• Amirani lava flow covers 5 km² / day
• Net volume 43 km³ / year
• Global resurfacing 0.1 cm / year
• All craters removed in ~1 million years
• Turns inside out 40 times over age of solar system

After quantities of lava are removed from below, the crust cracks and tilts, making tall, blocky mountains.
**Effusion Rates: Io v. Earth**

- Effusion rates 10-100x greater on Io than on Earth (today) for comparable eruption styles.
- Such effusion rates are believed to resemble that of the terrestrial planets in their youth, so Io provides unique insight into early processes on the Earth, Moon, Mercury, Venus, and Mars.

Effusion rate comparisons – contemporary eruptions

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**New Horizons - Jan 2007**

*Galileo - Nightside of Io - Visible*

- Glowing Lava
- Plume Gas & Dust + Aurora

**Io’s Nightside**

*New Horizons - Jupiter gravity assist to Pluto - Jan 2007*

- Tvashtar

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**Io’s Volcanoes & Geysers**

- Galileo - Nightside of Io - Visible
- New Horizons - Jan 2007
- Tvashtar
Observations are dayside only – there are no nightside observations. Does the atmosphere collapse?

Because SO₂ gas absorbs strongly at 1215Å, Lyman-α images provide a map of the SO₂ atmosphere on Io. Dark = more SO₂ gas.

Lyman-α Images $\rightarrow$ $N_{SO_2} \approx \text{few} \times 10^{16} \text{ cm}^{-2}$

Note the pronounced variability in the inferred abundance and distribution of the gas between 1998 & 1999. It is unclear at present whether this variability is temporal or longitudinal.

Io campaign observations, 1999

HST observations of O and S emissions near Io

(Left) Io’s Equatorial Emissions - HST/STIS image of OI 1356Å emission with Io at sub-Earth longitude 270° (western elongation) taken on October 14, 1997. Io, N, I, and B label the directions of Io north, Jupiter, and the nominal jovian magnetic field, respectively. This image is from Retherford et al. 2000 who showed that these emissions – Io’s “love handles” – rock back and forth with the tilt of the local magnetic field. (Right) Io’s Global Emissions - HST/STIS spectral images show UV emissions of atomic O and S that are global and extend far many Io radii, dropping approximately as a power-law with distance. From Wolven et al. 2001.

Modeling the neutral cloud as particles escaping Io and moving in Keplerian orbits around Jupiter – un-ionized.

Sample model output of the neutral cloud model (Matt Burger). The top panel shows column density of neutral atomic oxygen viewed from above Jupiter’s north pole. The sun is at the bottom and the two green circles show the orbits of Io and Europa. The source is $10^{20}$ atoms s⁻¹ with a spurer distribution (most probable speed of 1 km/s). The bottom image is a simulation of oxygen 1304Å intensity (emitted by the resonant scattering of sunlight) as it would be viewed from Earth.

Io’s peculiarities not entirely unexpected....

Io’s Orbital Period = 42 hours
Jupiter’s Spin Period = 10 hours
Jupiter’s Radio Emission Controlled by:
- Location of Io
- Magnetic Longitude
Early Explanations

- Dulk (1965)
- Goldreich & Lyndon-Bell (1969)

1979 Voyager flyby - The Io Alfvén Wave

- Io’s motion through Jupiter’s magnetic field induces strong electrical currents which propagate as MHD waves along the field lines towards Jupiter.

Voyager Radio Discoveries

- Repeated patterns of arcs in frequency-time spectrographs
- Indicates systematic beaming pattern, controlled by the geometry of Jupiter’s magnetic field.

Alfvén Wave Theory

- Io generates Alfvén waves
- Pattern of reflected waves carried downstream by corotating magnetospheric plasma
- Each Alfvén wave excites an arc of radio emission.

The Io Aurora

- Connerney et al.
- Clarke et al.

