Modeling Vapor and Heat Transport on Io

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Outline

• Motivation – Problem
• Methods and Modeling
  – Objectives
• Preliminary Analyses
• Limitations of Models and Research
• Conclusions – Future Work
Motivation – Problem

• Why does Loki show lower temperatures than other hotspots?
  – Greater total power output
• Why is the crust so uniform in temperature?
  – Profiles of surface show variations of less than a degree
• Why do single pixels show a wide $T$ distribution?
  – Fractions of pixels 100s of $K$ higher than average
• Current thermal models cannot explain this
• Can volatile transport (sulfur) explain these effects?

Howell and Lopes 2007
Methods – Objectives

• Extend thermal models to include volatile interactions
  – Horizontal transport from resurfacing wave
  – Vertical transport from depth
  – Trapped sulfur

• Testing the models – surface features and morphology

• Extension and testing at other hotspots
Methods – Horizontal Transport

- Resurfacing wave passes (advancing wave/foundering crust)
- Sublimates the sulfur
- Sulfur deposited in front and behind – carries heat
- Amount depends on crust and lava temperature
- May explain uniform and low T
  - Distribute T
  - Suppress high T
- Model how the sulfur behaves based on T, P, and abundance
- Compare to images – Galileo and Voyager
Methods – Vertical Transport

- Sulfur at depth is being heated
- Travels up through crust bringing heat with it
- Creates fumaroles with high T – lighter deposits in image
- Heat also distributed around surface
- May explain the large sub-pixel variations
- Model the amount of heat coming from depth and how the fumaroles are distributed
- Compare size, spacing, and number to images
Methods – Trapped sulfur

- Combination of horizontal and vertical
- Resurfacing wave sublimates sulfur
- Some sulfur gets trapped
- Trapped sulfur transported vertically through crust
Methods – Testing the models

- Tupan patera shows similar morphology to Loki
- Test the models developed for Loki at Tupan

Galileo image of Tupan patera (NASA/JPL)
Preliminary Analyses

• Preliminary Modeling
  – Hot surface/Cold surface
  – Radial transport

• Model and length scale comparisons
  – Ingersoll (1989) vs Moreno et al. (1991)
  – Both modeled SO$_2$ transport
Preliminary Modeling

- Io’s SO$_2$ dominated atmosphere has been modeled extensively
- Focused on Ingersoll (1989) and Moreno (1991) as a starting point
  - Nighttime/daytime models
  - Sublimation/volcano dominated models
  - Models predict length scales of sublimation/deposition
  - Modeled planetary atmosphere and locations of deposition
- We are modeling for less volatile S$_8$ which requires higher temperatures for transport
- We are also modeling for smaller scales such as hotspots and fumaroles
- Transport scales vary from red 40 km deposits (B & C) to 3.5 km to 5 km light deposits (A)

Voyager and Galileo Images of Loki (Morgan, 2008)
Preliminary Modeling

- Preliminary models based on Ingersoll’s equations for SO$_2$ transport
  - 4 fundamental equations – conservation of mass, momentum, and energy, and mass flux
  - Vertically integrated – horizontal motion only
  - Adapted for T and p needed for S$_8$ transport

- Model 1 – Hot vs. cold analytical model for S$_8$
  - Initial T = 350 K, $\alpha = 0.5$
  - Most sublimation/deposition occurred within 40 km
  - Consistent with red sulfur regions
Preliminary Modeling

• Model 2 – Numerical solution to model 1
  – Reduced Ingersoll’s 4 equations to 2 coupled differential equations involving the pressure and velocity
  – Used Python to solve for \( p(x) \) and \( v(x) \)
  – Used same initial parameters as Model 1
    • Consistent results
Pressure (Deposition), $\alpha=0.5$, $T_0=350$ K, $T_s=120$ K

Velocity (Deposition), $\alpha=0.5$, $T_0=350$ K, $T_s=120$ K

- Analytical
- Numerical
Preliminary Modeling

• Model 3 – Radial transport
  – Converted Ingersoll’s equation to cylindrical polar coordinates – more realistic, radial flow
  – Reduced the equations to 2 coupled differential equations again
  – $p(r)$ and $v(r)$ curves similar to Models 1 and 2
Model and Length Scale Comparisons

- Moreno (1991) also modeled SO$_2$ transport on Io
  - Used same fundamental equations as Ingersoll
  - Solved numerically for radial transport around a volcanic vent – most similar to our Model 3
  - Considered horizontal and vertical motion
    - Including vertical motion reduces length scales
    - Produces shocks
      - Material transitions from vertical to horizontal motion
      - Pressure, density and temperature increase rapidly
Model and Length Scale Comparisons

