Modeling of SO_2 IR Radiation in 19.3 μm From the Sublimation Atmosphere

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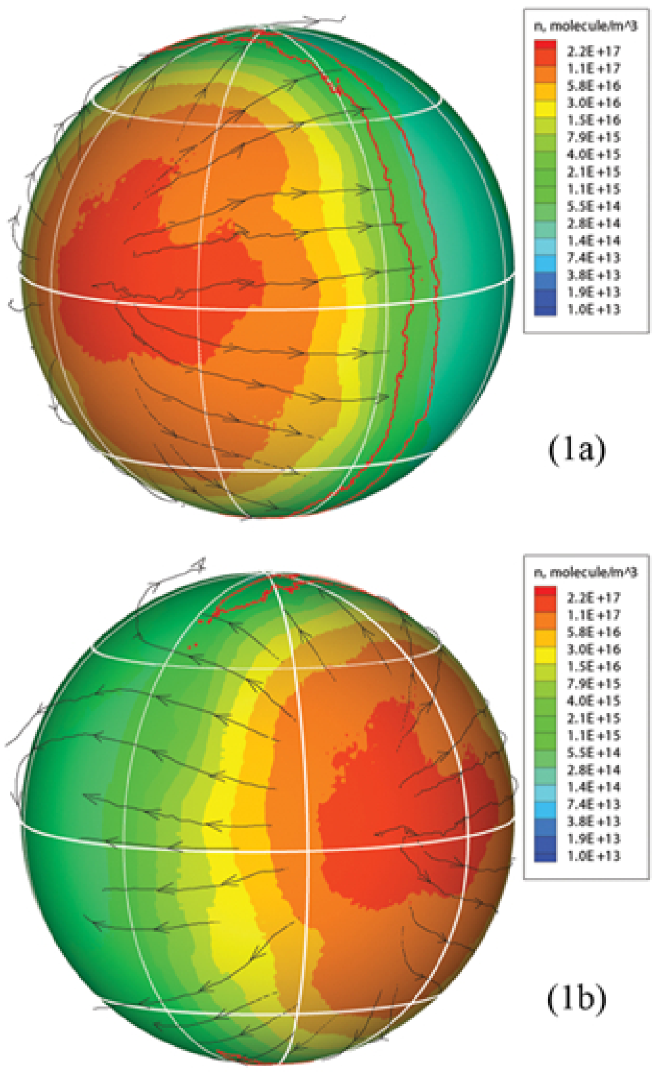
Introduction: The dynamics of Io's atmosphere are of scientific interest due to the complex interaction of the Jovian plasma torus with the tenuous atmosphere created by intense volcanic activity and sublimation from the surface. Io's rarefied atmosphere is simulated with the DSMC method. Circumplanetary flow develops away from the subsolar point toward the terminator and a shock forms due to condensation in the colder areas. Here we present results from a radiation transport simulation which takes as input a separate simulation of Io's rarefied atmosphere. Line of sight images for radiation from Io's 19.3 μm SO_2 band can be compared to observations to test the validity of the atmospheric model.

Atmospheric Model: The DSMC method is able to accurately model the rarefied flow present over much of Io, especially on the night side. DSMC uses a representative number of molecules to statistically approximate the collisions and movements of real molecules in the gas [1]. The simulation is fully three-dimensional and is also able to execute in parallel, meaning that it can be run on distributed memory supercomputers. The results presented here were run on 36 processors, where each processor's domain is a 10 degree azimuthal melon slice of the entire planetary atmosphere. Each processor contains 1.8 x 10^5 cells and simulates 3 x 10^6 molecules. Load balancing is performed by forcing a constant number of molecules to be sublimated from each surface cell and changing weighting between cells. The average run time for these simulations was ~50 hours wall clock time.



