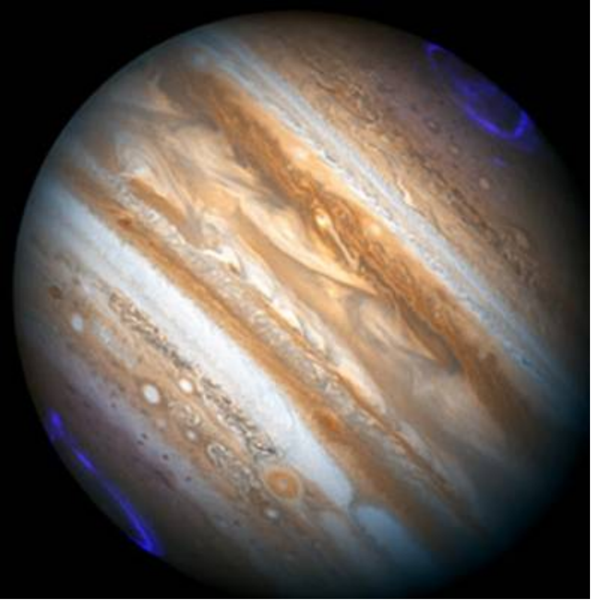
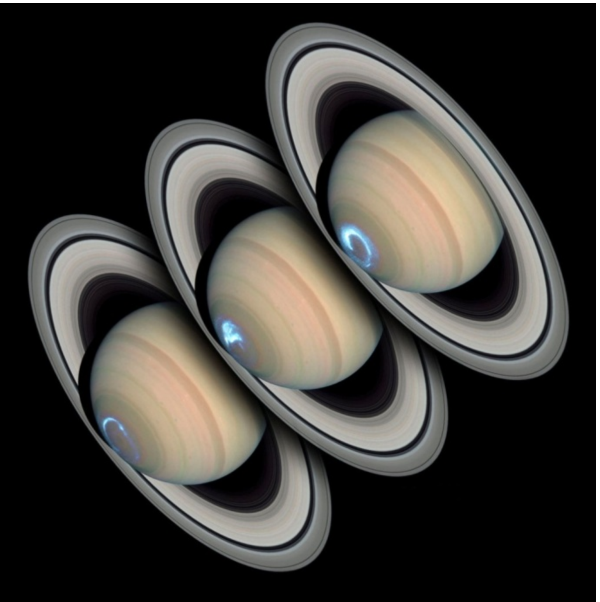
CPS seminar, August 27, 2012



Modeling of Jupiter and Saturn Auroral Emissions



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Introduction

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2000.4- 東北大学理学部→大学院理学研究科 修士・博士
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2009.4-2010.3 JST/CREST研究員(九大 田中高史教授)@東北大

2010.4- ISAS/JAXA プロジェクト研究員

研究テーマ

太陽風データ同化研究 ＊ (* at ISAS)

木星・土星オーロラ発光モデル ＊

木星超高層モデルによるオーロラ形成と多圏間角運動量輸送

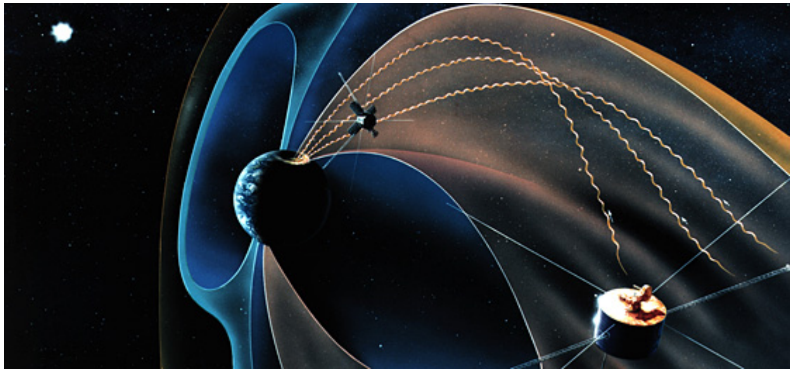
木星磁気圏の太陽風応答

(太陽風1次元モデル@木星・土星

http://sprg.isas.jaxa.jp/researchTeam/spacePlasma/staff/tao/)

Contents

Introduction



http://www.isas.jaxa.jp/j/japan_s_history/chapter06/05/01.shtml

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

Introduction : Jupiter/Saturn 1

Table. Parameters.

	Earth	Jupiter	Saturn
radius [km]	6370	71,492	60,268
mag. pause [radius]	10	50-100	20
rotation period [h]	24	9.9	10.7
mag. moment/field [G]	1/0.3	20,000/4	580/0.2
distance from Sun [AU]	1	5.2	9.6
SW travel time [min.]	3	200	50
ave. aurora [kR] power [W]	1-100 $1\text{-}100 \times 10^{9}$	10-1000 $1\text{-}10 \times 10^{12}$	1-100 $1\text{-}10 \times 10^{11}$

Jupiter : Galileo (1996-2003), Pioneer, Voyager, Ulysses, Cassini, New Horrizon, …

Saturn : Cassini (2004-), Pioneer, Voyager, …

Introduction : Jupiter/Saturn 2

Jupiter

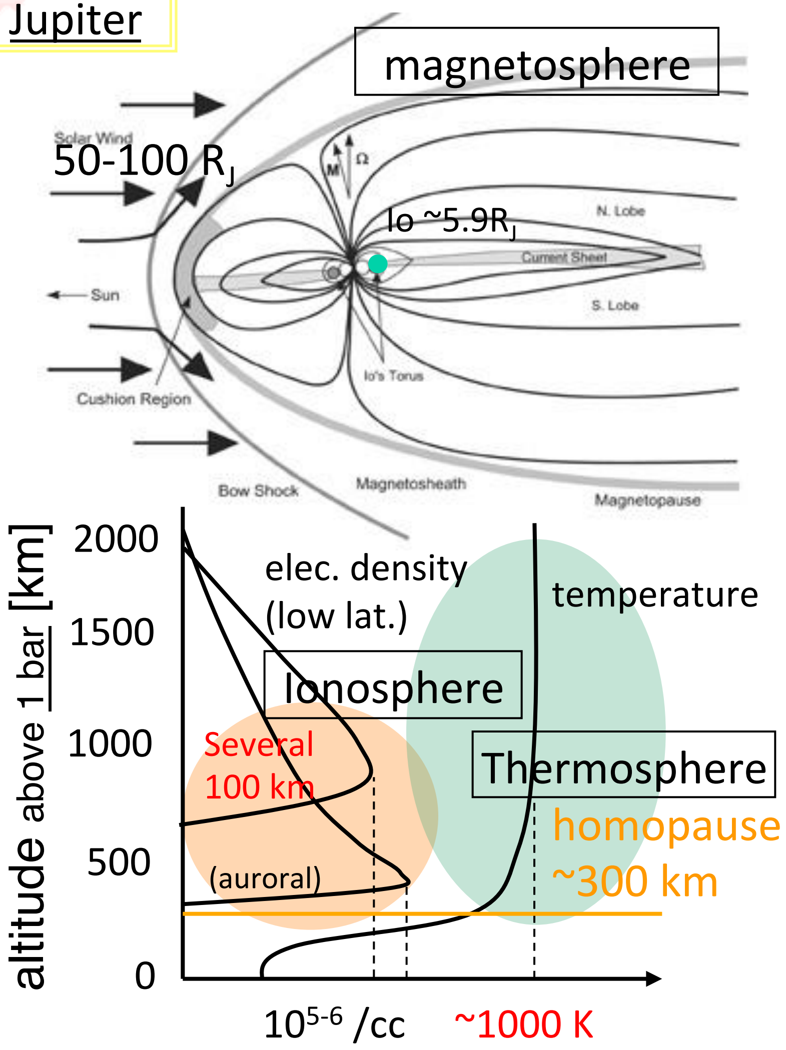


Fig. Jupiter's (top) magnetosphere [Khurana et al., 2004] and (bottom) ionosphere/thermosphere.

