Io Escape Processes

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Io has extensive volcanic activity
Io delivers a ton/sec of SO$_2$ dissociation products and volcanic species.

Io plasma torus:
- Ne~2000 cm$^{-3}$ O$^+$ S$^{++}$
- Ti~100eV Te~5eV

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 $\times 10^6$ Amps

Io, 6R$_j$
- $10^{28}$ S, O/sec
- $10^{27}$ Na/sec
“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:

\[ z_M = \frac{v_o^2}{2g} - \frac{gr_M^2}{2v_o^2} \]

- \( z \) = height
- \( r \) = radial distance from vent
- \( g \) = surface gravity
- \( v_o \) = ejection velocity

at vent, \( r_M=0 \), \[ v_o = \sqrt{2gz_M} \]

\( v_o \leq 1 \text{ km/sec} \)

\( v_{esc} = 2.56 \text{ km/sec} \)

\( \rightarrow \) 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.

![Diagram of sputtering process](image)

**Process characterized by:**

1. Yield = # particles removed per incident ion
2. E spectrum of sputtered particles

Both can be measured experimentally.

At Io:

\[ Y \sim 10-100 \]

\[ Y(E) \sim \frac{E}{(E+E_b)^3}, E_b \sim 0.5-4 \]
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.
### Other Species

**Table 19.2. Summary of Io Atmospheric Species**

<table>
<thead>
<tr>
<th>Species</th>
<th>Io Abundance*</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>SO₂</td>
<td>~ (1-10) x 10^{16} in ~ ± (30-45)° latitude band ~ (2-10?) x higher in active volcanos</td>
<td>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</td>
</tr>
<tr>
<td>S₂</td>
<td>1 x 10^{16}, Pele plume (t), SO₂/S₂ ~ (3-12)</td>
<td>Spencer et al. 2000</td>
</tr>
<tr>
<td>SO</td>
<td>~ (0.03-0.1) x SO₂</td>
<td>Lellouch 1996</td>
</tr>
<tr>
<td>NaCl</td>
<td>(0.003-0.013) x SO₂, active volcanos</td>
<td>Lellouch et al. 2003</td>
</tr>
<tr>
<td>S</td>
<td>3.6 x 10^{12} &lt; N₅ &lt; 1.3 x 10^{14} (t) ~ 9 x 10^{12}; at 2R_{I_o} (t) = 0.1 x O</td>
<td>Feaga et al. 2002 (upper limit revised up; see text) Wolven et al. 2001</td>
</tr>
<tr>
<td>O</td>
<td>&gt; (4-7) x 10^{13}, disk average ~ 1 x 10^{14}; at 2R_{I_o} (t) = 11 x S</td>
<td>Ballester 1989 Wolven et al. 2001</td>
</tr>
<tr>
<td>Na</td>
<td>4 x 10^{12}, disk average</td>
<td>Bouchez et al. 2000 [see also Burger et al. 2001, Retherford 2002]</td>
</tr>
<tr>
<td>K</td>
<td>(1-10)x10^{8}; Na/K = 10 ± 5 at (10-20) R_{I_o}</td>
<td>Brown 2001</td>
</tr>
<tr>
<td>Cl</td>
<td>~ 1 x 10^{13}, disk average</td>
<td>Feaga and McGrath (2002)</td>
</tr>
<tr>
<td>H</td>
<td>~ 2 x 10^{12}</td>
<td>Strobel &amp; Wolven 2001</td>
</tr>
<tr>
<td>CS₂</td>
<td>&lt; 2 x 10^{14}</td>
<td>McGrath et al. 2000; Spencer et al. 2000; Spencer et al. 2002</td>
</tr>
<tr>
<td>CO</td>
<td>&lt; (3.6-6) x 10^{17}</td>
<td>Lellouch et al. 1992</td>
</tr>
<tr>
<td>H₂S</td>
<td>&lt; (0.7-1.2) x 10^{16}</td>
<td>Lellouch et al. 1992</td>
</tr>
<tr>
<td>OCS, S₂O, ClO, CS, NaOH</td>
<td>Not detected (mm)</td>
<td>Lellouch et al. 1992</td>
</tr>
<tr>
<td>KCl</td>
<td>&lt; 1 x NaCl</td>
<td>Lellouch et al. 2003</td>
</tr>
</tbody>
</table>

