# VOLATILE CYCLING AND LAYERING ON MARS: OBSERVATIONS, THEORY AND MODELING.

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**Introduction:** With the release of Mars Odyssey Gamma Ray Spectrometer (GRS) results [1-3], which indicate the presence of vast reservoirs of near-surface ice in the martian polar regions (Figure 1), we are presented with an exquisite dilemma. These deposits, which are present as far down as 60º latitude in both hemispheres, are consistent with the suggestion of thermal models that ice will be best protected in these extended regions during periods of higher obliquity [4-5]. However, the current paradigm regarding the placement of these deposits, *i.e.*, diffusive deposition of water vapor, appears to be inconsistent with the large volume mixing ratios (~70%) inferred from the GRS data. This apparent conflict argues that diffusion alone cannot be the primary mechanism for the creation of these reservoirs, and that an alternate, large-scale process should be considered.

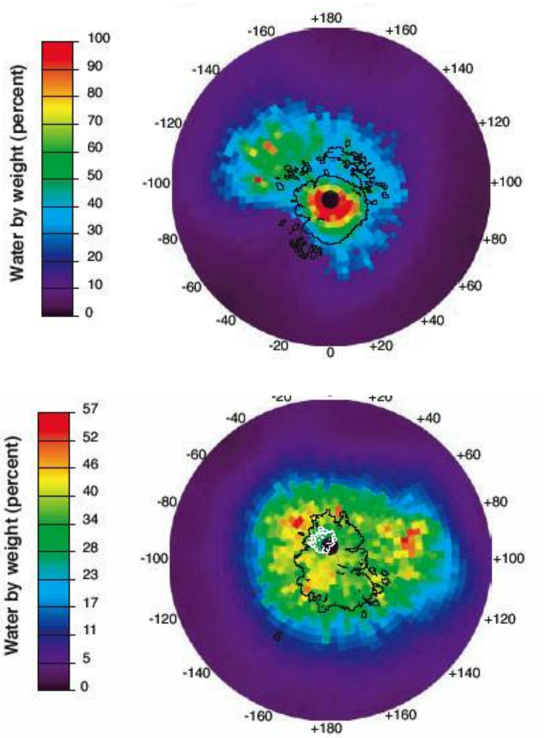

**Figure 1:** Surface ice distribution in northern (top) and southern (bottom) hemispheres, poleward of 60º latitude. Ice is nearly ubiquitous in polar regions.

Further, images of mantled, fretted and otherwise disaggregated terrain [6-9] (Figure 2) suggest that a more periodic volatilization/devolatilization is taking place on the martian surface, and may be more spatially widespread than previously thought. Areas of "pasted on" terrain on crater walls appear to show surface ice draped by a fine, dust mantle, while numerous MOC images of the mid-latitudes (30°-70°) reveal broken-up, mantled terrain that bears the morphological signature of past glacial or volatile-rich material. In many instances, such surface deposits appear to be cemented or otherwise physically altered.

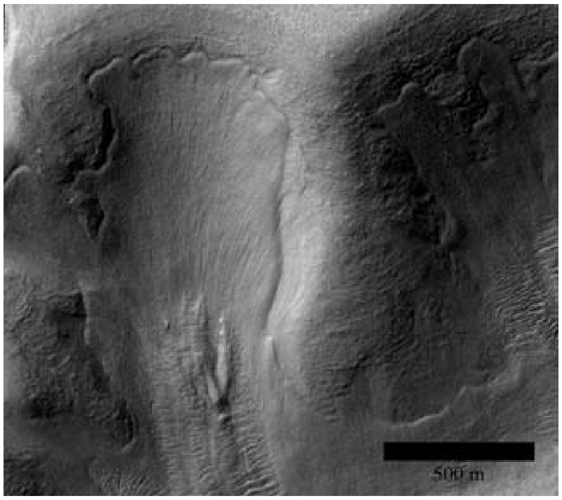

**Figure 2:** Volatile rich material in the high southern latitudes indicated by apparent flow down channel wall.

Based, then, on theoretical models, spacecraft observations, and new climate modeling of Mars' orbital cycles [10], we are led to an alternate conclusion about the ice deposits: that they form as subaerial ice sheets, the result of atmospheric saturation and direct surface deposition. This scenario not only provides a simple explanation for these observations, but may also help explain the formation of globally distributed, sedimentary-layered deposits

