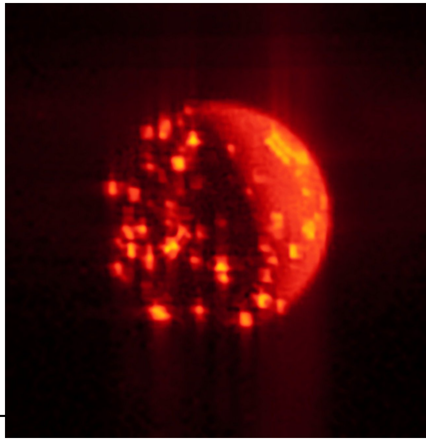
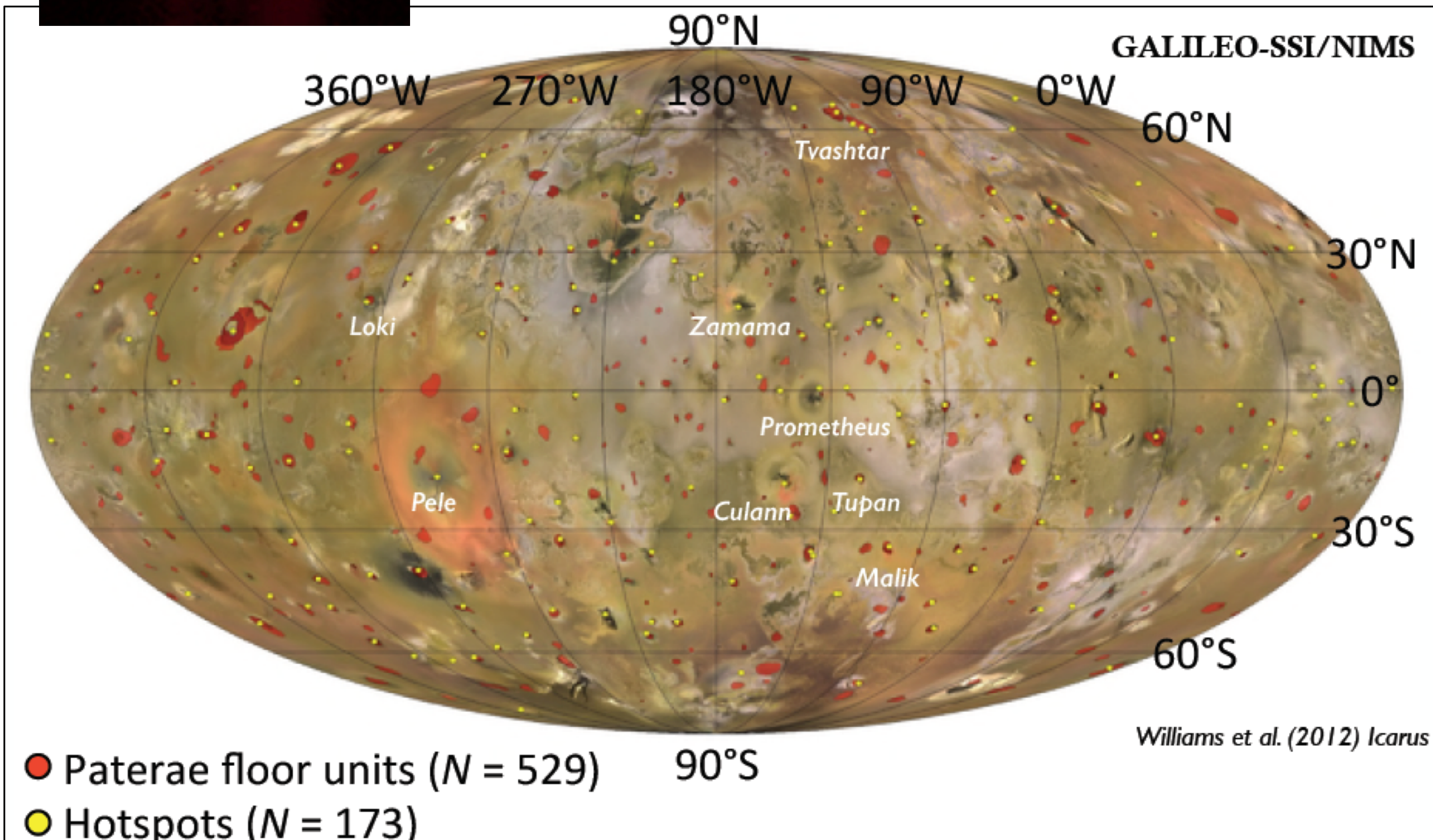
Io Escape Processes

