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The time variation of atomic oxygen around Io during volcanic active event observed by Hisaki/EXCEED

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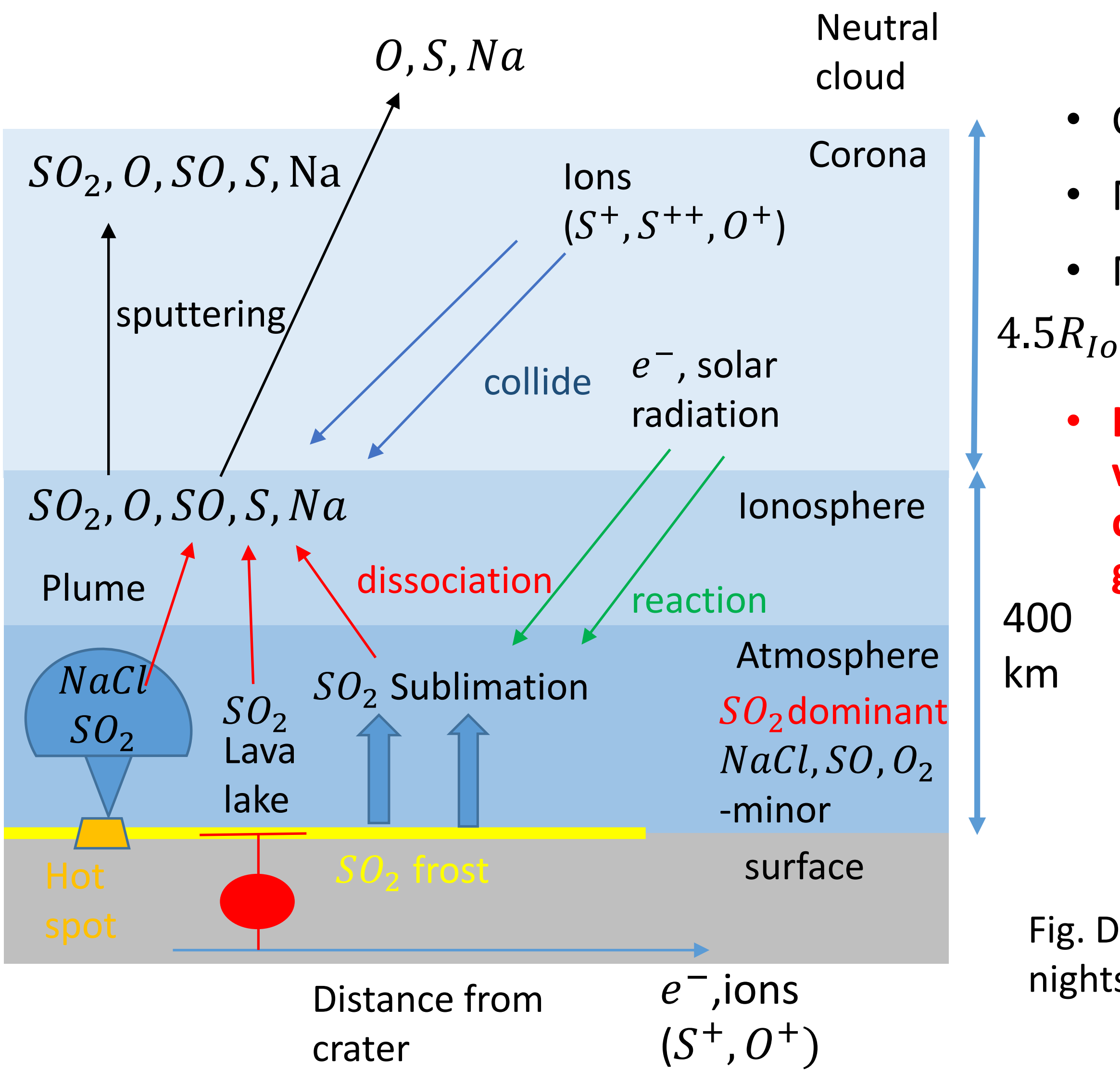
Generation and escape process of Io's atmosphere



- Column density $3 \times 10^{16}\ cm^{-2}$
- Major components; SO_2, SO, S, O
- Minor components; $NaCl, KCl$
- **It is debated how much volcanism and sublimation contribute Io's atmospheric generation**

Fig. Drawings of dayside (top) and nightside (bottom) atmosphere.

Simultaneous sodium and infrared observation during volcanic active period

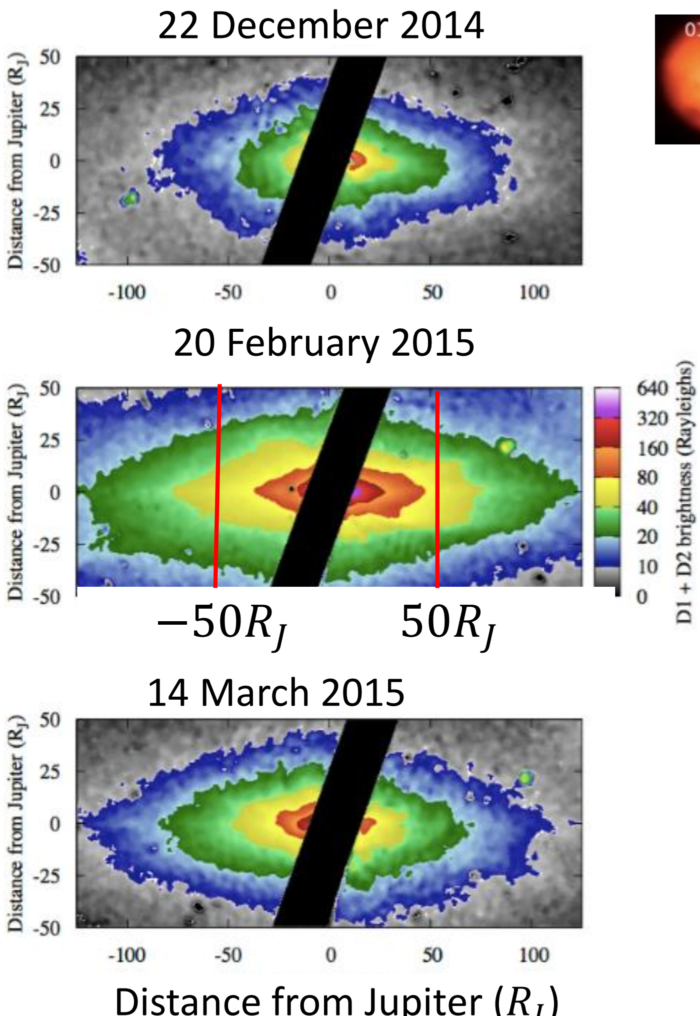


Fig. Three images of Jupiter's sodium nebula obtained in the observation period [*Yoneda et al,* 2015]

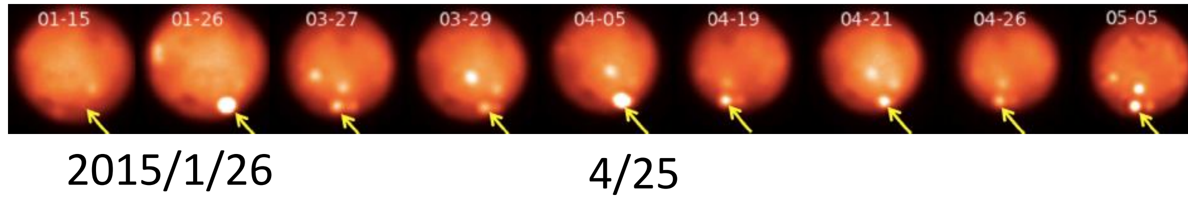


Fig. (Top) IR 3.8 μm images of Io [*de Kleer and de Peter* 2016] .

