Radiative Heat Balances in Jupiter's Stratosphere: Development of a Radiation Code for the Implementation to a GCM

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It is very important to investigate the atmosphere of giant planets, for the universal understandings of formation and evolution of planetary atmospheric circulations with different viewpoints from the investigations of terrestrial planets, as well as the clarifications of physical parameters specific to each planet. Moreover, the field of planetary science is broadening beyond our solar system, and gas giants are especially important existences in extra-solar stellar systems as far as our current understandings. Then we need to understand Jupiter, the closest gas giant to us, thoroughly as the first step.

Jupiter's stratosphere extends for more than 350 km above the visible cloud top, with the pressure range of roughly between 10^3 and 10^{-3} hPa. The atmospheric conditions there are affected by radiative processes by molecules in stratosphere, as well as eddies enhanced from the troposphere.The main absorber of the solar radiation in these heights is CH_4, while the cooling is created mainly by C_2H_6, C_2H_2, CH_4 and collision-induced transitions of H_2-H_2 and H_2-He.

We have developed a fast radiative scheme for calculating heating and cooling rates by these molecules based on the correlated *k*-distribution approach and suitable for implementation into general circulation models (GCMs) of Jupiter's stratosphere. In the presentation we showed the numerical results for heating/cooling rates calculated from 1-D profiles of temperatures and composition with the scheme, and investigated the radiative heat balances in Jupiter's stratosphere.

The band model calculated the heating/cooling rates in a good accuracy in comparison with the line-by-line calculations. For the atmospheric cooling, effects of CH_4 in 1200-1400 cm^{-1} and C_2H_2 in 600-860 cm^{-1} are dominant in upper stratosphere (above ~10^{-2} hPa), while C_2H_6 in 700-960 cm^{-1} is dominant in middle stratosphere (between ~10^{-2} and ~10^1 hPa) and collision-induced transitions is dominant in lower stratosphere (below ~10^1 hPa). Heating by the solar absorption of CH_4 makes a good heating/cooling balance below ~10^{-2} hPa. Most absorption are made in near-infrared wavelength (2000-9200 cm^{-1}), but absorptions in visible wavelength (10800-11800 cm^{-1}) may not be ignorable in lower stratosphere (up to ~5% of the total).

In the future we are implementation of this band radiation code to GCMs for Jupiter's/Saturn's stratosphere, and setting on the dynamical studies of giant planets with the GCMs. Such scientific works will also contribute to the preparations for the observations of Jupiter's stratosphere by JUICE-SWI, a sub-millimeter wave instrument onboard the JUICE (JUpiter ICy moon Explorer) spacecraft which will launch in 2022 and arrive at the Jupiter system in 2030.

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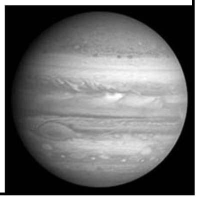
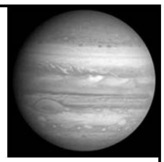


Why Jupiter?



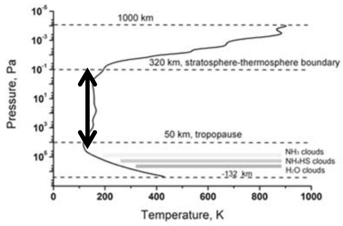
Towards the universal understandings of objects in the space (terrestrial planets, gas giants, brown dwarfs, stars…)

- For universal understandings of formation and evolution of planetary atmospheric circulations, with different viewpoints from the investigations of terrestrial planets. (clarifications of physical parameters specific to each planet)
- The field of planetary science is broadening beyond our solar system, and gas giants are especially important in extra-solar stellar systems as far as our current understandings. Then we need to understand Jupiter, the closest gas giant to us, thoroughly as the first step.

Atmosphere of Jupiter

Vertical structure: observed by Galileo Probe

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



[Seiff et al., 1998]

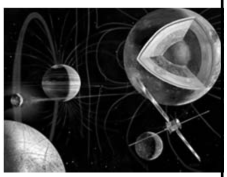
Here we focus on the stratosphere.

