Io and magntospheric plasma interaction derived from the HISAKI observation

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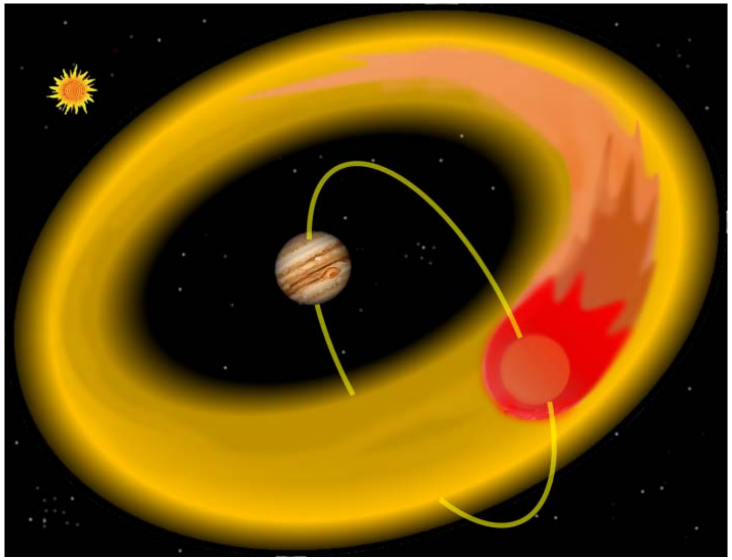
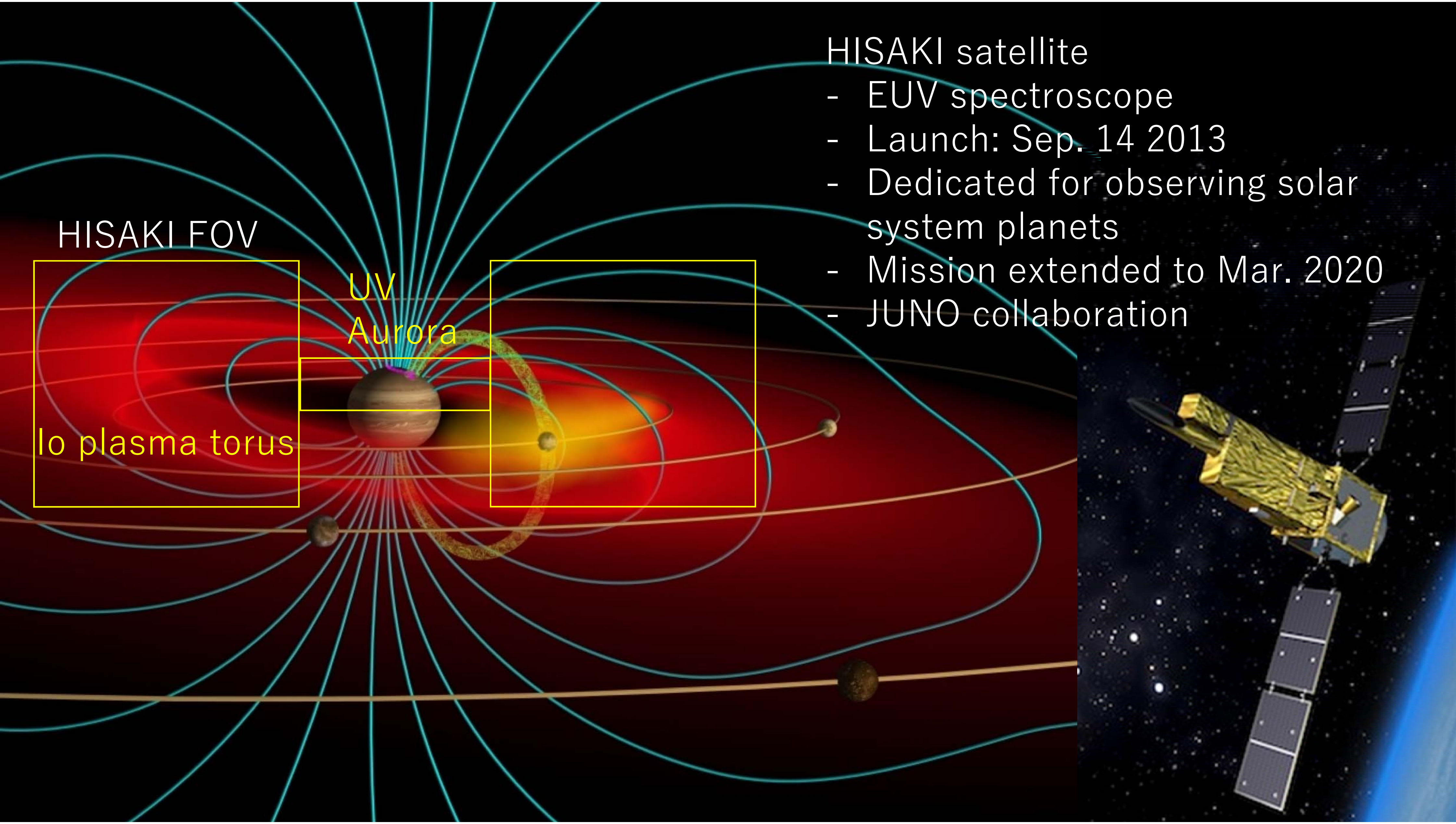
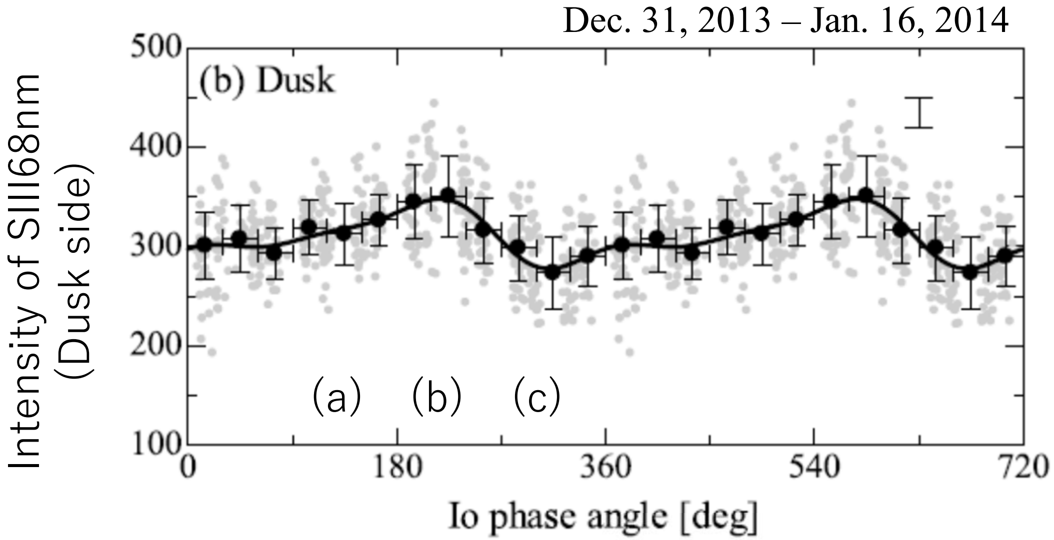



HISAKI satellite
- EUV spectroscope
- Launch: Sep. 14 2013
- Dedicated for observing solar system planets
- Mission extended to Mar. 2020
- JUNO collaboration
HISAKI FOV
UV Aurora
Io plasma torus

