Io's lower atmosphere: mapping chemical composition and $^{34}S/^{32}S$ ratio in SO_2

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Tried and failed


Credit: ALMA (ESO/NAOJ/NRAO), O. Dessibourg

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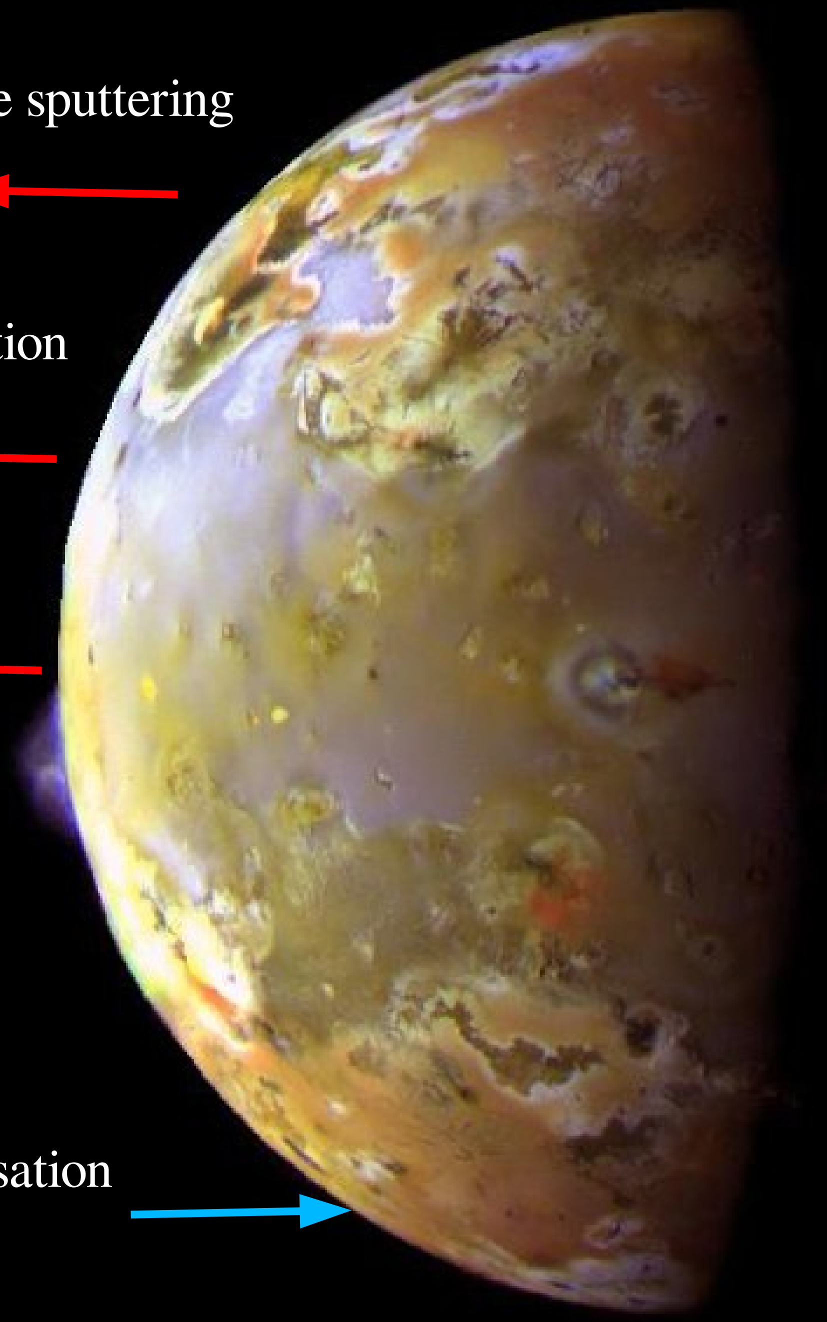
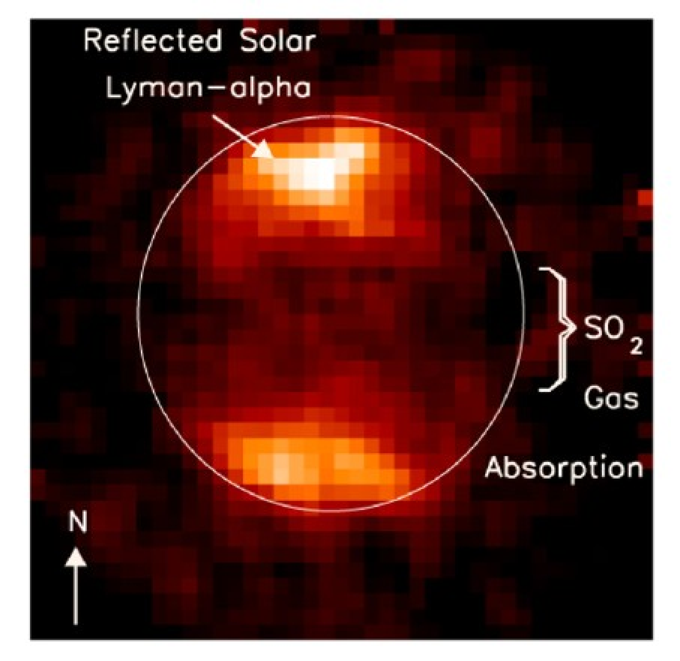
- **Thin (1-10 nbar)**
- **Mostly SO_2 (SO, NaCl, KCl…)**
- **Permanent but variable**
- **Large spatial variations**



