THE THERMAL STATE OF SO_2 FROST ON THE SURFACE OF IO.

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Introduction

Since the discovery of SO_2 frost on the surface of Io, [1,2,3] scientists have supposed that Io must also possess an SO_2 atmosphere, and various models for that atmosphere have been advanced. [4,5] Observations of the Ionian atmosphere [6,7] did not agree with the models' predictions, however. The inconsistency is that the measured daytime temperatures of Io are high enough that we would expect the widespread SO_2 on the surface to sublimate, yielding a reasonably dense SO_2 atmosphere. Such an atmosphere should have optical effects that are not observed [8,9,10]. Moreover, measurements of the density of Io's atmosphere show that it is thin and ballistic. (6 - 10 x 10^{15} cm^{-2}) [7]. Researchers have tried to address this problem with more refined thermal models of the Ionian surface [8,11]. Some models have looked toward the possible existence of near surface thermal gradients ("solid state greenhouse effect") as a way to keep Io's surface sufficiently cold despite the daily solar heat input.

The possible existence of temperature gradients in the near surface layers of airless bodies is not a new idea [i.e. 12]. Without atmospheric gases , radiative transfer in a regolith becomes important, both between regolithic grains and into space from near subsurface layers. Thus, when we observe the thermal emission from the surface of an airless planet we may actually be seeing IR energy that is escaping from the warmer subsurface layers, and we may deduce a surface temperature that is in actuality too high. This effect can be enhanced if the material comprising the regolith is translucent to visible or short wavelength energy, but opaque to the IR, like snow or frost. Kerton et al. [11] published a model of heat transfer in SO_2 on Io's surface which concluded that if this solid state greenhouse effect is taken into account, maximum daytime surface temperatures on Io can remain cold enough to explain the observed atmpshere. Specifically, maximum daytime temperatures calculated from this model are approximately 104 K, which leads to a ballistic atmosphere consistent with the upper limit of that observed by the Hubble Space Telescope [7]. The Kerton et al. model does not account explicitly for radiative transfer, but does include the effects of latent heat and vapor flow of gaseous SO_2 through porous SO_2 ice as well as planetary rotation. The Kerton et al. treatment was incomplete, however, in that they treated the absorption length in the regolith as a free parameter, and varied it until the calculation yielded a minimum surface temperature. However, the absorption length in any given medium is not a free parameter, but is determined by the known albedo of the medium. This study addresses this problem and expands on the work of Kerton et al. by applying the heat transfer model of Hapke [13] and Snyder Hale and Hapke [14] to SO_2 fields on Io.

The Model and Calculations

The Hapke model explicitly includes radiative transfer within the regolith both in the visible and IR, while also addressing conductive energy transfer [13]. The fully time dependent radiative transfer equation and heat transfer equation are solved numerically and simultaneously with XPP, a differential equation solving software package, using the CVODE solving routine. The equations are solved with a uniform time step and non-linear spatial grid for a slab of regolith approximately 1.5 meters thick. The time step is set by the user, but we typically used 0.004 Io rotational periods. The user defines the physical parameters of the medium such as its density, conductivity, thermal inertia, and albedo. We ran three classes of Io models : single layer, two layer, and three layer. In multi-layer models, the user defines the physical properties of each layer independently, as well as each layer's thickness. All models presented in this work assume a solar input appropriate for the sub- Jupiter face of Io. Physical parameters are taken from the analyses of Voyager observations of Io and Earth based observations.[15-18]

Single Layer Models: Single layer models were run assuming the the average physical parameters used by Kerton et al. Results are shown in figures 1 and 2. Maximum daytime temperatures with this model are somewhat too high to agree with atmospheric observations, and no large near-surface temperature gradient is seen. The calculated curves in figure 1 also do not agree with certain observations of Io's physical surface composition [18]. This indicates that a Io's regolith cannot be described by a single thick uniform layer.