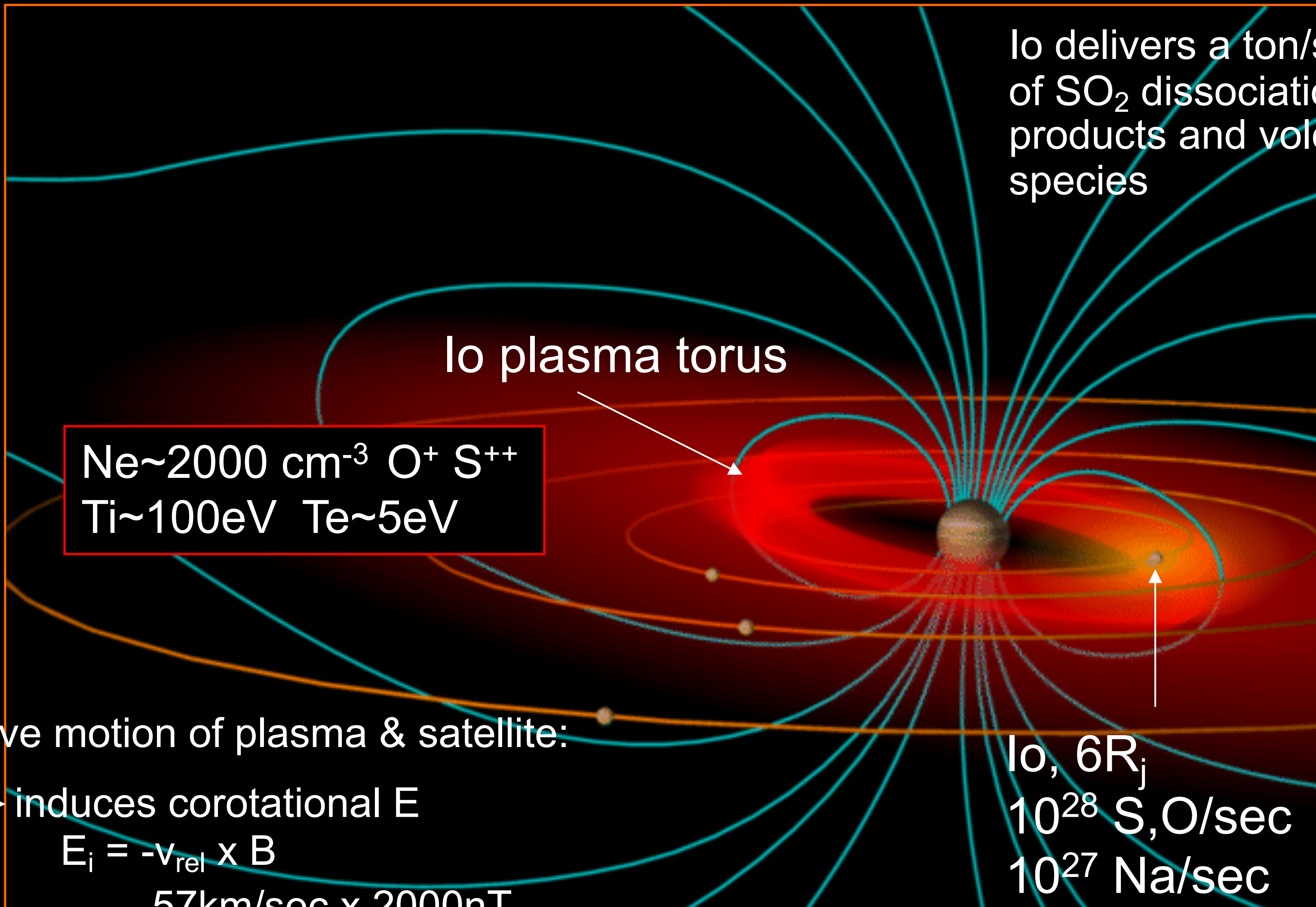
Melissa A. McGrath
SETI Institute

Io has extensive volcanic activity





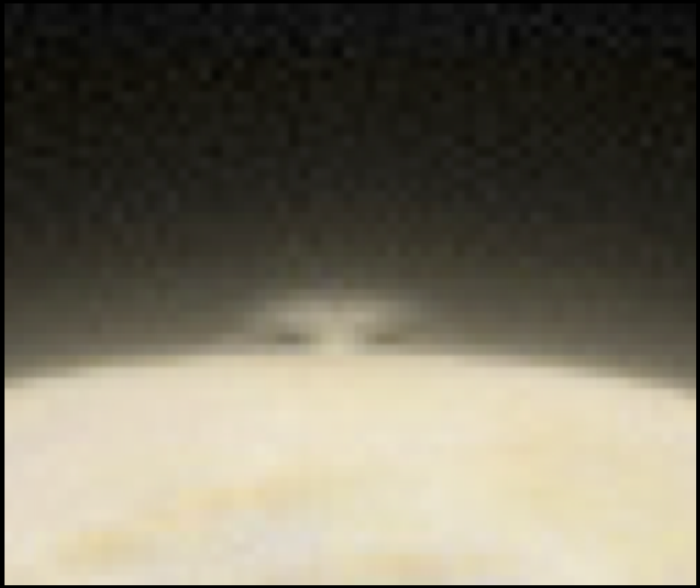
Io & the Jovian magnetosphere

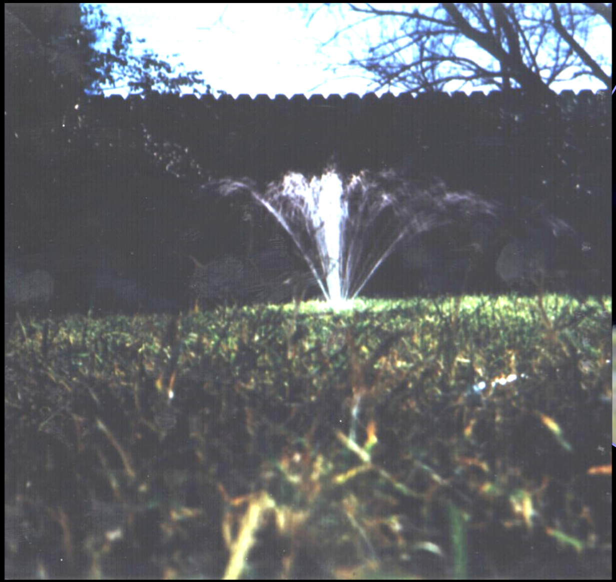


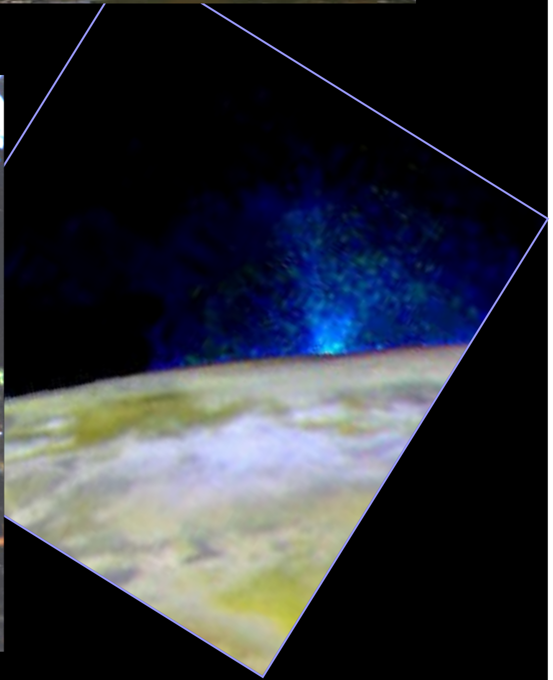
Relative motion of plasma & satellite:

- induces corotational E
  $E_i = -v_{rel} \times B$
  57km/sec x 2000nT
- ~500kV potential across Io
- drives currents of few x 10^6 Amps

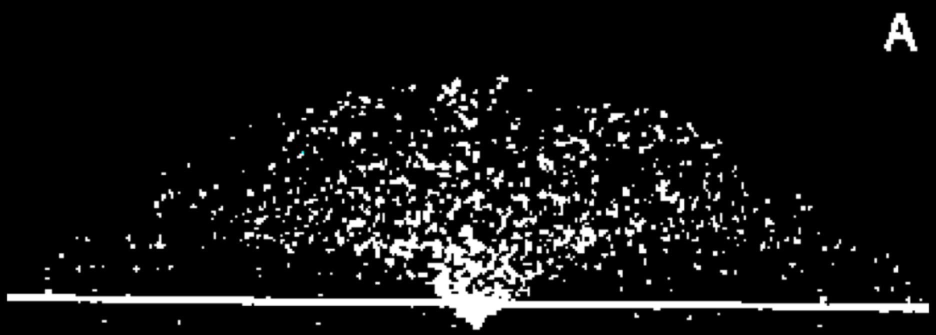
"Small" volcanoes (the majority, plume ht <10s of km) – nothing escapes

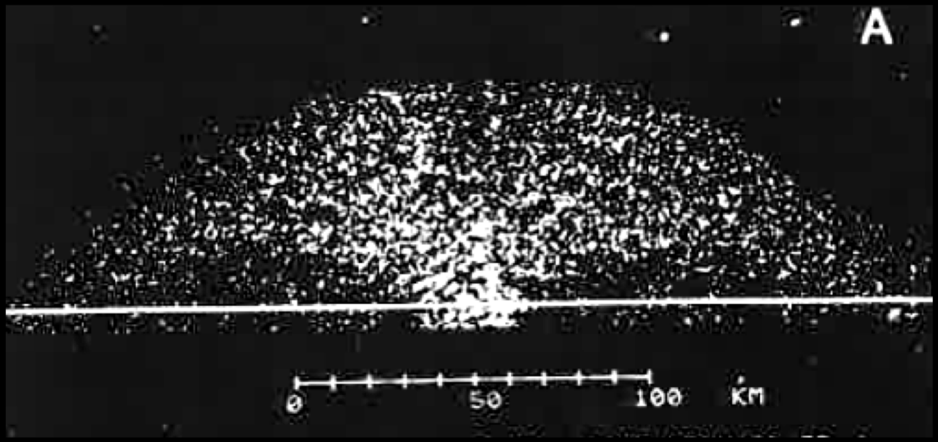


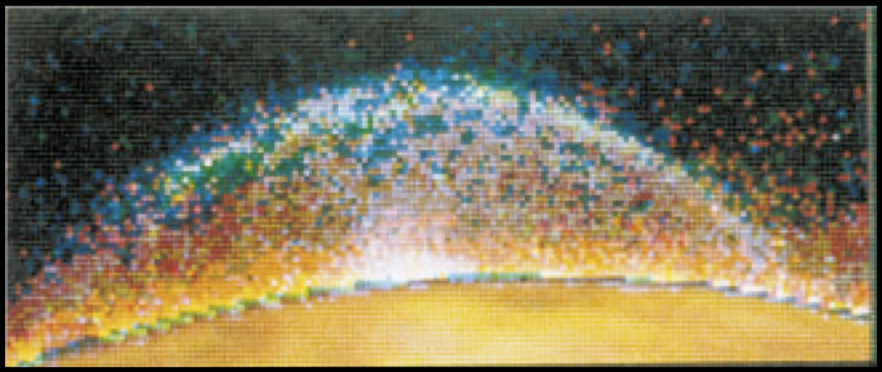




“Large” volcanoes – 100s of km in ht, only a few of these







Detailed modeling of plumes, ballistic & shock models

(*Strom et al. 1981*)

Limiting envelope for a set of ballistic trajectories:

$$z_M = v_o^2/2g - g r_M^2/2v_o^2$$

z = height

r = radial distance from vent

g = surface gravity

v_o = ejection velocity

at vent, $r_M=0$, → $v_o = \sqrt{2gz_M}$

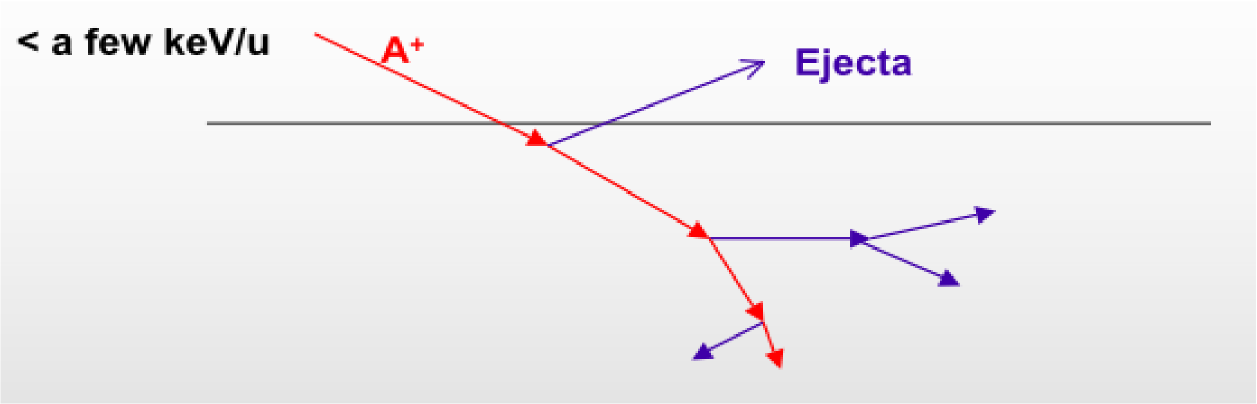
$v_o \leq 1$ km/sec

$v_{esc} = 2.56$ km/sec

➡ ***nothing escapes***

Surface sputtering

An elastic, multiple-collision-cascade process triggered by an ion impacting a solid surface that ejects multiple particles from relatively close to the surface.



