ひさき衛星がとらえた
衛星イオの火山活動変動

土屋史紀
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  2015年 : 火山活動に伴う変動
- イオ大気の成因及び大気散逸・イオン化過程

- エンセラダストーラス・エウロパ
- JUICE/RPWIによる地下海探査(氷殻)

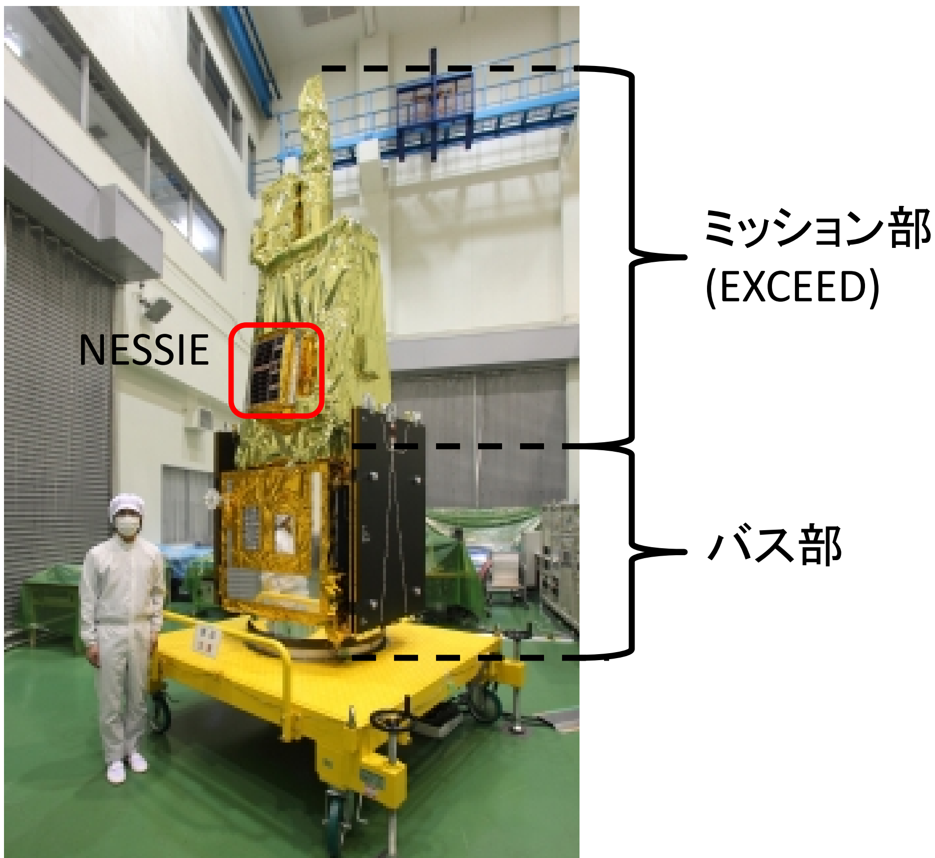
HISAKI衛星によるイオ火山活動観測

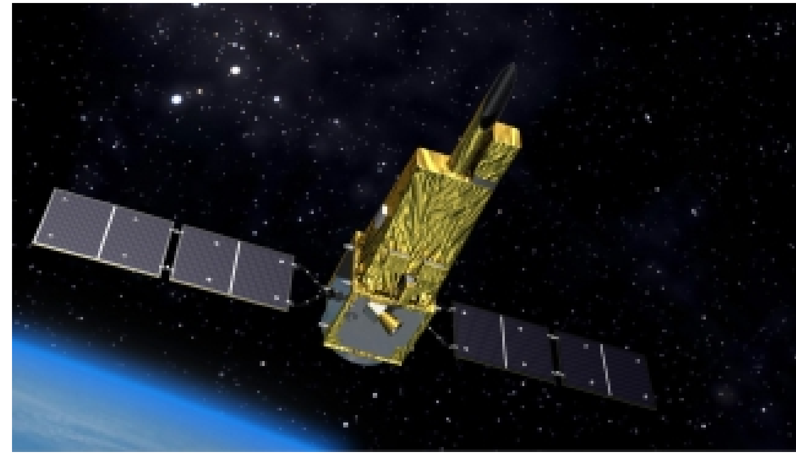
- イオの火山に関して観測から引き出せる量
  - イオからの散逸量総量
    - 中性原子密度(酸素)(古賀他,ポスター)
    - イオン密度の流出フラックス
  - 組成比(S/O等)
    - 大気の形成・大気の散逸過程が間に入る
  - これらの時間プロファイル

  - 積分サイエンス(微量成分の検出)

HISAKI衛星：概要

- Launch : Sep 14, 2013, Epsilon rocket
- Size：1m × 1m × 4m
- Orbit：950km × 1150km (LEO)
- Inclination: 31 deg
- Orbital period : 106 min





EXCEED：概要

(EXtreme ultraviolet spectrosCope for ExosphEric Dynamics)

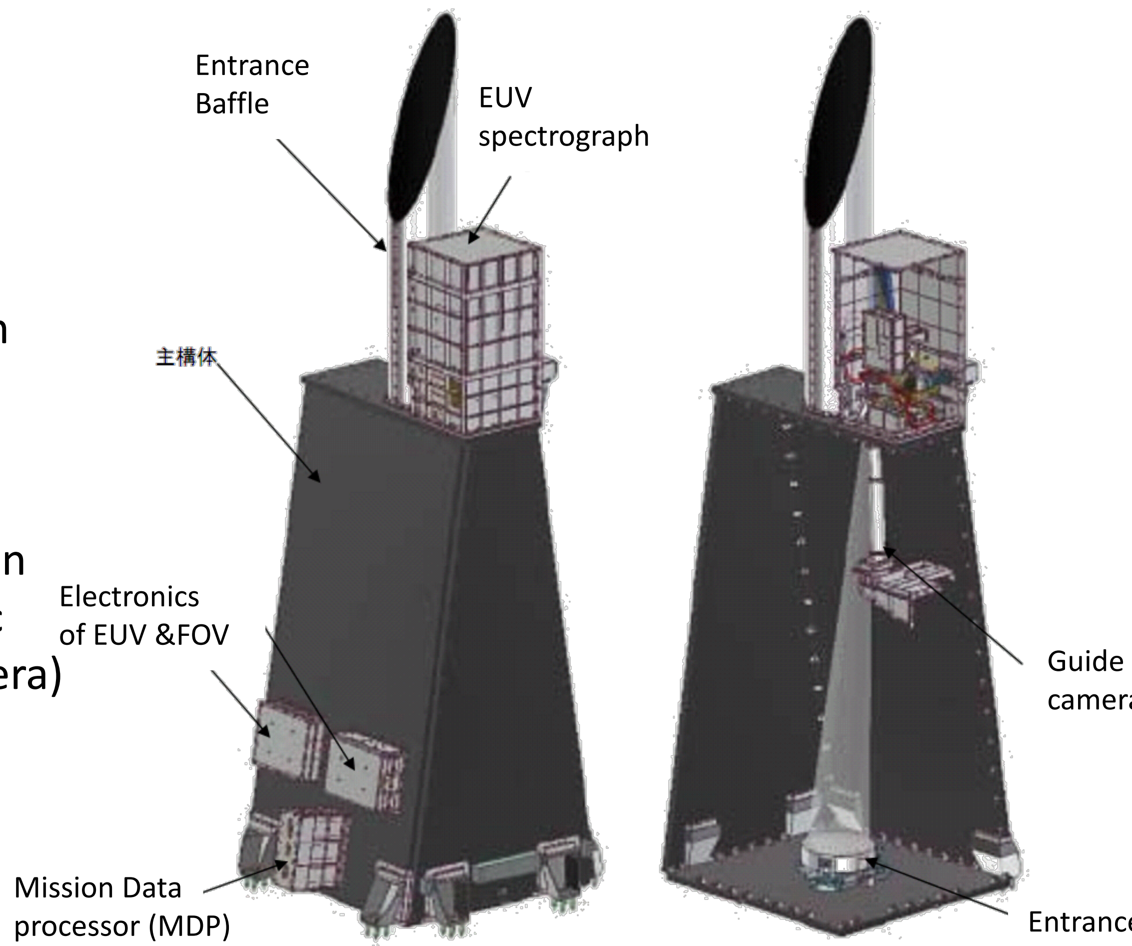
- An earth-orbiting Extreme Ultraviolet (EUV) spectroscopic mission
- EUV emissions from tenuous gases and plasmas around the planets
- Observation targets : Mercury, Venus, Mars, Jupiter, Saturn, and EUV stars

Major specifications

- Wavelength range: 55-145nm
- Spectral resolution: 0.4-1.0nm
- Spatial coverage ~370 arc-sec
- Spatial resolution : 17 arc-sec

- Pointing accuracy : ±2 arc-min
  (It improves to be ±2arc-sec
  with using a FOV guide camera)

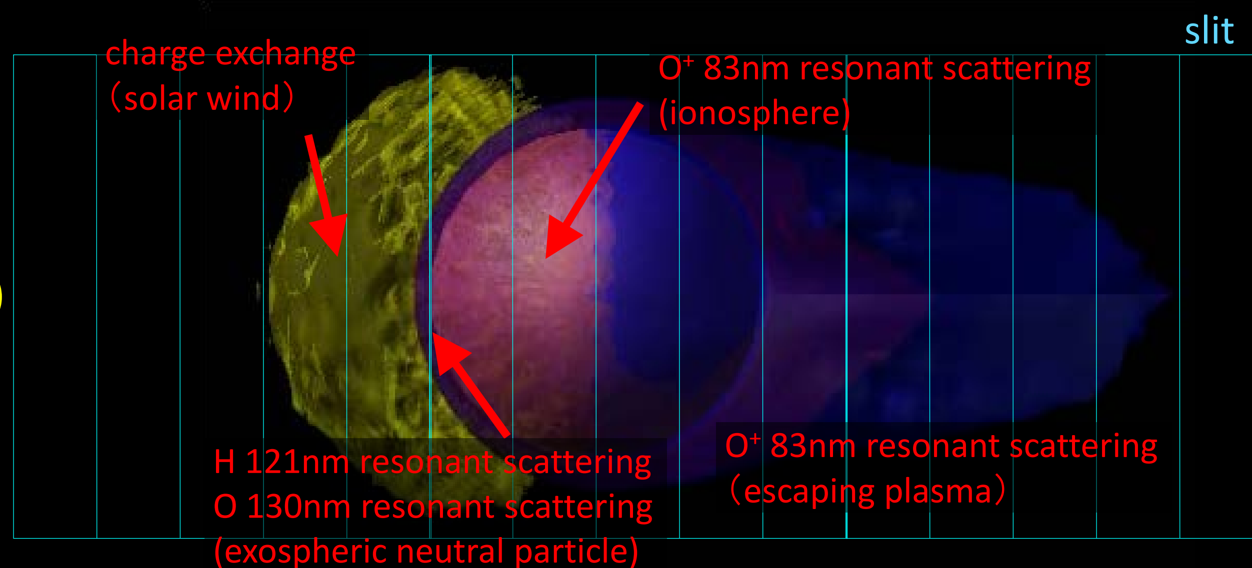
Yoshioka et al. (2014)
Yoshikawa et al. (2014)
Yamazaki et al. (2014)



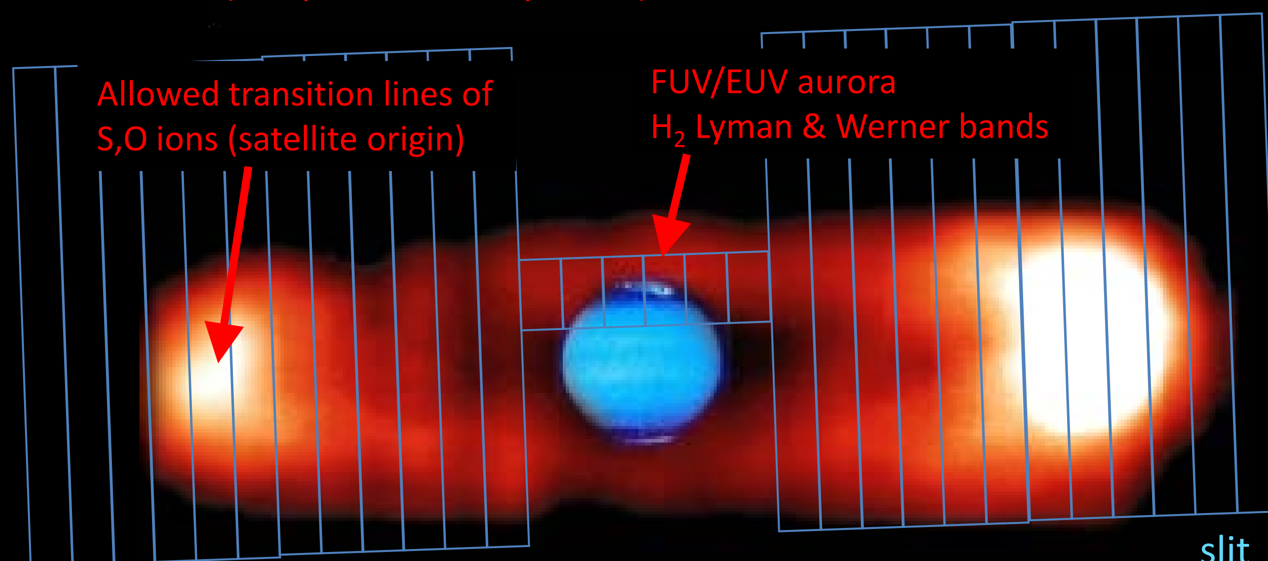
HISAKI(SPRINT-A)/EXCEED

HISAKI衛星：目的

Simultaneous observation of
exosphere, ionosphere,
and escaping plasma
down the tail
(Venus, Mars, and Mercury)

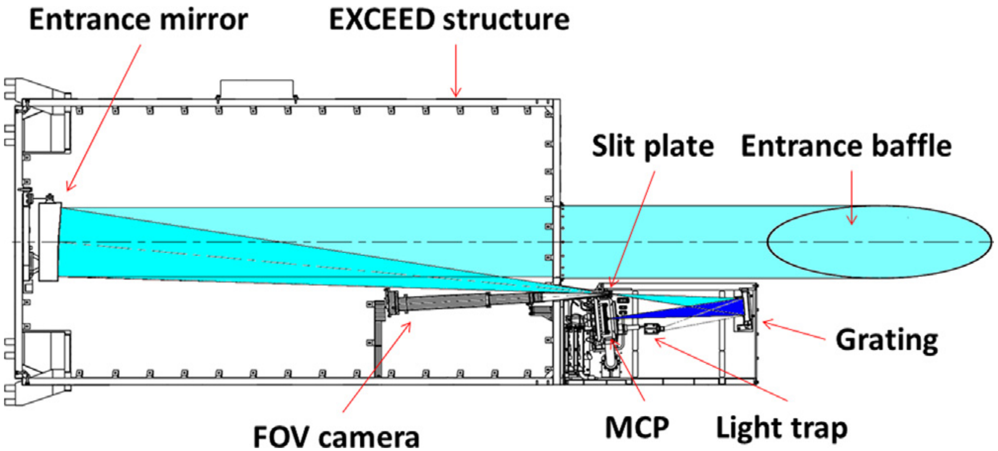


Aurora and gas torus
(Jupiter and Saturn)

