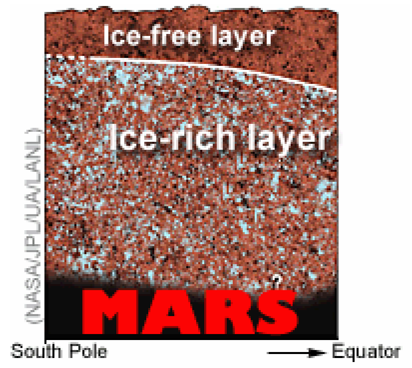
Hot Idea posted June 5, 2002



Dirty Ice on Mars

--- Instruments on the Odyssey spacecraft show that a lot of dirty ice sits within a meter of the surface in the south polar latitudes of Mars.

Written by G. Jeffrey Taylor
Hawai'i Institute of Geophysics and Planetology

The gamma-ray and neutron spectrometers onboard the orbiting 2001 Mars Odyssey spacecraft have detected strong signals from hydrogen quite close to the Martian surface. The concentration of hydrogen is so large that it must be in the form of ice. The amount of ice in the upper meter or so begins to rise at about -60° latitude and continues to increase toward the South Pole. Detailed analysis of the data indicates that the ice-rich layer resides beneath a hydrogen-poor upper layer. The thickness of the upper layer decreases from about 75 cm at -42° to about 20 cm at -77°. The amount of ice in the lower layer is between 20 and 50 wt% (weight percent), with a best estimate of 35 wt%. Because ice is much less dense than mineral grains, this translates to more ice than rock by volume. It's dirty ice. The results were reported in papers by William Boynton (University of Arizona) and the gamma-ray team, by William Feldman (Los Alamos National Laboratory) and others, and Igor Mitrofanov (Russian Space Research Institute) and others.

References:

Boynton, W. V. and others (2002) Distribution of hydrogen in the near-surface of Mars: Evidence for subsurface ice deposits. Published online May 30 2002; 10.1126/science.1073722 (*Science Express Reports.)* Author list

Feldman, W. C. and others (2002) Global distribution of neutrons from Mars: Results from Mars Odyssey. Published online May 30 2002; 10.1126/science.1073541 (*Science Express Reports.)* Author list

Mitrofanov, I. and others (2002) Maps of subsurface hydrogen from the high-energy neutron detector, Mars Odyssey. Published online May 30 2002; 10.1126/science.1073616 (*Science Express Reports.)* Author list

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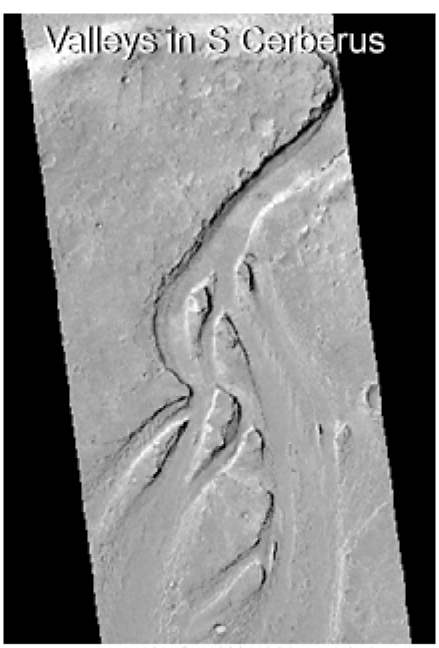
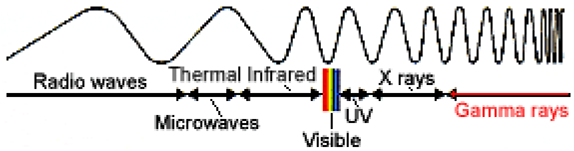


NASA/JPL/MSSS MOC image M21-01914

Where Has All the Water Gone?

The surface of Mars has been sculpted by water. There are vast networks of valleys carved by flowing water (see example at left in S. Cerberus, 206° W, 8° N; click image for higher resolution options.) Immense channels were scoured by water gushing at hundreds of millions to a billion cubic meters per second. Some channels flow into craters and other depressions, forming smooth, flat deposits interpreted as former lakes. [See **PSRD** article: For a Cup of Water on Mars]. Some lava flows show strong evidence of interaction with subsurface ice [See **PSRD** article: If Lava Mingled with Ground Ice on Mars]. The striking fluidized ejecta surrounding many Martian impact craters may indicate that the target contained ice or water that volatilized during the impact, creating a runny debris flow that surged outwards from the growing crater. Some gullies apparently formed by wet debris flowing down steep slopes. Because the debris covers wind-blown deposits, they might have formed quite recently. An ocean might even have covered the northern plains of Mars. [See **PSRD** article: Outflow Channels May Make a Case for a Bygone Ocean on Mars].

