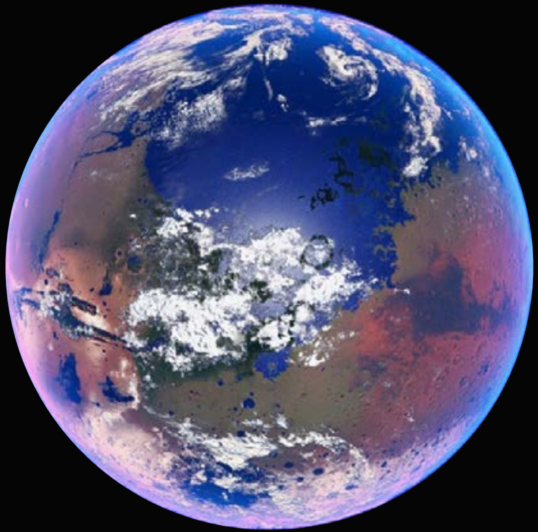
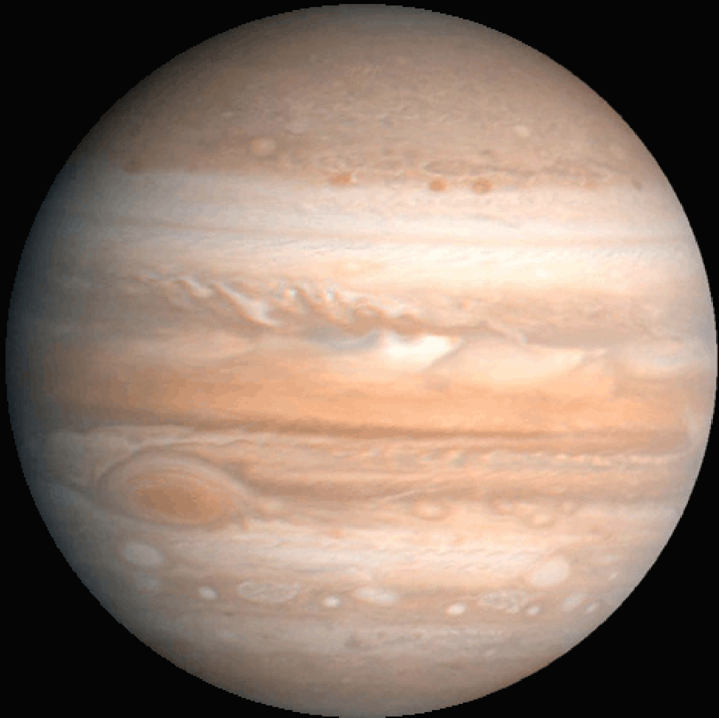
木星成層圏と火星古気候の放射計算

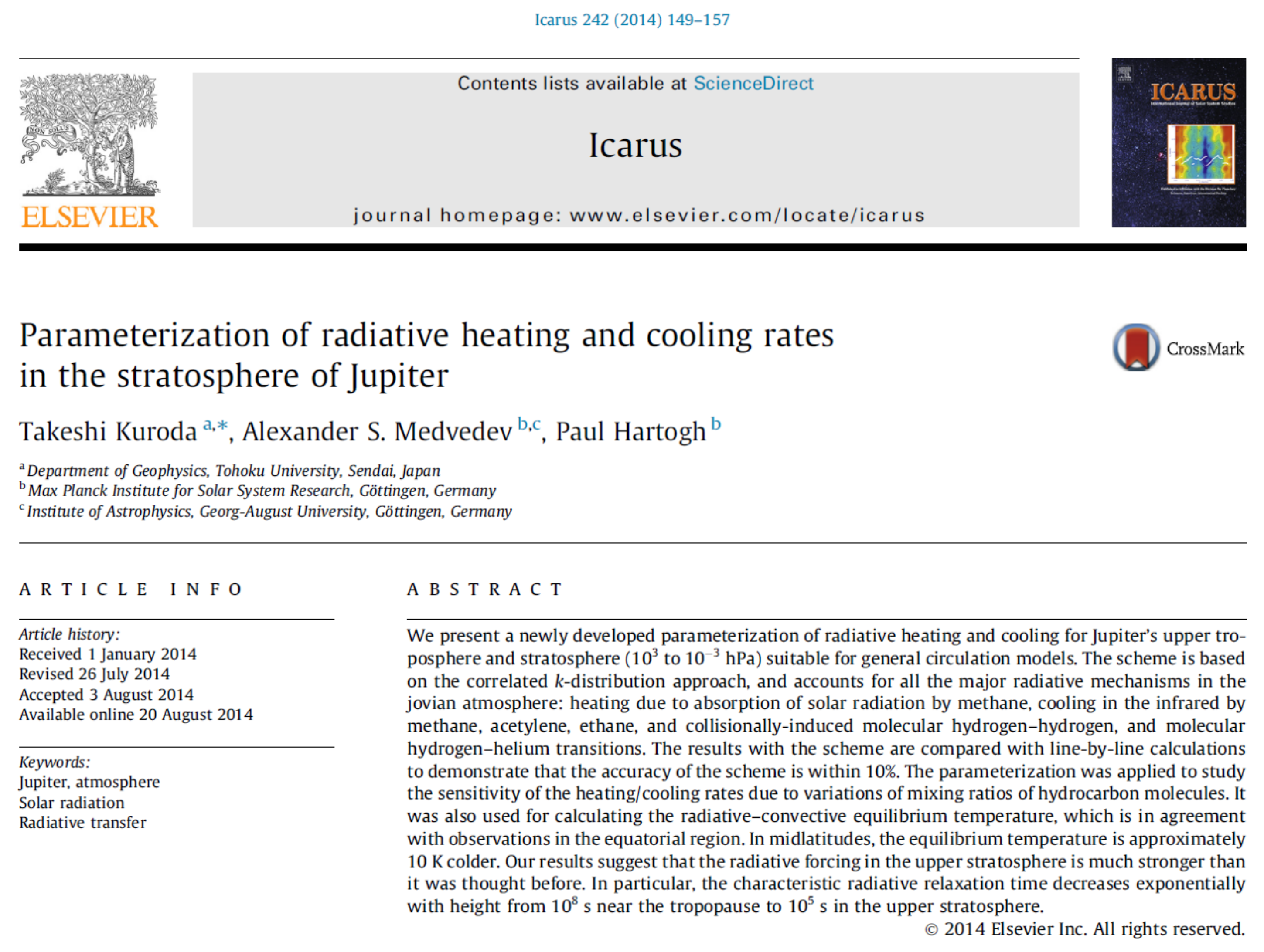




黒田 剛史

NICT/東北大学

木星成層圏の放射計算



Icarus 242 (2014) 149–157

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Parameterization of radiative heating and cooling rates in the stratosphere of Jupiter