**Spacecraft Observations:** Maps generated by the Mars Odyssey GRS team reveal the presence of massive ice deposits at latitudes poleward of 60º. The depth to which the GRS instrument is sensitive is dependent on the abundance on neutron-moderating hydrogen atoms, and therefore, is most shallow in regions with a high hydrogen abundance. We can thus infer that such deposits may be found only a few to a few tens of centimeters below the surface, and are likely covered by a dessicated surface layer [1]. The thickness of such deposits is uncertain, but, by assuming or stipulating values for surface thermal inertia, conductivity and crustal heat flow, as in [11], we can estimate that the bottom of such an ice rich layer is on the order of hundreds of meters deep.

The GRS results show a distribution of near-surface ice quite similar to the results of [4-5], based again, on the physical and thermophysical properties of the regolith. In their diffusion models, water vapor passes through the pore spaces of the soil, in response to the ambient vapor pressure of the overlying atmosphere, a value which is, in part, orbitally-driven. As obliquity varies, this vapor can freeze, sublimate and adsorb within and onto the regolith grains, according to the thermal forcing at any particular location. One assumption of these models is the porosity of the soil, which, even for poorly-consolidated regolith, never exceeds ~40%. In other words, the available volume for water vapor within the pore space is limited to 40%. The GRS data, however, yields abundances that are extremely high—as much as 70% by volume in the polar and sub-polar regions, and therefore emplacement via diffusion does not seem wholly consistent with GRS observations.

**Ice Deposition Model:** We propose that ice sheets form at the surface, with diffusion into the subsurface being of only secondary importance. Results from a full general circulation model (GCM) [10] support this contention. Whereas presently ice is stable only at the poles (Figure 3a), under periods of higher obliquity, the latitudes of stable, perennial ice change. An increase in obliquity to 35º--approximately that reached at the last obliquity maximum—shifts this zone of stable water ice towards the mid-latitudes, between 50º and 70º (Figure 3b). Ice will be deposited in large, localized sheets, predominantly during the wintertime, and in locations of favorable surface properties (*i.e.* high thermal inertia) and favorable atmospheric dynamics. This ice, deposited at a rate of several millimeters to a centimeter per year, will survive through the summer. Over time, ice in such regions may accumulate to potentially significant depths—model results indicate up to several tens of meters may be deposited locally over the course of a single high obliquity excursion.

Increasing obliquity to 45º, which is representative of the high obliquity excursions of 5-10 million years ago, pushes this region of stable water ice into the tropics, equatorward of 30º latitude (Figure 3c). Under such extreme conditions, the deposition and accumulation of ice is even more substantial, and may, in fact, be limited by the amount of volatiles available for sublimation and transport towards the tropics, a point we shall address in the next section.

Based upon these model results, it seems possible that the GRS signature we are observing is not the present-day diffusion and freezing of water ice in pore space below a preexisting surface, but rather the remnant of a deposited ice sheet(s) during past high obliquity phases, covered by a lag.

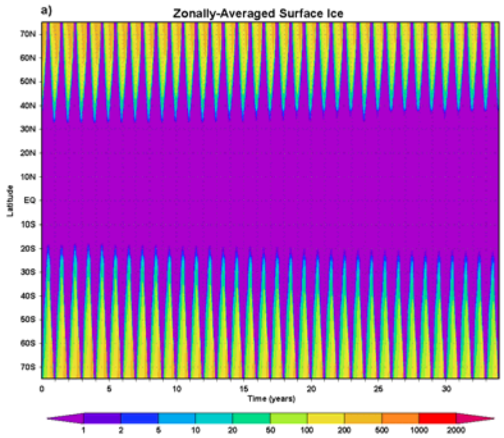

**Figure 3a:** Zonally-averaged surface ice (±75º latitude) at 25º obliquity run for 34 simulated martian years. Ice abundance is in μm.

