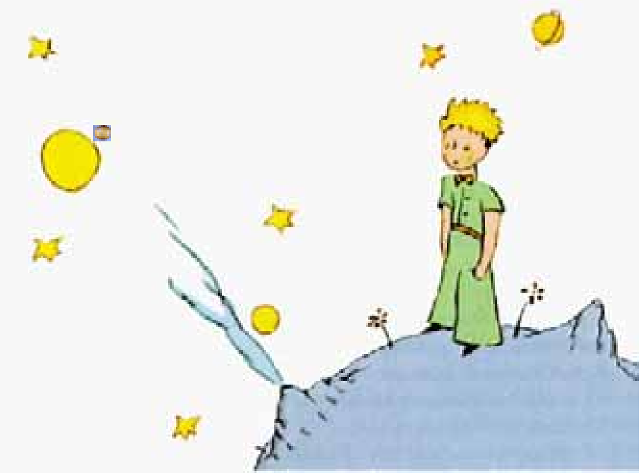

Simulations of Volcanic Plumes and Aurora on Io by the ASE/Astro "Io Group"

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Supported by NASA Planetary Atmospheres Program and the HST Archive Program

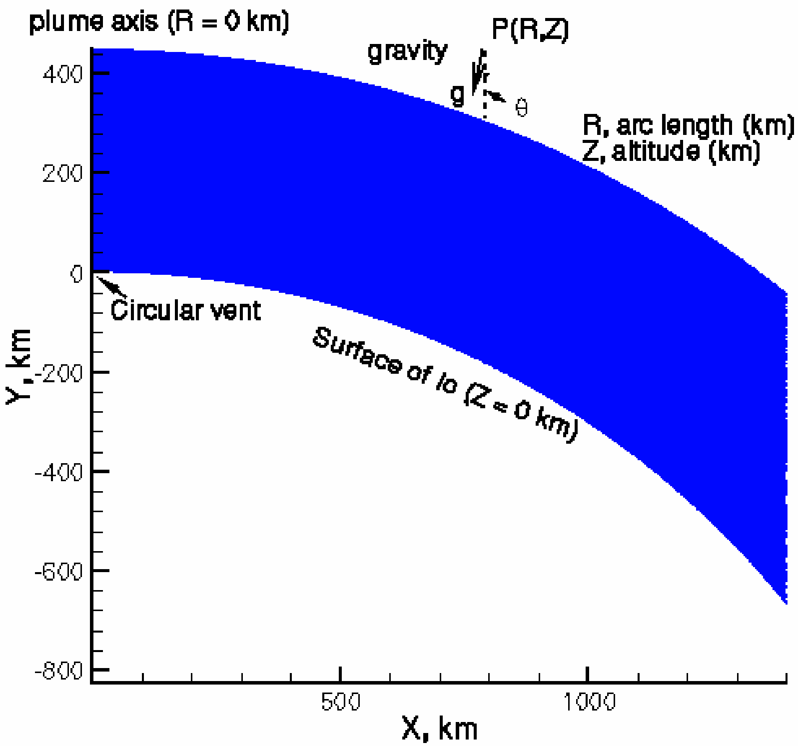
Two talks for the price of one

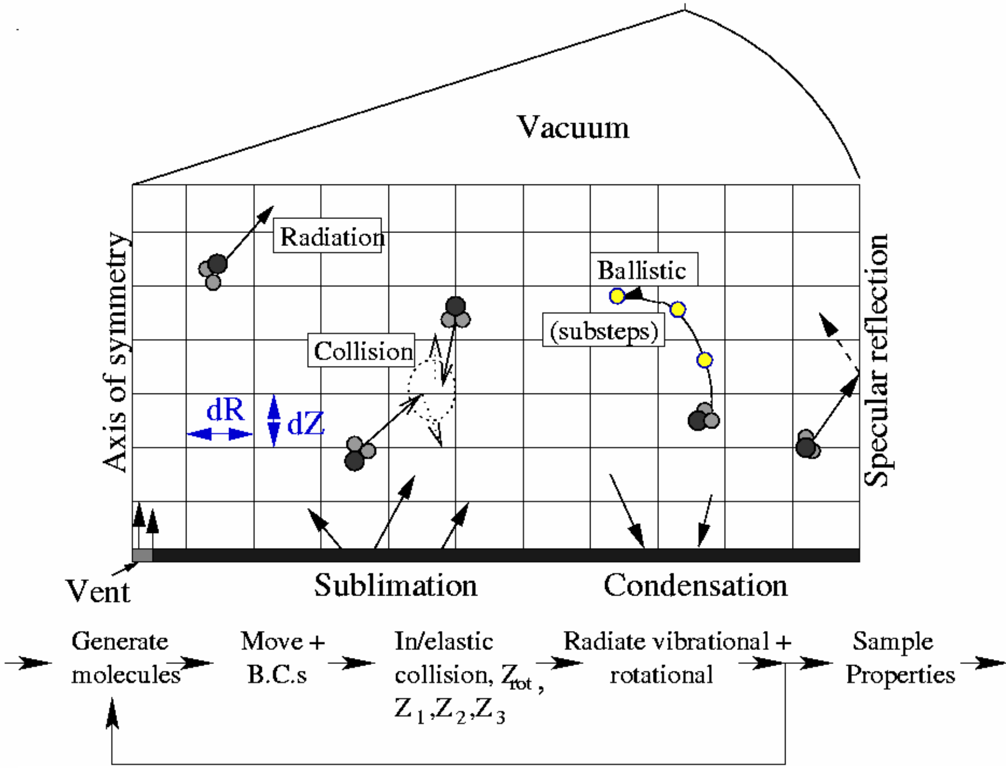
- Background on Io’s volcanic plumes
- Numerical methods and basic features associated with simulated plumes
  - -Flow Conditions (example results)
  - -Innovations DSMC methods (VT energy transfer, etc.)
  - -Gas/particle flow modeling
- Matching observations with the simulations
  - -Parametric study 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?

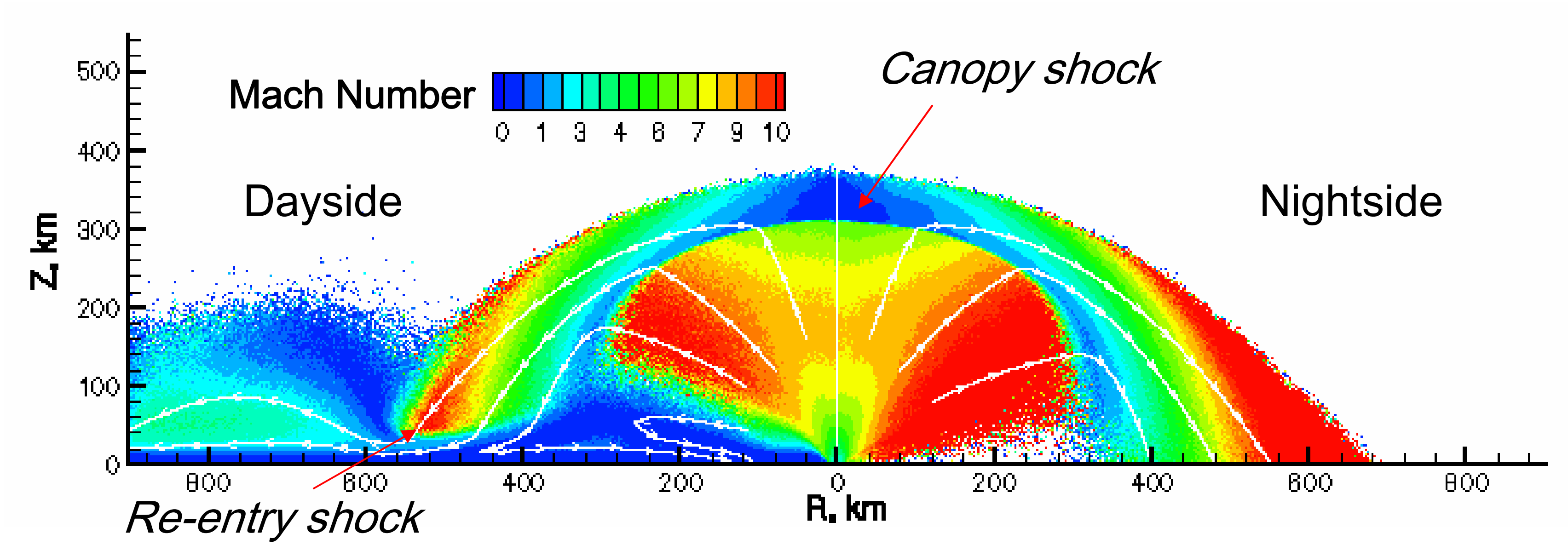
Schematic of Flow Conditions





- DSMC (direct simulation Monte Carlo) Method;
- Suitable for rarefied gas dynamic applications on Io;
- Axisymetric flow; spherical geometry
- Vibrational and rotational energy exchange;
- Infrared and microwave radiation;
- Two phase gas/particle flow

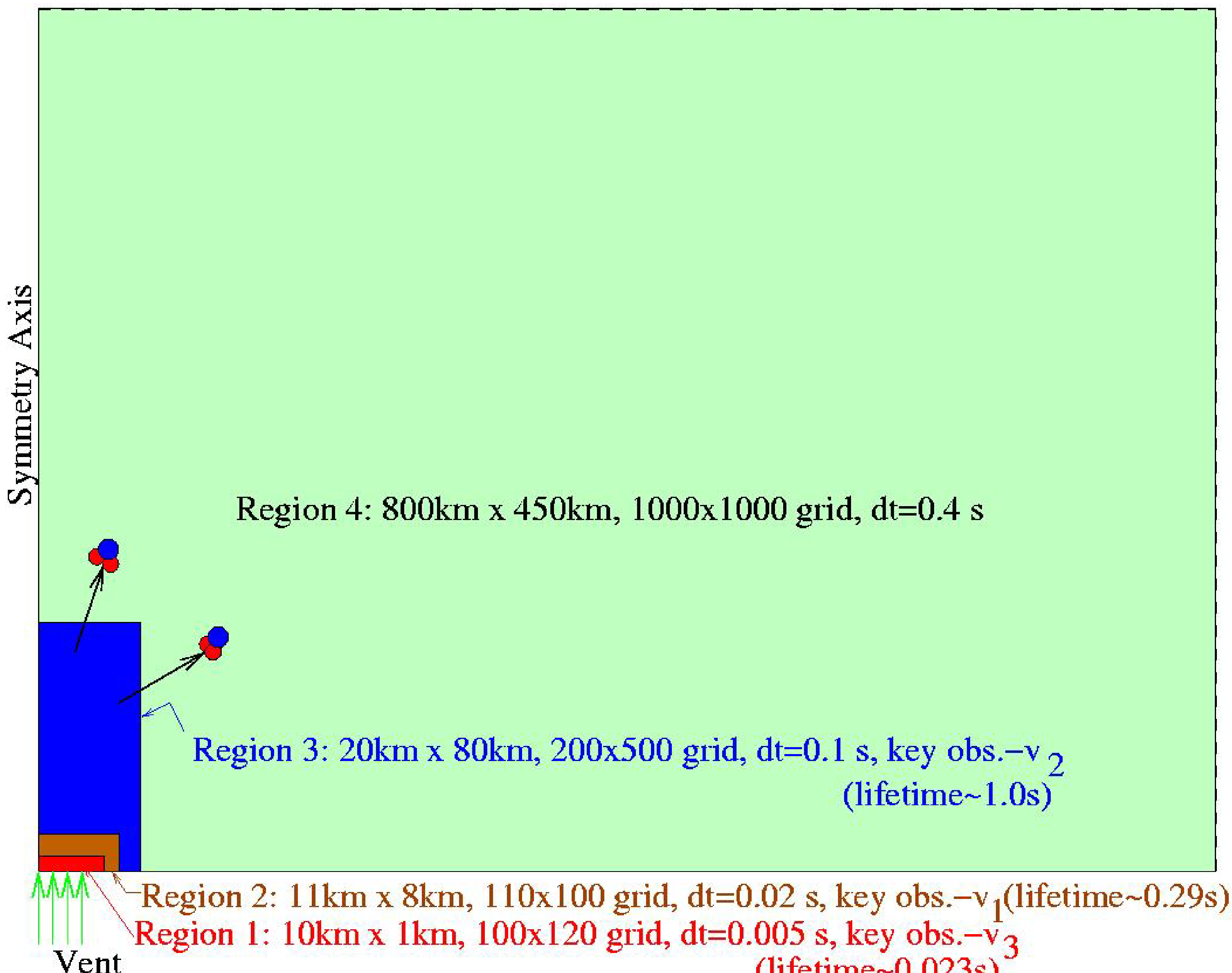
Basic Flow Features in Simulated Plumes



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

- SO_2 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

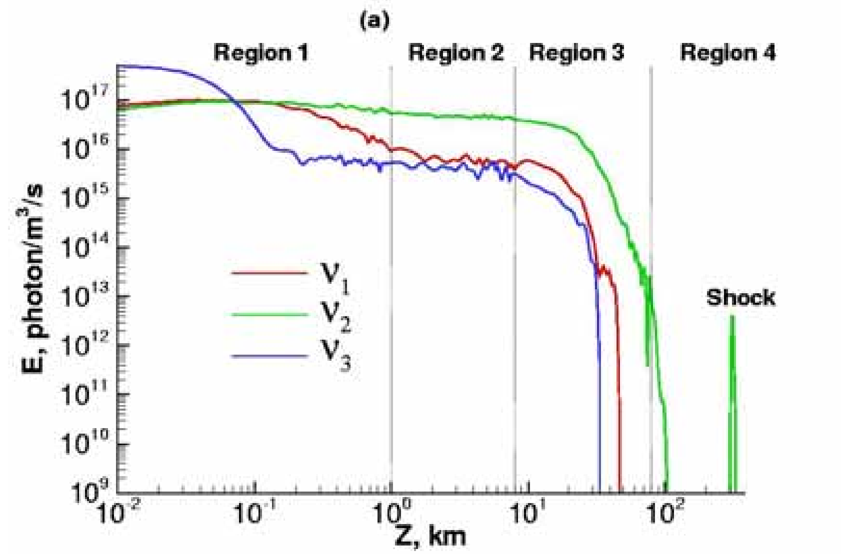
Decomposition of the Computational Domain

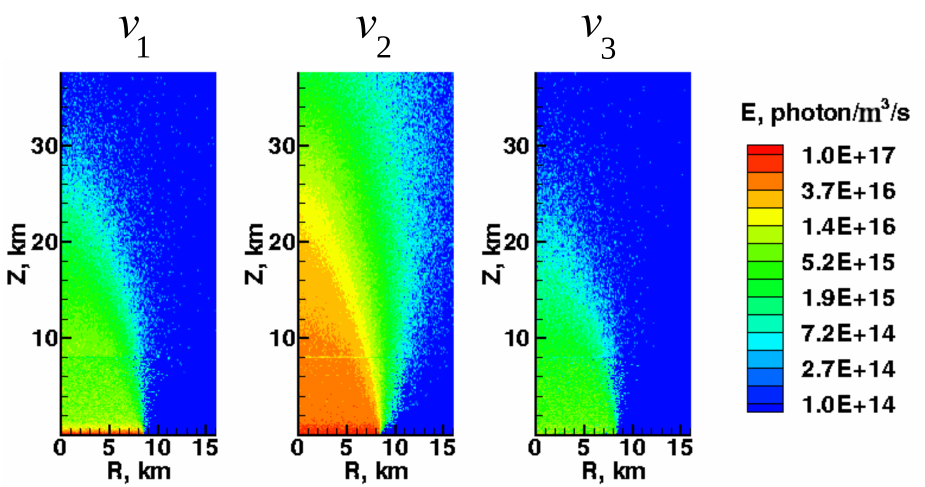


DSMC Emission Results for Pele Type Plume

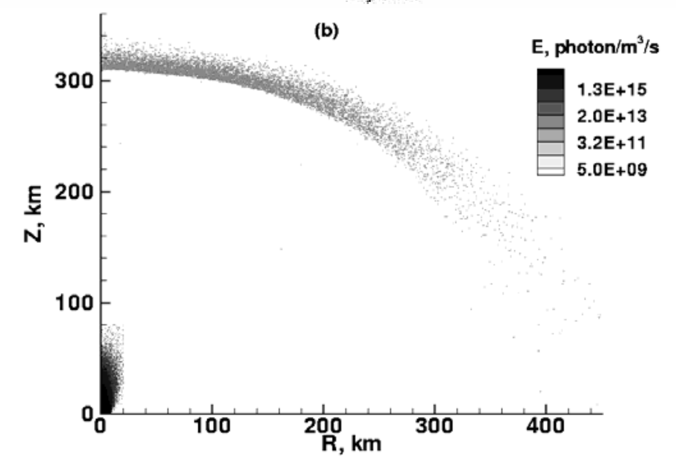
- v_1 and v_3 band emission rates drops one order of magnitude within 2 km. The rapid emission signatures are captured by calculation in region 1 and 2 with very fine spatial and temporal resolutions.