Takeshi Kuroda [a,*], Alexander S. Medvedev [b,c], Paul Hartogh [b]

[a] *Department of Geophysics, Tohoku University, Sendai, Japan*
[b] *Max Planck Institute for Solar System Research, Göttingen, Germany*
[c] *Institute of Astrophysics, Georg-August University, Göttingen, Germany*

ARTICLE INFO

Article history:
Received 1 January 2014
Revised 26 July 2014
Accepted 3 August 2014
Available online 20 August 2014

Keywords:
Jupiter, atmosphere
Solar radiation
Radiative transfer

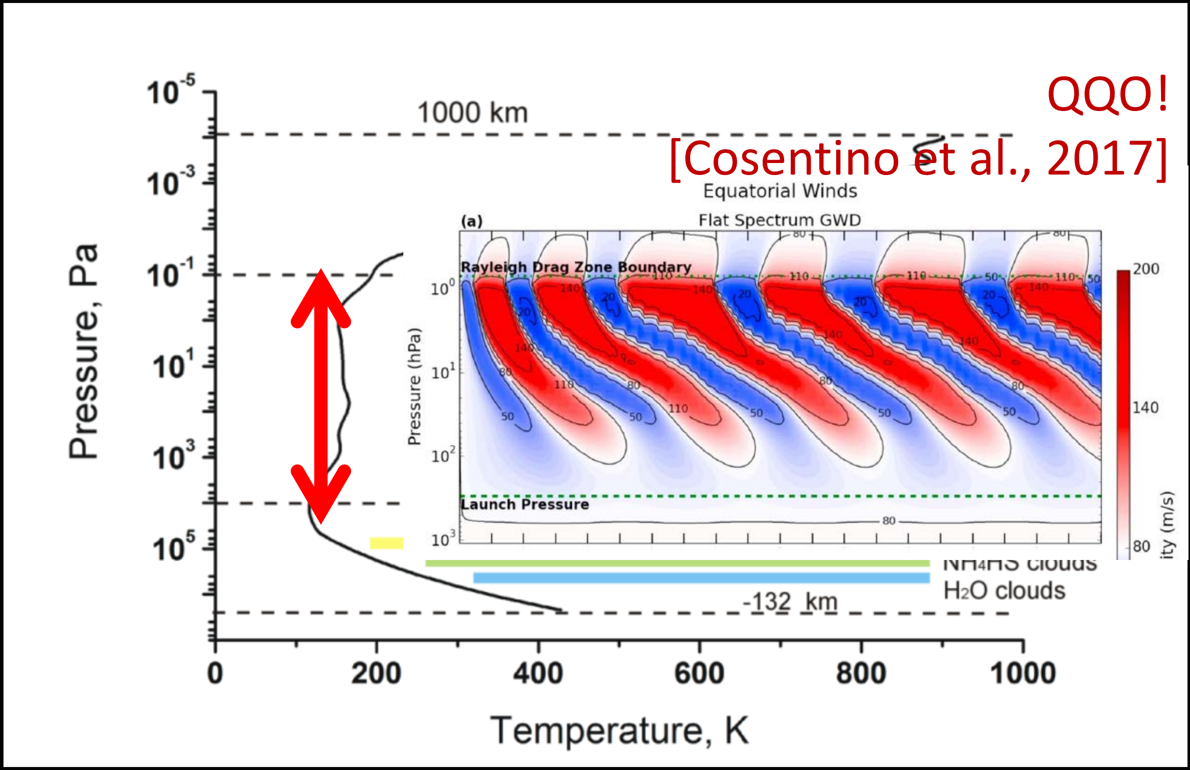
ABSTRACT

We present a newly developed parameterization of radiative heating and cooling for Jupiter's upper troposphere and stratosphere (10^3 to 10^{-3} hPa) suitable for general circulation models. The scheme is based on the correlated *k*-distribution approach, and accounts for all the major radiative mechanisms in the jovian atmosphere: heating due to absorption of solar radiation by methane, cooling in the infrared by methane, acetylene, ethane, and collisionally-induced molecular hydrogen–hydrogen, and molecular hydrogen–helium transitions. The results with the scheme are compared with line-by-line calculations to demonstrate that the accuracy of the scheme is within 10%. The parameterization was applied to study the sensitivity of the heating/cooling rates due to variations of mixing ratios of hydrocarbon molecules. It was also used for calculating the radiative–convective equilibrium temperature, which is in agreement with observations in the equatorial region. In midlatitudes, the equilibrium temperature is approximately 10 K colder. Our results suggest that the radiative forcing in the upper stratosphere is much stronger than it was thought before. In particular, the characteristic radiative relaxation time decreases exponentially with height from 10^8 s near the tropopause to 10^5 s in the upper stratosphere.

Atmosphere of Jupiter

- Thermosphere ($<10^{-3}$hPa)
- Stratosphere ($10^{2}\sim10^{-3}$hPa)
- Troposphere ($10^{4\text{-}5}\sim10^{2}$hPa)
  - With cloud layers
  - Driven by the internal heat source.

Vertical structure:
observed by Galileo Probe



QQO!
[Cosentino et al., 2017]

[Seiff et al., 1998]

Here we focus on the <u>stratosphere</u>.