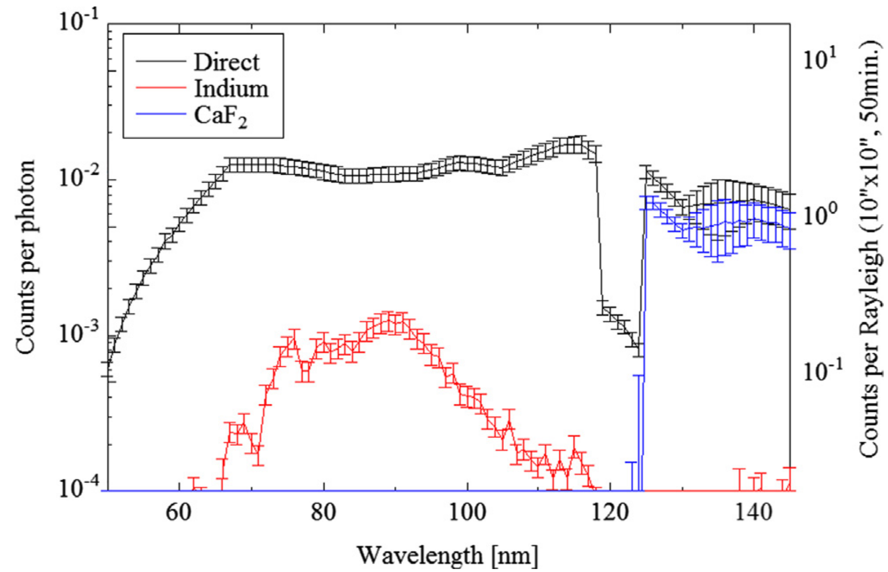


Io plasma torus : Cassini/UVIS
Jupiter's UV aurora : HST/WFPC2

極端紫外観測装置



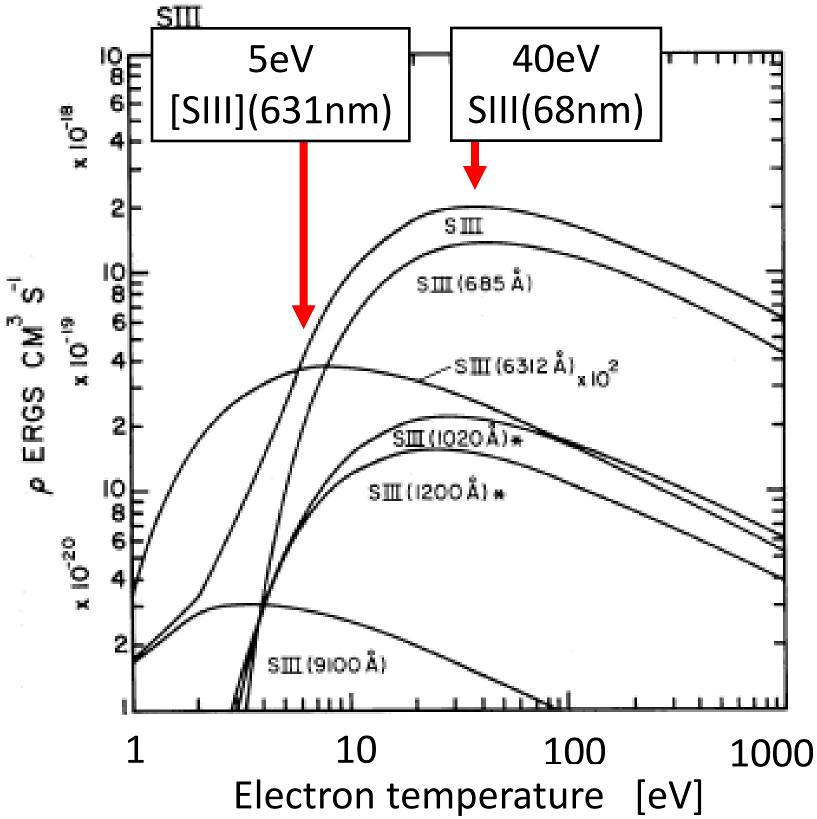
The optical layout of EXCEED.
The photons are incident on the entrance mirror through the baffle and collected on to the slit with its reflection angle of 5.4deg. The FOV guiding camera monitors the reflected light from the slit plate. Light that passes through the slit and filter is diffracted by the grating. Finally an MCP detector converts the photons into electron events.



Over all sensitivity of EXCEED for 3 types of filters as a function of wavelength. The estimated counts per unit brightness accumulated over a half orbital period can also be seen on the right vertical axis.

Yoshioka et al. (2014)

EUV spectroscopy : Plasma diagnostic



Volume emission rate of S++ as a function of ambient electron temperature (Shemansky 1987)

EUV spectroscopy:

For each ion emission lines

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

A_{ji}: The Einstein coefficient

f_j : Ion fraction in the state j

T_e, n_e Temperature & density of electrons

n_{ion} Ion density

Plasma parameters

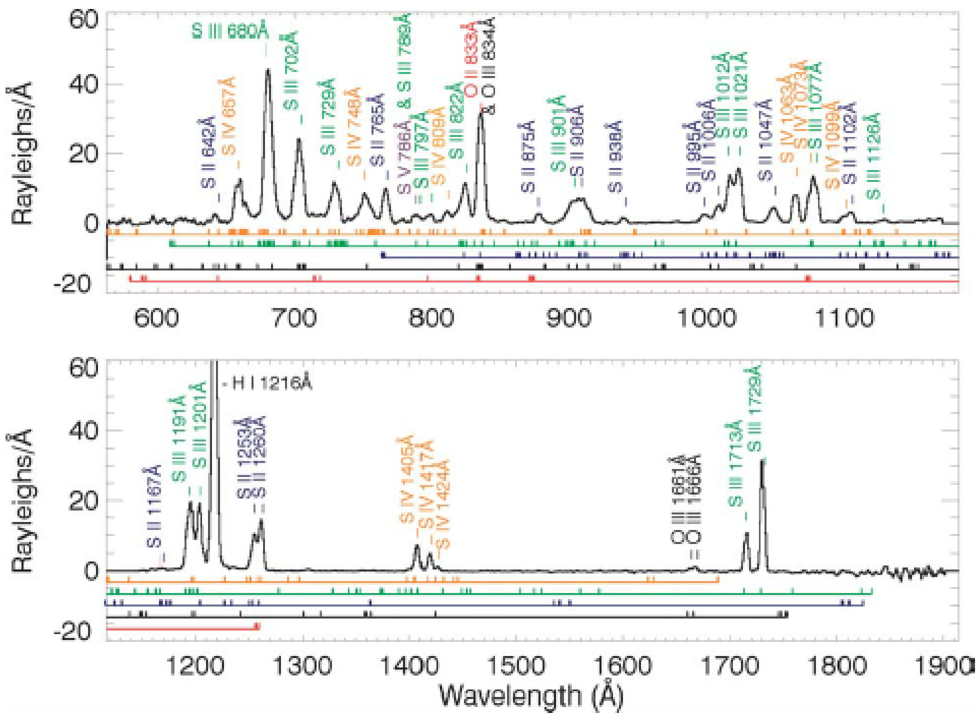
Ion and electron densities

Electron temperature

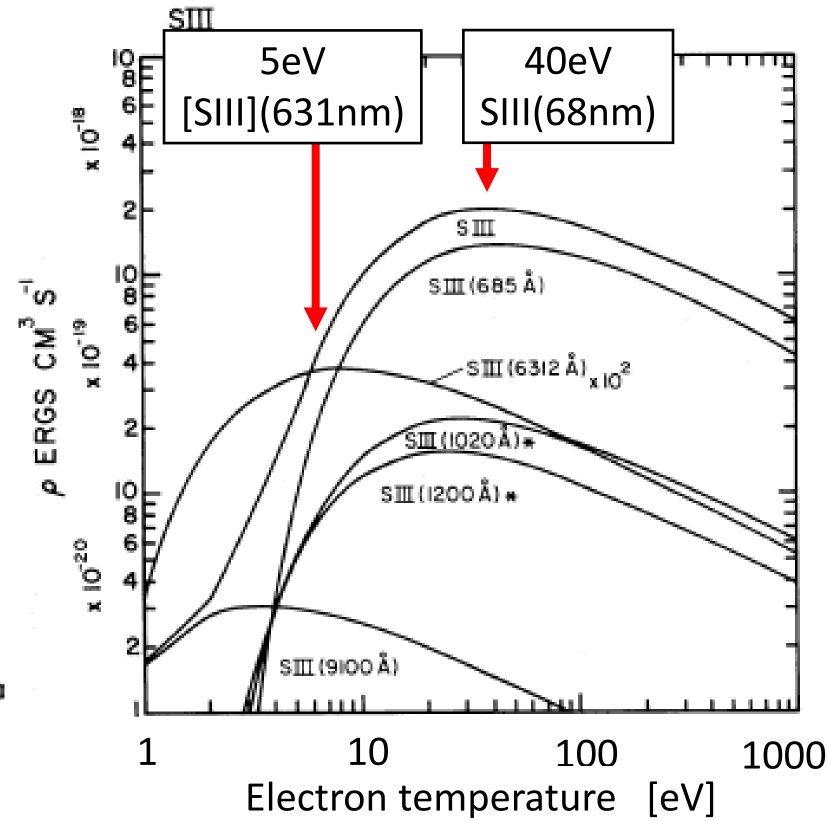
Hot electron fraction

Electron temperature and existence of hot electron (tens to hundreds of eV)

Observation of hot plasma



EUV-FUV spectra of Io plasma torus measured by Cassini/UVIS（Steffl et al. 2004）



Volume emission rate of S++ as a function of ambient electron temperature (Shemansky 1987)

EUV spectroscopy:

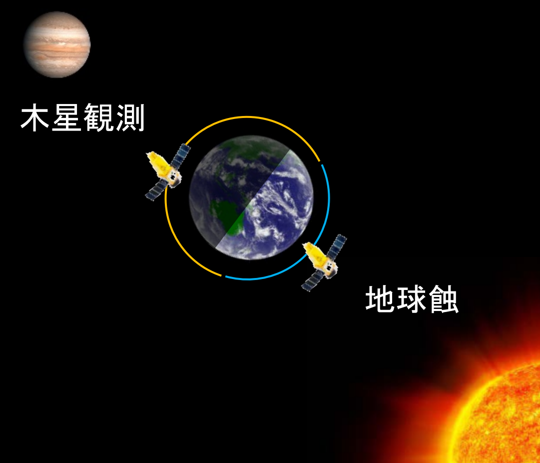
Densities of major ions in the Io plasma torus (S^{+},S^{2+},S^{3+}, & O^{+}+O^{2+})

視野ガイドカメラ

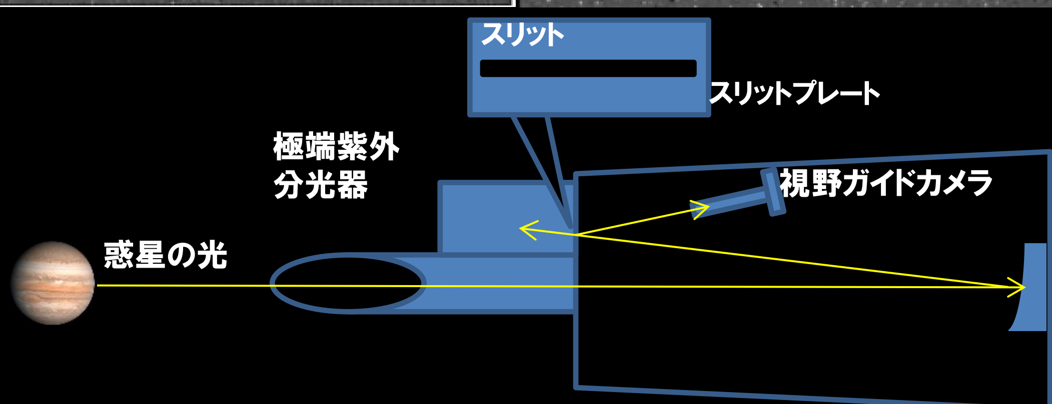
衛星バス部の指向精度(導入): ±2分角　→　±1秒角まで改善
視野ガイドカメラ:　観測対象をスリット内に導入
　　　　　　　　　　熱歪によるバス部-ミッション部間のアラインメント変化を補償

木星 (惑星追尾制御OFF)

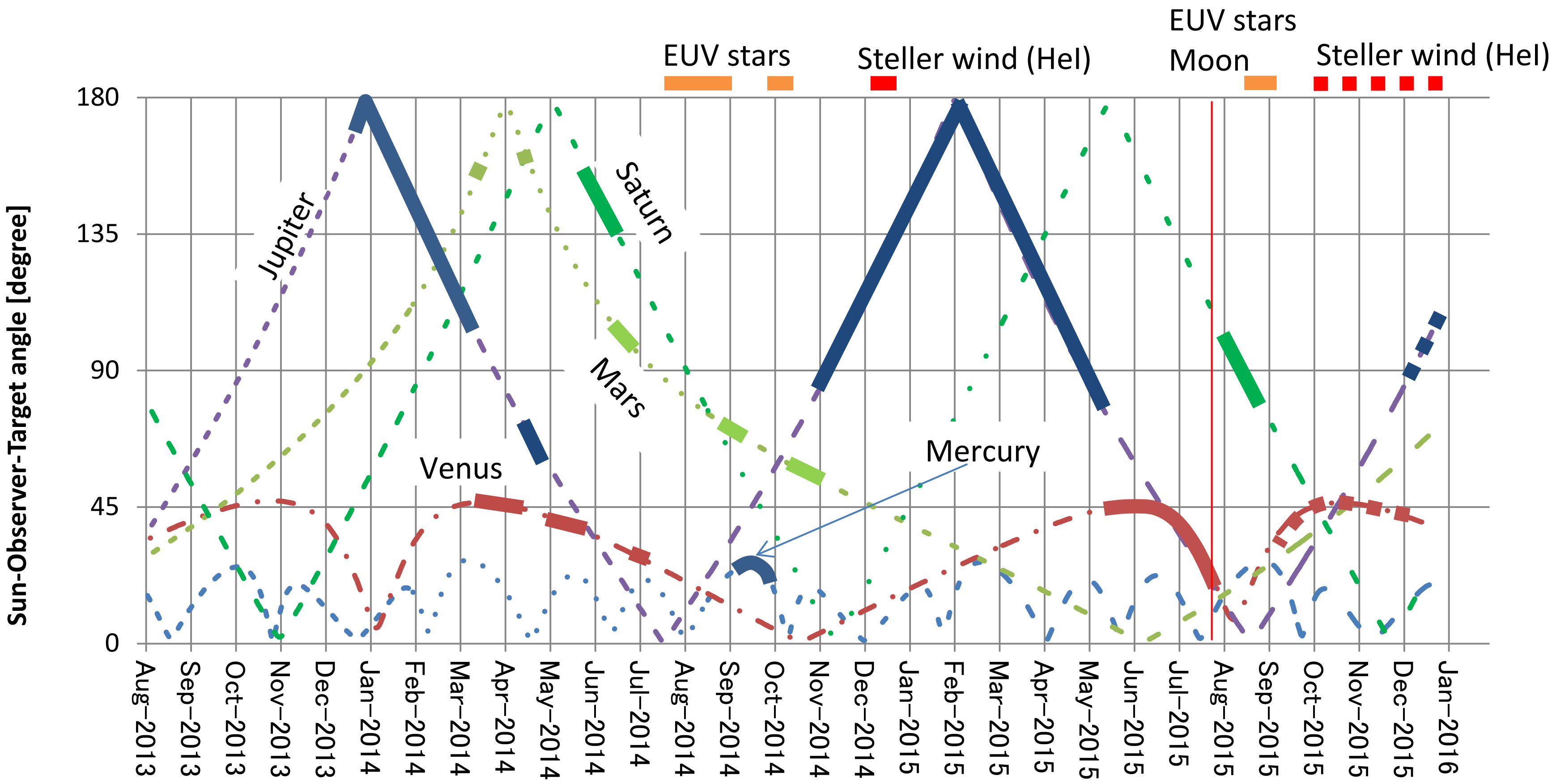
木星 (惑星追尾制御ON)



月 (追尾制御OFF)

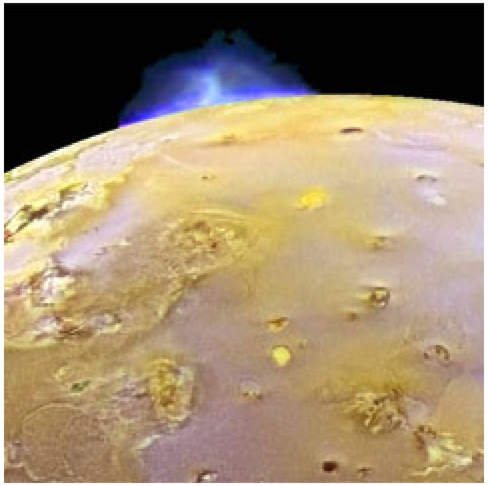


EXCEED：観測履歴と予定

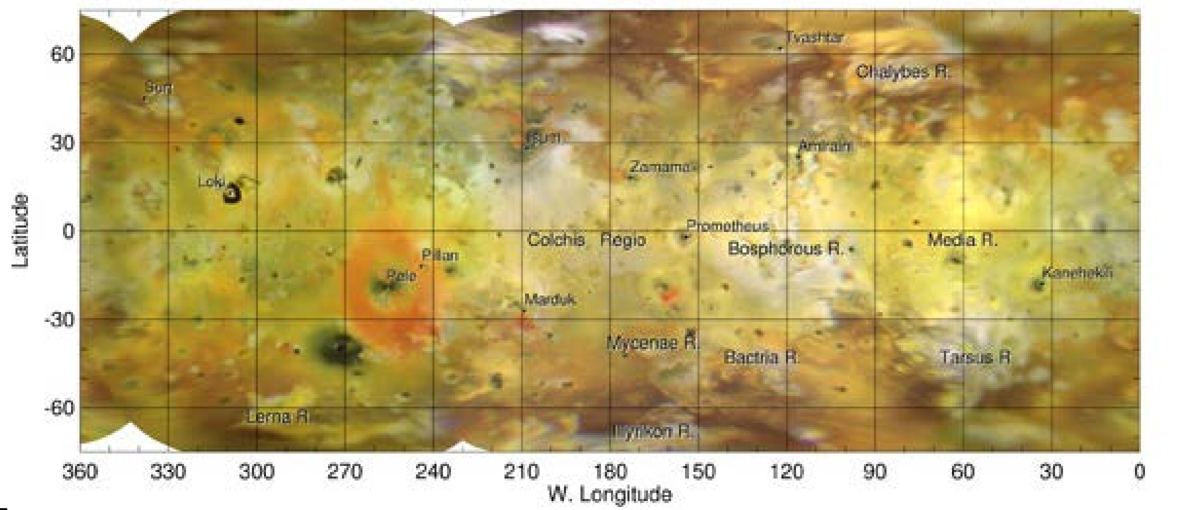


Jupiter :	Multi-instrument campaign
	Jan. 2014: HST , KitPeak, IRTF & GMRT
	Apr. 2014: X-ray (Chandra, XMM, Suzaku)
Venus :	VEX (Solar wind monitor)
Mars :	Comet Sinding Spring (19 Oct.)