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



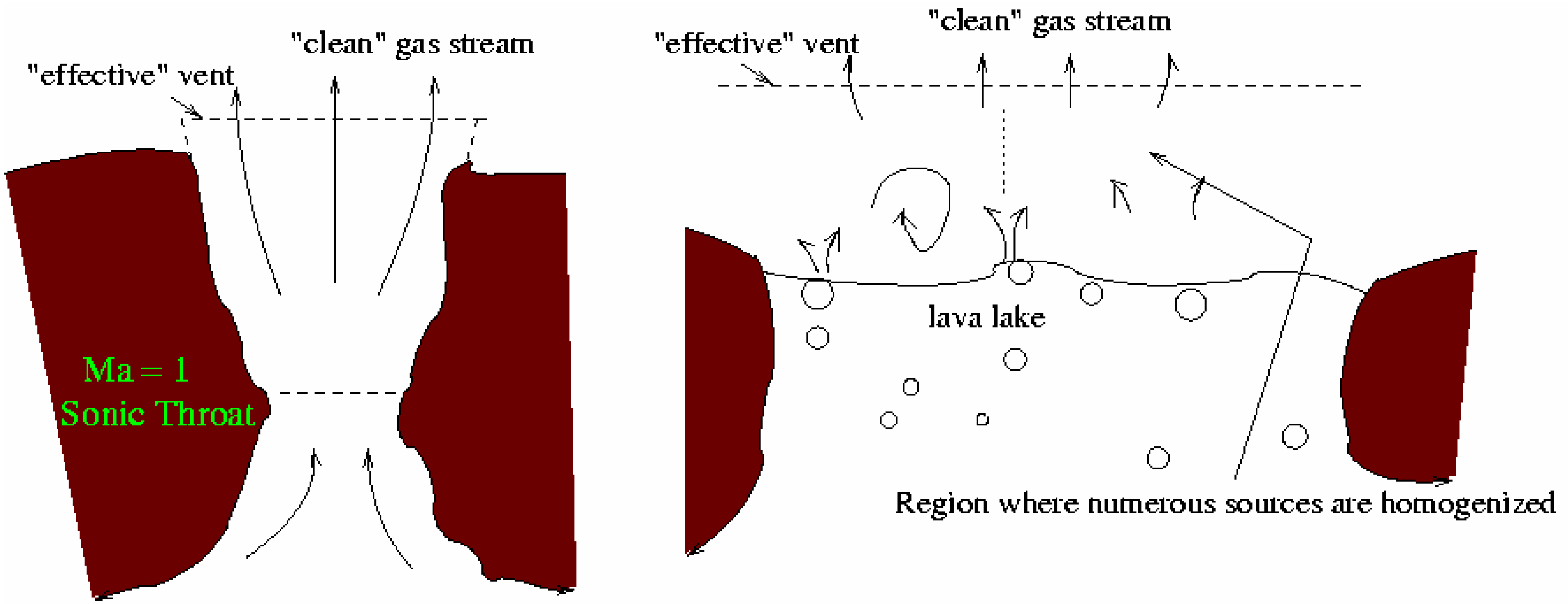


DSMC calculated photon emission rate contours for v_1, v_2 and v_3 vibrational bands near the plume core.



Profiles of emission rate along symmetry axis and contours of emission rate for v_2 band.

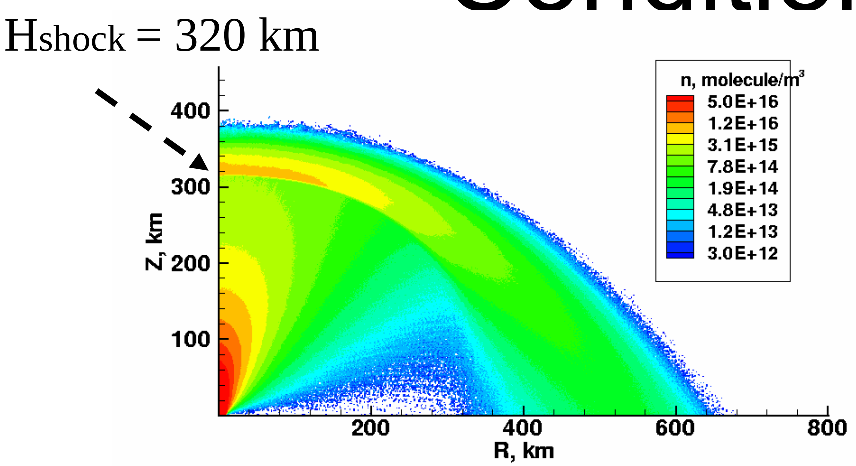
What are conditions at the “Effective” Vent

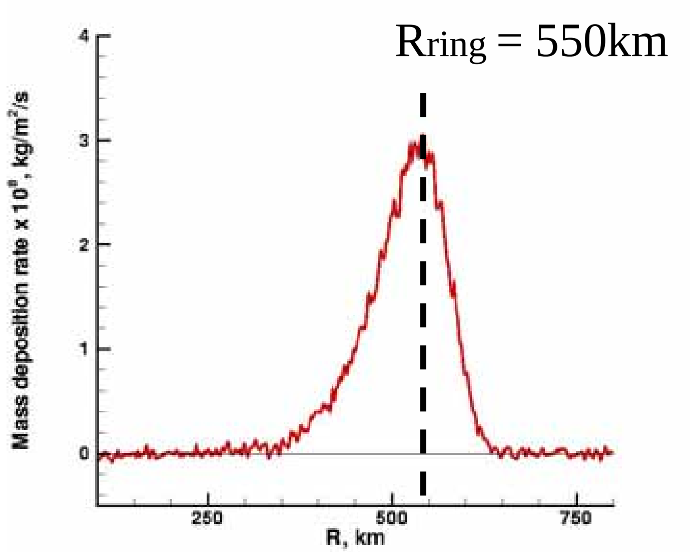


a) Volcanic tube

b) Lava Lake plume

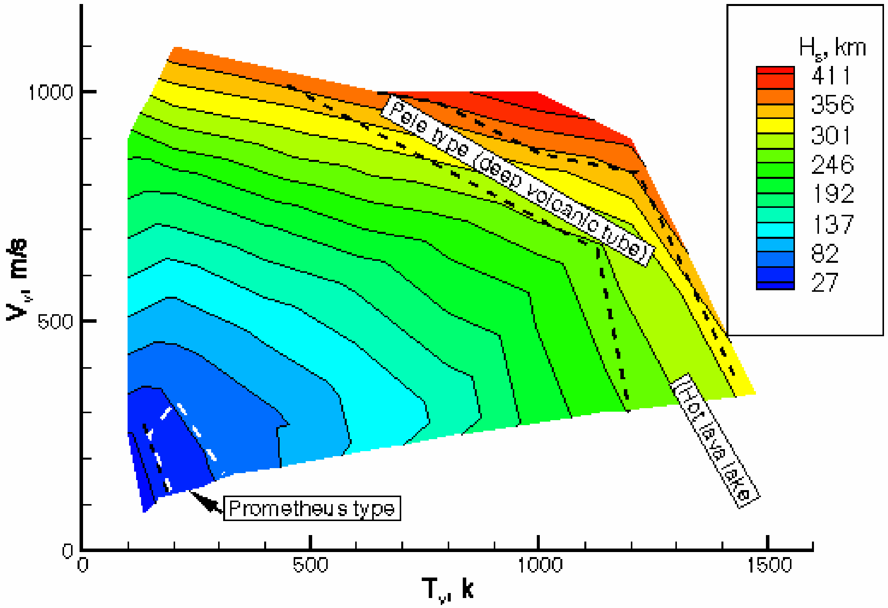
Parametric Study of Vent Conditions (T_{vent}, V_{vent})



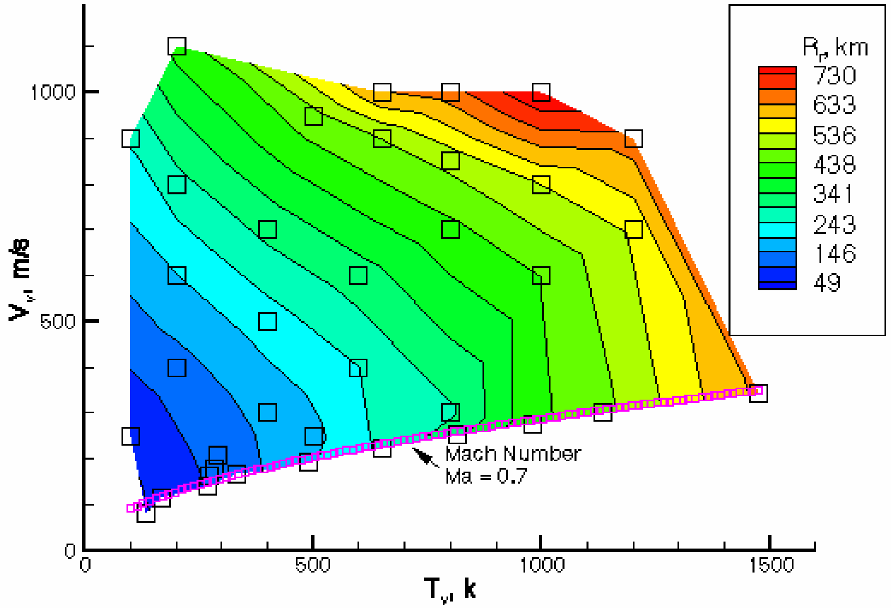


- Shock height and deposition depend on vent conditions.
- Goal: using parametric study results to constrain vent conditions based on observed shock height and peak deposition radius.
- Assumptions include fixed number density at the vent; optically thin gas; ~8 km vent radius; night side plume.

Parametric Study of Vent Conditions (T_{vent}, V_{vent})



Constant shock height (Hs)

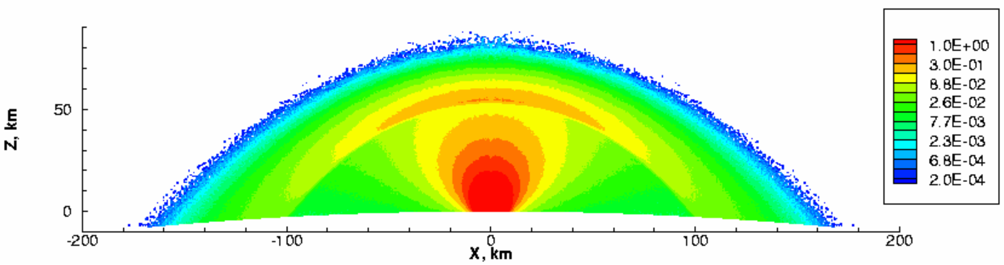


Constant peak deposition ring radius (Rr).

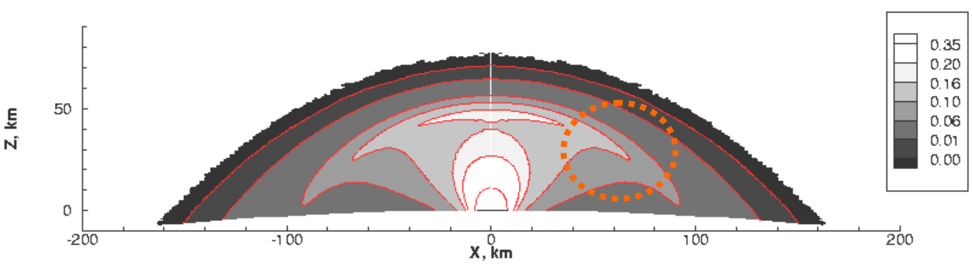
- Similar figures for other properties, such as the total mass, total emission power from each band, etc.

Matching Voyager Image of Prometheus

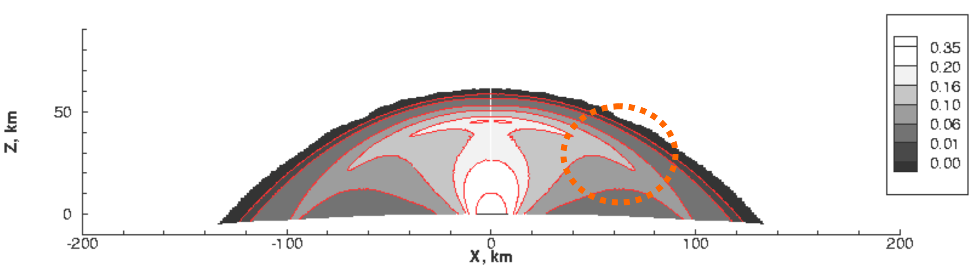
a) Voyager image



b) Gas number density



c) Gas column density (tangential)



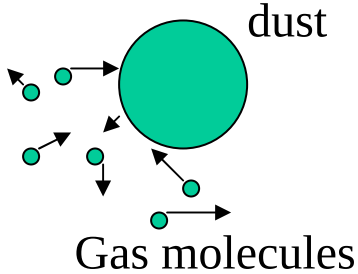
d) 1 nm particle column density (tangential)

- **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 SO_2.