JUICE-SWI (sub-millimeter instrument)

- The main objective of a sub-millimetre wave instrument is to investigate the structure, composition and dynamics of the middle atmosphere of Jupiter and exospheres of its moons, as well as thermophysical properties of the satellites surfaces. (from Yellow Book)
- JUICE-SWI is highly sensitive for CH_4, H_2O, HCN, CO and CS in Jupiter's stratosphere.
- From CH_4 molecular lines, vertical temperature profiles and wind velocities can be detected.
- CO and CS, which are chemically stable, can be used as tracers for the investigations of atmospheric flows (general circulation and dynamical processes).

PI: P. Hartogh (MPS)

Chosen for the JUICE mission! (02/21/2013)

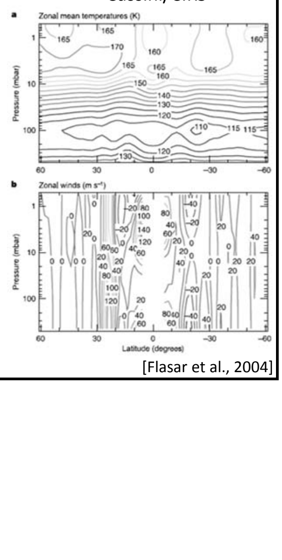


Collision of Shoemaker-Levy 9 [HST, 1994]: Origin of H_2O, CS, CO and HCN?

Jupiter's stratosphere

Temoperature and zonal wind fields observed by Cassini/CIRS

- Affected by radiative processes by molecules in stratosphere and eddies enhanced from the troposphere. (cf. troposphere: convection cell structures transport the energy and momentum)
- The estimation from the thermal wind equation and cloud tracking (for lower boundary wind speed) shows the existence of fast zonal wind jets of 60-140 m s^{-1} at 23N and 5N.



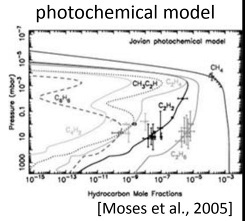
[Flasar et al., 2004]

Radiative processes of Jupiter's stratosphere

- 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.

We have developed a band radiative transfer model for Jupiter's stratosphere for the fast and effective calculations in the GCM (correlated k-distribution approach).

Mixing ratios of hydrocarbons from a photochemical model



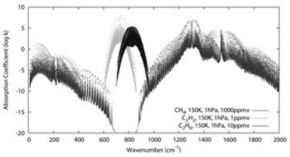
[Moses et al., 2005]

Here we show the numerical results for heating/cooling rates calculated from 1-D profiles of temperatures and composition, in comparison between correlated *k*-distribution and line-by-line approaches.

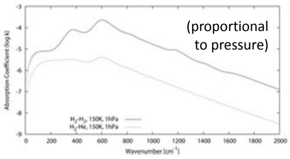
Calculations

Lines (1hPa, 150K) considered for the calculations (infrared: 10-2000 cm^{-1})

Molecules



Collision-induced transitions



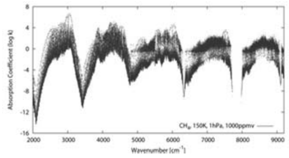
(proportional to pressure)

- Molecular lines of CH_4, C_2H_2 (600-860 cm^{-1}) and C_2H_6 (700-960 cm^{-1}): From HITRAN2008 [Rothman et al., 2009] with update for C_2H_6 (in 2009) and C_2H_2 (in 2011).
- Voigt profile is used for the calculation of line spectrum, with wing cutoff of 25 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).

