Mars low-latitude neutron distribution: Possible remnant near-surface water ice and a mechanism for its recent emplacement

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Abstract
The Mars Odyssey Gamma-Ray Spectrometer/Neutron Spectrometer/High Energy Neutron Detector has provided measurements of near-surface hydrogen, generally interpreted as resulting from water, in the equatorial and mid-latitudes. Water abundances as great as 10% by mass are inferred. Although such high abundances could be present as adsorbed water in clays or water of hydration of magnesium salts, other measurements suggest that this is not likely. The spatial pattern of where the water is located is not consistent with a dependence on composition, topography, present-day atmospheric water abundance, latitude, or thermophysical properties. The zonal distribution of water shows two maxima and two minima, which is very reminiscent of a distribution that is related to an atmospheric phenomenon. We suggest that the high water abundances could be due to transient ground ice that is present in the top meter of the surface. Ice would be stable at tens-of-centimeters depth at these latitudes if the atmospheric water abundance were more than about several times the present value, much as ice is stable poleward of about ±60° latitude for current water abundances. Higher atmospheric water abundances could have resulted relatively recently, even with the present orbital elements, if the south-polar cap had lost its annual covering of CO 2 ice; this would have exposed an underlying water-ice cap that could supply water to the atmosphere during southern summer. If this hypothesis is correct, then (i) the low-latitude water ice is unstable today and is in the process of sublimating and diffusing back into the atmosphere, and (ii) the current configuration of perennial CO 2 ice being present on the south cap but not on the north cap might not be representative of the present epoch over the last, say, ten thousand years.

Keywords: Mars; Neutrons; Mars Odyssey; Water ice; Mars climate

1. Introduction
The Gamma-Ray Spectrometer/Neutron Spectrometer/High-Energy Neutron Detector instrument suite (GRS/NS/HEND) on board the Mars Odyssey spacecraft is able to detect the presence of hydrogen in, at most, the top meter of the regolith, with a spatial resolution of about six hundred kilometers. Although hydrogen can be present in many forms, including bound OH in minerals, H 2 O 2 produced from atmospheric chemical processes, methane, etc., its most likely form is as H 2 O (Drake et al., 1988; Feldman et al., 2002, 2004b; Boynton et al., 2002; Mitrofanov et al., 2002). This is especially the case given the relatively large amounts of hydrogen that are inferred to be present, which may be inconsistent with other reservoirs. The GRS/NS/HEND is mapping, in essence, the water content of the uppermost surface layer (Drake et al., 1988; Feldman et al., 2002, 2004b; Boynton et al., 2002; Mitrofanov et al., 2002).
It was originally anticipated that the high-latitude regolith would contain water in the form of ground ice that was in diffusive equilibrium with the atmosphere, and that the low- and mid-latitude-regolith water would be most directly related to adsorbed water in diffusive equilibrium with the atmospheric water vapor (Drake et al., 1988). Although this expectation appears to have been borne out at the high latitudes (Feldman et al., 2002; Boynton et al., 2002; Mitrofanov et al., 2002; Mellon et al., 2004), the water abundances and distribution at low and mid latitudes is not so simple. A number of possible explanations have been put forward to explain the low- and mid-latitude water distribution, including the presence of hydrated magnesium sulfate salts, water-rich zeolites, and adsorbed water (see Feldman et al., 2004a). Here, we explore the question in more detail, in order to understand both the constraints on any possible explanation and alternative physical models that might be equally or more consistent with the observations.

We examine the relationship between the water in the regolith and the physical properties that might be playing a role in controlling the water abundance, in order to see what physical connections might exist. The apparent lack of a unique or a strong global relationship then drives us to consider nonequilibrium and nonsteady-state processes that might be controlling the water distribution.

2. Relationship between regolith water and physical properties

We expect to find water in the regolith at low and mid latitudes today. It could result, for example, from the presence of water that was a part of the original volcanic rock erupted to the surface. In this case, we might expect it to be present at an abundance of less than a couple of per cent or less (Crisp, 1984; McSween et al., 2001). It also could be present as adsorbed water, lightly bound to individual regolith grains by van der Waals forces and in equilibrium with water vapor in the surrounding pore space. Water will adsorb onto the surface whenever water vapor is present, and would be expected to be in equilibrium with atmospheric water vapor via diffusion through the porous regolith (Mooney et al., 1952; Zent and Quinn, 1995; Jakosky, 1985). For present-day atmospheric water abundances, there could be as little as a fraction of a per cent adsorbed water by mass for a basaltic regolith or as much as a few tens of per cent adsorbed water for a clay-rich regolith (see Jakosky, 1983a, 1983b).