NASA/JPL/University of Arizona

Atmospheric maps to identify sources

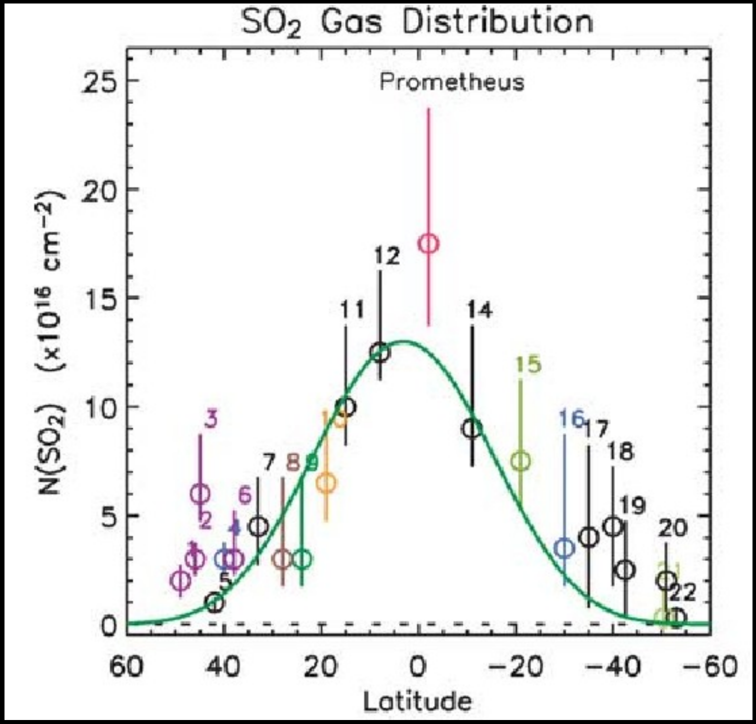


SO$_2$:
- concentrated in equatorial band,
- maximum on anti-jovian side
- decrease with latitude

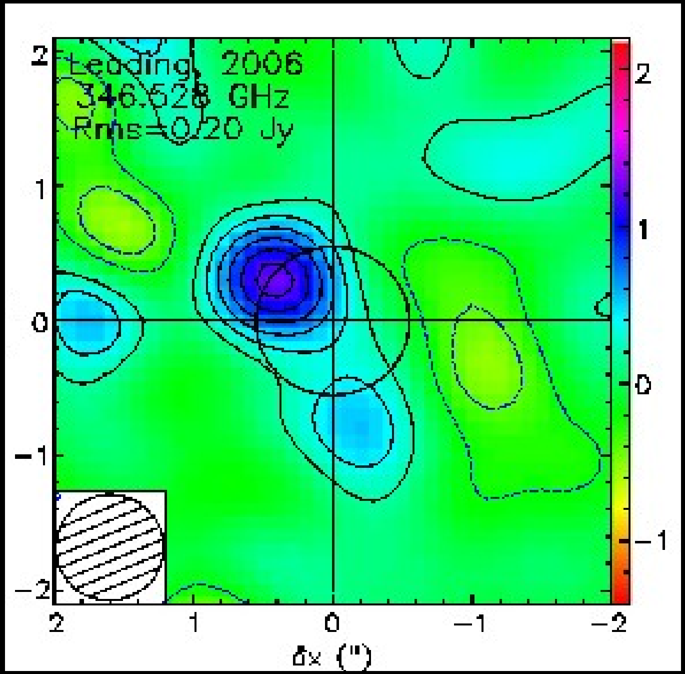
-> **sublimation-sustained?**

Feaga et al., 2009 :
Lyman-a SO_2 mapping

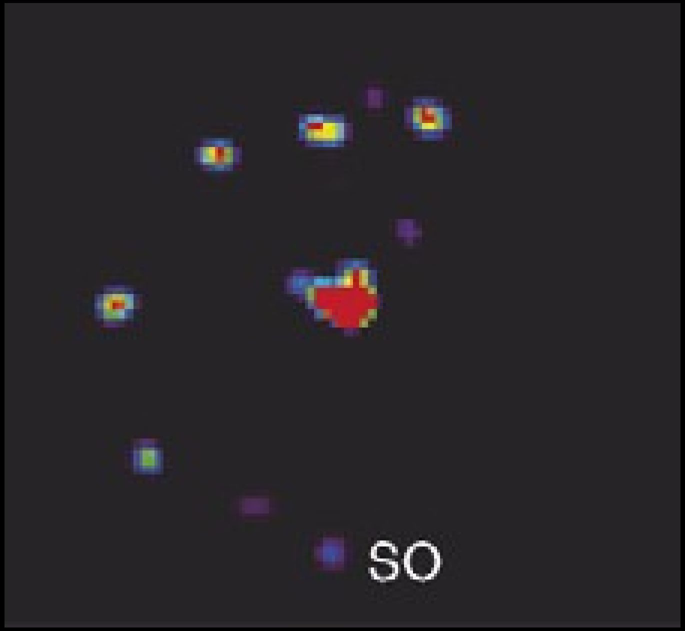
Jessup et al., 2004 :
HST SO_2 latitudinal mapping



Moullet et al., 2010 :
Submm SO line map



SO and NaCl:
- localized distribution,
- consistent with immediate **plume outgassing + additional source of SO** (SO_2 photolysis ?)



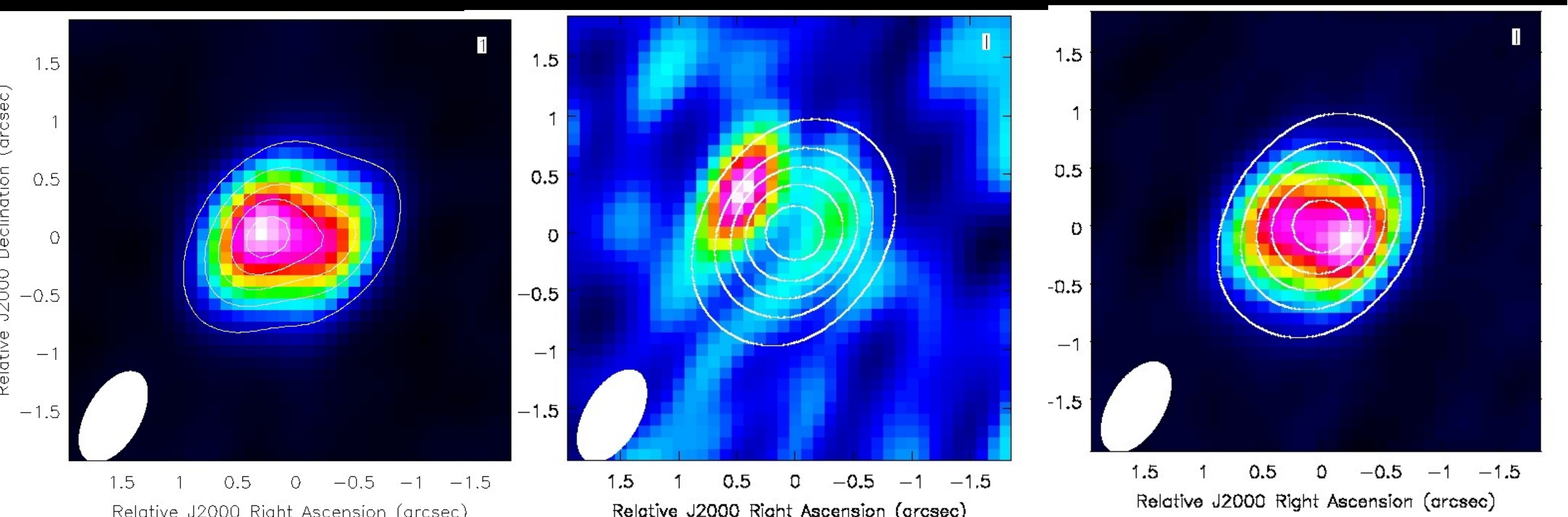
De Pater et al., 2007
SO emission in eclipse