Saturn

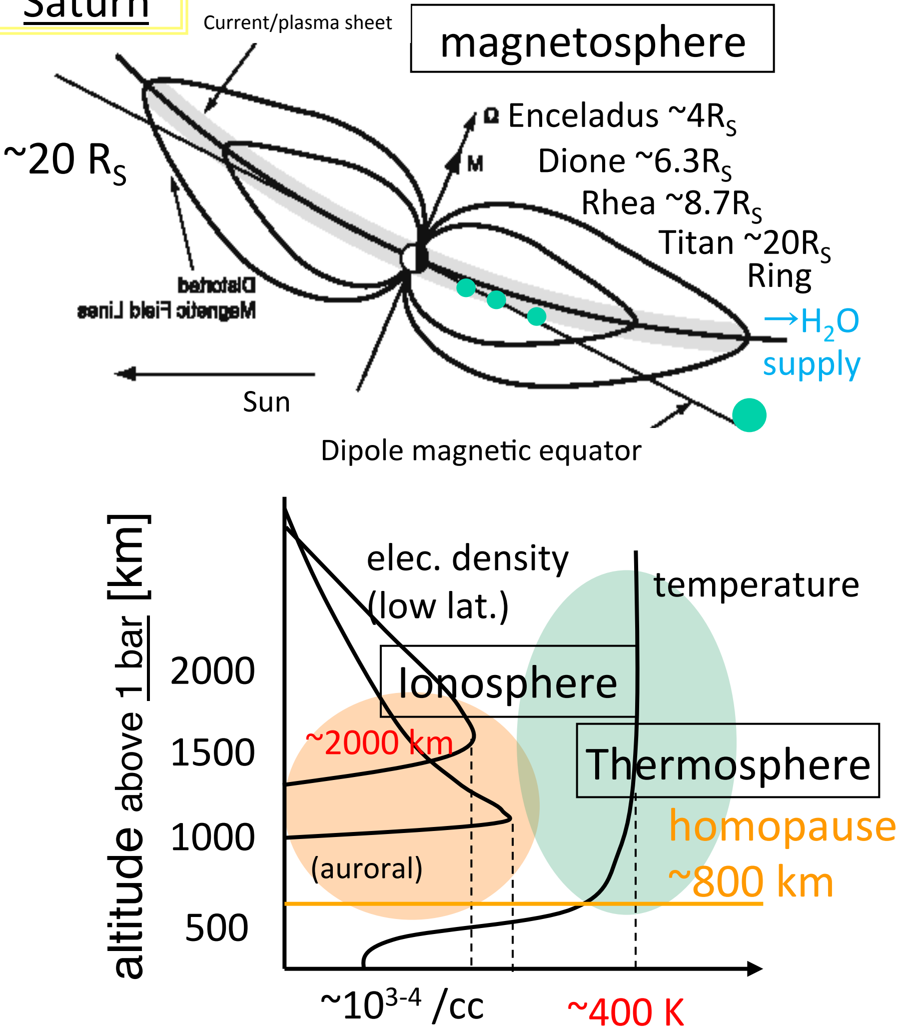


Fig. Saturn's (top) magnetosphere [after Arridge et al., 2008] and (bottom) ionosphere/thermosphere.

Intro.: Aurora at Outer Planets

Aurora : energy release process

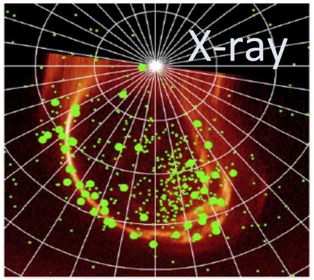
-activities of source magnetosphere and magnetosphere-ionosphere system

-atmospheric condition

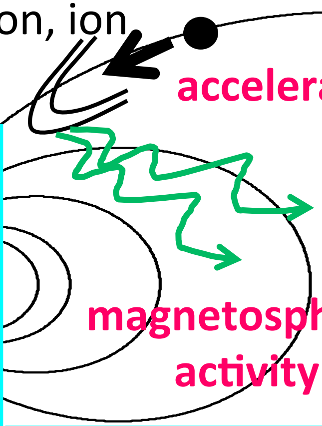
Auroral provides global feature and process in the system.

(moon footprint, reconnection point, …)

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



[Branduardi-Raymont et al., 2008]

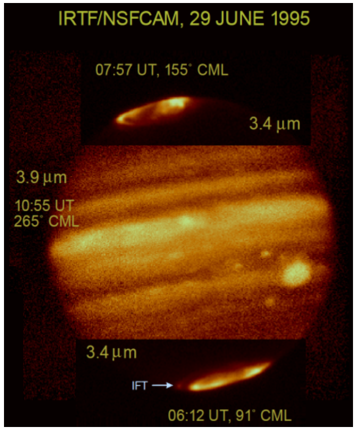


electron, ion

acceleration

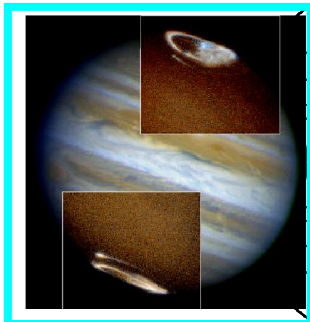
magnetospheric activity

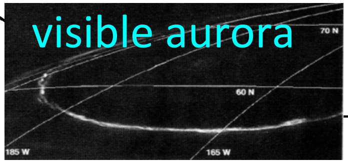
IR aurora



[Satoh&Connerney, 1999]

UV aurora

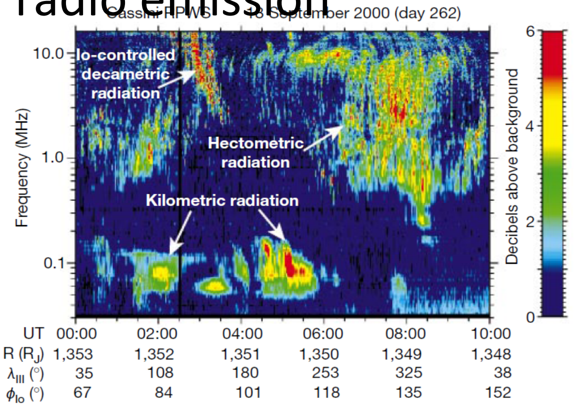




visible aurora

[Vasabada et al., 1999]

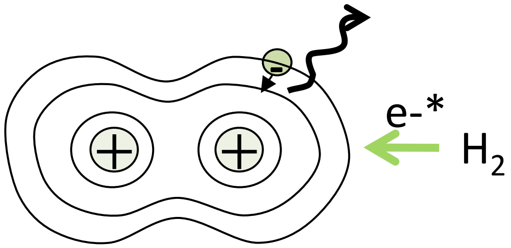
radio emission



[Gurnett et al., 2002]

Intro.: UV and IR Emissions

UV



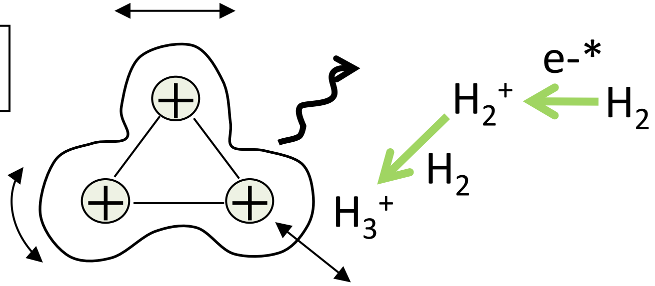
Electron transition of H and H_2 excited directly by collision with high energy electron

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

Gérard and Sigh [1982] Saturn・Jupiter

Gérard et al. [2009] Saturn

IR



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

H_3^+ is produced by auroral electron

$H_2 + e\text{-}^* \rightarrow H_2^+ + 2\ e\text{-}$, $H_2^+ + H_2 \rightarrow H_3^+ + H$

Melin et al. [2007, 2005]

Jupiter, Saturn (H_3^+ & intensity)