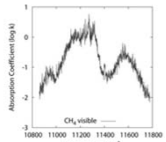
Calculations

Lines (1hPa, 150K) considered for the calculations (solar: 2000-11800 cm^{-1})

CH_4 (near-infrared)



CH_4(visible)



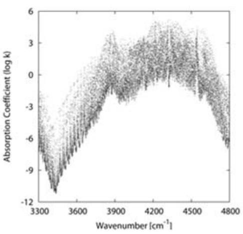
(constant to pressure and temperature)

- Molecular lines of CH_4 (2000-9200 cm^{-1}): From HITRAN2008.
- Voigt profile is used for the calculation of line spectrum, with wing cutoff of 25 cm^{-1} for all molecules.
- CH_4 line spectrum in visible wavelength (10800-11800 cm^{-1}): From O'Brien and Cao [2002].
- Between 960 and 2000 cm^{-1}, both the solar absorption and infrared emission are considered.

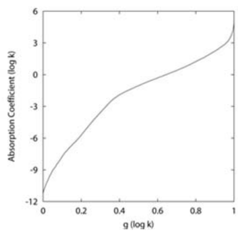
Calculations

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

CH_4 line spectrum (3300-4800 cm-1)



k-distribution of the line spectrum



- For fast calculations of fluxes, the line spectrum in each band is ordered to be a monotone increasing function.
- In our band model, the absorption and emission by molecules in each band are calculated with 12 k-distribution integration points.

Calculations

Coordinate of the band model

Band	IR(infrared) /SO(solar)	Wavenumber range [cm^{-1}]	Molecules
1	IR	10-150	CH_4, CIT
2	IR	150-300	CH_4, CIT
3	IR	300-600	CH_4, CIT
4	IR	600-700	CH_4, C_2H_2, CIT
5	IR	700-860	C_2H_2, C_2H_6, CIT
6	IR	860-960	CH_4, C_2H_6, CIT
7	IR, SO	960-1200	CH_4, CIT
8	IR, SO	1200-1400	CH_4, CIT
9	IR, SO	1400-1600	CH_4, CIT
10	IR, SO	1600-2000	CH_4, CIT
11	SO	2000-3300	CH_4
12	SO	3300-4800	CH_4
13	SO	4800-6300	CH_4
14	SO	6300-7800	CH_4
15	SO	7800-9200	CH_4
16	-	9200-10800	-
17	SO	10800-11800	CH_4

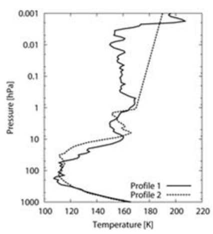
- Correlated k-distribution approach
- We made a table of k-distributions in 13 pressure grids (log-equal interval between 10^{-3} and 10^3 hPa), 3 temperature grids (100, 150 and 200 K) for 17 wavenumber bands.

- The atmospheric composition of molecules (1000 ppmv of CH_4, 1 ppmv of C_2H_2, 10 ppmv of C_2H_6, 89.8 % of H2, 10.2 % of He) is fixed in making the table.

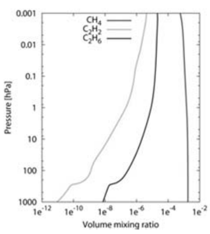
Calculations

Considered vertical profiles of temperature and composition

Temperature



Component

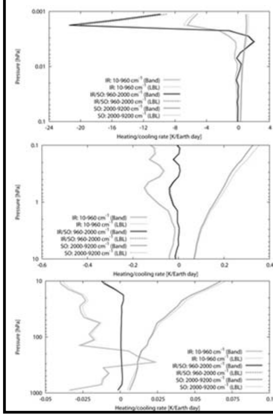


- Temperature: Galileo Probe [Seiff et al., 1998] (Profile 1) Voyager radio occultation [Lindal et al., 1981] and linear extrapolation (Profile 2)
- Component: From 1-D photochemical model [Moses et al., 2005]
- Calculation of solar radiation: Assumed zenith angle of 0°

Results

Solid: Band
Dashed: Line-by-line

Heating/cooling rates (Profile 1)