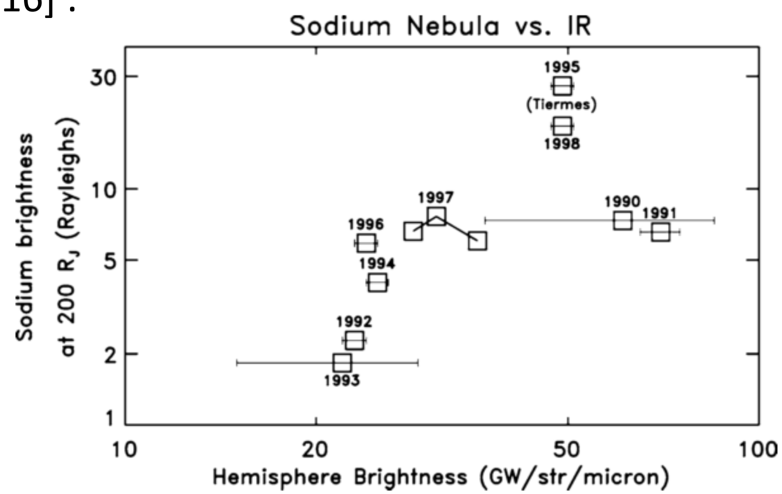


Fig 4. Relationship between of brightness of infrared emission at 3.5 μm and that of sodium nebula emission [*Mendillo et al.,* 2004].

we can monitor Io's volcanic activity by observing the time variation of sodium emissions remotely from the ground.

Purpose of this study

- Purpose

➢ To understand time variation and spatial variations of atomic oxygen supplied and escaping from Io.

- Way of study

① To investigate time variations in atomic oxygen emission at 130.4 nm during volcanically active event and compare them with variations of sodium nebula D-line emission

② To investigate dependence of Io phase angle in atomic oxygen emission

sodium nebula
emission at D-line
(50 R_J from Jupiter)
[*Yoneda et al.*, 2015]
<minor component>
- Volcanism

compare

atomic oxygen
emission at 130.4 nm
($\pm$23“ around Io)
(this study)
<major component>
- Volcanism
- Sublimation

Data analysis

- Period; 27 November 2014 - 14 May 2015 (from DOY -35 to 135)
- We overlapped the data whose center corresponds to the Io's location within a range of ±23"
- Phase angle dawn side 45-135°

  dusk side 225-315° (see below figure)
- Radiation noise >0.01 [count/pix/min]→ eliminate
- To avoid geocorna emission, only data whose Local time is between 20-4 hr is used

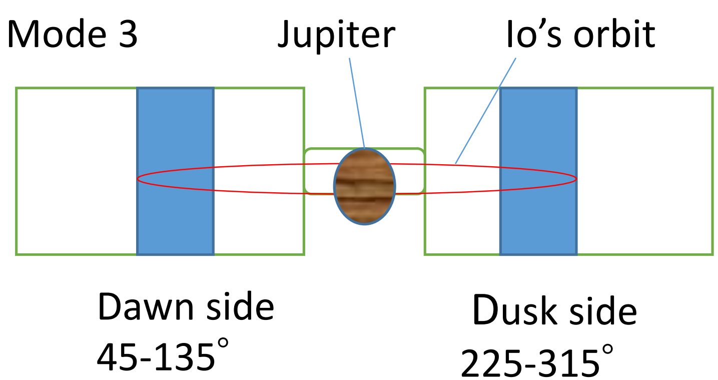


Fig . Slit of mode 3,which was used to observe UV emission in the Io torus

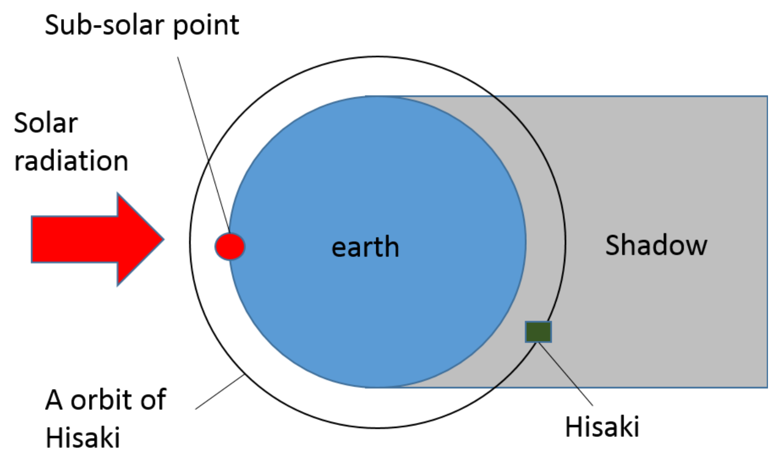
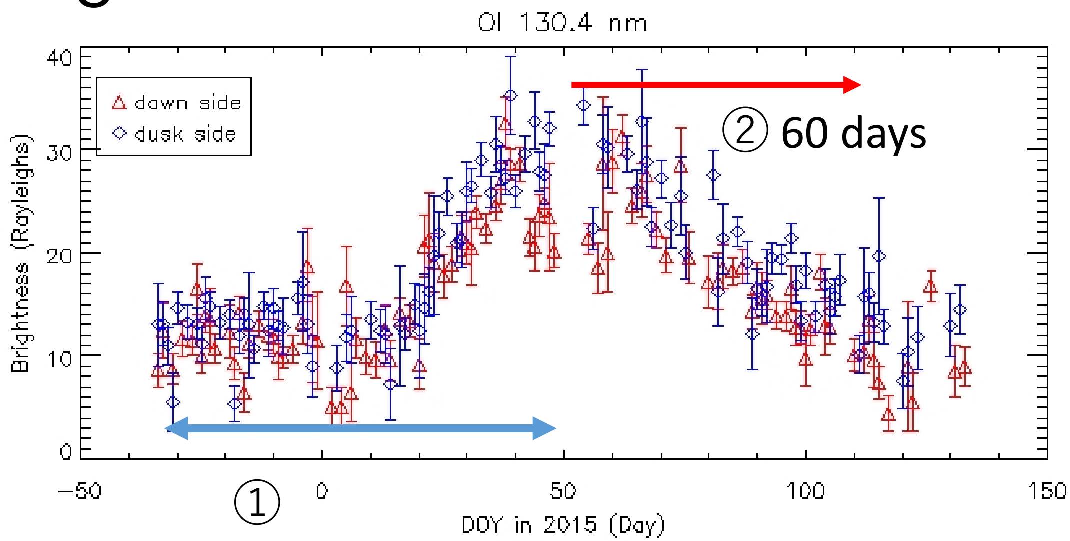