ALMA observations: high SNR simultaneous multi-species/isotopologues maps

- Atacama Large Millimeter Array (Chile): interferometric observations at 0.8 mm with 21-37 antennas
- Three observation dates (2012, 2015), centered at 65, 113, 272° W
- **Spatial resolution ~0.25-0.5"** (for a 1.1" disk)
- Targeting lines of SO_2, $^{34}SO_2$, KCl, NaCl, SO + surface thermal

Comparing molecular distributions

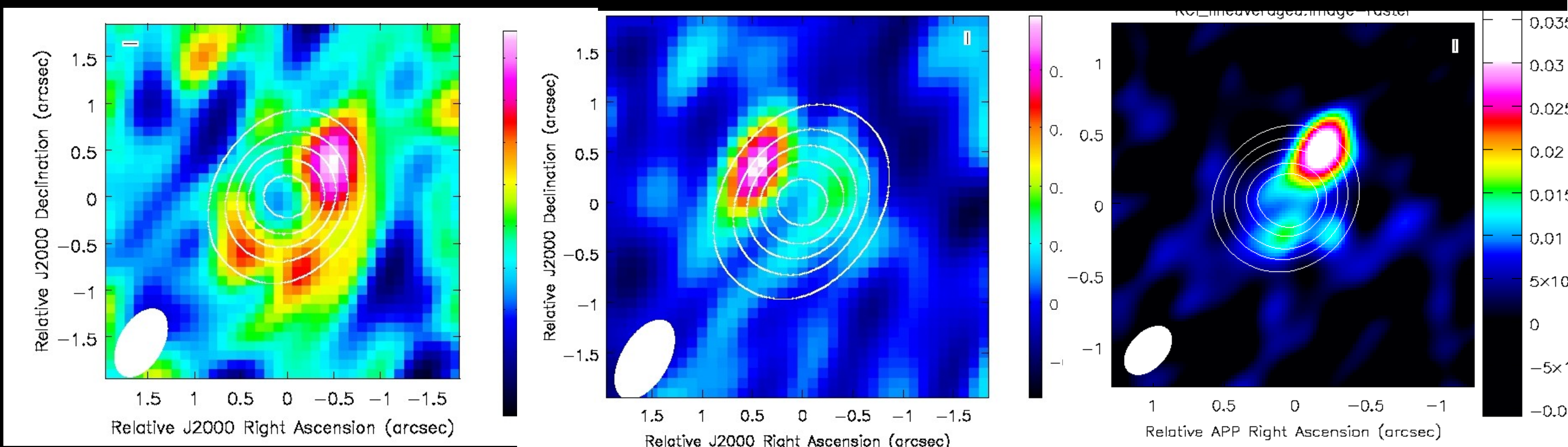
113°W SO_2 **113°W KCl** **113°W SO**



Simultaneous mapping of SO_2, KCl and SO show different distribution (extent and peak location): **Distinct atmospheric sources**