Process characterized by:

(1) Yield = # particles removed per incident ion

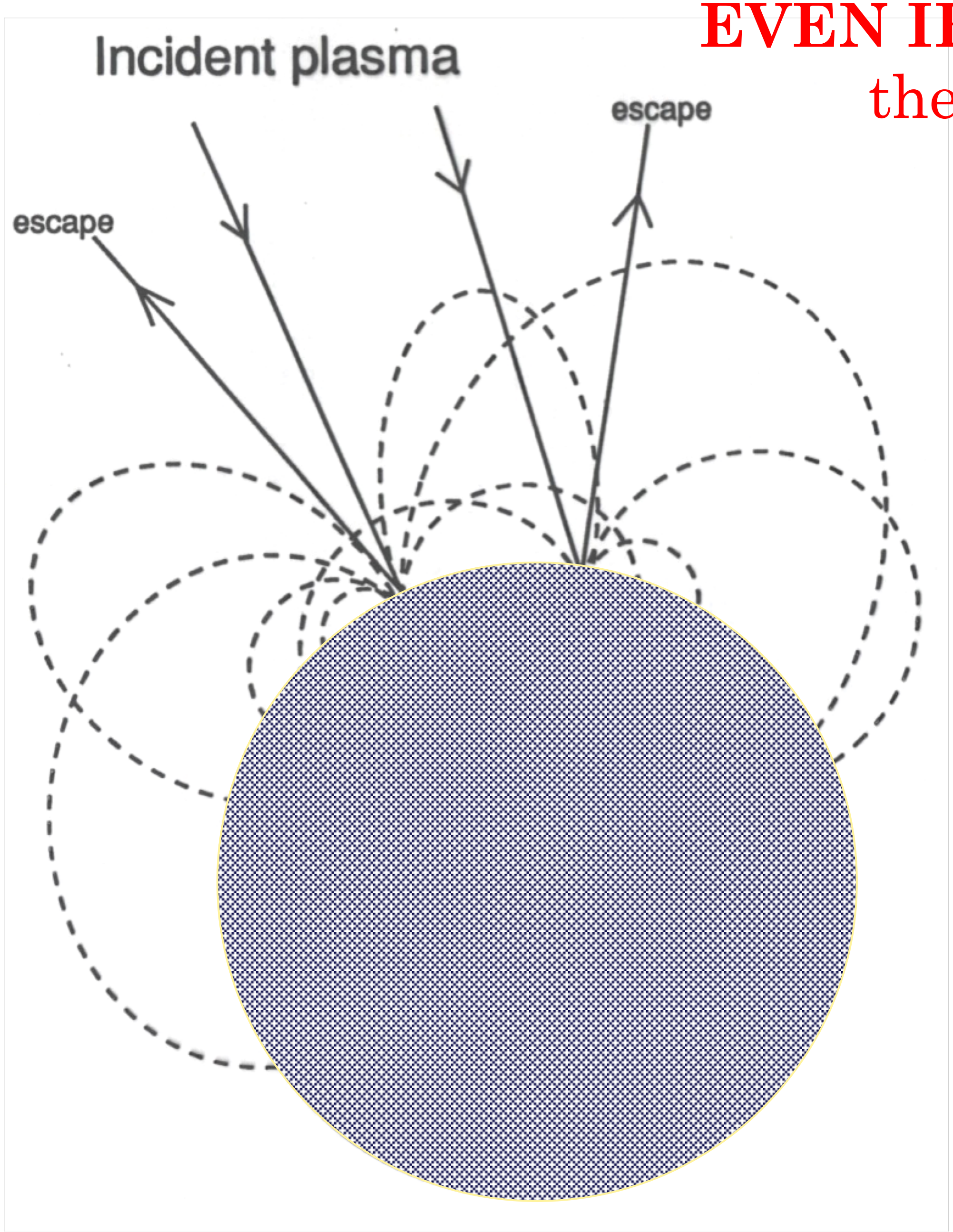
(2) E spectrum of sputtered particles

Both can be measured experimentally.

At Io:

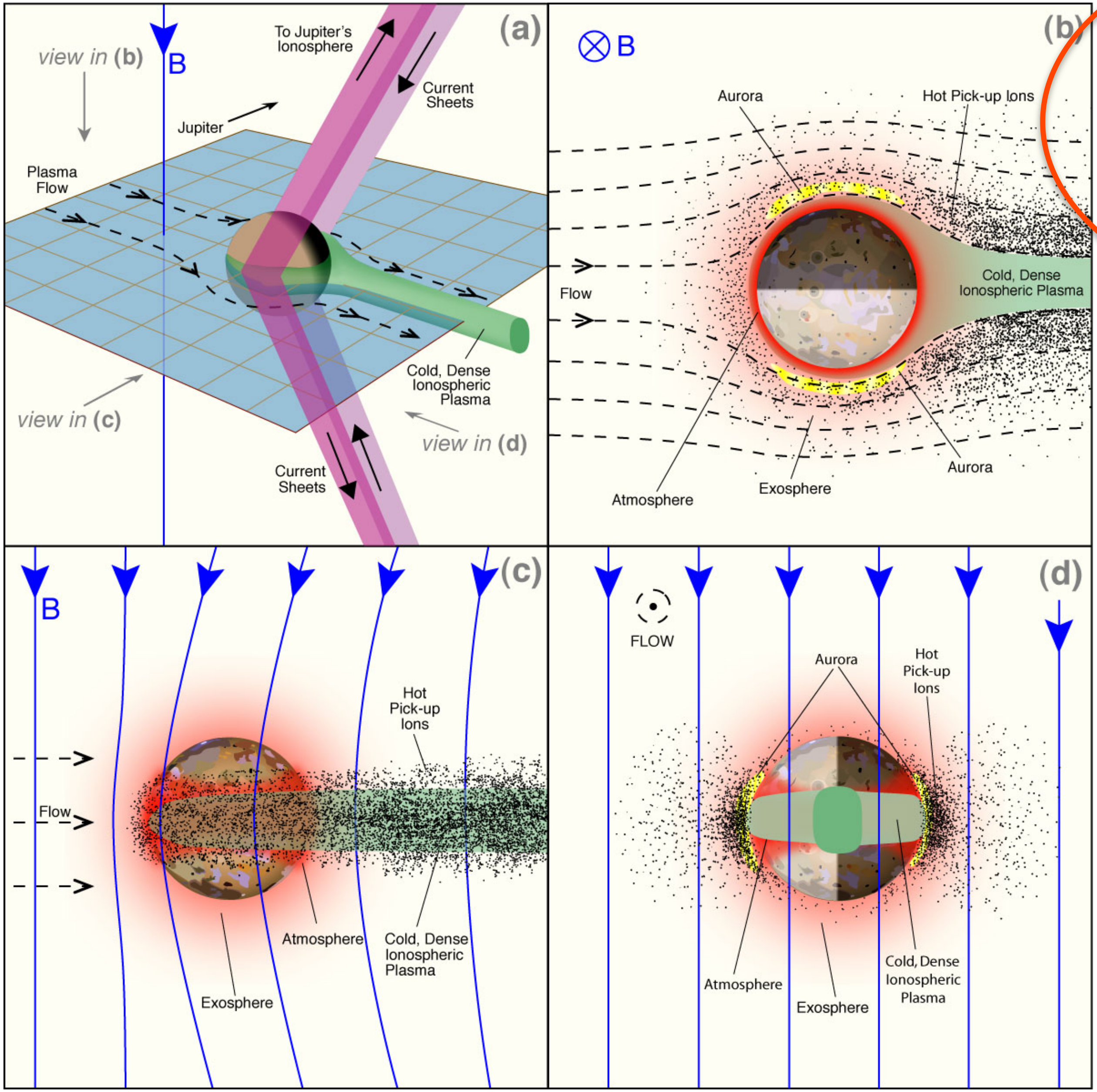
$Y \sim 10\text{-}100$

$Y(E) \sim E/(E+E_b)^3$, $E_b \sim 0.5\text{-}4$



EVEN IF all the plasma reached the surface, only a few % of sputtered particles would escape