Brightness in IPT: dependence on relative position of Io

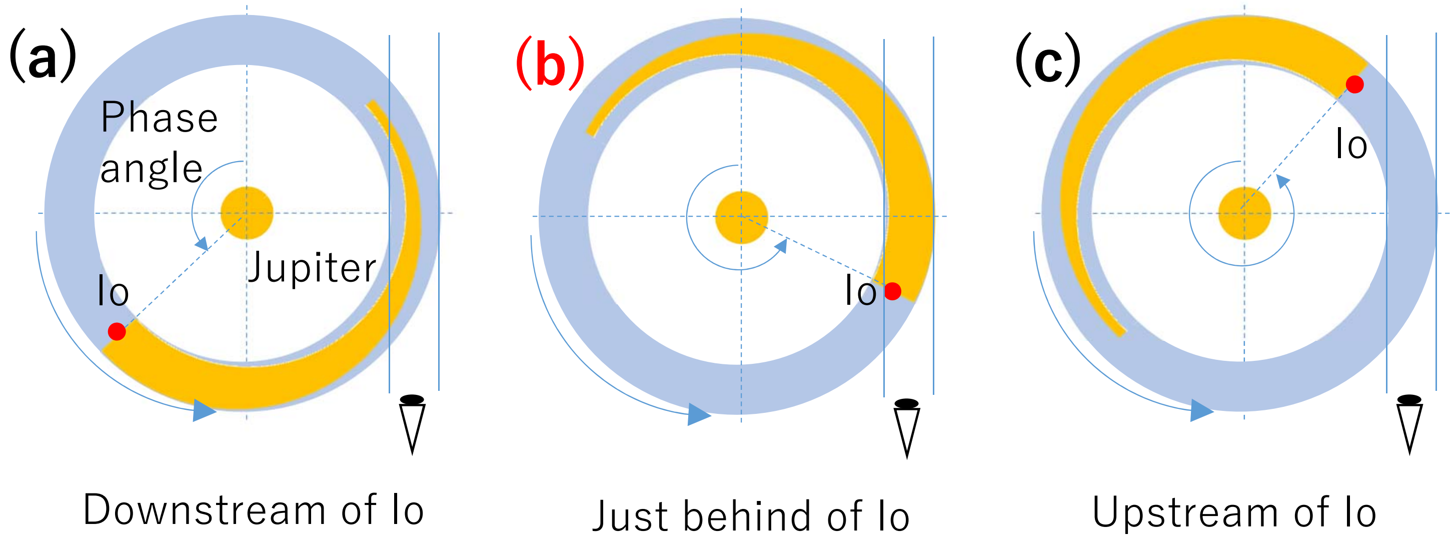


[Tsuchiya et al. 2015]

- Brightness of IPT enhances just downstream of Io
- Consistent with the Voyager result

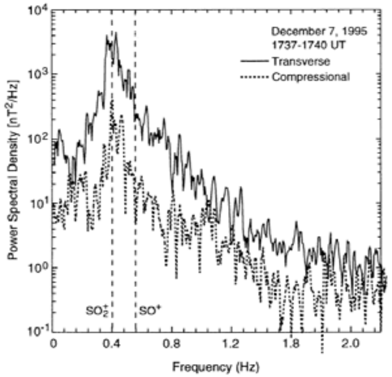
Increase in hot electron population just downstream of Io

- Rapid heating of electron around Io
- Cooling of the electron with time scales of several hours

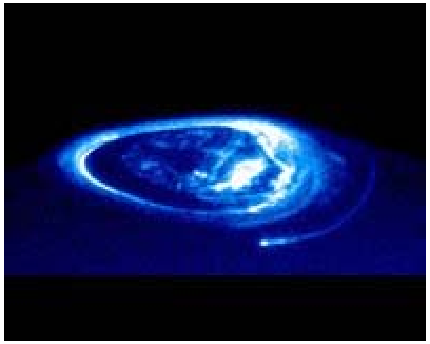


Background & Purpose of this study

- Unanswered question: Local electron heating process around Io
  Candidates:
  (1) SO_2 ion cyclotron wave around Io
  (2) Electron beam generated by Alfven wave at the foot of Io flux tube



Ion cyclotron wave around Io by Galileo S/C (Russell et al. 2001)



- Here, we developed an emission model of Io plasm torus to assess
  - Longitudinal extent of electron heating region
  - Temperature and density of electrons heated

Emission model of Io plasma torus

Equilibrium Io plasma torus (Eqs.(1) & (2))

Constant Electron density & Ion parameters

- Ne = 3000/cc, Ne,hot = 30/cc (1%)
- Ion composition (Yoshioka+ 2014)
- Ion temperature: T=60eV (Bagenal 1994)

Ambient thermal electron (Te~4-5eV)

$$\frac{\partial T_e}{\partial t} = \sum_\beta \nu_e^{\beta/e}(T_\beta - T_e) + \nu_e^{h/e}(T_h - T_e) - \frac{2}{3}\sum_\beta \rho_\beta n_\beta \quad (1)$$

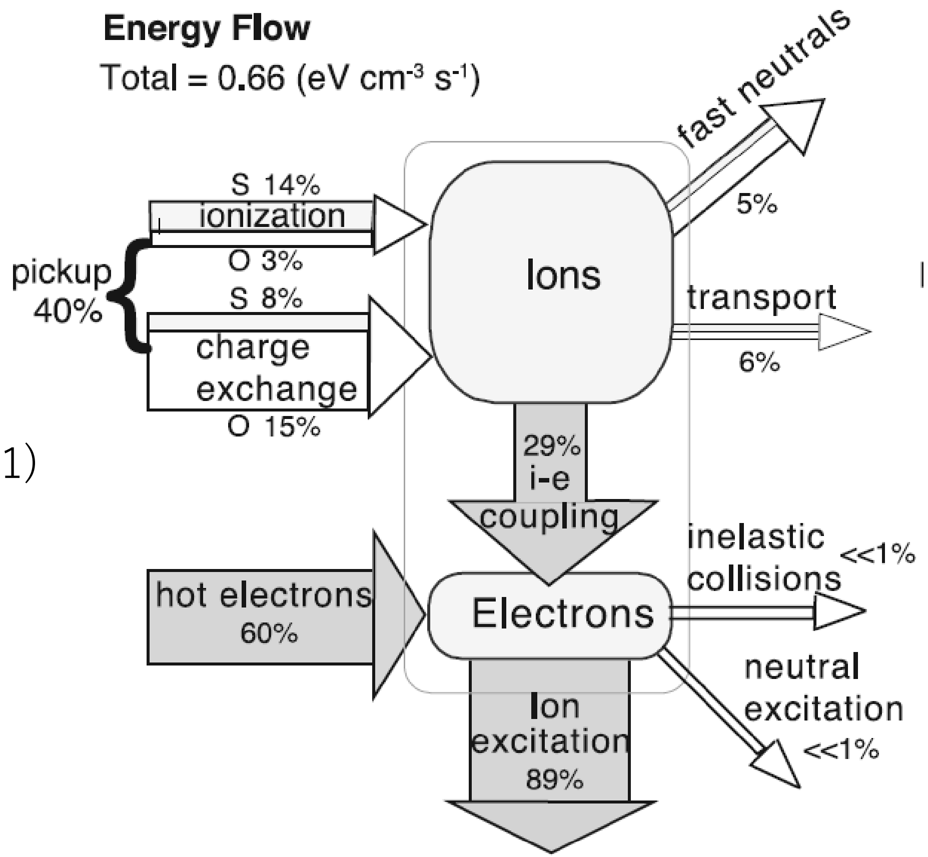
~2x10^{-5} eV/s (20% of source) ~8x10^{-5} eV/s (80% of source) ~1x10^{-4} eV/s (loss)