Radiative band model

Coordinate

CH_4: Absorber of the solar radiation
CH_4, C_2H_2, C_2H_6, collision-induced transitions of H_2-H_2 and H_2-He: Effective in the infrared cooling

Band	IR(infrared) /SO(solar)	Wavenumber range [cm^{-1}]	Molecules
1	IR	10-200	CH_4, H_2-H_2, H_2-He
2	IR	200-400	CH_4, H_2-H_2, H_2-He
3	IR	400-600	CH_4, H_2-H_2, H_2-He
4	IR	600-700	CH_4, C_2H_2, H_2-H_2, H_2-He
5	IR	700-860	C_2H_2, C_2H_6, H_2-H_2, H_2-He
6	IR	860-960	CH_4, C_2H_6, H_2-H_2, H_2-He
7	IR, SO	960-1200	CH_4, H_2-H_2, H_2-He
8	IR, SO	1200-1400	CH_4, H_2-H_2, H_2-He
9	IR, SO	1400-1700	CH_4, H_2-H_2, H_2-He
10	IR, SO	1700-2100	CH_4, H_2-H_2, H_2-He
11	SO	2100-3450	CH_4, H_2-H_2
12	SO	3450-4800	CH_4, H_2-H_2
13	SO	4800-6300	CH_4, H_2-H_2
14	SO	6300-7800	CH_4, H_2-H_2
15	SO	7800-9200	CH_4, H_2-H_2
16	SO	9300-10800	CH_4, H_2-H_2
17	SO	10800-11800	CH_4, H_2-H_2

- Correlated k-distribution approach
- We made a table of k-distributions in 13 pressure grids (log-equal interval between 10^{-3} and 10^3 hPa), 3 temperature grids (100, 150 and 200 K) for 17 wavenumber bands.

- The atmospheric composition of molecules (1000 ppmv of CH_4, 1 ppmv of C_2H_2, 10 ppmv of C_2H_6, 86.4 % of H_2, 13.6 % of He) is fixed in making the table.

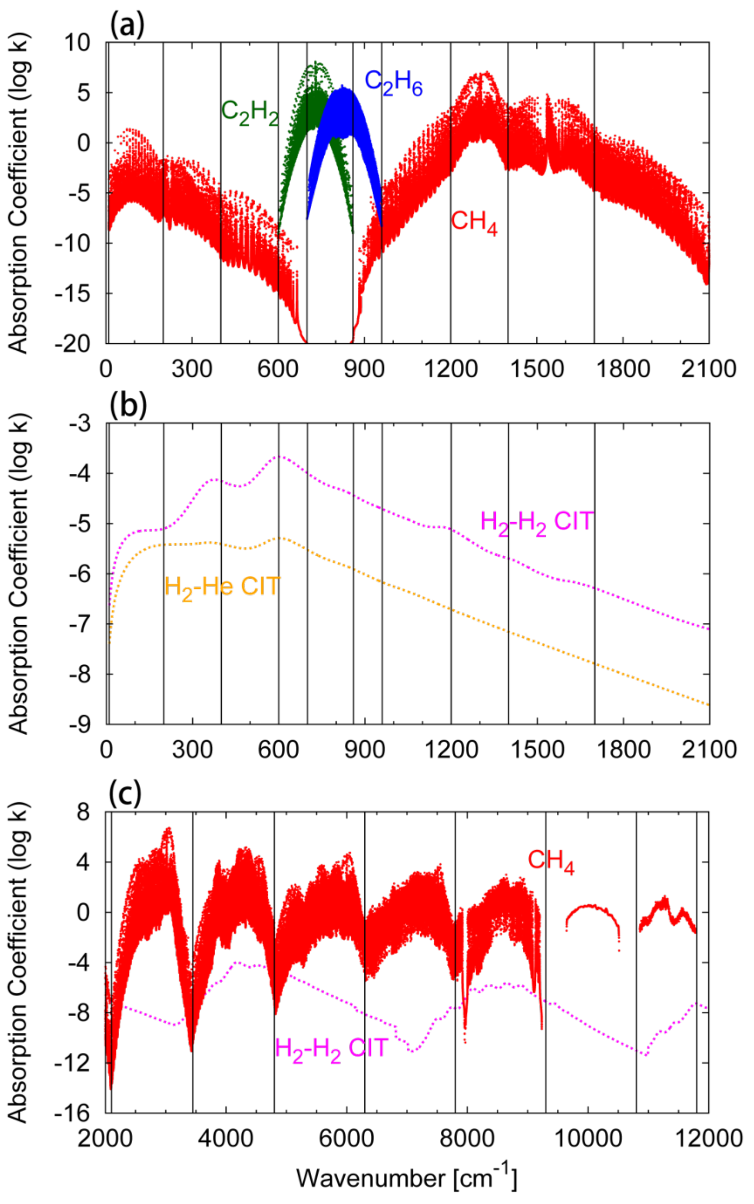
Radiative band model

Line spectra
(1 hPa, 150K)

Molecules (infrared)

Collision-induced transitions (infrared)

