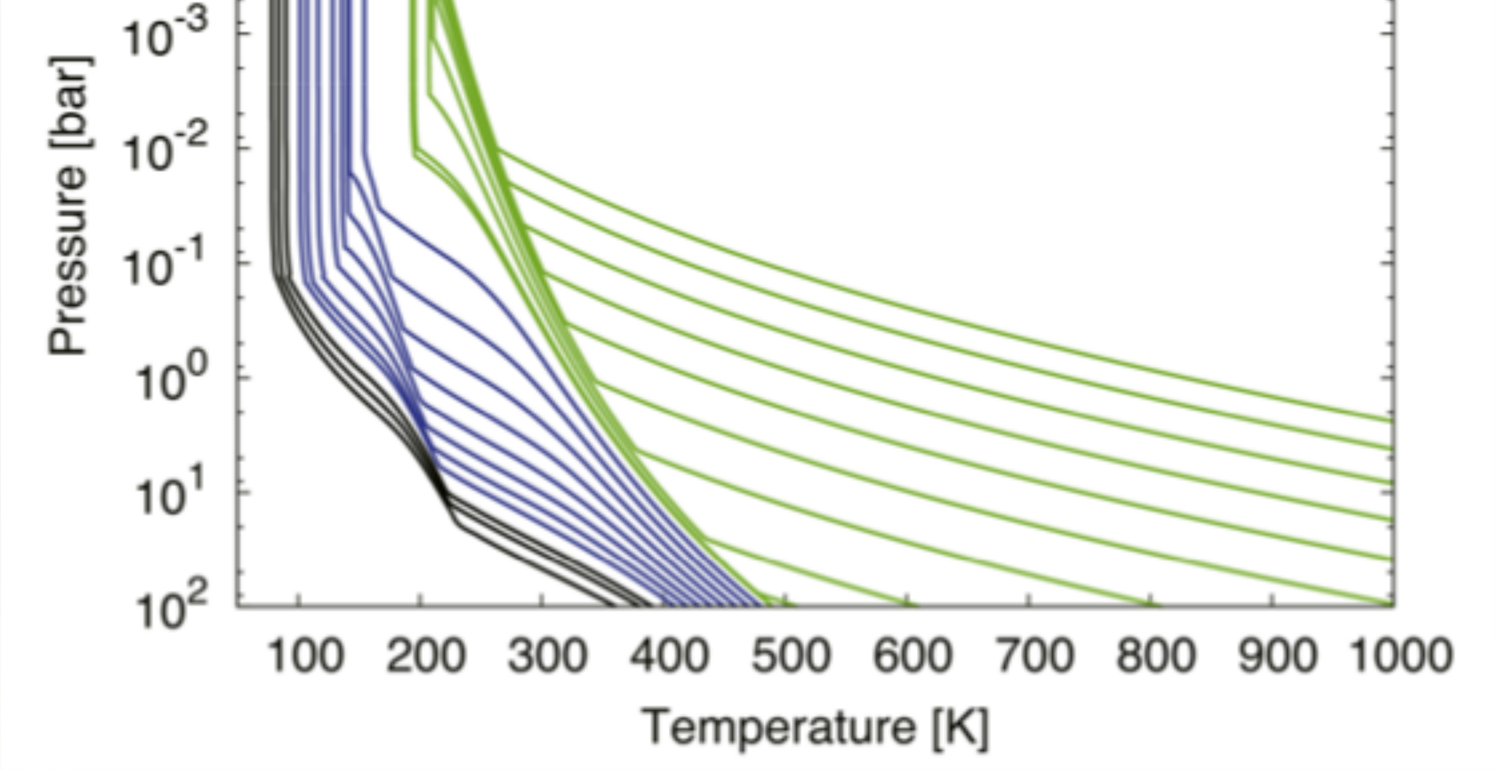
Take Home Message

Condensation in atmosphere is very important.