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

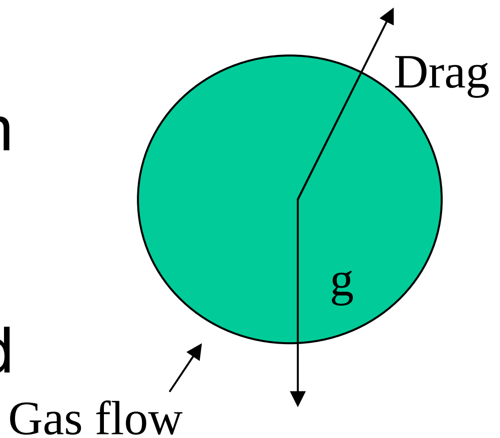


ii) Drag model (assuming free-molecular flow – particle diameter based Kn >> 1, $C_d = f(s)$ (Bird, 1994).)

1. Obtain smooth steady gas flowfield

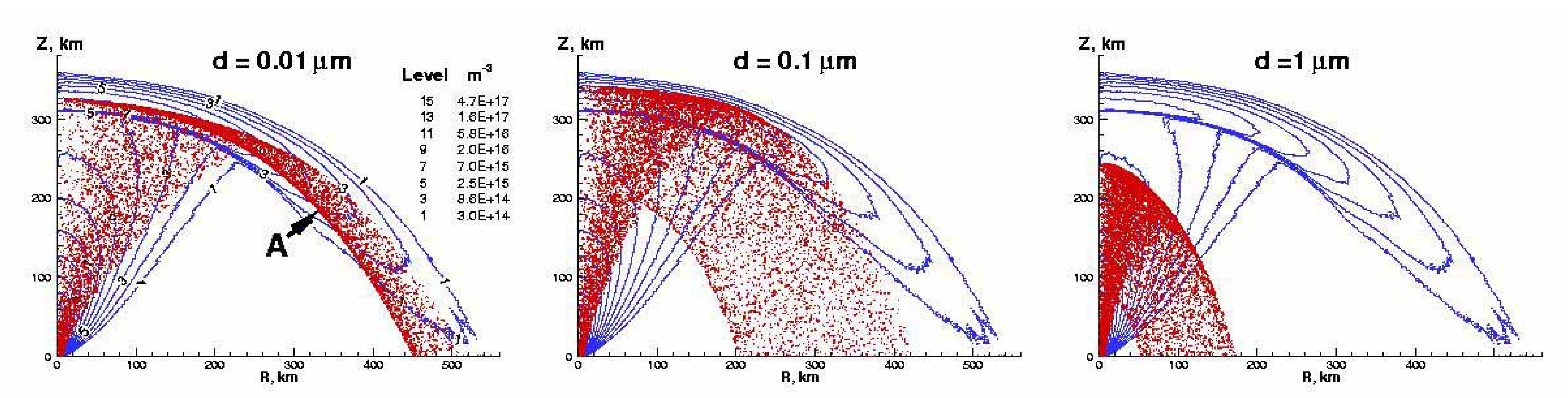
2. Release particles at zero velocity from the vent and calculate the drag on the particle.

3. Calculate acceleration of particles and move them

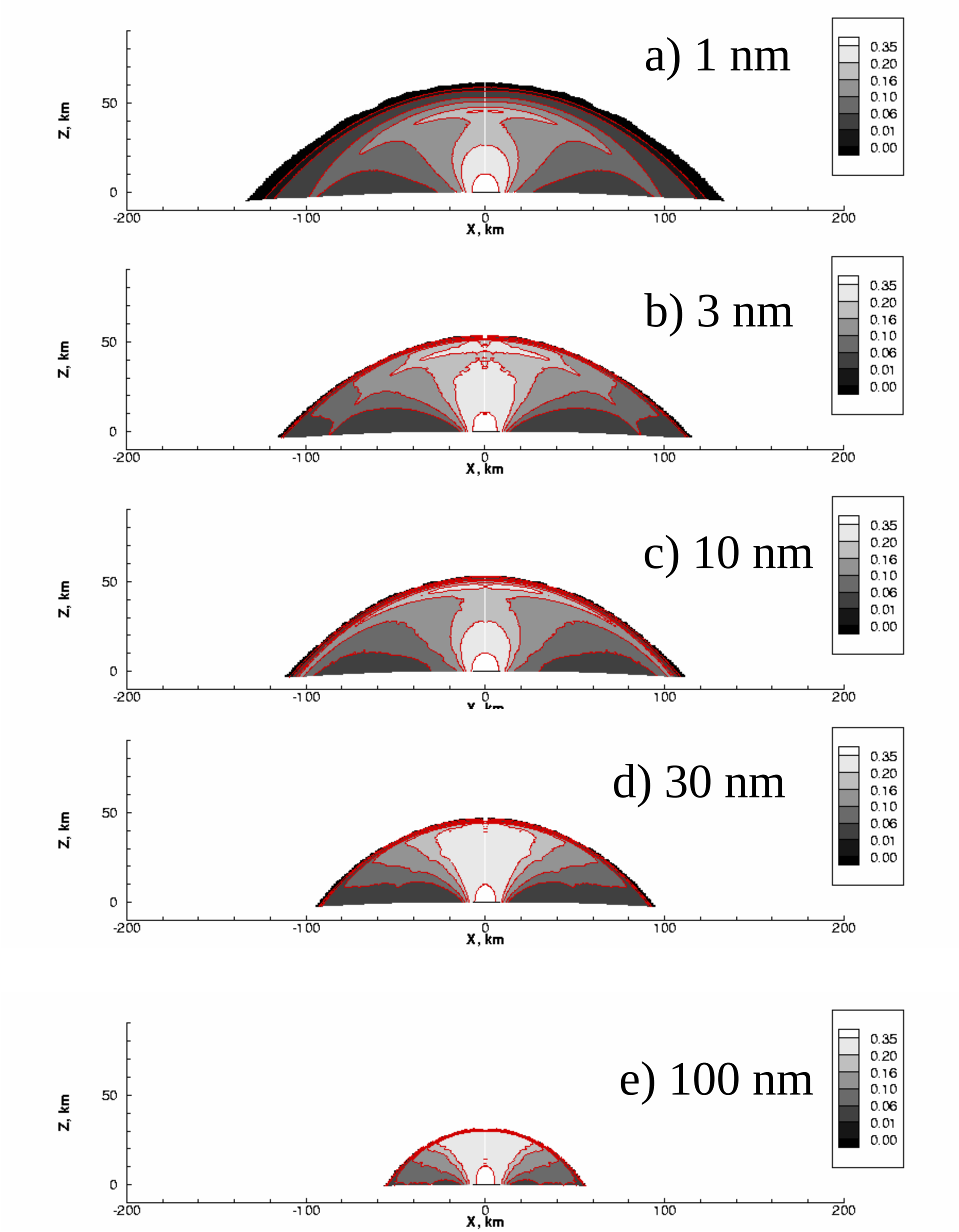


Gas/particle Flow

- Concentration of particles near the shock is seen for particle with size of 0.01 μm up to 0.1 μ 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



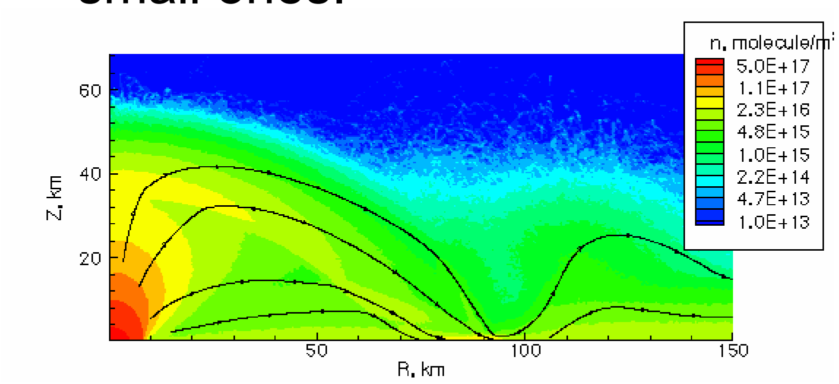
• Small particles (~1 nm) track gas flow well, reproduce plume image in the outer portion of the plume.

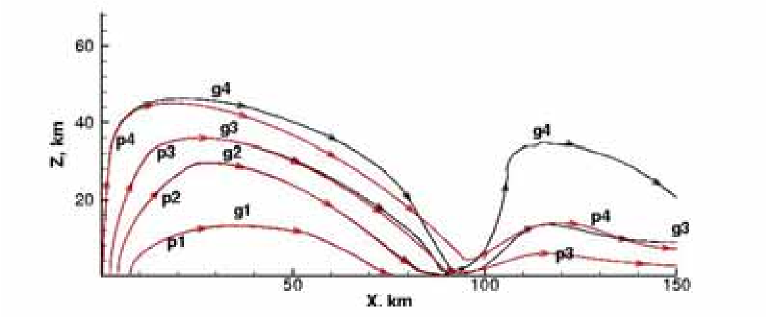
• Decoupling between gas and particle motion starts early for large particles.

• Upper limit of particle size in the outer portion of the plume is 10 nm. consistent with Collins 1981.

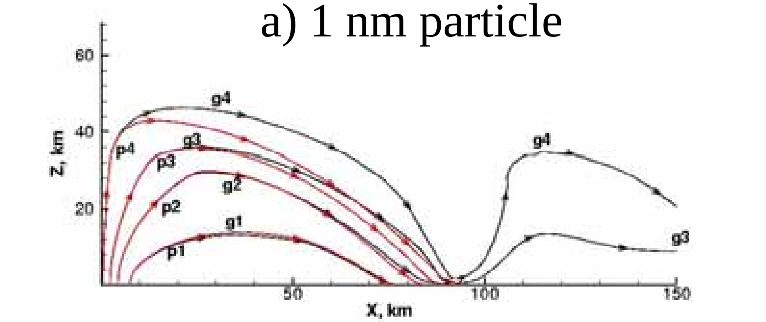
Particle Size Dependence of the Response Behavior

- 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.





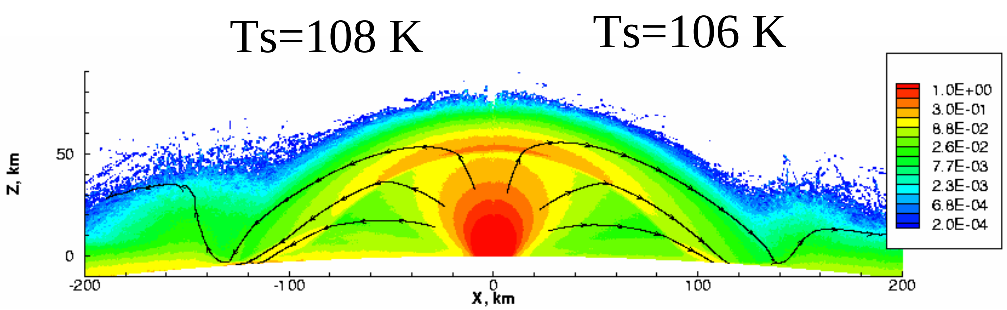
a) 1 nm particle

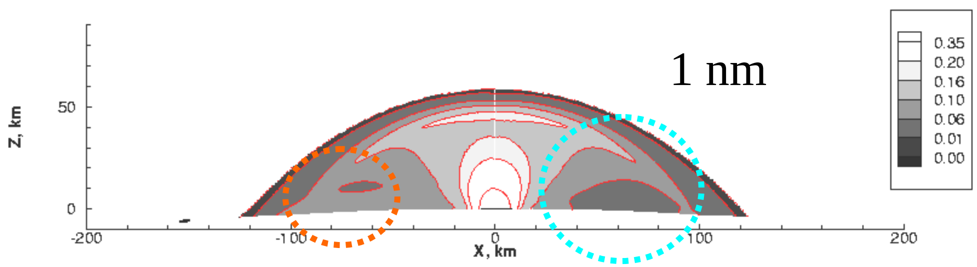


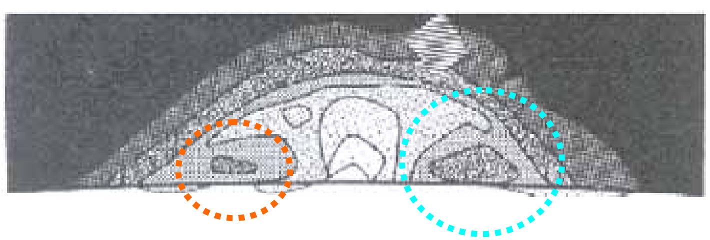
b) 3 nm particle

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

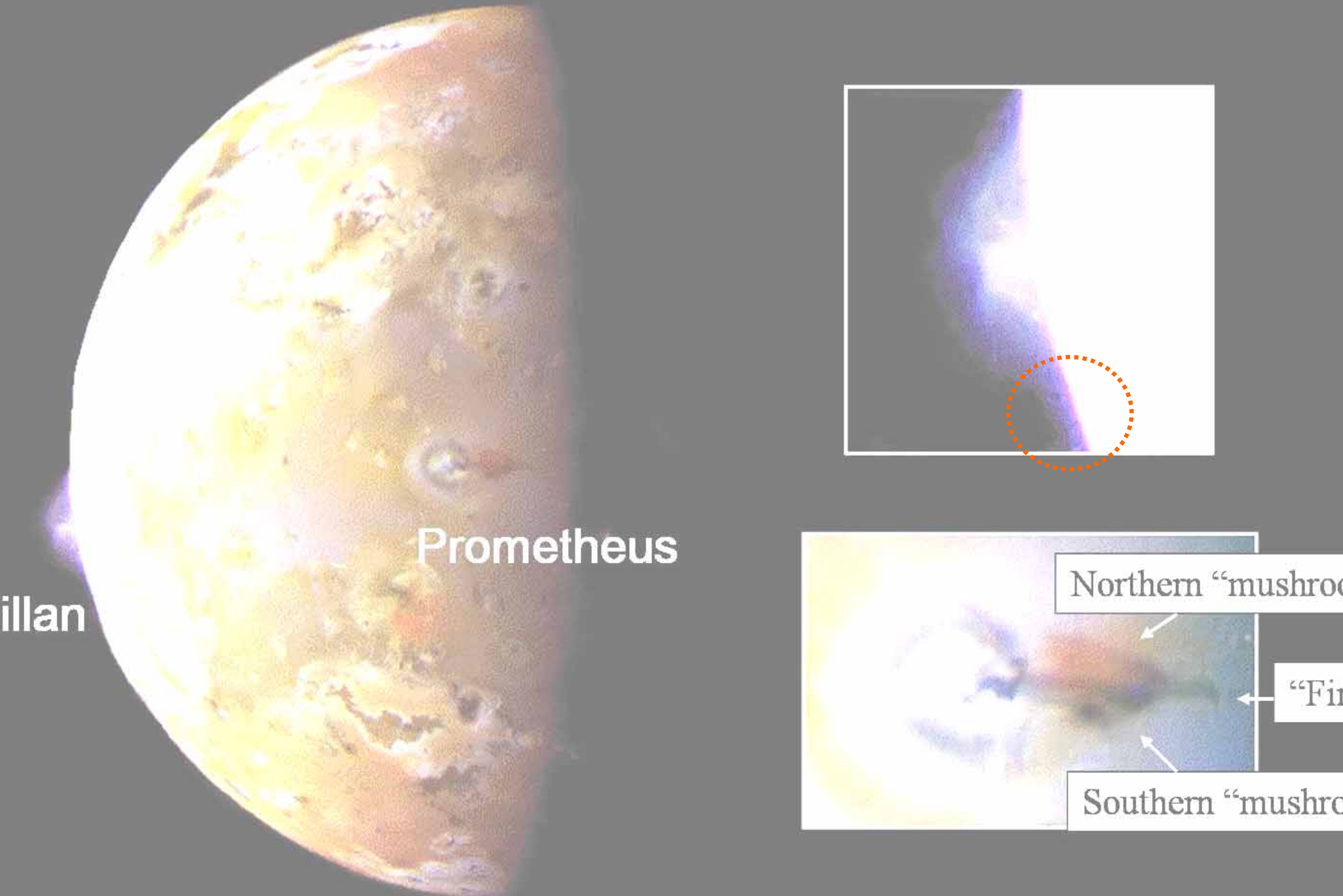






- A relatively high brightness near the surface (within ~5 km above the surface on the left side of the plume) is also seen in the Voyager image of Prometheus indicating a high particle column density there.