All this evidence points to a leading role for water in carving the Martian surface. But there are no rivers, lakes, oceans, or even puddles now. Where did all that water go? Most studies suggest much of it is deep underground. Some is trapped in mineral grains. For example, the Viking landers indicated that the soil contains about 1% chemically bound water. Estimates of how much water is underground vary, ranging from an amount that could cover all of Mars to a depth of 10 meters to as much as 1.5 kilometers. Most expert guesses come in around a few hundred meters. We need some direct measurements on how much water there is underground, but there have not been any direct measurements of the amount of water in the subsurface--until now. The Odyssey gamma-ray spectrometer suite of instruments analyzed the amount of water in the upper meter or so.



Gamma-Ray and Neutron Eyes

Mars is continuously bombarded with cosmic rays, which are mostly high-energy protons. The protons interact with the surface, causing assorted nuclear reactions. The reactions produce neutrons, which collide with surrounding nuclei. The nuclei become excited, and emit gamma rays as they return to their original, humdrum state. Gamma rays are a form of electromagnetic radiation; they have the shortest wavelength and highest energy. The gamma rays are characteristic of specific nuclear interactions in the surface, so measuring their intensity and wavelength allow a measurement of the abundance of several elements. One of these is hydrogen, which has a prominent gamma ray emission at 2.223 million electron volts (a measure of the energy of the gamma ray). This can be measured from orbit with the Gamma-Ray Spectrometer (GRS for short).

The neutrons start out with high energies, so they are called fast neutrons. As they interact with the nuclei of atoms in the surface the neutrons begin to slow down, reaching an intermediate range called epithermal neutrons. The slowing-down process is not too efficient because the neutrons bounce off many nuclei without losing much energy (hence speed). However, when neutrons interact with hydrogen nuclei, which are about the same mass as neutrons, they lose considerable energy, becoming thermal, or slow, neutrons. (The thermal neutrons can be captured by other atomic nuclei, which then can emit additional gamma rays.) The more hydrogen there is in the surface, the more thermal neutrons relative to epithermal neutrons. Many neutrons escape from the surface, flying up into space where they can be detected by the neutron detector on Mars Odyssey. The same technique was used to identify hydrogen enrichments, interpreted as water ice, in the polar regions of the Moon.