Ambient hot electron (Th~200eV)

$$\frac{\partial T_h}{\partial t} = 0 \quad (2)$$

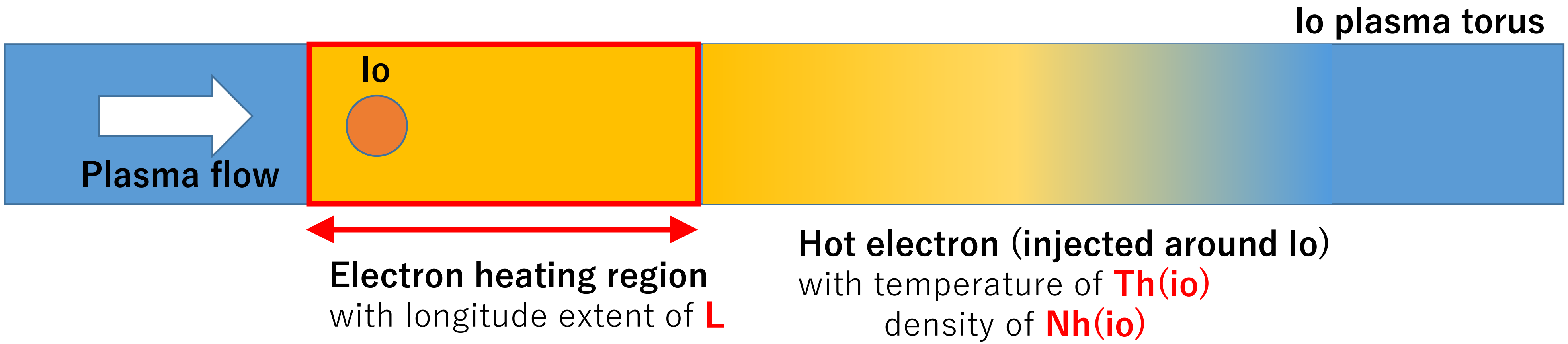
Hot electron injected around Io

$$\frac{\partial T_{h,Io}}{\partial t} = \sum_\beta \nu_e^{\beta/h}(T_\beta - T_{h,Io}) - \nu_e^{e/h}(T_{h,Io} - T_e) - \frac{2}{3}\sum_\beta \rho_\beta n_\beta \quad (3)$$



Delemere & Bagenal (2007)

Emission model of Io plasma torus



Procedure

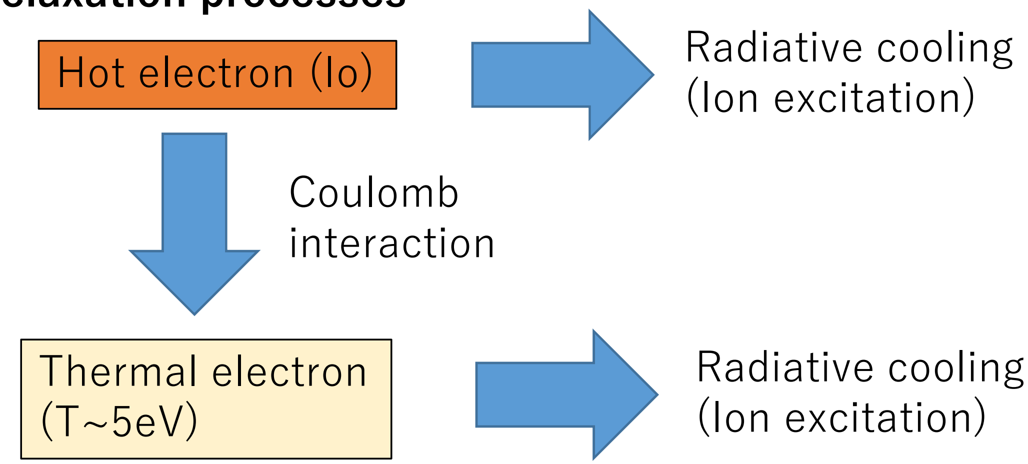
(1) Equilibrium Io plasma torus
with typical plasma parameters
(density, temperature, composition)

(2) Inject hot electron in the "heating region"

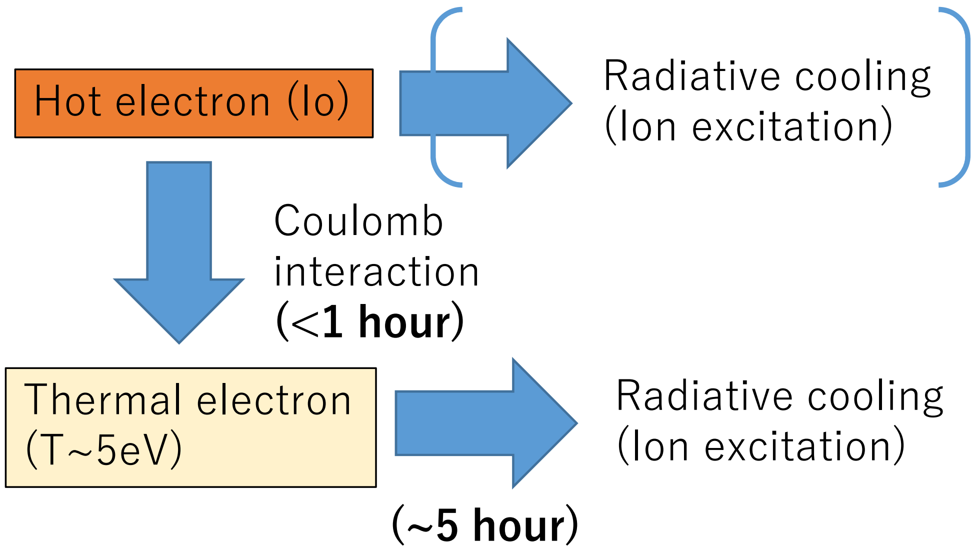
(3) Solve relaxation process
to find electron temperature distribution

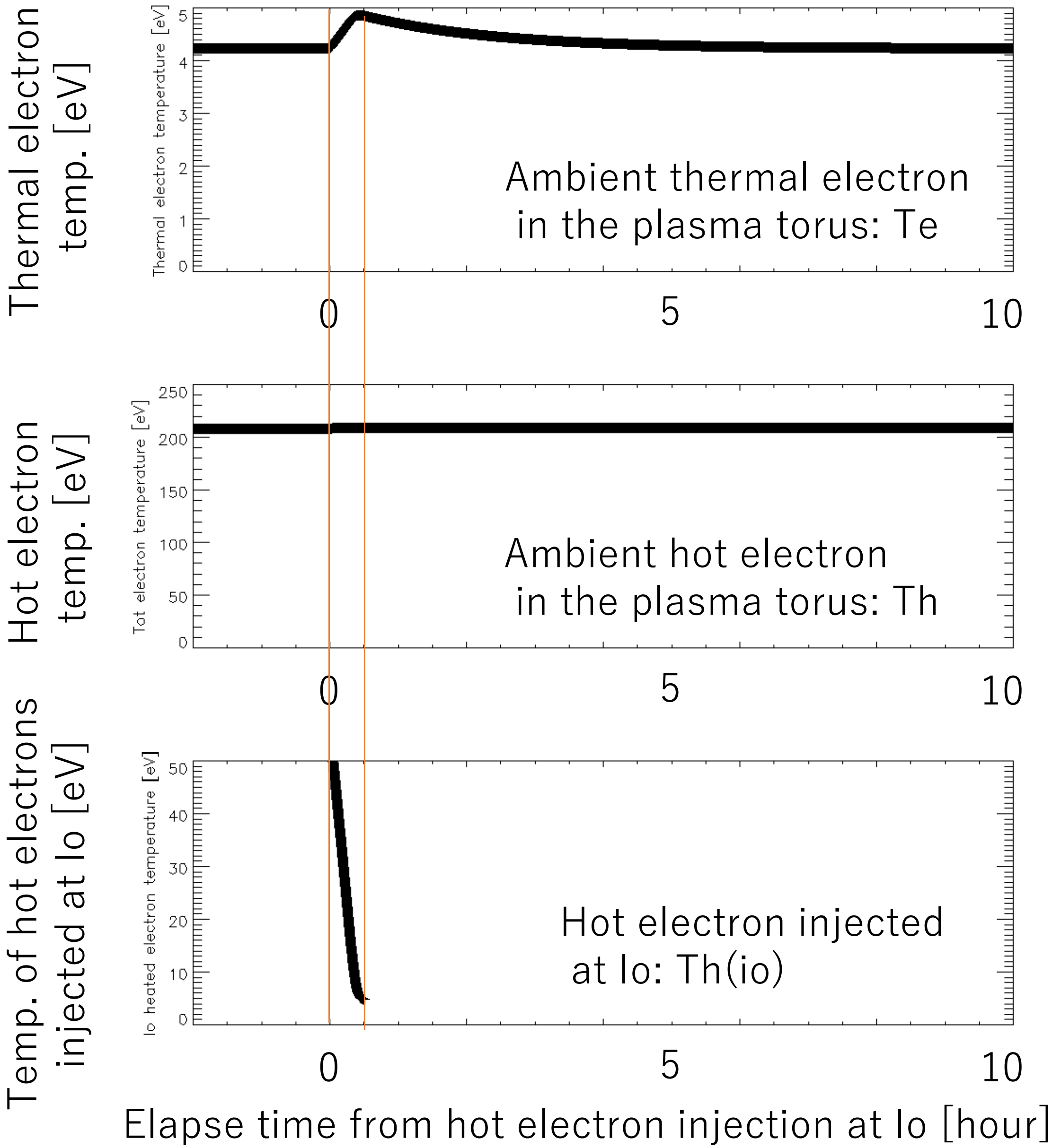
(4) Model emission distribution
& comparison with the HISAKI observation
(SII 76.5nm, SII 126nm)