* 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 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

\[ \Phi_{\text{escape}} = \frac{n(z) v_0}{2 \sqrt{\pi}} \left( \frac{v_{\text{esc.}}^2}{v_0^2} + 1 \right) \exp \left( - \frac{v_{\text{esc.}}^2}{v_0^2} \right) \]  
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
- \( v_{\text{esc.}} = \sqrt{\frac{2GM_{\text{planet}}}{R_{\text{planet}} + z}} \) 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).

\[ S = \text{solar heating (photons)} \]
\[ P = \text{plasma heating} \]
\[ J = \text{Joule heating} \]

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

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

**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:

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

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

\[
\cos \theta_2 = (E/E_{\text{max}})^{1/2}
\]
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.
Cold torus: Ne~1000 cm^{-3} S^+ Ti~Te~1eV

Neutral cloud: SO_2, SO, O, S, Na

Warm torus: 90% of plasma Ne~2000 cm^{-3} O^+, S^{++} Ti~100eV Te~5eV

Thomas et al. 2004
Charge exchange

An ion encounters a neutral and they exchange charge:

\[ \text{A}^+ + \text{B} \rightarrow \text{A} + \text{B}^+ \]

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

<table>
<thead>
<tr>
<th>Process</th>
<th>Na in Atmosphere as Na</th>
<th>Na in Atmosphere as Na₂S₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exobase</td>
<td>(1R_{Io}) (10^{24})</td>
<td>(1R_{Io}) (10^{15})</td>
</tr>
<tr>
<td>Jeans escape 1000 K</td>
<td>(8 \times 10^{26})</td>
<td>(5 \times 10^{26})</td>
</tr>
<tr>
<td>Atmospheric sputtering</td>
<td>(1 \times 10^{26})</td>
<td>(6 \times 10^{25})</td>
</tr>
<tr>
<td>“Exospheric” ejection&quot;</td>
<td>(3 \times 10^{25})</td>
<td>(2 \times 10^{25})</td>
</tr>
</tbody>
</table>

Sieveka & Johnson 1984

<table>
<thead>
<tr>
<th>Target</th>
<th>(Y_{es})</th>
<th>Sputter from exobase</th>
<th>Charge transfer</th>
<th>Single collision</th>
<th>Electron ionization</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>In</td>
<td>Out(^b)</td>
<td>O(^+)</td>
</tr>
<tr>
<td>SO₂</td>
<td>4.1</td>
<td>(1.3 \times 10^{28})</td>
<td>(3.4 \times 10^{27})</td>
<td>(4.8 \times 10^{27})</td>
<td>(6.4 \times 10^{27})</td>
</tr>
<tr>
<td>SO</td>
<td>6.2</td>
<td>(3.1 \times 10^{28})</td>
<td>(8.6 \times 10^{27})</td>
<td>(1.5 \times 10^{28})</td>
<td>(1.4 \times 10^{28})</td>
</tr>
<tr>
<td>O₂</td>
<td>11.3</td>
<td>(3.5 \times 10^{28})</td>
<td>(6.3 \times 10^{27})</td>
<td>(1.4 \times 10^{28})</td>
<td>(1.6 \times 10^{28})</td>
</tr>
<tr>
<td>S</td>
<td>13.5</td>
<td>(4.2 \times 10^{28})</td>
<td>(1.7 \times 10^{28})</td>
<td>(2.8 \times 10^{28})</td>
<td>(2.3 \times 10^{28})</td>
</tr>
<tr>
<td>O</td>
<td>17.5</td>
<td>(5.4 \times 10^{28})</td>
<td>(9.1 \times 10^{27})</td>
<td>(2.1 \times 10^{28})</td>
<td>(2.2 \times 10^{28})</td>
</tr>
</tbody>
</table>

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