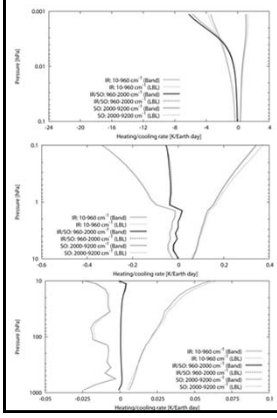


- Differences between band and line-by-line calculations are very small.
- Mid- and far-infrared radiation (10-960 cm^{-1}): Dominant for cooling below ~2.5×10^{-3} hPa.
- Infrared and solar radiation (960-2000 cm^{-1}): Dominant for cooling above ~2.5×10^{-3} hPa, and very small effects below.
- Solar radiation in near-infrared and visible (2000-11800 cm^{-1}): Dominant for heating, especially below ~1×10^{-2} hPa. Absorption in visible (10800-11800 cm^{-1}) is small (up to ~5% of the total below ~100 hPa).

Results

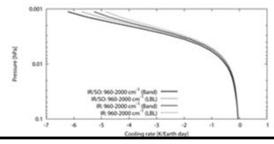
Solid: Band
Dashed: Line-by-line

Heating/cooling rates (Profile 2)



- The balance of heating/cooling is the same as Profile 1.
- If the effect of solar radiation in 960-2000 cm^{-1} is turned off, the cooling in upper atmosphere becomes weaker in up to ~1 K/day. (The effect of CH_4 band in 1200-1400 cm^{-1} is dominant)

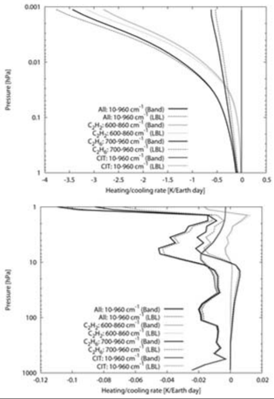
Sensitivity of solar radiation in 900-2000 cm^{-1}



Results

Solid: Band
Dashed: Line-by-line

Sensitivity of molecules (Profile 2)



About the effect of cooling in mid- and far-infrared (10-960 cm^{-1}):

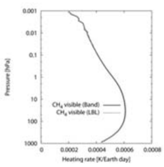
- C_2H_2 is dominant above ~0.03 hPa (up to ~3 K/day).
- C_2H_6 is dominant between 0.03-10 hPa (up to ~0.3 K/day in this height region).
- Collision-induced transitions are dominant below ~10 hPa (up tp ~0.02 K/day).
- The effect of CH_4 is very small in this wavelength region.

Summary (1/2)

- Jupiter's stratosphere may be a very interesting target in the standpoint of atmospheric dynamics and beyond, and we are developing a GCM for the investigations.
- Fast and effective calculations are needed for the GCM, and we have developed a band radiative transfer model based on the correlated k-distribution approach (framework of 'mstrnX', Sekiguchi and Nakajima [2008]).
- The band model can calculate the heating/cooling rates in a good accuracy in comparison with the line-by-line calculations.
- The effects of CH_4 in 1200-1400 cm^{-1} and C_2H_2 in 600-860 cm^{-1} are dominant for cooling in upper stratosphere (above ~10^{-2} hPa).
- The effect of C_2H_6 in 700-960 cm^{-1} is dominant for cooling in middle stratosphere (between ~10^{-2} and ~10^{1} hPa).
- The effect of collision-induced transitions is dominant for cooling in lower stratosphere (below ~10^{1} hPa).

Summary (2/2)

- Heating by solar absorption is made by CH_4, making a good heating/cooling balance below ~10^{-2} hPa.
- Most absorptions are made in near-infrared wavelength, but absorptions in visible wavelength may not be ignorable in lower stratosphere (up to ~5% of the total).



Future works

- Comparison of the results of calculated heat balances with a preceding study [Yelle et al., 2001]
- Implementation of this band radiation code to German GCMs for Jupiter's/Saturn's stratosphere
- Setting on the dynamical studies of giant planets with the GCMs
- Observations by JUICE-SWI