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The interaction of Io's plumes and sublimation atmosphere

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ABSTRACT

Io's volcanic plumes are the ultimate source of its SO_2 atmosphere, but past eruptions have covered the moon in surface frost which sublimates in sunlight. Today, Io's atmosphere is a result of some combination of volcanism and sublimation, but it is unknown exactly how these processes work together to create the observed atmosphere. We use the direct simulation Monte Carlo (DSMC) method to model the interaction of giant plumes with a sublimation atmosphere. Axisymmetric plume/atmosphere simulations demonstrate that the total mass of SO_2 above Io's surface is only poorly approximated as the sum of independent volcanic and sublimated components. A simple analytic model is developed to show how variation in the mass of erupting gas above Io's surface can counteract variation in the mass of its hydrostatic atmosphere as surface temperature changes over a Jupiter year. Three-dimensional, unsteady simulations of giant plumes over an Io day are also presented, showing how plume material becomes suspended in the sublimation atmosphere. We find that a plume which produces some total mass above Io's surface at night will cause a net increase in the noon-time atmosphere of only a fraction of the night-time value. However, as much as seven times the night-side mass of the plume will become suspended in the sublimation atmosphere, altering its composition and displacing sublimated material.

1. Introduction

Large SO_2 plumes on Io were first observed by Voyager (Smythe et al., 1979). They are distributed over Io's surface and many extend well above its atmosphere. Voyager observations also showed that Io's atmosphere consists mostly of SO_2 (Pearl et al., 1979), the ultimate source of which is thought to be the plumes. However, much of Io's surface is coated with SO_2 frost (Fanale et al., 1979), Smith et al. (1979), which sublimates in sunlight and could produce an atmosphere by itself. It is not clear to what extent Io's atmosphere is supported by sublimation rather than (direct) volcanism, and there is evidence supporting both sublimation-driven and plume-driven models. Some early observations (some are reviewed in Cruikshank and Murphy (1973)) found post-eclipse brightening, thought to be due to the condensation of the atmosphere into high-albedo frost during eclipse (suggesting that much of Io's atmosphere seen at other times is sublimated). However, post-eclipse brightening has rarely been noted in more recent observations (reviewed in Bellucci et al. (2004), although those authors did see post-eclipse brightening in the infrared).

Other studies have sought to determine the distribution of Io's atmosphere over its surface (Lellouch et al. (1992); Ballester et al. (1990); Trafton et al. (1996); Jessup et al. (2004); Feaga et al. (2009), and Spencer et al. (2005), to list a few). Recent papers like (Feaga et al., 2009) and (Spencer et al., 2005) have largely been consistent with a sublimation-driven atmosphere, finding a smoothly-varying daytime atmosphere with only a slow decrease in density with latitude, and with higher column densities and extent on Io's anti-Jovian hemisphere (which does not undergo eclipse). Observing Io over the course of almost a whole Jupiter year, Tsang et al. (2012) saw seasonal variations in Io's atmosphere, strongly suggesting that the atmosphere depends on insolation. Some exceptions to the majority of recent observations that seem to show a broad, asymmetric, and insolation-dependent atmosphere are the observations of Tsang et al. (2015) of Io emerging from eclipse. Starting almost immediately after re-emergence they saw little change in atmospheric SO_2, suggesting that there was no collapse of the atmosphere onto the surface during eclipse. Jessup and Spencer (2015) used HST/STIS to observe several longitudes at different times during Io's day and found almost no time-of-day dependence of Io's atmosphere. Assuming that the atmosphere is in vapor pressure equilibrium with the frost at the surface and that the column density is proportional to the surface pressure, the models used by Tsang et al. (2015) and Jessup and Spencer (2015) yield best-fit thermal inertias for Io's surface frost which

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are high compared to some other estimates ($> 300\ \mathrm{Wm^{-2}s^{-1/2}K^{-1}}$ by Tsang et al. and $> 2000\ \mathrm{Wm^{-2}s^{-1/2}K^{-1}}$ by Jessup and Spencer, compared to $70\ \mathrm{Wm^{-2}s^{-1/2}K^{-1}}$ by Rathbun et al. (2004), and $200\ \mathrm{Wm^{-2}s^{-1/2}K^{-1}}$ by Walker (2012).

Early modeling of Io's atmosphere was performed by Ingersoll et al. (1985) and Moreno et al. (1991). Direct simulation Monte Carlo (DSMC) modeling of Io's rarefied atmosphere and plumes began with Austin and Goldstein (1996, 2000). Zhang et al. (2003, 2004) performed axisymmetric simulations of Prometheus and Pele, also using DSMC. They constrained vent conditions by canopy heights, ring radii, and UV brightness data from Voyager data via (Strom and Schneider, 1982). They were able to demonstrate canopy shock formation, "bounces" of the falling gas leading to a multiple ring structure when a sublimation atmosphere is present, and the importance of non-LTE rotational cooling. McDoniel et al. (2015) built on this with three-dimensional simulations of the Pele plume that showed how the shape of the plume's deposition pattern could be almost entirely explained by the geometry of the lava lake at Pele. DSMC simulations of Io's atmosphere improved with the work of Moore et al. (2009), who simulated a one-dimensional atmosphere through eclipse. Walker et al. (2010) performed three-dimensional simulations of Io's rarefied atmosphere incorporating the frost map of Douté et al. (2001) and a rotating surface temperature distribution. Walker et al. (2012) added a surface temperature model that solves the one-dimensional heat conduction equation in depth, includes the effects of eclipse, and fits thermophysical parameters for Io's surface, finding a best-fit frost albedo of 0.55 and a frost thermal inertia of $200\ \mathrm{Wm^{-2}s^{-1/2}K^{-1}}$.