Kim et al.[1994] Perry et al.[1999]

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]

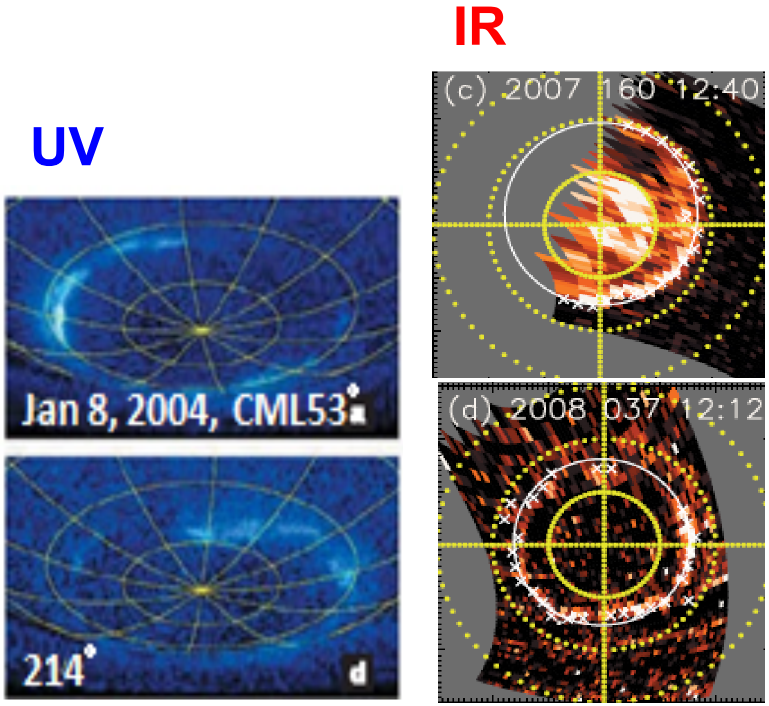


Fig. Saturn UV aurora [Clarke et al., 2005] and IR polar event [Badman et al., 2011].

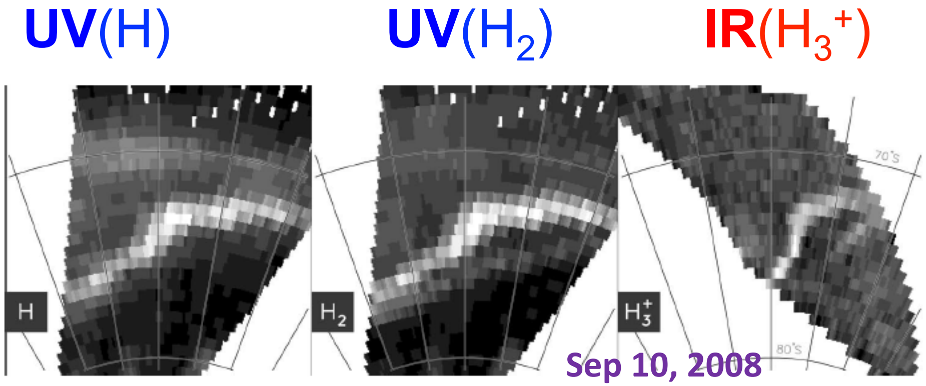
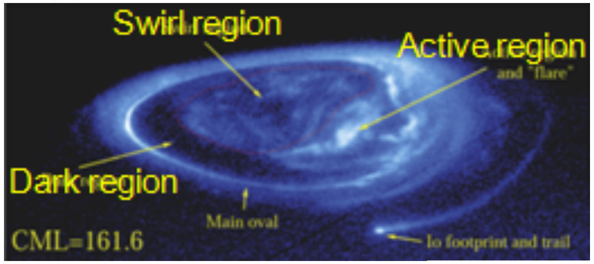


Fig. Simultaneous obs by Cassini [Melin et al., 2011].

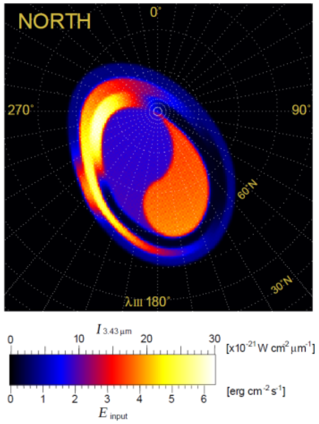
Intro.: Obs. Characteristics (Jupiter)



UV

Fig. Jupiter UV (↑) [Grodent et al., 2003] and IR (→) obs. [Satoh and Connerney, 1999]

IR



UV **IR**

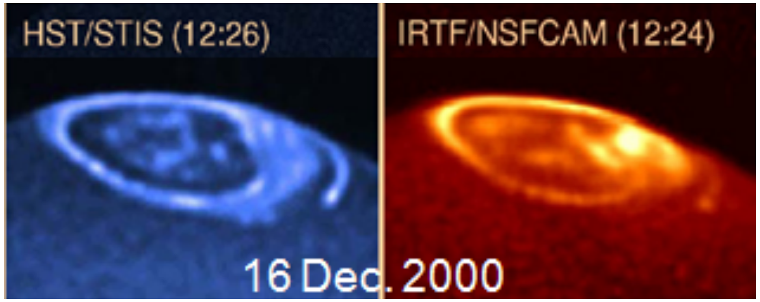


Fig. Jupiter UV & IR [Clarke et al., 2004]

<Saturn obs.>

<u>Polar region</u>

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]

<u>along the main oval</u>

UV & IR relation varies

<u>Io footprint & tail</u>

UV : comparable to that of the main oval

IR : lower than most of the main oval

<u>Equatorward of the main oval</u>

UV : appear, IR : disappear

What condition provides "UV & less IR"?

<u>Polar region</u>

different features

less differences between Jovian UV/IR than Saturn?

time variation?

Purpose & Approach

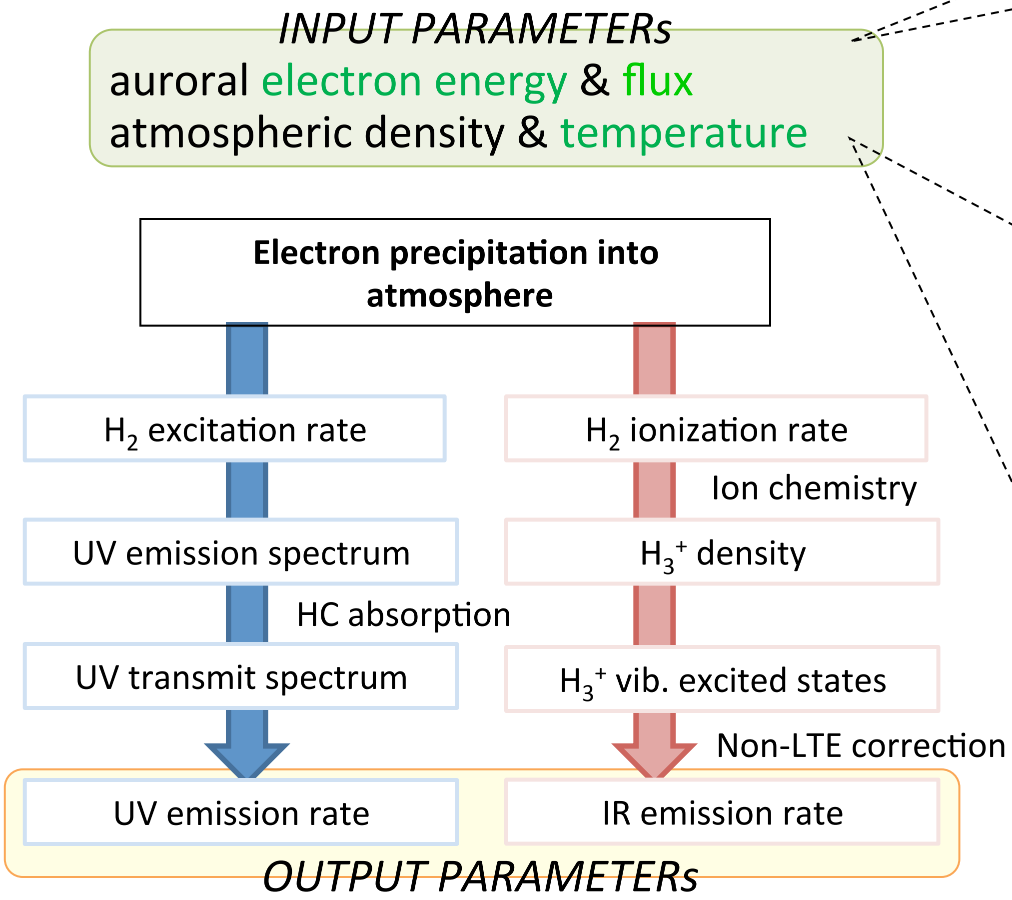
What UV & IR simultaneous obs. tell us?
→Simultaneous estimation of UV & IR emissions is essential.