Relaxation processes



Example of electron temperature change





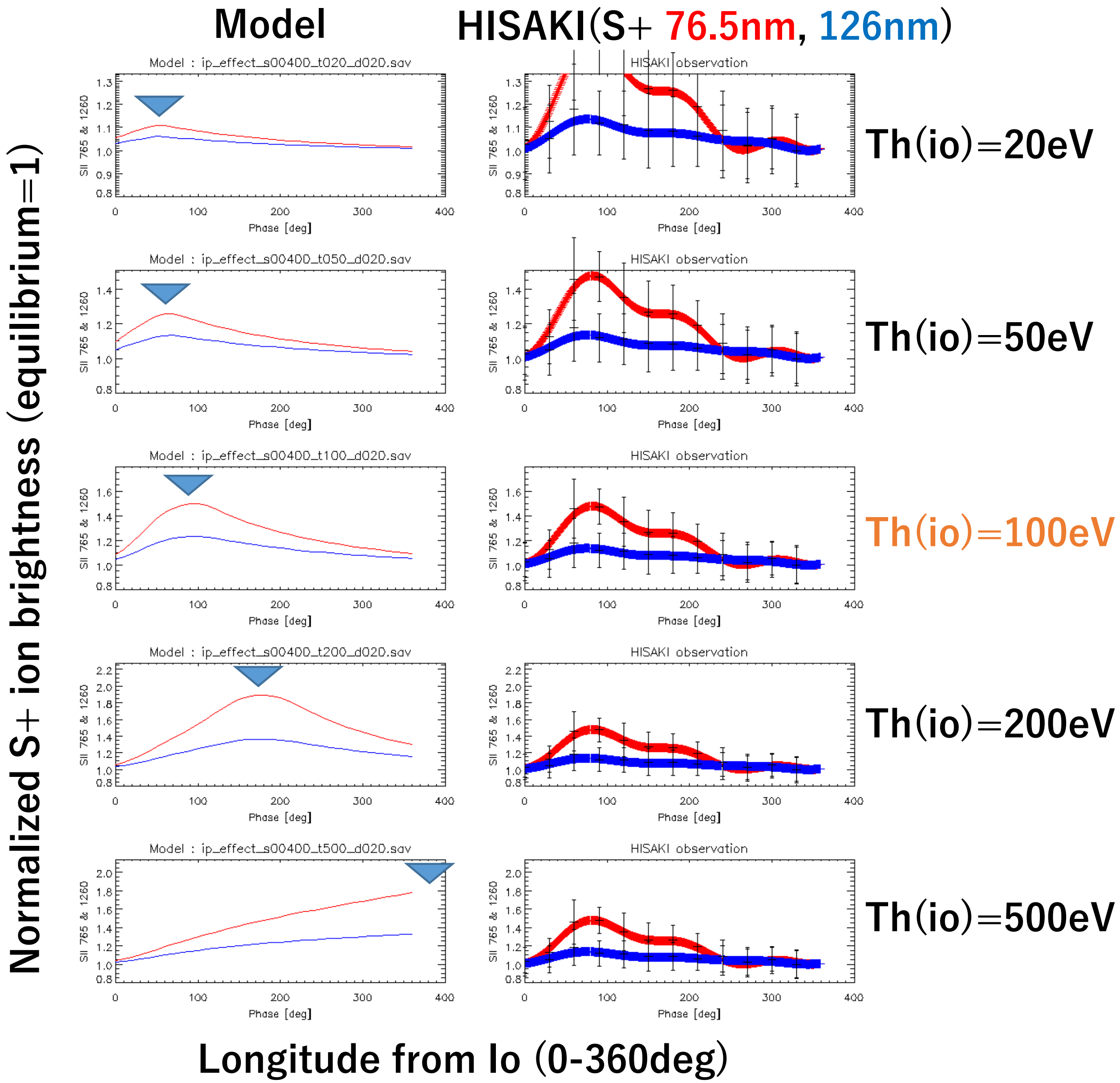
Parameters of hot electron injected at Io

Th(io) = 50eV

Nh(io) = 30/cc (1% of ambient plasma)