If water is present as an adsorbed species, we would expect its abundance to relate directly to the physical properties of the regolith and atmosphere, as these control the equilibrium abundance of bound water. One would expect that surface or subsurface temperature, surface composition, and atmospheric water abundance each would exert partial control on the amount of adsorbed water. In addition, other properties that might relate directly to these include latitude (which is related to both atmospheric water abundance and subsurface temperature), thermal inertia and albedo (which control temperature, with albedo also being a good first-order surrogate for composition), and local elevation (which affects dynamical transport of water through the atmosphere as well as the near-surface atmospheric water-vapor number density).

Figure 1 shows a map of the amount of hydrogen present in the regolith, expressed as the equivalent amount of water. As both neutrons and gamma rays that are detected by the GRS/NS/HEND and which are sensitive to water emanate from the upper ~1 m of the regolith, these values are representative of the water content of the uppermost meter or so of the regolith. Values outside of the high latitudes where ice is expected to be present range from a low of about 2% to a high of over 10% (Feldman et al., 2004a). Also shown in Fig. 1 for comparison are maps of many of the physical properties that might exert some control over the amount of water in the regolith. There are some intriguing connections, with boundaries in the water abundance corresponding in some instances with boundaries in other properties. However, not every boundary in the regolith water abundance corresponds to a boundary in one of the controlling parameters. There is no simple correlation that is able to explain all of the global variations, and not every component of the regolith water distribution corresponds to variations in any of the potential controlling parameters. For example, the high water abundances in the Arabia region (near the middle of the map in Fig. 1) correspond to the high albedo of this region, but the local agreement is not compelling and the high-albedo terrain in the Tharsis region and to the west contains a wide range of water abundances.

We explored the quantitative connections between the regolith water abundance and each of the physical properties that might be controlling the abundance. We did this by calculating the degree of correlation between the epithermal neutron abundance (from which the water abundance is derived) and each of the physical parameters in Fig. 1, after smoothing the latter data sets in order to match the spatial resolution of the neutron measurements. Data were compared between latitudes of ±45° latitude only, in order to not include the high-latitude regions in which ice in diffusive equilibrium with the atmosphere is thought to exist. Table 1 shows the results, and an example cross plot between the epithermal neutron abundance and one of the parameters (in this case, mean regolith temperature) is shown in Fig. 2. The largest correlation coefficients are between the neutron abundance and the peak annual atmospheric water abundance, the mean annual subsurface temperature, and the latitude. Each of these might be expected to show a causal connection to the neutrons. However, in each case the correlation coefficient was less than 0.3, indicating only a very weak connection at best. Clearly, neither a comparison by inspection of Fig. 1 nor a quantitative comparison shows a compelling relationship, and no single parameter is able by itself to explain a significant fraction of the water distribution.
Fig. 1. Maps showing the abundance of hydrogen and of different physical properties that might control the water distribution in the regolith. Each map is between ±45° latitude. From top to bottom, the maps are the water-equivalent abundance of hydrogen (Feldman et al., 2004a, 2004b), the annual peak abundance of atmospheric water vapor as derived from MGS TES measurements (Smith, 2002; M.D. Smith, personal communication, 2003), the mean annual surface temperature (derived from the models of (Mellon et al., 2004)), the topography (Smith et al., 1999), the mean annual abundance of atmospheric water vapor as adjusted to a common datum to “correct” for topography (Smith, 2002; M.D. Smith, personal communication, 2003), the thermal inertia of the surface (Mellon et al., 2000), the mean annual abundance of atmospheric water vapor as measured without a topographic correction, and the bolometric albedo as measured from MGS TES measurements (see Christensen et al., 2001).
It is possible that a combination of several different physical properties affects the water distribution. One can envision a situation in which each of several controlling properties shows only a small correlation with the observed neutron distribution, but that a combination of several of them would correlate more strongly. To explore this possibility, we did a multi-dimensional least-squares fit of all of the parameters to the neutron abundance. Only elevation, mean temperature, peak water abundance, and latitude showed any possible contribution, so a least-squares fit also was done again using only these parameters. Figure 3 shows a cross plot between the observed neutron distribution and the least-squares fit based on these four parameters. Again, there is only a weak correlation at best, and the appearance of the cross plot suggests that the basic controlling properties have not yet been accounted for.

