Modeling of Jupiter and Saturn Auroral Emissions

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Introduction

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木星磁気圏の太陽風応答
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Introduction

Investigation Methods at Earth
- Ground-based observation
  - aurora, magnetic field variation
- In-situ observation (magnetosphere etc.)
  - plasma, magnetic/electric fields
- Remote-sensing observation
  - aurora/plasma/ENA imaging, radio emission

at outer planetary magnetosphere
with different environment

http://www.isas.jaxa.jp/j/japan_s_history/chapter06/05/01.shtml
# Introduction: Jupiter/Saturn

## Table. Parameters.

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<th>Earth</th>
<th>Jupiter</th>
<th>Saturn</th>
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<td>1-10×10¹²</td>
<td>1-10×10¹¹</td>
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</table>


Saturn: Cassini (2004-), Pioneer, Voyager, …
Introduction: Jupiter/Saturn 2

**Jupiter**
- Magnetosphere: 50-100 R\_J
- Io: ~5.9 R\_J
- ~5.9 R\_J

**Saturn**
- Magnetosphere
- Enceladus: ~4 R\_S
- Dione: ~6.3 R\_S
- Rhea: ~8.7 R\_S
- Titan: ~20 R\_S

*Fig.* Jupiter’s (top) magnetosphere [Khurana et al., 2004] and (bottom) ionosphere/thermosphere.

*Fig.* Saturn’s (top) magnetosphere [after Arridge et al., 2008] and (bottom) ionosphere/thermosphere.
Intro.: Aurora at Outer Planets

Aurora: energy release process
- activities of source magnetosphere and magnetosphere-ionosphere system
- atmospheric condition
Auroral provides global feature and process in the system.
(moon footprint, reconnection point, …)

Ultraviolet (UV) & Infrared (IR) aurorae reflect different processes.

[Branduardi-Raymont et al., 2008]
**Intro.: UV and IR Emissions**

**UV**

Electron transition of $H$ and $H_2$ excited directly by collision with high energy electron.

Hydrocarbon (HC) molecules in low altitude absorb short UV wavelength.

**IR**

Change of vibrational and rotational states of $H_3^+$ excited by background temperature (thermal excitation).

$H_3^+$ is produced by auroral electron

$$H_2 + e^- \rightarrow H_2^+ + 2 e^- , H_2^+ + H_2 \rightarrow H_3^+ + H$$

---

Gérard and Sigh [1982] Saturn • Jupiter

Gérard et al. [2009] Saturn

Melin et al. [2007, 2005]

Jupiter, Saturn ($H_3^+$ & intensity)


Jupiter (ion chemistry)

Grodent et al. [2001] Jupiter’s UV&IR emission profile

◆ Our model: Jupiter & Saturn’s UV & IR emission profile to compare
Intro.: Obs. Characteristics (Saturn)

<Saturn obs.>
Polar region
  UV: very low, IR: varies [Stallard et al., 2008]
  UV&IR difference is larger than MO [Melin et al., 2012]

What causes “IR & less UV?”

cf. for main oval, similar morphology and location in statistical obs. [e.g., Badman et al., 2011]

Fig. Saturn UV aurora [Clarke et al., 2005] and IR polar event [Badman et al., 2011].

Fig. Simultaneous obs by Cassini [Melin et al., 2011].
Intro.: Obs. Characteristics (Jupiter)

<Saturn obs.>
Polar region
UV: very low, IR: varies [Stallard et al., 2008]
UV&IR difference is larger than MO [Melin et al., 2012]
What causes “IR & less UV?”

<Jupiter simultaneous obs.> [Clarke et al., 2004] along the main oval
UV & IR relation varies
Io footprint & tail
UV: comparable to that of the main oval
IR: lower than most of the main oval
Equatorward of the main oval
UV: appear, IR: disappear
What condition provides “UV & less IR?”

Polar region
different features
less differences between Jovian UV/IR than Saturn?
time variation?
Purpose & Approach

What UV & IR simultaneous obs. tell us?

→ Simultaneous estimation of UV & IR emissions is essential.

Jupiter & Saturn environment (e.g., atmosphere, dynamics etc.) and observed aurorae have similarity and difference

→ Unique opportunity for comparison.