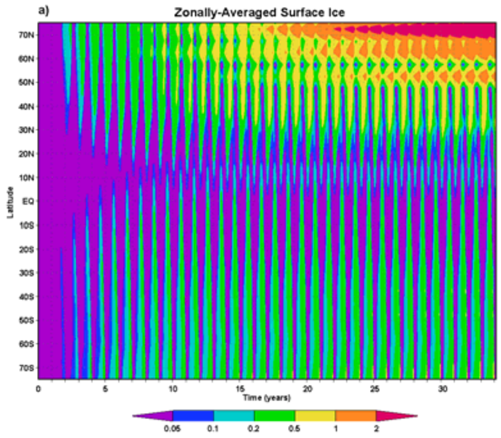

**Figure 3b:** Same as Fig. 3a, but for 35º obliquity. Ice abundance is in cm. Surface ice predominantly located in high mid-latitudes, between 50º-70ºN latitude.

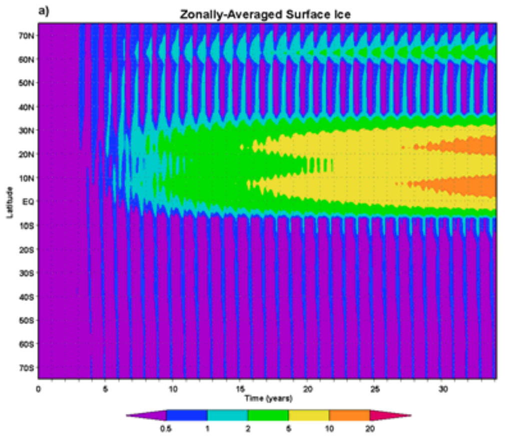

**Figure 3c:** Same as Fig. 3a, but for 45° obliquity. Ice abundance is in cm. Surface ice predominantly located in tropics, between ±30° latitude.

**Dusty Ice Sheets:** Given a layer of pure water ice, we should expect sublimation to occur on timescales roughly equivalent to deposition, hence these large sheets would disappear on roughly $10^4$ year timescales, leaving no residual by the occurrence of the next obliquity cycle. However, the inclusion of a small fraction of dust with the ice, can alter the behavior of the ice dramatically. We currently see exposed dust- and ice-rich regions on the martian surface (most notably the polar layered deposits [PLD]), so it is clear that a process of dust entrainment, deposition or sedimentation must take place during the creation of these areas. It has been suggested [12] that higher obliquity states are associated with higher atmospheric dust abundances, so it is reasonable to assume that these lower latitude ice regions may contain at least a similar fraction of dust than present-day polar regions.

As the surface ice becomes unstable and sublimes, the dust will accumulate near the surface, slowly creating a thicker lag deposit, and lowering the ability of subsequent water vapor to reach the atmosphere. Such a lag deposit of perhaps only a few tens of centimeters to a meter [13] is all that is required to maintain the stability of the underneath ice. The dry valleys of Antarctica provide a terrestrial analog to this process. Marchant *et al.* [14] indicate the presence of such a lag deposit ("sublimation till") over Miocene-aged glacier ice in the Beacon Valley, Antarctica that has effectively shielded the remaining glacier ice from further sublimation. The required depth of such a till was between 40-70cm. Assuming a 10% dust content on martian ice (and that the martian atmosphere behaves in a similar way to the terrestrial one), it would require the sublimation of 4-7m of surface ice to achieve similar depths.