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



illan
Prometheus
Northern “mushroo
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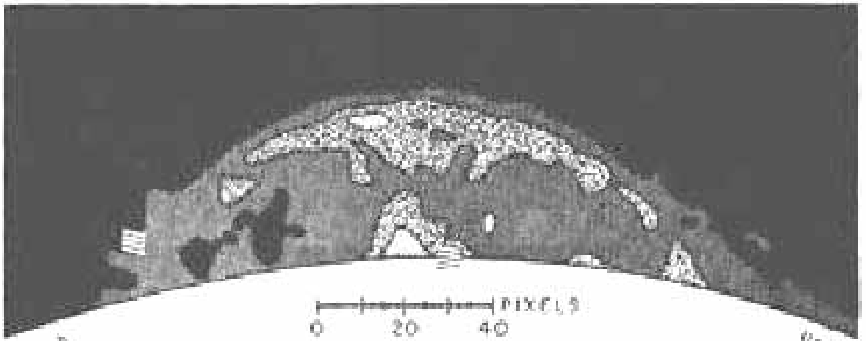
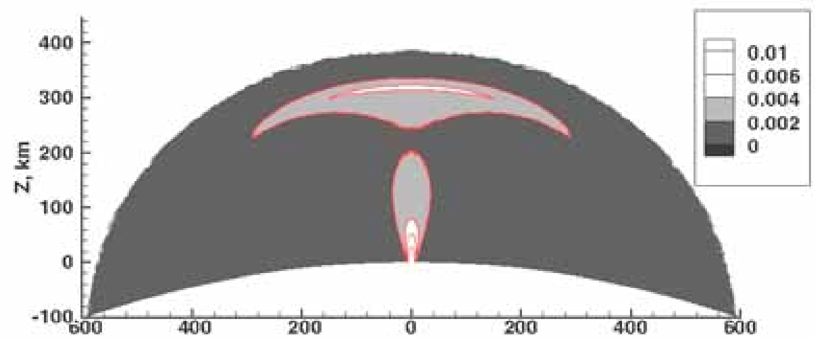
Southern “mushro

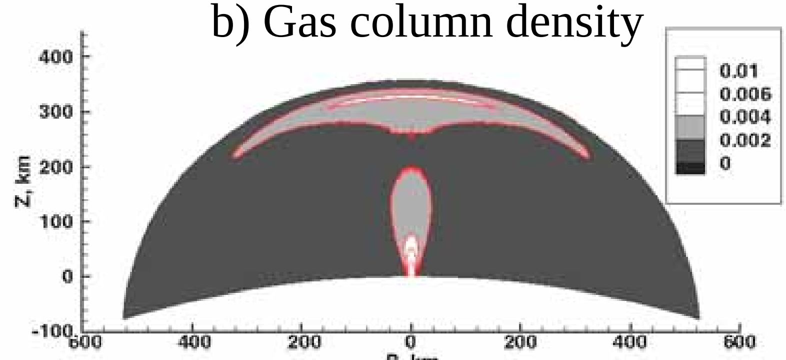
Matching Voyager Image of Pele



a) Voyager image of Pele



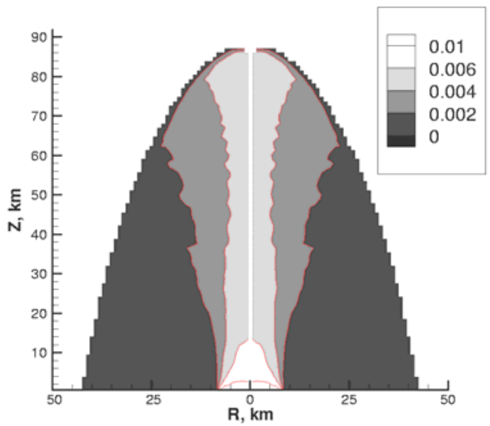
b) Gas column density



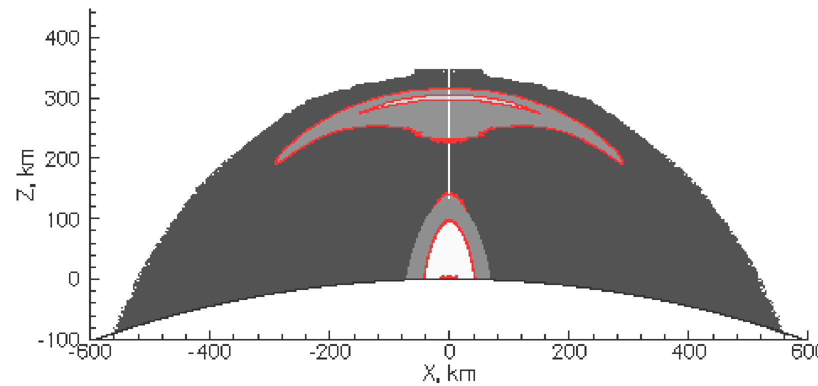
c) 1 nm particle column density

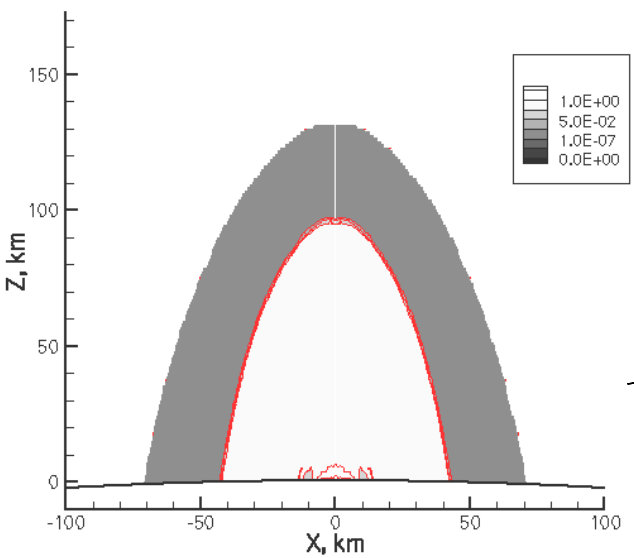
- Such qualitative similarities were also found for Pele.
- The “cone” shape contours in the vent vicinity in the Voyager image cannot be reproduced by 1 nm particle plume.

Matching Voyager Image of Pele

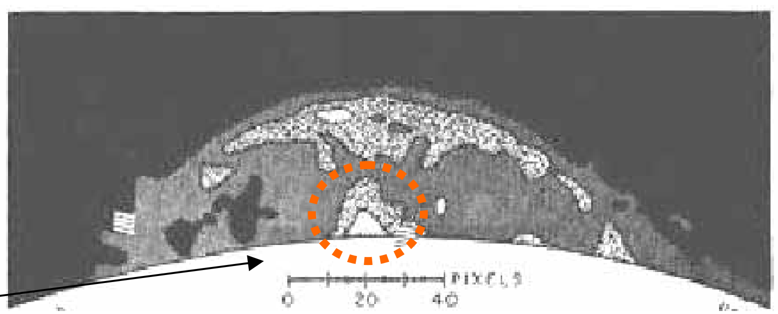


a) 10 micron



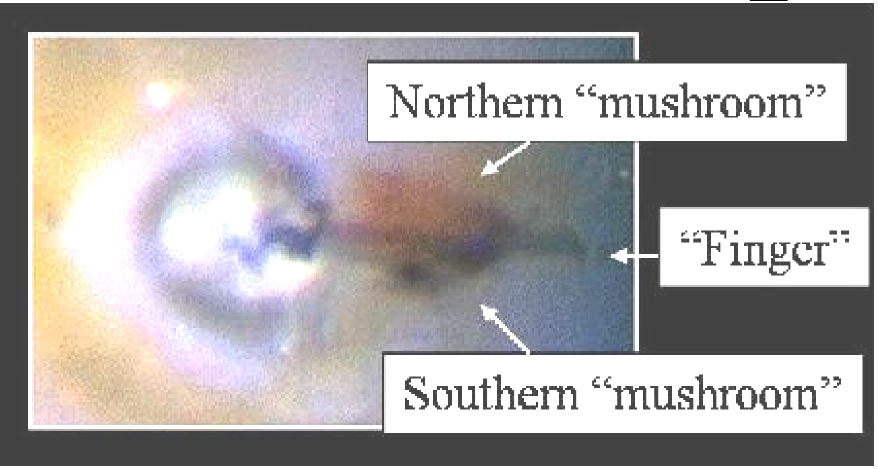


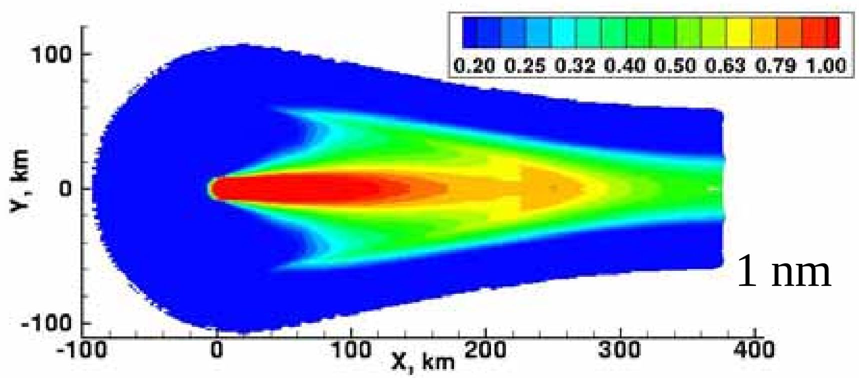
b) Log normal size distribution (5-10 micron) with r^6 size-dependent scatter efficiency.

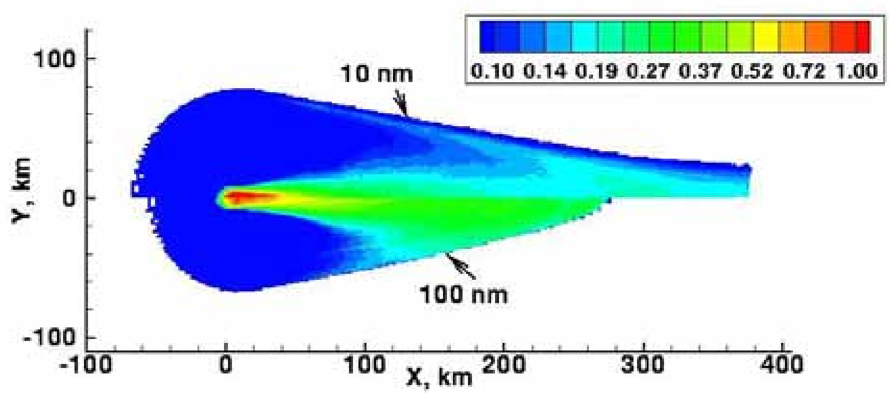


c) Better match to Voyager image

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 ~78deg. 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

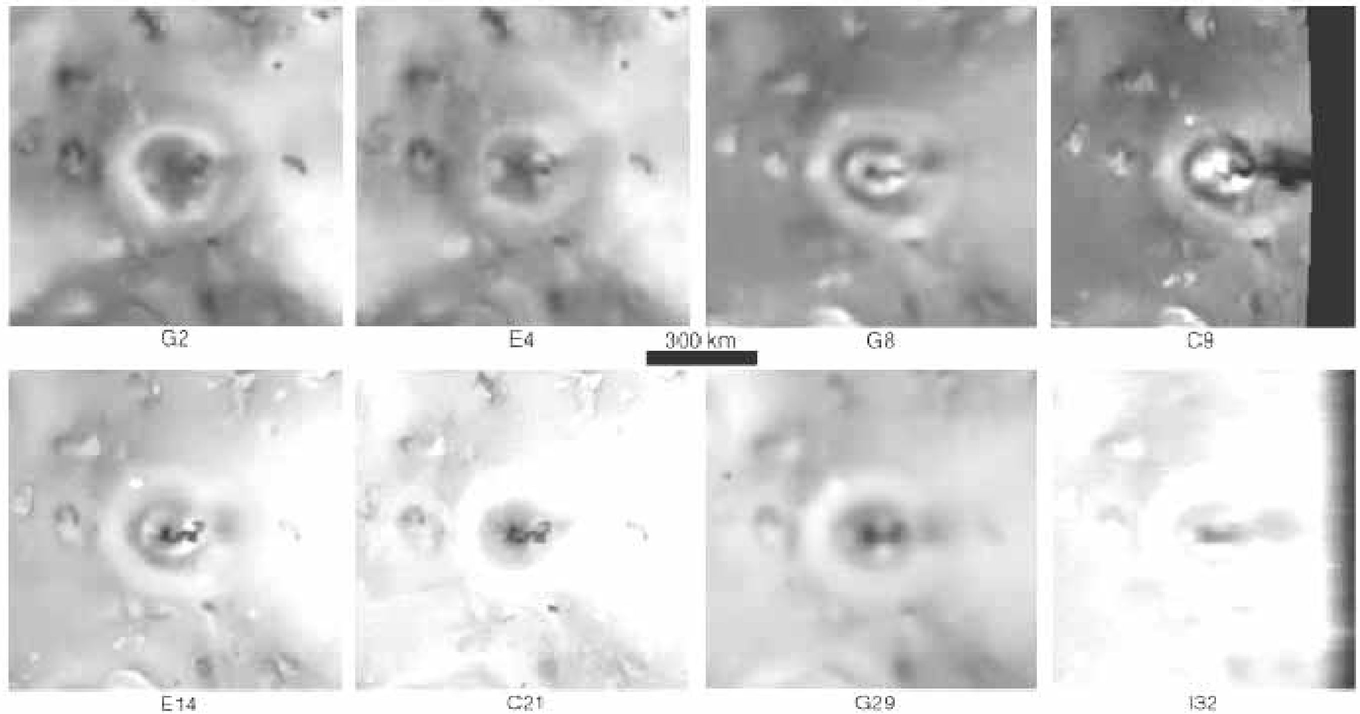
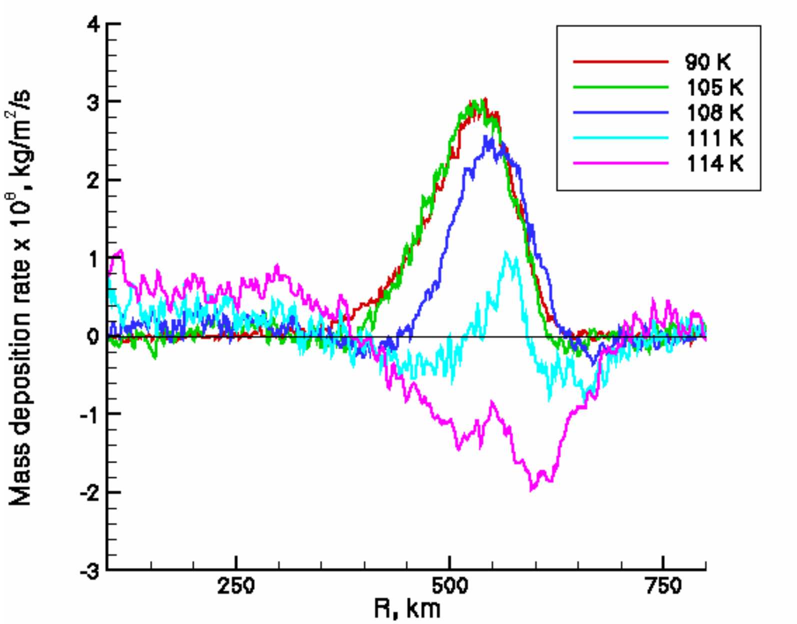