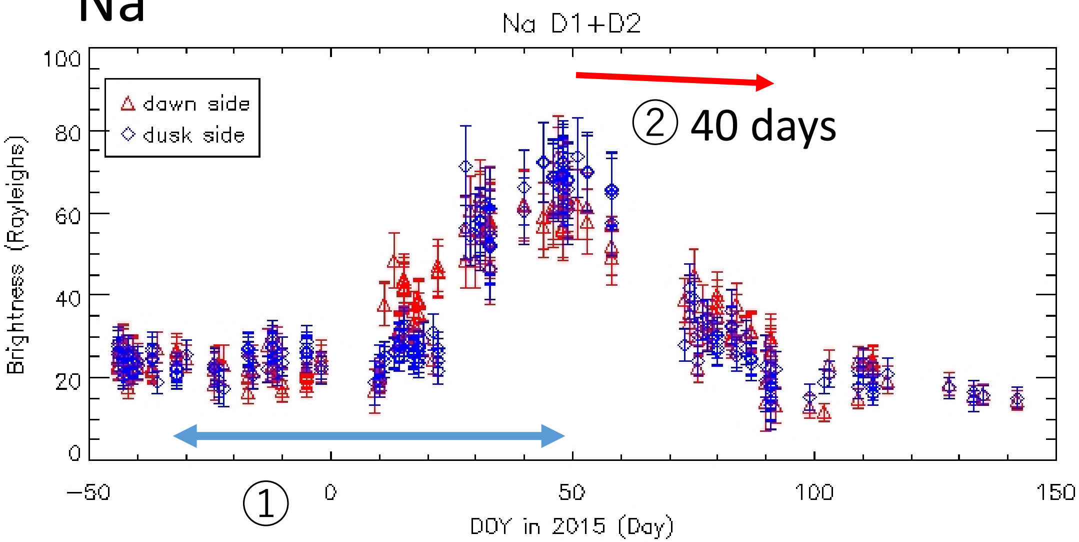
Fig . Explanation of local time

During 2014-2015

O



Na



Important features

① The time variation of atomic oxygen emission is well correlated with that of sodium emission (DOY -35-50)

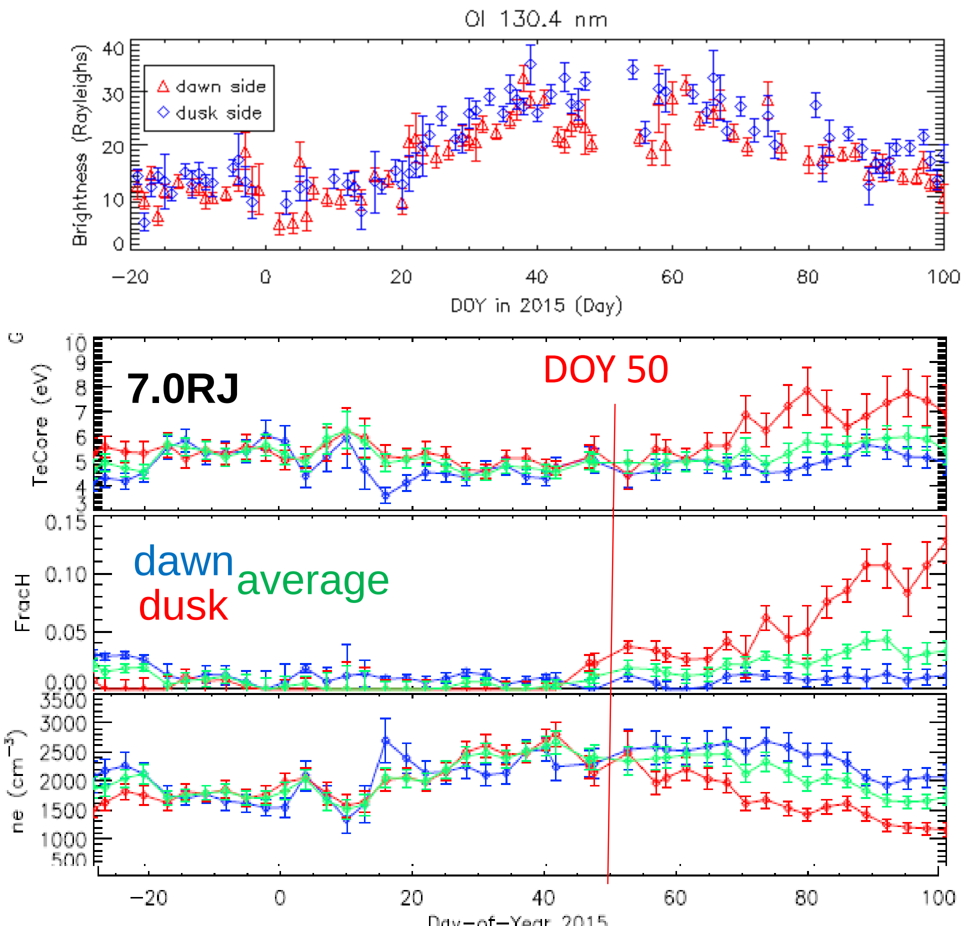
② The duration declining from peak to original value of atomic oxygen emission is longer than that of sodium emission (DOY 50-)

Fig . (Top) The time variation of atomic oxygen emissions at 130.4 nm in the dawn side and the dusk . (Bottom) The time variation of D1+D2 neutral sodium nebula emission.
Day of year (DOY) 1 = 1 January 2015.

① Declining speed (DOY -50)

- Two candidates which can explain the difference of declining time

➢ Increase of core electron temperature and hot electron fraction



Electron impact excitation

$$O + e^- \rightarrow O^* + e^-$$

Variations

(DOY 50 → DOY 100)

Core electron temperature

5 eV → 6 eV

Hot electron fraction

2 % → 4 %

Electron density

2500 cm^{-2} →

1700 cm^{-2}

Fig. (Top) The time variation of atomic oxygen emission at 130.4 nm in season 2(Bottom) plasma diagnosis from the data of Hisaki/EXCEED. [Kagitani et al., private communication, 2016]

① Declining speed (DOY -50)

- Two candidates which can explain the difference of declining time scale
  - the difference of source regions between sodium chloride and sulfur dioxide
- Boiling point; $NaCl$ (650 K under 10^{-12} bar) [*Ewing and Stern* 1974]

  $\gg SO_2$ (113 K under 6.0×10^{-10} bar) [*Ingersoll* 1989]
- $NaCl$ is emitted only in plume because of high boiling point.
- SO_2 is likely to be emitted not only in plume but in wide lava lake area.