Width of heating region: $L = \pm 8R_{IO}$

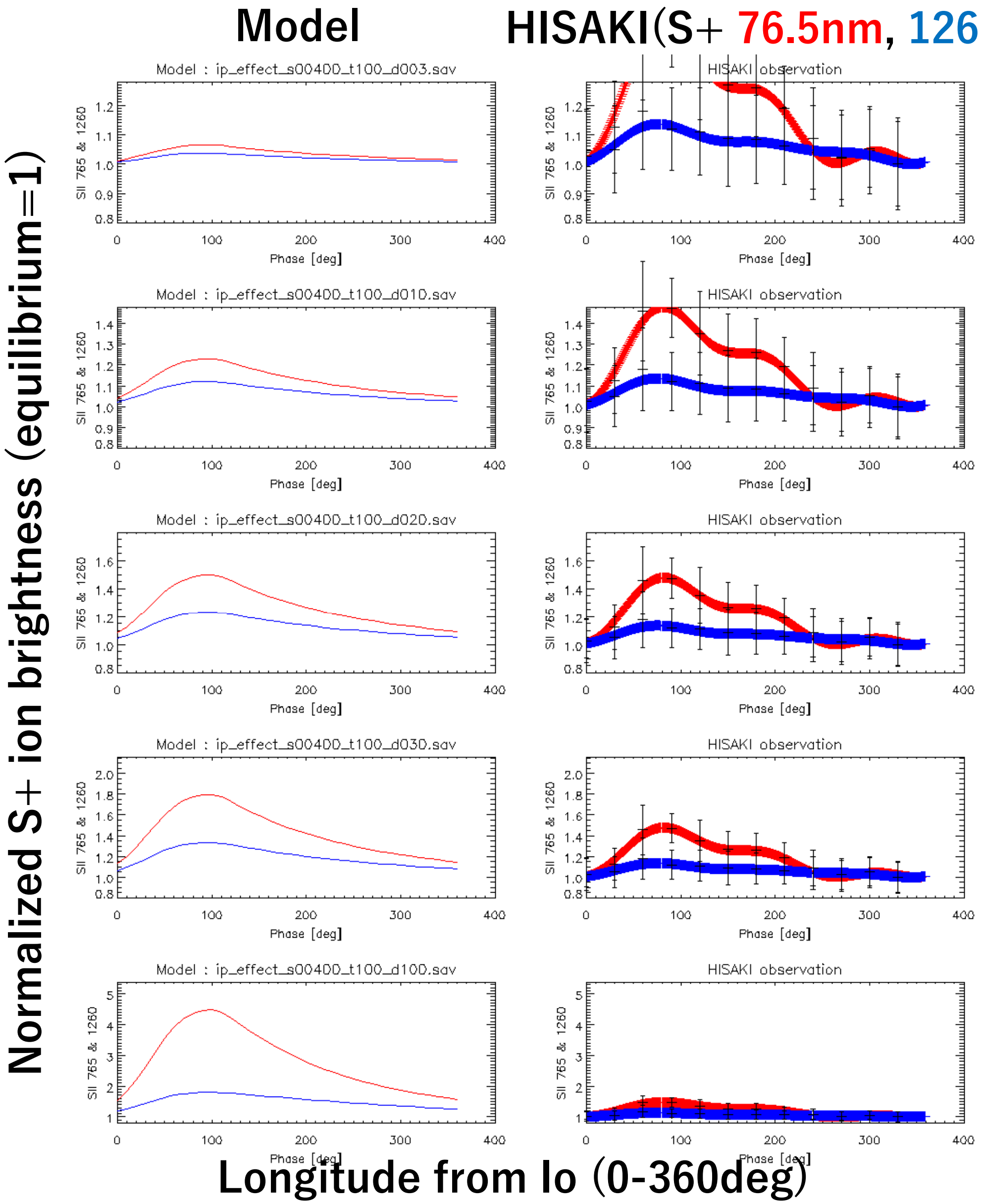
Th(io) dependence



Fixed parameters
- **L=** ±**8R$_{IO}$** (Io's corona)
- **Nh(Io) = 20/cc**
  (1% of ambient electron)

- Longitude at peak brightness depends on temperature of injected hot electron
- This corresponds to cooling time of the injected electron
- **Th(io)~100K**

Nh(io) dependence



Nh(io)=3/cc (0.1%)

Nh(io)=10/cc (0.3%)

Nh(io)=20/cc (0.6%)

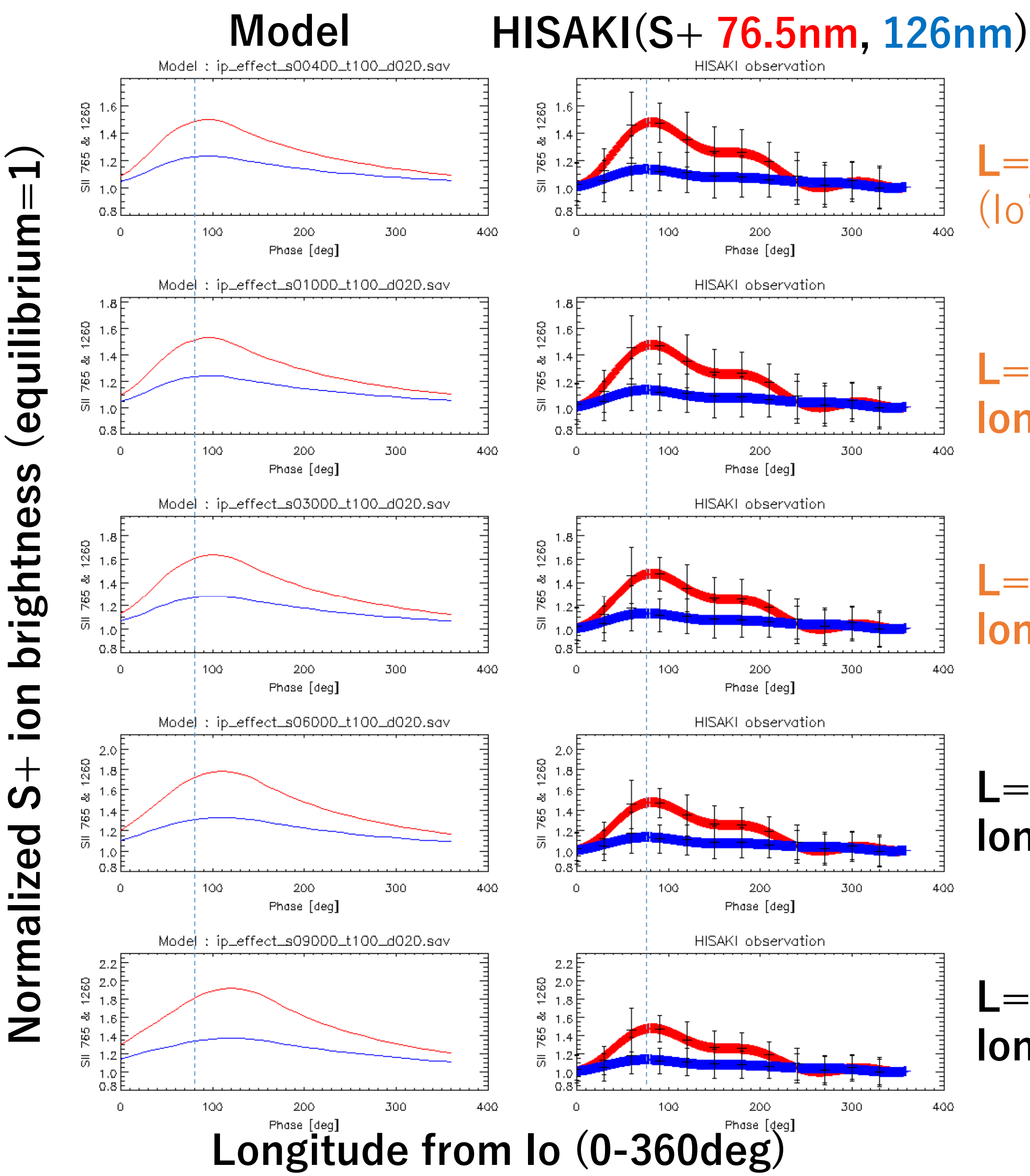
Nh(io)=30/cc (1%)

Nh(io)=100/cc (3%)

Fixed parameters
- **L= ±8R_{IO}** (Io's corona)
- **Th(Io) = 100 K** (x20 of ambient electron)

- Brightness and ratio of two wavelengths strongly depends on density of injected hot electron
- **Nh(io)~20/cc**

L(heating region) dependence



$L = \pm 8R_{IO}$ (Io's corona)

L=10deg longitude

L=30deg longitude

L=60deg longitude

L=90deg longitude

Fixed parameters
- **Nh(io) = 20/cc**
- **Th(Io) = 100 K**

- Model is not so sensitive to 'L'.
- Longitude at peak brightness has weak dependence on 'L'.
- Longitudinal extent of the heating region is **less than ~30deg**

Summary

- Local electron heating downstream of Io was found from the Voyager and HISAKI observation. Electron heating mechanism is still not resolved.
- Here, we developed an emission model of Io plasm torus associated with the Io phase effect to assess