[Goal] Understand planetary environment from the UV/IR emissions at Jupiter/Saturn

[Approach] Develop a model to investigate their dependence on incident electron energy and the atmospheric temperature

[Application] polar emissions (IR enhancement at Saturn & similarity at Jupiter)
Model: Overview

**INPUT PARAMETERS**
- auroral electron energy & flux
- atmospheric density & temperature

**OUTPUT PARAMETERS**

Electron precipitation into atmosphere
- \( \text{H}_2 \) excitation rate
- \( \text{H}_2 \) ionization rate
- UV emission spectrum
- \( \text{H}_3^+ \) density
- \( \text{H}_3^+ \) vib. excited states
- HC absorption
- UV transmit spectrum
- Non-LTE correction
- UV emission rate
- IR emission rate

Maxwellian distribution is assumed for electron spectrum.

Fig. Vertical profiles assumed in this study for (a) (b) Jupiter [Grodent et al., 2001; Gladstone et al., 1996; Perry et al., 1999] and (c)(d) Saturn [Gérard et al., 2009; Moses et al., 2000; Muller-Wodarg et al., 2006; Moore et al., 2009].
Model: Electron Precipitation

We use the parameterization providing ionization and excitation profiles based on the results by Monte Carlo simulation [Hiraki and Tao, 2008]. This is applicable to ambient H$_2$ atmosphere.

This provides altitude profiles of ionization and excitation rates momentary.

Fig. Altitude profiles of ionization rate for Jupiter (left) and Saturn (right).
Model : UV Estimation

Electron precipitation into atmosphere

H₂ excitation rate

UV emission spectrum

HC absorption

UV transmit spectrum

UV emission rate

Werner band

\[ I_{W,v',v''}^W = I_C q_{v',0} \sum_{v''} A_{v'v''}^C \text{ [Gérard and Singh, 1982]} \]

\( I_{v'v''}^W \): transition rate [1/s]

\( I_C \): excited rate [1/s]

\( q_{v',0}^{X-C} \): Frank-Condon factors (ratio of \( v' \) in C states) [Spindler, 1968]

\( A_{v'v''} \): Einstein coefficient (\( v' \rightarrow v'' \)) [Allison and Dalgarno, 1970]

Lyman band

We add contribution from E&F states (25%) [Gérard and Singh, 1982].

Transmitted spectrum is obtained as follows

\[ I_{obs}(\lambda) = I_0(\lambda) \exp \left( - \int \sum_s \sigma_{CH_s} N_{CH_s}(z) dz \right) \]

\( I_0 \): original emission intensity

\( N_{CH_s} \): density of HCs molecule

\( \sigma_{CH_s} \): absorption cross section [Parkinson et al., 2006]

UV emission rate is obtained as altitude integration of \( I_{obs} \).

Fig. HC abs. cross section

Fig. spectrum before/after HC abs.
Model: IR Estimation

Ion chemistry
diffusive H⁺ & H₃⁺ including
H₂O influx (for Saturn) and
H₂ vibrational states.

IR emission intensity

\[ I_{LTE}(\omega_{if}, z) = \eta(z) N_{H_3^+} g(2J + 1) \frac{hc \omega_{if} A_{if} \exp(-E_f/kT)}{Q(T)} \]

- \( I_{LTE} \): emission intensity [W/m³], \( \omega_{if} \): wave length [m],
- \( N_{H_3^+} \): H₃⁺ density [m⁻³], \( g \): nuclear spin weight,
- \( J \): rotational quantum number of the upper level of transition,
- \( h \): Planck constant 6.61x10⁻³⁴ [J s], \( c \): 3x10⁸ [m/s], \( A_{if} \): Einstein coefficient [s⁻¹]
- \( E_f \): Energy of upper level of transition [J], \( k \): Boltzmann constant  1.38 x 10⁻²³ [J/K]
- \( T \): temperature [K], \( Q \): Partition function \( Q = \sum_i (2J + 1)g_i \exp(-E_i/kT) \)

[Neals and Tannyson, 1995].

LTE ratio \( \eta(z) \) vibrational density calc. [Oka and Epp, 2004; Melin et al., 2005]

\[ \frac{dn_v}{dt} = \sum_v [A_{vv'}n_v - A_{v'v}n_{v'}] + \sum_v [k_{vv'}n_v - k_{v'v}n_{v'}]n_{H_2} = 0 \]

- \( n_v \): H₃⁺ density in v state, \( n_{H_2} \): H₂ density
- \( A_{vv'}, k_{v'v} \): Einstein & collision coefficient (v→v')
Results: Altitude Profiles

**Jupiter case**

10 keV & 150 nA/m² case
-UV (117-174 nm): 38.2 kR
-IR(Q(1,0)) 33.0 μW/m² str

![Fig. (a) Ion density and (b) emission rate profiles for Jupiter.](image)