These arguments suggest that no combination of relevant physical parameters is able to explain the current regolith water distribution. Tempering this conclusion is the fact that the measurements that refer to the physical properties of the surface materials all relate formally to different thicknesses of regolith. Albedo refers to the uppermost micrometers, thermal inertia to a layer between 1 and 10 cm thick, and the GRS/NS/HEND-derived water abundances to a layer roughly a meter thick. If properties are not uniform over this range of depths, these characteristics might not be referring to the same materials. In this case, it is possible that vertical structure within the subsurface could be complicating the comparisons. However, the relatively strong correlation between albedo and thermal inertia, or thermal inertia and radar properties (which also refer to a thicker layer in some cases; see Jakosky and Christensen, 1986), suggests that this may not be the case in general.

Taken in total, the data suggests that it is unlikely that the geographical distribution of regolith water detected by the GRS/NS/HEND represents a steady-state equilibrium of adsorbed water at the present epoch, with the abundance controlled by the relevant physical properties.

There is another reason why the hydrogen is not likely to be present as adsorbed water. Basalt is a much poorer adsorber than is clay. Water adsorbed on basalt at Mars ambient conditions would constitute less than 1% of the material by mass (e.g., Zent and Quinn, 1995; Jakosky, 1983a). The relatively high water abundances, at levels of up to 10%, are not likely to occur as adsorbed water unless a significant fraction of the surface is made of clay minerals. Although the presence of clays such as montmorillonite or nontronite, thermal inertia to a layer between 1 and 10 cm thick, albedo refers to the uppermost micrometers, and the GRSTODYSSEY GRS/NS and mean annual temperature. The latter could hypothetically be controlling the former, but the obvious lack of strong correlation suggests otherwise.

Table 1

| Correlation coefficient between epithermal neutrons and potentially relevant controlling physical properties (see text for discussion; the data sets are those shown in Fig. 1) |
|----------------------------------|--------------|----------------|----------------|----------------|----------------|-----------------|----------------|----------------|----------------|
| Neutrons                         | Max H₂O      | Latitude       | Temp            | Elevation      | Topo-corrected H₂O | Thermal inertia | Uncorrected H₂O | Albedo          |
| 1                                | -0.28        | -0.263         | 0.252           | 0.202          | 0.087            | 0.082          | -0.072         | -0.063          |
| Max H₂O                          | -0.28        | 1              | -0.284          | -0.668         | -0.049           | 0.03           | 0.39           | 0.108           |
| Latitude                         | -0.263       | 0.559          | 1               | -0.092         | -0.54            | 0.285          | 0.005          | 0.594           | 0.147           |
| Temp                             | 0.252        | -0.284         | -0.092          | 1              | -0.031           | 0.327          | 0.214          | 0.14            | -0.427          |
| Elevation                        | 0.202        | -0.668         | -0.54           | -0.031         | 1                | -0.115         | -0.127         | -0.488          | 0.002           |
| Topo-corrected H₂O               | 0.087        | -0.049         | 0.285           | 0.327          | -0.115           | 1              | -0.053         | 0.623           | 0.247           |
| Thermal inertia                  | 0.082        | 0.03           | 0.005           | 0.214          | -0.127           | -0.053         | 1              | -0.041          | -0.284          |
| Uncorrected H₂O                  | -0.072       | 0.39           | 0.594           | 0.14           | -0.488           | 0.623          | -0.041         | 1              | 0.286           |
| Albedo                           | -0.064       | 0.108          | 0.147           | -0.427         | 0.002            | 0.247          | -0.284         | 0.286           | 1              |
ite has been suggested based on the Viking biology experiments (e.g., Clark et al., 1982), spectral evidence suggests that basalts dominate and that clays are present only in very small abundances if at all (e.g., Bell and McCord, 1989; Bandfield et al., 2000). There is no evidence to suggest that clays are present in amounts that would be sufficient to account for the high hydrogen abundances that are observed, or that their spatial distribution would be such as to produce the observed water distribution. And, the lack of correlation with the albedo (which is a good approximation to the distribution of materials of like composition) or the thermal inertia (which shows the presence of centimeters-or-thicker deposits of dust) supports this view that weathered materials do not contain the water.

This conclusion drives us to explore more-complicated nonequilibrium processes and time-dependent solutions.