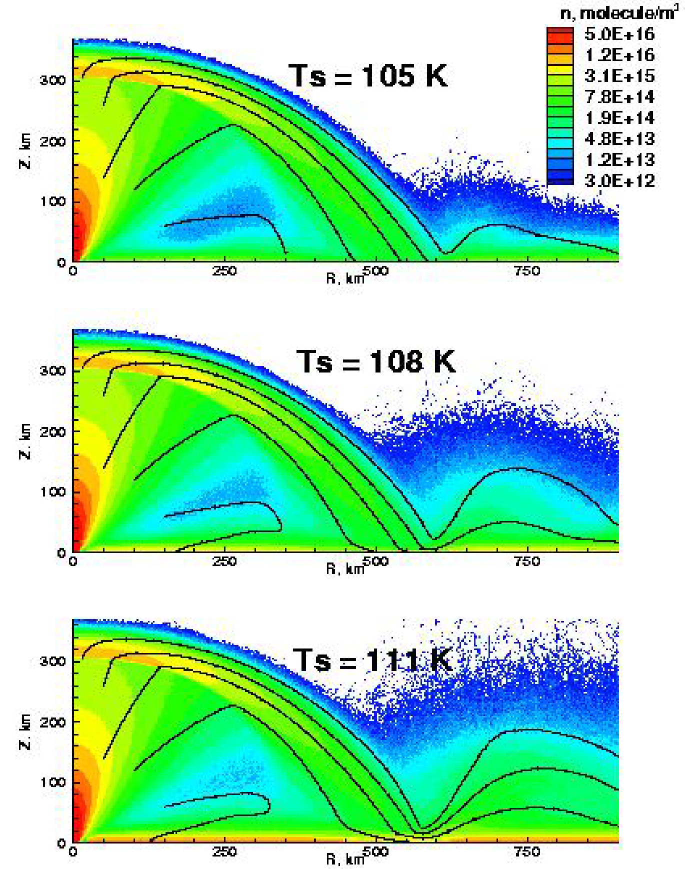
Figure 10. Surface changes at Prometheus. Violet filter images.

Geissler *et al*, 2003

Parametric Study on Surface Temperature

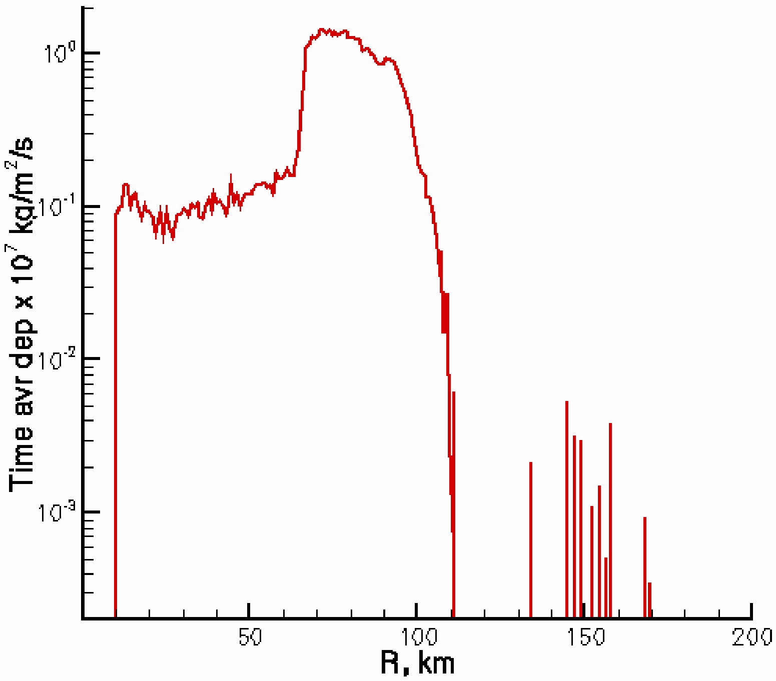
- At low surface temperature, the falling gas simply pours onto the ground and condenses unimpeded.
- As the surface temperature rises to ~111 K, a nearly horizontal re-entry shock and well defined bounce region are formed.
- Deposition ring forms at R = ~500 km.
- Depletion effects appear at high surface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





Number density contours with different surface temperature (right) and profiles of deposition rate (left).

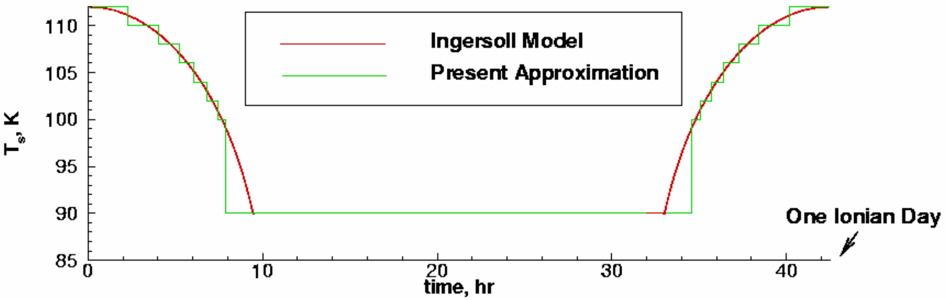
Gas Deposition Pattern around Prome



- 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.

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

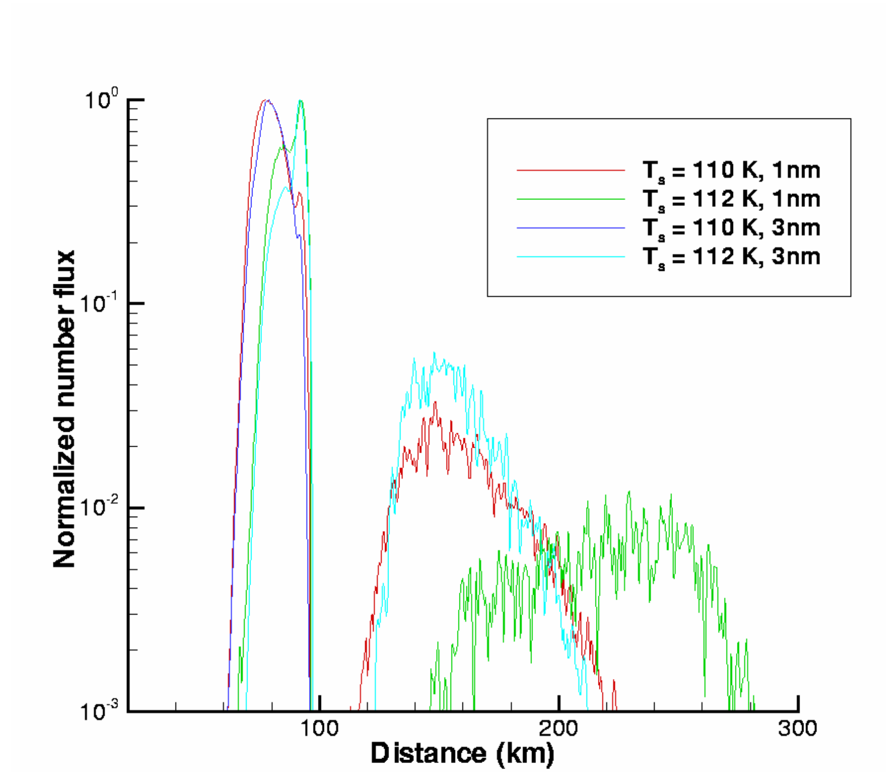
Ingersoll, *et al*, 1985

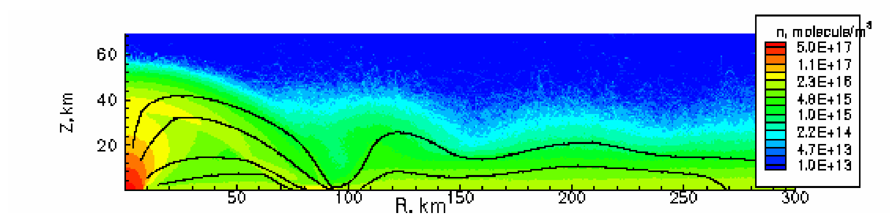


b) Surface temperature as a function of time

Particle Deposition Pattern around Prometheus

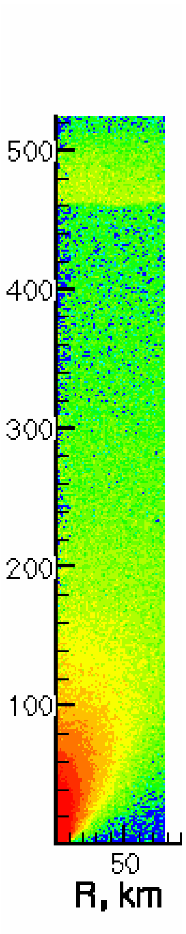
- The deposition of nano-particles in plumes with relatively high surface temperatures are examined.
- Due to the “bouncing” with the gas flow, outer rings are indeed seen in the nano-particle deposition profiles.



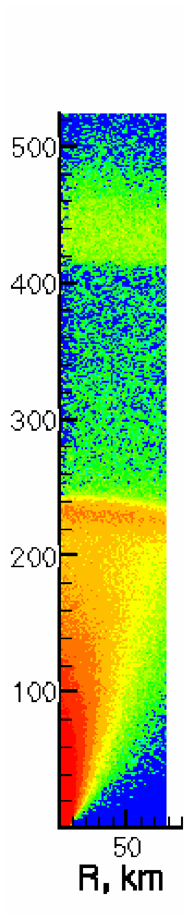


The Effects of Unsteadiness of Volcanic Sources

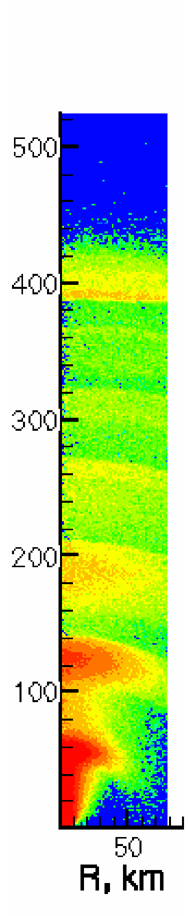
a) 30 min.



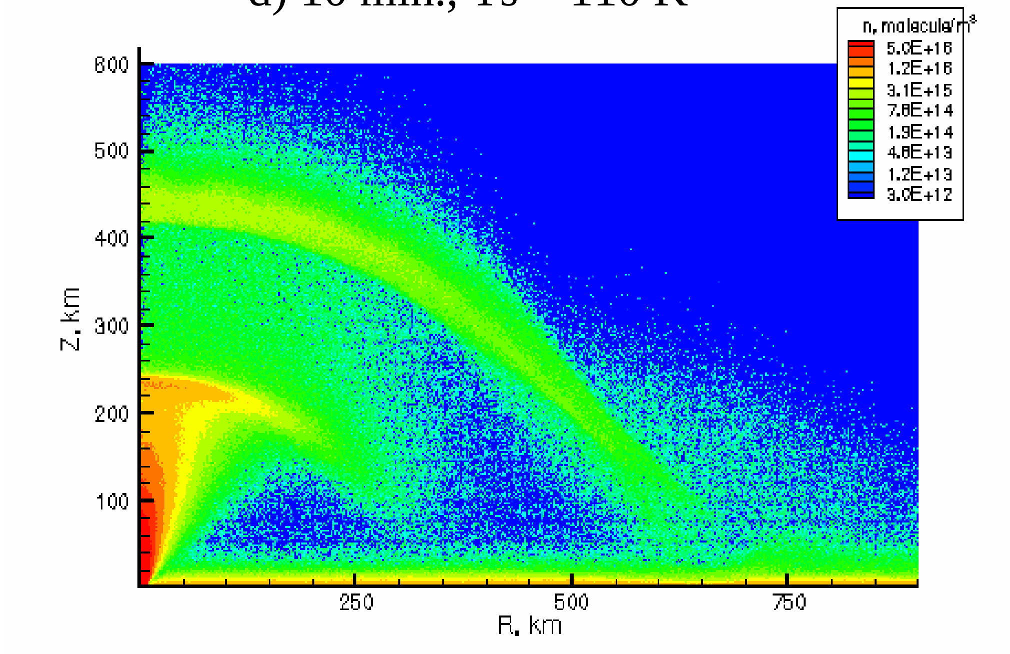
b) 10 min.



c) 1 min.



