Simulations of Volcanic Plumes and Aurora on Io by the ASE/Astro “Io Group”


ASE/EM and Astronomy Departments

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Two talks for the price of one

• Background on Io’s volcanic plumes
• Numerical methods and basic features associated with simulated plumes
  - Flow Conditions (example results)
  - Innovations DSMC methods (VT energy transfer, etc.)
  - Gas/particle flow modeling
• Matching observations with the simulations
  - Parametric study on vent conditions
  - Reproducing Voyager plume images by gas and dust flow
  - Plume deposition profiles

And then…..
• Background on Io’s aurora
• Numerical simulations of electron motion and Io’s full atmosphere
• Why does the wake glow?
• DSMC (direct simulation Monte Carlo) Method;
• Suitable for rarefied gas dynamic applications on Io;
• Axisymmetric flow; spherical geometry
• Vibrational and rotational energy exchange;
• Infrared and microwave radiation;
• Two phase gas/particle flow
Basic Flow Features in Simulated Plumes

Comparison of Mach number contours of dayside (left, Ts = 115 K) and nightside (right, Ts = 90 K) Pele type plume.

- SO2 gas erupts from the vent (located at R = 0 km) at around Mach 3, expands, accelerates, until gravity slows it down.
- A canopy shaped shock is formed at an altitude of about 300 km.
- A re-entry shock is formed for plume on dayside.
Decomposition of the Computational Domain

Region 1: 10km x 1km, 100x120 grid, dt=0.005 s, key obs.\(-v_3\) (lifetime~0.023s)

Region 2: 11km x 8km, 110x100 grid, dt=0.02 s, key obs.\(-v_1\) (lifetime~0.29s)

Region 3: 20km x 80km, 200x500 grid, dt=0.1 s, key obs.\(-v_2\) (lifetime~1.0s)

Region 4: 800km x 450km, 1000x1000 grid, dt=0.4 s
DSMC Emission Results for Pele Type Plume

- $v_1$ and $v_3$ band emission rates drops one order of magnitude within 2 km. The rapid emission signatures are captured by calculation in region 1 and 2 with very fine spatial and temporal resolutions.

- Emission from $v_2$ band re-appears at the shock.

DSMC calculated photon emission rate contours for $v_1$, $v_2$ and $v_3$ vibrational bands near the plume core.
What are conditions at the “Effective” Vent

a) Volcanic tube
b) Lava Lake plume
Parametric Study of Vent Conditions ($T_{\text{vent}}, V_{\text{vent}}$)

- Shock height and deposition depend on vent conditions.

- Goal: using parametric study results to constrain vent conditions based on observed shock height and peak deposition radius.

- Assumptions include fixed number density at the vent; optically thin gas; ~8 km vent radius; night side plume.

$H_{\text{shock}} = 320\, \text{km}$

$R_{\text{ring}} = 550\, \text{km}$
Parametric Study of Vent Conditions \((T_{\text{vent}}, V_{\text{vent}})\)

- Constant shock height \((H_s)\)
- Constant peak deposition ring radius \((R_r)\)

- Similar figures for other properties, such as the total mass, total emission power from each band, etc.
Matching Voyager Image of Prometheus

- Encouraging semi-quantitative similarities of the integrated gas column density to the Voyager image (Strom & Schneider, 1981) of Prometheus.

- The Voyager image likely shows the solar reflection of the fine particulates in the plume (<10 nm, Collins 1981).

- The column density of 1 nm refractory particle plumes indeed shows convincing similarities to the Voyager image as does the gas.
Gas/particle Flow Modeling

Two “Overlay” Methods (assuming dilute particle flow) —
Particles are assumed to be spherical, refractory and have a density of liquid SO₂.

i) Gas/particle collision model (costly for 1 micron and larger particles).

ii) Drag model (assuming free-molecular flow – particle diameter based Kn >> 1, C_d = f(s) (Bird, 1994).)

1. Obtain smooth steady gas flowfield
2. Release particles at zero velocity from the vent and calculate the drag on the particle.
3. Calculate acceleration of particles and move them
Gas/particle Flow

- Concentration of particles near the shock is seen for particle with size of 0.01 $\mu$m up to 0.1 $\mu$m (agree with size range analyzed by Collins ‘81)
- A sorting of particles by size inside the plume and on the surface
  - finer particles falling further away from the vent
  - large particles stay close to the axis and land close to the vent
Parametric Study of Particle Size

- Small particles (~1 nm) track gas flow well, reproduce plume image in the outer portion of the plume.