3. Time-variable processes

Time-dependent processes might explain the observed water distribution if they can result in greater regolith water abundances at some time in the past and if the regolith could have retained at least some of its water up to the present. One way for this to occur is if the atmospheric water content had been greater at a previous time, creating a situation in which ground ice could be stable over a larger fraction of the planet. If this occurred recently enough that any ground ice that was deposited would not have had enough time to sublime and diffuse into the atmosphere, there could be a residual ground ice present even though it is not stable today.

Ground ice could be stable at low latitudes if the atmospheric water vapor content were greater than it is today. At present-day atmospheric water abundances, the condensation temperature of the atmosphere is around 198 K (Farmer and Doms, 1979; Mellon and Jakosky, 1993). This means that, where the regolith temperature is lower than this, water vapor could diffuse from the atmosphere into the regolith and condense out as ice. (The situation is a little more complicated than this due to the seasonal variations of both atmospheric water content and subsurface temperature; the actual criterion is that the time-dependent vapor diffusion allow a net condensation of water as ice over the course of a year, but this is not too different for our purposes here. See Mellon and Jakosky (1993, 1995) and Mellon et al. (2004) for detailed discussion of this point.) At the present epoch, ground ice is stable poleward of about ±60° latitude, at depths that vary between a couple of tens of centimeters and a meter (Mellon et al., 2004). This distribution matches up well with the extremely high water content inferred from the GRS/NS/HEND measurements (Feldman et al., 2002, 2004b; Boynton et al., 2002), and is suggestive of the presence of ground ice in these locations.

An increase in atmospheric water content would result in a higher condensation temperature. This means that areas that are at lower latitudes, with warmer temperatures, would then be within the stability region for ice, and ice would be expected to form there. As the water content of the atmosphere increases, the boundary separating locations where ice is not stable from those for which ice is stable would move to lower latitudes.

This can be seen in Fig. 4, which shows the calculated regions of ice stability within the regolith for enhanced atmospheric water abundances. These calculations are based on the models described by Mellon et al. (2004), and include an approximation to the effects of the seasonally dependent terms. A doubling of the water content will substantially increase the area in which ice is stable. And a five-fold increase to 100 pr µm of water allows ice to be stable within the regolith over a large fraction of the planet.

One way to increase the water content is to raise the planet's obliquity. At higher obliquity, the polar caps tilt more toward the Sun during summer and are heated up to higher temperatures, and more water vapor will sublime into the atmosphere; this water can be carried to lower latitudes, and could saturate the atmosphere and deposit onto the ground or into the subsurface as ice (Jakosky and Carr, 1985; Mischna et al., 2003). Atmospheric water contents as high as 100 pr µm can occur for obliquities less than 35° (Jakosky et al., 1993, 1995; Mischna et al., 2003) that might have occurred as recently as a few times 10^5 years ago (Ward, 1992; Laskar et al., 2002). However, for this model to be correct, ice would have to have survived at the equator, at depths of substantially less than a meter, for longer than 10^5 years. It is possible that the regolith could be this impermeable to diffusion, especially given the global distribution of cemented materials (“duricrust”) that might have decreased permeability (e.g., Jakosky and Christensen, 1986); however, while possible, this scenario seems forced at best.

We examine an alternative scenario that can yield the same increased atmospheric water contents at much more recent times.

The present-day atmospheric water content represents a balance between summertime sublimation of water into the atmosphere from the north-polar residual water-ice cap, wintertime condensation and deposition onto both the north and south caps, seasonal exchange with adsorbed water in the top few centimeters of the regolith, and advective transport through the atmosphere resulting from global winds (Jakosky, 1983a, 1983b, 1985; Haberle and Jakosky, 1990; Zent et al., 1993; Houben et al., 1997; Richardson and Wilson, 2002).

The polar caps represent the major reservoirs for supply to and loss from the atmosphere. The peak northern hemisphere water abundance of about 100 pr µm results from summertime sublimation from the exposed north-polar water-ice cap (Haberle and Jakosky, 1990; Jakosky and Haberle, 1992; Smith, 2002). Much lower southern hemisphere water contents result because the south cap has not been observed to lose its CO2 ice cover and to expose underlying water ice. As a result, the cap never warms to temperatures that would result in sublimation of significant quan-
Fig. 4. Maps showing regions of ice stability for different atmospheric water contents. Each map is between ±45° latitude, with white showing where ice is not stable, and the color indicating the depth to stable ice. Maps are shown for annual average atmospheric water contents of 10, 20, 40, and 100 pr μm. Calculated using the algorithm of Mellon et al. (2004).