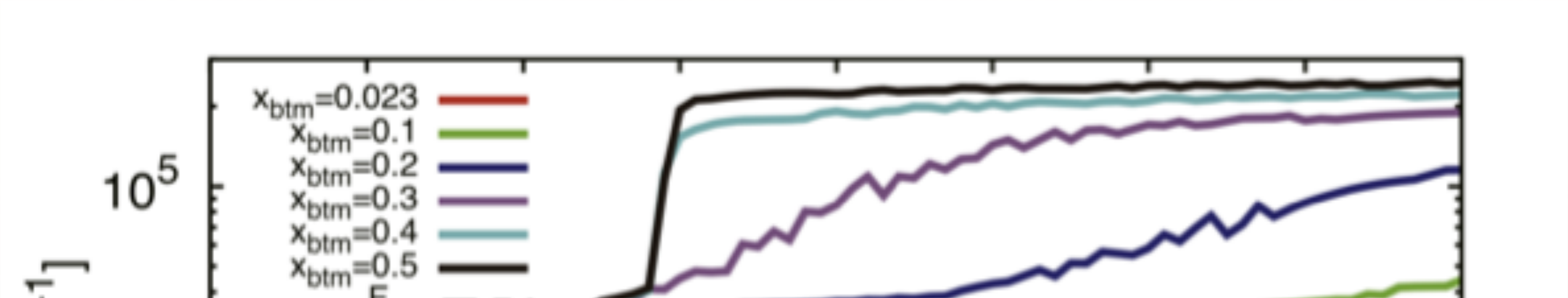
It should change Luminosity & Evolution.