Io: Satellite with active volcanos



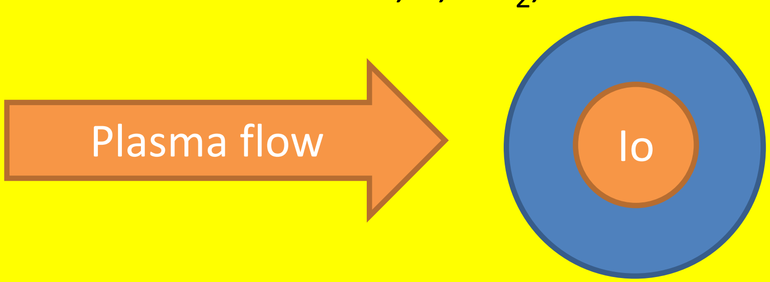
Galileo image of Io showing an erupting volcano on the limb (NASA/JPL)



Io's volcanic surface features based on Galileo photo (NASA/JPL)

Io plasma torus:
e^-, S^+, S^{2+}, S^{3+}, O^+, O^{2+}

(2) Neutral cloud
S,O, SO_2,SO

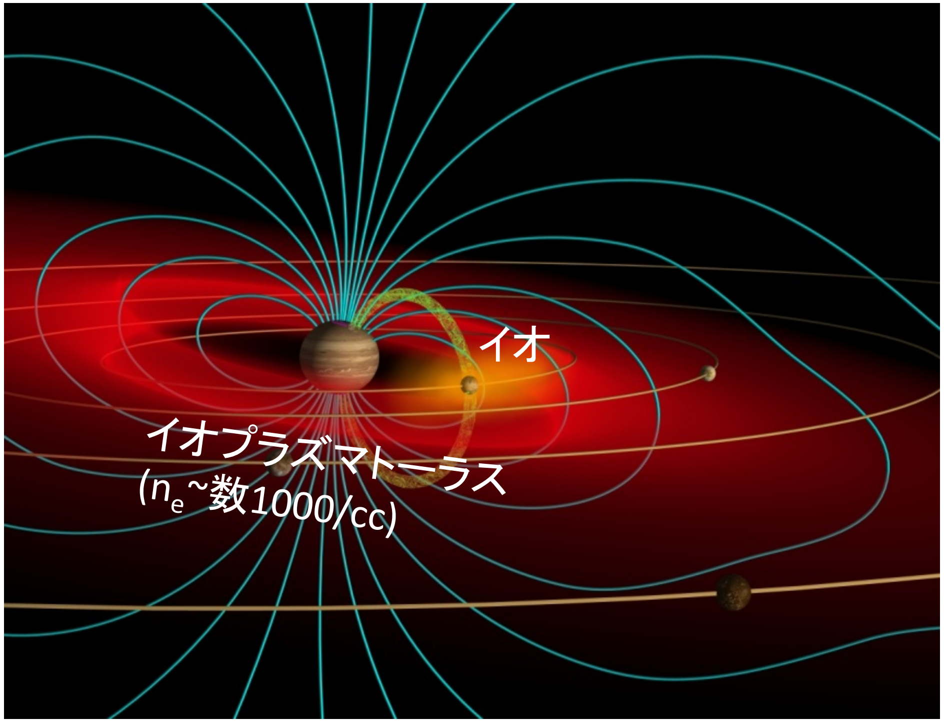


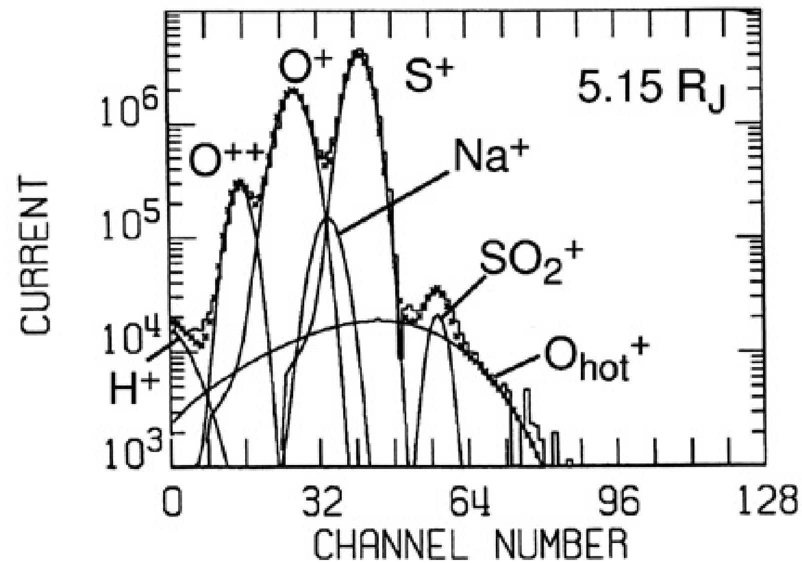
(1) Volcanic gas: SO_2,SO, S_2 (,NaCl)

(3) Ionization & change in ionization state
- Electron impact ionization
- Recombination
- Charge exchange

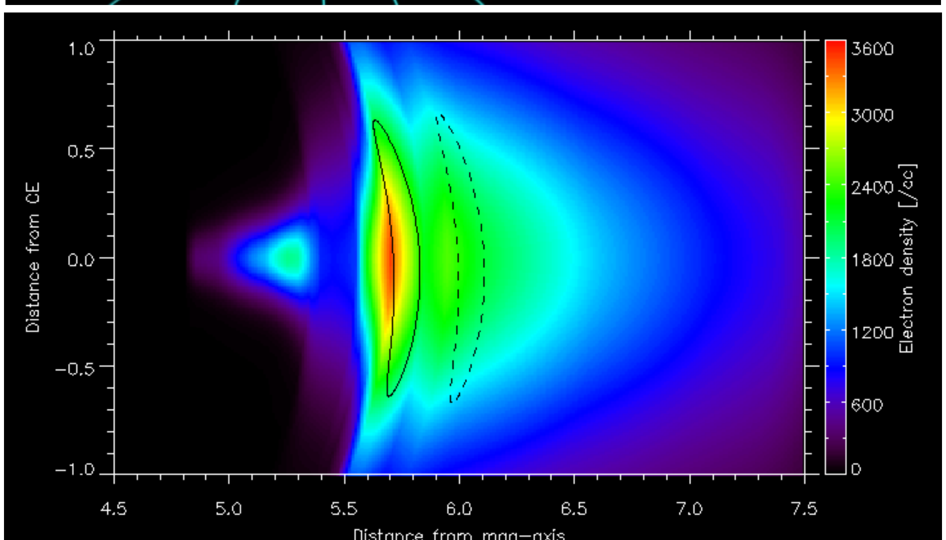
Rate of each chemical reaction depends on plasma density & temperature

Io plasma torus





Ion mass/charge distribution in the Io plasma torus measured by Voyager (Thomas et al. 2004)



イオから磁気圏への定常的なガスの散逸: 1 ton/sec
磁気圏イオンの90%の質量を供給

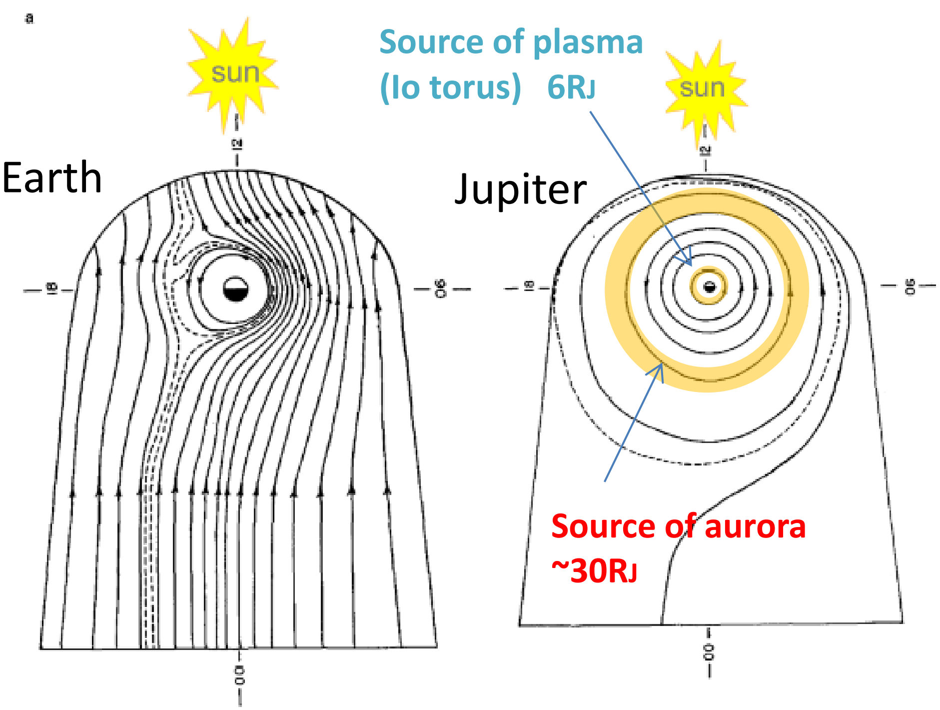
太陽系年代の積算量: イオ表層2km分の物質に相当
(Schneider & Bagenal 2007)

衛星イオ、プラズマトーラスと磁気圏

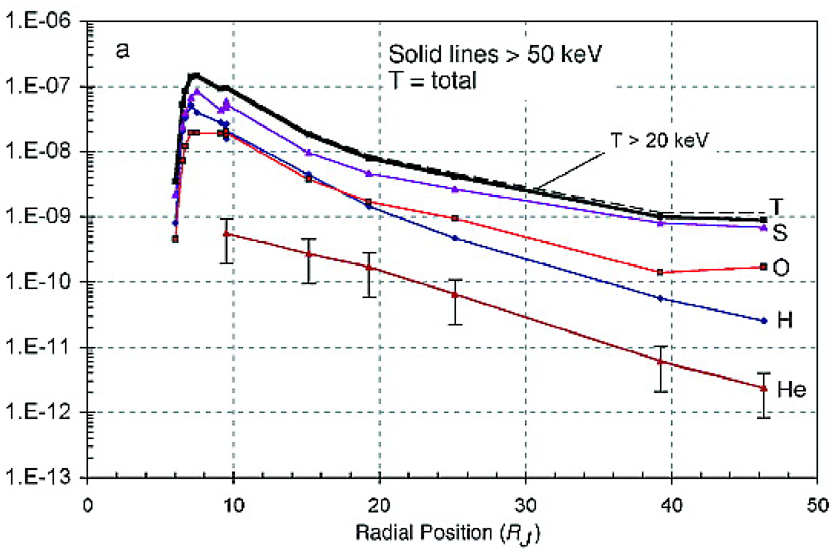
木星 : 共回転が卓越
・・・惑星自転により駆動
地球 : 太陽風方向のプラズマ流が卓越
・・・ 太陽風により駆動

プラズマトーラスからプラズマが外向き輸送

- 磁気圏の「磁気ディスク構造」を支えるプラズマ圧を供給
- 木星の自転運動量を磁気圏プラズマに供給



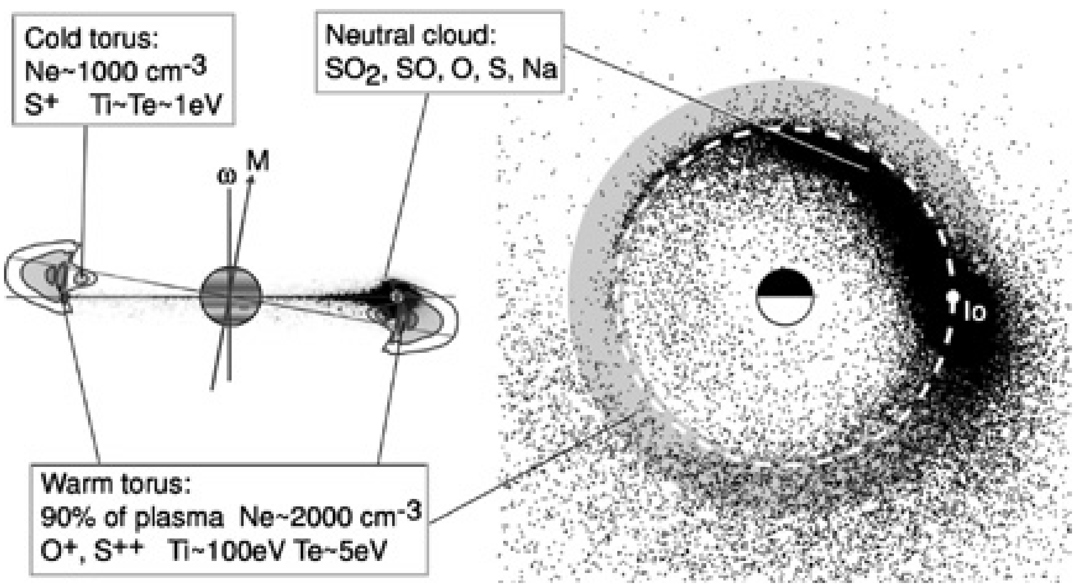
Global plasma convection :
Earth & Jupiter (Kivelson 2005)



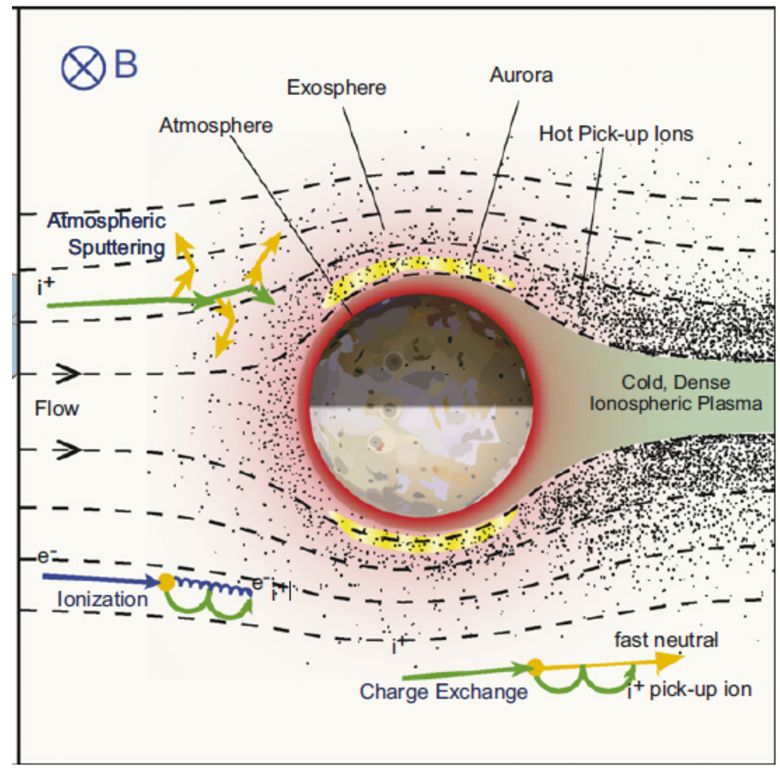
Radial distribution of plasma pressure in the Jovian magnetosphere observed by Galileo (Mauk et al. 2004)