- Decoupling between gas and particle motion starts early for large particles.

- Upper limit of particle size in the outer portion of the plume is 10 nm. Consistent with Collins 1981.
Particle Size Dependence of the Response Behavior

- 1 nm particle tracks the gas flow well.

- Larger particles are less responsive to the accelerating gas flow.

- The turning flow near the re-entry shock acts like a cyclone separator: the larger particles are sorted from the small ones.

Comparisons of gas streamlines (black) and trajectories of entrained particles (red). The surface temperature is 110 K and the gas number density contours are shown on the left.
Matching Voyager Image of Prometheus

- A relatively high brightness near the surface (within ~5 km above the surface on the left side of the plume) is also seen in the Voyager image of Prometheus indicating a high particle column density there.

- This feature can also be reproduced by a plume of nano-size particle at a slightly higher surface temperature.
Matching Voyager Image of Pele

- Such qualitative similarities were also found for Pele.
- The “cone” shape contours in the vent vicinity in the Voyager image cannot be reproduced by 1 nm particle plume.
Matching Voyager Image of Pele

a) 10 micron

b) Log normal size distribution (5-10 micron) with $r^6$ size-dependent scatter efficiency.

c) Better match to Voyager image
Matching Plume Shadow

- A remarkable reddish shadow cast by Prometheus is seen in the Galileo image.

- The solar zenith angle at the Prometheus vent is ~78°. The column densities projected from the sun onto Io's surface at this angle were calculated.

- The "finger" shape is found to be best reproduced by a plume of ~10-100 nm particles. The "mushroom" shape may be reproduced by 1 nm particles.
Reproducing the Multiple Ring Deposition Structure around Prometheus

Figure 10. Surface changes at Prometheus, Violet filter images.

Geissler et al, 2003
Parametric Study on Surface Temperature

- At low surface temperature, the falling gas simply pours onto the ground and condenses unimpeded.
- As the surface temperature rises to ~111 K, a nearly horizontal re-entry shock and well defined bounce region are formed.
- Deposition ring forms at R = ~500 km.
- Depletion effects appear at high surface temperature.

Number density contours with different surface temperature (right) and profiles of deposition rate (left).
Gas Deposition Pattern around Prometheus

- Gas deposition pattern varies as surface temperature changes.
- No multiple rings structure is seen in the time averaged deposition profile.
- May imply that the source strength is unsteady.
- However, “bounce” in the flow and/or dust deposition may be other possible causes of the multiple ring structure.

\[ T_s = (T_{\text{subsolar}} - 50) \cos^{1/4} \theta + 50 \]

Ingersoll, et al, 1985

b) Surface temperature as a function of time
Particle Deposition Pattern around Prometheus

- The deposition of nano-particles in plumes with relatively high surface temperatures are examined.
- Due to the “bouncing” with the gas flow, outer rings are indeed seen in the nano-particle deposition profiles.
The Effects of Unsteadiness of Volcanic Sources

- $V_v$ is pulsed sinusoidally. Other parameters kept constant.
- Stronger moving shocks for long period pulsing.
- Stationary shock for very short period pulsing.
Plume Conclusions

• Volcanic plumes on Jupiter's moon Io are modeled using the direct simulation Monte Carlo (DSMC) method.

• A sophisticated model including - spherical geometry, variable gravity, internal energy exchange (discrete vibration-translation and continuous rotation-translation energy exchange) in the gas, infrared and microwave emission from the gas, multi-domain sequential calculation to resolve the fast emission event and opacity, has been developed.

• Two-phase gas/particle flows are modeled using “overlay” techniques.