Once the lag deposit is in place, remaining ice would be effectively shielded for the remainder of the obliquity cycle, or ~$10^5$ years. Slow diffusion up through the lag, and down into the regolith may still occur, but on timescales sufficiently long to insure the survival of some ice over obliquity timescales. This process may reoccur during the next obliquity cycle, creating a new dust/ice layer on top of any previously existing dust/ice layers.

As we mentioned in the previous section, during very high obliquity, the deposition of surface ice may be source-limited, a result of the very process we invoke to maintain ice stability at lower latitudes. Should sublimation at the polar caps become too extensive, a sublimation lag may develop, cutting off the primary source of volatiles to the rest of the planet. So while ice may be stable in the tropics, for example, at 45° obliquity, there may be a lack of vapor with which to build up a substantial tropical ice reservoir.

We may speculate about processes by which such a constraint may be avoided. A novel approach involves the "scrubbing" of the atmosphere during low obliquity periods, as water ice returns to the poles. During low obliquity, the maintenance of a strong polar vortex may inhibit the transport of dust to the poles, while allowing atmospheric vapor to readily diffuse poleward. Along with the concentration of surface ice due to the unequal surface areas involved, this mechanism may make the development of a sublimation lag extremely difficult in the poles.

And so we have developed a simple mechanism for the global distribution of water ice by invoking only orbital parameters and the thermophysical conditions of the surface, which is illustrated in Figure 4. The deposition of a layer of dusty ice at a given location will commence once ice at that latitude becomes stable (b). The period of time for which ice will be deposited is clearly dependent on the length of time that obliquity is above some "critical" value, which is different for each latitude. Once Mars' obliquity drops below this "critical" value, ice at lower latitudes is thermally unstable, and will quickly sublime (c), leaving behind the residual lag deposit. For the remainder of the obliquity cycle, ice beneath this lag is quasi-stable and will remain at least until the following obliquity cycle (d). At this point, we argue that one of two processes may occur. If obliquity again rises above the "critical" value, a new layer of ice and dust may form on the new surface. Such behavior may already be seen in the PLD, for which exposed layers of ice-dust-ice are readily apparent. If, however, obliquity does not again rise above the "critical" value, subsequent mechanisms may act to modify the surface and near surface, including the deposition or movement of dust or sand, and other processes responsible for creating the surface morphology observed in these regions.

**Discussion:** We have shown that the existence of mantled ice sheets in the high latitudes of Mars where the GRS water abundance is highest appears plausible on the basis of imaging observations [6-7]; indeed, some of these observations suggest the presence of more extensive and now substantially devolatilized deposits at even lower latitudes [6]. We note that this scenario suggests something foundational to our understanding of Mars climatic and geologic history: that ongoing volatile redistribution due to changes in obliquity and other orbital elements can generate extensive sedimentary deposits of ice and/or lag. Accumulation of these units may be an important mechanism in the formation of mid- and low-latitude layered terrains [8].

The advantage of the layering mechanism discussed above is its simplicity. A single mechanism for ice distribution can be used to explain both layered volatile and layered sedimentary deposits presently observed on the martian surface [8]. It requires no *ad hoc* assumptions about the properties of the surface, or the presence of liquid water. Indeed, the only assumption we must make (which is well grounded) is that dust must be present along with ice during deposition.

**References:** [1] Boynton, W.V. et al. (2002) *Science, 297,* 81-85. [2] Feldman, W.C. et al. (2002) *Science, 297,* 75-78. [3] Mitrofanov, I. et al. (2002) *Science, 297,* 78-81. [4] Mellon, M.T. and Jakosky, B.M. (1993) *JGR, 98,* 3345-3364. [5] Mellon, M.T. and Jakosky, B.M. (1995) *JGR, 100*, 11,781-11,799. [6] Mustard, J.F. et al. (2001) *Nature, 412,* 411-414. [7] Carr, M.H. (2001) *JGR, 106,* 23,571-23,594. [8] Malin, M.C. and Edgett, K.S. (2001) *JGR, 106,* 23,429-23,570. [9] Kreslavsky, M.A. and Head, J.W. (2002) *GRL, 29,* 1719. [10] Mischna, M.A. et al. (2003) *JGR, in press.* [11] Mellon, M.T. et al. (1997) *JGR, 102,* 19,357-19,369. [12] Toon, O.B. et al. (1980) *Icarus, 44,* 552-607. [13] Hofstadter, M.D. and Murray, B.C. (1990) *Icarus, 84,* 352-261. [14] Marchant, D.R. et al. (2002) *GSA Bulletin, 114,* 718-730.