d) 10 min., Ts = 110 K

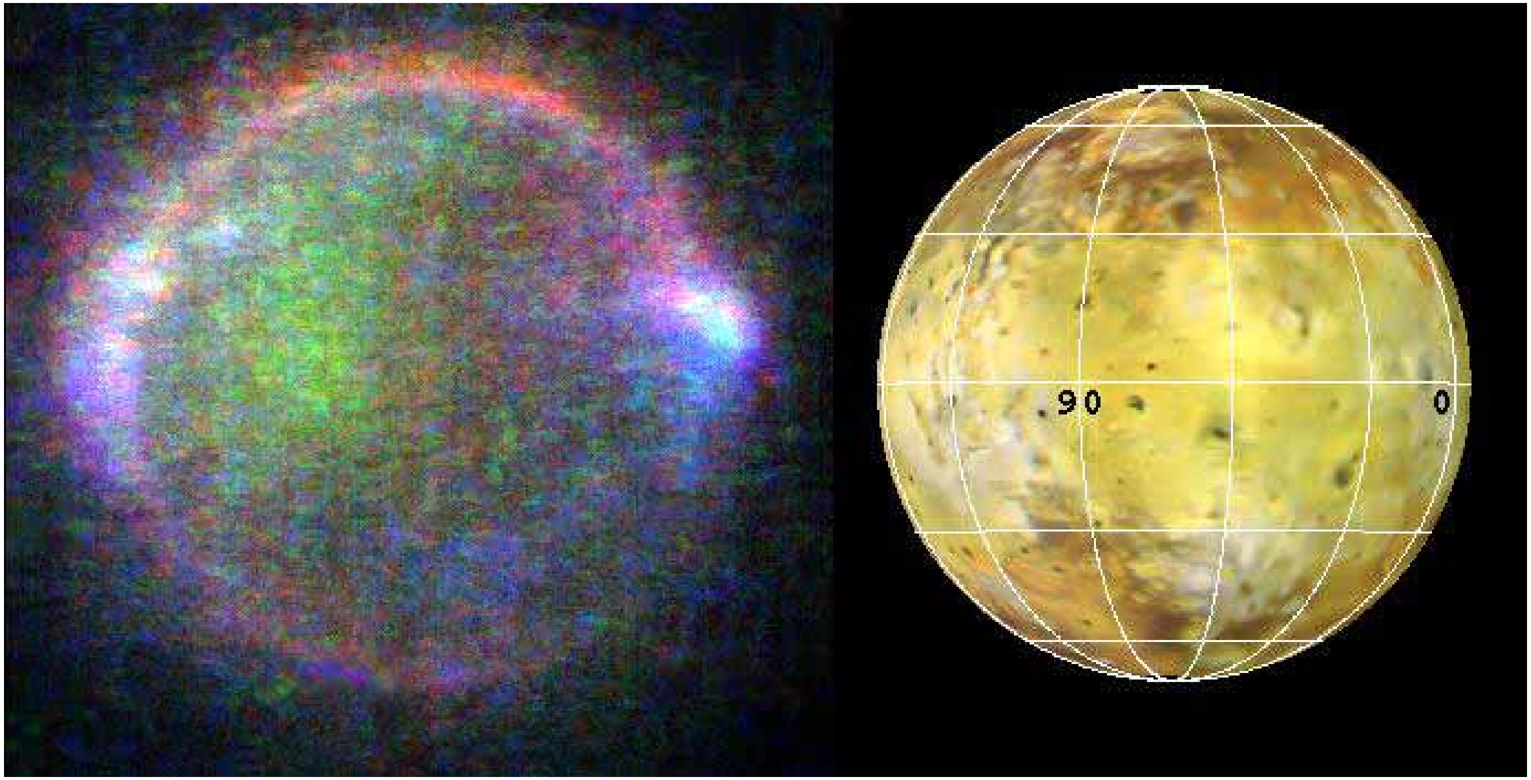


- V_v is pulsed sinusoidally. Other parameters kept constant.
- Stronger moving shocks for long period pulsing.
- Stationary shock for very short period pulsing.

Plume Conclusions

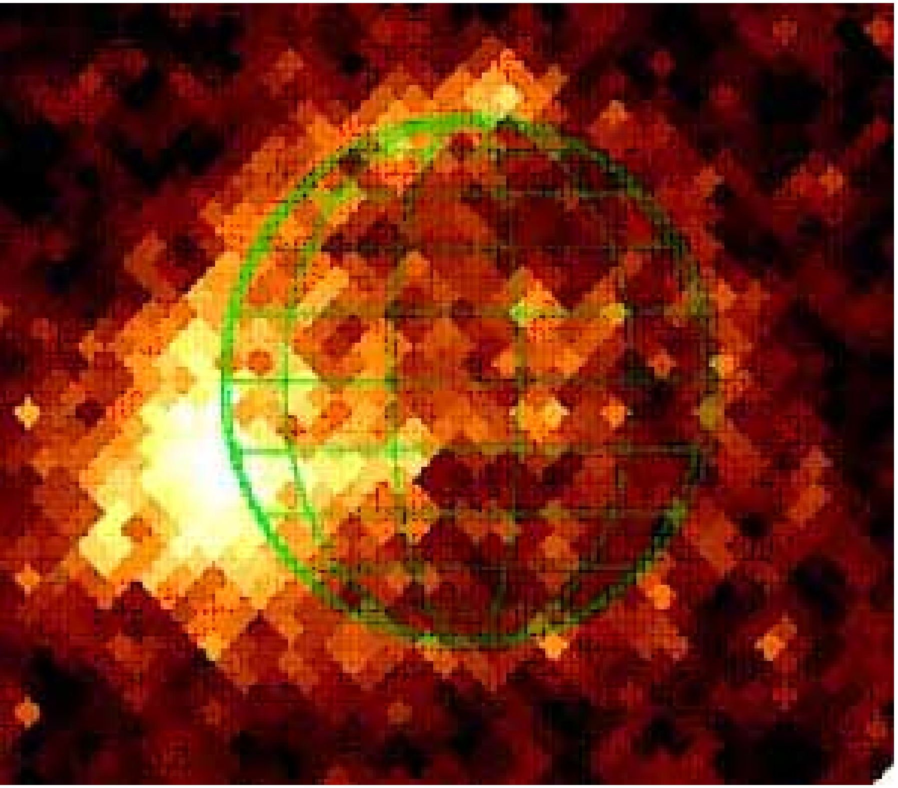
- Volcanic plumes on Jupiter's moon Io are modeled using the direct simulation Monte Carlo (DSMC) method.
- A sophisticated model including - spherical geometry, variable gravity, internal energy exchange (discrete vibration-translation and continuous rotation-translation energy exchange) in the gas, 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



Geissler 1999, Science 285.

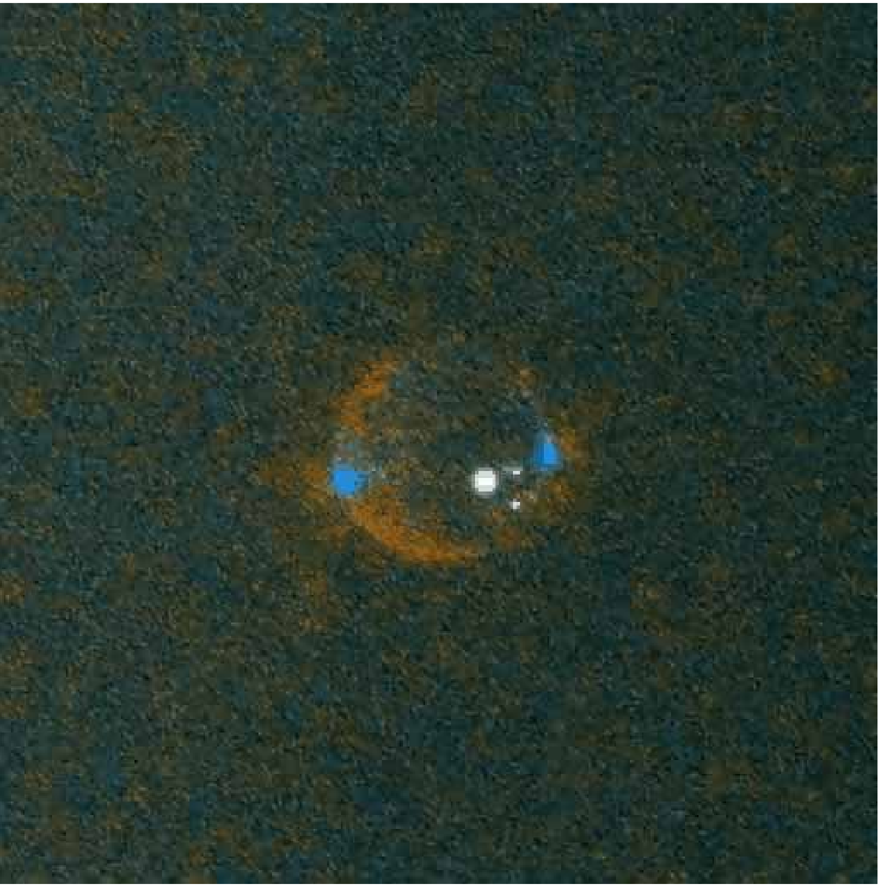
HST Io Auroral Observation



Trauger *et al.* 1997DPS29.1802T

- •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

Io Auroral Observation II

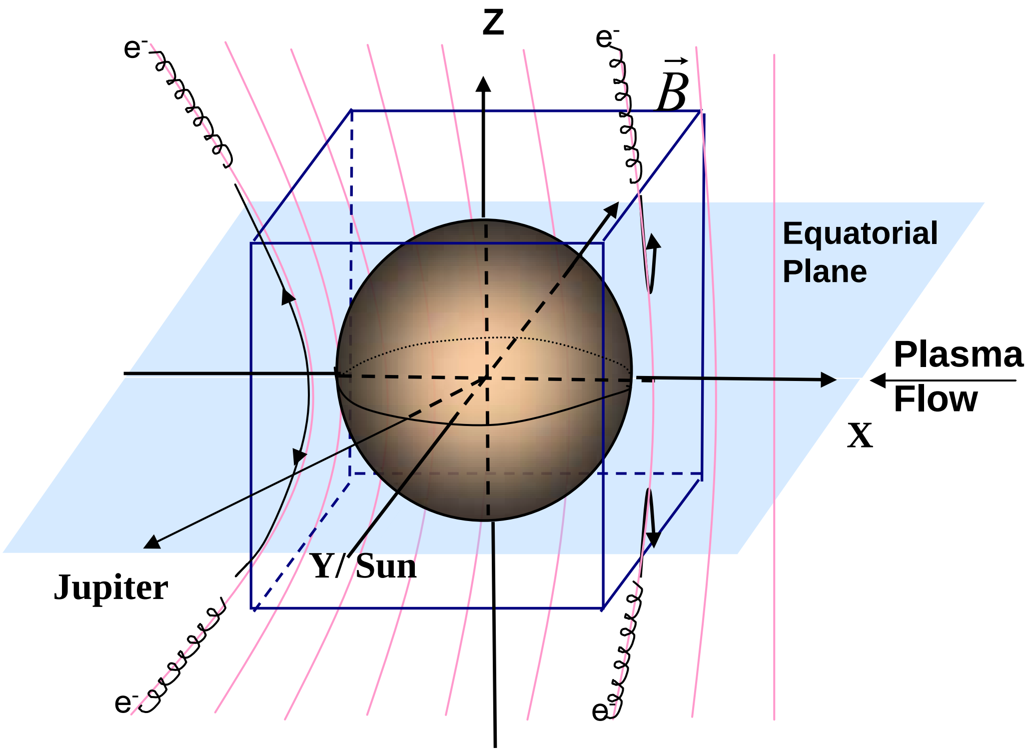


Cassini movie of emission around Io in eclipse (Porco *et al.*, 2003)

- 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

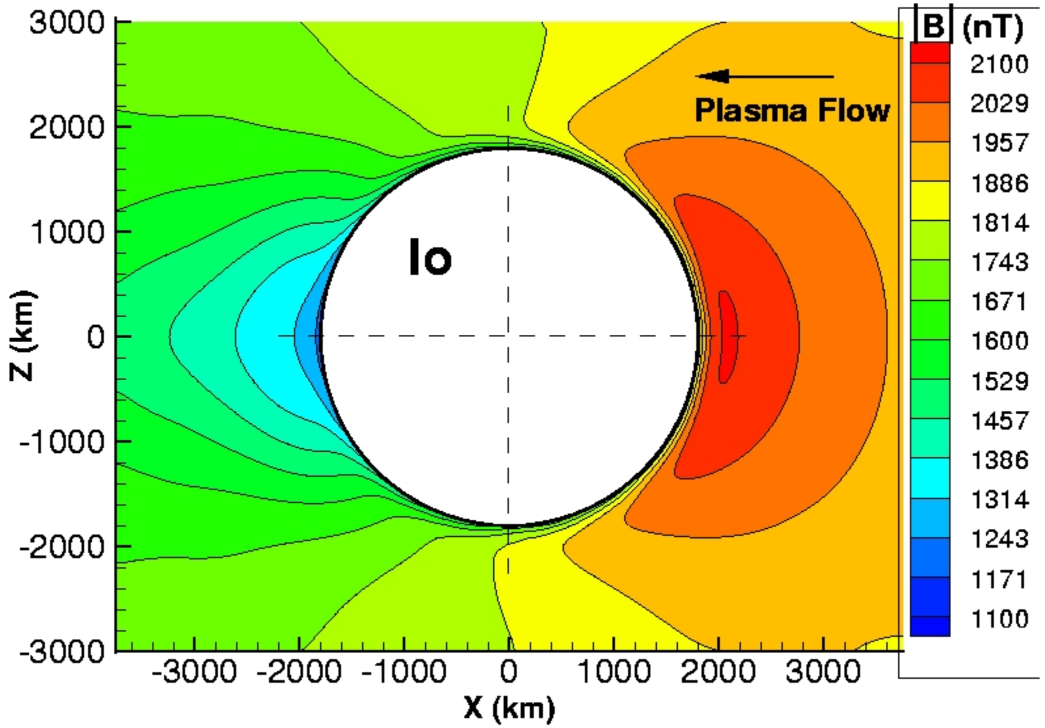
Simulation Domain

- 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 Δ=60km 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

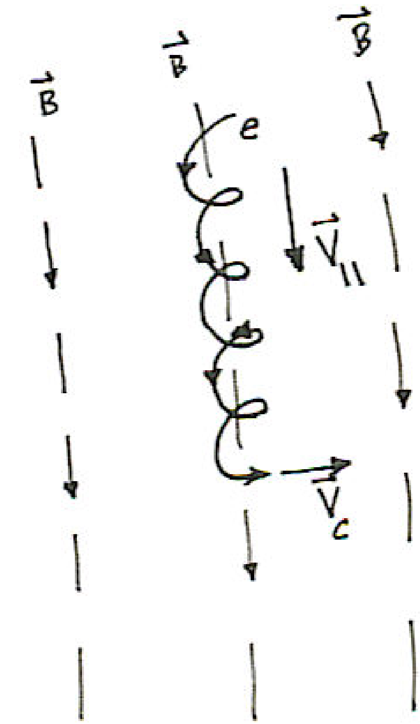
- Convenient to divide electron velocity into components perpendicular and parallel to the magnetic field:

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

$\vec{v}_c$ = Gyration velocity about field lines

$\frac{\vec{E}\times\vec{B}}{B^2}$ = 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>5eV, and the relevant atmospheric scale is ~8 km, so we move the electron purely along the field lines