Physics Included in Model:
- Plasma heating modeled by a radial influx of energy.
- Non-uniform frost coverage which acts as the source for the sublimation atmosphere [2].
- Planet rotation
- Unit sticking coefficent
- Vibrational and rotational energy exchange
- Thermal inertia of the surface
- Quantized model of vibrational radiation

Figure 1ab - Number density contours at 3 km altitude overlayed with streamlines (black) and the sonic line (red). A shock is seen near the terminator from both the sonic line and the termination of streamtraces. A view of the dusk side is shown in (a) while the dawn side is shown in (b).

Results: The dayside atmosphere densities are primarily controlled by the surface temperature, despite non-uniformities in surface frost coverage.

The vibrational temperature exhibits an interesting structure due to the short radiative lifetime of the 19.3 μm band and intense plasma heating. The vibrational temperature rises with altitude near the subsolar point because the plasma energy can not penetrate the denser column.

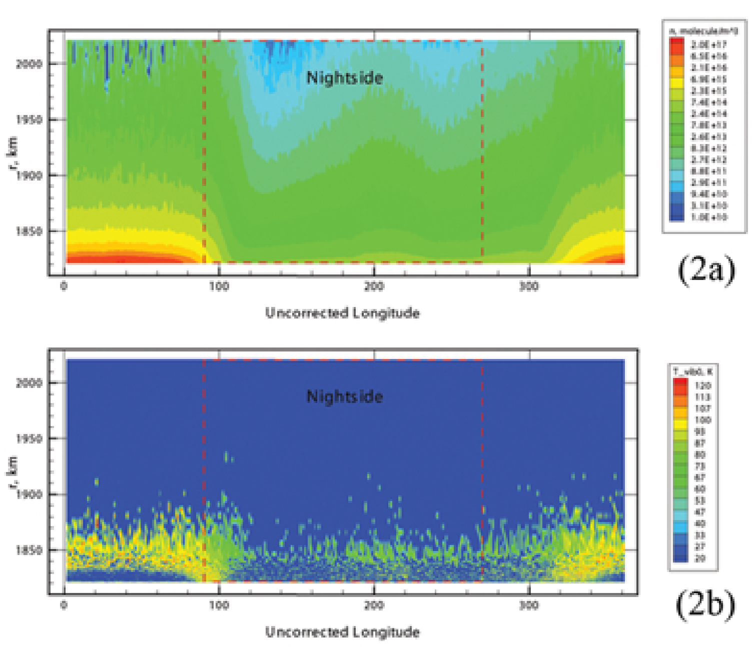
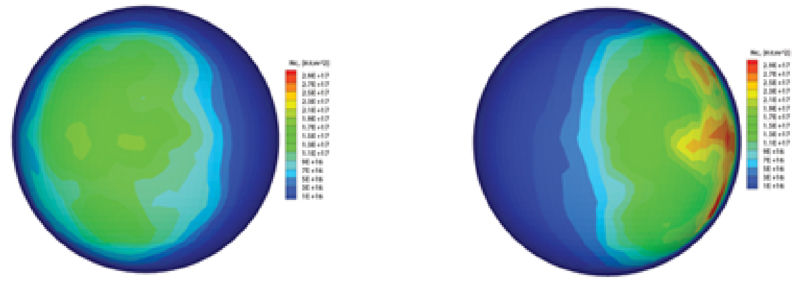


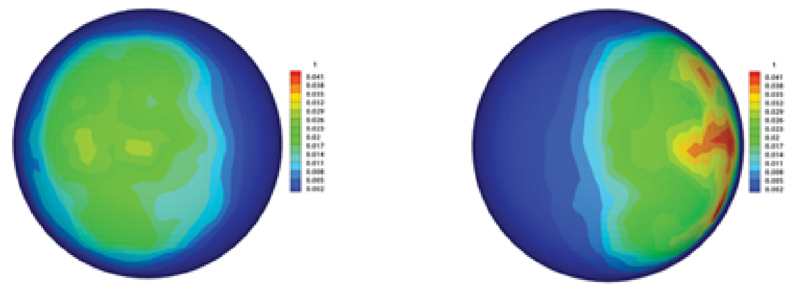
Figure 2 ab - (a) Number density contours and (b) vibrational temperature contours in the 19.3 μm band for a slice through the equator of Io. The vertical axis is the distance from the center of Io and the horizontal axis is 180 degrees out of phase with the actual longitude. The subsolar point is at 0°.