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

Maxwellian distribution is assumed for electron spectrum.



INPUT PARAMETERs

auroral electron energy & flux

atmospheric density & temperature

Electron precipitation into atmosphere

H_2 excitation rate

UV emission spectrum

HC absorption

UV transmit spectrum

H_2 ionization rate

Ion chemistry

H_3^+ density

H_3^+ vib. excited states

Non-LTE correction

UV emission rate

IR emission rate

OUTPUT PARAMETERs

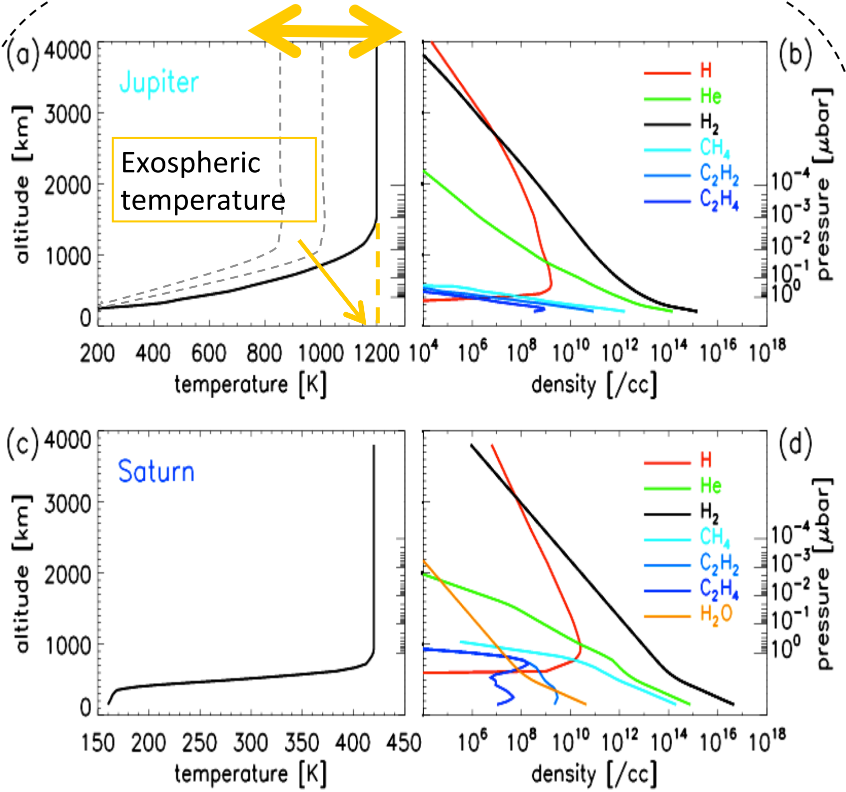
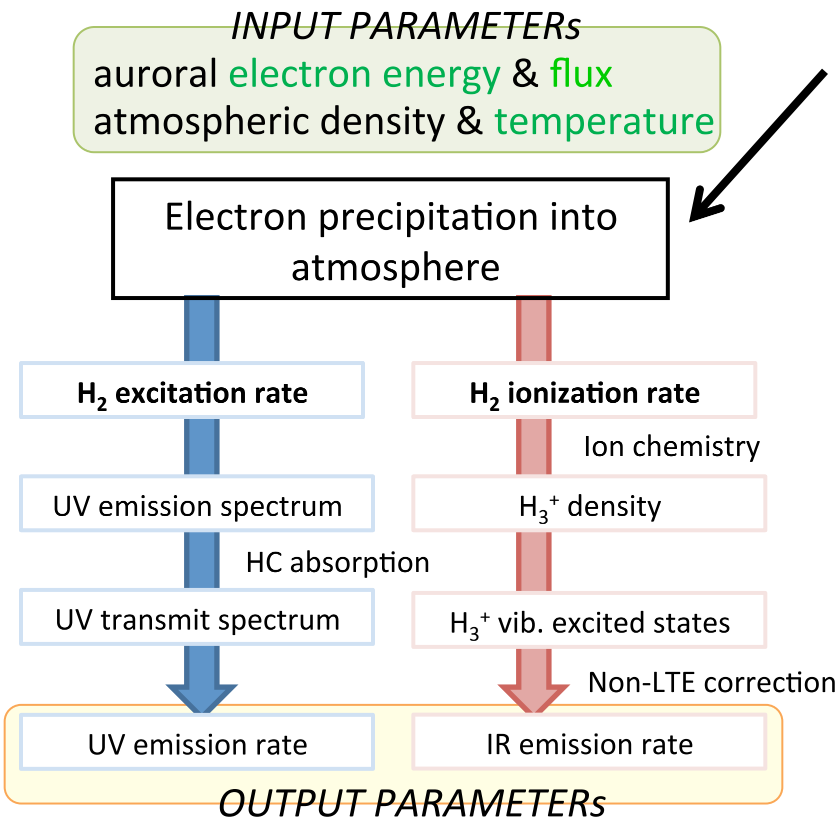


Fig. Vertical profiles assumed in this study for (a)(b) Jupiter [Grodent et al., 2001; Gladstone et al., 1996; Perry et al., 1999] and (c)(d) Saturn [Gérard et al., 2009; Moses et al., 2000; Muller-Wodarg et al., 2006; Moore et al., 2009].

Model : Electron Precipitation



INPUT PARAMETERs

auroral electron energy & flux

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Electron precipitation into atmosphere

H_2 excitation rate

UV emission spectrum

HC absorption

UV transmit spectrum

H_2 ionization rate

Ion chemistry

H_3^+ density

H_3^+ vib. excited states

Non-LTE correction

UV emission rate

IR emission rate

OUTPUT PARAMETERs

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.

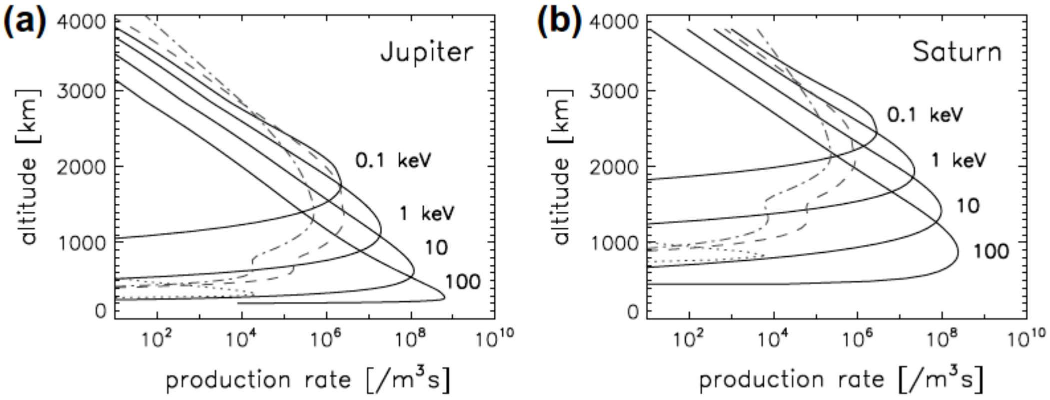
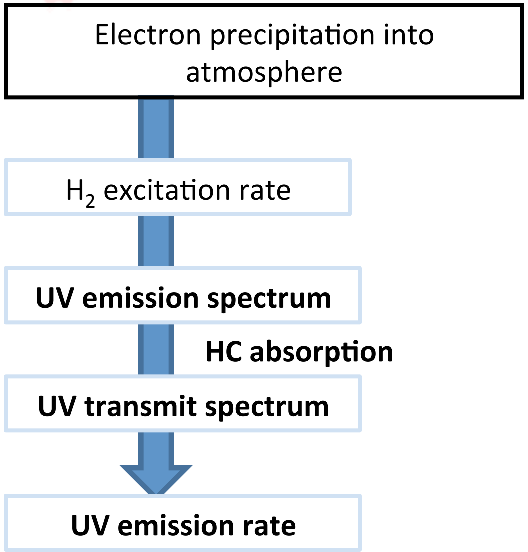


Fig. Altitude profiles of ionization rate for Jupiter (left) and Saturn (right).