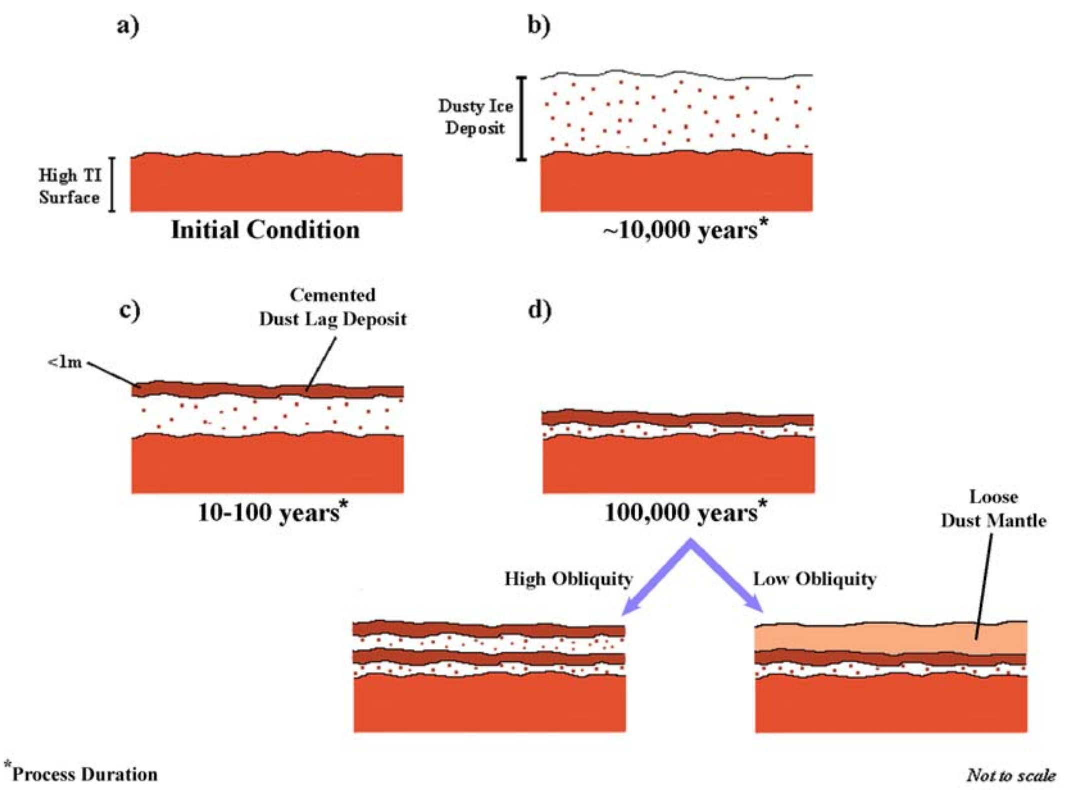

**Figure 4:** Timeline of surface layering mechanism over obliquity timescales (indicated times are phase durations, not accumulated time during process). a) initial exposed regolith b) becomes site for residual ice deposition due to variation in astronomical elements. Accumulation goes on for $\sim 10^4$ yrs before c) elements change again, area becomes unstable for water ice and net sublimation occurs. However, dust in ice accumulates during sublimation, and generates an isolating lag within $10^1$-$10^2$ years than can d) greatly reduce ice loss over an astronomical cycle. The cycle can continue, developing layers or area may become buried in unconsolidated