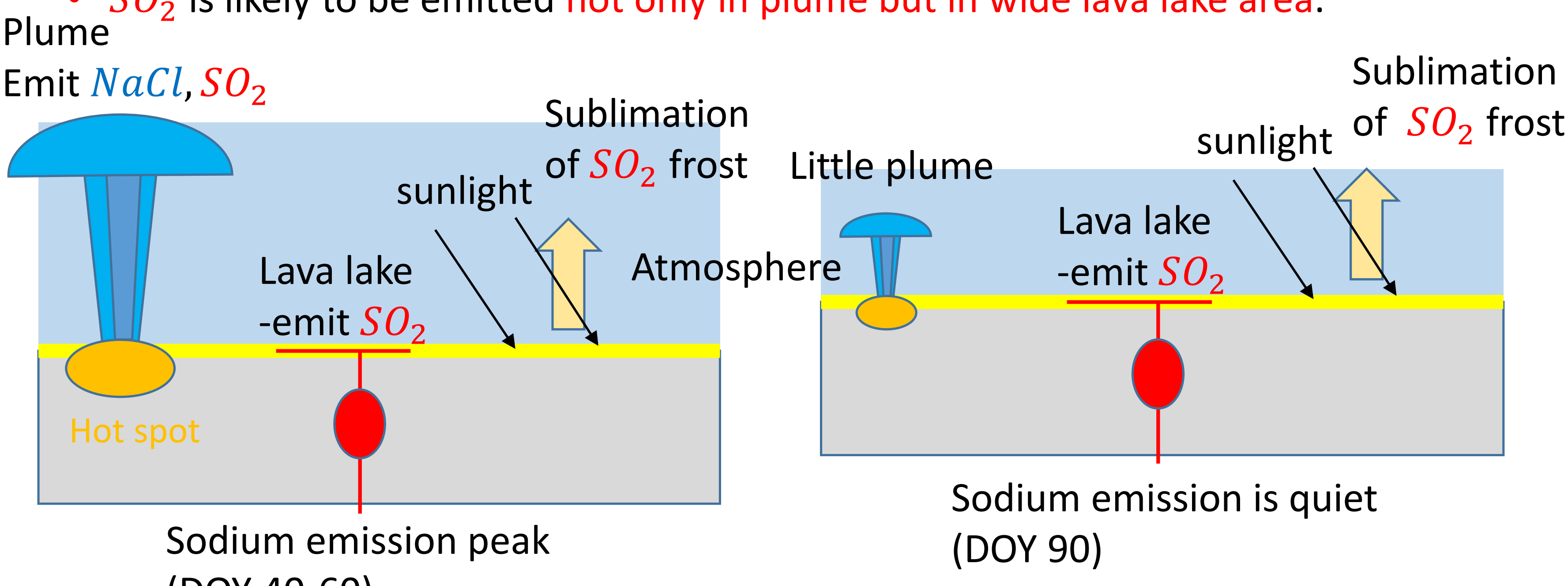


Fig. Suggestion of Io's atmospheric generation process (refer to *Lopes et al.*, [2004])

② Contribution of sublimation and volcanism

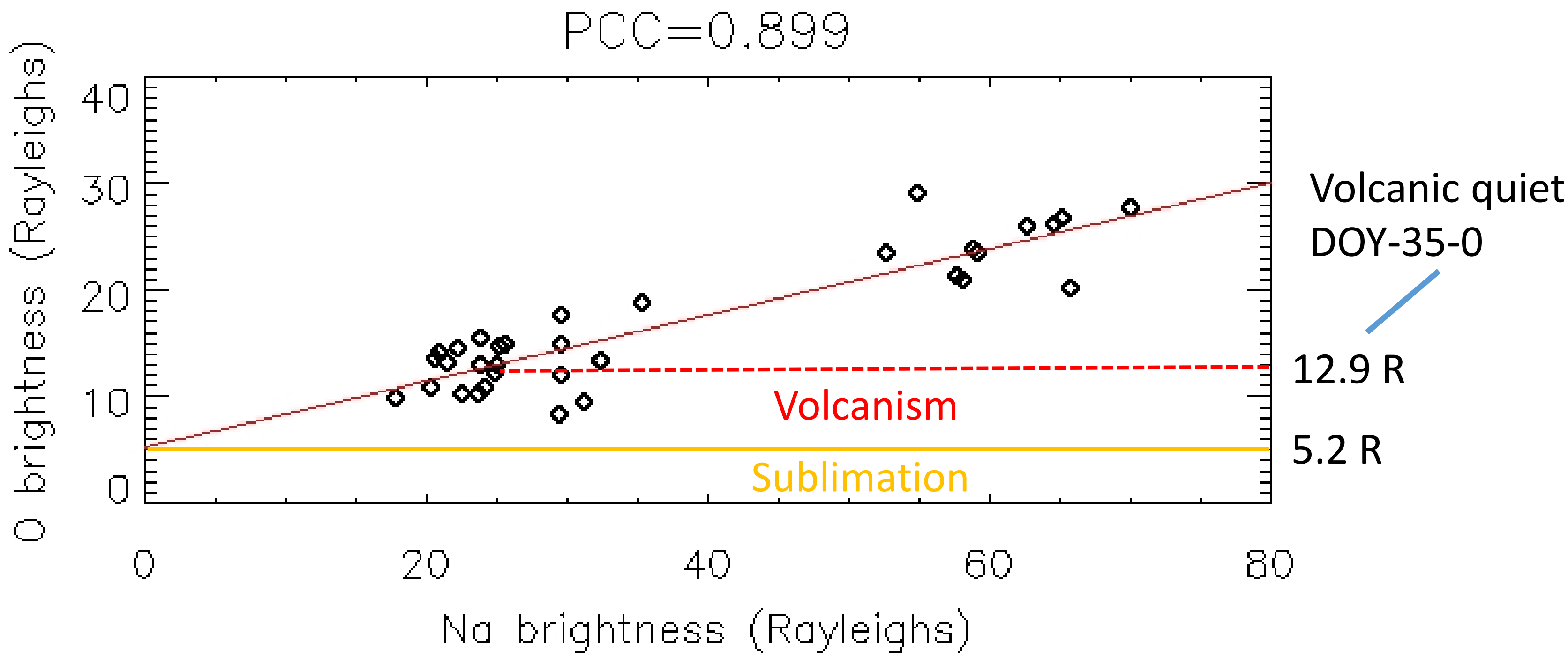
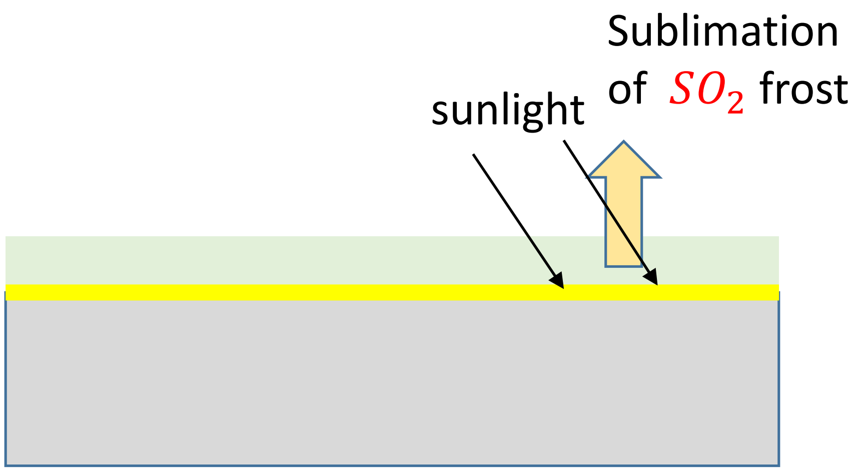