Model : UV Estimation



Electron precipitation into atmosphere

H_2 excitation rate

UV emission spectrum

HC absorption

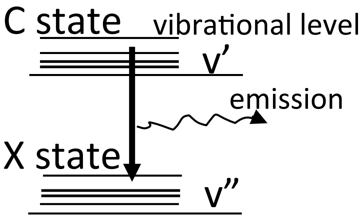
UV transmit spectrum

UV emission rate

Werner band

$$I^{\mathrm{W}}_{\nu',\nu''} = I_{\mathrm{C}}\, q^{\mathrm{X}\to\mathrm{C}}_{\nu',0} \frac{A^{\mathrm{C}\to\mathrm{X}}_{\nu'\nu''}}{\sum_{\nu''} A_{\nu'\nu''}}$$

[Gérard and Singh, 1982]



$I_{v'v''}{}^{W}$: transition rate [/s]

Ic: excited rate [/s]

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

$A_{v'v''}$: Einstein coefficient (v’→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

$$I_{\mathrm{obs}}(\lambda) = I_0(\lambda)\exp\left(-\int_z \sum_s \sigma_{\mathrm{CH_s}} N_{\mathrm{CH_s}}(z)dz\right)$$

I_0: original emission intensity

N_{CHs}: density of HCs molecule

σ_{CHs}: absorption cross section

[Parkinson et al., 2006]

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

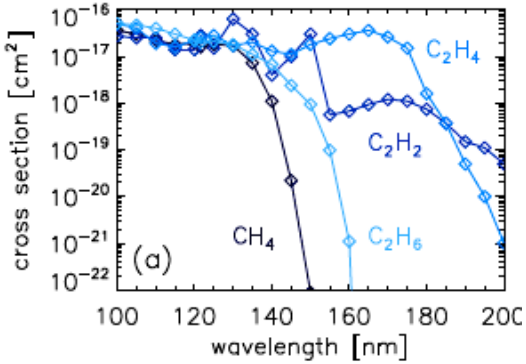


Fig. HC abs. cross section

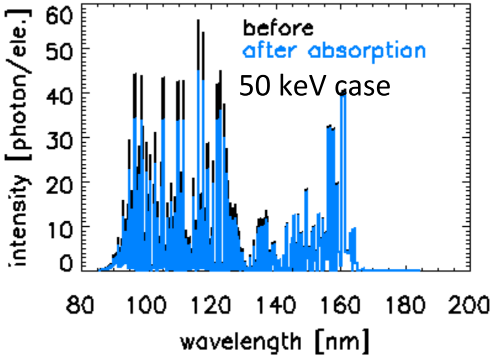
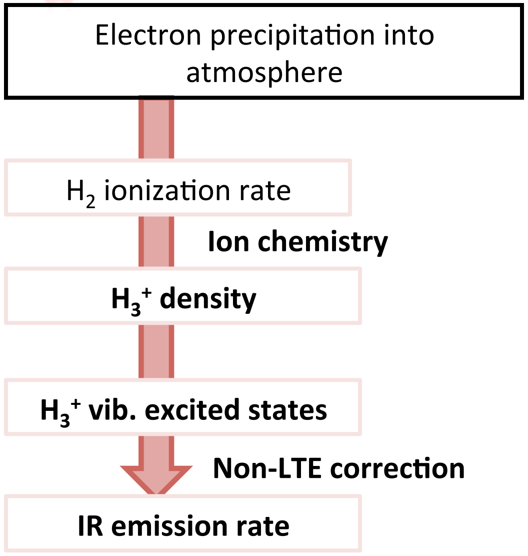


Fig. spectrum before/after HC abs.

Model : IR Estimation



Electron precipitation into atmosphere

H_2 ionization rate

Ion chemistry

H_3^+ density

H_3^+ vib. excited states

Non-LTE correction

IR emission rate

Ion chemistry

diffusive H^+ & H_3^+ including H_2O influx (for Saturn) and H_2 vibrational states.

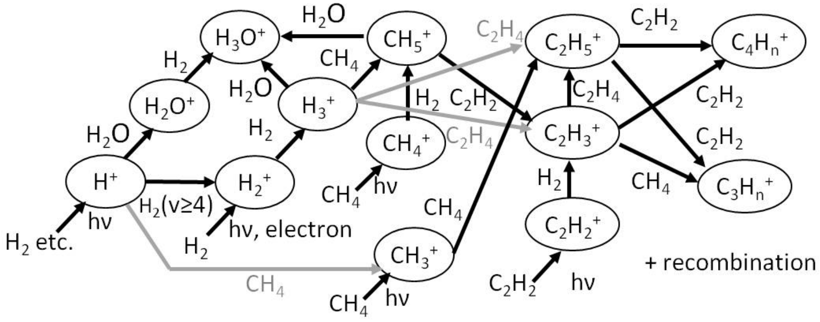


Fig. ion chemistry

IR emission intensity

$$I_{\mathrm{LTE}}(\omega_{\mathrm{if}}, z) = \eta(z)\, N_{H_3^+}\, g\left(2J+1\right) hc\,\omega_{\mathrm{if}} A_{\mathrm{if}} \exp\left(-E_{\mathrm{f}}/kT\right)/Q(T)$$

vibrational excited H_3^+ density

I_{LTE} : emission intensity [W/m^3], ω_{if} wave length [/m],
$N_{H_3^+}$: H_3^+ density [/m^3], *g* : nuclear spin weight,
J : rotational quantum number of the upper level of transition,
h : Prank constant 6.61x10^{-34} [J s], *c* : 3x10^8 [m/s], A_{if} : Einstein coefficient [/s]
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 $Q \equiv \sum_{\mathrm{i}} (2J+1) g_{\mathrm{i}} \exp\left(-E_{\mathrm{i}}/kT\right)$

[Neals and Tannyson, 1995].

