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

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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** ($10^2 \sim 10^{-3}$ hPa)
  - With cloud layers
  - Driven by the internal heat source.
- **Troposphere** ($10^4-5 \sim 10^2$ hPa)

[Seiff et al., 1998]

Here we focus on the stratosphere.
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$_2$O, 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).
Jupiter’s stratosphere

- 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 23\(^\circ\)N and 5\(^\circ\)N.

[Flasar et al., 2004]
Radiative processes of Jupiter’s stratosphere

- **CH$_4$:** Absorber of the solar radiation
- **CH$_4$, C$_2$H$_2$, C$_2$H$_6$,** 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).

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

- Molecular lines of CH₄, C₂H₂ (600-860 cm⁻¹) and C₂H₆ (700-960 cm⁻¹): From HITRAN2008 [Rothman et al., 2009] with update for C₂H₆ (in 2009) and C₂H₂ (in 2011).

### Voigt profile

- Voigt profile is used for the calculation of line spectrum, with wing cutoff of 25 cm⁻¹ for all molecules.

### Collision-induced transitions

Calculations

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

- 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

CH$_4$ line spectrum
(3300-4800 cm$^{-1}$)

• 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

<table>
<thead>
<tr>
<th>Band</th>
<th>IR(infrared) / SO(solar)</th>
<th>Wavenumber range [cm(^{-1})]</th>
<th>Molecules</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>IR</td>
<td>10-150</td>
<td>CH(_4), CIT</td>
</tr>
<tr>
<td>2</td>
<td>IR</td>
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<td>IR</td>
<td>600-700</td>
<td>CH(_4), C(_2)H(_2), CIT</td>
</tr>
<tr>
<td>5</td>
<td>IR</td>
<td>700-860</td>
<td>C(_2)H(_2), C(_2)H(_6), CIT</td>
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<tr>
<td>6</td>
<td>IR</td>
<td>860-960</td>
<td>CH(_4), C(_2)H(_6), CIT</td>
</tr>
<tr>
<td>7</td>
<td>IR, SO</td>
<td>960-1200</td>
<td>CH(_4), CIT</td>
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<td>1200-1400</td>
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<td>IR, SO</td>
<td>1400-1600</td>
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<tr>
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<td>1600-2000</td>
<td>CH(_4), CIT</td>
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<tr>
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<tr>
<td>17</td>
<td>SO</td>
<td>10800-11800</td>
<td>CH(_4)</td>
</tr>
</tbody>
</table>

- **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\(_2\)H\(_2\), 10 ppmv of C\(_2\)H\(_6\), 89.8 % of H\(_2\), 10.2 % of He) is fixed in making the table.
Calculations

- **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°

Considered vertical profiles of temperature and composition.
Results

Differences between band and line-by-line calculations are very small.

Mid- and far-infrared radiation (10-960 cm$^{-1}$): Dominant for cooling below $\sim 2.5 \times 10^{-3}$ hPa.

Infrared and solar radiation (960-2000 cm$^{-1}$): Dominant for cooling above $\sim 2.5 \times 10^{-3}$ hPa, and very small effects below.

Solar radiation in near-infrared and visible (2000-11800 cm$^{-1}$): Dominant for heating, especially below $\sim 1 \times 10^{-2}$ hPa. Absorption in visible (10800-11800 cm$^{-1}$) is small (up to $\sim 5\%$ of the total below $\sim 100$ hPa).
Results

- 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 \(~1\text{ K/day}\). (The effect of CH\(_4\) band in 1200-1400 cm\(^{-1}\) is dominant)

Sensitivity of solar radiation in 900-2000 cm\(^{-1}\)
Results

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

- \(\text{C}_2\text{H}_2\) is dominant above \(\sim 0.03\) hPa (up to \(\sim 3\) K/day).
- \(\text{C}_2\text{H}_6\) is dominant between 0.03-10 hPa (up to \(\sim 0.3\) K/day in this height region).
- Collision-induced transitions are dominant below \(\sim 10\) hPa (up to \(\sim 0.02\) K/day).
- The effect of \(\text{CH}_4\) 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 (using the 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$_2$H$_2$ in 600-860 cm$^{-1}$ are dominant for cooling in upper stratosphere (above $\sim$10$^{-2}$ hPa).

• The effect of C$_2$H$_6$ in 700-960 cm$^{-1}$ is dominant for cooling in middle stratosphere (between $\sim$10$^{-2}$ and $\sim$10$^1$ hPa).

• The effect of collision-induced transitions is dominant for cooling in lower stratosphere (below $\sim$10$^1$ hPa).
Summary (2/2)

• Heating by solar absorption is made by CH$_4$, making a good heating/cooling balance below $\sim 10^{-2}$ hPa.

• Most absorptions are made in near-infrared wavelength, but absorptions in visible wavelength may not be ignorable in lower stratosphere (up to $\sim 5\%$ 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