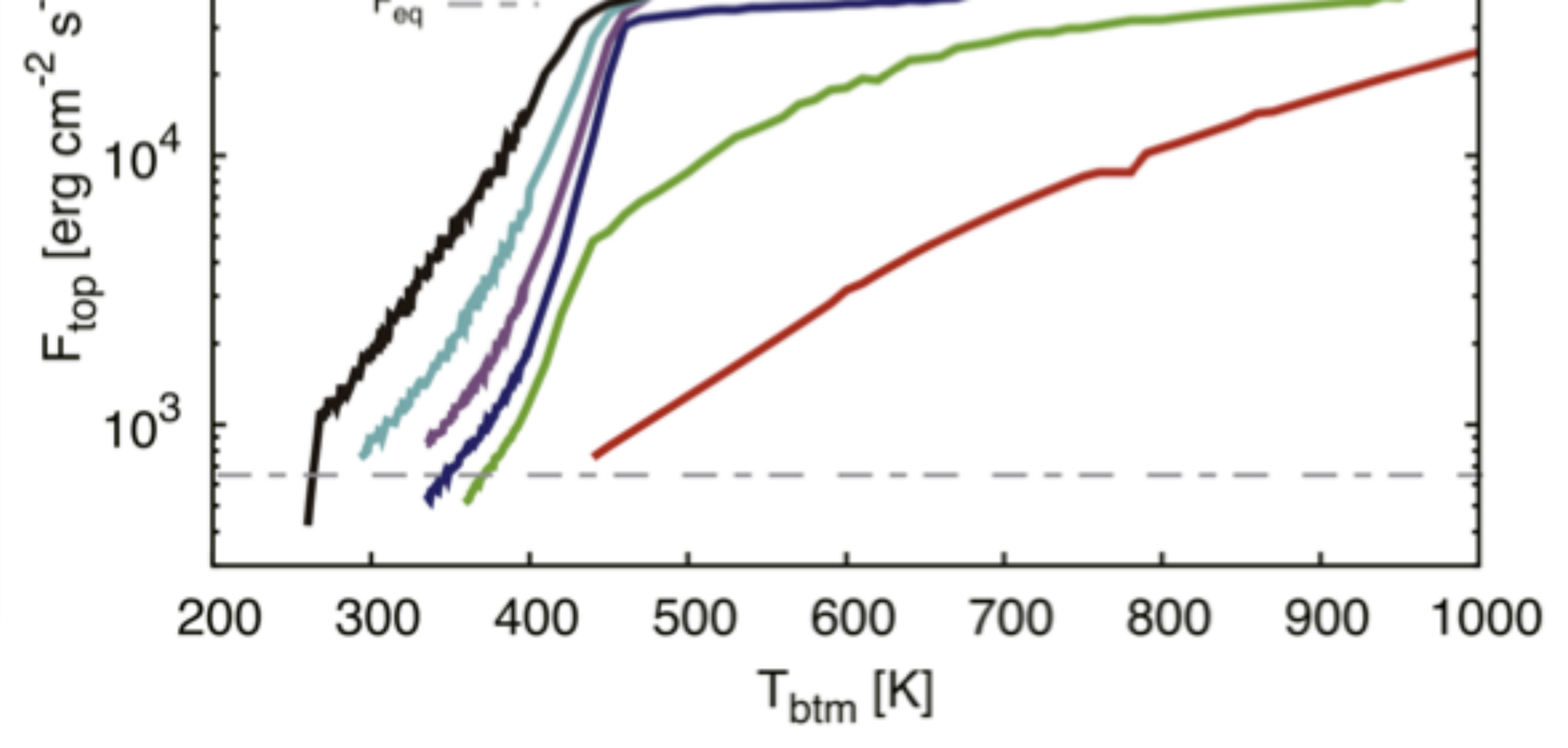
Appendix

Atmospheric Structure

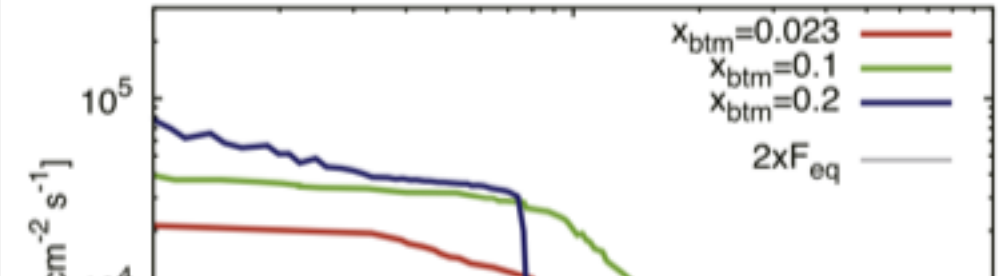


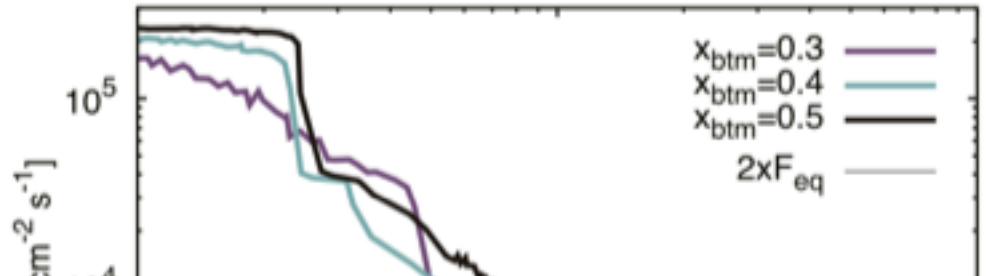
The Outgoing Flux

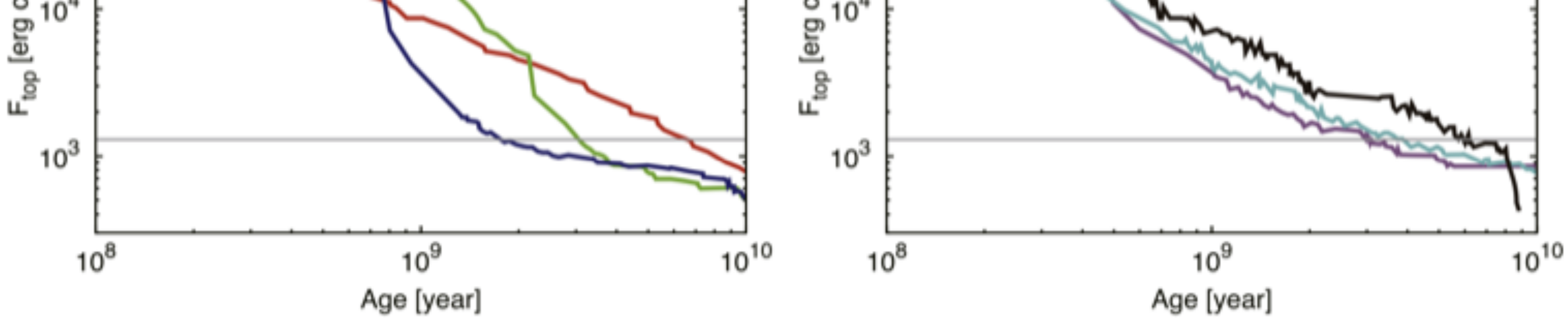




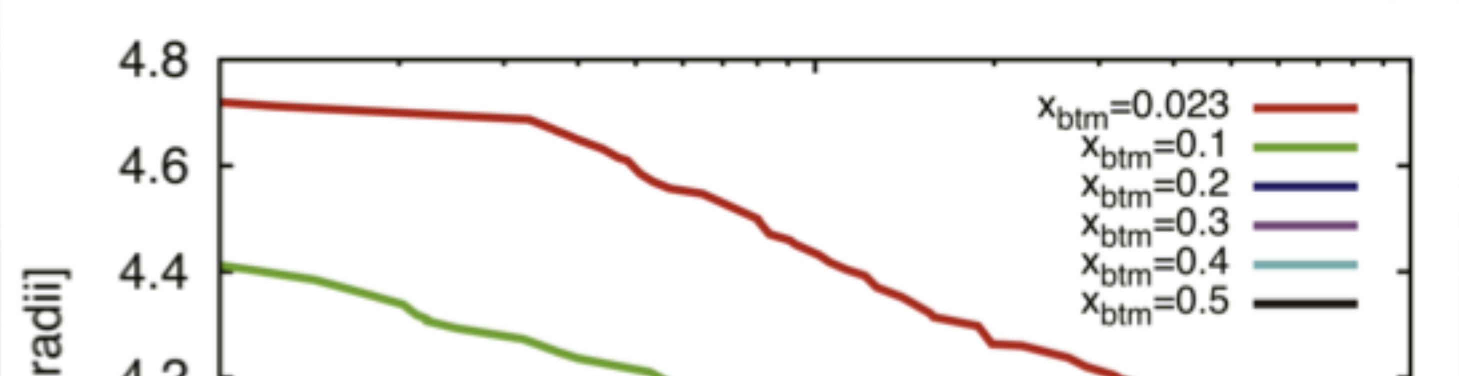
The Effect on Thermal Evolution

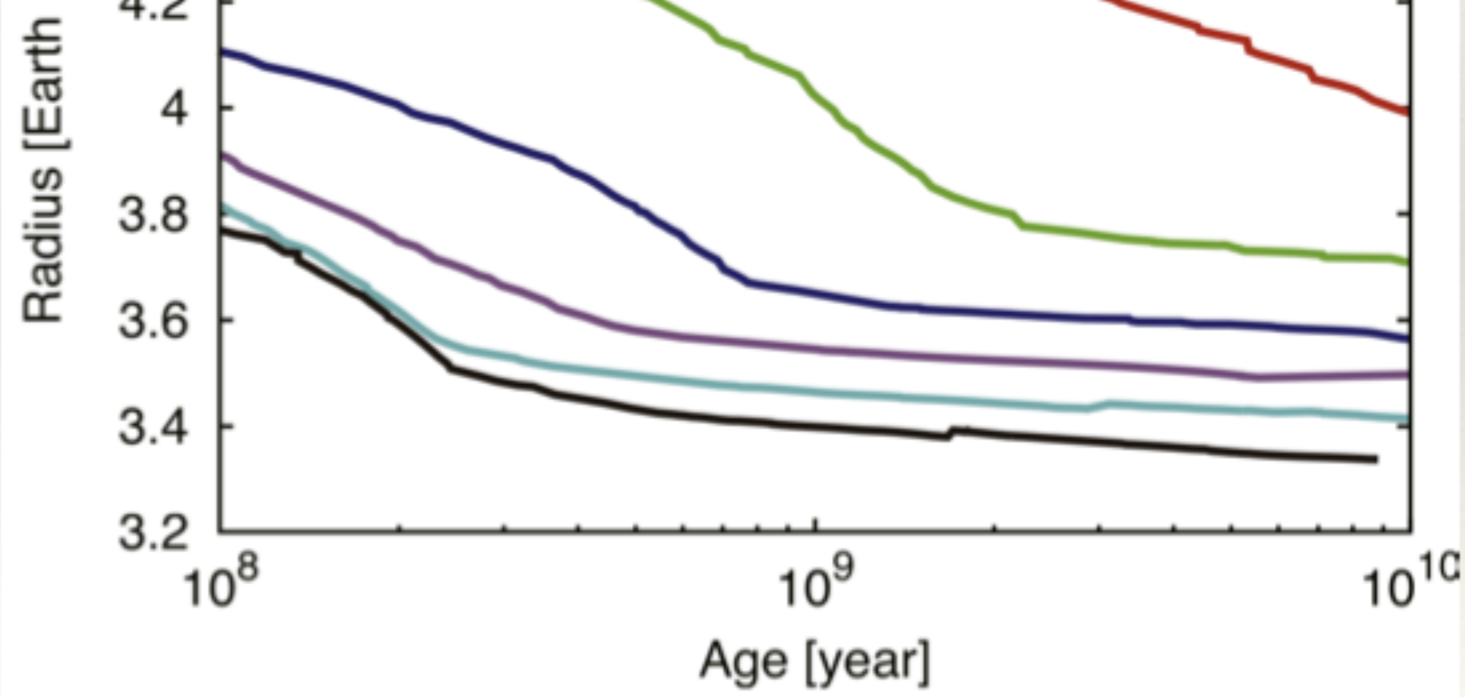




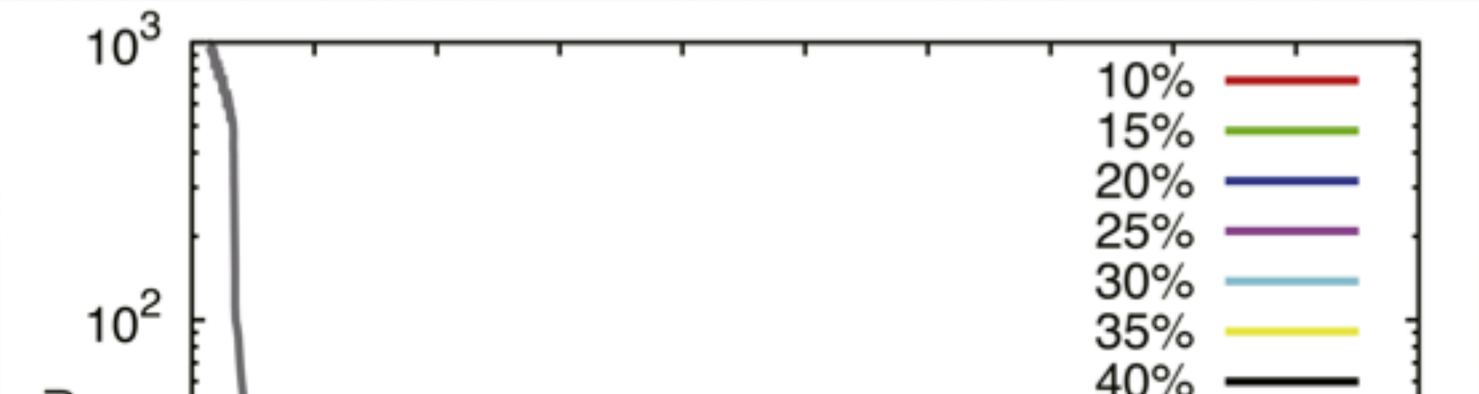


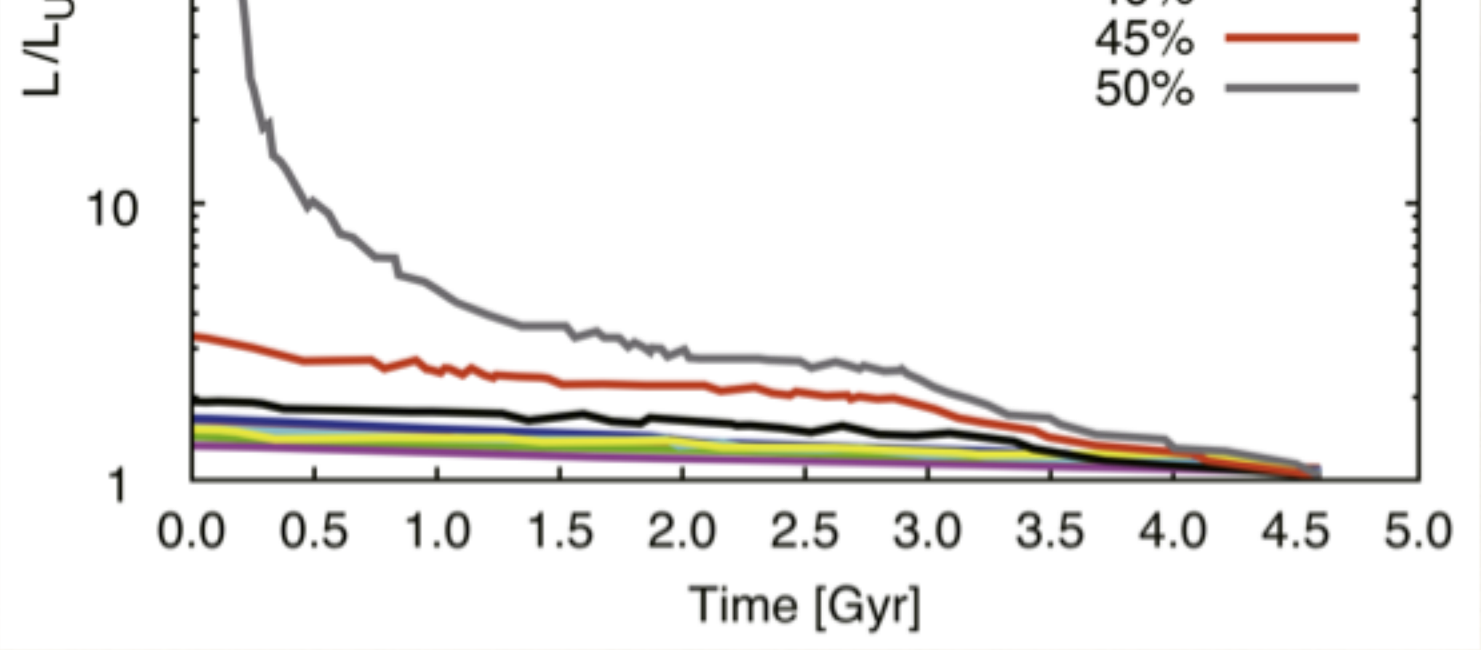
The Effect on Planetary Radius





Implication for Uranus





Methods: Atmospheric structure