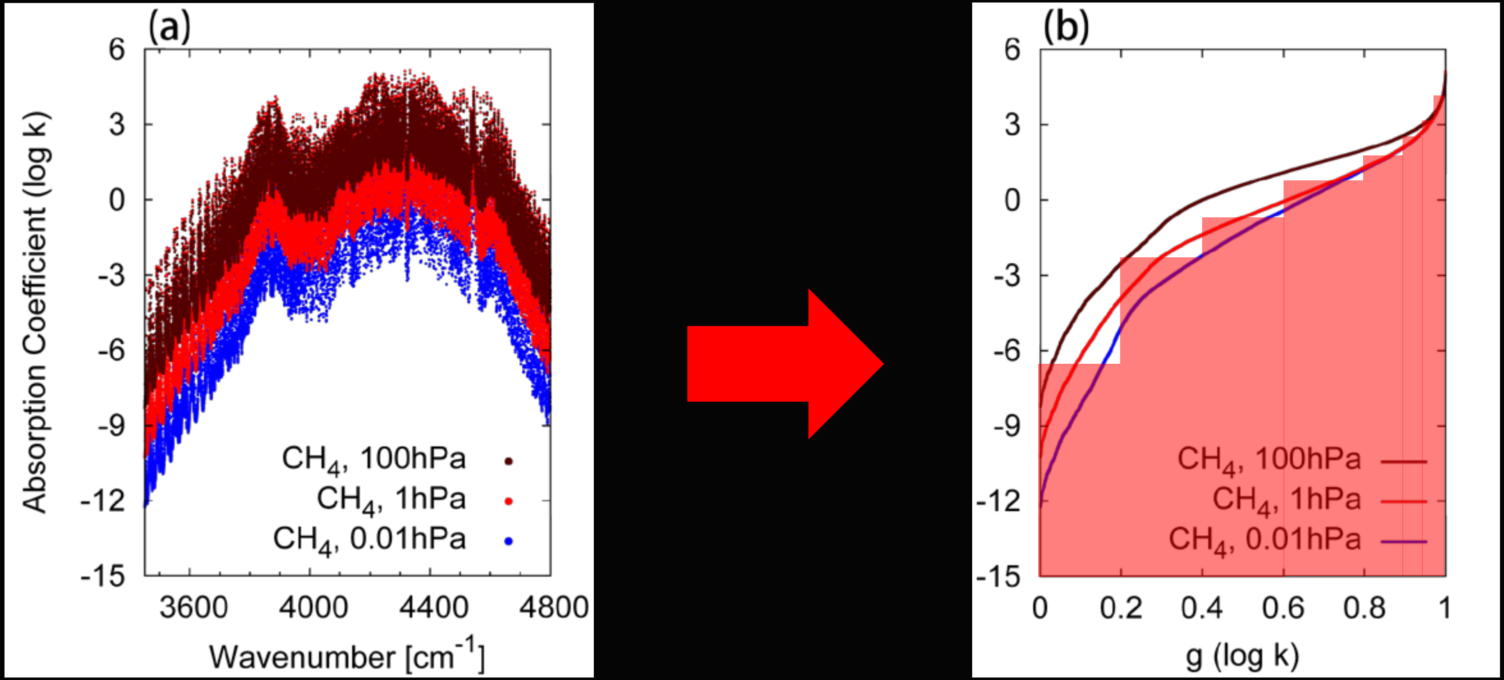
For solar absorption



- Infrared molecular lines (CH_4 10-1800 cm^{-1}, C_2H_2 600-860 cm^{-1}, C_2H_6 700-960 cm^{-1}): From HITRAN2008 [Rothman et al., 2009]
- CH_4 lines in 1800-9200 cm^{-1}: From higher-resolution profile by Sromovsky et al. [2012]
- Visible CH_4 lines: From Fink et al. [1977] and O'Brien and Cao [2002]
- Voigt profile is used for the calculation of line spectrum, with wing cutoff of 35 cm^{-1} for all molecules.
- Collision-induced transitions of H_2-H_2 and H_2-He: From Borysow [2002] (H_2-H_2) and Borysow et al. [1988] (H_2-He).

Radiative band model

About k-distribution
[e.g. Liou, 2002]


CH_4 line spectra (3450-4800 cm^{-1})

k-distribution of the line spectra

- For fast calculations of fluxes, the line spectrum in each band is ordered to be a monotone increasing function.
- The absorption and emission by molecules in each band are calculated with 12 k-distribution integration points per a molecule (144 points in the bands the lines of 2 molecules are overlapped).
- The effects of collision-induced transitions are added.

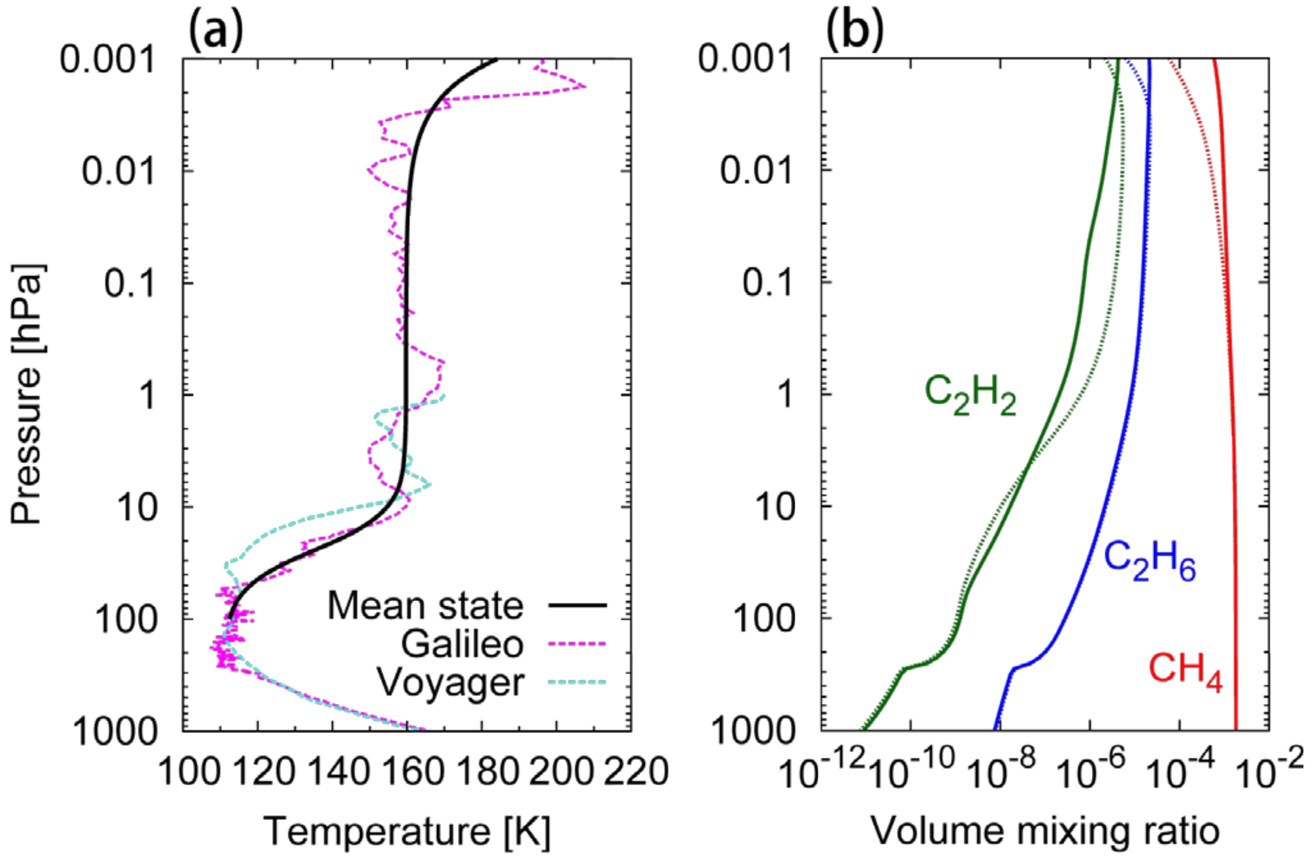
1-D calculation

Setting

1-D calculation with equally-spaced 60 layers between 10^{-3} and 10^{3} hPa has been performed.

