ON THE MASS BALANCE AT IAPETUS' POLES: EXPLORING THE LIMITING EFFECTS OF THE DARK OVERBURDEN.
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Introduction: It has been shown through both measurements [1] and simulations [2] that there currently exists a dark ice-free porous material overlaying water ice on Cassini Regio. Mass transfer through this porous media in a vacuum is limited by Knudsen diffusion, which results in values orders of magnitude smaller than Hertz-Langmuir sublimation. The availability of water ice for transport from this region is thus controlled by mass transfer through the dark material overburden. Exogenic deposition models predict dark high latitudes on the leading hemisphere of Iapetus [3]. To counter this effect, the theory of thermal segregation suggests that Iapetus' polar regions have been brightened via ballistic transport of water and its subsequent cold trapping [4,5]. Thus the limiting effect of the dark material on transport of water ice will greatly impact the current mass balance at the poles, and depending on when the effects of impact gardening on the recycling of the surface became negligible, could also have shaped the current albedo distribution. The effects of the overburden on the global stability and transport of H_2O is addressed here in order to gain insight into its effect on the polar albedo distribution and mass balance.

Methods: Due to the recent measurements of the dark terrain's porous ice-free overburden thickness and the observed linear trend between it and bolometric Bond albedo [2], an estimate of the current stability of water ice within the dark terrain can be produced. The thermal model from Rivera-Valentin *et al.* [2] is used as the basis for the following models.

Sublimation model: Mass transfer through a porous overburden on an airless body at low temperatures has been shown to be in the Knudsen regime [6], where pore wall molecular interactions become a significant means of kinetic energy loss thus greatly inhibiting the sublimation rate compared to the widely used Hertz-Langmuir equation, which has been shown to produce an upper bound estimate of the mass loss rate [7,8,9] and is given by:

$$J_L = P_{sat}\sqrt{\frac{M}{2\pi RT}} \tag{1}$$

where J_L is mass flux, P_{sat} is the saturation vapor pressure, R is the gas constant, M is molecular weight, and T is temperature [10,11]. Accounting for Knudsen diffusion within the overburden, the rate limiting formula used to model mass loss is:

$$J_T = J_L\left(1+\frac{3}{8}\left(\frac{z\tau}{r_0\phi}\right)\right)^{-1} \tag{2}$$

where z is the regolith thickness, ϕ and τ are the porosity and tortuosity of the medium respectively, and r_0 is the pore radius. This along with the global thermal model of Rivera-Valentin *et al.* [2] is used to construct a global mass loss map.

Polar mass balance model: Transport of H_2O is modeled for one hop across the surface analytically by a method established by Blackburn [12]. In this model, the total flux reaching a given latitude range is given as the sum of the fractional flux leaving the latitudes below it at every point with the proper ballistics to enter the observed latitude range spread over its surface area. This fractional amount is a function of the sublimation temperature, which provides the velocity distribution of the molecules and incorporates the geometry of the problem. The total mass balance for a given point is then the net difference between the expected incoming H_2O and the outbound sublimating flux. The simplifications inherent to the mathematical framework in this methodology provide a lower limit to the resulting incoming mass flux as it does not account for flux from latitudes above the investigated range and only observes one molecular hop.

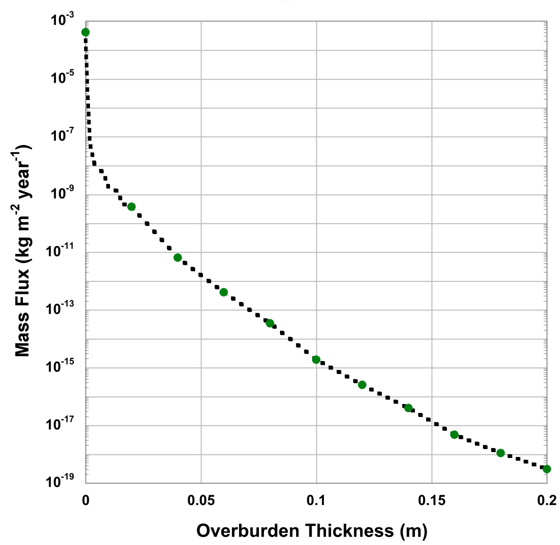

Fig. 1: Sublimation rate of water ice through the porous overburden on a semi-log scale. The heat and mass transfer model was run for various overburden thicknesses with the results shown in circles. The dashed line is a best fit to the points.