Stratosphere

$$\sigma T^4 = F_0 \frac{\tau + 1}{2} + \frac{\sigma T_{\rm eq}^4}{2}\left[1 + \frac{\kappa_{\rm th}}{\kappa_{\rm v}} + \left(\frac{\kappa_{\rm v}}{\kappa_{\rm th}} - \frac{\kappa_{\rm th}}{\kappa_{\rm v}}\right) e^{-\tau_{\rm v}}\right]$$ Matsui&Abe(1986)

F0: planetary flux › T: temperature › Teq: equilibrium temperature

Troposphere

No condensation ⟶ $$\frac{d\ln T}{d\ln P} = \left(\frac{\partial \ln T}{\partial \ln P}\right)_{\rm dry} = \left(\frac{\partial \ln T}{\partial \ln P}\right)_S$$

With condensation

With condensation ⟶ $$\frac{}{d\ln P} = \left(\frac{}{\partial \ln P}\right)_{\mathrm{dry}} \frac{}{1+\sum_{i=j+1}^{N} \frac{R_g}{C_p}\frac{x_i}{1-x_i}\frac{d\ln p_i^*}{d\ln T}}$$

Condensation curve: p*(T): NH3, CH4=>Sanchez-Lavega et al. (2004), H2O => Nakajima et al. (1992)

Opacities

Line profiles: calculated by HITRAN2012 (Rothman et al. 2013)

The Rosseland mean opacities is used

$$\frac{1}{\kappa_{\mathrm{th}}} = \int_0^\infty \frac{1}{\kappa_\nu}\frac{dB_\nu(T_{\mathrm{atm}})}{dT}d\nu \Bigg/ \int_0^\infty \frac{dB_\nu(T_{\mathrm{atm}})}{dT}d\nu$$

The tropopause is determined by the flux profile

Methods: Interior structure

Hydrostatic equilibrium

$$\frac{\partial P}{\partial M_r} = -\frac{GM_r}{4\pi r^4}$$

$$\frac{\partial r}{\partial M_r} = -\frac{1}{4\pi r^2 \rho}$$

$$\frac{\partial T}{\partial M_r} = -\frac{\partial P}{\partial M_r}\frac{T}{P}\nabla$$

Equations of state

H-He	Saumon et al. (1995)
H2O	Lyon et al. (1992), SESAME 7150

Rocky core: MgSiO3 (Interpolated by Vinet EOS)