Two Layer Models: A variety of two layer models were run with varying physical properties; all possessed a "fluffy" highly underdense low thermal inertia SO_2 layer over a subsurface layer of either more dense SO_2 frost or "average" Io materials [16]. Sample results are also presented in figures 1 and 2. This model's results agree better with certain observations [18]. The introduction of a second layer, however, steepens the near surface temperature gradient, and slightly decreases the actual surface temperature.

Three Layer Models: Various three layer models were also run, all of which possessed a low thermal inertia SO_2 layer at the top. Figures 1 and 2 show a three layer model with a 0.5 mm "fluffy" layer overlying a 1 mm layer of more dense SO_2 frost, overlying a denser layer of "average Io" materials [16]. Results are qualitatively similar to the two layer results, but the maximum daytime surface temperature is lower ($\approx$ 105K vs. 109K for the 2 layer model) and the near surface temperature gradient is less than that of the two layer model. Though the subsurface character of Io is unknown, the three layer model represents a physically reasonable model of frost deposited over other regolith materials.

Implications, Discussion and Future Work

We have demonstrated that physically reasonable models of ionian SO_2 frost fields yield surface tempertaures that are low enough to be consistent with observations of the ionian atmosphere. Absorption lengths that are inconsistent with the

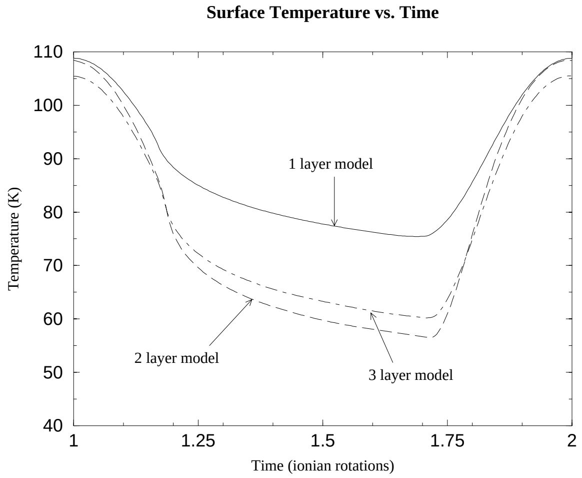

Figure 1: Sample profiles of surface temperature versus time on Io for 1 layer, 2 layer, and 3 layer models.

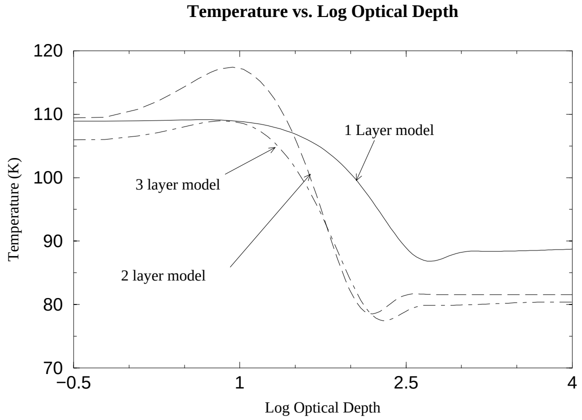

Figure 2: Temperature versus log optical depth at local noon for 1 layer, 2 layer, and 3 layer Io models.

measured albedo need not be postulated. Physically, our model implies that the actual surface of Io may be colder than previously thought, and that near surface temperture gradients may be present. This model is consistent with observations of Io and makes no unreasonable assumptions about the character of its surface, though it should be noted that it does not address the physics of SO$_2$ sublimation, such as latent heat or diffusion of SO$_2$ gas through an ice matrix. In the future we plan to include heat and visible radiation input from jovian thermal emission and reflected sunlight. We also plan to further explore diffusion processes, as our calculations show that the ionian subsurface may still be hot enough for SO$_2$ to sublime. Presumably SO$_2$ gas diffusing upward through a cold ice matrix will recondense onto that cold matrix, but further exploration is warranted.

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