Temperature

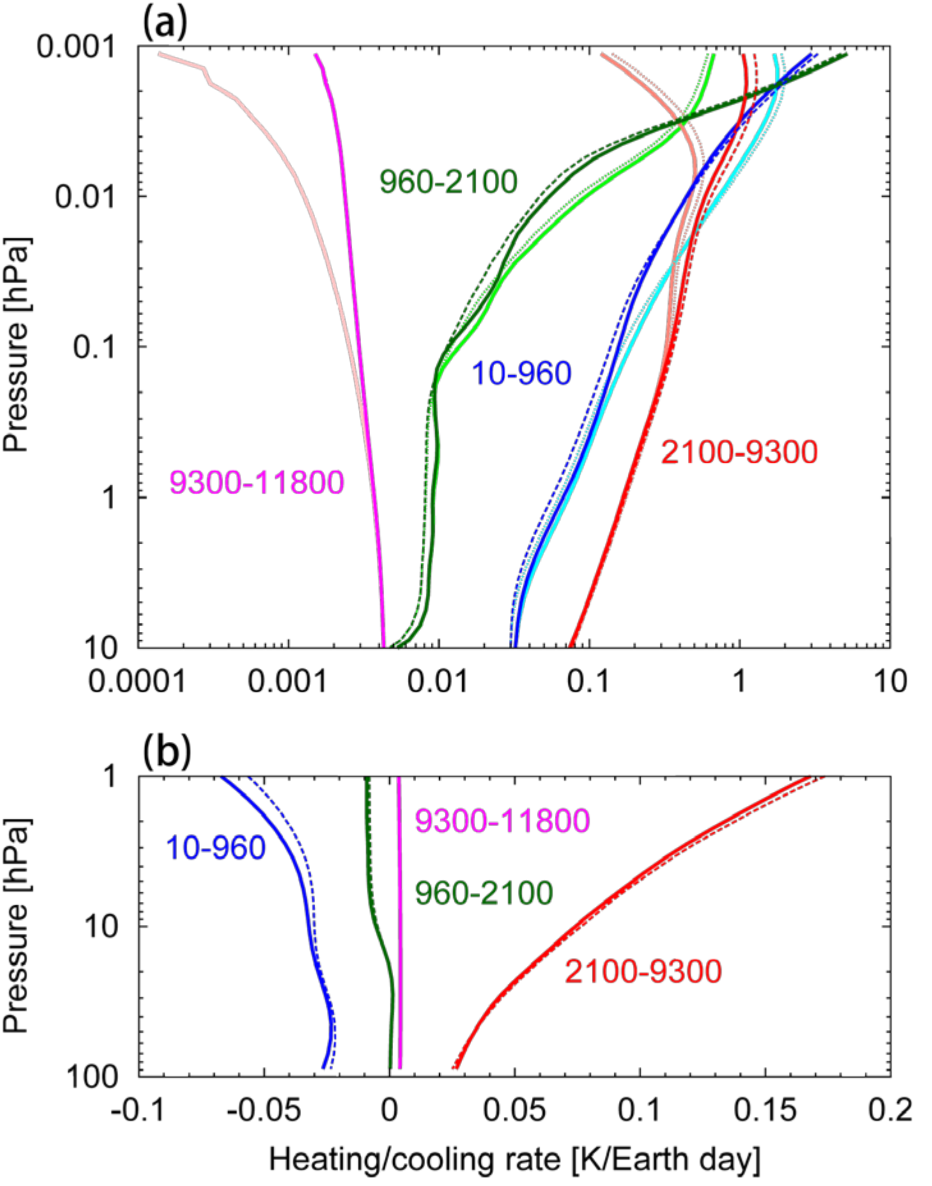
Component



- Temperature: 'Mean state' from Galileo Probe observation [Yelle et al., 2001]
- Component: From 1-D photochemical model [Moses et al., 2005]
  2 kinds of results (Models A and C)

1-D calculation

(Solid: Band, Dashed: Line-by-line)



Heating/cooling rates

- Calculation of solar radiation: Assumed zenith angle of 0°
- Differences between band and line-by-line calculations are very small.
- Mid- and far-infrared radiation (10-960 cm^{-1}): Dominant for cooling below ~2.5×10^{-3} hPa.
- CH_4 infrared radiation (960-2000 cm^{-1}): Can be dominant for cooling above ~2.5×10^{-3} hPa, and very small effects below.
- Heating/cooling rates in upper stratosphere strongly depend on the composition.