Perovskite+Ferromagnesiowstite

⟶ Stixrude & Lithgow-Bertelloni (2005)

$$\nabla = \nabla_{\rm ad} = \left(\frac{\quad}{\partial \ln P}\right)_S$$

Post-perovskite+Ferromagnesiowstite

$\longrightarrow$ Tsuchiya et al. (2004)

The mixture of **H-He+H2O** is assumed **the volume additive low**

$$\frac{1}{\rho} = (1 - Z_0)\left(\frac{X}{\rho_H} + \frac{Y}{\rho_{He}}\right) + \frac{Z_0}{\rho_{H_2O}}$$

mass fraction for hydrogen and helium, X=0.75, Y=0.25

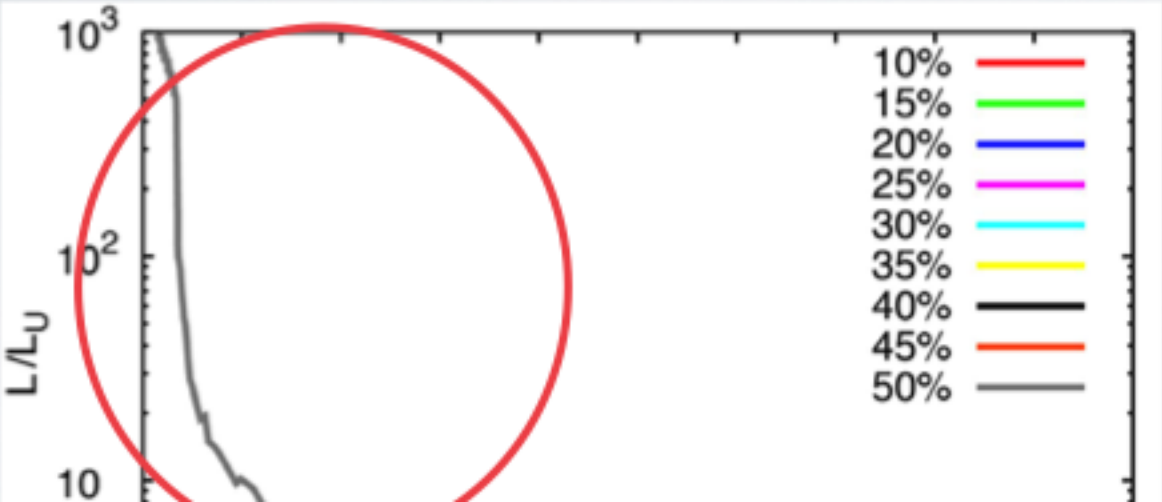
H2O mass fraction Z0=0.3

$$S = XS_H + YS_{He} + Z_0 S_{H_2O} + S_{\rm mix}$$

($S_{\rm mix}$ => mixing entropy for ideal gases)

validity: Soubiran&Militzer(2015)

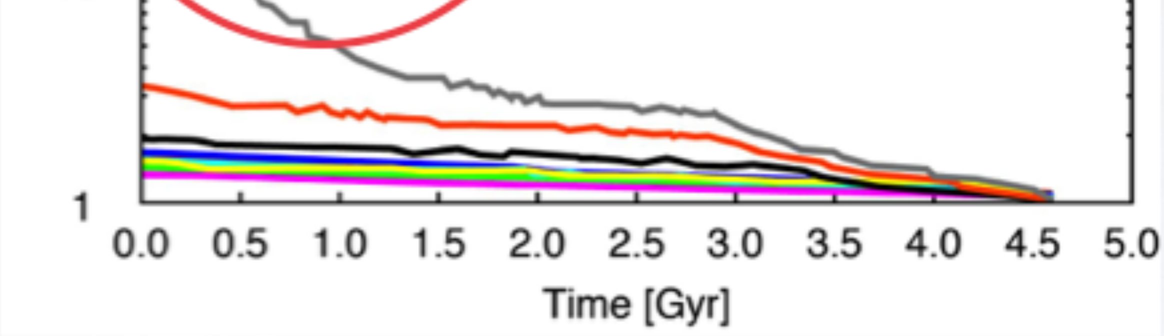
Results 3: The dependence on the initial ice mol fraction



The small mol fraction of ice cannot shorten the timescale

↓

A significant amount of



ice constituents is required

↓

Global event is needed to mix the ice constituents in the atmosphere