Io plasma torusのイオン生成過程
イオン化過程と領域

- 散逸過程・領域
  - 電離圏イオンの流出
  - Coronaからのイオンピックアップ　(電子衝突電離・電荷交換反応)
  - Extended cloudからのイオンピックアップ
  - これらの寄与：未解明



Global distribution of ion (Io plasma torus) and neutral gas (extended neutral cloud) along the orbit of Io. (Thomas et al., 2004)



The interaction of magnetospheric plasma with Io's atmosphere. (Bagenal , 2007)

Io plasma torusのイオン生成過程

プラズマ収支：Neutral cloud theory

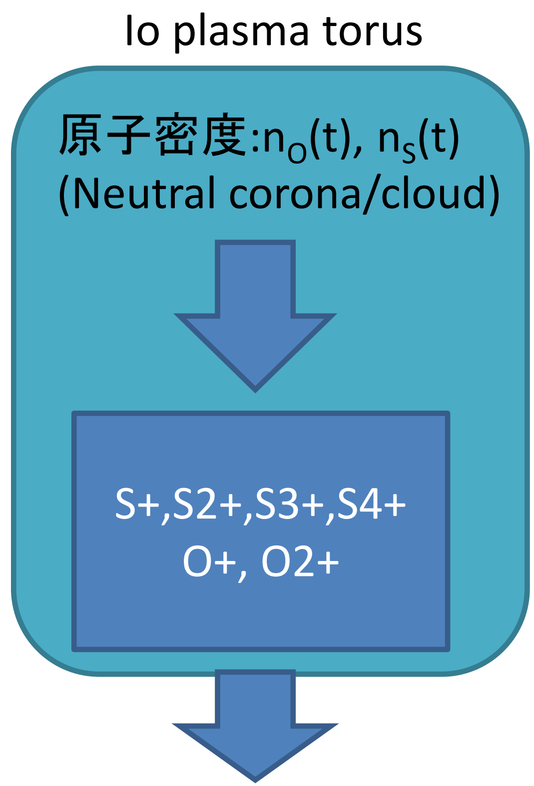
$$\frac{\partial n_\alpha}{\partial t} = \mathcal{S}_m - \mathcal{L}_m \qquad \frac{\partial\left(\frac{3}{2} n_\alpha T_\alpha\right)}{\partial t} = \mathcal{S}_\mathcal{E} - \mathcal{L}_\mathcal{E}$$

$$\mathcal{S}_m = I_{\alpha\_} n_{\alpha\_} n_e + I^h_{\alpha\_} n_{\alpha\_} n_{e,hot} + R_{\alpha_+} n_{\alpha_+} n_e + \sum_{\gamma,\beta} k_{\gamma,\beta} n_\gamma n_\beta$$

$$\mathcal{L}_m = I_\alpha n_\alpha n_e + I^h_\alpha n_\alpha n_{e,hot} + R_\alpha n_\alpha n_e + \sum_\beta k_{\alpha,\beta} n_\alpha n_\beta + \boxed{\frac{n_\alpha}{\tau}}$$

$$\mathcal{S}_\mathcal{E} = I_{\alpha\_} n_e n_{\alpha\_} T_{\alpha\_} + I^h_{\alpha\_} n_{e,hot} n_{\alpha\_} T_{\alpha\_} + R_{\alpha_+} n_{\alpha_+} n_e T_{\alpha_+} + \sum_{\gamma,\beta} k_{\gamma,\beta} n_\gamma n_\beta T_\beta + \sum_{\beta=i,e} \nu^{\alpha/\beta} n_\alpha (T_\beta - T_\alpha)$$

$$\mathcal{L}_\mathcal{E} = I_\alpha n_e n_\alpha T_\alpha + I^h_\alpha n_{e,hot} n_\alpha T_\alpha + R_\alpha n_\alpha n_e T_\alpha + \sum_{\alpha,\beta} k_{\alpha,\beta} n_\alpha n_\beta T_\alpha + \boxed{\frac{n_\alpha T_\alpha}{\tau}}$$



磁気圏外側へ輸送
時間スケール：τ

Transport time scale
14days (5 Sept 2000)
64days (14 Jan 2001)

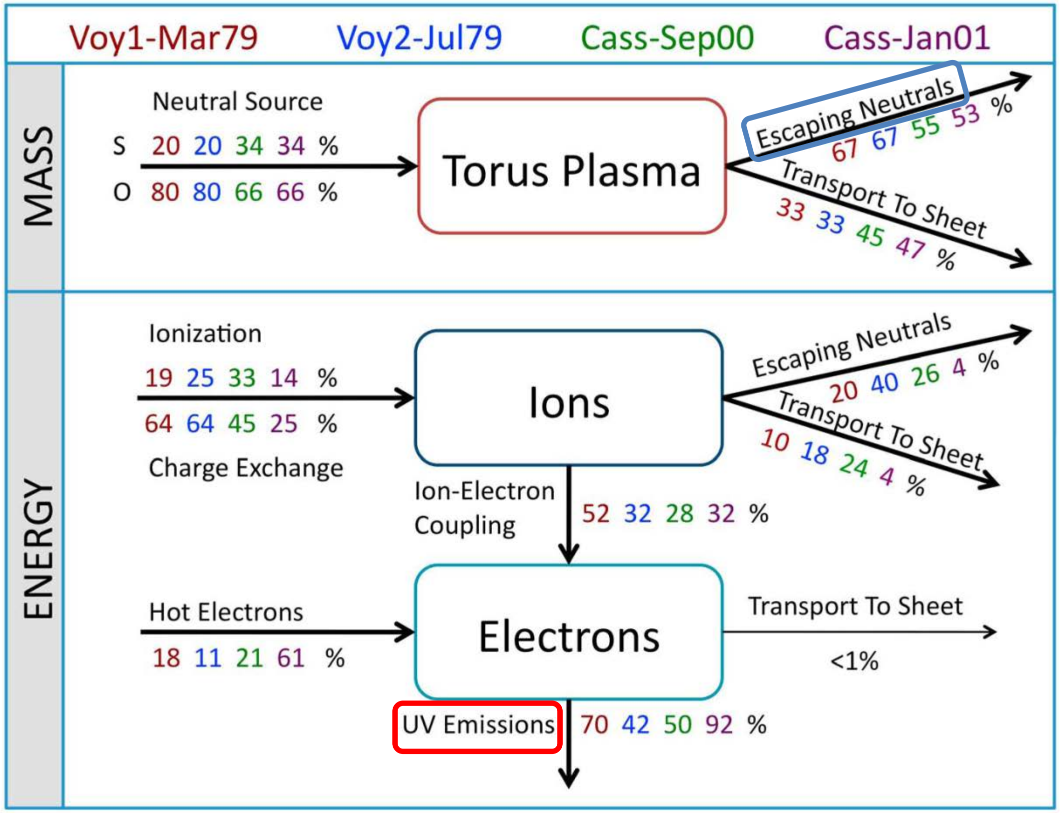
電子衝突電離	$X^{n+} + e^- \rightarrow X^{(n+1)+} + 2e^-$
再結合	$X^{(n+1)+} + e^- \rightarrow X^{n+}$
電荷交換反応	$X^{(n+1)+} + Y^{n+} \rightarrow X^{n+} + Y^{(n+1)+}$
クーロン衝突	イオン-電子間のエネルギー輸送

プラズマ輸送によるLoss

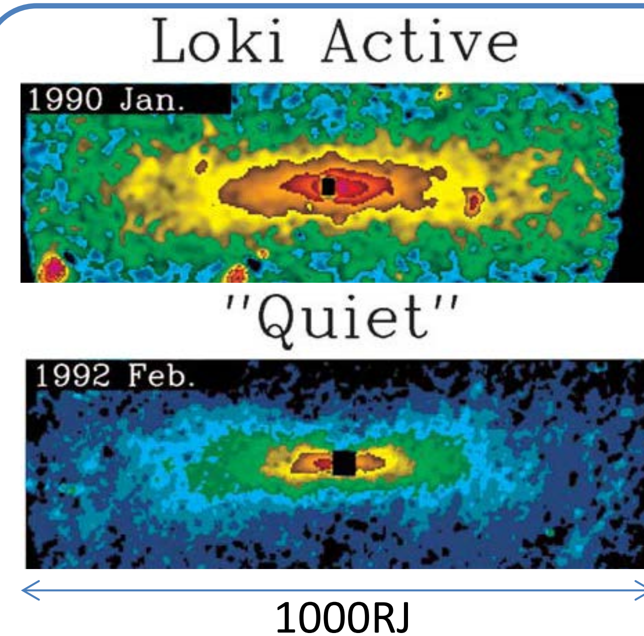
(Delamere et al. 2003,2014)

Io plasma torusのイオン生成過程

プラズマ収支：Neutral cloud theory



Mass & energy flows in the Io plasma torus
(Bagenal & Delamare 2011)



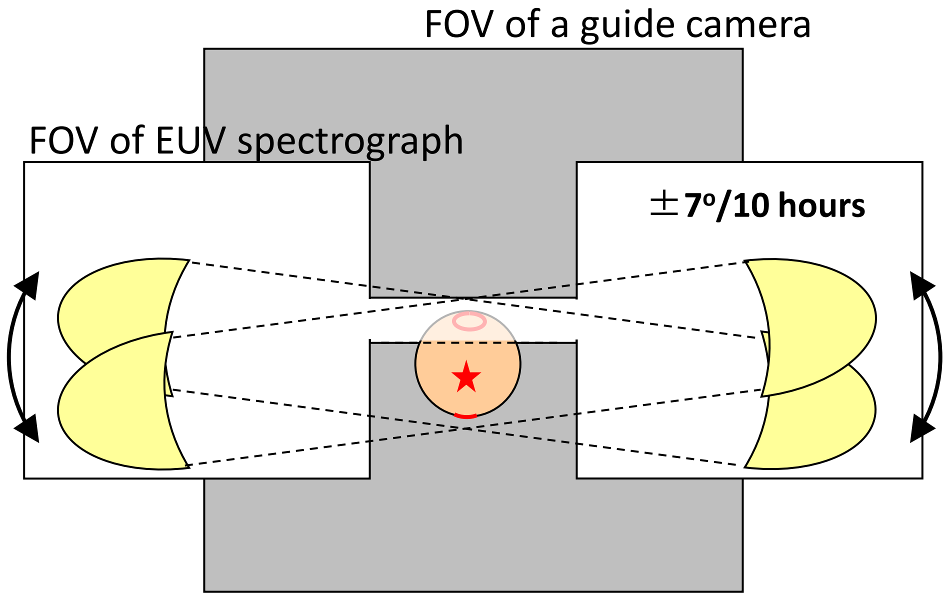
Na nebula (Mendilo et al. 2004)

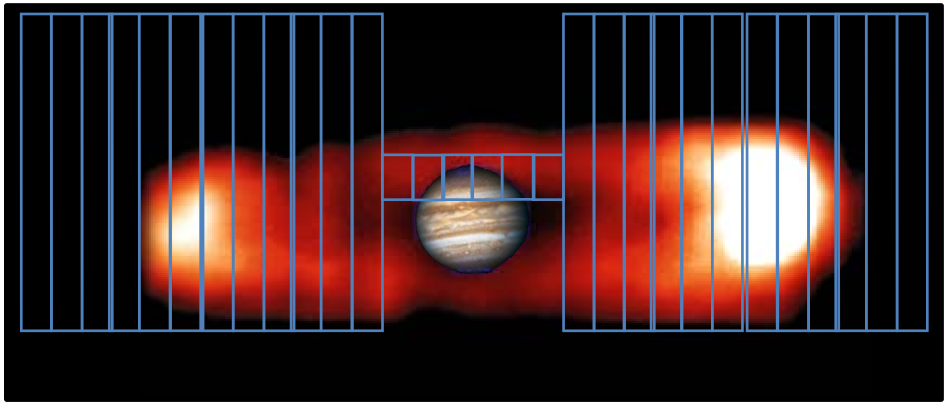
EUV emission of the plasma torus
(Cassini/UVIS observation)

イオからの散逸ガス
 1/2-2/3は高速中性粒子として
 1/3-1/2はプラズマとして系外へ輸送

HISAKI衛星による
Io plasma torus/aurora観測

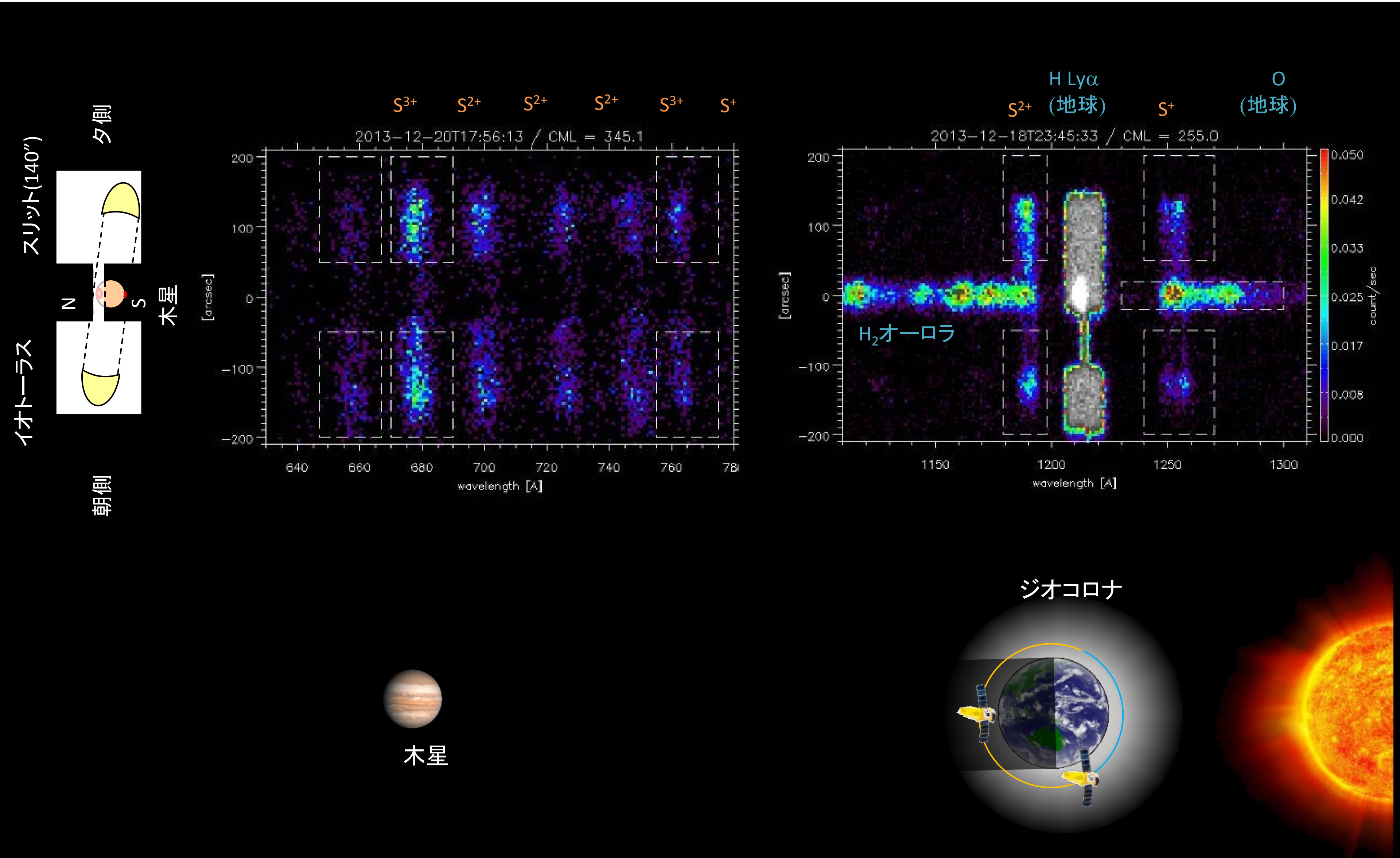
- 140-arcsec slit is using for the Jupiter observation. (2013/12-2014/2, 2014/4, 2014/12-2015/5)
- Northern aurora is guided to the slit center and the slit is parallel to the Jovian rotational equator.
- Wide slit enables to measure whole emissions from Io plasma torus (IPT)
- With a help of the guide camera , the satellite attitude control system kept the telescope pointing within an accuracy of 2 arc-sec.