Results: Figure 1 shows the expected sublimation flux at the equator for several studied overburden thicknesses. The kinetics of mass transfer through the overburden along with thermal diffusion into the regolith greatly limits the sublimation rate of water ice. The difference between surface sublimation rates and those of Knudsen diffusion are several magnitudes and occurs with the addition of very small amounts of regolith, dropping from 10^{-3} to 10^{-8} kg m^{-2} year^{-1} with only 0.4 cm of regolith. Assuming an ice density of 917 kg m^{-3}, these fluxes amount to a thickness of approximately 1 μm per year on the surface to 1 μm per 100 ka with the addition of 0.4 cm of regolith.

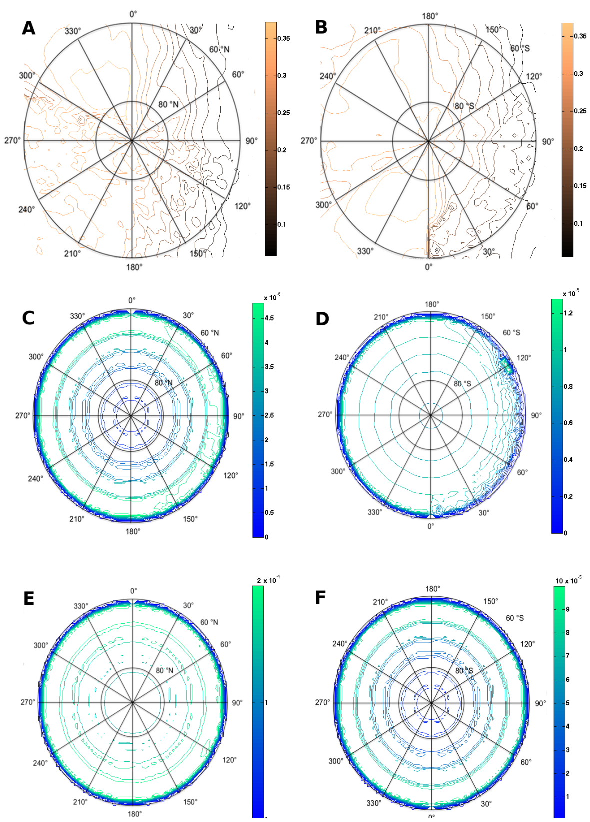

Fig. 2: Simulated accumulation maps for both northern high latitudes and southern polar terrain for case 1, which included the overburden's effect in Cassini Regio (C and D), and case 2, which assumed surface sublimation (E and F). The top row (A and B) is the bolometric Bond albedo maps for the high latitude terrain from Blackburn *et al.* [13]. The northern polar region results are in the left column while the southern polar region is in the right.

Ballistic transport to the poles was binned in 5° intervals from 60° to 90° latitude. In order to compare and contrast the effects of the overburden on the mass balance, two cases were simulated. Case 1 includes the overburden's effects on mass transfer while case 2 includes the mass flux ignoring diffusion through the overburden. The resulting mass balance maps along with the current bolometric Bond albedo of the region are shown in Figure 2. The primary effect of the overburden is to largely limit the availability of water molecules for ballistic transport, implying that the sublimation flux from the studied surface becomes the dominant factor in the mass balance.

Conclusions: Approximations to the mass balance at high latitudes show that most of the accumulation of water ice does not occur at the pole, but rather is offset to a latitude range of 60° to 70°. This is primarily due to the availability of kinetic energy for long-range ballistic transport, but is also partially due to the fact that the ballistic transport model did not incorporate mass transfer from latitudes above those considered. However, as can be seen from the sublimation flux maps, the source for this flux is limited, and this may only serve to further migrate this region of maximum accumulation towards the pole. Indeed, it has been shown that the maximum bolometric Bond albedo on Iapetus is offset from the poles and located near 70° N [13,14]. Since the accumulation maps attained assuming only surface sublimation across Iapetus also demonstrate this offset, then it can be assumed that the primary mechanism that has shifted the location of the highest bolometric Bond albedo on Iapetus is mass transport.

Tamayo *et al.* [3] estimated that the rate of ice deposition at the polar regions should be on the order of tens of μm per Myr to overcome exogenic sources. Estimates on the ballistic transport to the latitude range between 85° and 90° N, suggest that even with the limiting effects of the overburden, hundreds of μm per Myr of ice deposit and remain at the pole after the outbound sublimation flux is accounted for. Since the polar region mass balance approximations should be considered a lower estimate due to the simplifications within the ballistic transport model, then the overburden is not expected to limit the availability of water ice to the poles below the estimated inbound exogenic flux of ~50 μm per Myr attained by Tamayo *et al.* [3].

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