KCl mapping: first detection

66°W **113°W** **272°W**

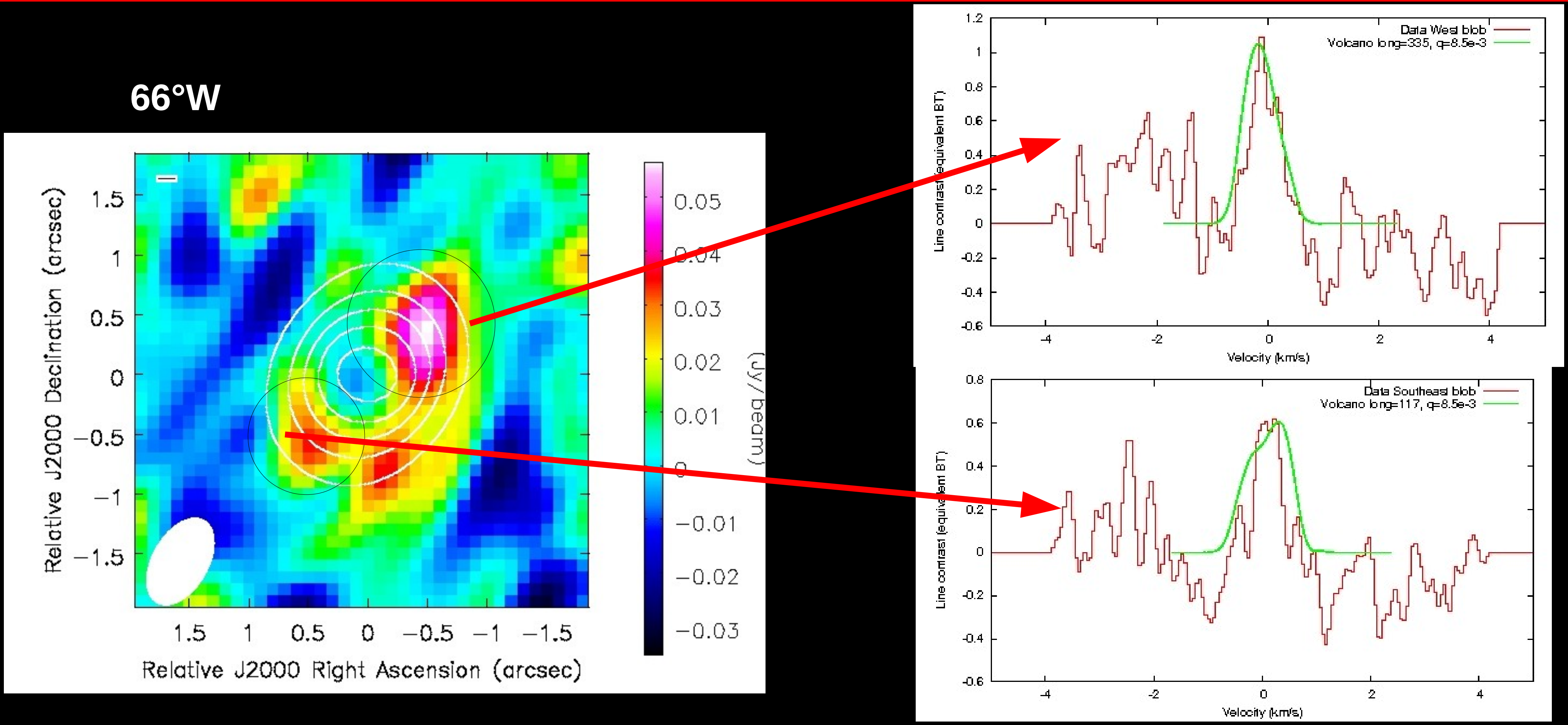


KCl emission distributed in small-scale 'blobs', 3-8σ

→ **purely volcanic (plume) sustained KCl from active eruptions?**

Atmospheric KCl expected to be the K-carrier to the torus

KCl volcanic modeling

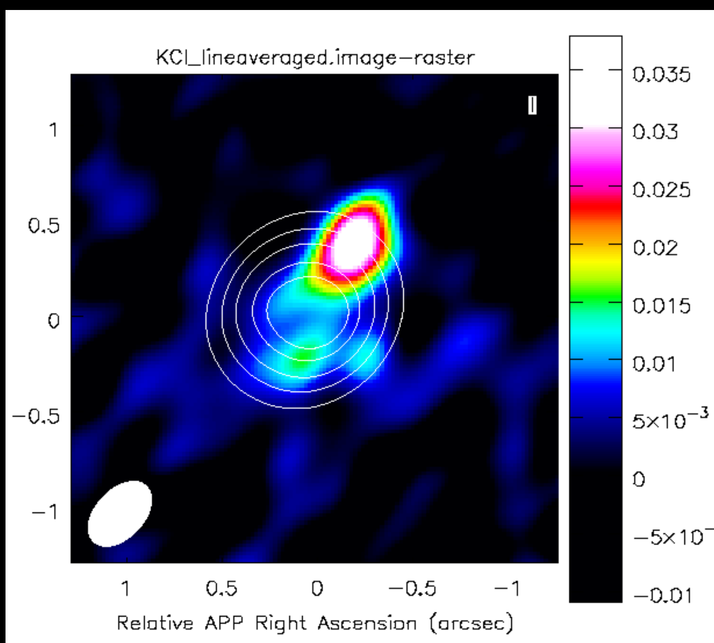


KCl local emission consistent with single small plume with KCl/SO_2~8.5e-3

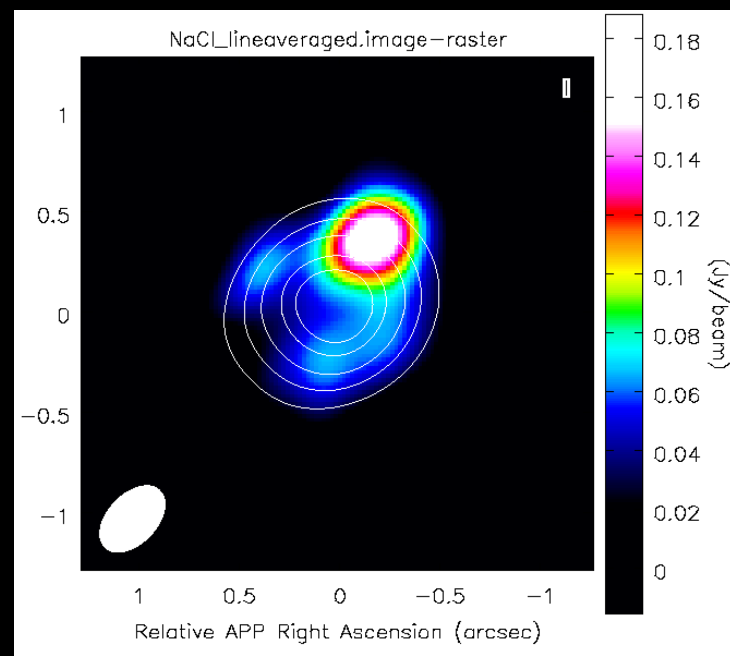
Ratio expected by plume chemistry (Schaefer &Fegley, 2005)

Comparing KCl and NaCl (2015)

KCl



NaCl



- High Level of co-location – common sources

- Atmospheric NaCl/KCl is 5 - 6.5,
lower than cosmic Na/K (16) and corona Na/K (10 +/-3, Brown 2001)

Rationale behind attempting to map $^{34}SO_2$

Rotational lines are **sensitive to the first 1-2 scale heights (~up to 50 km):** probe regions of recently produced SO_2 gas, less affected by escape, ...

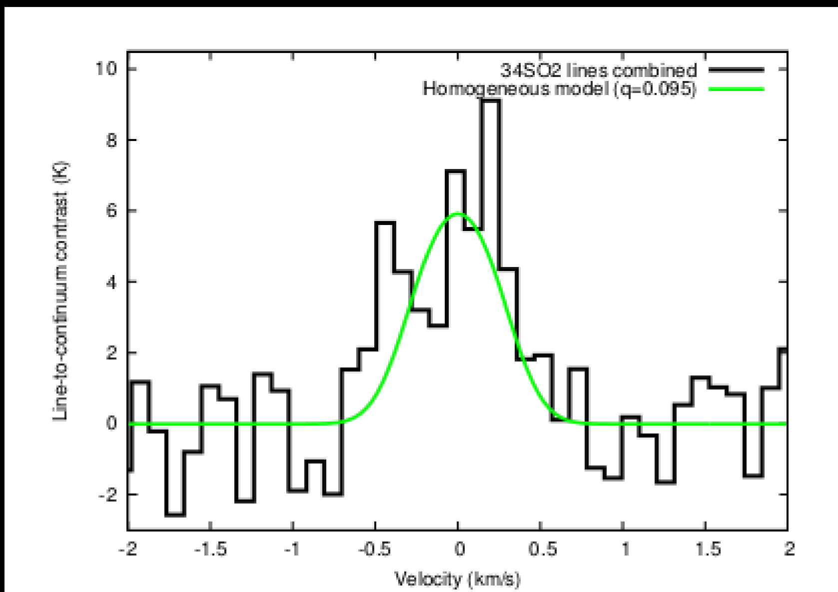
- could show trends in sublimation efficiency (latitude/ longitude/ geography)