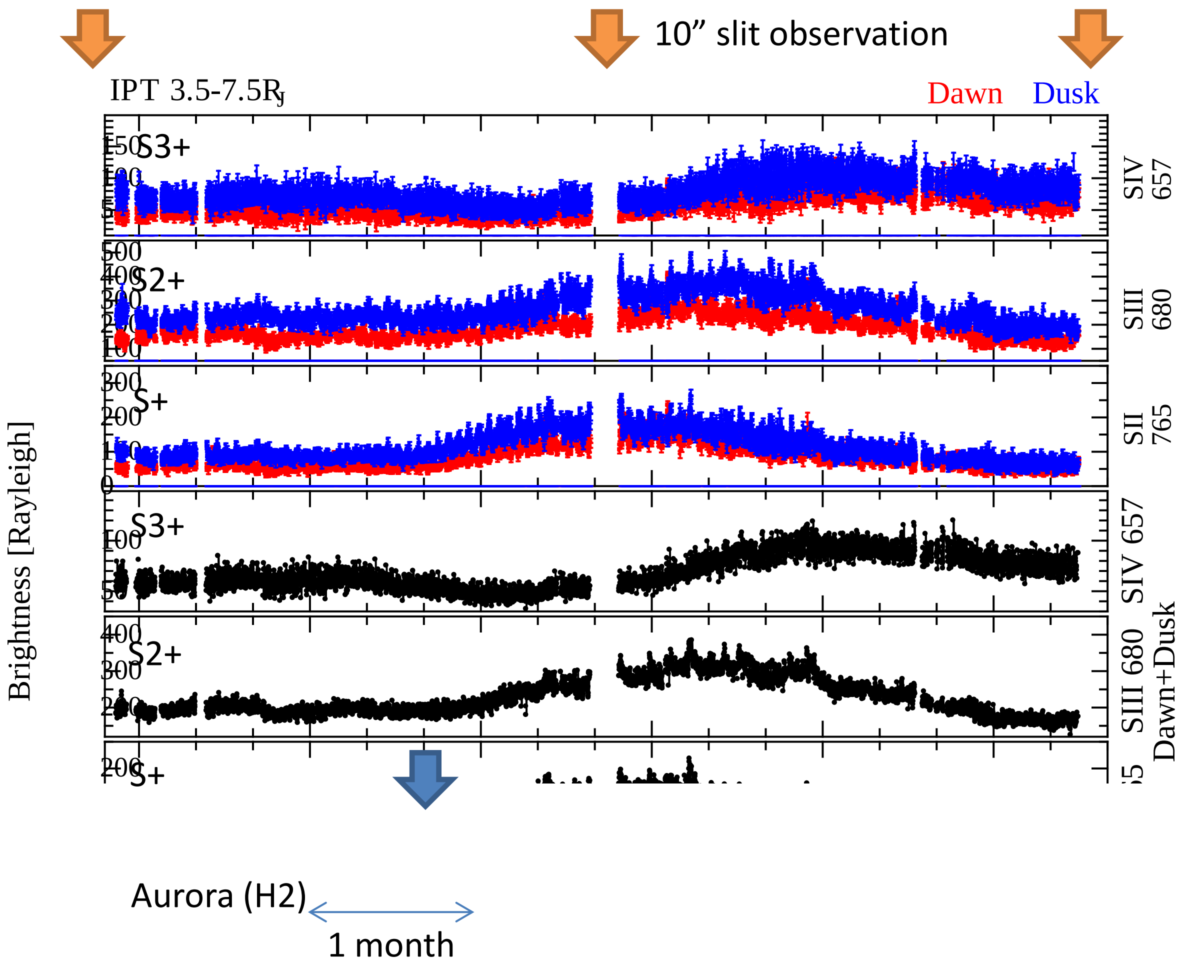
Typical observation mode for Jupiter’s aurora and Io plasma torus.

HISAKI衛星による
Io plasma torus/aurora観測



HISAKI衛星による観測 2015

From 2014-11-28 to 2015-05-14

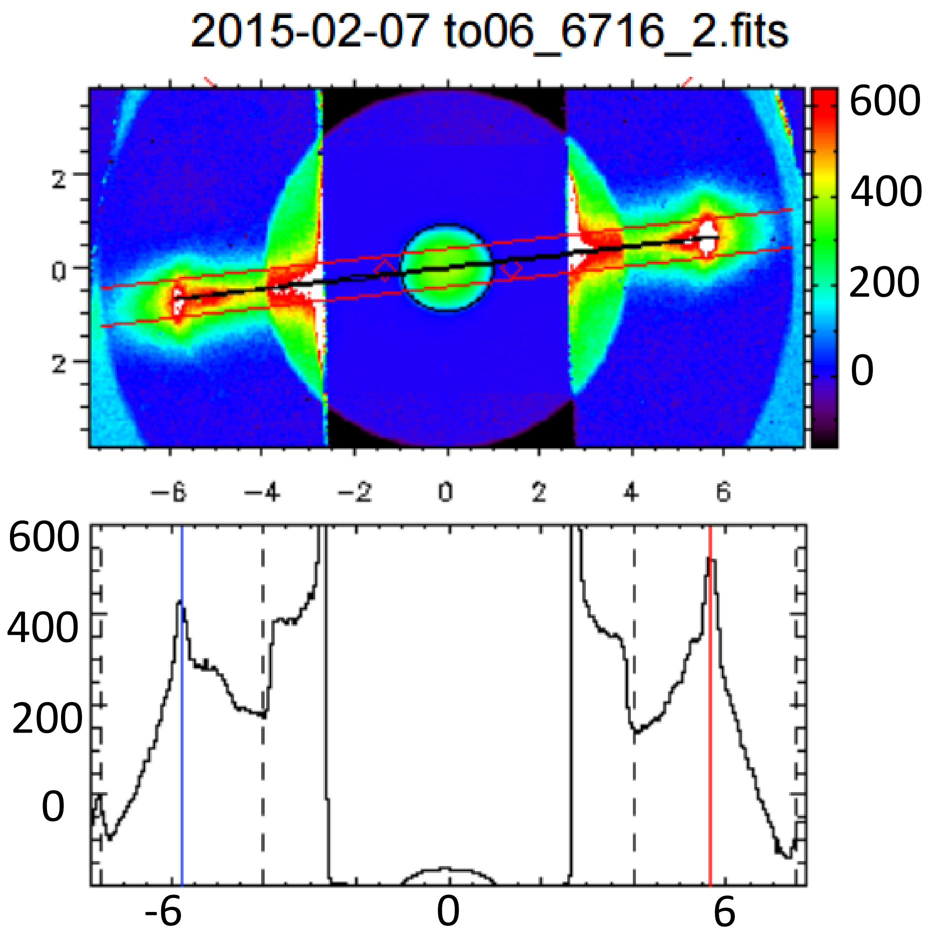


- A volcanic eruption seemed to start before DOY20.
- Response of IPT to volcanic activity on Io
- IPT Increasing in SII and SIII & decreasing in SIV.
- SII had a maximum on DOY60, SIII on DOY70, and SIV on DOY90
- SII and SIII had retuned to the pre-event level at the end of the observation. SIV still kept higher brightness.

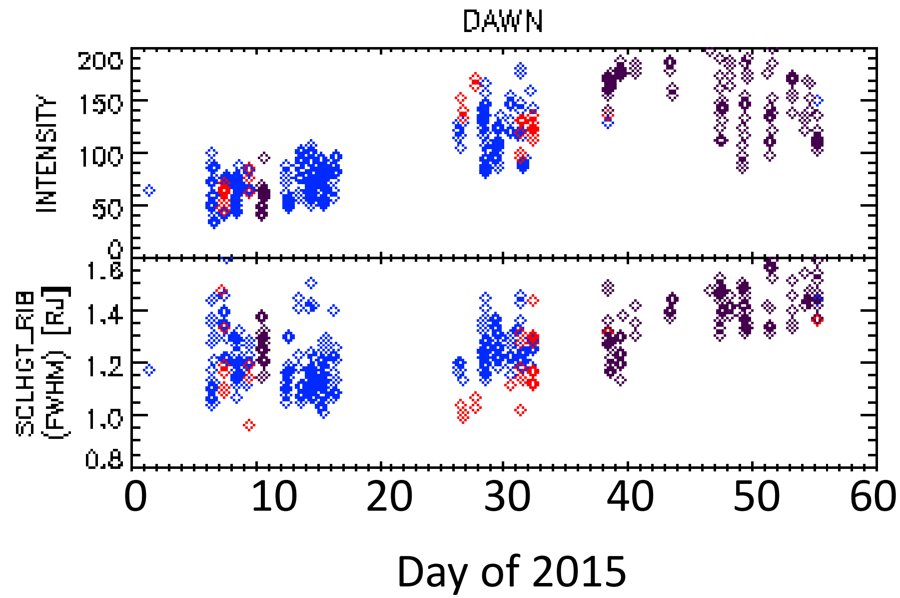
- Unusual aurora enhancements during DOY 60 to 100.
- Sudden brightening in Io torus associated with the aurora enhancements

発生タイミング・継続時間が予測できない時間変動現象の観測：モニタが非常に有効な手段

地上観測(ハワイ・ハレアカラT60)



Kagitani et al.

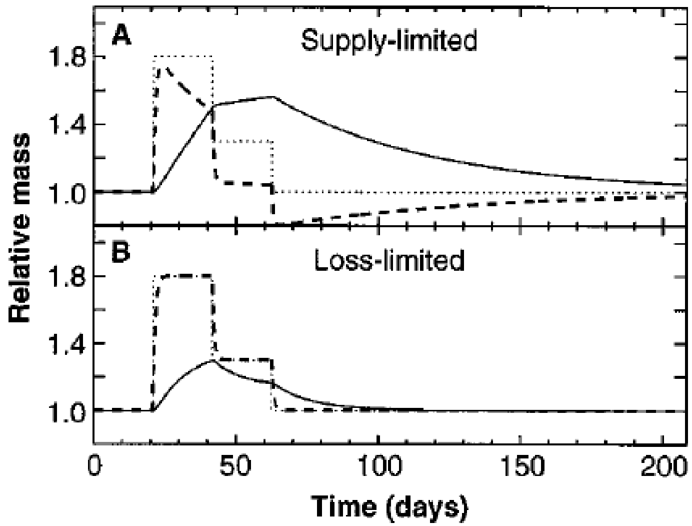


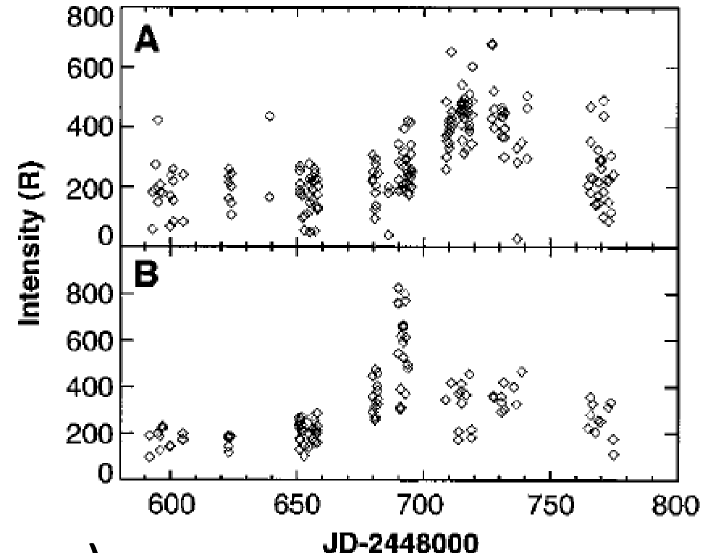
Tohoku-U 60-cm telescope at Haleakala
Narrow-band coronagraph

Wavelength:	[SII] 671.6nm/673.1nm
Platescale:	1.09”/bin or ~**0.05RJ/bin**
Integration:	20min/frame
# of data:	864 (dawn:564, dusk:545)

火山活動？

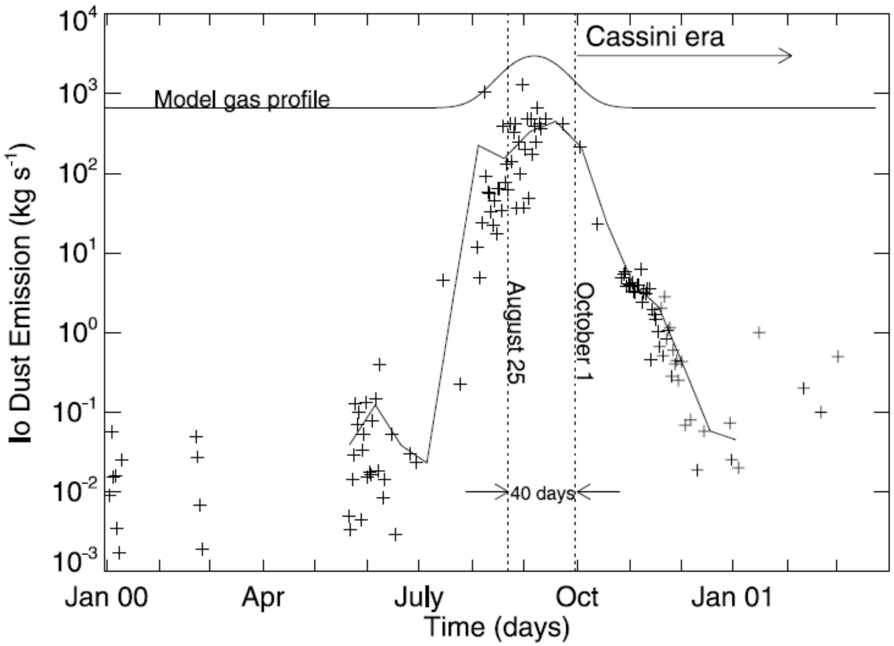
過去の観測(1)

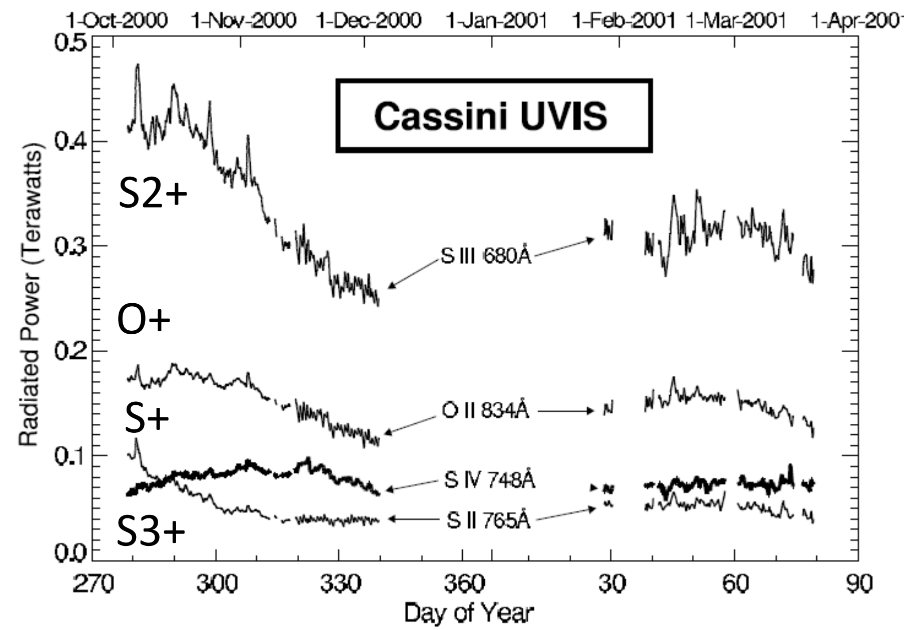




- Brown & Bouchez (1997,Science)
  - Ground-based observation (Na, S+)
  - Stabilization mechanism
    - Supply limited: Supply rate decreases as plasma density increases.
    - Loss limited: Loss rate increases as plasma density increases.
    - The observation supported the loss limited scenario.
  - However, both Na and S+ are not major constituents of the neutral cloud and the plasma torus.