LTE ratio η(z)

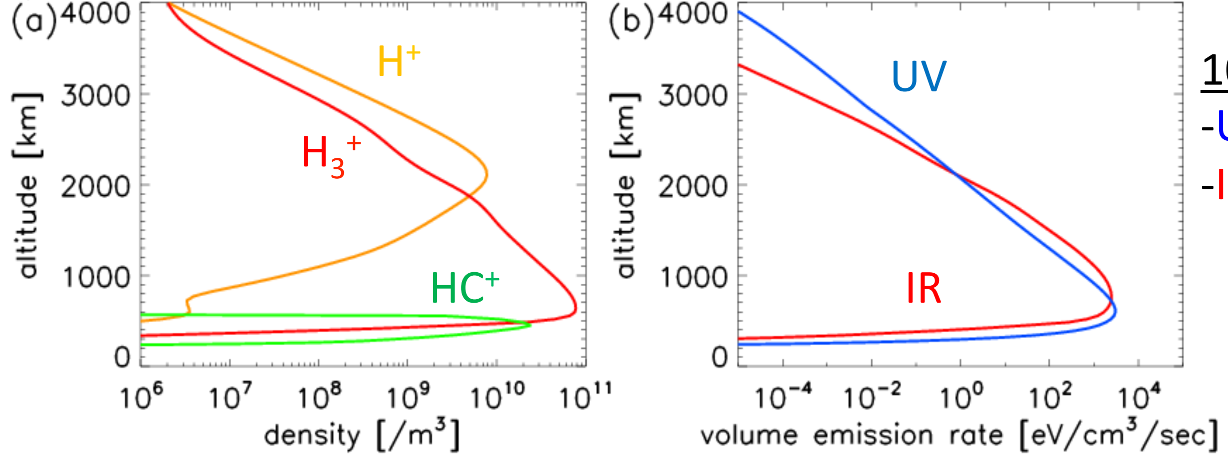
vibrational density calc. [Oka and Epp, 2004; Melin et al., 2005]

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

n_v : H_3^+ density in v state, n_{H2} : H_2 density
$A_{v\,v'}$, $k_{v\,v'}$:Einstein & collision coefficient (v→v')

Results : Altitude Profiles

Jupiter case



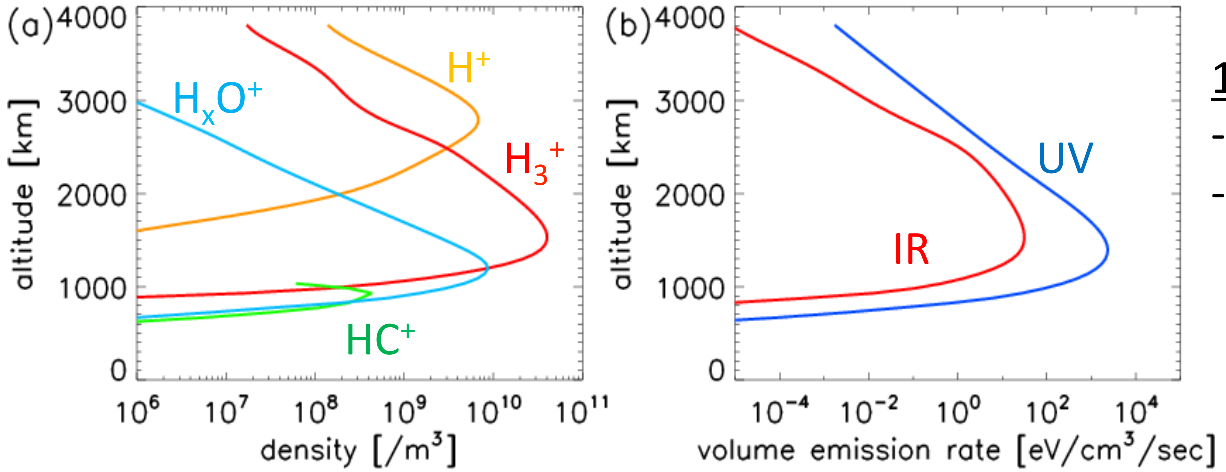
10 keV & 150 nA/m^2 case

-UV (117-174 nm): 38.2 kR

-IR(Q(1,0)) 33.0 μW/m^2 str

Fig. (a) Ion density and (b) emission rate profiles for Jupiter.

Saturn case



10 keV & 150 nA/m^2 case

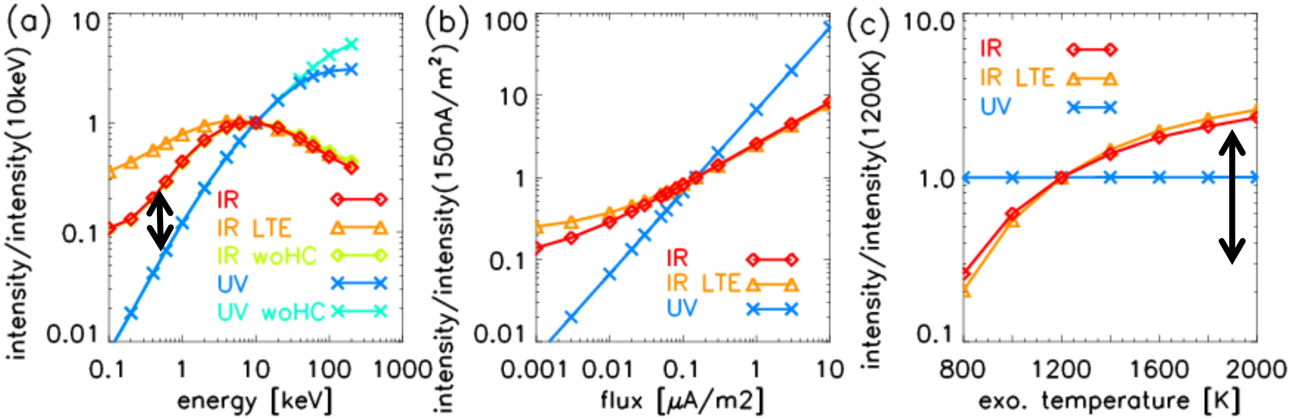
-UV (117-174 nm): 37.3 kR

-IR(Q(1,0)) 0.53 μW/m^2 str

Fig. (a) Ion density and (b) emission rate profiles for Saturn.

Results : UV&IR Dependences

Jupiter case



Saturn case

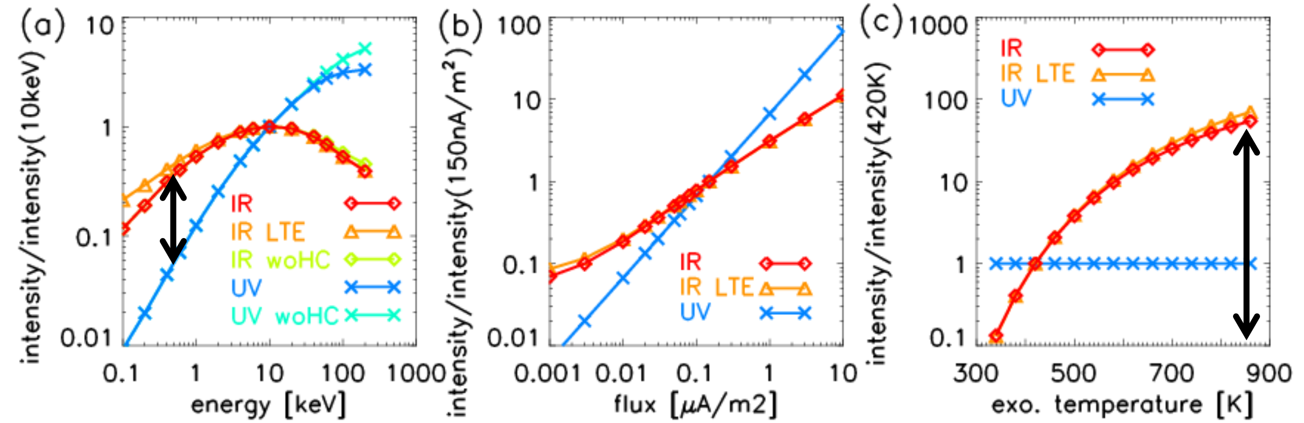


Fig. (a) UV & (b) IR ratio to 10 keV & 0.15 μA/m^2 case, (c) required temperature decrease/increase to compensate for the IR variation at Jupiter and Saturn.