  (1) longitudinal extent of the heating region

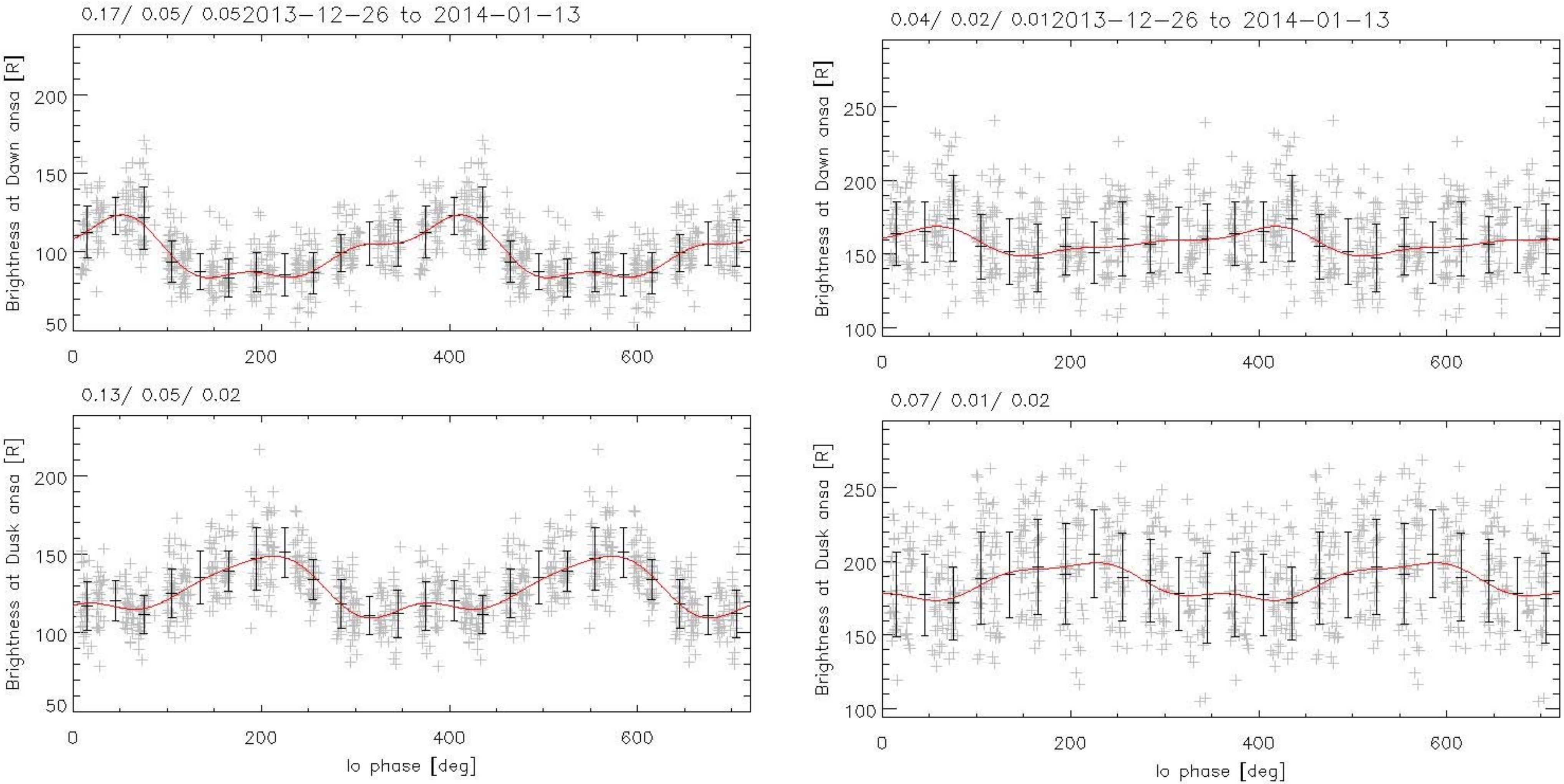
  (2) temperature and density of electrons heated

Comparison of the model result with the HISAKI observation suggests

- **Th(io) ~ 100K, Nh(io) ~ 20/cc** <--> Th=200eV, Nh=30/cc
- This could contribute a few tens % of total energy budget in the plasma torus
- Longitude extent of heating region is less than 30 deg.

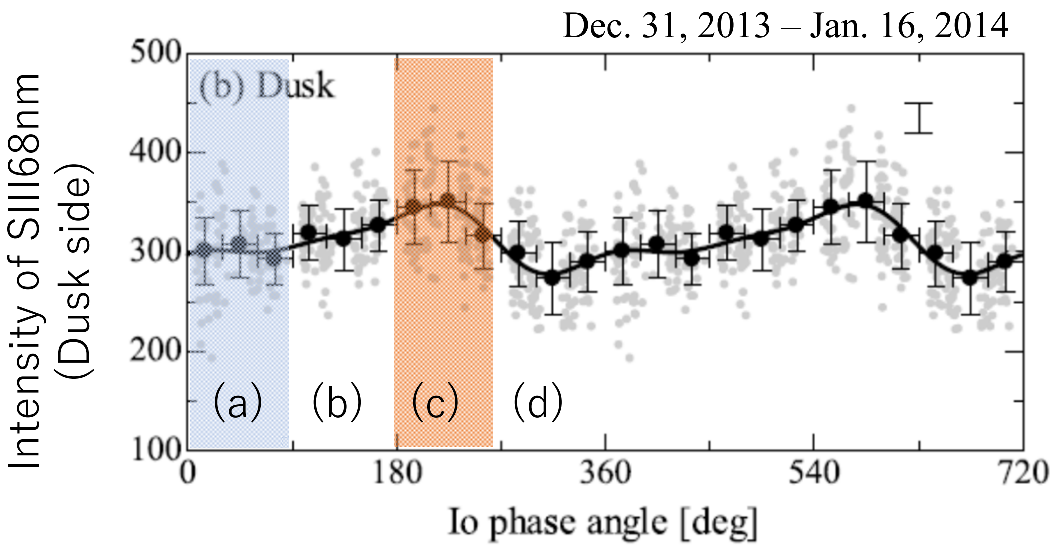
Future work: Theoretical estimation of Th(io) & Nh(io)