過去の観測(2)





- Galileo & Cassini spacecraft (Delamere et al. 2004)
  - Observation of S^+, S^{2+}, S^{3+}, O^+ and O^{2+}
  - ‘Neutral cloud theory’ successfully accounted for ion composition changes and estimated neutral source and plasma loss rates
    - Neutral source: >1.8 tons/s to 0.7 tons/s
    - Plasma loss: Transport loss time scale : 14days to 64days

Sodium Nebula: Proxy of Io's volcanic activity
Mendillo et al. (2004)

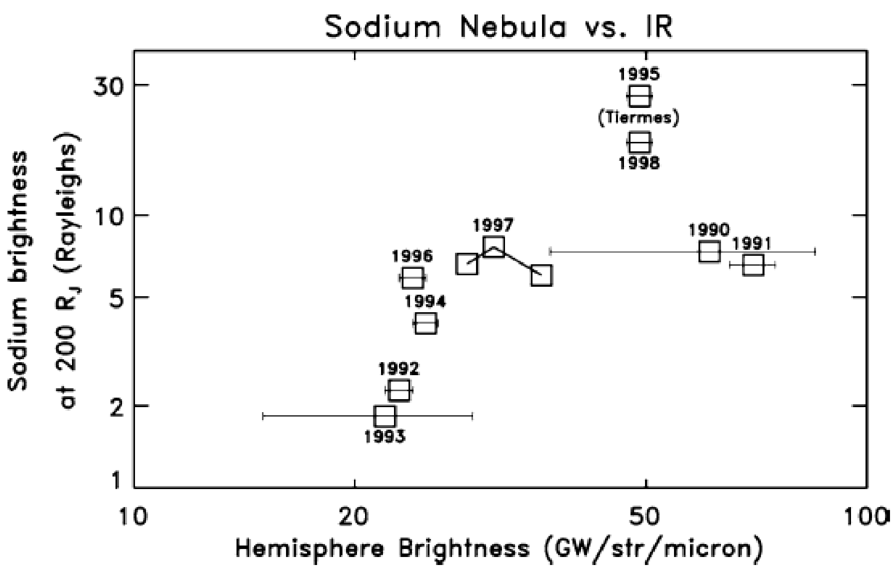
D-line brightness of the sodium nebula is controlled by Io's volcanic activity.

Source of fast sodium

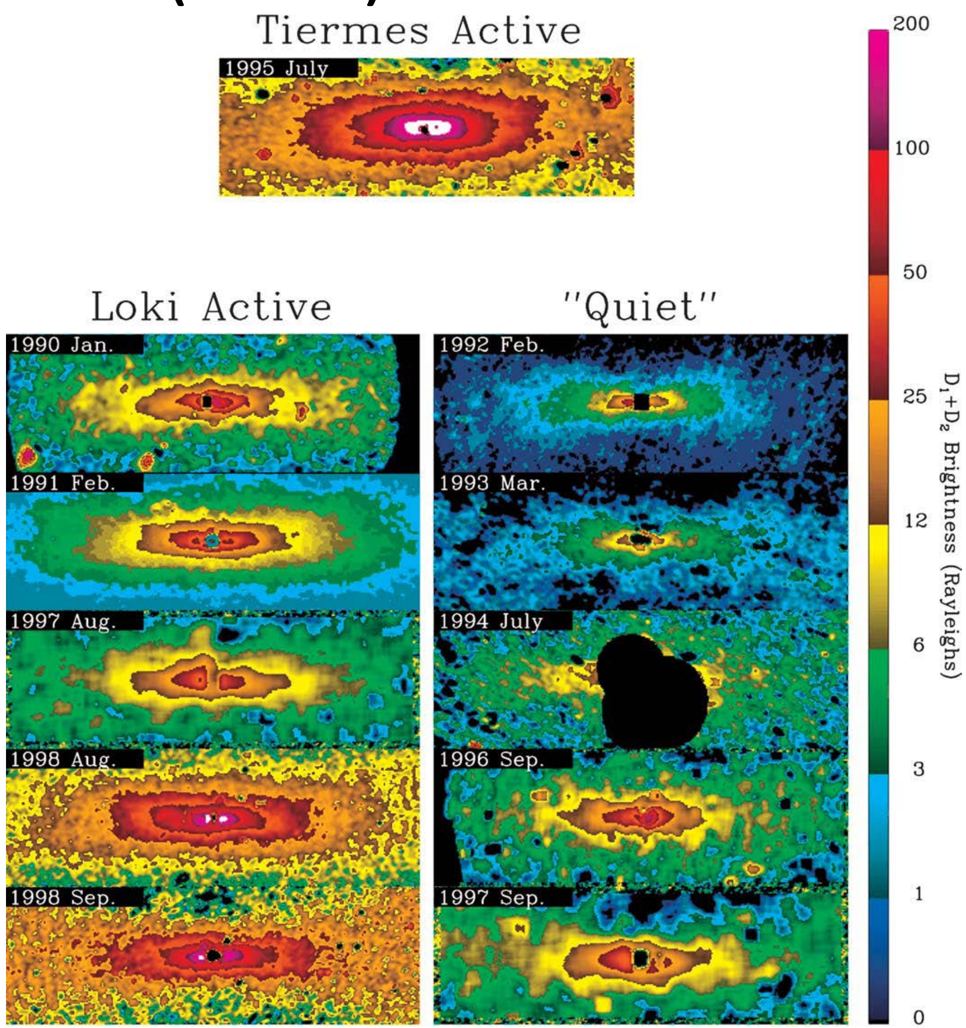
- Ionospheric escape of a molecular sodium ion

  NaX+ → Na* + X+

Relation between Lava flow and sodium remains to be devised.

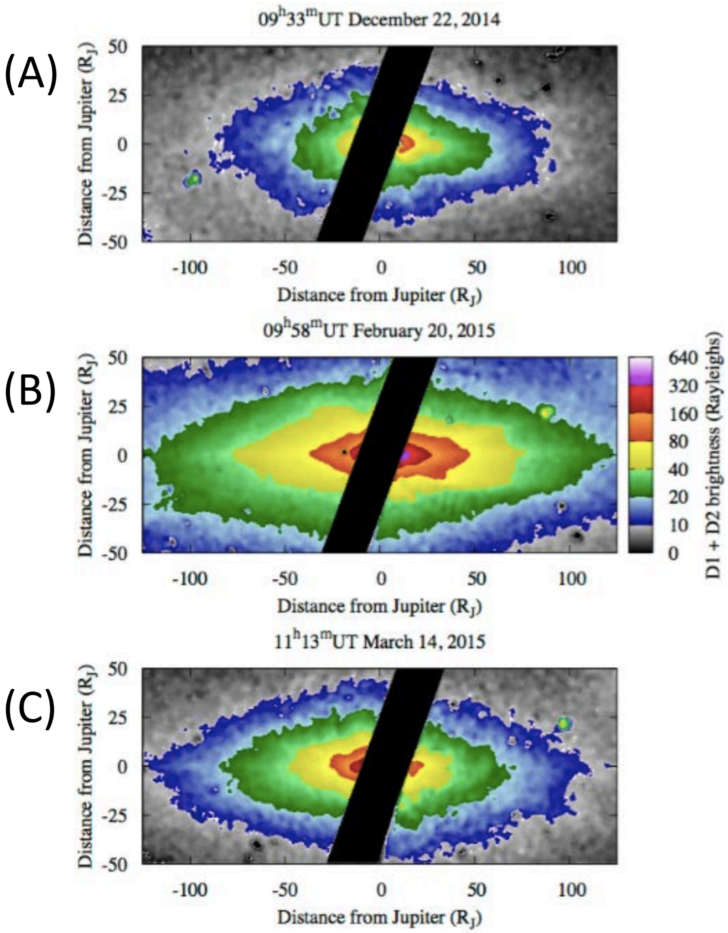


Io’s sub-jovian hemispheric brightness at 3.5 μm vs. the brightness of the sodium nebula at 200*RJ* from Jupiter



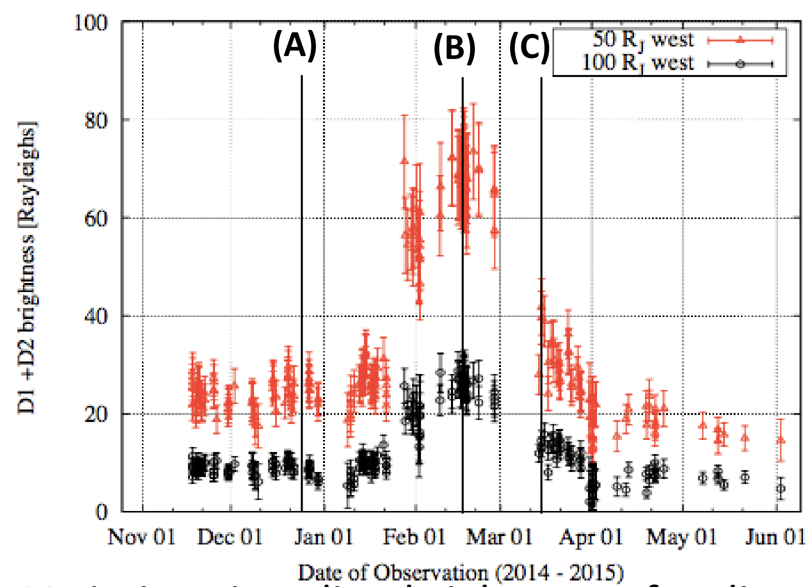
Jupiter’s sodium nebula and Io’s volcanic activity analyses for the 9-year period 1990–1998.

Sodium Nebula: Proxy of Io's volcanic activity



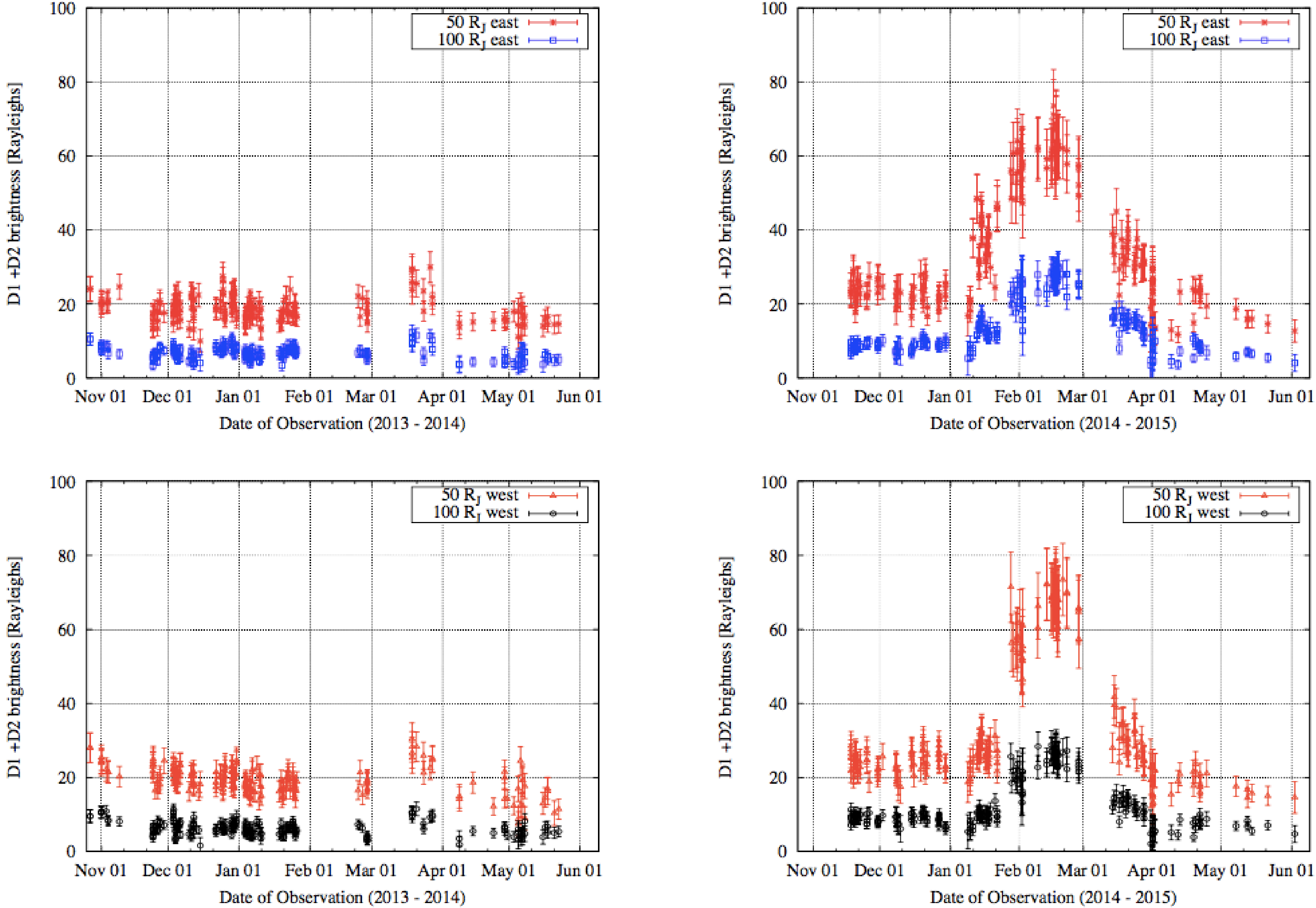
Images of Jupiter's sodium nebula obtained before (top), during (middle), and after (bottom) the volcanic enhancement seen in January - March, 2015

Observing site: Haleakala observatory, University of Hawaii/Tohoku University
Period: December 2014 – April 2015
(Yoneda et al., under review)



Variations in D-line brightness of sodium nebula at 50 and 100 RJ west from Jupiter.

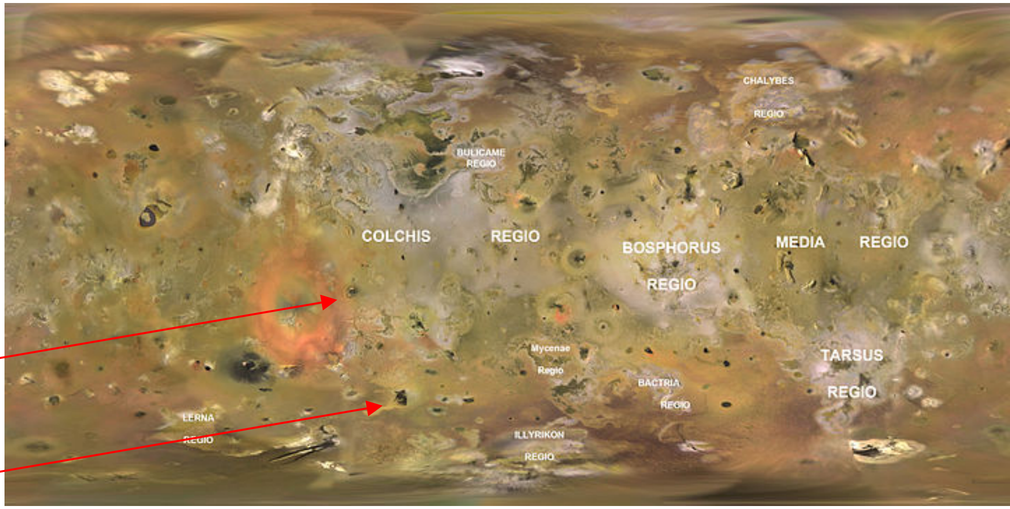
Sodium Nebula: Proxy of Io's volcanic activity



Io IR observation in 2015 (Spencer et al.)