→ variation of UV/IR ratio for Jupiter seems smaller than that for Saturn

→ similar UV & IR emission at Jupiter than Saturn

Discussion : Jupiter-Saturn Comparison

(i) Dependence of IR emission on atmospheric temperature is larger at Saturn (10^3) than Jupiter (10)

→ Jupiter with 300-820 K shows large IR variation

(ii) Slope of IR around 1 keV is larger at Jupiter

→ temp. and H_2O effect

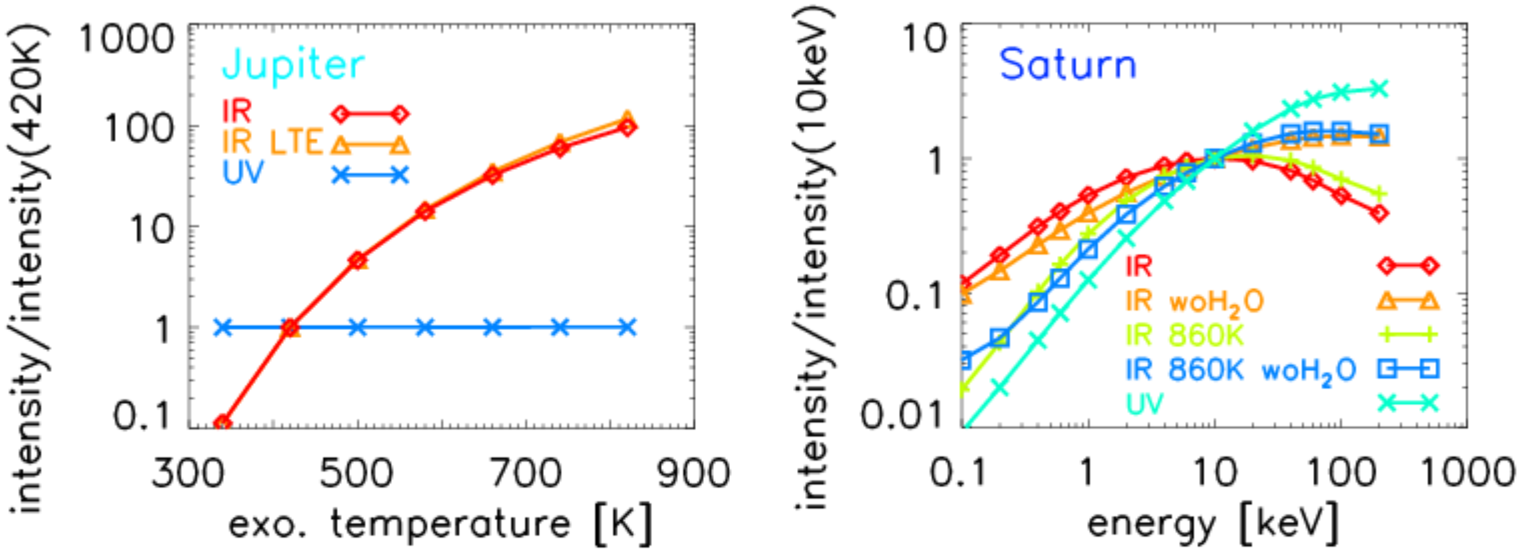


Fig. Dependence check : (a) emission vs temperature at Jupiter and (b) emission vs electron energy at Saturn.

Discussion : Saturn Polar IR (1/2)

Consider intensity ratio :

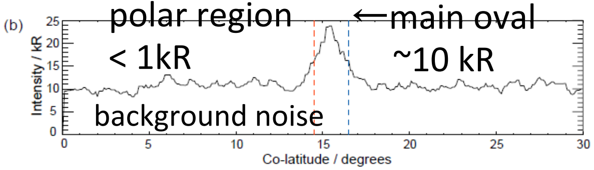
<IR> (main oval) : (polar event [Stallard et al., 2008]) = 1 : 1

<UV> (main oval ~10s kR) : (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



polar region

< 1kR

←main oval

~10 kR

background noise

Fig. UV co-lat. profile [Badman et al., 2006]

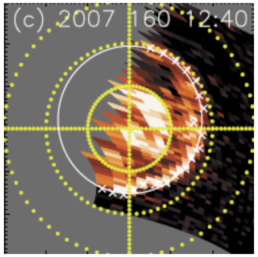


Fig. IR polar event [Badman et al., 2011]

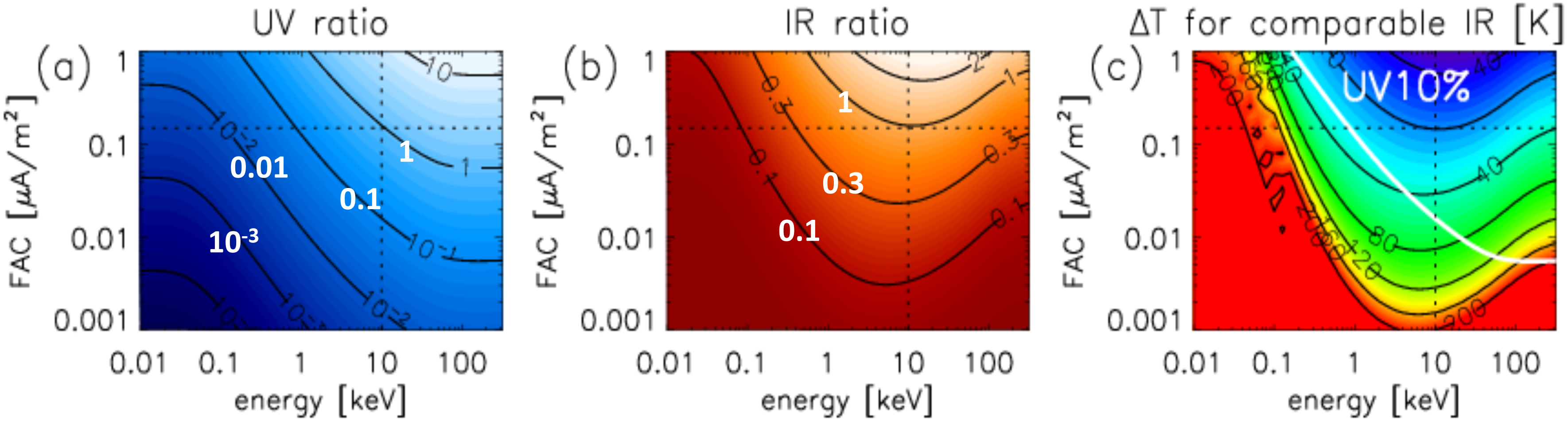


Fig. (a) UV & (b) IR ratio to 10 keV & 0.15 μA/m² case, (c) required temperature decrease/increase to compensate for the IR variation at Saturn.

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/cm^2 mean E: 0.6–1.6 keV

x 0.01 (∵@Saturn 9.6 AU)
-> 0.002–0.01 erg/s/cm^2 = 0.002–0.01 μA/m^2 & 1 keV
-> 100 K enhancement would provide polar IR emission of intensity equal to that of the main oval.

IMAGE (FUV SI-13) 19:25 July 22, 2004

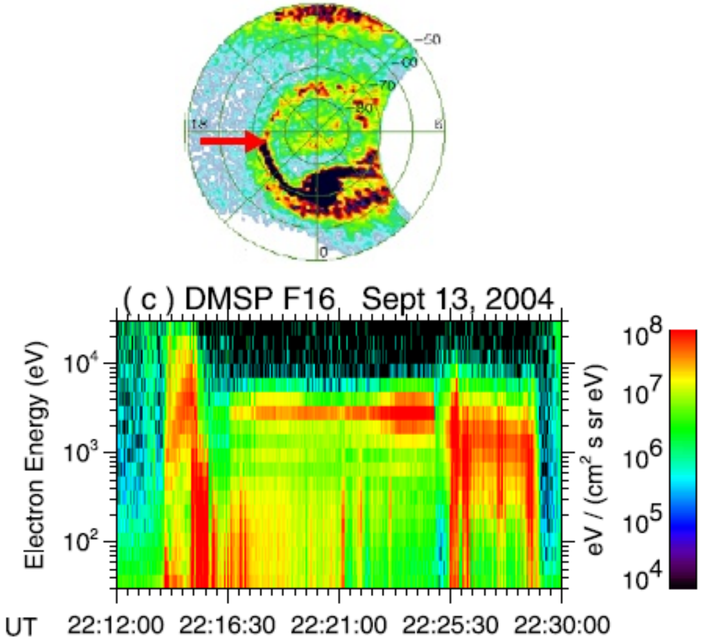


Fig. Earth’s polar rain aurora and ET diagram [Zhang et al., 2007]