Fig. Correlation between neutral oxygen and sodium emission from DOY-35-50

② Contribution of sublimation and volcanism

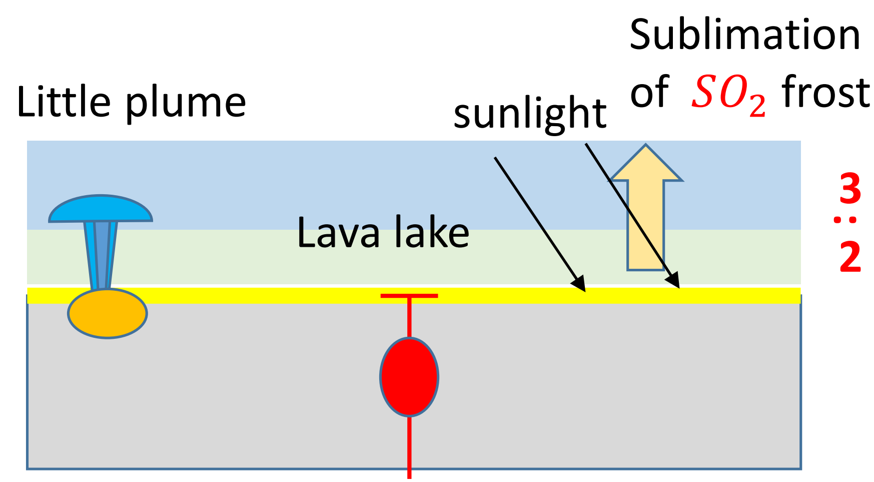


If volcanism did not occur
(sodium emission was 0 R)

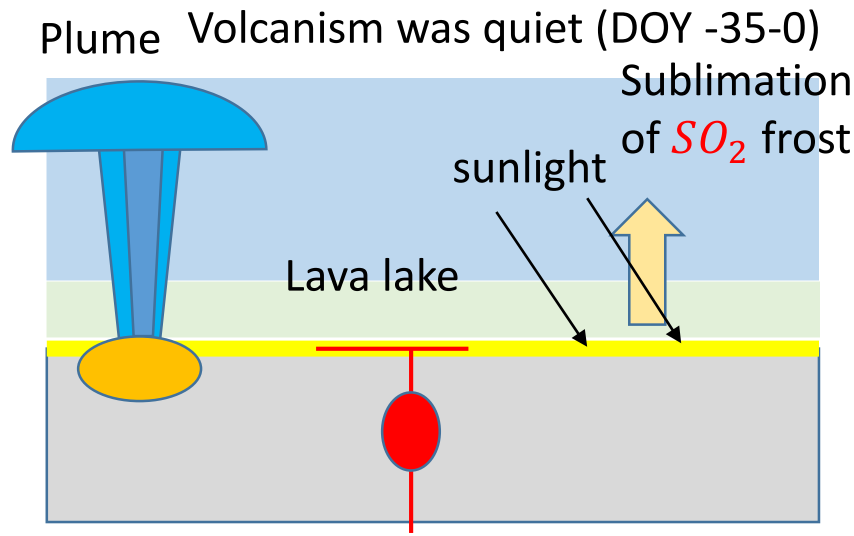
Atmosphere which is supplied by

Fig . Schematic explanation of contribution of Io’s atmospheric generation

This study

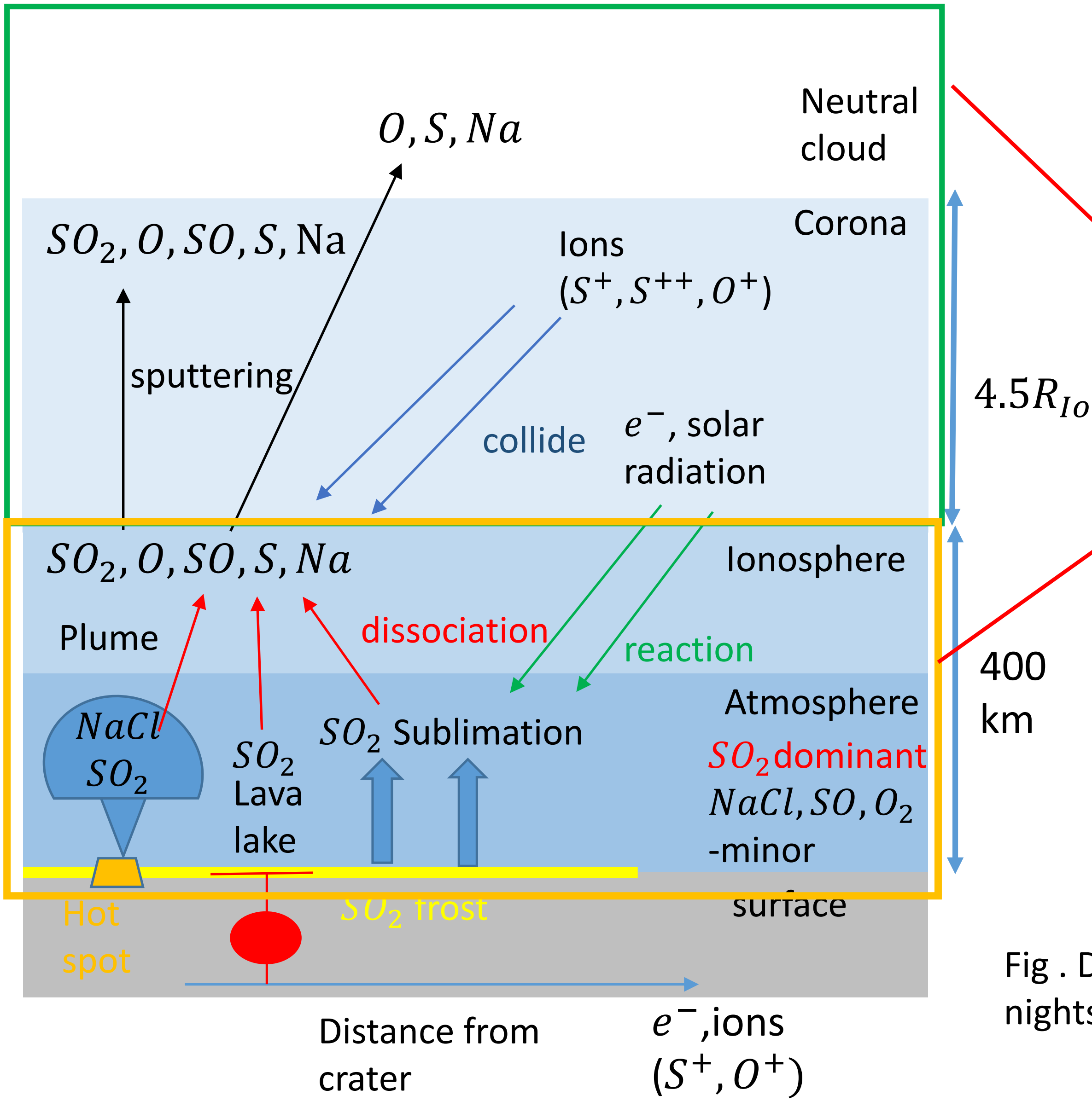


Volcanism was quiet (DOY -35-0)



Volcanism was active (DOY 40-60)

Generation and escape process of Io's atmosphere



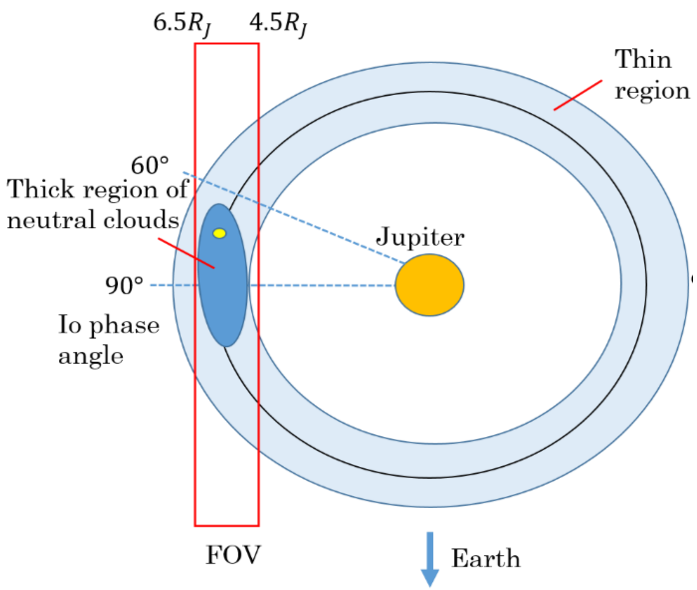
Spatial resolution of Hisaki/EXCEED is rough (17")

Which regions we mainly observed by Hisaki/EXCEED?