Late Jan.:	Kurdalagon	de Kleer and de Pater
2/04/2015:	Loki faint	
	Kurdalagon(?)	visible - quite faint but very near the limb.
2/05/2015:	Kurdalagon	LBT(Large Binocular Telescope) (Conrad et al.)
2/18/2015:	Loki still faint	
	Pillan bright eruption	
3/15/2015:	Loki still faint	
	Pillan visible but fainter	
3/22/2015:	No obvious bright activity	

Kurdalagon may be the most likely candidate for causing the observed torus brightening



Pillan

Kurdalagon

HISAKI観測量と火山噴出量の関係

- イオトーラス・磁気圏のプラズマ：S,O
  火山活動の変動によってイオトーラス・磁気圏のプラズマ密度が変化することに不思議はないが．．．

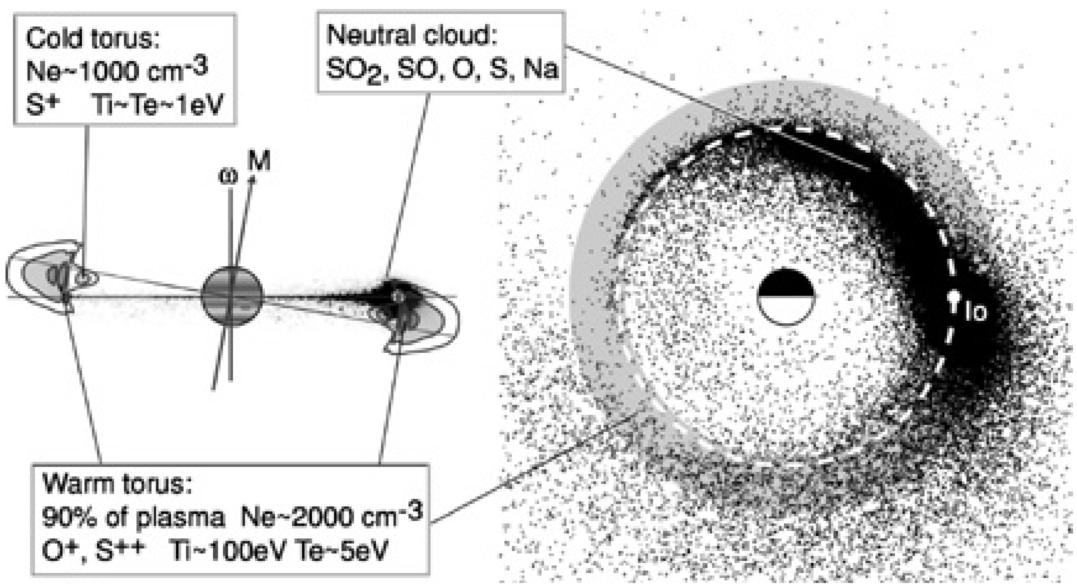
- 火山噴出による原子・分子の初速 $v < 1\mathrm{km/sec}$
- イオ重力圏からの脱出速度 $v_{esc} = 2.6\mathrm{km/sec}$
- 火山からの噴出ガスは大気にバッファされる

1) 大気から磁気圏への散逸過程は？
2) 大気が火山活動により受ける影響は？

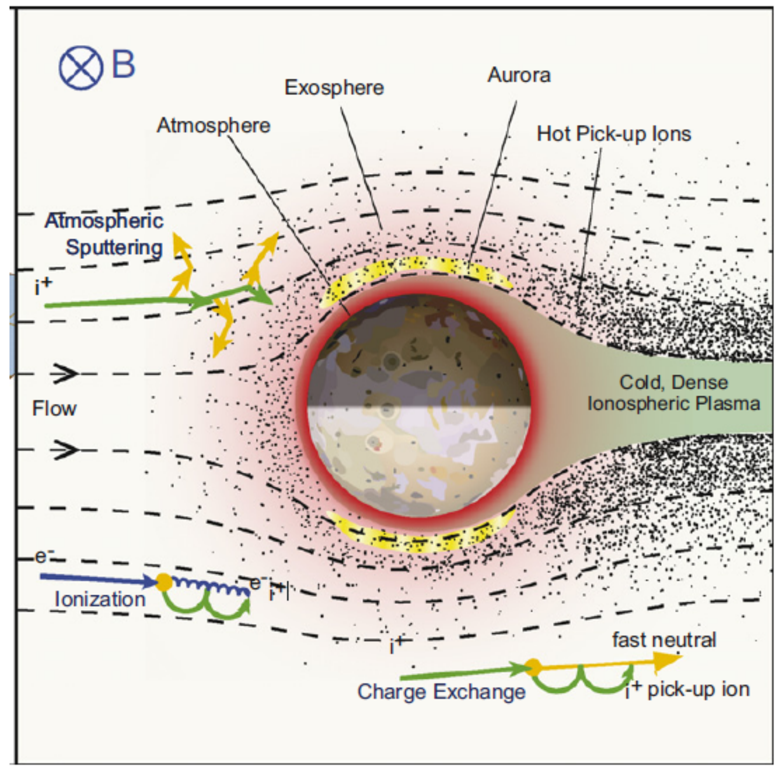
(1)大気から磁気圏への散逸過程

- 電離圏イオンの流出
- Atmospheric sputtering
  - Coronaからのイオンピックアップ　(電子衝突電離・電荷交換反応)
  - Extended cloudからのイオンピックアップ

イオン化領域:イオ近傍か広域か？:未解明



Global distribution of ion (Io plasma torus) and neutral gas (extended neutral cloud) along the orbit of Io. (Thomas et al., 2004)



The interaction of magnetospheric plasma with Io's atmosphere. (Bagenal , 2007)

(2)大気が火山活動により受ける影響

Io' atmosphere

Tenuous but well collisionally thick

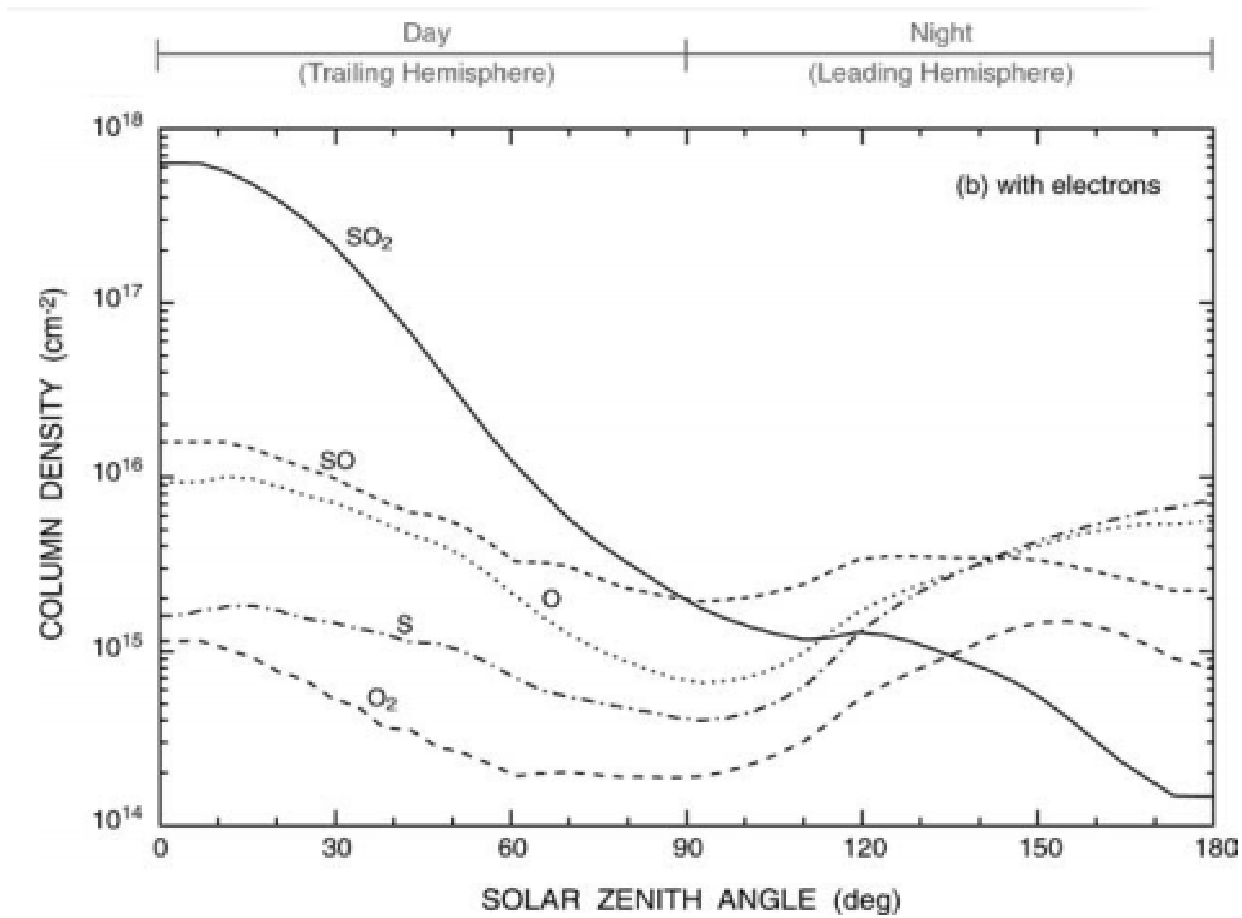
Typical column density: $3 \times 10^{16} cm^{-2}$ (0.6nbar)

Origin of Io' atmosphere

1) Ion sputtering with Io's surface
   - Moon & Mercury
2) SO2 sublimation
3) Volcanic support

Sublimation vs. Volcanic support

Sublimation: sensitive to Io's surface temperature

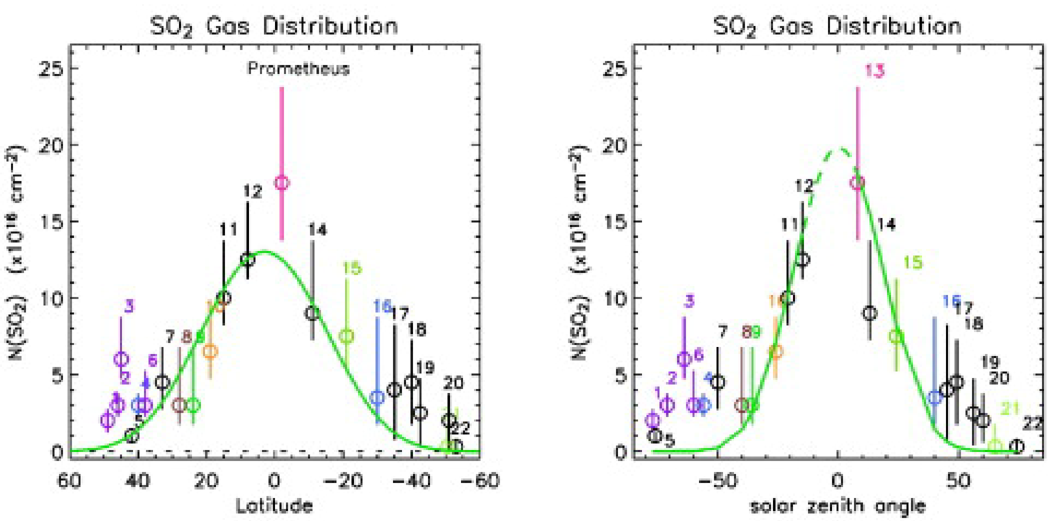


Smyth and Wong (2004)

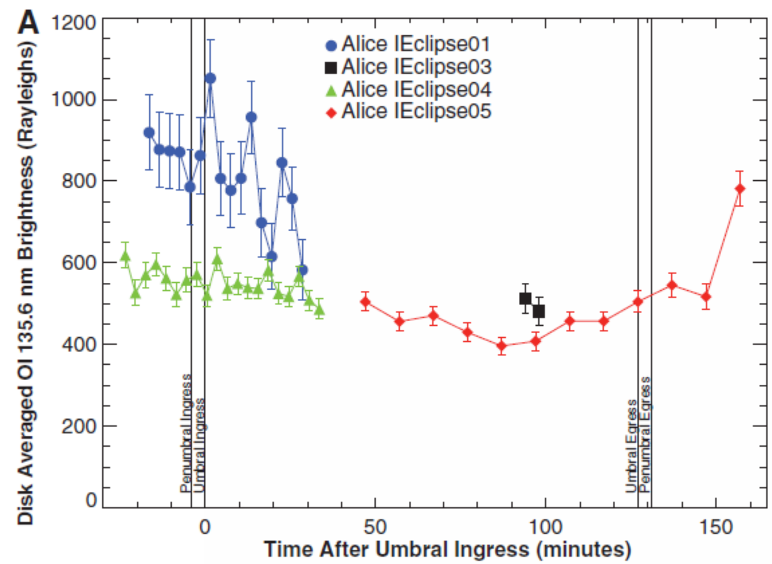
Observation of Io’s atmosphere

SO2 sublimation

- SO2カラム密度の緯度分布
- 蝕中の酸素原子発光強度減少
- Plumeがない領域でのSO2大気の存在

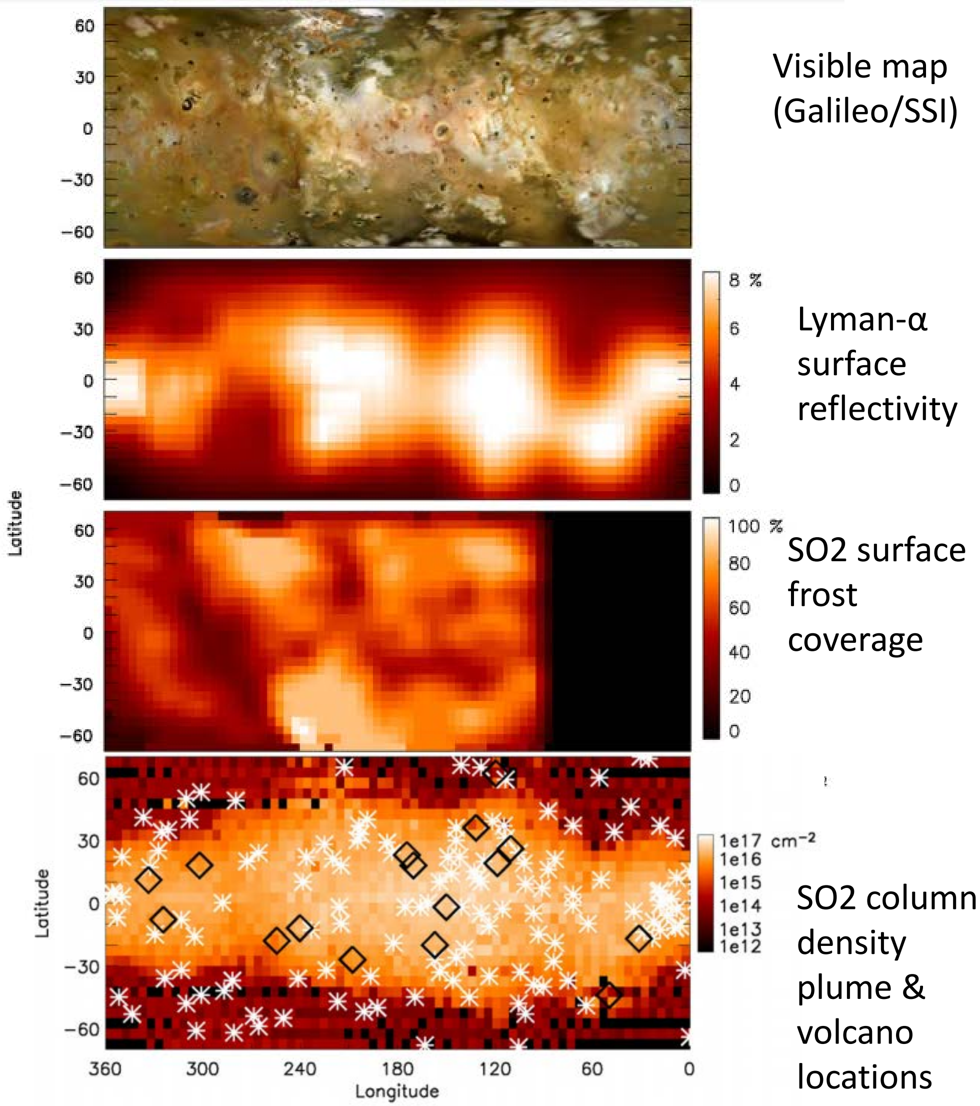


Near UV (~280nm) SO2 absorption (HST) vs. sublimation model (Jessup et al. 2004)
(left) equilibrium with average sunlight
(right) instantaneous equilibrium



Time series of Io’s auroral emissions in Eclipse observed by NH/Alice. Disk Averaged OI 135.6 nm Brightness (electron impact excitation). Volcanoes supply 1 to 3% of the dayside atmosphere. (Retherford et al. 2007)