- Infrared
- Ultraviolet

- Energetic particles bombard atmosphere
- ‘Wake’ emission extends halfway around Jupiter

Io Plasma torus:

- Total mass ~ 2 Mton
- Source @ 1 ton/s replaced in 23 days
Jupiter’s 3 Types of Aurora

- Steady Main Auroral Oval
- Variable Polar Aurora
- Aurora associated with moons

Main Aurora

- Shape constant, fixed in magnetic co-ordinates
- Magnetic anomaly in north
- Steady intensity
- ~1° Narrow

Neutral Cloud vs. Plasma Torus

- Strong electrodynamic interaction
- Mega-amp currents connect Io and Jupiter
- Plasma interaction with Io’s atmosphere
- Heated atmosphere escapes
- ~20% plasma source local
Local Io Source

Local hot pick-up source:
3-20 x 10^26 s^-1 <100 kg s^-1

“cold slug”:
3-20 x 10^26 s^-1 ~ 10-70 kg s^-1

Total ion source 200-900 kg s^-1 - Mostly far from Io

Io Interaction Energy Flow

Precipitating electrons (10-100 keV): ~3 x 10^11 W
IR+UV auroral spots: 2 x 10^12 W
Poynting flux per hemisphere: 5 x 10^11 W
Io Interaction ~10^12 W
Io-DAM: 10^12-10^13 W

Local Interaction Torus/Corona

T1 ~ 60-100 eV
Tecl ~ 5 eV

Pickup=source of energy
(at 60 km/s)

Tpu(O+)=270 eV
Tpu(S)=540 eV
Tpu(SO2)=1080 eV

Pick up =source of a current through Io

Model: Prescribed Neutral density profiles around Io

Prescribed neutral atmosphere:
N_x, N_S, N_O2, N_SO2

Composition after interaction

Flux tubes which flow in dense SO2 atmosphere
-> removal of S,O ions
-> dominated by SO2+
Consequence: Ion/Energy Supply to the Torus is Very Small

1) Atomic recombination: $S^+ + e \rightarrow S \quad \text{----------- SLOW}
2) Molecular recombination: $SO_2^+ + e \rightarrow SO + O \quad \text{------- FAST}

\[ (\text{T}_{\text{el}} = 1 \text{ eV}, n_{\text{el}} = 10,000 \text{ cm}^{-3}) \quad \Rightarrow \quad T_{\text{recomb}} \approx 1 \text{ hour} \]

\[ T_{\text{torus}} = 10\text{h} \quad T_{\text{coulomb}} = 10 \text{ days} \quad T_{\text{transport}} = 30 \text{ days} \]

**THUS:**
- Main local interaction output: $SO_2^+$
- $SO_2^+$ disappear rapidly -> atomic O and S clouds? probably

Local contribution to mass/energy supply to the Torus: VERY SMALL \(\Rightarrow\) Bulk of the mass (500-1000 kg/s) and energy supply comes from GIANT NEUTRAL CLOUDS

Lack of ionization in the wake: field-aligned electron beams

More Sophisticated modeling – Multi-fluid MHD -> Hybrid (Fluid e-, kinetic ions)

Plasma Production at Io
Schneider & Trauger

Neutral Sodium

Ionized Sulfur

Io Plasma torus
Total mass \(\approx 2 \text{ Mton}\)
Source @ \(\approx 1 \text{ ton/s}\)
\(\sim 3 \times 10^{28} \text{ ions/s}\) replaced in 23 days

Io Cold, Inner Plasma Torus
(Schneider & Trauger)
Total thermal energy ~6 x 10^{17} J
UV power @ 1.5 Twatt cools electrons in ~7 hours
Ion pick-up @ 2 Twatt generates total energy in 4 days

Where does the energy come from?
The rotation of Jupiter– coupled by the magnetic field

45 days as Cassini approached Jupiter, Integration over multiple lines in the EUV

Torus Chemistry Models

Input = neutral clouds of S and O
Homogeneous "cubic-cm" model

Neutral Cloud Theory:
Source = atomic O, S
Ionization, Charge Exchange, Recombination
Radiative Cooling
Ion-Electron coupling - Coulomb collisions