• Vent conditions are constrained. Observed plume image, plume shadow, deposition pattern are for the first time reasonably matched with the simulated plumes.
Modeling Io’s Aurora

HST Io Auroral Observation

- Plasma flows right to left
- Image is of [OI] 630nm emission
- Wake bright spot is tilted relative to Io’s equator and extends ~250km high
- Little upstream emission
- Bright “equatorial band”
- Limb glow extends from the wake spot to the north polar region
- Diffuse emission present

Trauger et al. 1997DPS29.1802T
Io Auroral Observation II

- During Cassini flyby of Jupiter, several images of Io’s emissions were taken
- White spot is Pele
- UV emission shown as blue
- Atomic Oxygen emission (630 nm) is red
- Showed temporal variability of emission
  - Io starts below plasma torus equator and crosses it as the eclipse progresses
  - Emission bright spots appear to track magnetic field tilt

Cassini movie of emission around Io in eclipse (Porco et al., 2003)
Simulation Domain

- Io is at the center of a 6000kmx6000kmx6000km cube
- The X-axis is aligned in the direction of the plasma flow
- The Y-axis points towards the sun/earth
- Cartesian grid of size $\Delta=60$km is used for magnetic field interpolation
- Thermal electrons are input along the top and bottom boundaries and removed if they cross any boundary
Magnetic Field Model

- Pre-computed 3D MHD model for Io located at the plasma torus equator (Combi 1998)
  - Includes ion mass loading and no intrinsic field for Io
  - Matched free parameters for best agreement with Galileo flyby data
  - Can get magnetic field at different torus latitudes by rotation
- The field increases (~15%) upstream and decreases (~25%) downstream
Motion in a Magnetic Field

• Convenient to divide electron velocity into components perpendicular and parallel to the magnetic field:

\[ \vec{v}_e = \vec{v}_\perp + \vec{v}_\parallel, \quad \vec{v}_\perp = \vec{v}_c + \frac{\vec{E} \times \vec{B}}{B^2} \]

\[ \vec{v}_c = \text{Gyration velocity about field lines} \]

\[ \frac{\vec{E} \times \vec{B}}{B^2} = \text{Drift velocity due to electric field} \]

• We neglect the drift velocity (small compared to \( \vec{v}_\parallel \)) and diffusion across field lines (collision frequency small)

• The radius of gyration, \( r_g = v_\perp m_e / qB \), is <6 m for \( E_e > 5 \text{eV} \), and the relevant atmospheric scale is \( \sim 8 \text{ km} \), so we move the electron purely along the field lines
Magnetic Moment

- An adiabatic invariant for a given electron is: 
  \[ \mu_{\text{mag}} = \frac{1}{2} m_e v_c^2 \]

- Since this is constant along the electron path, a relation for the change in velocity with changing magnetic field strength along a field line can be obtained:

  \[
  \sin \alpha = \sin \alpha_0 \sqrt{\frac{|\vec{B}|}{|\vec{B}_0|}}, \quad \tan \alpha = \frac{\vec{v}_c}{\vec{v}_\parallel}, \quad \vec{v}_c^2 + \vec{v}_\parallel^2 = \text{const}
  \]

- Note that \( \alpha = 90^\circ \) corresponds to \( \vec{v}_\parallel = 0 \) and that the electron will then reflect (mirror) the electron at:

  \[
  |\vec{B}_{\text{mirror}}| = \frac{|\vec{B}_0|}{\sin^2 \alpha_0}
  \]
Volcanic Atmosphere Model

• Pre-computed independent volcanoes (Zhang 2004)
  – Two “template” volcanic types – Large (Pele) and Small (Prometheus)
  – 53 volcanoes accounted for on Io
  – Assume 0.1% O concentration (by number) based on equilibrium vent species’ concentrations computed by Zolotov and Fegley (1998)
  – Plasma heated with energy flux of 5 mW/m²
Sublimation Atmosphere Model

- Pre-computed 2D steady state sublimation atmosphere (Wong 2000)
  - Continuum model – has limited applicability at high altitudes but it is the best available
  - Multi-species model, we use just the SO$_2$ and O data since they are dominant
  - Atmosphere model for Io in sunlight (not eclipse)
  - Includes photoreactions, plasma reactions
  - Latitudinal dependence added using (Strobel and Wolven):
    \[
    \frac{n(\theta)}{n_{\text{Pole}}} = 1 + \frac{n_{\text{Equator}}}{n_{\text{Pole}}} e^{-\frac{\theta}{0.625}}^6
    \]