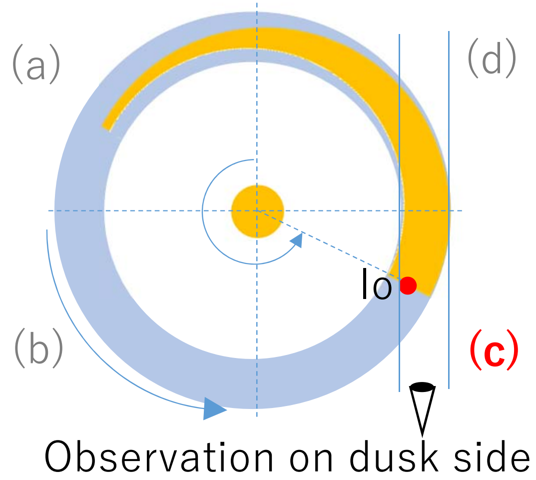
Io phase dependence SII 765A & 1260A



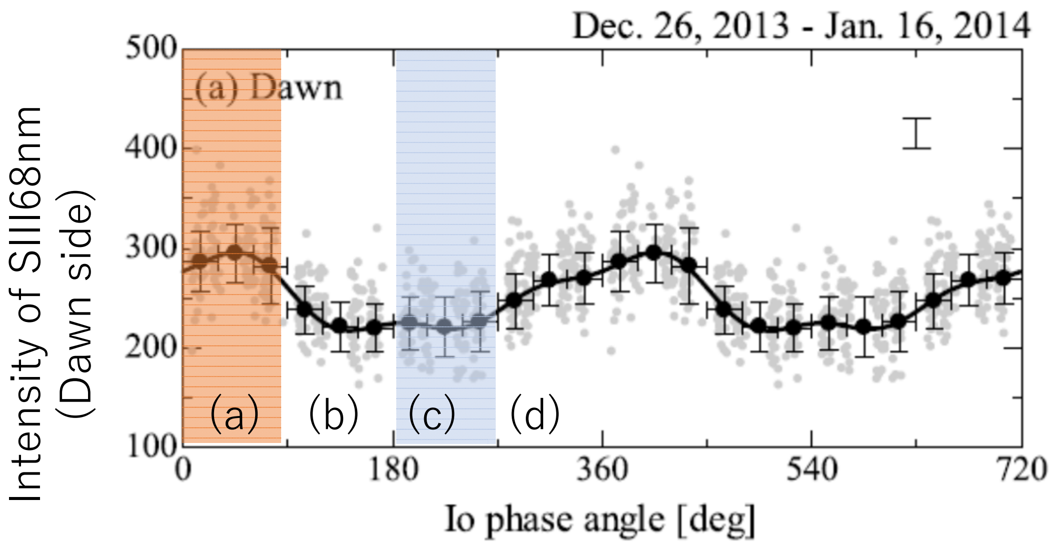
Io phase dependence

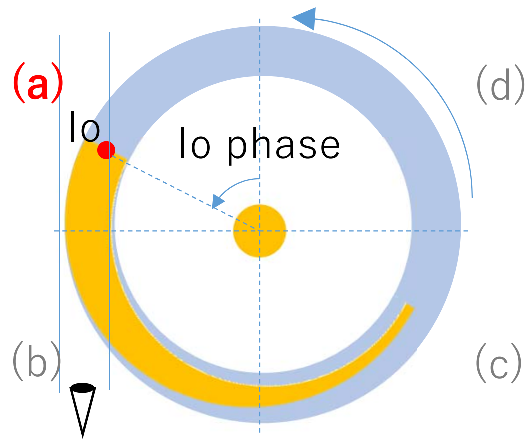
[Tsuchiya et al. 2015]





- Brightness of IPT enhances downstream of Io
- Consistent with the Voyager result





Increase in hot electron population just downstream of Io and fast cooling of the electron (2-6 hours) accounts for the Io phase dependence of the torus brightness.

Spectral analysis

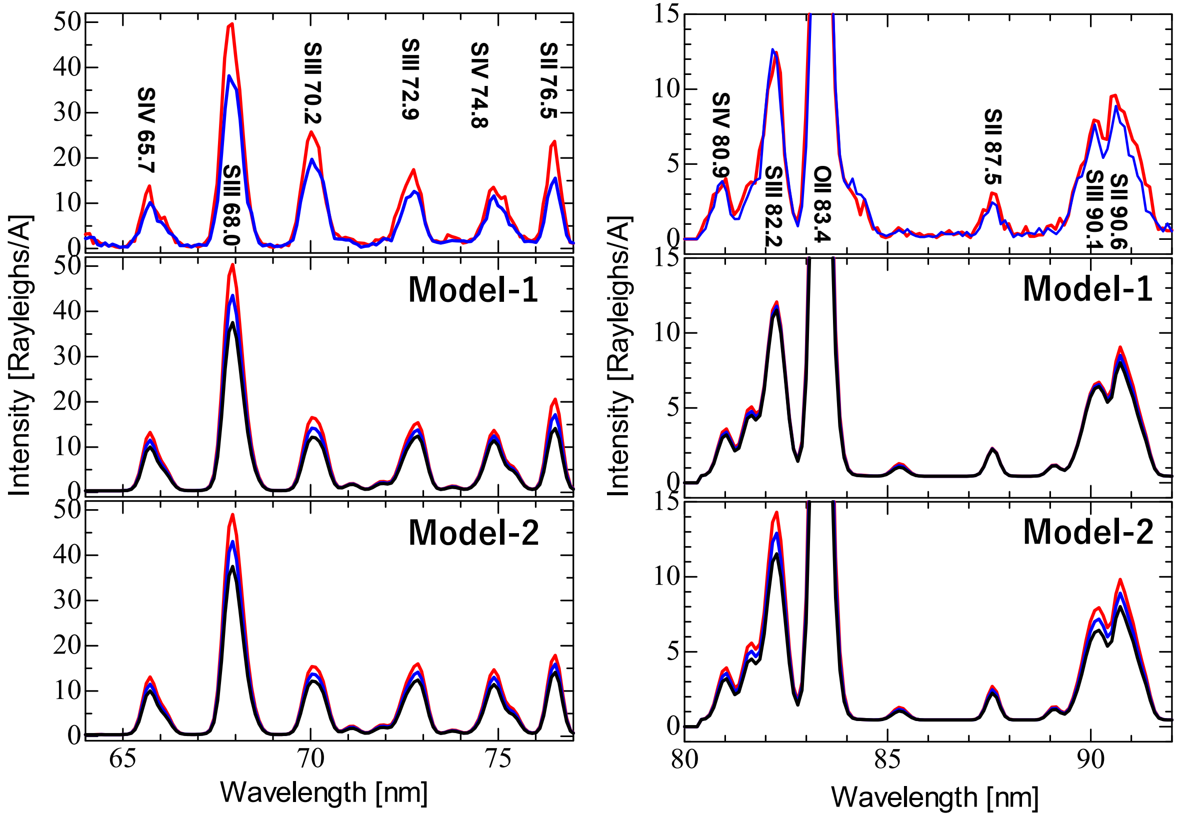
Thermal electron temperature vs Hot electron population

[Tsuchiya et al. 2015]

Model spectra $I[R]=10^{-6}\int_{LOS} A_{ji}\, f_j(T_e, n_e, f_{he})\, n_{ion}\, dl$

(Two electron temperature model based on CHANTI Ver7.1)

- A_{ji} The Einstein coefficient
- n_e Electron density
- f_{he} <u>Hot electron fraction</u>
- f_j Ion fraction in the state j
- T_e, <u>Thermal electron temp.</u>
- n_{ion} Ion density



Observation at dawn side

Red: just downstream of Io

Blue: far downstream of Io

Model spectra (T_e=4.3eV)
f_{he}=1.0%
f_{he}=1.7%
f_{he}=2.5%

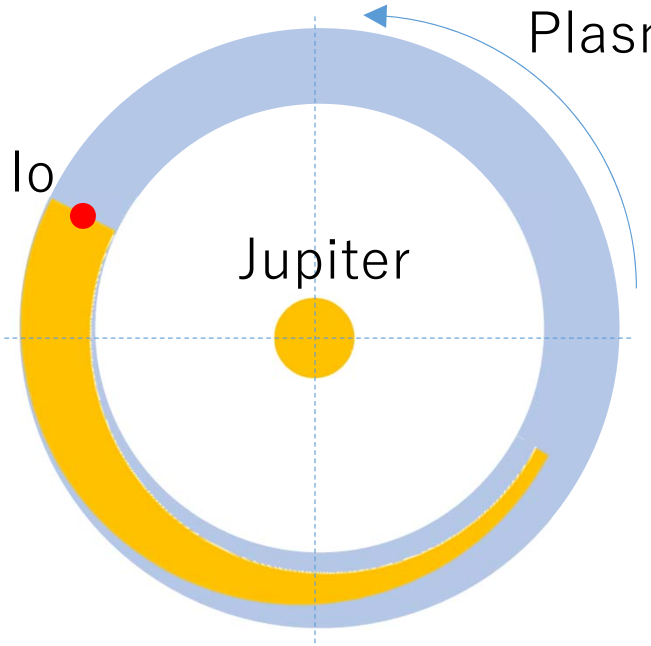
Model-1
(fixed thermal electron temperature)

Model spectra (f_{he} = 1.0%)
T_e=4.3eV
T_e=4.5eV
T_e=4.7eV

Model-2
(fixed hot electron fraction)

Observation is consistent with model-1 and explained by hot electron population.