Electron heating:
Necessary to provide UV emitted power
Usually specified as \( F_{\text{hot}} = \frac{N_{\text{hot}}}{N_{\text{cold}}} \) and \( T_{\text{hot}} \)

Homogeneous Volume
Five Parameters:
Transport Timescale - \( \tau_{\text{transport}} \)
Source of Neutrals - \( S_{\text{neutrals}} \)
Oxygen to Sulfur Ratio - \( O/S_{\text{neutrals}} \)
Hot Electron Fraction
- \( F_{\text{hot}} = \frac{N_{\text{hot}}}{N_{\text{cold}}} \)
Hot Electron Temperature - \( T_{\text{hot}} \)

Output:
Neutral, Ion, Electron Densities
Ion Temperatures
Thermal Electron temperatures
Mass, Energy Flows
Charge Exchange Reactions @ L=6

<table>
<thead>
<tr>
<th>Reaction</th>
<th>( k ) (cm(^3) s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>( S^+ + S^+ \rightarrow S^+ + S^+ )</td>
<td>( k_0 = 8.1 \times 10^9 )</td>
</tr>
<tr>
<td>( S + S^+ \rightarrow S^+ + S )</td>
<td>( k_1 = 2.4 \times 10^{10} )</td>
</tr>
<tr>
<td>( S + S^+ \rightarrow S^+ + S^+ )</td>
<td>( k_2 = 3 \times 10^{10} )</td>
</tr>
<tr>
<td>( S + S^+ \rightarrow S^+ + S^+ )</td>
<td>( k_3 = 7.8 \times 10^{9} )</td>
</tr>
<tr>
<td>( O + O^+ \rightarrow O^+ + O )</td>
<td>( k_5 = 1.32 \times 10^{8} )</td>
</tr>
<tr>
<td>( O + O^+ \rightarrow O^+ + O^+ )</td>
<td>( k_6 = 5.2 \times 10^{10} )</td>
</tr>
<tr>
<td>( O + O^+ \rightarrow O^+ + O )</td>
<td>( k_7 = 5.4 \times 10^{9} )</td>
</tr>
<tr>
<td>( S + O^+ \rightarrow S^+ + O )</td>
<td>( k_8 = 6 \times 10^{11} )</td>
</tr>
<tr>
<td>( S + O^+ \rightarrow S^+ + O^+ )</td>
<td>( k_{10} = 2.34 \times 10^{8} )</td>
</tr>
<tr>
<td>( O + O^+ \rightarrow O^+ + S^+ )</td>
<td>( k_{12} = 2.3 \times 10^{9} )</td>
</tr>
<tr>
<td>( O + S^+ \rightarrow O^+ + S^+ )</td>
<td>( k_{13} = 1.4 \times 10^{9} )</td>
</tr>
<tr>
<td>( O + S^+ \rightarrow O^+ + S^+ )</td>
<td>( k_{14} = 1.92 \times 10^{8} )</td>
</tr>
<tr>
<td>( S^+ + S^+ \rightarrow S^+ + S^+ )</td>
<td>( k_{15} = 9 \times 10^{10} )</td>
</tr>
<tr>
<td>( S^+ + S^+ \rightarrow S^+ + S^+ )</td>
<td>( k_{16} = 3.6 \times 10^{10} )</td>
</tr>
</tbody>
</table>

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Europa

Observations of oxygen UV emissions (specifically ratio of OI 1356A / 1304A) are consistent with predominately O\(_2\) with small amount (2%) atomic O. Radio occultations have revealed Europa to have a substantial ionosphere but the spatial and temporal variations have eluded a consistent clear explanation.

HST/STIS observations at OI 1304 and 1356A wavelengths show the emissions are not uniform but the spatial and temporal variations are not consistent with a simple picture of either photoproduction or sputtering from brighter (purer water) regions, nor with longitude. From McGrath et al. 2009.

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January Steady-State Model

Outer Planets Flagship Mission

ESA – Ganymede Orbiter
Cosmic Vision selection??