Io's Local Interaction



- Electrodynamics: Currents from ion/neutral collisions and pickup **deflect flow**

  Saur et al. 2002

- Heating, ionization and charge-exchange in atmosphere

  Smyth 1998

- Cooling, deceleration of upstream plasma
- Acceleration of downstream plasma

  Delamere et al. 2003

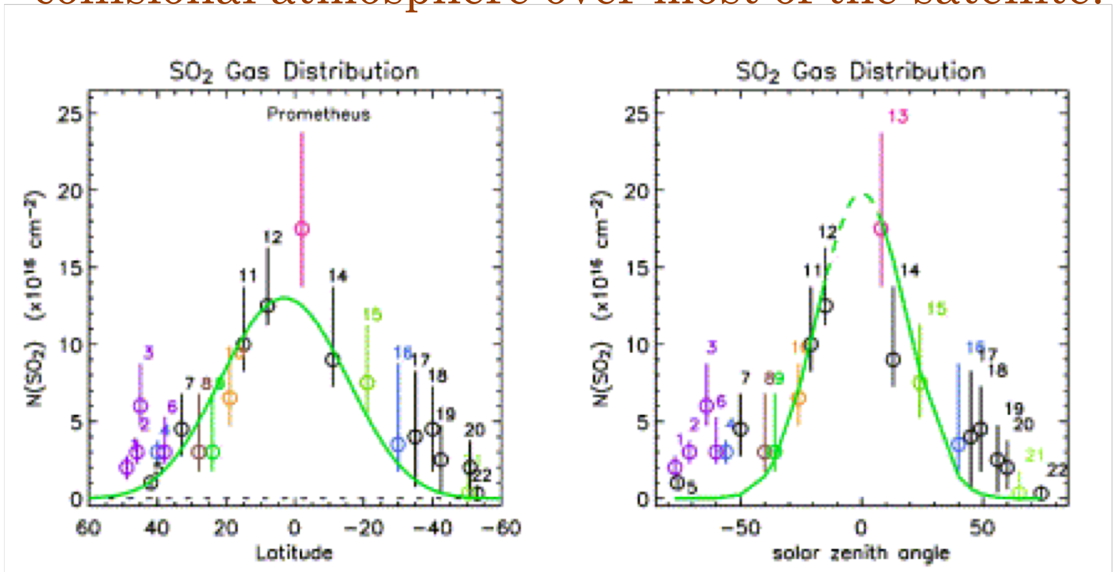
Slide courtesy of Fran Bagenal

Potential escape processes at Io

From surface:
(1) Volcanoes
(2) Sputtering

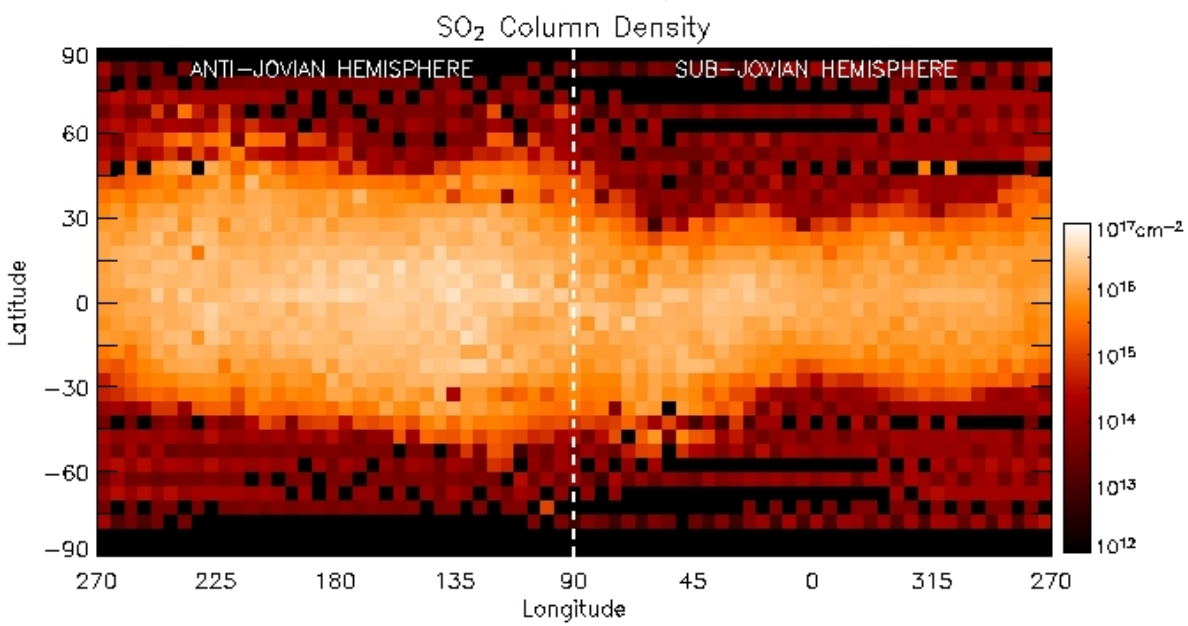
Volcanoes and sputtering primarily feed an atmosphere, but do not contribute to escape from Io. Escape occurs almost exclusively from the atmosphere.

Volcanoes predominant output is SO_2 gas, which at temperatures relevant for Io condenses to cover the surface with SO_2 frost, and also produces a collisional atmosphere over most of the satellite.



Anywhere the temperature is low enough (e.g., poles, terminator, far from hot spots) SO_2 condenses; everywhere else it's part of the collisional atmosphere. Most of the dissociation products of SO_2 do not condense.

Jessup et al. 2004



Feaga et al. 2009

Other Species

Table 19.2. Summary of Io Atmospheric Species

McGrath et al. 2004

Species	Io Abundance*	Reference
SO_2	~ (1-10) × 10^{16} in ~ ± (30-45)° latitude band ~ (2-10?) × higher in active volcanos	Synthesis of all observations; see §19.2.2, 19.2.3, and 19.2.4 McGrath *et al.* 2000; Spencer *et al.* 2000; Spencer *et al.* 2002, Jessup *et al.* 2003
S_2	1 × 10^{16}, Pele plume (t), SO_2/S_2 ~ (3-12)	Spencer *et al.* 2000
SO	~ (0.03-0.1) × SO_2	Lellouch 1996
NaCl	(0.003-0.013) × SO_2, active volcanos	Lellouch *et al.* 2003
O_2	Inferred (modeling)	Kumar (1982,1985); Summers 1985; Summers & Strobel 1996; Wong & Johnson 1995,1996; Wong & Smyth 2000; Moses *et al.* 2002a, 2002b
S	$3.6 \times 10^{12} < \mathcal{N}_S < 1.3 \times 10^{14}$ (t) ~ 9 × 10^{12}; at $2R_{Io}$ (t) = 0.1 × O	Feaga *et al.* 2002 (upper limit revised up; see text) Wolven *et al.* 2001
O	> (4-7) × 10^{13}, disk average ~ 1 × 10^{14}; at $2R_{Io}$ (t) = 11 × S	Ballester 1989 Wolven *et al.* 2001
Na	4 × 10^{12}, disk average	Bouchez *et al.* 2000 [see also Burger *et al.* 2001, Retherford 2002]
K	(1-10)×10^8; Na/K = 10 ± 5 at (10-20) R_{Io}	Brown 2001
Cl	~ 1 × 10^{13}, disk average	Feaga and McGrath (2002)
H	~ 2 × 10^{12}	Strobel & Wolven 2001
CS_2	< 2 × 10^{14}	McGrath *et al.* 2000; Spencer *et al.* 2000; Spencer *et al.* 2002
CO	< (3.6-6) × 10^{17}	Lellouch *et al.* 1992
H_2S	< (0.7-1.2) × 10^{16}	Lellouch *et al.* 1992
OCS, S_2O, ClO, CS, NaOH	Not detected (mm)	Lellouch *et al.* 1992
KCl	< 1 × NaCl	Lellouch *et al.* 2003

* Numbers in vertical column density, cm^{-2}, unless otherwise noted; (t) = tangential

Potential escape processes at Io - 2

From atmosphere:

(3) **Thermal**: Jeans escape

(4) A host of **non-thermal processes** including:

- Ionization of atmosphere by photons and electrons; ions are then swept up the by Jovian magnetic field.
- Elastic collisions between plasma ions and atmosphere neutrals
- Charge exchange between fast plasma ions & slow atmosphere neutrals

These processes have been considered extensively by numerous authors for many years, and the relative importance of each has been calculated and modeled in some detail.