- lowest values of $^{34}S/^{32}S$ ratio in lower atmosphere may be the closest indication to ratio in frost (only $^{33}S/^{32}S$ measured in frost, Howell 1989)

- comparison with ratios over Jupiter's tracking Io's 'spraying'

- verify previous estimate of $^{34}S/^{32}S$ in SO_2 (APEX)

Previous $^{34}SO_2$ detection in gas phase



First (low SNR) $^{34}SO_2$ detection with APEX antenna (Moullet et al. 2013):

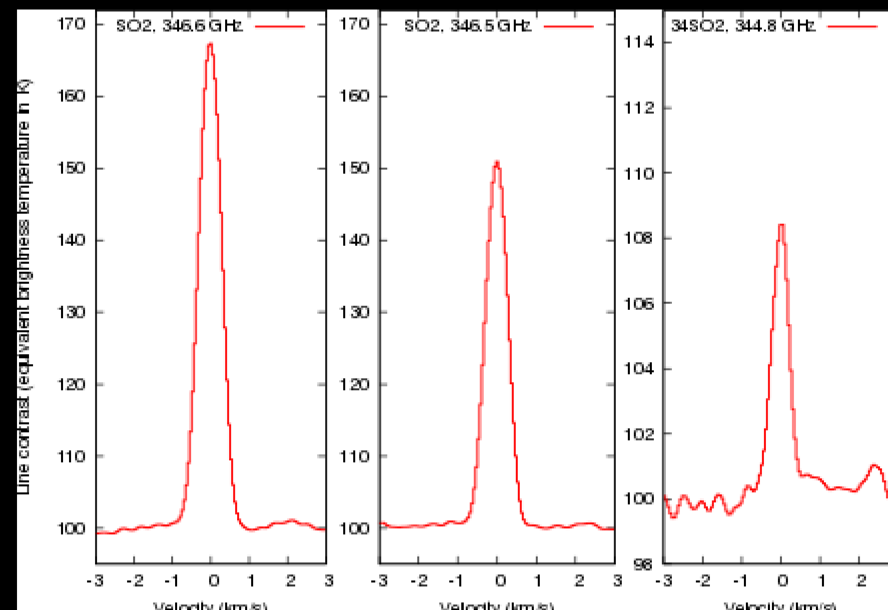
→ inferred very high $^{34}S/^{32}S$ in SO_2
0.08-0.095 +/-0.15 (Earth: 0.044)

Possible issues:

low SNR
incorrect interpretation due to spatially-averaged data
incorrect assumption of spatially uniform abundance ratio
Incorrect assumption on temperature profile (non-uniform)

ALMA Disk-averaged spectra

- **High SNR on** $^{34}SO_2$ lines (>45) (undetected $^{33}SO_2$ lines)



- **$^{34}SO_2/^{32}SO_2$ 0.07-0.075**

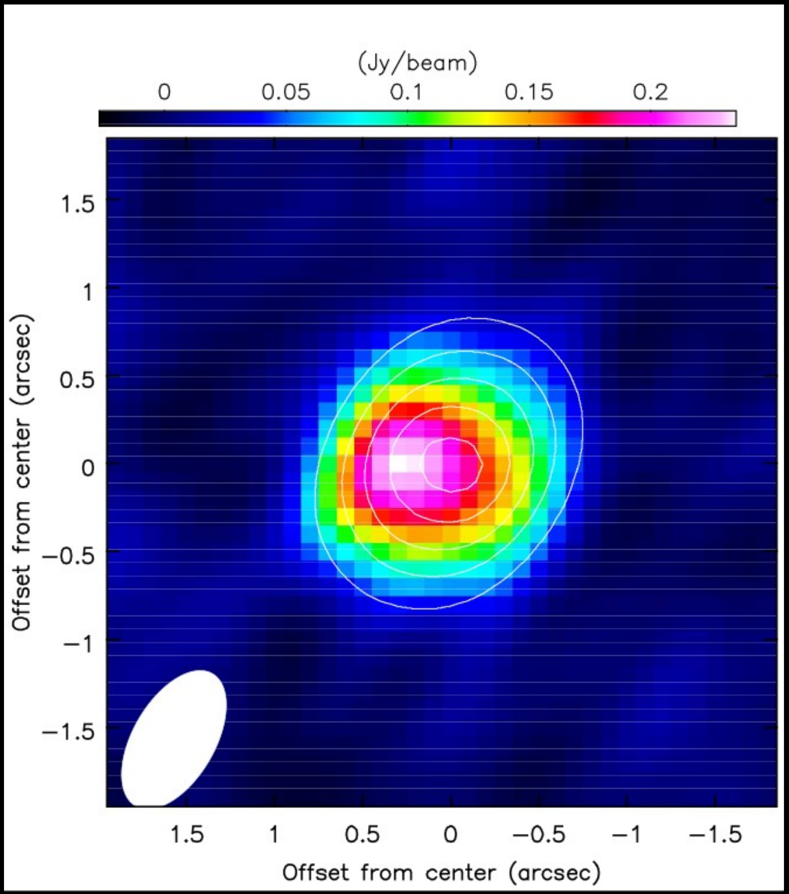
  –> compatible with APEX measurement

Such an enrichment in ^{34}S would be hard to explain:

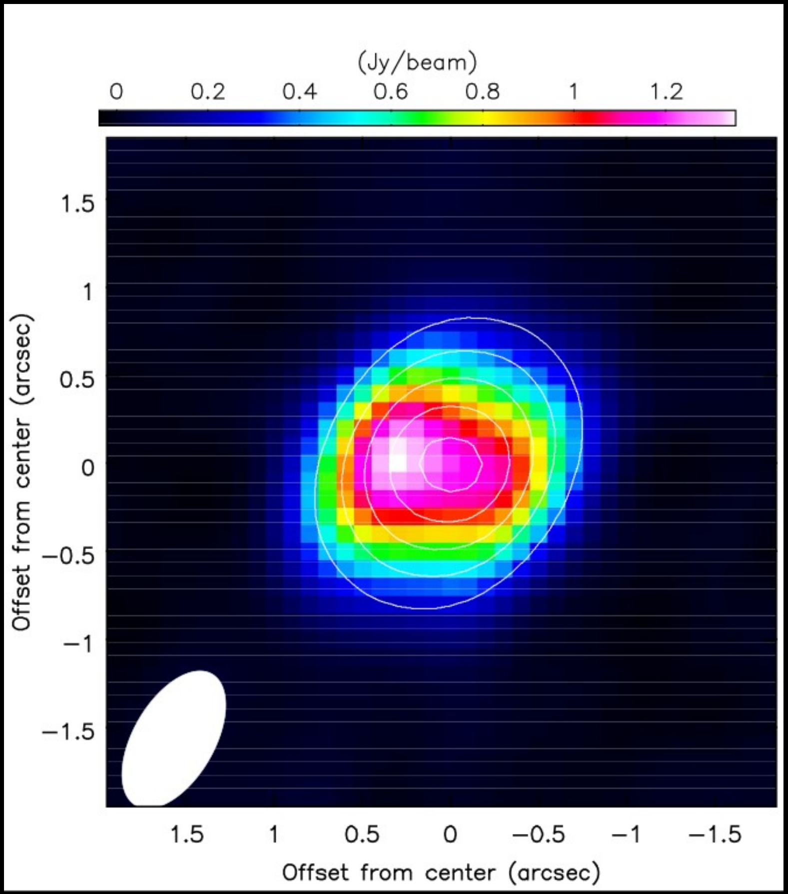
Ionian magmas enriched in ^{34}S? (no such anomalies on Earth)
Compounded fractionation in frost from sublimation/condensation cycle
Compounded effect from fractionation in photolysis (→ SO)

Variable $^{34}SO_2/^{32}SO_2$ abundance ratio?

$^{34}SO_2$

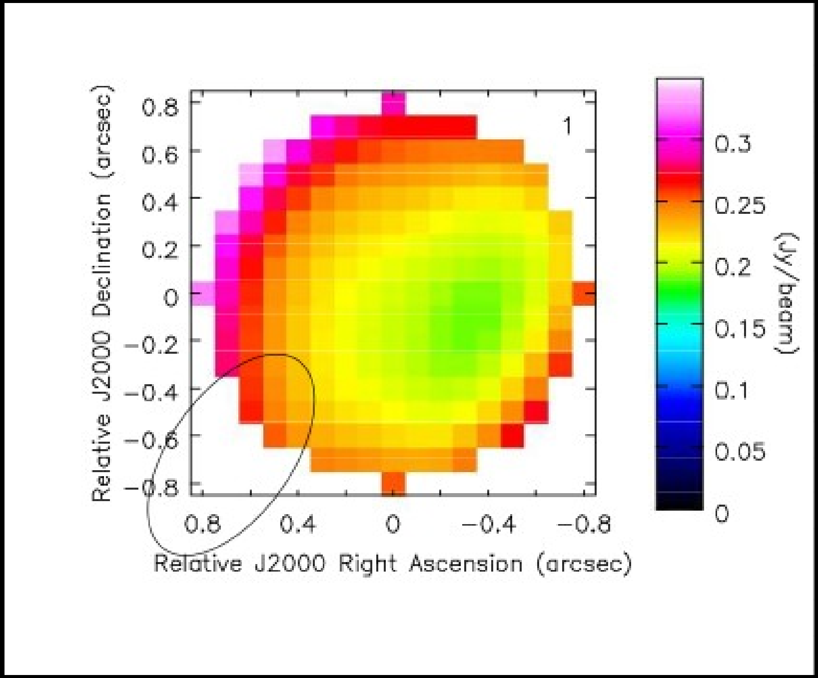


$^{32}SO_2$



Similar large-scale distribution of line emission

Line emission ratio is not a direct indicator of ratio of abundances:
lines not optically thin



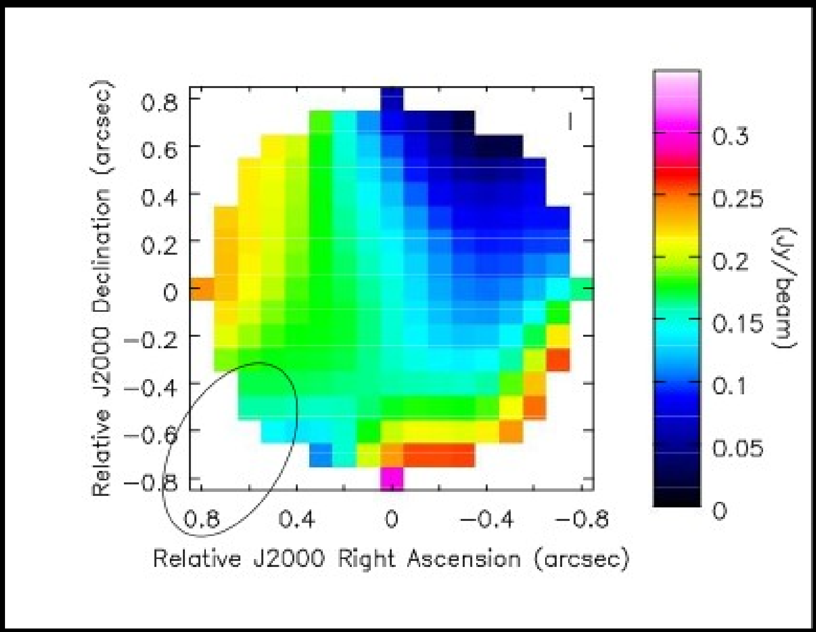
For uniform $^{34}SO_2/^{32}SO_2$ abundance ratio, $^{34}SO_2/^{32}SO_2$ line ratio traces probed column density:

geographic pressure variations + airmass/limb sounding

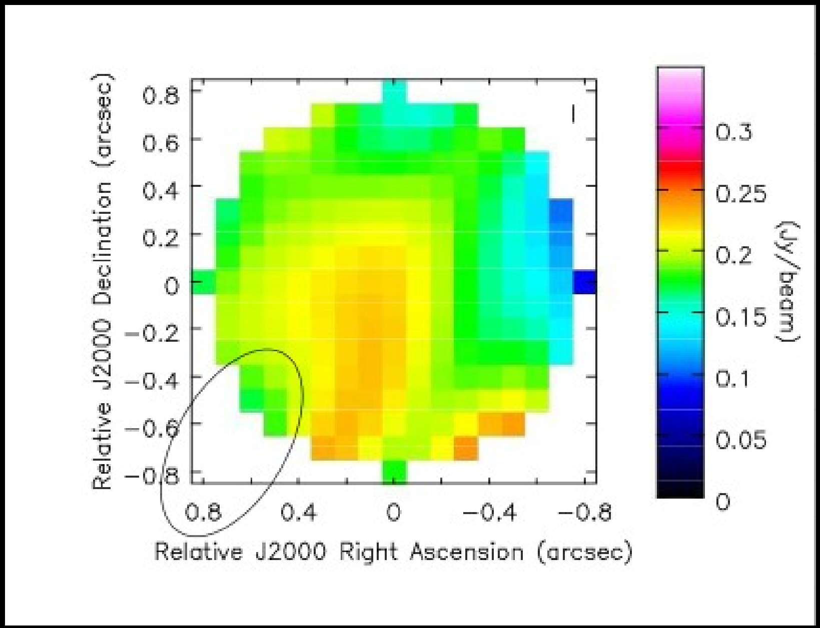
Modeled $^{34}SO_2/^{32}SO_2$ line ratio for $^{32}SO_2$ distribution consistent with data

Observed line emission ratio does not strictly trace probed column density, especially at mid-high latitude

October 17, 2012



October 19, 2012



Even taking into account the possibility of variations of $^{34}SO_2/^{32}SO_2$ abundance ratio, local $^{34}SO_2/^{32}SO_2$ abundance ratio still appear much higher than Earth reference

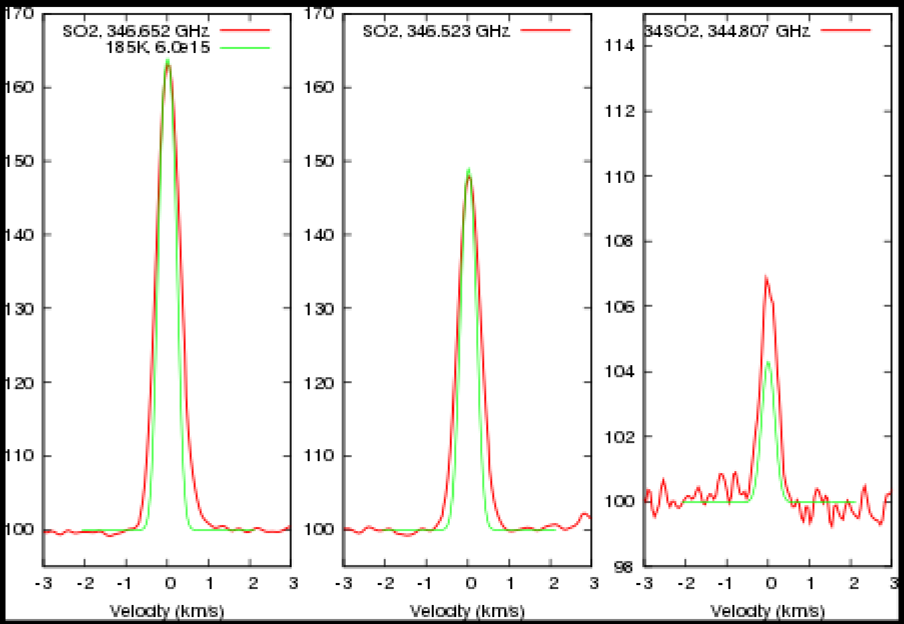
The devil may be in the radiative transfer model assumptions

Rotational lines are **sensitive to the first 1-2 scale heights (~up to 50 km)**

$^{32}SO_2$ lines have similar intensity than $^{34}SO_2$ lines, but column density ~20 times larger: significant difference in opacity

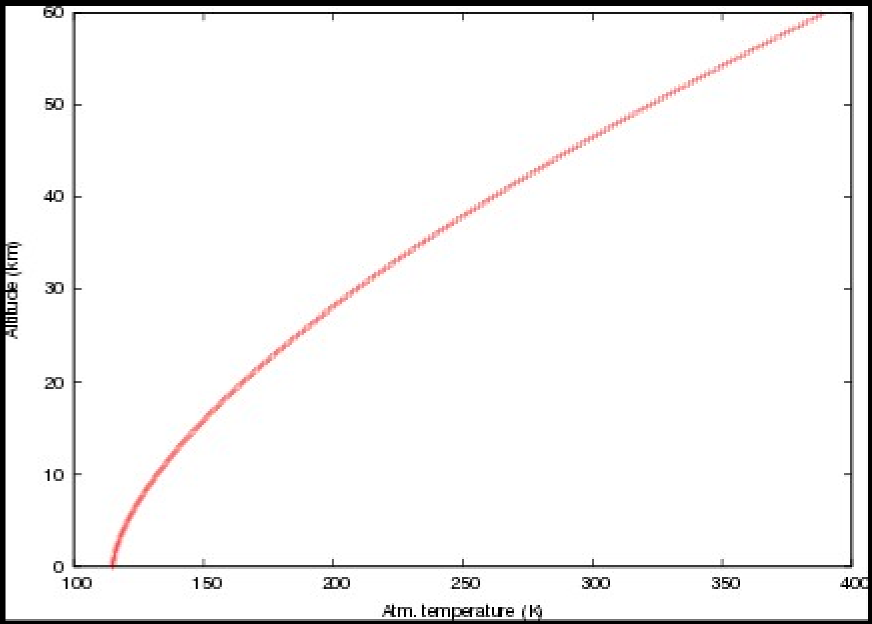
$^{34}SO_2$ lines are optically thin (probe down to ground)
$^{34}SO_2$ lines are much less thin (tau=1 at 0-30 km)