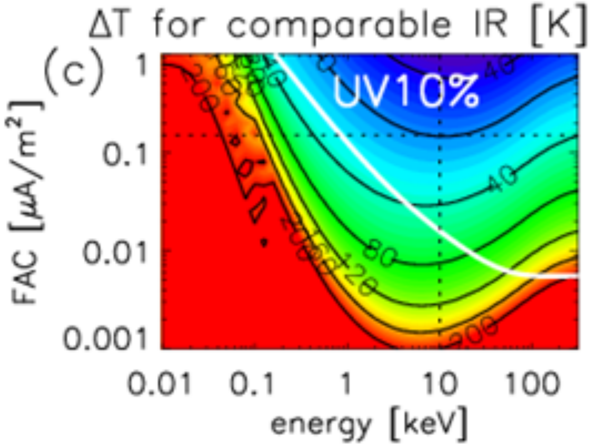
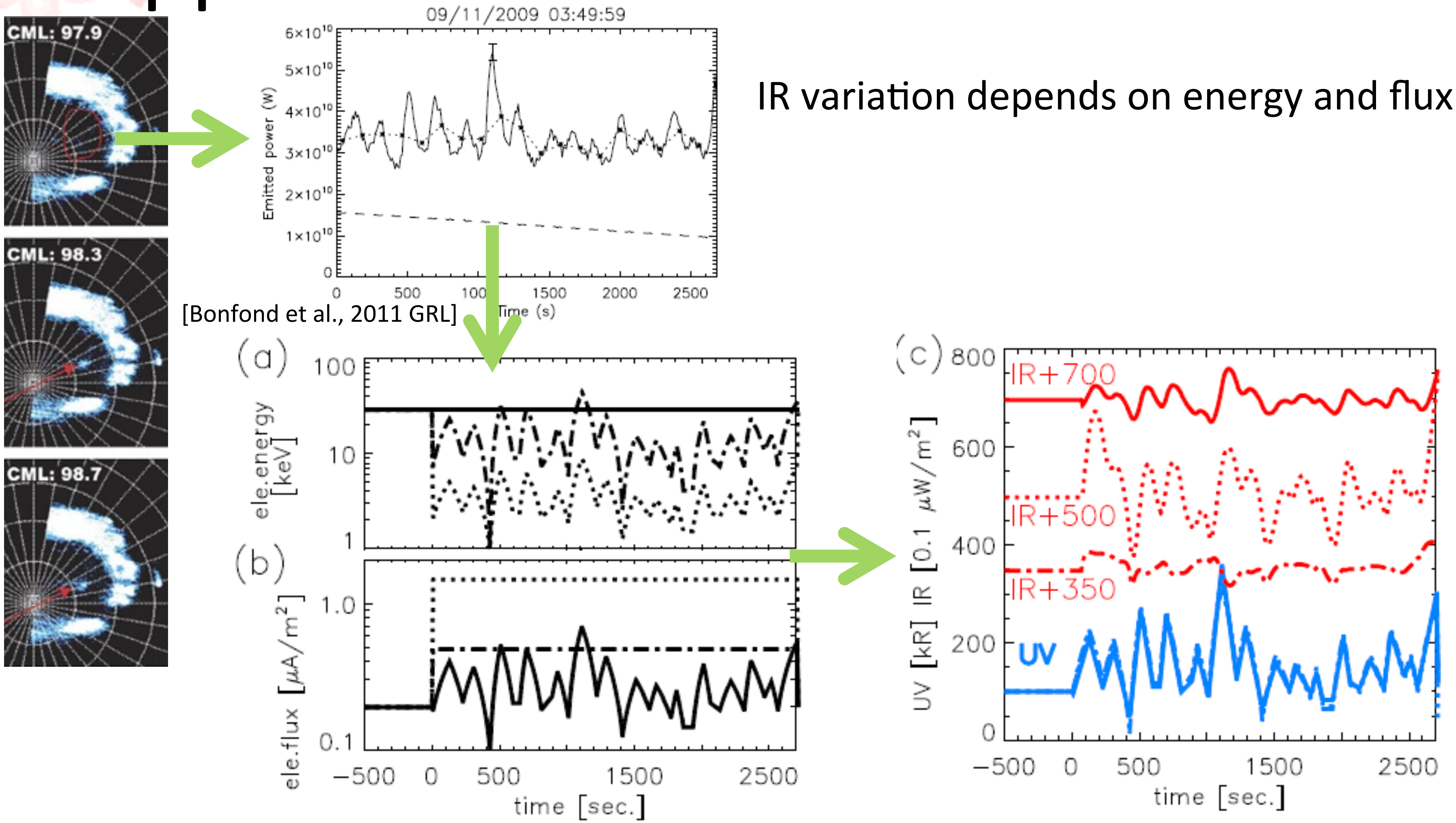


Fig. Required temperature decrease/increase to compensate for the IR variation at Saturn.

App1. UV Quasi-Periodic Emission



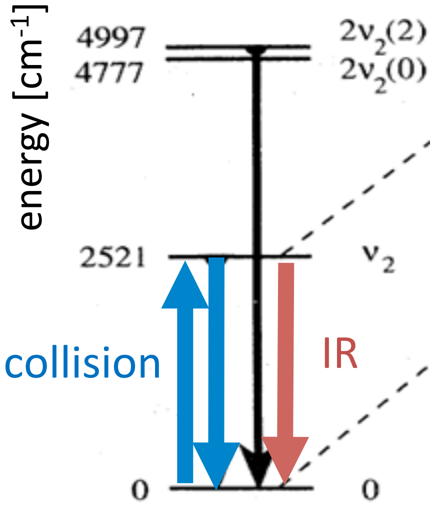
IR variation depends on energy and flux.

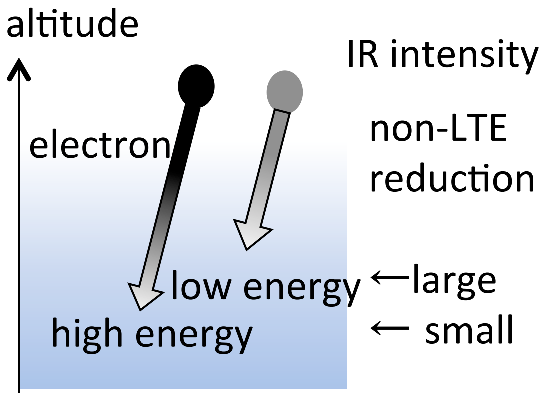
[Bonfond et al., 2011 GRL]

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.

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
→ <u>Auroral electron energy estimation!</u>

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.

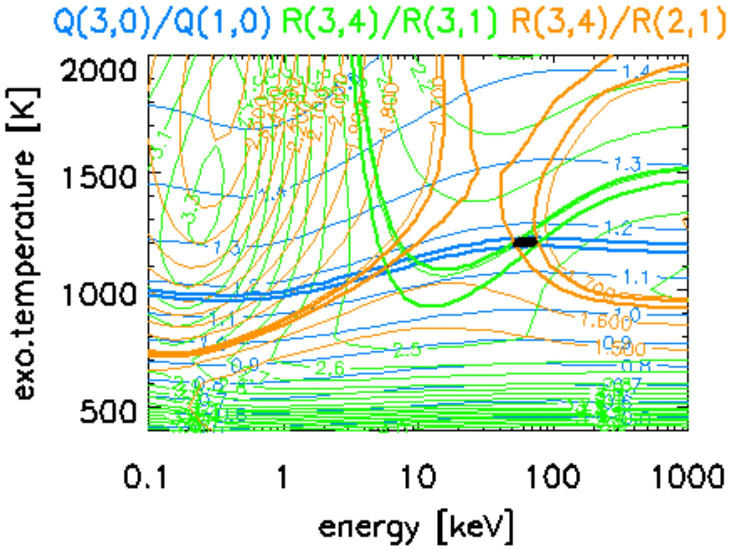


Fig. Example of estimation including error.

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_2O 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