[A great reference for more detail is Sieveka & Johnson 1984.]

Thermal ("Jeans") escape = thermal evaporation

$$\Phi_{ecape} = \frac{n(z)v_0}{2\sqrt{\pi}}\left(\frac{v_{esc}^2}{v_0^2}+1\right)\exp\left(-\frac{v_{esc}^2}{v_0^2}\right)$$ particles m^{-2} s^{-1}

where n(z) is the number density

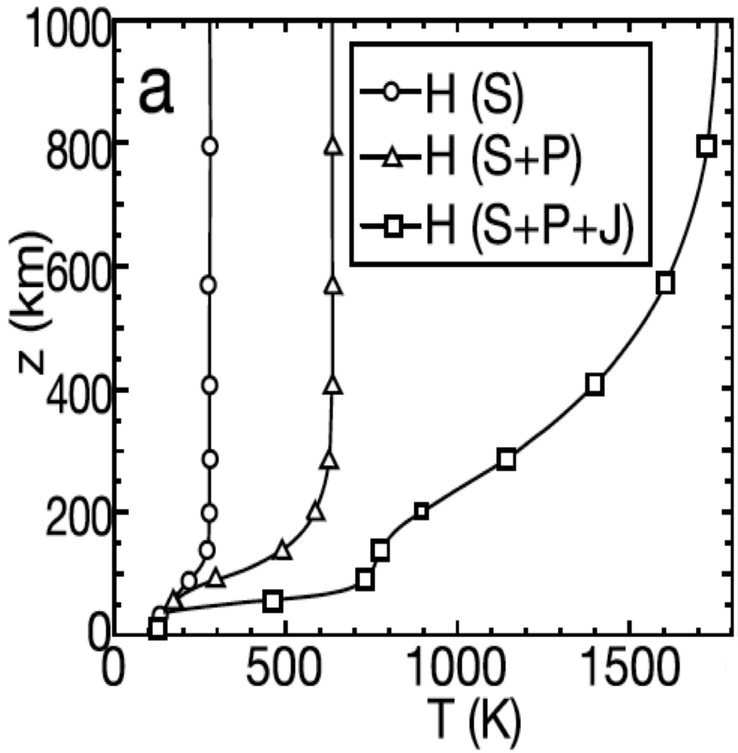
$$v_0 = \sqrt{\frac{2kT}{m}}$$ is the most probable velocity, as above

$$v_{esc} = \sqrt{\frac{2GM_{planet}}{(R_{planet}+z)}}$$ is the escape velocity

–Important factor is the final exponential term.

To get a handle on Jeans escape we need to understand the structure of the atmosphere, viz. temperature and composition vs altitude.

The thermal structure is dominated by plasma energy deposition and the current system (which produces so-called Joule heating just another form of ion-neutral collisions which is parameterized by the electron current).



S = solar heating (photons)
P = plasma heating
J = Joule heating

Exobase, boundary between collisional and non-collisional regimes of the atmosphere, is ~500km

Strobel et al. 1994

Jeans escape at Io is most often calculated using a temperature of T=1000K.

Numerous models for the composition vs altitude exist:

- Kumar 1982 – sublimation atmosphere
- Summers & Strobel 1996 – sublimation atmosphere
- Wong & Johnson 1996
- Moses et al. 2002 – volcano atmosphere

Summers & Strobel 1996

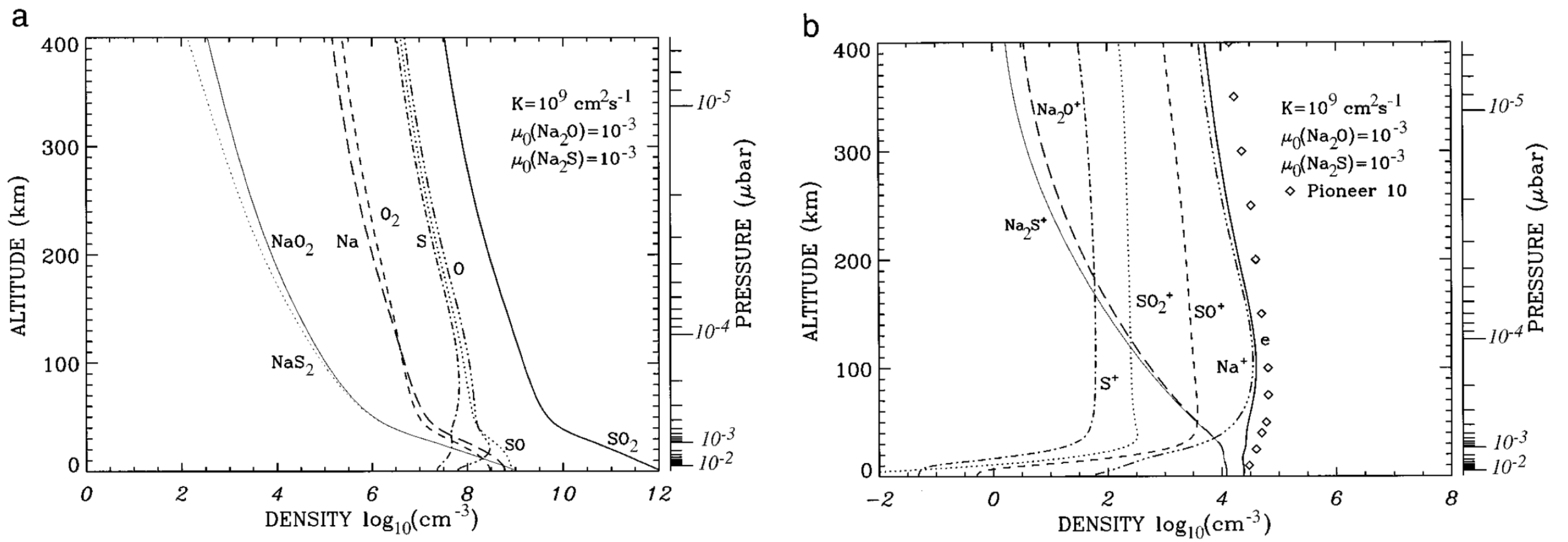


FIG. 7. (a) Major constituents of the neutral atmosphere from the surface to 400-km altitude for the high-density SO_2 case B2 with high values of the eddy mixing coefficient $K_{zz} = 10^9$, and (b) major ions and n_e for B2.

Ionization

This is simple because you mostly just look up or calculate the cross sections/rates using the known plasma characteristics. Once something is ionized it's fate is pretty simple – it is captured and swept away by the magnetic field into the torus. One caveat is the ionosphere, which is part of the "steady state" atmosphere (I'll mention some caveats later).

Elastic collisions

Often approximated using the hard sphere formulation where the cross section is determined by the physical size of the colliding objects (familiar example is billiard balls).

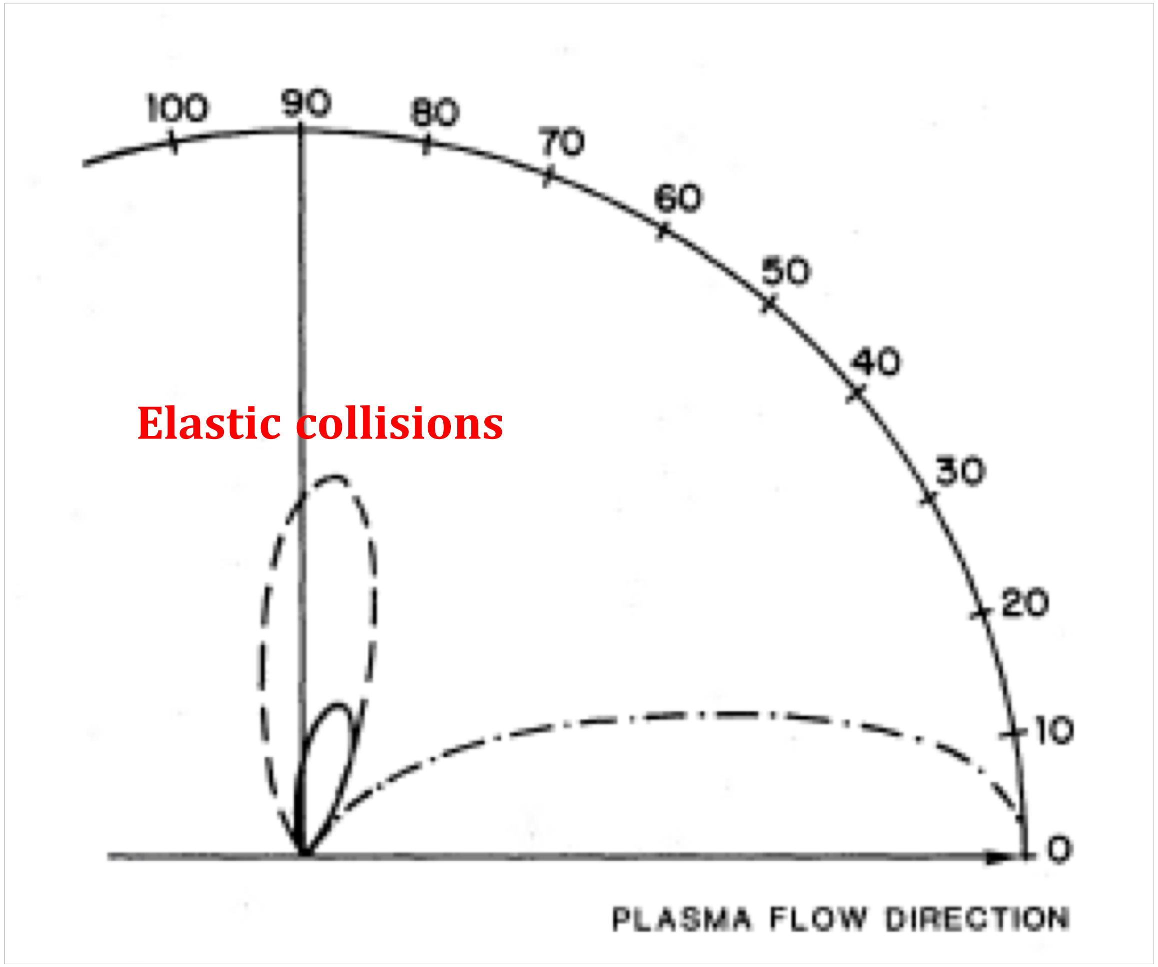
Using a Thomas-Fermi Coulomb potential is much more accurate for ion-neutral collisions, and provides simple formulas for energy distribution and direction of impacting and target species after collision:

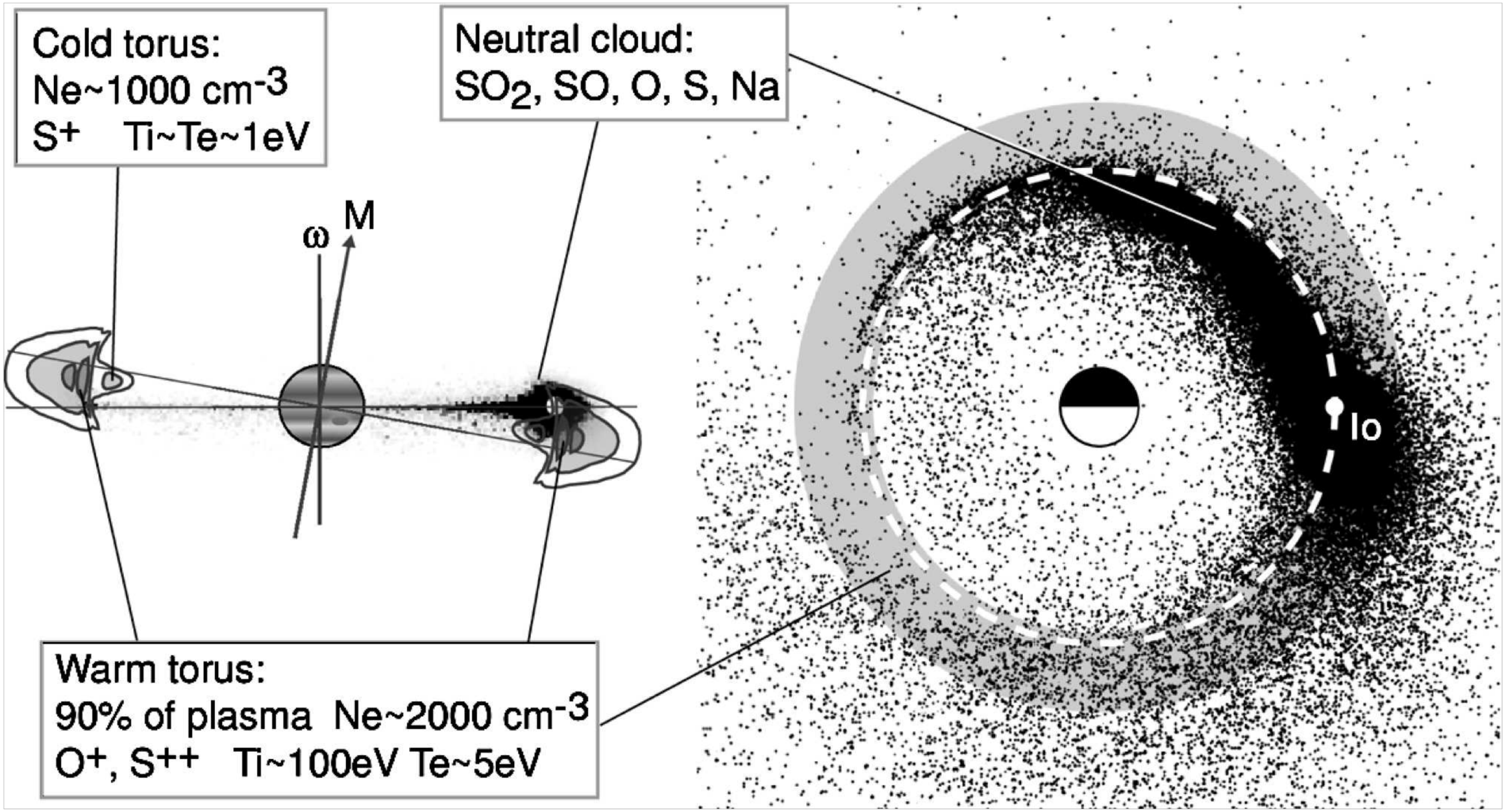
$$\frac{d\sigma}{dt} \approx \frac{\pi a_{12}{}^2}{2t^{3/2}} \left\{ \frac{\lambda t^{1/6}}{[1 + (2\lambda t^{2/3})^{2/3}]^{3/2}} \right\}$$

$$\cos\theta_1 = [1 - (E/E_1)(M_1 + M_2)/2M_1]/(1 - E/E_1)^{1/2}$$

$$\cos\theta_2 = (E/E_{max})^{1/2}$$

Elastic collisions result primarily in low energy target particles directed ~90° away from the impactors. Most of these escape Io but not Jupiter so they go into Jupiter orbit near Io and form neutral clouds.