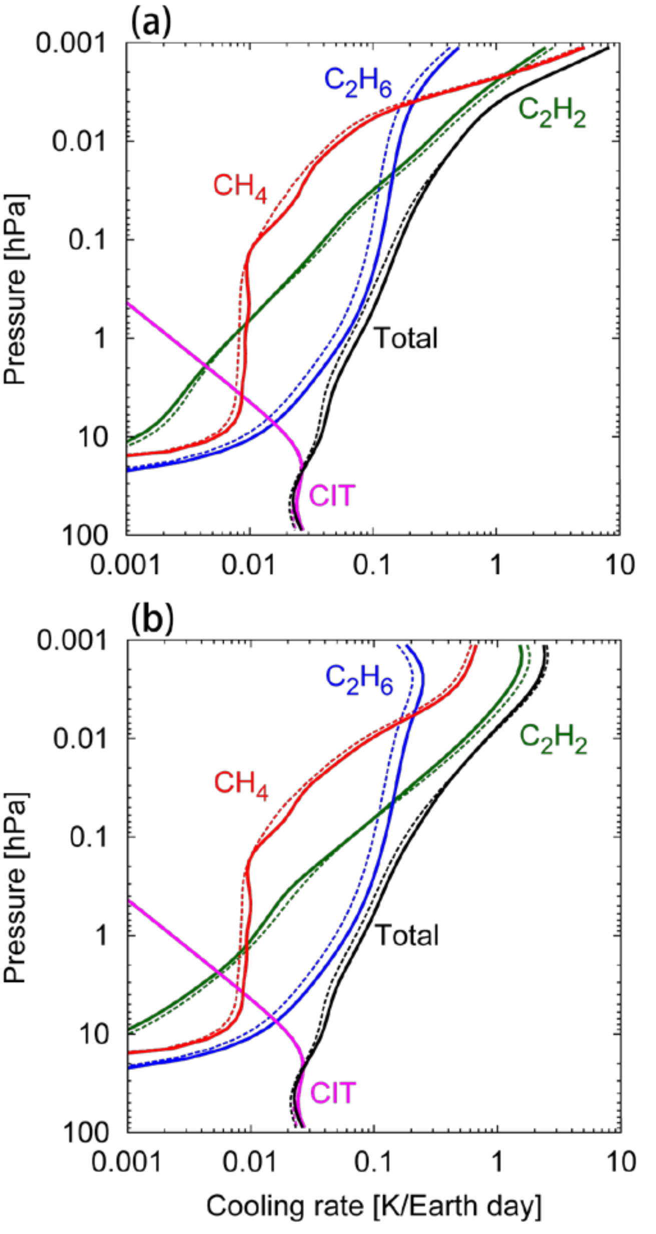
1-D calculation

Sensitivity of molecules (infrared cooling)

(Solid: Band, Dashed: Line-by-line)

'Model A' component

'Model C' component



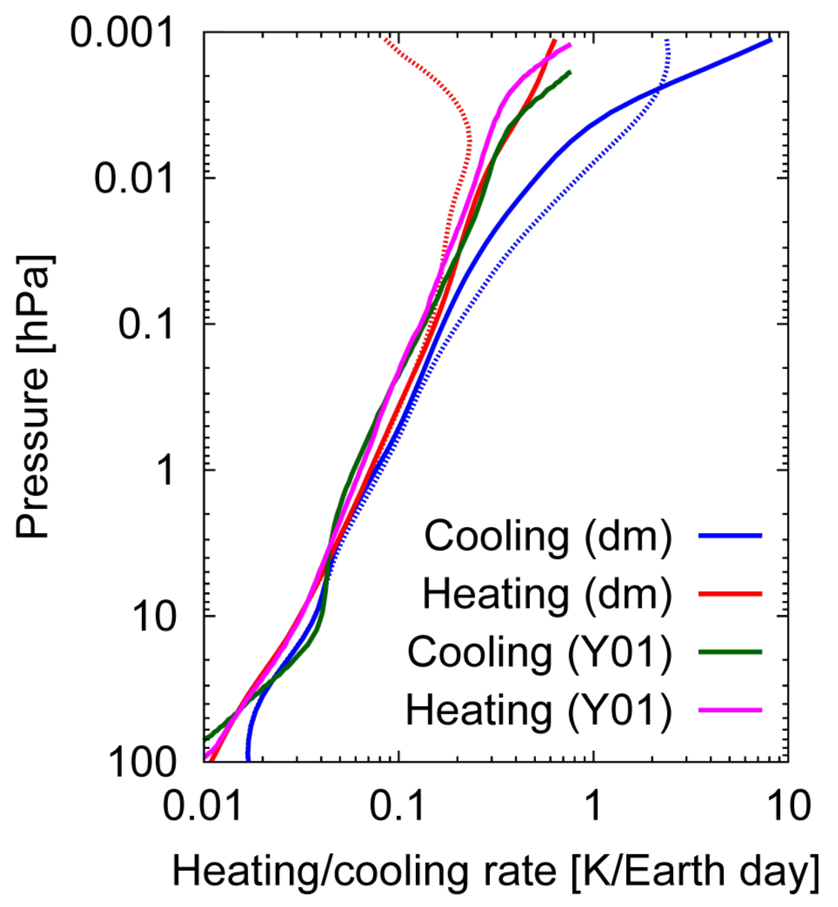
About the effect of cooling in 10-2100 cm^{-1}:

- C_2H_2 is dominant above ~0.03 hPa (up to ~3 K/day).
- C_2H_6 is dominant between 0.03-10 hPa (up to ~0.2 K/day in this height region).
- Collision-induced transitions are dominant below ~10 hPa (up tp ~0.03 K/day).
- CH_4 can be dominant around the boundary to thermosphere, but its effect is small in most of the stratosphere.

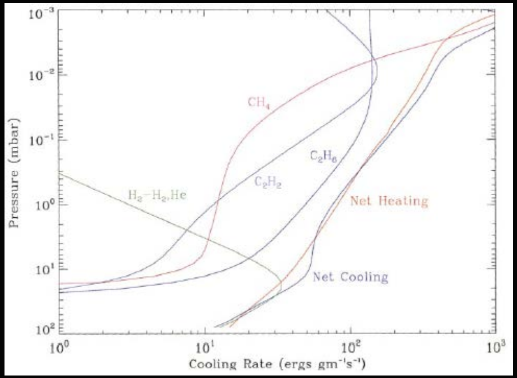
1-D calculation

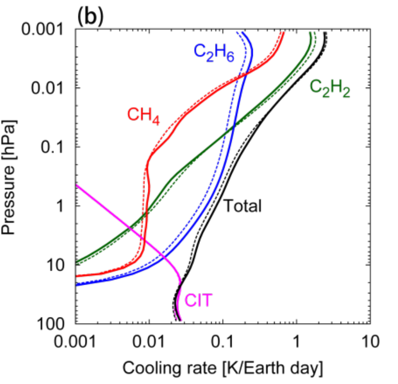
Total heating/cooling rate (in comparison with a preceding study)

Total day-mean heating&cooling rates in comparison with Yelle et al. (2001)



[Yelle et al., 2001]