Quantities of water. This difference in cap behavior is reflected in the existence of a strong gradient in average atmospheric water content from north to south, as seen in Fig. 1 (Jakosky and Farmer, 1982; Smith, 2002).

Water ice is expected to be present beneath the south polar CO₂ ice because it is less volatile than CO₂ ice. The covering of CO₂ frost acts as a cold trap to remove water vapor from the atmosphere. If the south cap were to entirely lose its CO₂ ice covering at the present epoch, it would expose this underlying water ice. With CO₂ frost no longer present, the south cap would heat up to higher temperatures during summer than does the north cap, as the planet is presently closest to the Sun during southern summer, and significant quantities of water would sublime into the atmosphere. The peak southern water content could be as great as several hundred pr μm (Davies et al., 1977; Jakosky et al., 1993, 1995). The low-latitude atmospheric water content reflects the control by the polar regions, and lies between the annual average polar amounts; observations and models suggest that it is about equal to the average of the annual average water vapor abundance over the two polar caps (Jakosky and Farmer, 1982; Smith, 2002; Richardson and Wilson, 2002). Thus, at a time when there is a supply of water to the atmosphere from both summer polar caps, equatorial water abundances should increase substantially. The annual average atmospheric water content over the north polar cap is about 30 pr μm; the annual average over an exposed south polar is likely to be closer to 150 pr μm, assuming that it has the same properties as does the northern water-ice cap (see Davies et al., 1977; Jakosky et al., 1993, 1995). Thus, it is possible that the annual average atmospheric water content could be 100 pr μm, five or more times greater than the present observed values. As Fig. 4 shows, this would result in substantial deposition of water ice into the low-latitude subsurface.

Can the south cap lose its CO₂ covering at the present epoch? Theoretical models of the seasonal CO₂ cycle suggest that the south residual cap has two distinctly different stable states (Jakosky and Haberle, 1990). In one state, CO₂ can be present year round, and the wintertime condensation and summertime sublimation exactly or nearly balance. In the second state, the CO₂ ice can disappear by about mid-summer, exposing the underlying material. This material then will heat up substantially during the remainder of summer. The resulting downward-conducted heat con-
In addition, one can envision processes by which the cap might jump back and forth between these two stable states (Jakosky and Haberle, 1990). A small perturbation to the energy balance could remove a small residual covering of CO₂, if it is thin, and expose the underlying water ice at end of summer, thereby triggering a jump from a “covered” to an “uncovered” state. Similarly, deposition of clean water ice from the opposite pole could raise the albedo, causing a cooling of the cap and a possible jump to a “covered” state. (While the changing argument of periapsis might also trigger such a jump, this would occur on much longer timescales rather than the interannual timescale discussed here.)

There is some evidence that the cap might occupy each of these stable states at times. Atmospheric water measurements made from Earth in 1969 showed a much greater southern hemisphere abundance than has been seen subsequently. The water vapor abundance was high enough to be interpreted at that time as indicating the presence of a residual water-ice cap in the south (Barker et al., 1970; Jakosky and Barker, 1984). More recently, observations from the Mars Global Surveyor and the Mars Express spacecraft have suggested that there are portions of the south cap which have exposed summertime water ice (Titus et al., 2002; Bibring et al., 2004). This exposure, if it varies from year to year, might explain the factor-of-ten interannual variability in southern summer atmospheric water abundance (e.g., see Clancy et al., 1992). The behavior of the south-polar “Swiss-cheese” terrain also suggests year-to-year variability in the CO₂-ice cover (Malin et al., 2001). The appearance of the terrain, and the increase in the size of the holes that takes place over a year, both suggest that the CO₂-ice cover is variable and that there could be a significant redistribution of water ice taking place. Whether this redistribution represents an increasing exposure of water ice at the expense of CO₂ ice and we are witnessing an increasing uncovering of a water-ice cap, or whether it represents a redistribution of the geographical coverage with no change in the total coverage is not known.

If the south polar region contained an exposed water-ice cap during summer, the resulting enhancement of atmospheric water content might result in water ice being stable over a large fraction of the planet. With ice stable, water vapor can diffuse into the subsurface and condense out as ice in a relatively short time (Mellon and Jakosky, 1995). The time for a significant amount of water ice to condense within the regolith could be as short as 10³–10⁴ years; this is short compared to the time in which either the obliquity or the argument of perihelion would change as the orbital elements evolve. If the cap only recently became covered again with CO₂ frost, sufficient time might not have elapsed for the low-latitude water ice, now unstable with respect to sublimation, to diffuse back into the atmosphere.