Magnetic Moment

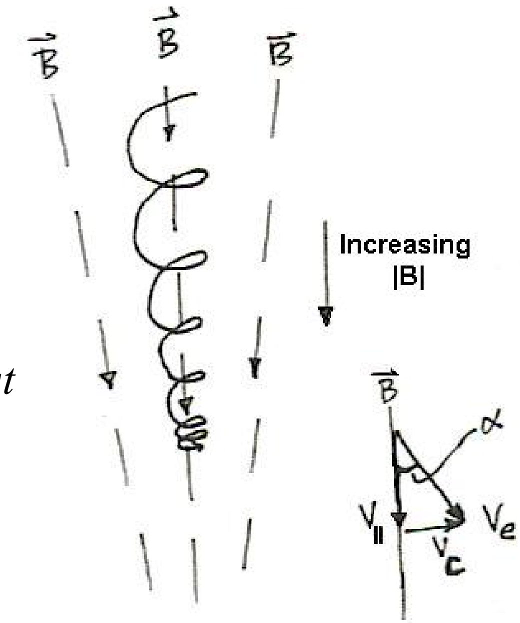
- An adiabatic invariant for a given electron is: $\mu_{mag} = \frac{\frac{1}{2} m_e v_c^2}{|\vec{B}|}$

- 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:

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

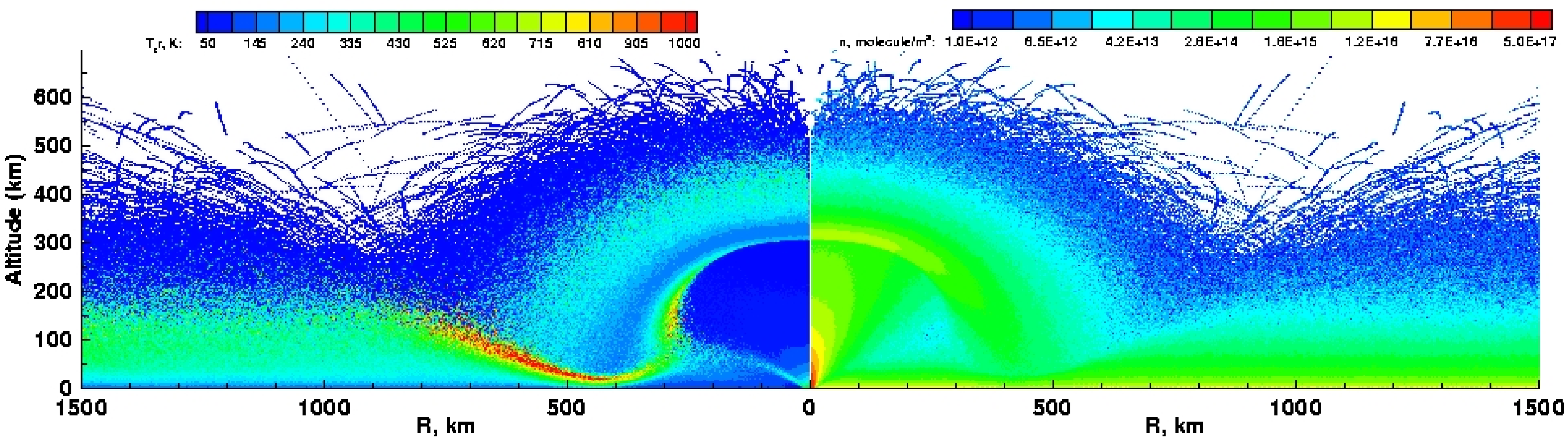
- Note that α=90° corresponds to $\vec{v}_{\|} = 0$ and that the electron will then reflect (mirror) the electron at:

$$|\vec{B}_{mirror}| = \frac{|\vec{B}_0|}{\sin^2\alpha_0}$$



Volcanic Atmosphere Model

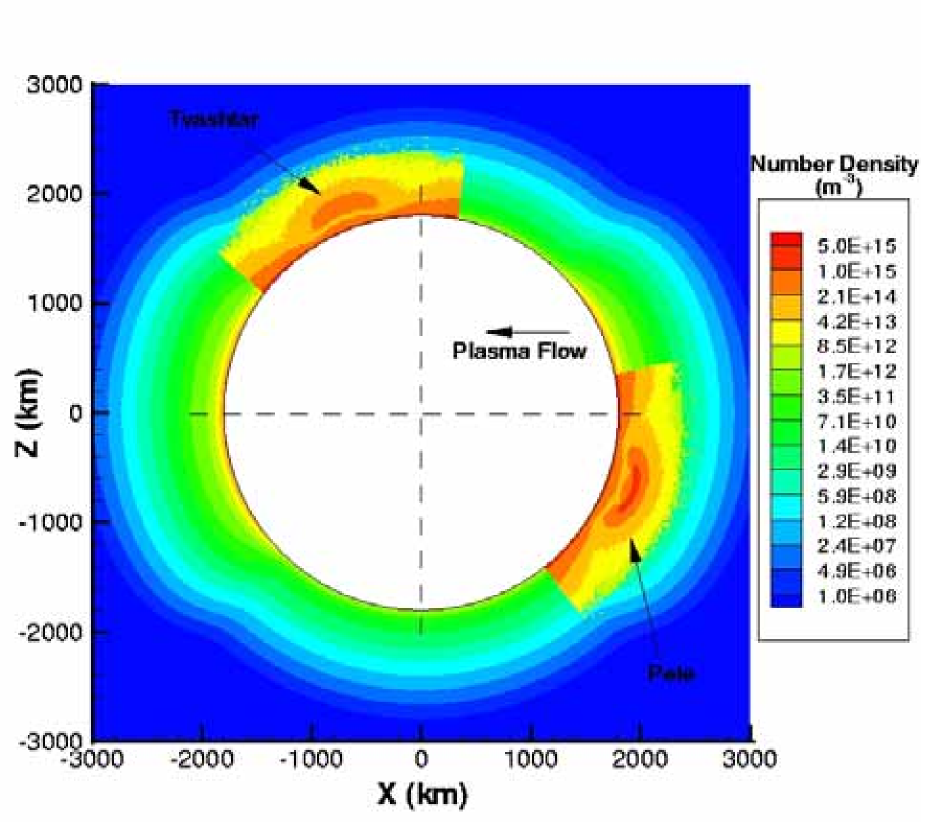
- Pre-computed independent volcanoes (Zhang 2004)
  - Two "template" volcanic types – Large (Pele) and Small (Prometheus)
  - 53 volcanoes accounted for on Io
  - Assume 0.1% O concentration (by number) based on equilibrium vent species' concentrations computed by Zolotov and Fegley (1998)
  - Plasma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



Sublimation Atmosphere Model

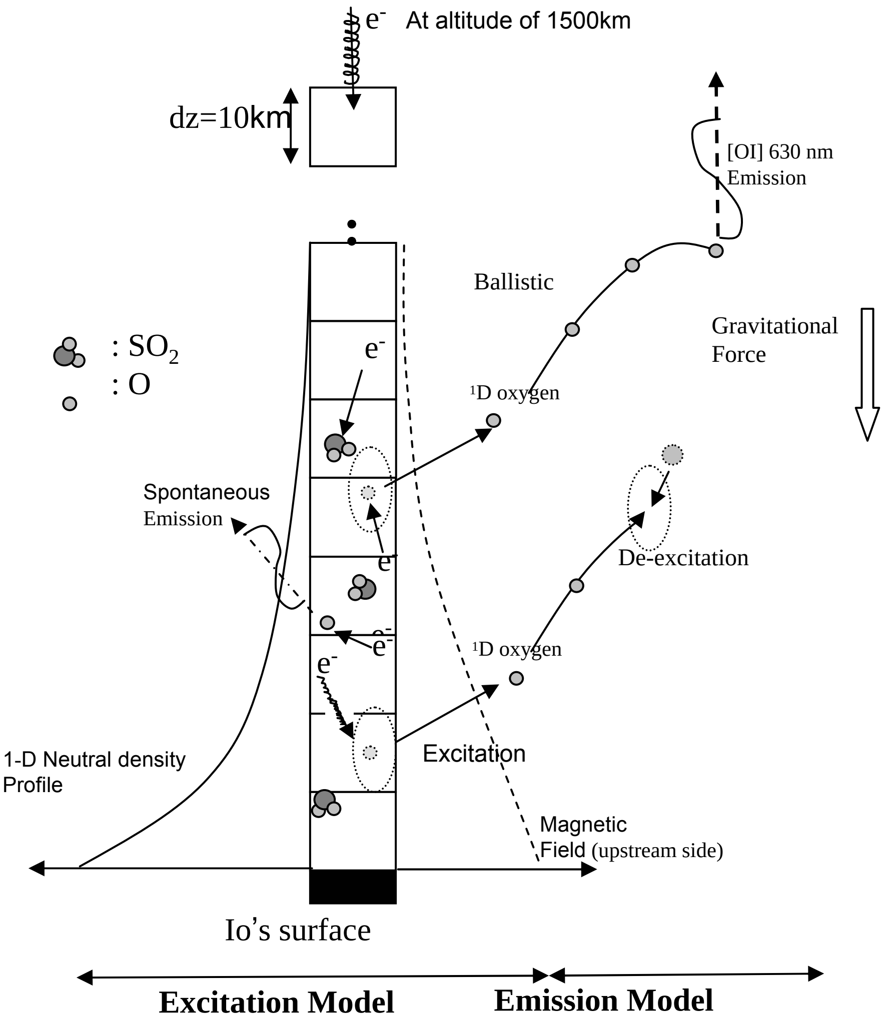
- Pre-computed 2D steady state sublimation atmosphere (Wong 2000)
  - Continuum model – has limited applicability at high altitudes but it is the best available
  - Multi-species model, we use just the SO_2 and O data since they are dominant
  - Atmosphere model for Io in sunlight (not eclipse)
  - Includes photoreactions, plasma reactions
  - Latitudinal dependence added using (Strobel and Wolven) :

$$\frac{n(\theta)}{n_{Pole}} = 1 + \frac{n_{Equator}}{n_{Pole}} e^{\left[-\frac{\theta}{0.625}\right]^6}$$



Local SO_2 number density profile as viewed from earth (Y = 300km). Notice the latitudinal variation and the superposition of the plumes.

Simulation Overview

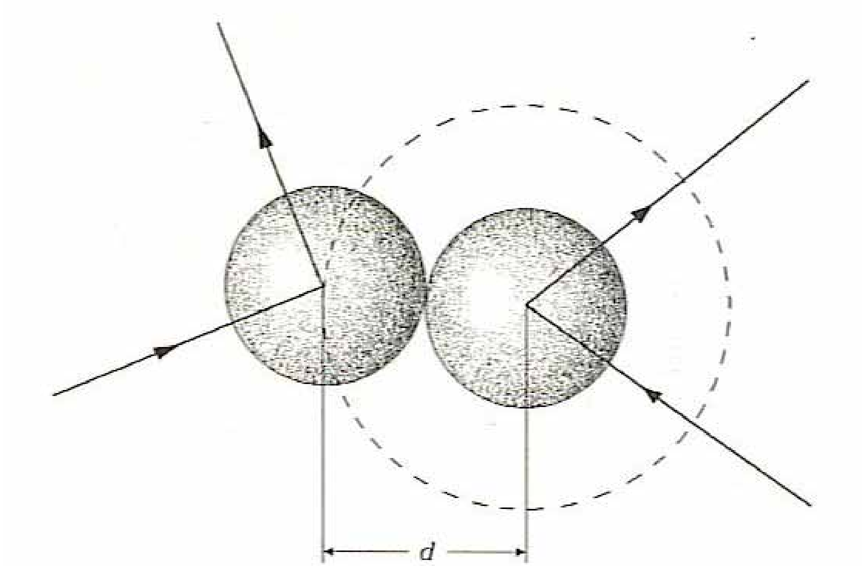


- Model split into two independent parts: Excitation and Emission
- Excitation:
  - Electrons input and move along field lines through the domain
  - Occasionally electrons collide with the neutral atmosphere
  - Location of excited oxygen is stored for use in Emission
- Emission:
  - Excited oxygen 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:

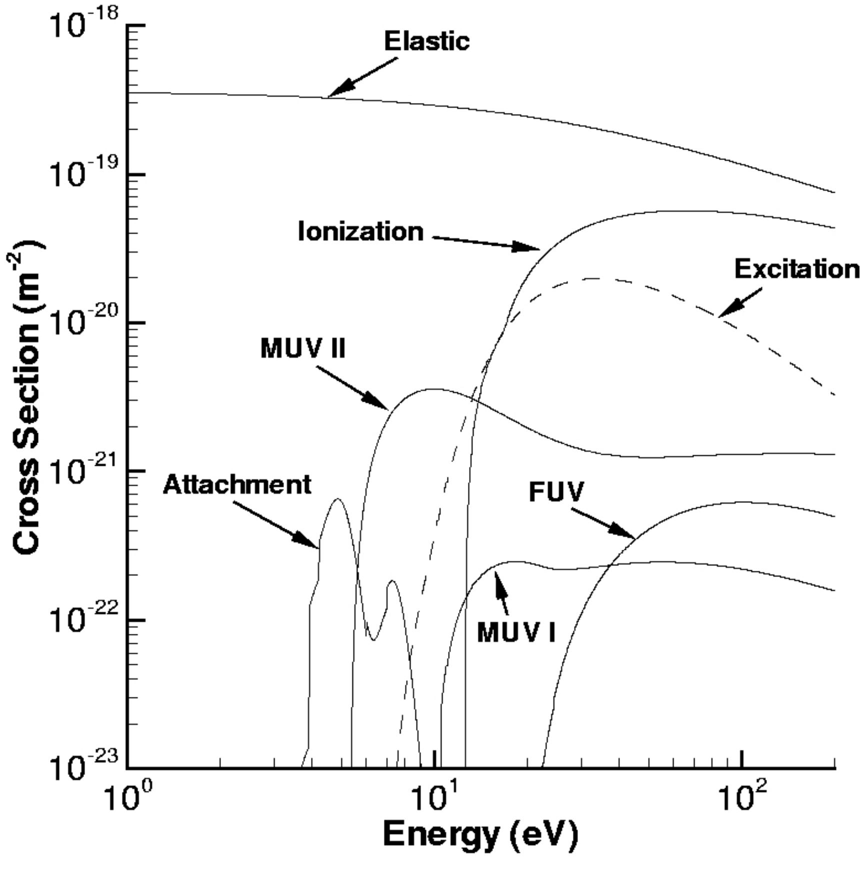
$$\sigma_{ij}^{tot}(E) = \sum_{k}^{N_{RxN}} \sigma_{ij}^{k}(E)$$