Problems of the previous analyses

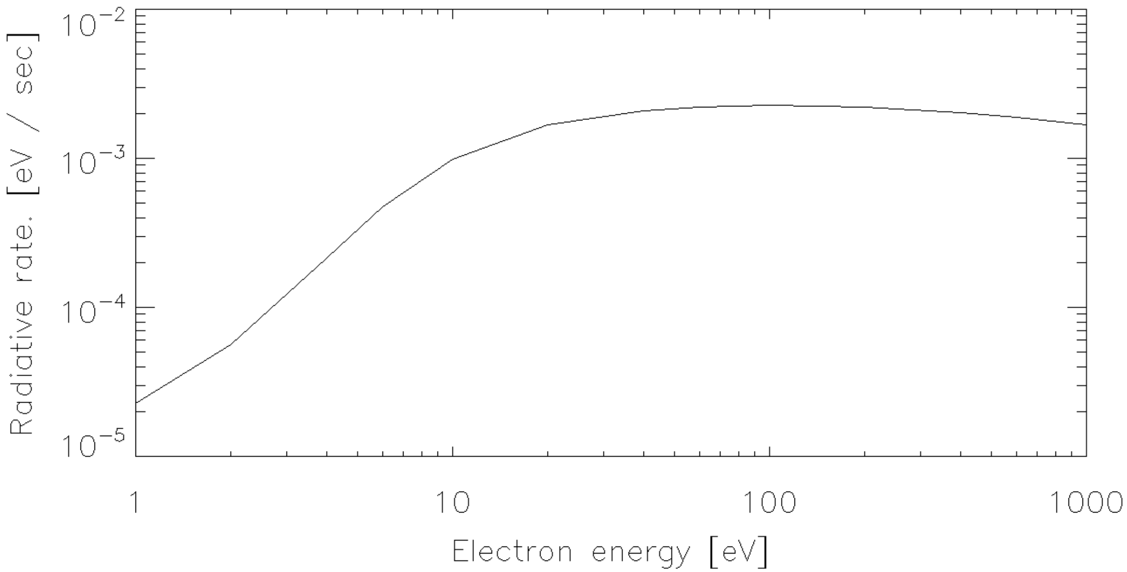


Is enhanced emission region extended behind Io related with

- Longitude extent of the heating region ?

  and / or

- Relaxation time scale of hot electron in co-rotating plasma flow in the plasma torus ?



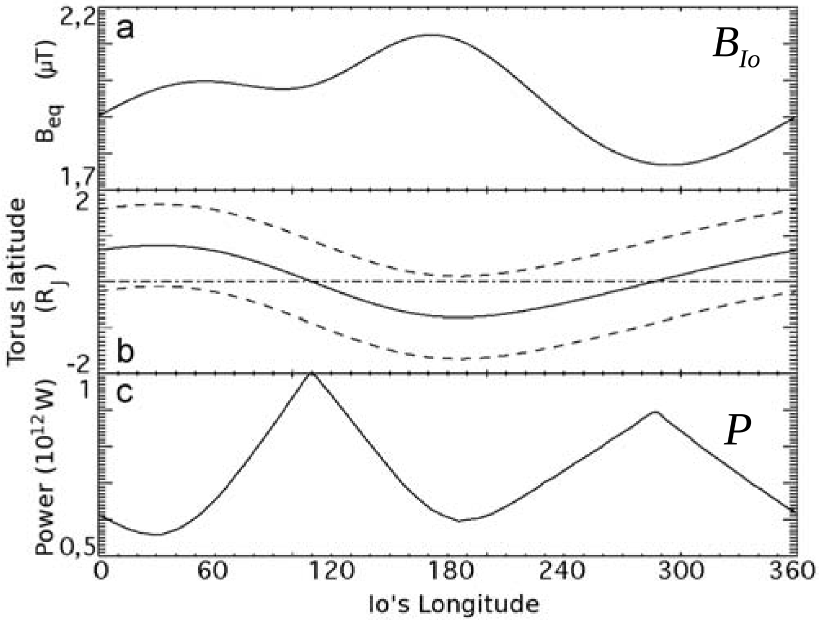
Emission rate from plasma in Io plasma tous
(Typical plasma composition & CHIANTI v8.0)

EUV spectroscopy is not sensitive to electron temperature for > 40eV

Possible mechanisms of the hot electron production
(1)Energy from trans-hemispheric electron beam

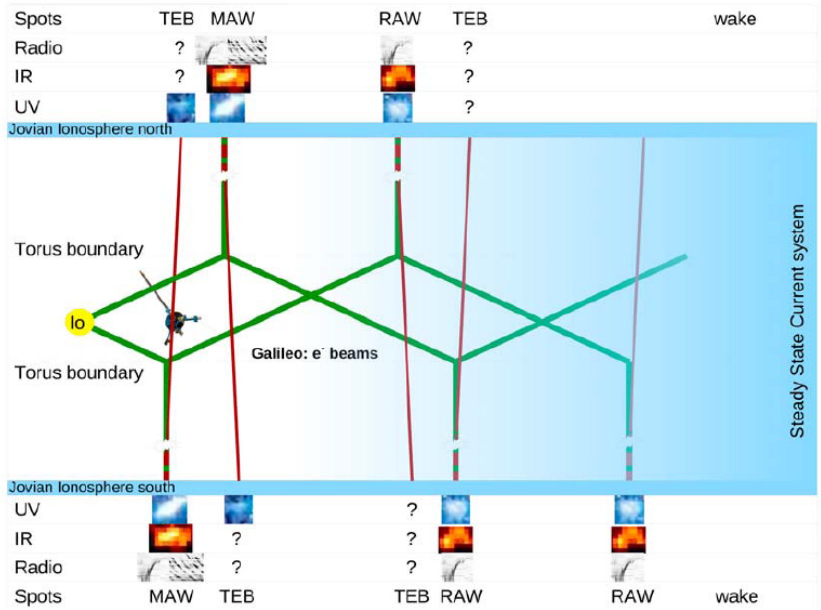
Power generated at Io

$$E_{Io} = -V_{Io} \times B_{Io}$$
$$J = 2R_{Io}E_{Io}\Sigma_A \quad \left(\Sigma_A = \sqrt{\frac{\rho_{Io}}{\mu_0 B_{Io}^2}}\right)$$
$$P = 4R_{Io}^2 E_{Io}^2 \Sigma_A \approx 1TW$$



Hess et al. 2008, 2011

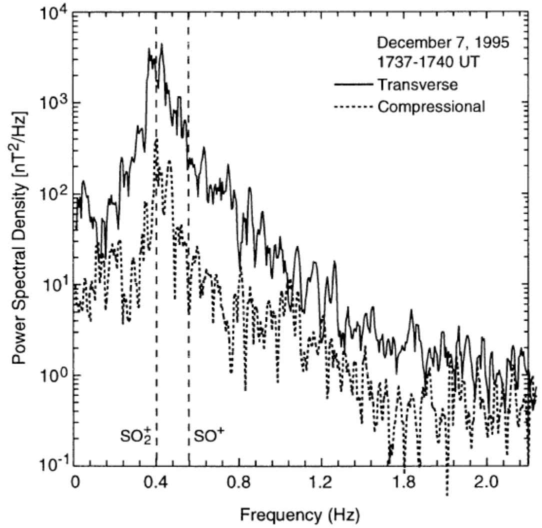
- Possible scenario
  - Alfven wave generated at Io and transfer to low altitude along the field line
  - Electron acceleration at low altitude and generate trans-hemispheric electron beam (TEB)
  - Electron heating in IPT during the passage of the beam
- Based on energy transmission model by Hess+(2013), **several fresh electron beams are needed** to account for 140GW energy input to IPT.



Possible mechanisms of the hot electron production
(2)Energy from SO_2 pickup ion through ICW

	Source rate (/s) *1	Mass input rate (kg/s)	Pickup energy (eV)	Energy input rate(TW)
SO_2	8E+26(5%)	8.6E+01	1090	0.14
S	5E+27(32%)	2.7E+02	540	0.45
O	1E+28(63%)	2.7E+02	270	0.44
	100%	630kg/sec		1.0TW

*1: Based on the Galileo flyby of Io (J0) (Huddleston et al., 1998)



Ion cyclotron wave around Io by Galileo S/C (Russell et al. 2001)

Does pick up energy of SO2 transfer to hot electron efficiently ?