Radiation Model: Infrared radiation from Io received by a distant observer is modeled utilizing the backward Monte Carlo method [3]. In this approach rays falling on the detector are traced backward through the atmosphere to the points of emission. Rays traveling forward through the atmosphere provide line of sight data, and are necessary to model the observed intensity. The model accounts for the non-LTE state of the atmosphere and reflection of radiation from the surface. The choice of the spectral band 529-531 cm^{-1} is motivated by the existence of observational data in this range obtained by Spencer et al. [4]. The Spectral variation of the absorption coefficient was modeled with the line-by-line method, with the line positions from the HITRAN database.



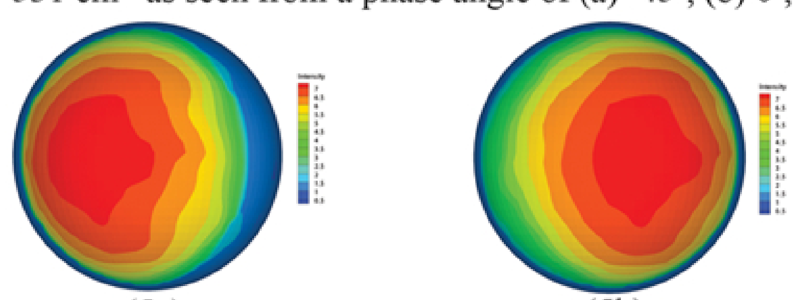
(3a) (3b) (3c)

Figure 3abc - Column density of the atmosphere along lines of sight where the phase angle is (a) -45°, (b) 0°, (c) +45°.



(4a) (4b) (4c)

Figure 4abc - Band averaged optical depth of the atmosphere in the range 529-531 cm^{-1} as seen from a phase angle of (a) -45°, (b) 0°, (c) +45°.



(5a) (5b) (5c)

Figure 5abc - Band averaged specific intensity in the range 529-531 cm^{-1} as seen from a phase angle of (a) -45°, (b) 0°, (c) +45°.

Results: The atmosphere is optically thin in the 529-531 cm^{-1} band, and is most opaque in regions of Io with the highest surface temperature. The highest column density occurs as seen from a phase angle of -45° because the regions of strong frost sublimation lie on the limb, where the path through the atmosphere is the longest. The majority of radiation originates from the surface, as validated by the presence of the dark limb. The magnitude of the optical depth at zero phase angle is similar to the results of Spencer et al., but differs in the distribution across Io's disk.

Conclusions:
- A strong circumplanetary flow develops away from the subsolar point at a subsolar temperature of 120 K reaching a mach number of 1.5 near the terminator.
- A shock is formed when the flow condenses out on the night side, but is intensified at dusk because of frost depletion and a higher temperature in that area.
- Non-uniform frost coverage leads to weak flows, but the atmospheric column density is dominated by the surface temperature.
- The optical depth distribution of the atmosphere is controlled by the distribution of the surface temperature.
- The radiation intensity is dominated by the surface emission.

References: [1] Bird, *Molecular Gas Dynamics and the Direct Simulation of Gas Flow*, Oxford University Press, 1994. [2] Doute, "Mapping SO_2 Frost on Io by the Modeling of NIMS Hyperspectral Images", *Icarus*, Vol. 149, 107-132, 2004. [3] Walters, "Rigorous Development for Radiation Heat Transfer in Nonhomogeneous Absorbing, Emitting, and Scattering Media", *Int. J. Heat Mass Transf.*, Vol. 5, 131-176, 1992. [4] Spencer, "Mid-infrared Detection of Large Longitudinal Asymmetries in Io's SO_2 Atmosphere", *Icarus*, Vol. 176, 283-304, 2005.

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