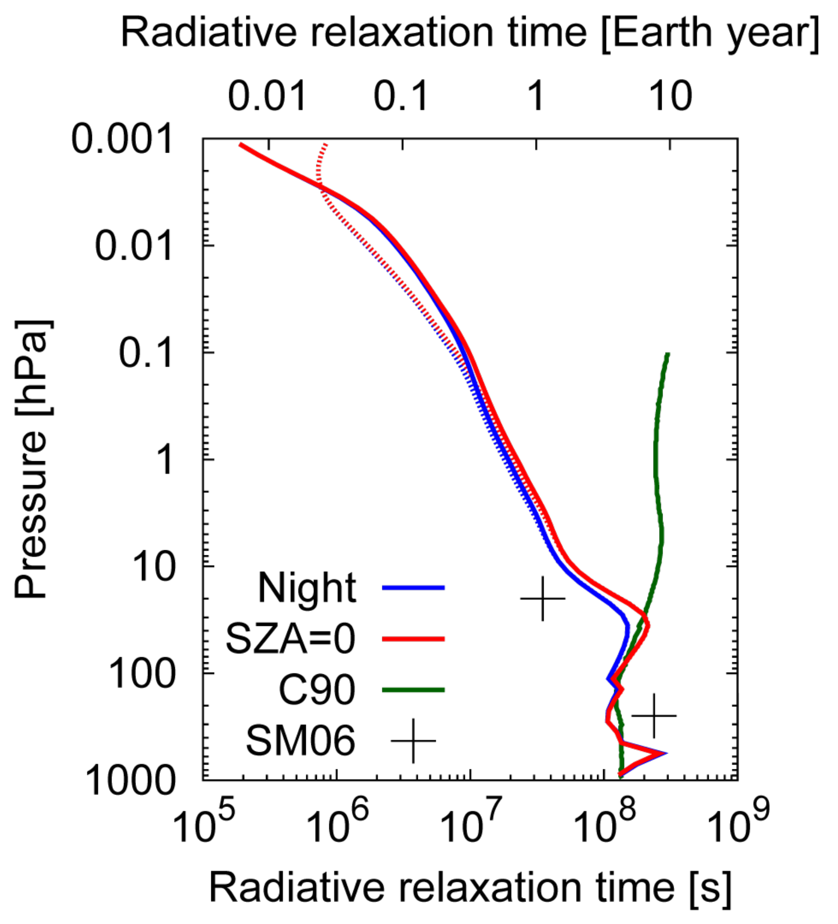
- Our calculations of day-mean net heating and cooling rates are in a good agreement with the results of Yelle et al. (2001), with radiative equilibrium.
- Above 0.1 hPa, our cooling rates exceed the heating rates, mainly due to stronger cooling by C_2H_2 in our model.

1-D calculation

$$\tau = -\frac{\Delta T}{\Delta Q}$$

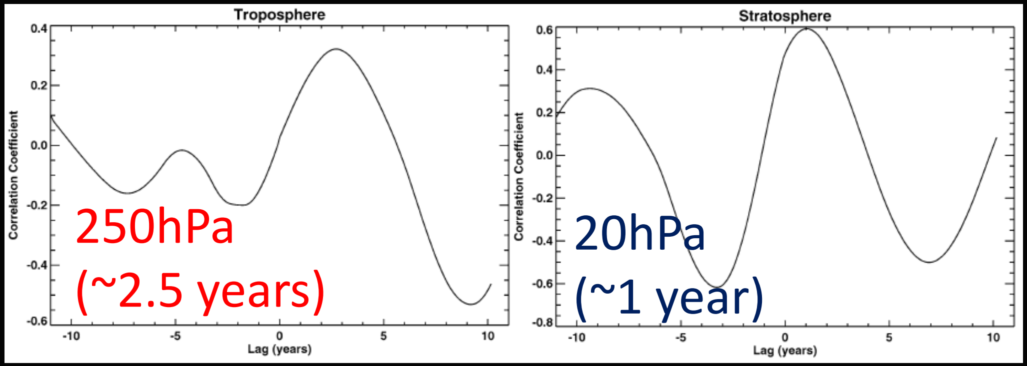
(From the difference of heating/ cooling rates for different temperature)

Daytime & nighttime,
Models A and C components



Radiative relaxation time

Cross correlation of subsolar latitude with the hemispheric temperature contrast (40°N-40°S) from IRTF observation (1979—2001) [Simon-Miller et al., 2006]

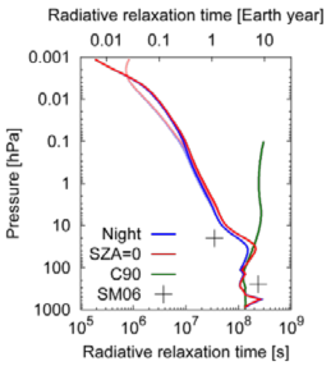


- The hemispheric temperature contrast lags the solar forcing longer in troposphere (~2.5 years) than in stratosphere (~1 year), which means the radiative relaxation time should be longer in troposphere.
- Our model shows qualitatively consistent results with the observation, while a preceding study [Conrath et al., 1990] does not.

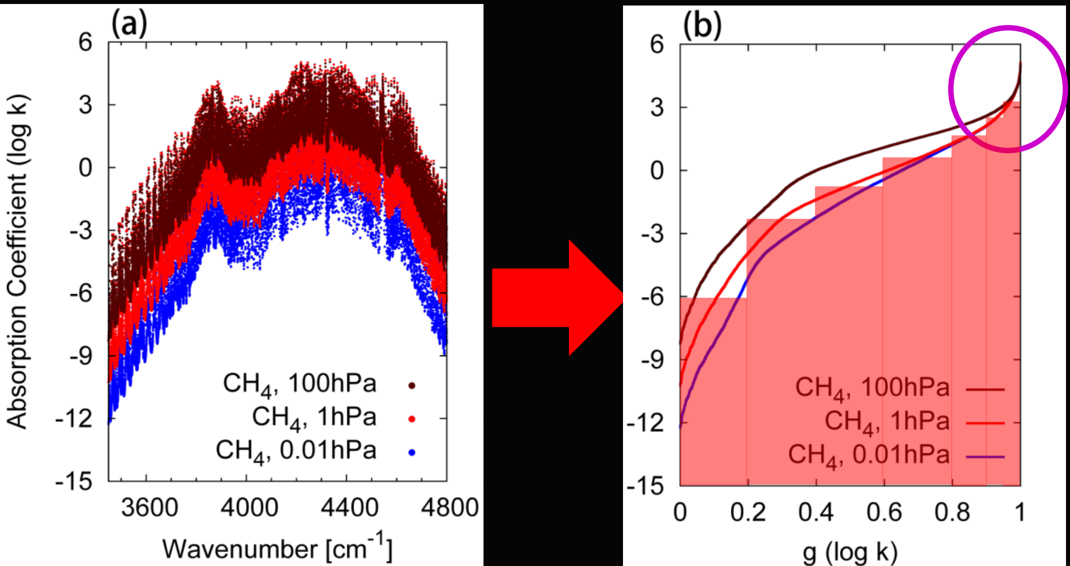
1-D calculation

Equation of solar heating rate in Conrath et al. [1990]