Thomas et al. 2004

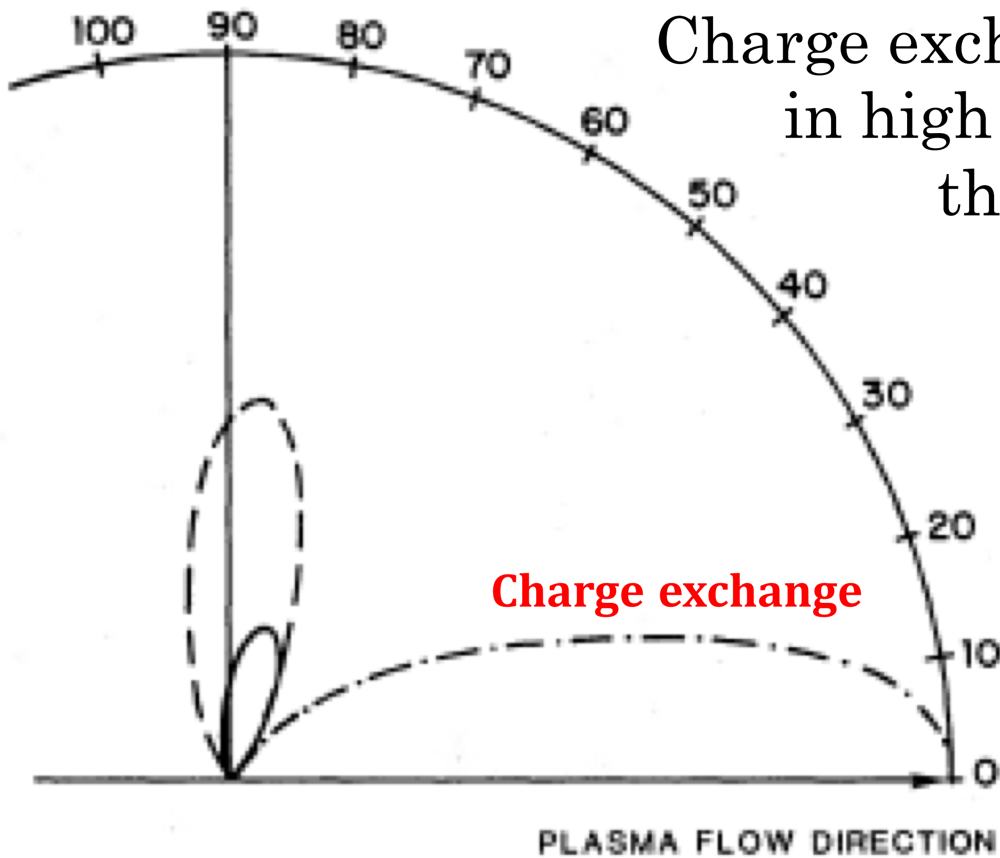
Charge exchange

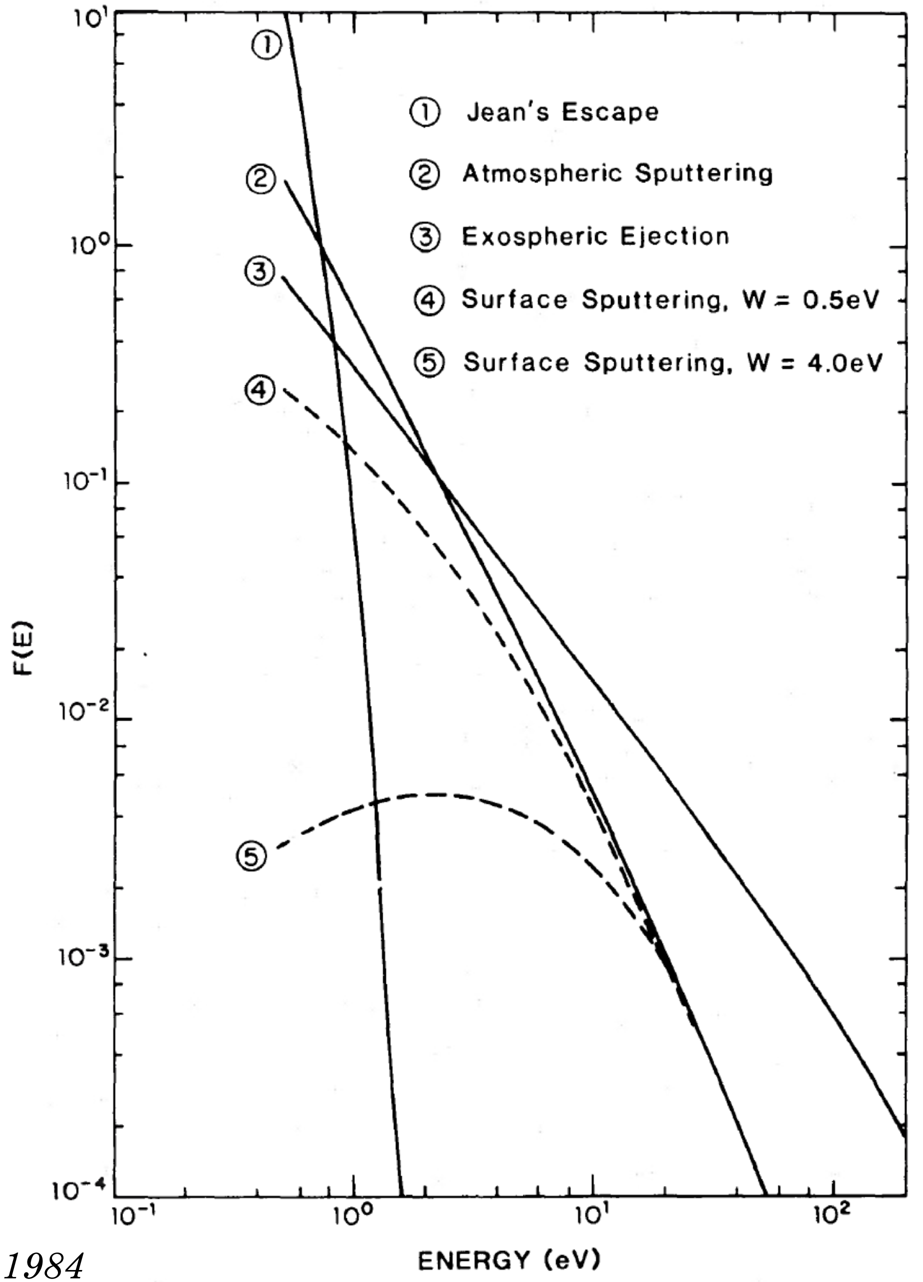
An ion encounters a neutral and they exchange charge:

$$A^+ + B \rightarrow A + B^+$$

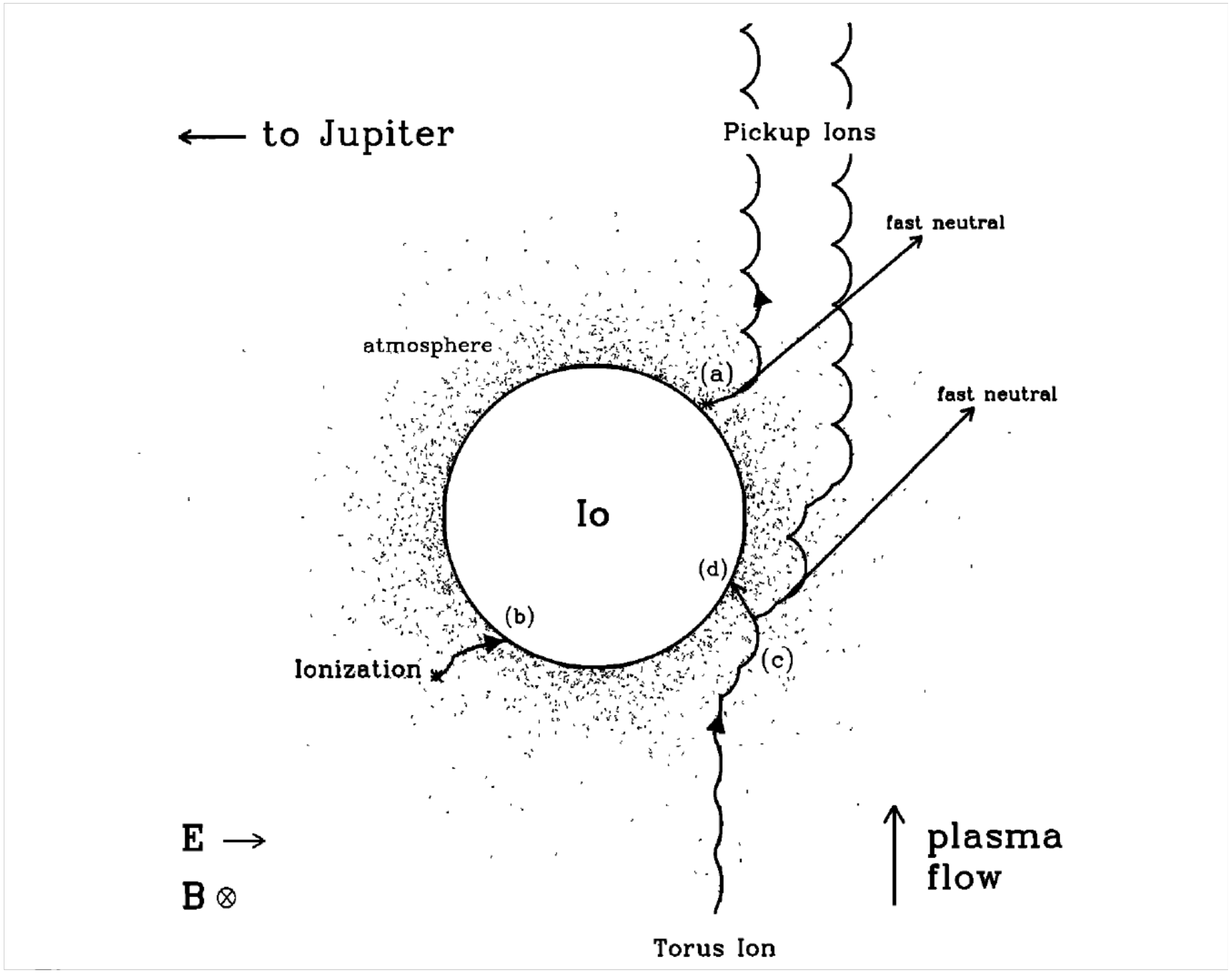
A ends up with the same velocity as A^+. This is important at Io because the ions have much higher energies than the neutrals, so CHEX provides a viable process for energizing neutrals to escape speed.

Charge exchange results primarily in high energy target particles that are forward directed and escape Jupiter as well as Io.