A problem for many attempts to explain observations of Io's atmosphere as the result of some combination of sublimation and volcanism is that very little work has been done on the interaction of these two processes, although the modeling of either process independently has been quite successful. When interpreting observations of Io's atmosphere many authors specify that the plumes cause local increases in density, sometimes with no explicit model. Explicit models are often very simple, as in Tsang et al. (2012) where a constant "volcanic component" was added to a time-varying "sublimation component" (in vapor pressure equilibrium with the surface frost) to fit to column density observations. Similarly, Walker et al. (2012) and Moore et al. (2010) superimposed separately-computed volcanic plumes on their simulations of Io's atmosphere. Walker et al. (2011) did simulate atmospheric flow over a hot spot at Loki though the surface did not emit material. Notably, Ingersoll et al. (1985) worked out a simple model for the plume/atmosphere interaction where plumes were treated as sources of constant mass flux. Because frost on the surface attempts to maintain vapor pressure equilibrium, Ingersoll found that a volcanic source does not increase surface pressure by a constant amount but by an amount proportional to the square root of surface temperature and inversely proportional to the sticking coefficient (where there is frost and a significant sublimation atmosphere).

In this work, DSMC is used to simulate volcanism and sublimation simultaneously to explain how the presence of plumes affects the total mass and the composition of Io's atmosphere relative to a baseline sublimation-only case. Axisymmetric simulations illustrate the physics involved and show how the combined effect of volcanism and sublimation is only poorly approximated as the sum of independent processes. A simple analytic model for the interaction is developed and applied to the work of Tsang et al. (2012) on seasonal variation in Io's atmosphere, showing how the presence of plumes should have less of an effect on the total mass of Io's atmosphere when surface temperatures are high (contrary to a result in Ingersoll (1989)). Finally, three-dimensional simulations of giant plumes on Io's equator and at 30° north latitude over an Io day show how material from a realistic Pele-type plume can become suspended in a sublimation atmosphere, potentially altering the composition of the atmosphere substantially while having relatively little effect on its total mass.

2. Method

We simulate Io's plumes and atmosphere using the UT group's Direct Simulation Monte Carlo (DSMC) code, a previous version of which was used in the plume simulations of Zhang et al. (2003); 2004) and McDoniel et al. (2015), and in atmospheric and plasma simulations by Walker et al. (2010, 2012) and Moore et al. (2009), 2012). DSMC is a statistical particle method in which the behavior of the real gas flow is obtained by extrapolation from the computed motions and collisions of a number of representative molecules (Bird, 1994). It is suitable for rarefied flows where molecular mean free paths are comparable to important flow length scales. The UT code has the ability to compute high speed molecule/ion collisions and chemical reactions, two-phase flow, droplet formation, and radiation. The code is specialized for planetary atmosphere simulations, with a spherical geometry, variable gravitational acceleration, and incorporates parameters specific to SO_2 for modeling internal energy exchange and radiation from rotational and vibrational modes. The DSMC boundary condition can also be coupled to the unsteady output of a continuum solver or another DSMC domain for modeling unsteady plume dynamics (Stewart et al., 2009) and (Prem et al., 2014).

Typical simulations are performed on the supercomputers at the Texas Advanced Computing Center. Axisymmetric simulations used only 12–16 processors while three-dimensional simulations used ~ 2000 processors. Each processor is responsible for the simulation of up to about 8×10^5 computational particles in $\sim 40,000$ cells. Many features of the simulations here are the same as for the giant plume simulations in McDoniel et al. (2015), although here only gas (not dust) is simulated and plumes erupt from simple 8 km radius round holes (as in Zhang et al. (2003)) rather than from complicated source geometries. We make this simplification because it has little impact on the overall structure of the plume and the precise shape of the plume's deposition ring is unimportant for this work. We also do not simulate plasma, which is potentially important insofar as it strips material from and alters the structure of the upper atmosphere. All simulations use the load-balancing method described in our earlier work, which dynamically positions processor boundaries so as to distribute the simulated molecules evenly among the processors.

Three additions to the method were necessary in order to add a sublimation atmosphere to the existing model for plumes. First, the surface of Io is assumed to be entirely covered in SO_2 frost, except where there is a plume source. Using the same method from Zhang et al. (2003) and Walker et al. (2010), the frost sublimates SO_2 as a function of surface temperature such that it achieves vapor pressure equilibrium according to an equation from Wagman (1979). For axisymmetric plume simulations the surface temperature is taken to be a constant. For three-dimensional, unsteady simulations the surface temperature distribution on the day-side is given by $T_s[\mathrm{K}] = (118 - 70)\cos^{1/4}\phi + 70$, where ϕ is the angle from the sub-solar point. The night-side surface temperature is set to 70 K. The sub-solar point moves around Io's equator at a rate of 4.3633×10^{-5} radians/s (a 40 h day, though note that Io's day is actually closer to 42 hours long). This is a simple surface model compared to the one in Walker et al. (2012) which made use of a frost map and a model for thermal inertia of the surface, but it suffices to demonstrate interesting features of the plume/atmosphere interaction.

Second, a weighting scheme was introduced for the three-dimensional simulations so that relatively more simulated particles would be found near plume sources. Instead of using a single