NASA – Europa Orbiter
2012 new start??

• about 1 year of multiple moon flybys
• Europa orbit ~100-200 km
• ~3 months survival?

• How to characterize the currents in the ionosphere so that the induction current (in the ocean) can be separated?
**Ambient Plasma at Europa**

**Bagenal & Delamere**

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**Jupiter Density**

- V1-PLS
- GLL-PLS midnight
- GLL-PLS noon
- V1-PWS
- Frank et al. 2002
- Rim study

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**Europa's ionosphere - Variable**

- **Galileo PWS data**
  - Kurth et al. 2001
- **Galileo PLS data**
  - 9.2-9.6 Rj

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**PWS**

Kurth et al. 2000

- 1996 Dec 19  E4  100 cm$^{-3}$
- 1997 Feb 20  E6  60 cm$^{-3}$
- 1997 Nov 6   E11 160 cm$^{-3}$
- 1997 Dec 16  E12 550 cm$^{-3}$
- 1998 Mar 29  E14 50 cm$^{-3}$
- 1998 May 31  E15 200 cm$^{-3}$
- 1998 Sep 26  E17 170 cm$^{-3}$
- 1999 Feb 1   E19 120 cm$^{-3}$
- 2000 Jan 3   E26 50 cm$^{-3}$

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**Galileo Radio Occultation Data for Europa**

- **Kurth et al. 2001**
- **Galileo PLS data**
  - 9.2-9.6 Rj

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**Europa Observations**

- **Electron Density**
  - cm$^{-3}$

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Satellite-plasma interactions of Io and Europa

Ions and electrons trapped by Jupiter's magnetic field alter and erode the surface, producing a tenuous atmosphere composed mostly of \( \text{O}_2 \) with an extended neutral torus of \( \text{H}_2 \). From Johnson et al. 2004.

Atmospheres

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Io</th>
<th>Europa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius (km)</td>
<td>1820</td>
<td>5555</td>
</tr>
<tr>
<td>Mass (10^24 kg)</td>
<td>0.8889</td>
<td>0.0479</td>
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<tr>
<td>Gravity (m/s^2)</td>
<td>1.25</td>
<td>0.10</td>
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<tr>
<td>Escape Speed (km/s)</td>
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<td>2.02</td>
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<tr>
<td>Composition</td>
<td>( \text{SO}_2 )</td>
<td>( \text{D}_2 )</td>
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<tr>
<td>Molecular Mass (amu)</td>
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<td>32</td>
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<tr>
<td>Albedo</td>
<td>0.63</td>
<td>0.64</td>
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<tr>
<td>Temperature (K)</td>
<td>97</td>
<td>97</td>
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<tr>
<td>Surface Pressure (bar)</td>
<td>9.2E-10</td>
<td>3.3E-12</td>
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<tr>
<td>Scale Height (km)</td>
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<td>19</td>
</tr>
<tr>
<td>Radius/H</td>
<td>2.36</td>
<td>3.2</td>
</tr>
<tr>
<td>Column Mass (kg/m^2)</td>
<td>3.1E-15</td>
<td>2.6E-09</td>
</tr>
<tr>
<td>Total Mass (kg)</td>
<td>2.1E+01</td>
<td>7.3E+06</td>
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<tr>
<td>Column No. Density (cm^-3)</td>
<td>5.0E+20</td>
<td>3.0E+28</td>
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<tr>
<td>Surf. No. Density (cm^-3)</td>
<td>6.5E+16</td>
<td>2.3E+24</td>
</tr>
<tr>
<td>Surface Density (kg/m^3)</td>
<td>7.2E+19</td>
<td>3.3E+14</td>
</tr>
</tbody>
</table>

Conclusions

1. Physical chemistry models are getting better – and nimble
2. Factor ~5 variation in mass flow – related to atmosphere?
4. Source and transport rates correlated?
5. Modeling past data may help us find some key observations that could allow us to determine plasma conditions from Earth.