Local SO$_2$ number density profile as viewed from earth (Y = 300km). Notice the latitudinal variation and the superposition of the plumes.
Simulation Overview

- Model split into two independent parts: Excitation and Emission

- **Excitation:**
  - Electrons input and move along field lines through the domain
  - Occasionally electrons collide with the neutral atmosphere
  - Location of excited oxygen is stored for use in Emission

- **Emission:**
  - Excited oxygen are given initial velocities based on local temperature and bulk velocity
  - The oxygen moves until it either collides or emits
Cross Sections

- A cross section is a measure of the effective area of a target molecule for producing an interaction (collision)
  - Possible interaction types: Ionization, Dissociation, Attachment, Excitation, etc.
- The total cross section for species i colliding with j is:

\[
\sigma_{ij}^{tot}(E) = \sum_{k}^{N_{R\times N}} \sigma_{ij}^{k}(E)
\]
Included Cross Sections

The simulation includes electron-SO₂ and electron-O interaction cross sections as functions of energy.
Collisions

• In a time interval $\Delta t$, the collision probability is:

$$P_{\text{Collision}} \approx 1 - e^{-\Delta t \sum_{i} n_i \sigma_{ie}^{\text{tot}} \bar{v}_{rel,j}}$$

where $N_s$ is the number of target species (SO$_2$ and O), $\sigma_{ie}^{\text{tot}}$ is the total interaction cross section for species $i$ with the electron, and $\bar{v}_{r,i}$ is the relative velocity.

• A collision occurs if a random number is less than $P_{\text{Collision}}$.

• Choose the collision type (elastic, ionization, excitation, etc.) by comparing the position of a second random number on the scale:

$$P_k(E) = \frac{\sigma_{ie}^k(E)}{\sigma_{ie}^{\text{tot}}(E)}$$

0 $\rightarrow$ Elastic $\rightarrow$ Excitation $\rightarrow$ Ionization $\rightarrow$ MUV I $\rightarrow$ MUV II

$P_{\text{E}}$ $P_{\text{E}} + P_{\text{Ion}}$ $1$
Emission

- Excited oxygen given an initial velocity based on local temperature, bulk velocity and corrected for the electron excitation collision
- The rate of emission is given by the Einstein A coefficient (the inverse of A is the mean lifetime of the state)
- [OI] 630 nm is a ‘forbidden’ line emission – it does not emit through the first-order mode, therefore \( A_{630\text{nm}} \approx 5.1 \times 10^{-3} \) (lifetime \( \approx 190 \) sec)
- If a collision occurs before the oxygen atom emits, then it is assumed to de-excite (without emission)
- To match observations, the emission events are line-of-sight integrated
Boundary Conditions

\[ n_e = (f_s)^4 n_p \]
\[ T_e = 5 \text{eV} \]
Random \( \alpha \)

Electrons scatter

\[ n_e = (f_s)n_p \]
\[ T_e = 5 \text{eV} \]
Random \( \alpha \)

Domain Boundary

\[ n_e = n_p \]
\[ T_e = 5 \text{eV} \]
Random \( \alpha \)

\[ V_{\text{plasma}} = 7 \text{ km/s} \]
\[ V_{||} = 850 \text{ km/s} \]

50000 km to Torus "edge"

151000 km to Torus "Edge"

Geodetic Equator
Auroral Simulation - Deposition

• High electron energy deposition in Pele and Tvashtar

• Higher deposition in the wake than on the upstream side

• Wake deposition is inclined relative to the equator due to electron depletion across Io
Auroral Simulation – Emission I

- Wake bright spot is tilted relative to Io’s equator
- Pele, quenches upstream emission
- No bright equatorial “band” seen in simulation
- Limb glow is not present probably due to Tvashtar and error in latitudinal dependence of atmosphere.
Conclusions

• Lack of upstream emission due to:
  – Magnetic mirror effect reflecting ~60% of electrons
  – Presence of Pele on the leading edge

• Collisional quenching reduces low altitude and volcanic 630 nm emission

• Asymmetric north/south flux tube depletion results in wake spot tilt – not the magnetic field tilt

• Current Work:
  – Improvements to pre-computed volcanoes
  – Implementing Smyth and Wong’s 2004 atmosphere
  – Modeling collapse of dayside atmosphere as eclipse progresses