$$Q_S = \boxed{\rho} g \mu_0 \sum_{i=1}^{3} \frac{d \ln(\hat{p}_i N_1)}{dp} F_{\odot i} A_i \times \left[1 + \left(\frac{A_i d_i \mu_0}{2 S_i \gamma_i \hat{p}_i N_i} \right)^{1/2} \right]^{-1} + \boxed{\rho} g \frac{dN_1}{dp} \times (\bar{F}_{\odot a} \Delta\nu_a C_a e^{-C_a N_1/\mu_0} + (\bar{F}_{\odot b} \Delta\nu_b C_b e^{-C_b N_1/\mu_0}).$$



k-distribution



Radiative relaxation time

- The radiative relaxation time by Conrath et al. [1990] was shown to be longer in upper atmosphere, which contradicts the observations.
- It is because their model is simple and the heating/cooling rate is expressed to be proportional to the atmospheric density (pressure), which should underestimate the radiative effects in upper atmosphere.

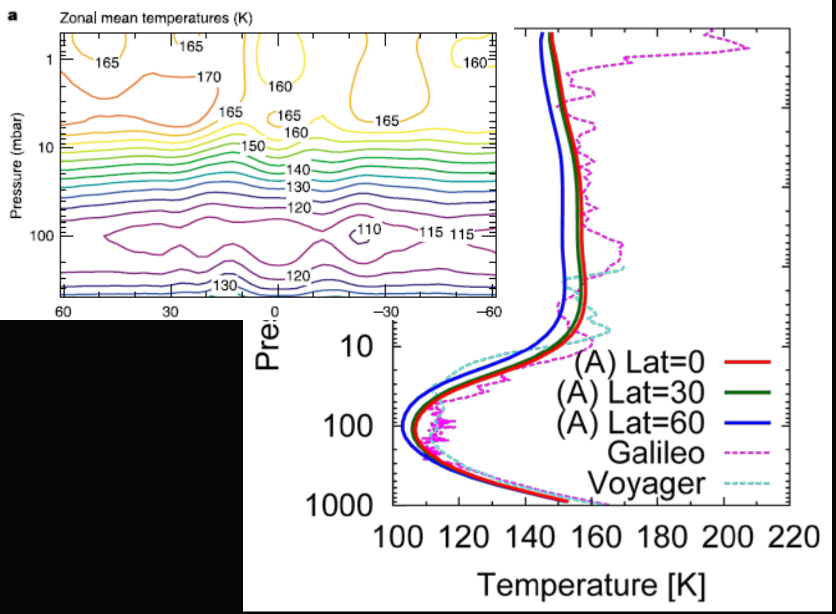
← At the peaks of spectra, the absorption coefficient becomes almost constant against the pressure. (except the peaks, proportional to pressute)

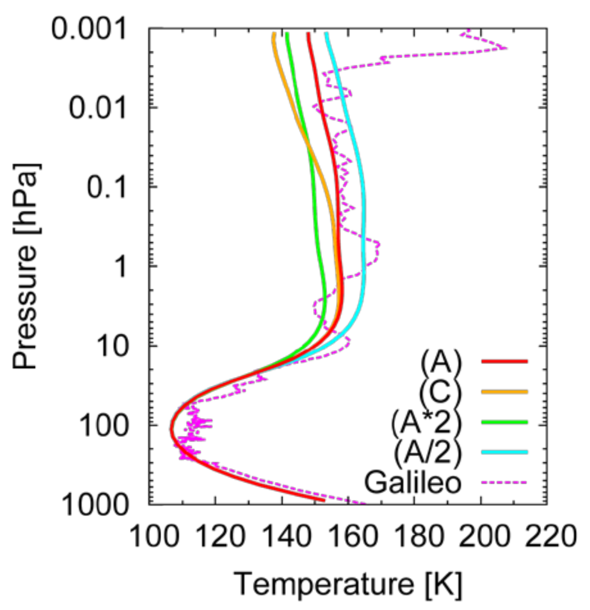
1-D calculation

Radiative-convective equilibrium temperature

Different latitudes
(with observations)

Different components (Model A, Model C,
Model A with twice more/less C_2H_2 and C_2H_6)

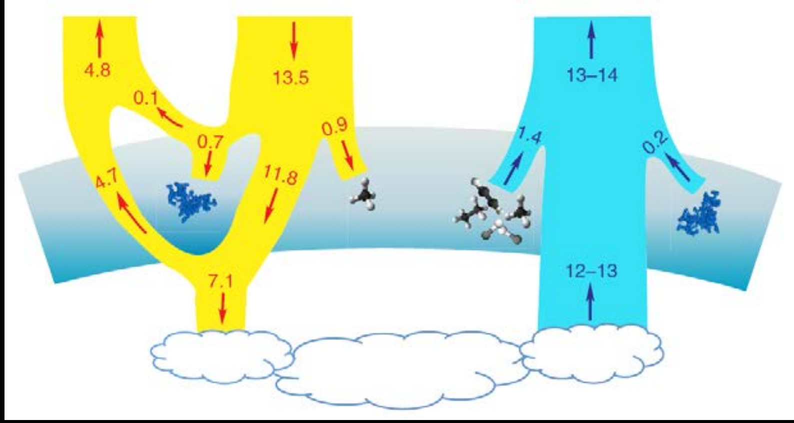




- Radiative-convective equilibrium temperature is close to the observed vertical profiles, except the top of stratosphere (due to the lack of non-LTE effects…?)
- In higher latitude, the equilibrium temperature is several Kelvins colder than the equator in overall (the observed temperature field shows very small latitudinal anomaly). Note that the radiative effects of stratospheric hazes [e.g. Zhang et al., 2013], which may affect the temperature in high latitudes, are not included.
- In the upper stratosphere, it is sensitive to the components.

まとめ

- 0.1～100hPa (下部・中部成層圏)では観測の温度プロファイルで放射対流平衡が成り立ち、それは再現されている
- それより上の高度はnon-LTEを考慮する必要あり？
  成層圏・熱圏結合も検討 (JUICE SWI-RPWI連携)
- 木星成層圏のヘイズの効果は未導入
  将来的な導入は必要



[Zhang et al., 2015]

放射加熱率
[K/E. day]

ヘイズなし

ヘイズ加熱導入

ヘイズ加熱＋冷却導入