Fig . Drawings of dayside (top) and nightside (bottom) atmosphere.

Io phase angle dependence

- which atomic oxygen emission in this study reflects mainly the emission from atmosphere or that from corona and neutral cloud is unknown.



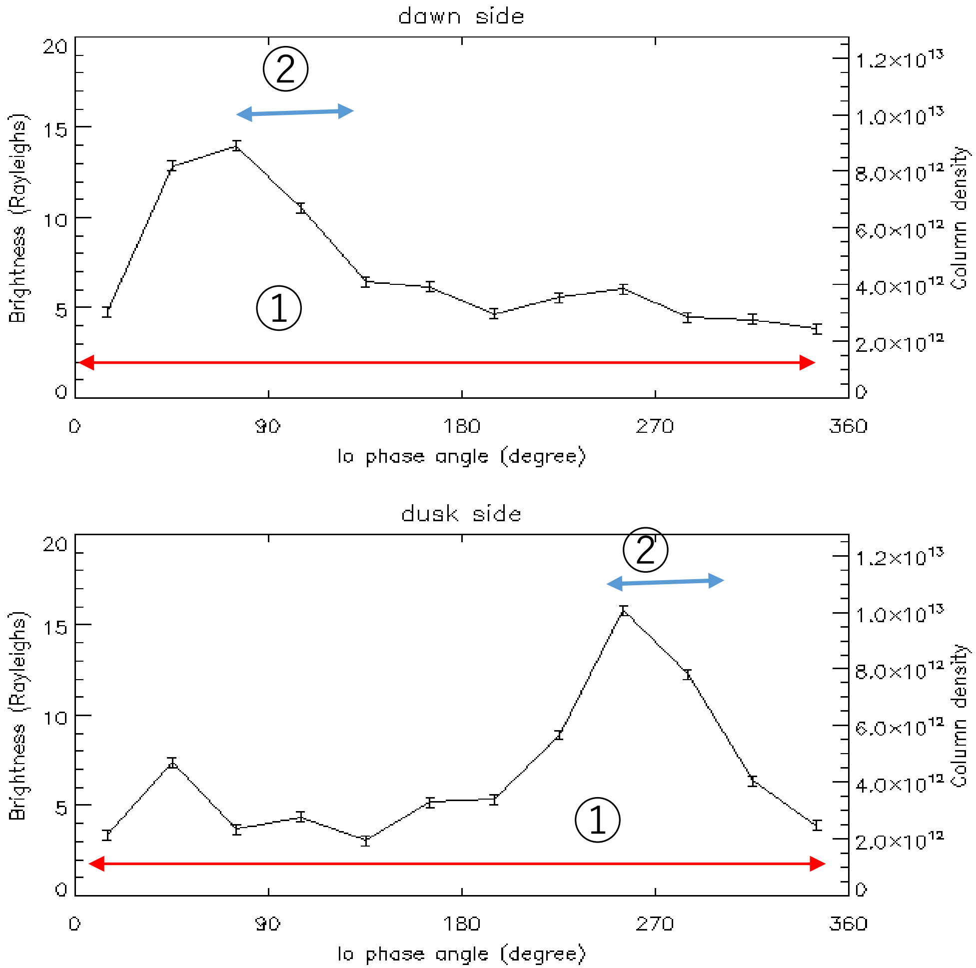


Fig . (Top) Schematic picture of oxygen neutral cloud around Io orbit (Bottom) Io phase dependence of atomic oxygen emission at 130.4 nm (DOY -35 to -1)

Generation and escape process of Io's atmosphere

Regions of atomic oxygen emission we observed mainly using Hisaki/EXCEED

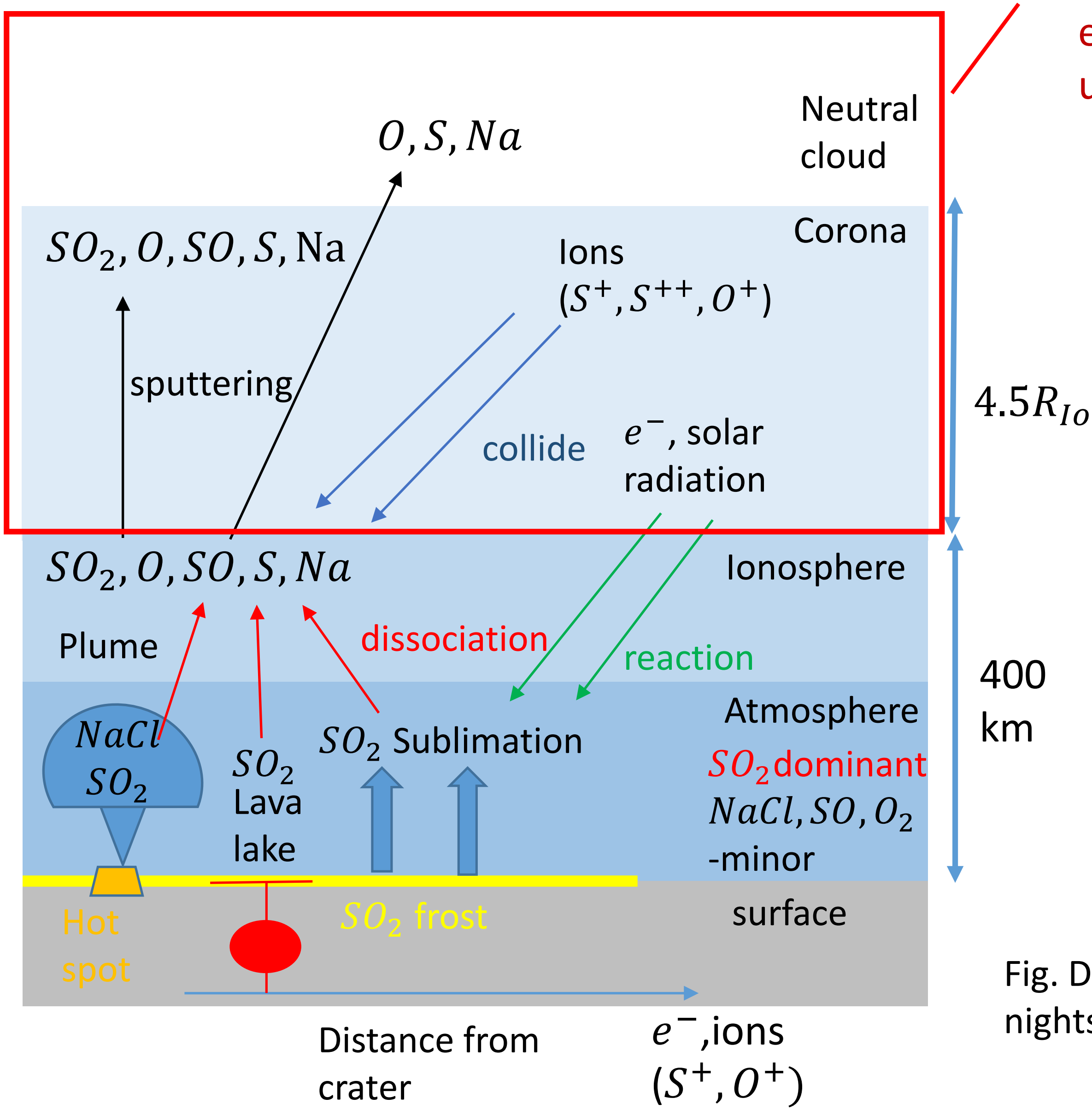


Fig. Drawings of dayside (top) and nightside (bottom) atmosphere.