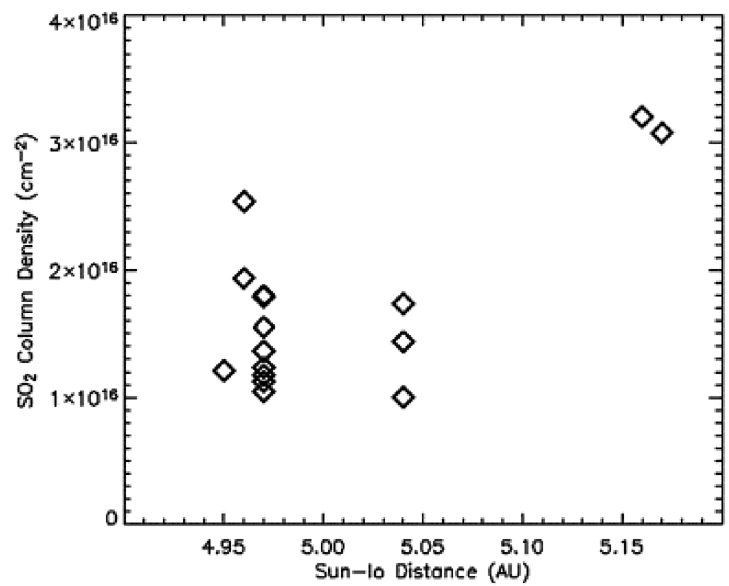
Observation of Io’s atmosphere



SO2 Ly-α absorption (HST) (Feaga et al. 2009)

Volcanic support

- SO2カラム密度と、SO2 frost, Plumeの空間分布
- 太陽直下点カラム密度と太陽-木星距離との間の相関
- 昼夜境界(低温領域)でのSO2検出(Pele)
- 時間変動

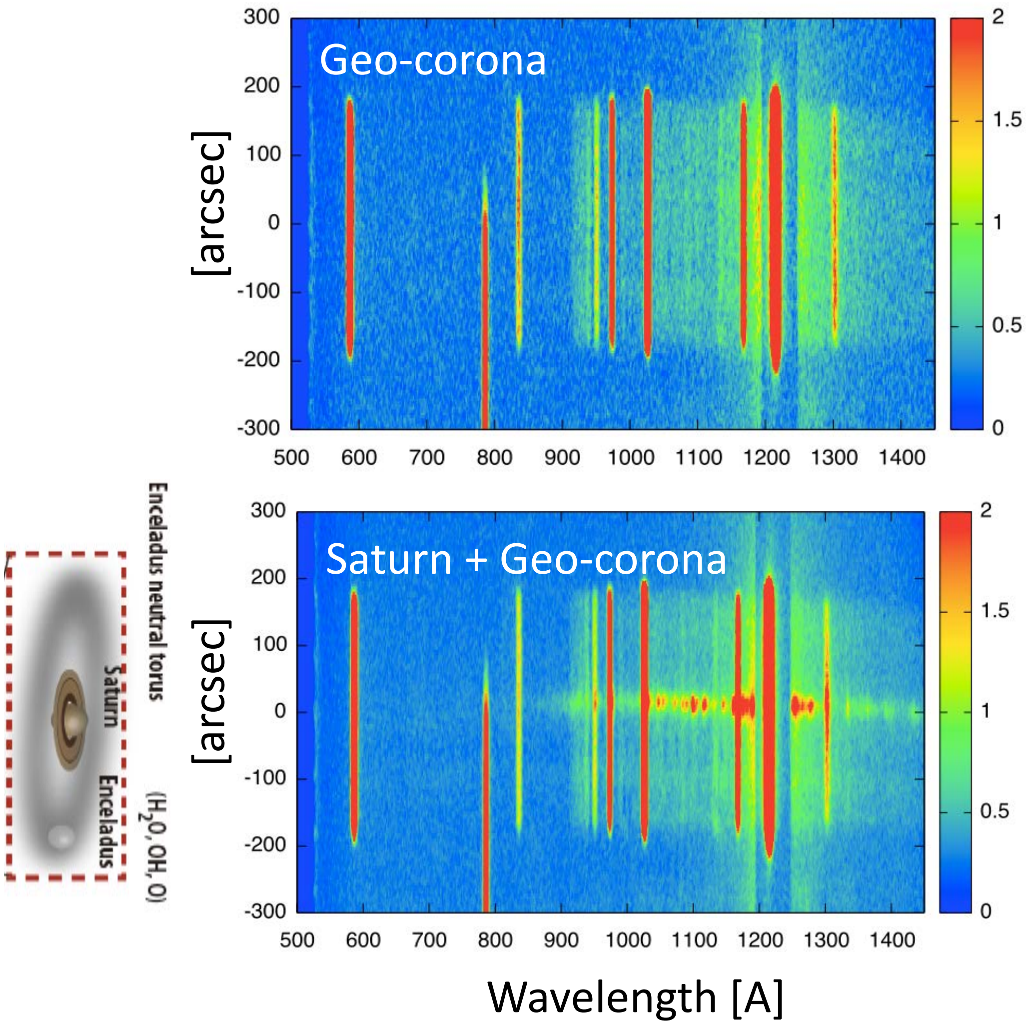


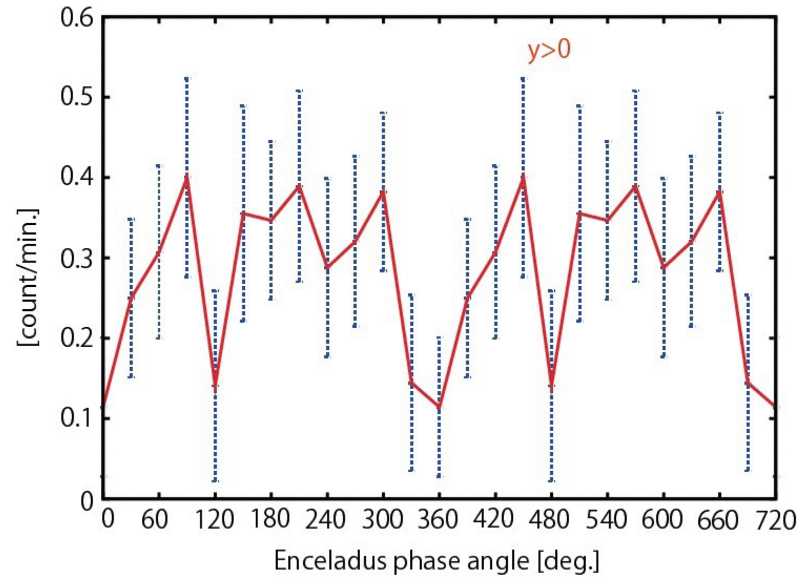
SO2 column density vs. Io-Sun distance
(Feaga et al. 2009)

まとめ

- HISAKI衛星　2015/1にイオ火山活動に伴うプラズマ発光強度変動を観測
- 連続観測が威力を発揮
- 観測から引き出せる量
  - イオからその重力圏外への散逸量総量
  - 組成比(S/O等)
  - 積分サイエンス(微量成分の検出)
- 今後
  - プラズマ診断によるイオン密度の定量
  - Neutral cloud theoryを用いた物質収支の検討
- 大気の形成過程･重力圏外への散逸過程が未解明

Enceradus Tadokoro et al.





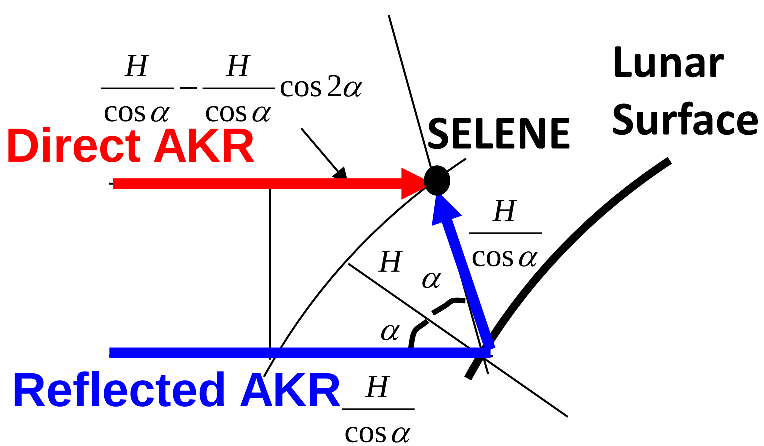
Observation period:
2014-05-23 to 06-16 (3 weeks)
2015-08-01 to 08-21 (3 weeks)

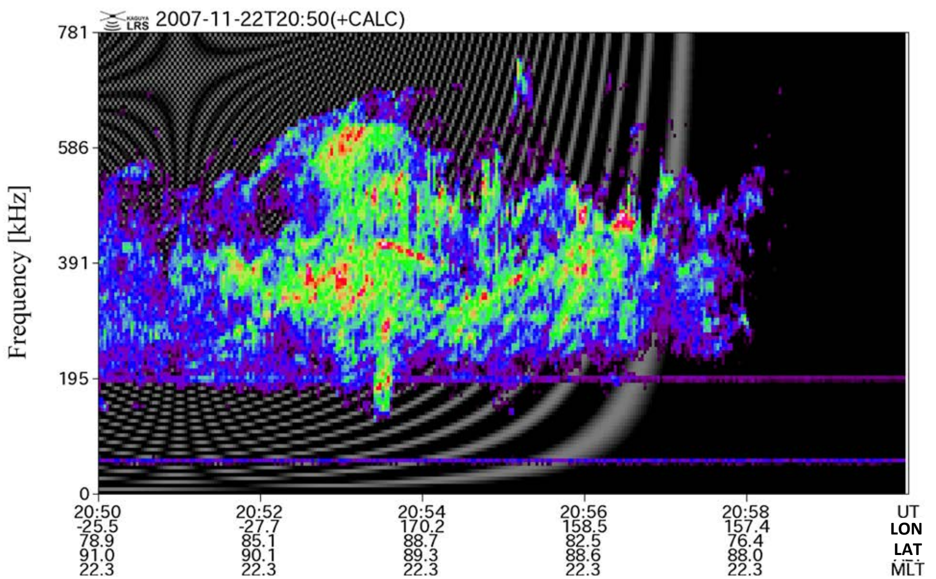
Ganymede: subsurface ocean JUICE/RPWI/HF 熊本、笠羽、土屋(東北大)

Concept of PSSR for JUICE/RPWI/HF

Passive SubSurface Radar (PSSR):
An operation mode of JUICE/RPWI/HF for determination of the thickness of ice crust layer of the Jupiter's icy moon.

The idea is based on the observations of interference of direct and reflected AKR by SELENE (Kaguya).





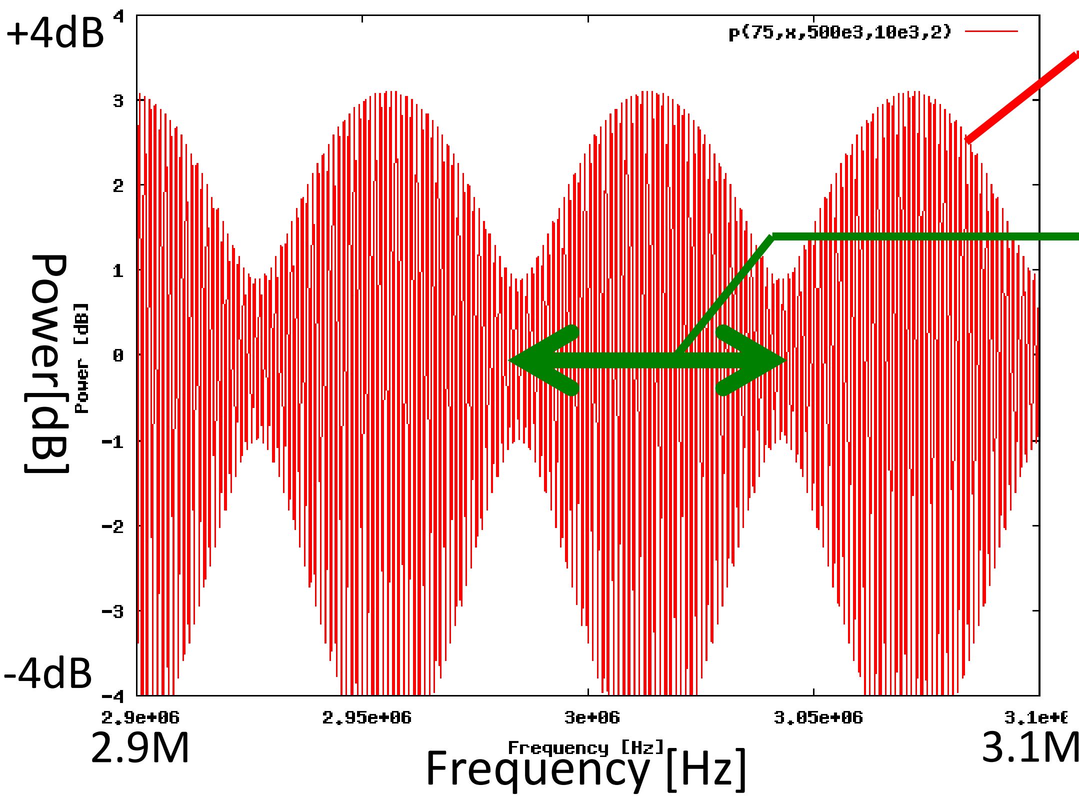
(Ono et al., 2010)

Expected spectrum of interfered direct and reflected HOM

$$P = 10\log_{10}\left|1 - R_S \exp\left[i \cdot 2\pi f \frac{H}{c}\frac{1+\cos 2\alpha}{\cos\alpha}\right] - T_S R_{SS} T_S A_{ice} \exp\left[i \cdot 2\pi f \frac{H+D}{c}\frac{1+\cos 2\alpha}{\cos\alpha}\right]\right|^2$$

Surface echo

Subsurface echo



Interference patterns
($\Delta f \lesssim$ 100Hz)

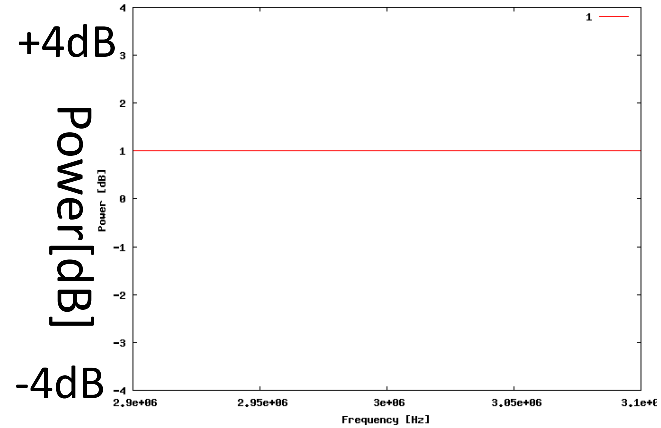
Beat (➔D)
(Δf ~ 100kHz)

S/C altitude: H = 500km
Ice thickness: D = 10km
TiO_2&FeO: $F_{TiO2\&FeO}$ = 10%

Comparison: 1 wave & 2 waves & 3 waves

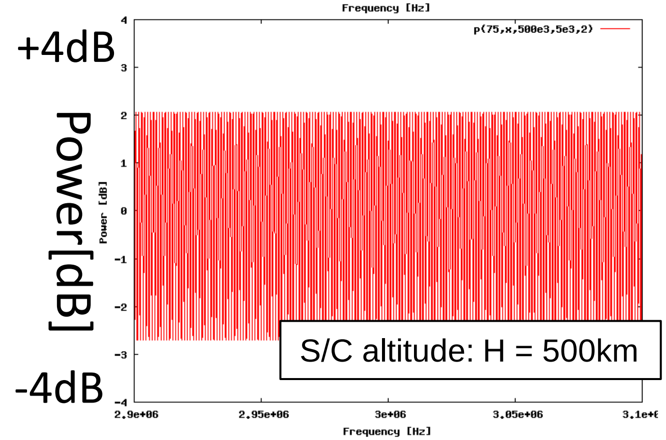
Direct HOM

$$P = 10\log_{10}\left|1\right|$$



Direct HOM **Surface echo**

$$P = 10\log_{10}\left|1 - R_S \exp\left[i \cdot 2\pi f \frac{H}{c}\frac{1+\cos 2\alpha}{\cos\alpha}\right]\right|$$



Direct HOM **Surface echo**

$$P = 10\log_{10}\left|1 - R_S \exp\left[i \cdot 2\pi f \frac{H}{c}\frac{1+\cos 2\alpha}{\cos\alpha}\right] - T_S R_{SS} T_S A_{ice} \exp\left[i \cdot 2\pi f \frac{H+D}{c}\frac{1+\cos 2\alpha}{\cos\alpha}\right]\right|^2$$

Subsurface echo