Thus, it is possible that a south-polar-cap configuration in which it is covered with CO₂ year round might not be representative of the most recent epochs, despite this being the state observed from spacecraft. Instead, the more repre-
sentative state could be with the south cap losing its CO$_2$ ice covering during summer. This could have been the case as recently as a few decades ago, a hundred years ago, or a thousand years ago, at which time water ice could have been stable quasi-globally even under the present orbital conditions. Ice deposited 100 or 1000 years ago might still be present as a transient phase even though it would not be stable today.

4. Discussion

Several potential explanations for the high regolith water content have been put forward. In addition to the possibility described here involving transient, unstable ground ice, possibilities include the presence of hydrated magnesium sulfate salts, water-rich zeolites, and adsorbed water (see Feldman et al., 2004a). Hydrated magnesium salts are especially interesting due to the high sulfur abundances seen at the Viking and Pathfinder landing sites (Clark, 1978) and the high abundance of magnesium salts identified at the Mars Exploration Rover Opportunity site (Squyres et al., 2004). The apparent lack of correlation with remote-sensing-derived indicators of composition, however, makes these explanations somewhat problematic.

Is the transient-ground-ice model proposed here consistent with the geographical distribution of regolith water measured from the GRS/NS? The distribution of ground ice predicted from our model at high atmospheric water content (Fig. 4) is driven in large part by (i) the temperature as controlled by the thermal inertia and albedo, and (ii) the topography, as it affects the modeled near-surface atmospheric water vapor number density. As none of these parameters match well with the neutron distribution, it would be expected that the geographical distribution of ground ice predicted from the model would not match well either, and this is in fact the case. Let us explore a couple of the pertinent issues.

The simple model used here assumes a uniform water vapor abundance in the atmosphere, modulated only by the topography. In reality, the water vapor abundance varies from this uniform mixing ratio by more than a factor of two (Jakosky and Farmer, 1982; Smith, 2002). This variation presumably results from the role of atmospheric transport in redistributing the water in systematic but nonuniform ways. A proper regolith model should include this actual variability as a boundary condition. However, neither the map of the actual nor the topographically adjusted water vapor abundances matches well with the neutron distribution, so that a model incorporating these as a boundary condition probably would not match well with the water distribution either.

At the same time, the geographical distribution of atmospheric water vapor would be different if both the north and the south polar caps were supplying water to the atmosphere. In theory, one could use the modeled atmospheric transport to produce a modeled distribution of water and then use this as a boundary condition. However, the significant differences seen between the different models of atmospheric circulation (e.g., Houben et al., 1997; Richardson and Wilson, 2002) suggest that there still are factors that we do not understand that are controlling the instantaneous and net atmospheric circulation and transport.

One interesting point, though, is that the hydrogen distribution shows a zonal wave-number two behavior, with two maxima and two minima around the equator (see Fig. 1). This is similar to the wave-number two behavior of the atmospheric circulation, in which the topography drives a net average upward motion over topographically high regions and downward motion over low regions (Webster, 1977; Pollack et al., 1981). This again suggests an atmospheric phenomenon controlling the distribution, consistent with the modulation of atmospheric water vapor that might be produced by the atmospheric circulation.

A different question relates to the occurrence of high-latitude ground ice. That ice appears to be in vapor-diffusive equilibrium with the present-day atmosphere (see Mellon et al., 2004). Is it possible for the high-latitude ice to be in equilibrium at the present and for low-latitude ice to be out of equilibrium? In fact, this is the behavior that one would expect for a climate that oscillates between two states. At low atmospheric water abundance, as seen today, ice would be stable only poleward of about ±60° latitude. At high atmospheric water abundance, ice would be stable over larger areas; at the same time, there would be no change to the high-latitude ice. If the climate switches between the two states, then, the high-latitude ice would always be present while the low-latitude ice would come and go.

At present, none of the possible explanations provides a satisfying match to the observed distribution of water in the regolith. Is it possible to further test any of the hypotheses or to identify analyses that would help us to choose between them? A detection of a decrease in low-latitude water over time would be strong evidence for the continuing disappearance of transient water. Similarly, evidence related to the interannual behavior of CO$_2$ ice on the south polar cap would provide an important boundary condition for the presence and stability of ground ice. On the other side of the hypotheses, detection of abundant widely distributed magnesium salts or zeolites would be an important discriminator between models. Absent these, landing on the surface, digging down, and searching for local ground ice might be the most definitive (albeit the most expensive) test.

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