Conclusions

- The time variation of atomic oxygen emission is well correlated with that of sodium emission (DOY -35 and 50)

➢ The ratio of production amount of atomic oxygen due to sublimation to that due to volcanism is estimated to be approximately 2:3.

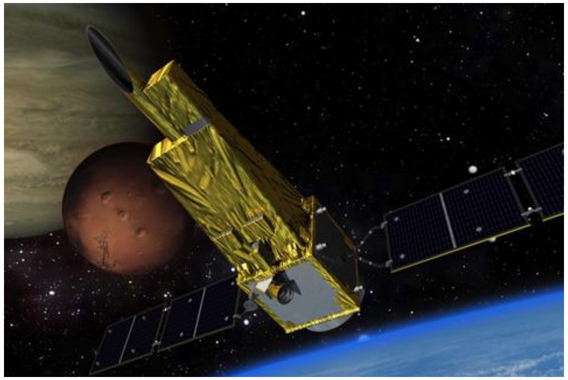
- Declining time period from peak to the normal value; sodium emission (40 days), atomic oxygen emission (60 days)

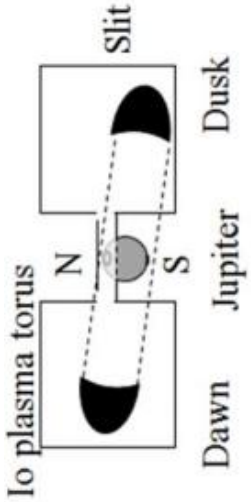
➢ Possible explanation; Increase of electron temperature and difference of source between SO_2 and $NaCl$

- Analysis of Io phase angle dependence shows atomic oxygen distributes uniformly along the Io's orbit.

Instrument; Hisaki/EXCEED

- The Sprint-A (Hisaki) satellite with EUV spectrometer (EXCEED) is orbiting around earth and make spectral image around planet
- Flight altitude　950−1150 km
- Revolution period　106 minutes (13 orbits per day)
- Wavelength range　52.0-148.0 nm
- Wavelength resolution　0.3-0.9 nm
- Spatial resolution　17”





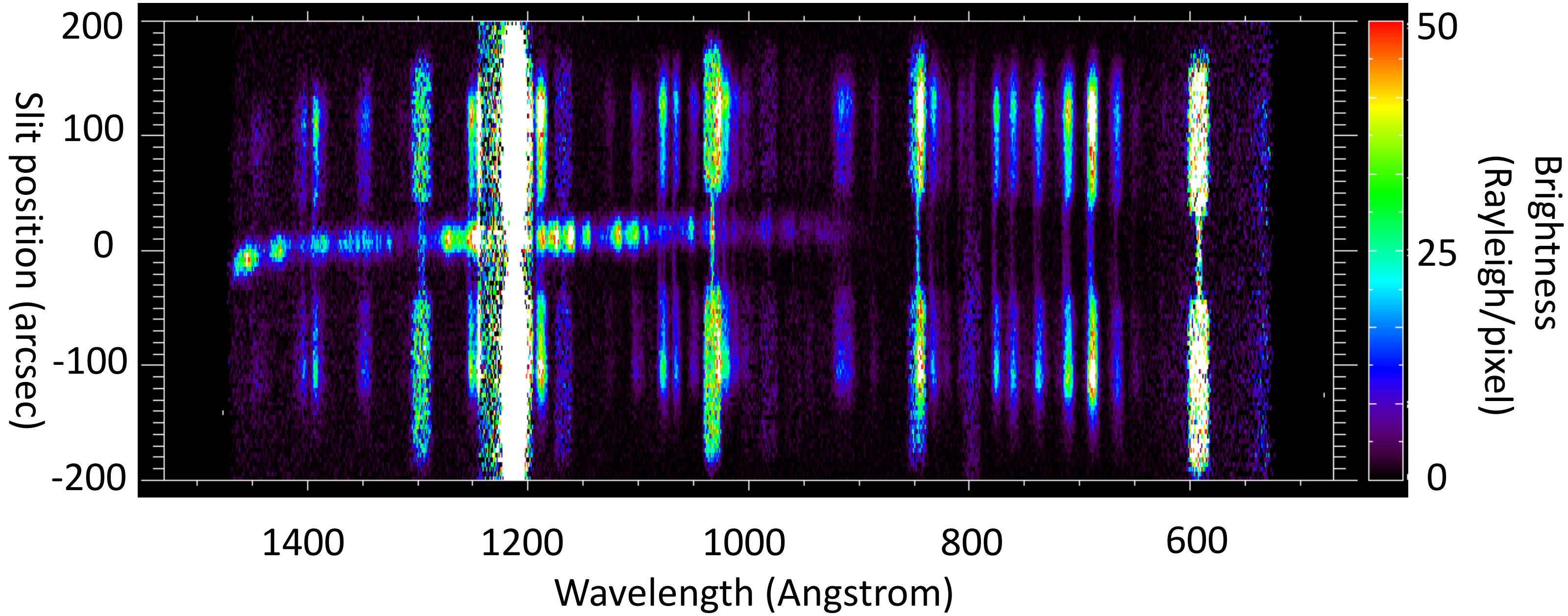


Fig 5. (left) schematic explanation of the dumbbell-shape slit observation [*Yoshikawa et al.,* 2014],(Right) spectral image of Io torus observed by dumbbell-shape slit

Mechanism of emission of atomic oxygen at 130.4 nm and sodium D-line

- Two process are considerable of emission at 130.4 nm around Io

  Column density; *N(O)*, Brightness $B_{130.4\,nm} = B_{RS} + B_{EI}$ (Rayleighs)

  [*Skinner and Durrance* 1986]

