Radiation model development and its use for exoplanets

Masanori Onishi¹, George L. Hashimoto², Kiyoshi Kuramoto³, Yoshiyuki O. Takahashi¹, Masaki Ishiwatari³, Yasuto Takahashi³, Yoshi-Yuki Hayashi¹

¹. Kobe University, 2. Okayama University, 3. Hokkaido University
1. Introduction

Radiative transfer model is a fundamental tool to clarify planetary environment

**Spectral analyses of radiation from a planet**
which give us information about temperature and composition of its atmosphere

- Estimate composition: e.g. Kreidberg et al., 2014

**Energy budget calculations**
with which we can proceed to discuss such as circulation of an atmosphere and evolution of a planet

- Habitable zone: e.g. Kopparapu et al., 2013
- Planetary evolution: e.g. Hamano et al., 2013

A high resolution spectral calculation is required

A high speed calculation covering a wide spectral range is required
2. Model Overview

1. Line-by-line model

- Vertical profile
  - Pressure
  - Temperature
  - Composition
- Opacity calculation
  - Wavenumber
  - Optical Depth
  - Single scattering Albedo
- Optical data
  - Line absorption: HITRAN, HITEMP
  - Continuum absorption: MT_CKD 2.5, UV absorption
  - Scattering: Rayleigh scattering
- Flux calculation
  - Wavenumber
  - Upward & Downward Flux
- Boundary condition
  - Solar flux
  - Surface albedo

2. k-distribution model for GCM

- Line-by-line opacity data
  - Optical Depth
  - Single scattering Albedo
- Absorption Coefficient
  - Band number

Under Development!
3. Application to exoplanets

Tropopause of steam atmosphere and inner edge of habitable zone

Inner edge of habitable zone:

1. Runaway greenhouse limit:
   net solar irradiance = radiation limit
2. Water loss limit:
   a planet has ocean as long as 4.6 billion yr.
   - Kasting+1993: 0.95AU
   - Kopparapu+2013: 0.99AU

The model stratosphere was taken to be isothermal at 200K; this assumption has negligible effect on the runaway greenhouse limit but may have a significant effect on the “water loss” limit. (Kasting+1993)

We are trying to estimate tropopause temperature by 1-D lime-by-line model.
3. Application to exoplanets

**Model & Setup**

- Atmosphere ($\text{H}_2\text{O} + \text{non-absorption gas}$)

**Temperature profile**
- $\text{H}_2\text{O}$ + non-absorption gas ($10^5$ [Pa])
- Convective atmosphere up to TOA
- Moist pseudoadiabatic lapse rate
- Surface temperature: 280, 300, 320, 340, 350, 360 [K]

**Optical depth**
- Line absorption: HITRAN 2008
- Continuum absorption: MT_CKD 2.5, Chan et al., 1993
- Rayleigh scattering cross section: Goldblatt et al., 2013

**Radiation budget**
- Solar irradiance: 5800[K] black body
- Surface albedo: 0 – 3000 cm$^{-1}$: 0.0
- > 3000 cm$^{-1}$: 0.2
- Wavenumber range: 0 – 100000 cm$^{-1}$

**Estimate of tropopause**

Pressure
- Heating rate change point:
- Heating
- Cooling

Heating rate
3. Application to exoplanets

**Results: Estimate of tropopause temperature & mixing ratio**

![Temperature profile](image1.png)

- Temperature profile:
  - Surface T: 360 K
  - 350 K
  - 340 K
  - 320 K
  - 300 K
  - 280 K

- Tropopause temperature:
  - Kasting+1993, Kopparapu+2013 (=200K)

![H₂O volume mixing ratio profile](image2.png)

- H₂O volume mixing ratio profile:
  - Surface T: 360 K
  - 350K
  - 340K
  - 320K
  - 300K
  - 280K

- H₂O volume mixing ratio: $3 \times 10^{-3}$

- This study
- 200 K tropopause

Water loss limit is estimated near the previous studies.

**We have been developing k-distribution model and trying to calculate 1-D radiative convective profiles.**
3. Application to exoplanets

Comparison of Earth atmosphere

Earth’s atmosphere has lower tropopuase than this study.

Different points between both:
- this study is lack of O₃
- 1-d model and 3-d Earth

Surface temperature: 300K
3. Application to exoplanets

Atmospheric evolution and tropopause level

Solar irradiance

Absorption cross section

Atmospheric evolution

H$_2$O, CO$_2$, N$_2$

H$_2$O, CO$_2$, N$_2$, O$_2$, O$_3$

1. General circulation is modified?

2. Chemical radical is well mixed?

H$_2$O: HITRAN2008, MT_CKD2.5, Chan+1993
O$_3$: HITRAN2008, MT_CKD2.5
O$_2$: Hudson 1971, Cook&Metzger 1964, Watanabe&Marmo 1956, Nagata&Todomatsu 1973
N$_2$: Hudson 1971, Cook&Metzger 1964, Watanabe&Marmo 1956
4. Summary

- We have been developing a radiative transfer model for exoplanets.
  - Line-by-line model and k-distribution model for GCM (under development)

- The model is applied to exoplanet atmosphere.
  - We estimate tropopause temperature of convective atmosphere by 1-D line-by-line model.
  - Tropopause temperatures are lower than 200K as in surface temperature is lower than 340 K.
  - Water loss limit is estimated near the previous studies.