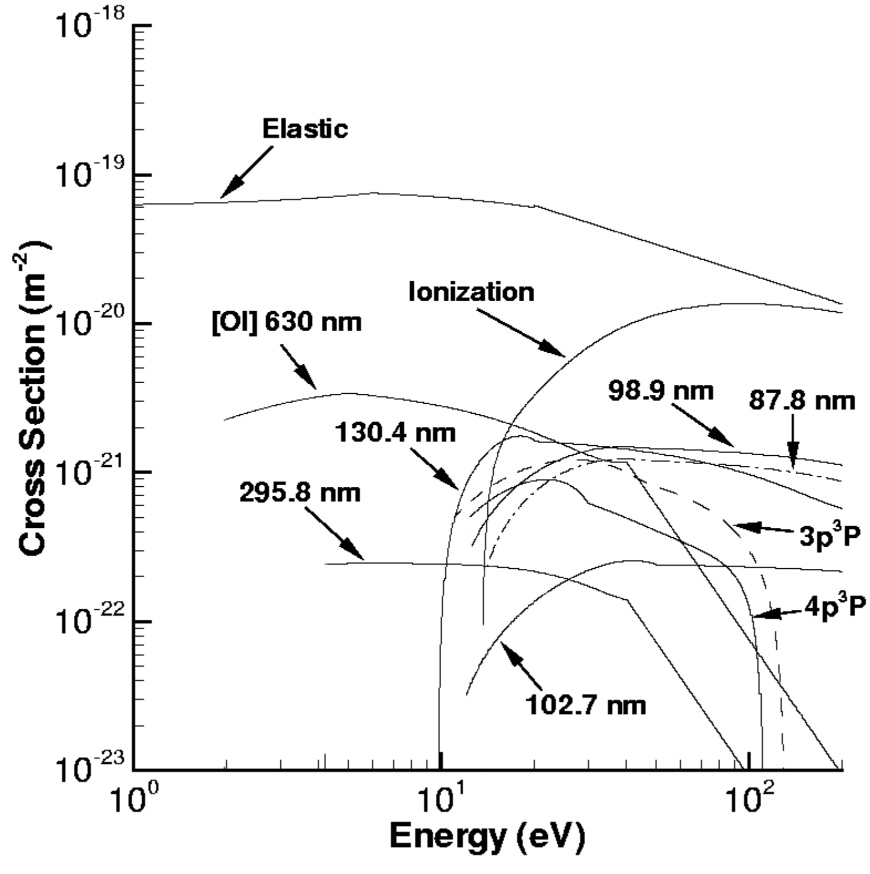
Hard sphere collision (Bird 1994)

Included Cross Sections

The simulation includes electron-SO_2 and electron-O interaction cross sections as functions of energy



SO_2 cross sections



O cross sections

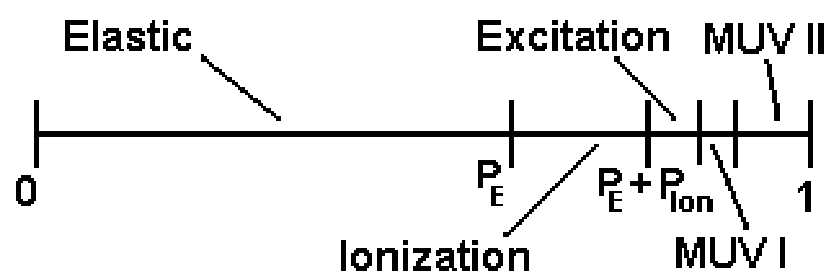
Collisions

- In a time interval Δt, the collision probability is:

$$P_{Collision} \approx 1 - e^{\left(-\Delta t * \sum_{i}^{N_S} n_i \overline{\sigma}_{ie}^{tot} \overline{v}_{rel,i}\right)}$$

where N_s is the number of target species (SO_2 and O), $\overline{\sigma}_{ie}^{tot}$ is the total interaction cross section for species *i* with the electron, and $\overline{v}_{r,i}$ is the relative velocity

- A collision occurs if a random number is less than $P_{Collision}$
- Choose the collision type (elastic, ionization, excitation, etc.) by comparing the position of a second random number on the scale:

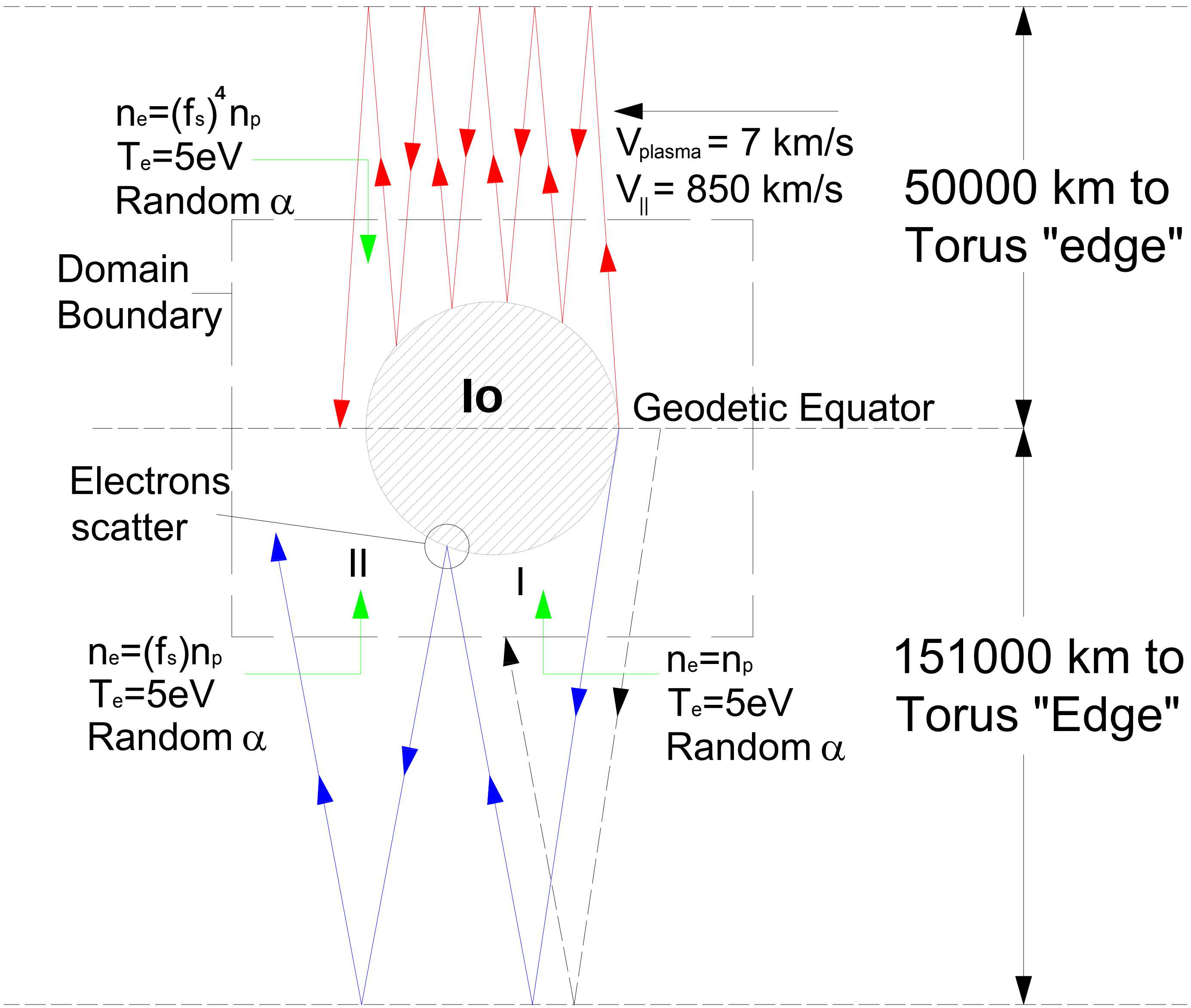


$$P_k(E) = \frac{\sigma_{ie}^{k}(E)}{\sigma_{ie}^{tot}(E)}$$

Emission

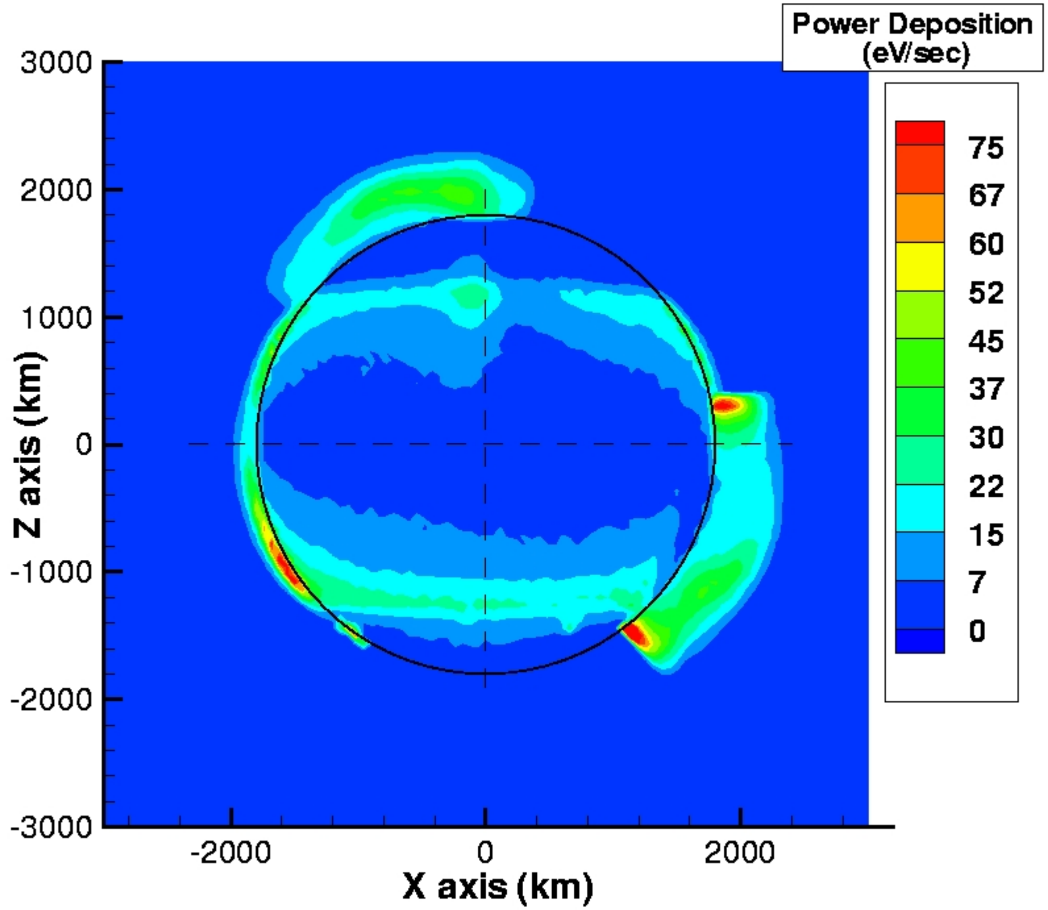
- Excited oxygen given an initial velocity based on local temperature, bulk velocity and corrected for the electron excitation collision
- The rate of emission is given by the Einstein A coefficient (the inverse of A is the mean lifetime of the state)
- [OI] 630 nm is a ‘forbidden’ line emission – it does not emit through the first-order mode, therefore A_{630nm}~$5.1x10^{-3}$ (lifetime ~ 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



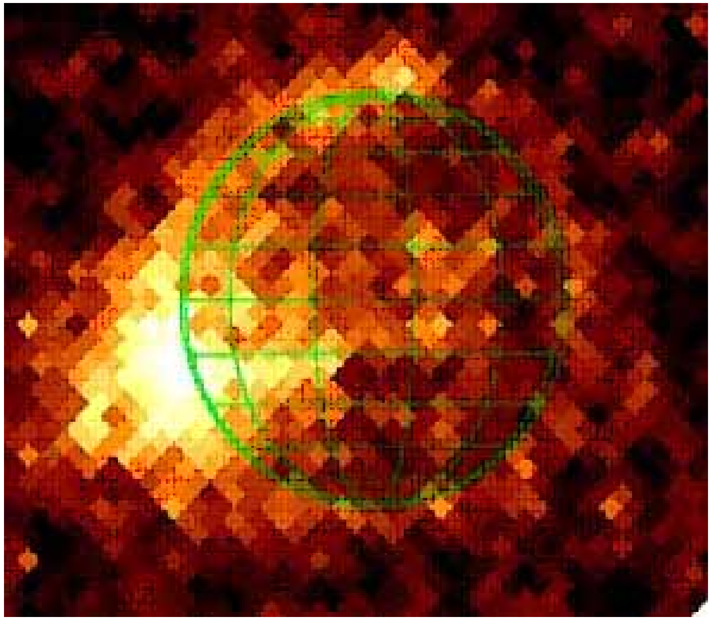
Auroral Simulation - Deposition

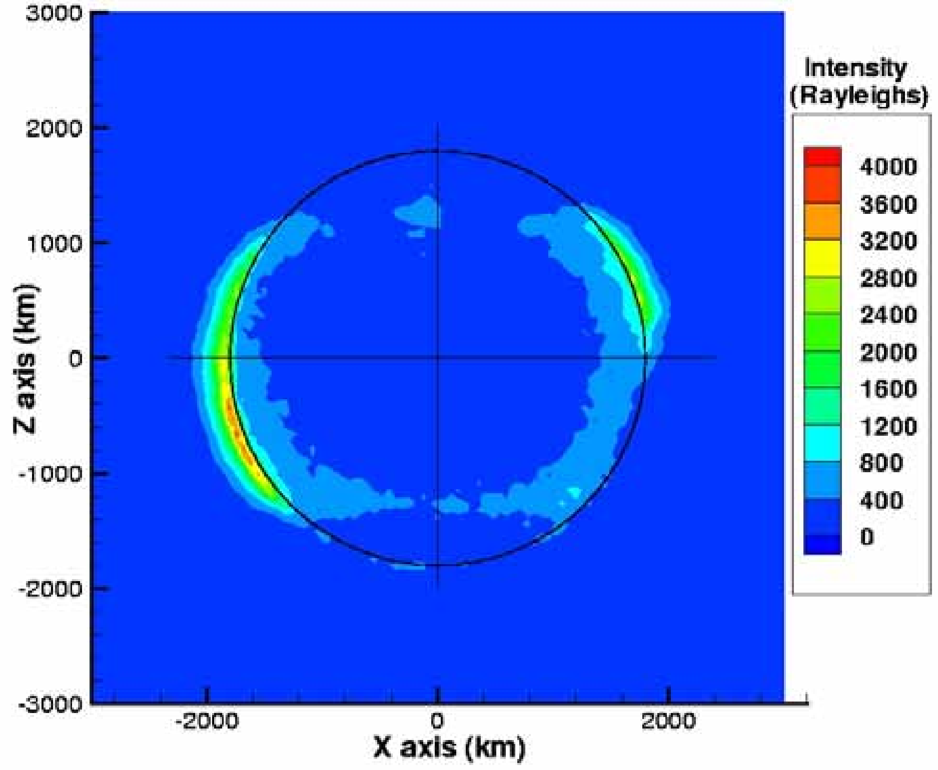
- High electron energy deposition in Pele and Tvashtar
- Higher deposition in the wake than on the upstream side
- Wake deposition is inclined relative to the equator due to electron depletion across Io



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