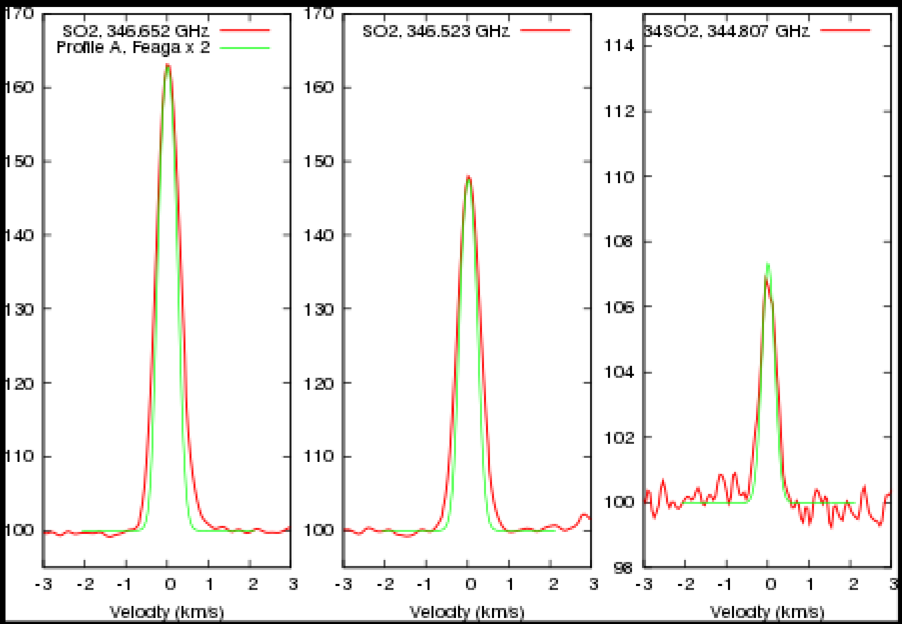
→ any temperature gradient across the first scale height can completely change the interpretation of line ratio in terms of abundance ratio



Line fits for with a uniform temperature profile and earth-like $^{34}SO_2/^{32}SO_2$ abundance ratio :

$^{34}SO_2$ line intensity is underestimated





Example of fitted temperature profile which could reconcile ALMA data with a Earth-like $^{34}SO_2/^{32}SO_2$ abundance ratio

Corresponding line fits

No direct constraints available on temperature profile in the lower atmosphere

Models predict either small mesosphere ('thick' atmosphere case) or just stratosphere ('thin' case)

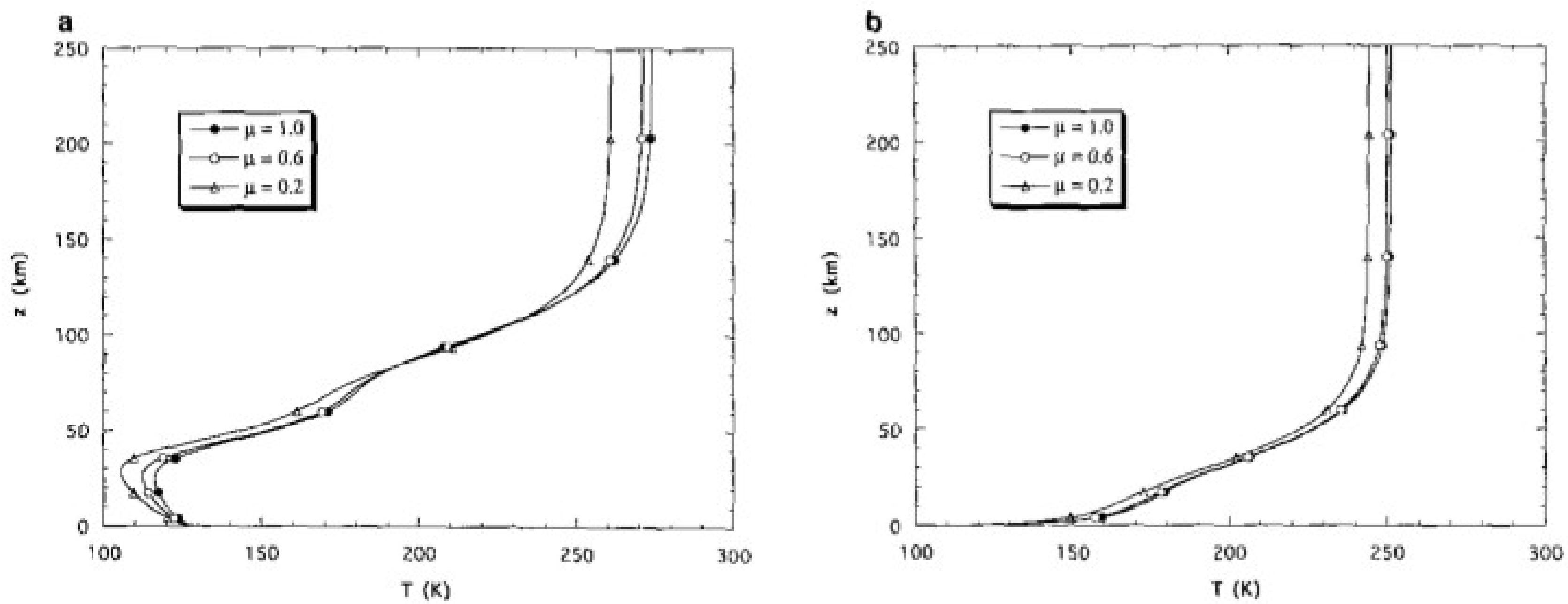


FIG. 4. Io's vertical temperature profiles calculated with a fixed surface temperature T_0 and a fixed surface pressure p_0. (a) T_0 = 130 and $p_0 = 1.3 \times 10^{-7}$ bar. (b) T_0 = 115 and $p_0 = 0.3 \times 10^{-9}$ bar.

Strobel et al., 1994

What we would need for a robust assessment

- strongly constrain thermal profile (and its spatial variations)

- target much fainter SO_2 lines (tau <<0.1) for which differential opacity contribution does not play as much a factor

- target SO lines rather than SO_2 (less opaque)

In all cases, high spatial resolution is needed to separate regions with different opacity regimes (limb)

Other isotopic ratios in Io's atmosphere that could be explored through ultra-sensitive mm spectroscopy to relate Io-genic material to material in the Jupiter system

^{37}Cl (KaCl, NaCl)

^{41}K (KaCl, NaCl) more challenging

Much less abundant species → fewer interpretations issues due to differential probing