**Saturn case**

10 keV & 150 nA/m² case
-UV (117-174 nm): 37.3 kR
-IR(Q(1,0)) 0.53 μW/m² str

![Fig. (a) Ion density and (b) emission rate profiles for Saturn.](image)
Results: UV&IR Dependences

Jupiter case

→ variation of UV/IR ratio for Jupiter seems smaller than that for Saturn
→ similar UV & IR emission at Jupiter than Saturn

Saturn case

Fig. (a) UV & (b) IR ratio to 10 keV & 0.15 μA/m² case, (c) required temperature decrease/increase to compensate for the IR variation at Jupiter and Saturn.
Discussion: Jupiter-Saturn Comparison

(i) Dependence of IR emission on atmospheric temperature is larger at Saturn \((10^3)\) than Jupiter (10)
\[
\rightarrow \text{Jupiter with 300-820 K shows large IR variation}
\]

(ii) Slope of IR around 1 keV is larger at Jupiter
\[
\rightarrow \text{temp. and } \text{H}_2\text{O} \text{ effect}
\]

Fig. Dependence check: (a) emission vs temperature at Jupiter and (b) emission vs electron energy at Saturn.
Discussion: Saturn Polar IR (1/2)

Consider intensity ratio:

\[ <\text{IR}> \text{ (main oval)} : (\text{polar event [Stallard et al., 2008]}) = 1 : 1 \]

\[ <\text{UV}> \text{ (main oval ~10s kR)} : (\text{polar emission < 1 kR}) = 1 : <0.1 \]

To obtain these intensities required either

1) small electron flux in open region and >100s K temperature enhancement

2) intense electron flux and a few 10s K temperature enhancement

Fig. (a) UV & (b) IR ratio to 10 keV & 0.15 μA/m² case, (c) required temperature decrease/increase to compensate for the IR variation at Saturn.
Discussion: Saturn Polar IR (2/2)

Comparison with observations at Earth:
“Polar rain” aurora [Zhang et al., 2007]
flux : 0.2–0.9 erg/s/cm² mean E: 0.6–1.6 keV

x 0.01 (∵ @Saturn 9.6 AU)
-> 0.002–0.01 erg/s/cm² = 0.002–0.01 μA/m² & 1 keV
-> 100 K enhancement would provide polar IR emission of intensity equal to that of the main oval.

Fig. Required temperature decrease/increase to compensate for the IR variation at Saturn.
App1. UV Quasi-Periodic Emission

IR variation depends on energy and flux.

Fig. Setting of auroral electron (a) energy and (b) number flux for test the polar auroral variation and (c) estimated UV and IR intensity variations for constant energy with variable flux (solid) and for variable energy with constant flux (dot-dashed and dotted) cases.

[Bonfond et al., 2011 GRL]
App2. Ele. Energy Estimation using IR

At high altitude (small H$_2$ density) → small vibrationally excited H$_3^+$ = “non-LTE” effect

Since this effect depends on H$_2$ density & IR lines, comparison between IR lines affected by large and small non-LTE effect would tell us altitude they emit → Auroral electron energy estimation!

ex. IR ratios [1.16, 2.41, 1.67] (60 keV, 1200 K case) → Energy & temperature is determined using at least three line ratios

→ If small error observation is achieved, auroral electron energy and temperature are determined accurately from IR lines.

Fig. Example of estimation including error.
Summary

We have developed a new UV and IR emission model for the outer planets:

1) Different UV/IR dependences are seen between Jupiter and Saturn
   • *Increase of IR due to electron energy is greater at Jupiter than at Saturn.*
   • *Temperature sensitivity of IR is greater at Saturn than at Jupiter.*
   → caused by differences in the atmospheric temperature and H$_2$O existence

2) Polar aurora might reflect these characteristics
   • Saturn IR polar event & Jupiter’s coexistent UV&IR emission in pole

   [Tao et al., Icarus, 2011]

3) Time variation of IR-UV correlation depends on ele. energy and time scale
   • IR variations due to <10 keV ele. energy case correlate with UV with ~100 sec time lag. IR due
     to >10 keV modulations vary differently and are sometimes inversely correlated with UV.

   [Tao et al., ISPS proceeding paper, accepted]

4) We propose energy estimation method using several IR lines
   • Since the departure from LTE varies with vibrational levels and altitude, measurements of the
     relative emission line intensities reveals the altitude of emission and hence the electron energy.

   [Tao et al., Icarus, in press]

Multi-wavelength auroral observation: at Saturn (Cassini), at Jupiter (Juno, Juice, ...) 
To maximize insight: compare model with obs. and expand other wavelength