1. Solar resonant scattering；absorb sunlight at 130.4 nm selectively

$$B_{RS} = \frac{1}{10^6}\int n(z) g dz = \frac{1}{10^6} N(O) g \quad \text{(Rayleighs)}$$

$$g = \pi F_\lambda \left(\frac{\pi e^2}{mc^2}\right) f \ (\text{photons} \cdot \text{s}^{-1})$$

g; *g*-factor, related to solar irradiance
$n(z)$; oxygen number density

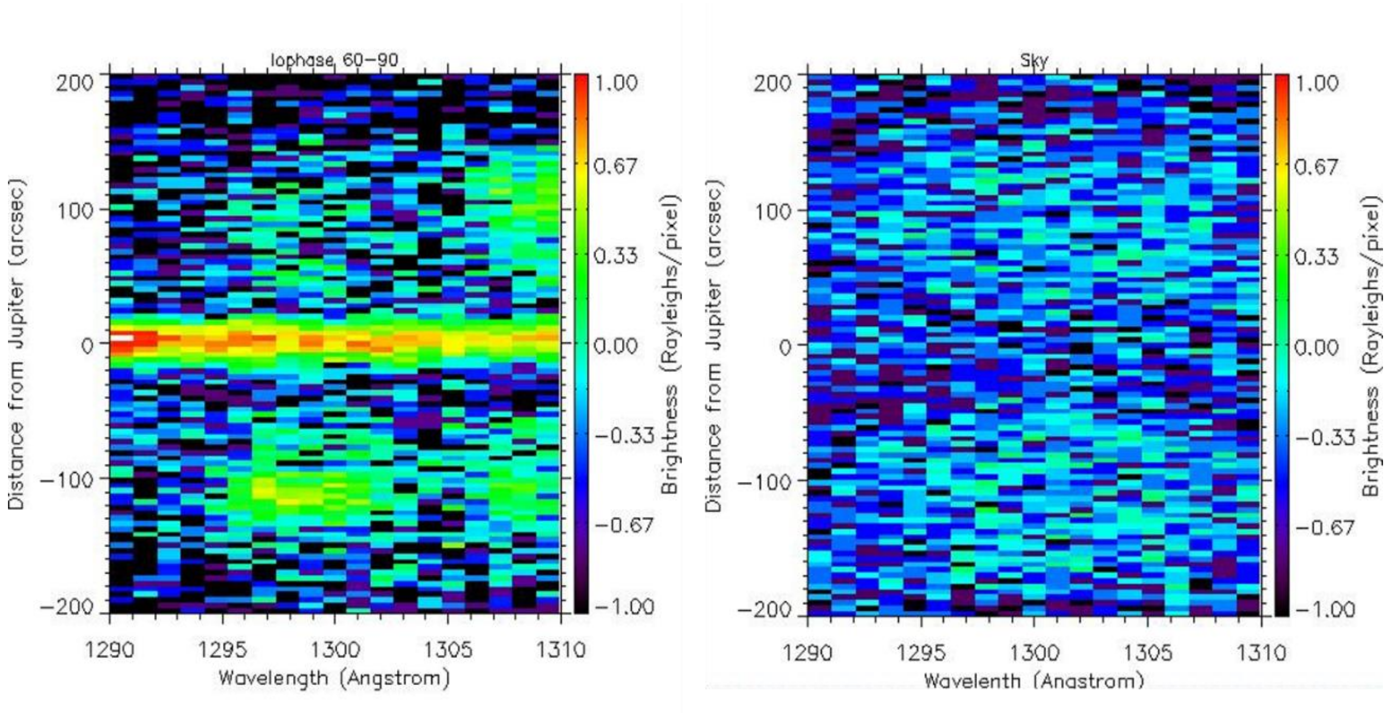
- Sodium D-line emission is mainly caused by solar resonant scattering

2. Electron impact excitation；$O + e^- \rightarrow O^* + e^-$

$$B_{EI} = \int n(z) n_e \alpha(n_e, T_e) dz = n_e \alpha(T_e) N(O) \quad (Rayleighs)$$

n_e ;electron density
T_e ;electron temperature
α ;rate coefficient for electron impact excitations

- Contribution of emission at 130.4 nm $B_{EI} : B_{RS} = 2:1$



.(Left) Spectral image subtracting off-Jupiter from on-Jupiter mode using a dumbbell-shaped slit. Io phase angle of this image is limited to 60-90°. (Right) Spectral image of off-Jupiter (sky) using the same slit.

Io phase angle dependence

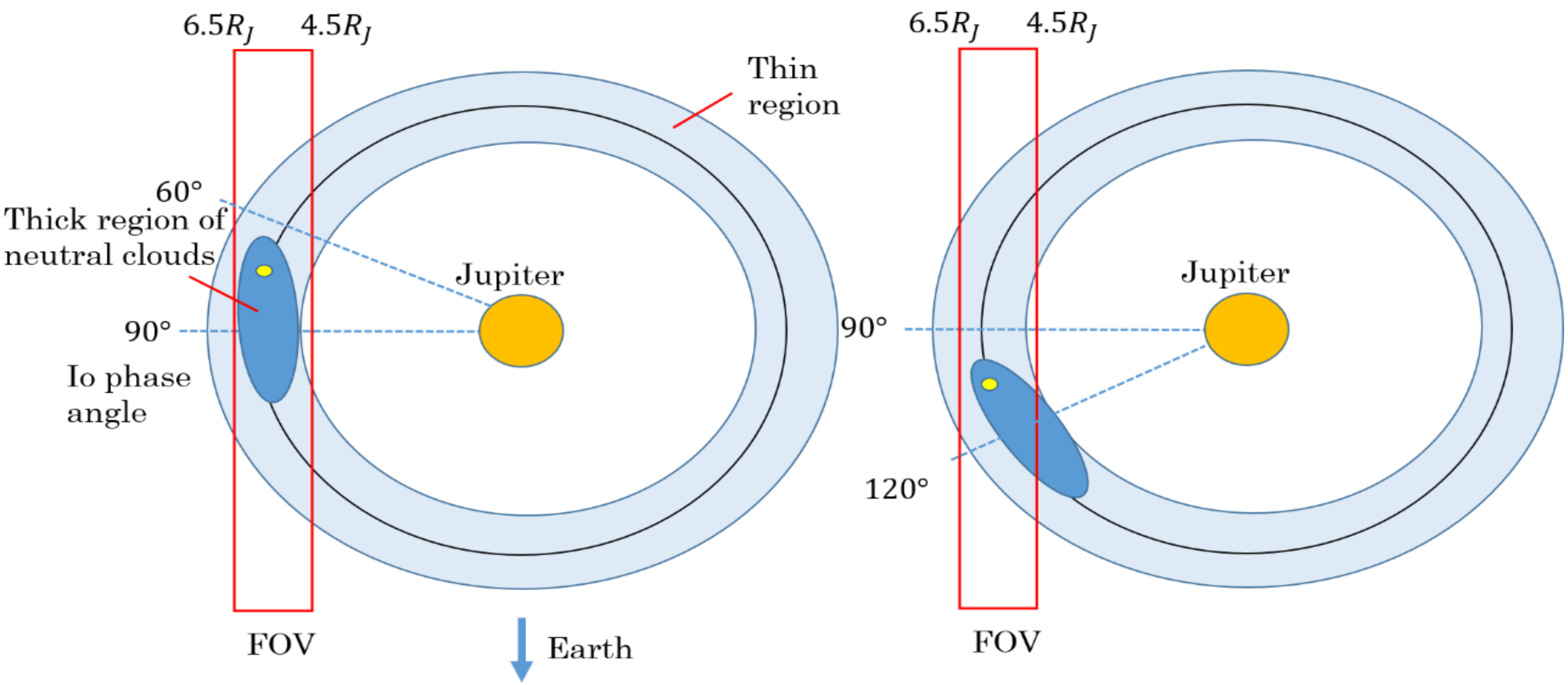


Fig. Schematic drawings of distribution of atomic oxygen for the explanation of the plots for the cases on Io phase angle of $60 - 90°$ (left) and that of $90 - 120°$ (right), respectively.