Sieveka & Johnson 1984



Wilson & Schneider 1999

Relative importance of these processes

Process	Na in Atmosphere as Na		Na in Atmosphere as Na_2S^d	
Exobase	$1R_{Io}$	$2R_{Io}$	$1R_{Io}$	$2R_{Io}$
Jeans escape 1000 K	10^{24}	10^{27}	10^{15}	10^{22}
Atmospheric sputtering	1×10^{26}	8×10^{26}	6×10^{25}	5×10^{26}
"Exospheric" ejection[e]	3×10^{25}	5×10^{26}	2×10^{25}	3×10^{26}

Sieveka & Johnson 1984

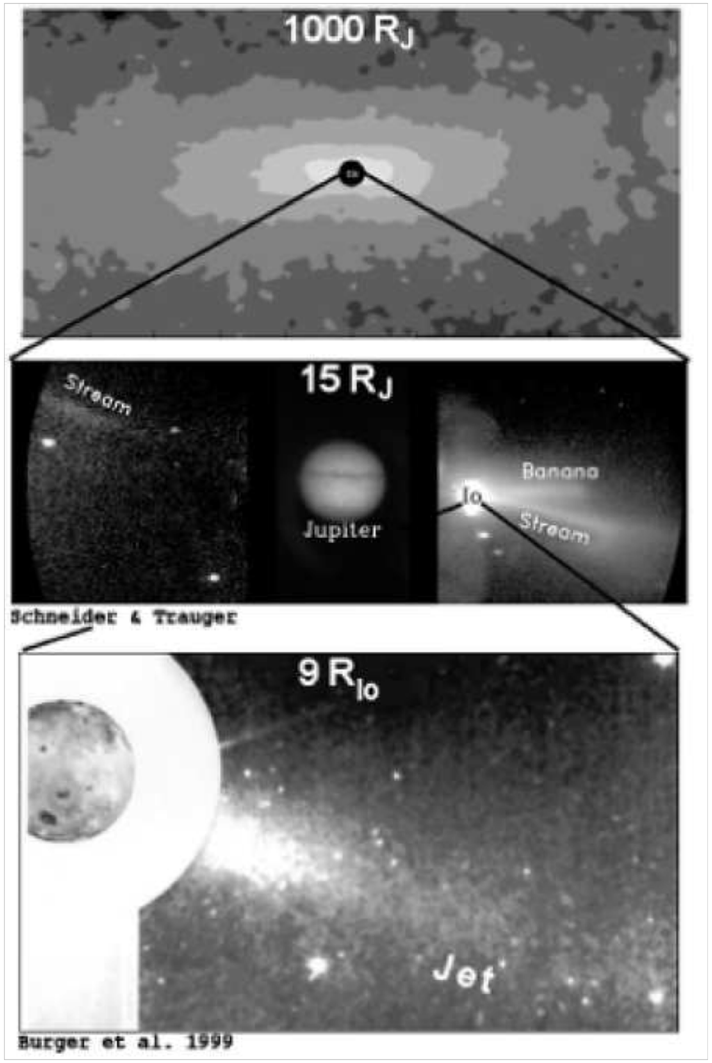
Coronal Sources[a] ($\#sec^{-1}$)

Target	Y_{es}	Sputter from exobase	Charge transfer		Single collision		Electron ionization	
			In	Out[b]	O^+	S^+	In	Out[b]
SO_2	4.1	1.3×10^{28}	3.4×10^{27}	4.8×10^{27}	6.4×10^{27}	7.0×10^{27}	8.8×10^{27}	1.9×10^{28}
							1.3×10^{26}	1.9×10^{27c}
SO	6.2	3.1×10^{28}	8.6×10^{27}	1.5×10^{28}	1.4×10^{28}	2.4×10^{28}	3.2×10^{27}	7.8×10^{27}
O_2	11.3	3.5×10^{28}	6.3×10^{27}	1.4×10^{28}	1.6×10^{28}	2.6×10^{28}	2.5×10^{27}	7.7×10^{27}
S	13.5	4.2×10^{28}	1.7×10^{28}	2.8×10^{28}	2.3×10^{28}	3.6×10^{28}	3.1×10^{28}	6.4×10^{28}
O	17.5	5.4×10^{28}	9.1×10^{27}	2.1×10^{28}	2.2×10^{28}	3.5×10^{28}	3.4×10^{27}	1.0×10^{28}

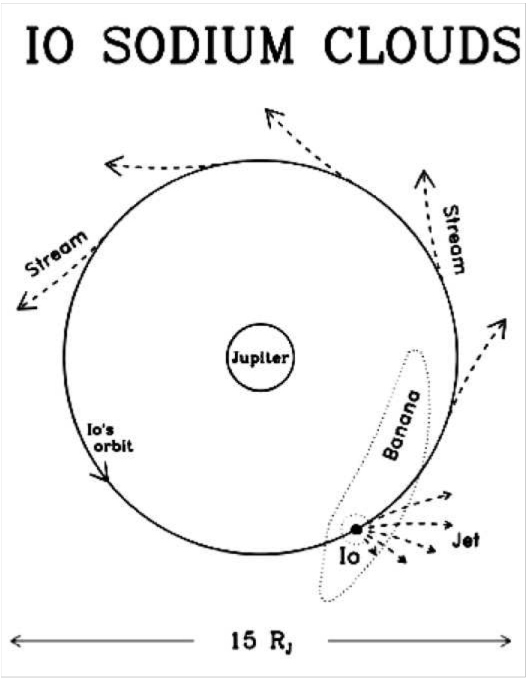
McGrath & Johnson 1987

Na is highly visible at Io via resonant scattering of sunlight so provides an excellent tracer of some of these processes.

View of Na emission from Earth



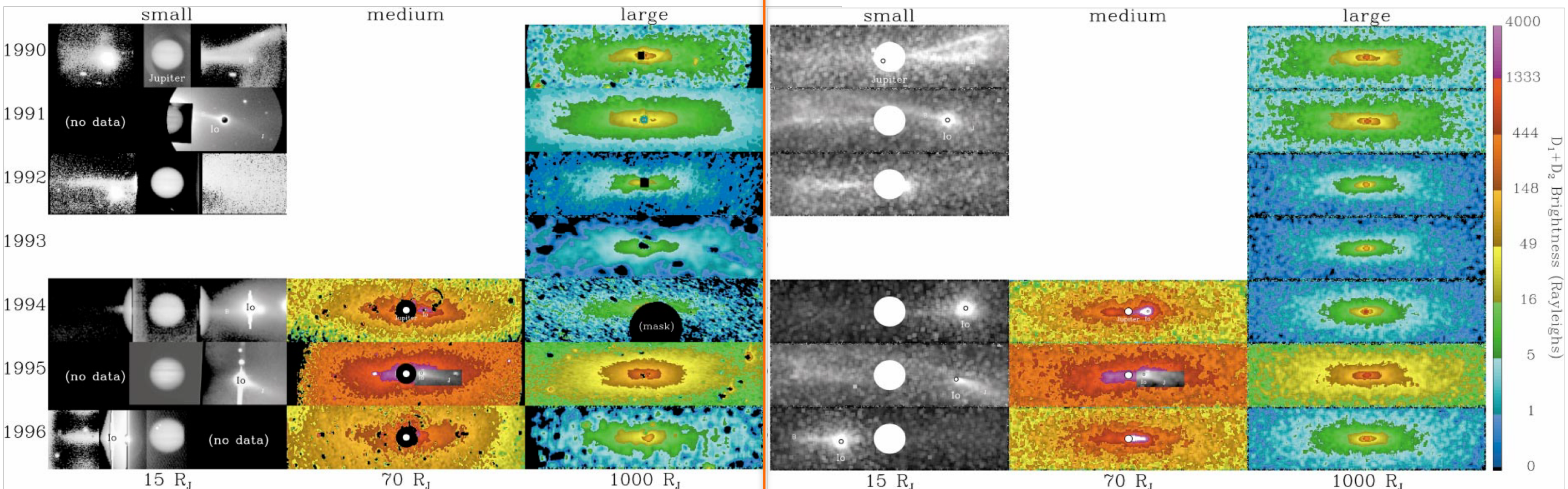
View from above Jupiter N pole



Thomas et al. 2004

Data

Best model



The most important things to keep in mind for escape processes at Io:

- Io is immersed in a dense, heavy-ion plasma
- Io is subjected to a strong electric field that drives substantial currents at the satellite
- Io has a stable, collisional atmosphere

Summary

- Escape at Io is dominated by non-thermal processes involving Jovian magnetospheric plasma and neutrals in Io's atmosphere and neutral clouds.

- Independent of the indisputable observational evidence for a collisional atmosphere at Io, the supply rates for S,O,Na require such an atmosphere.

- Observed Na clouds and jets confirm that non-thermal processes dominate the escape at Io.

- To what extent do volcanoes affect the atmosphere at the exobase? Is the atmosphere well mixed due to active plumes?

The End