- Length scale of deposition for Moreno
  - Deposition rate directly proportional to excess pressure
    - Mass flux = C \times (p_v - p)
  - Large pressure drop = large drop in deposition rate
  - Point where pressure drops by one order of magnitude
  - SO\textsubscript{2} deposition \sim 9 \text{ km} for T = 130 \text{ K}
  - Scales to \sim 5 \text{ km} for S\textsubscript{8} at 300 \text{ K}

Portions of daytime (A, C) and nighttime (B) P vs \Theta plots for a volcanic SO\textsubscript{2} atmosphere from Moreno et al. Plot D is a digitized version of A and B.
<table>
<thead>
<tr>
<th>Compound</th>
<th>Model</th>
<th>Coordinate System</th>
<th>Sticking Coeff.</th>
<th>Length</th>
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</thead>
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<tr>
<td>$S_8$</td>
<td>Ingersoll</td>
<td>Cartesian</td>
<td>0.5</td>
<td>40 km</td>
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<td></td>
<td>Moreno</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5 km$^1$</td>
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</tbody>
</table>

$^1$ 9 km length for $SO_2$ at 120 K scaled for $S_8$ at 300 K
Model and Length Scale Comparisons

Ingersoll based model
- Horizontal motion
- Analytical/Numerical
- Hot surface vs. cold surface
- Length scales of deposition consistent with red sulfur deposits

Moreno scaled model
- Horizontal and vertical motion
- Numerical
- Deposition around volcanic vent
- Length scales of deposition consistent with light patera deposits

We want a model that produces both length scales of deposition and explains the temperature variations seen at Loki.
Limitations of Models & Research

• Ingersoll’s equations provide theoretical basis and starting point for research
• BUT...Ingersoll’s assumptions limit the possible models
• Other limitations to consider
  – Daytime vs. nighttime conditions
Limitations – Ingersoll’s Assumptions

• Ingersoll made 3 assumptions to simplify his equations
  – Assumption #1: Atmosphere and gases in hydrostatic equilibrium – vertical averaging
  – Assumption #2: Effects of turbulent transfer or viscous dissipation were negligible
  – Assumption #3: Simplified geometries – hot surface next to cold surface
Limitations – Hydrostatic equilibrium – Vertical Averaging

- Assumption #1: Atmosphere and gases assumed to be in hydrostatic equilibrium and vertical averaging
- Allowed Ingersoll to vertically integrate equations
  - Equations became functions of only the horizontal direction
  - Velocity constant with altitude (vertical accelerations small)
- Allowed analytical solution, but overly simplistic
  - Particles leaving vent or surface have vertical velocity component and acceleration
- Considering the vertical component changes the length scales – Moreno’s models showed this
- Can we neglect vertical motion and accelerations at some small distance from a vent where horizontal motion dominant?
  - Maybe, but any model near a vent must consider vertical component
- Need to quantify the distance at which hydrostatic equilibrium and vertical averaging are valid and where they are not valid
Limitations – Turbulent transfer

• Assumption #2: Turbulent transfer or viscous dissipation assumed negligible
• Simplifies equations and allows analytical solution
• Ingersoll (1985) considered turbulent transfer and got similar results to Ingersoll (1989)
• Turbulent transfer can likely be neglected in our models too
Limitations – Simple geometries

- Assumption #3: Simple geometries
- Ingersoll’s simplified geometries serve as a starting point for our models
- Our models will be more complex
  - Hot surface/Cold surface – sulfur moved in one direction
  - Horizontal transport model – sulfur moves in more than one direction
Limitations – Time of day

- Our preliminary models assumed nighttime conditions
  - Ambient SO$_2$ atmosphere condenses out at night
  - Simplifies the models
  - Vapor transport only from volcanic sources
- Presence of daytime atmosphere may shorten the length scales
- Need to quantify how much an ambient atmosphere changes the length scales
Conclusions – Future Work

- Preliminary analyses show encouraging results and predict length scales of deposition consistent with known deposits of sulfur
- Want to explain questions of temperature and morphological features at Loki
  - Include thermal contributions in models
  - Use preliminary models as basis for more complex models – Horizontal transport, Vertical transport, etc
- Want to extend models of lava cooling on Io to include volatiles
  - Loki
  - Other volcanoes
- Increase overall understanding of eruption temperatures and lava compositions on Io
  - Interior structure and composition