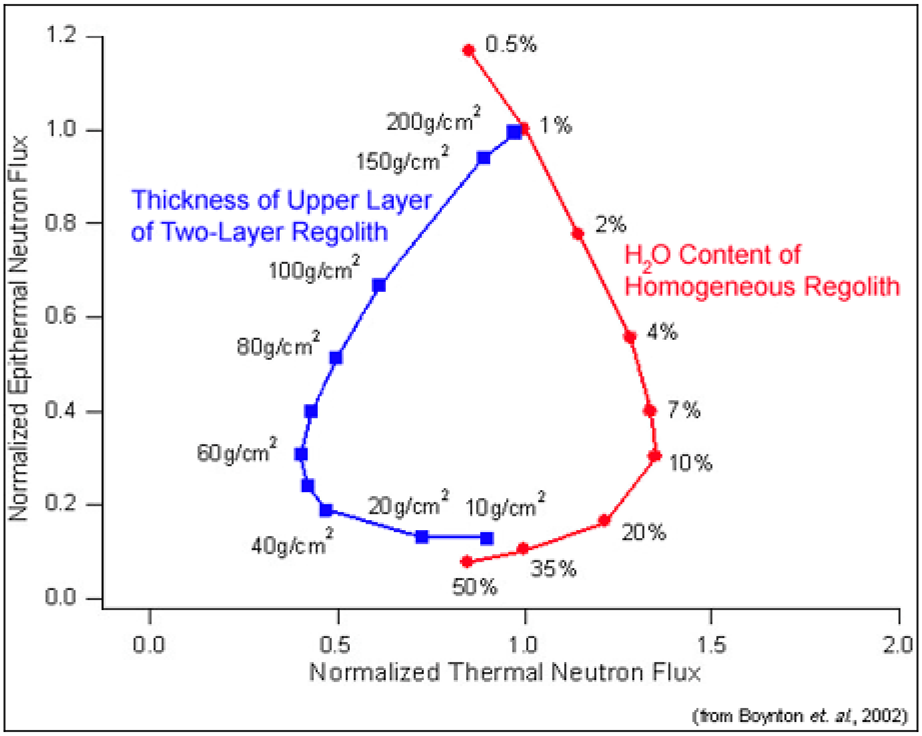
A Huge Amount of Hydrogen

The Odyssey GRS did not detect much hydrogen in equatorial regions during the initial two months of measurements. It's winter in the northern hemisphere of Mars, so the ground in high northern latitudes is still blanketed by carbon dioxide frost, which obscures the signal from hydrogen. The southern hemisphere tells a different story. As we move from about -45^{o} the hydrogen signal from the GRS increases steadily toward the South Pole. This is accompanied by a steady decrease in epithermal neutrons, which is also consistent with the presence of hydrogen.

The GRS team had to convert the count rates of gamma rays and neutrons to the abundance of hydrogen. This is not a simple task because the relationship between concentration and gamma-ray signal is complex. It depends on whether hydrogen is distributed uniformly in the upper meter or so. To figure this out the U.S. members of the team used a computer program developed at Los Alamos National Laboratory to calculate the expected neutron and gamma-ray signals from surfaces with one or two layers with a variety of water (hence hydrogen) contents. This required some assumptions. A central one is that the bulk chemical composition of the soil is the same as the dirt measured at the Mars Pathfinder landing site. It also requires calibrating the measurements. That is not completely done as yet, so the GRS team normalized the data to 1 wt% H_2O at the Viking landing sites, which are in equatorial regions.

The calculations show that if the Martian surface layer, called the regolith, has H_2O uniformly distributed, the flux of thermal neutrons escaping from the surface increases as epithermal neutrons decrease. This inverse correlation holds until H_2O reaches about 10 wt%, at which point the thermal neutron flux decreases as the epithermal neutron flux decreases. The switch in behavior happens because hydrogen is such a strong moderator of neutron energy that when there's too much of it lots of the thermal neutrons are captured.

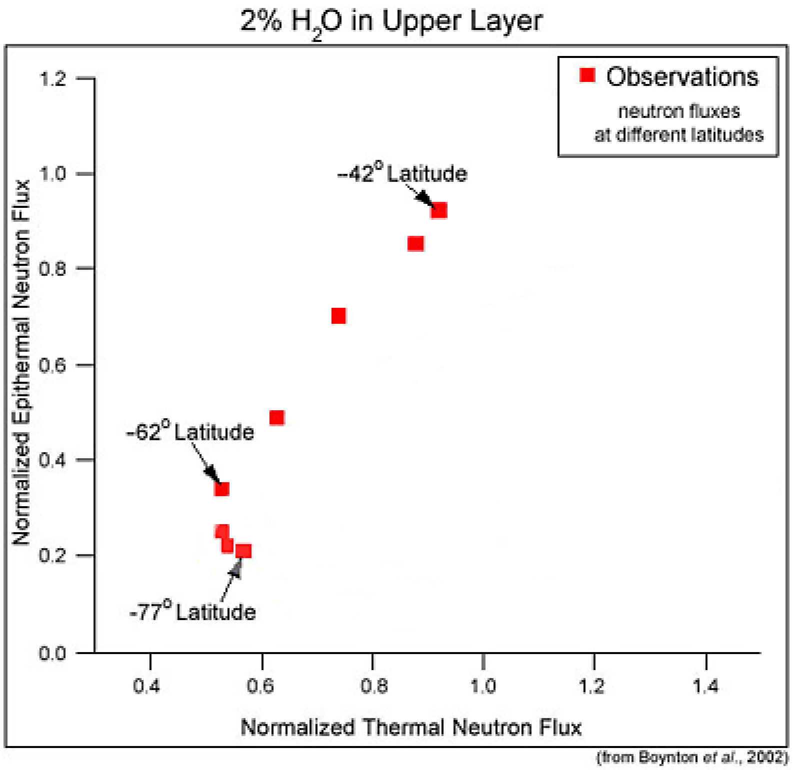
If the regolith is layered, with a hydrogen-poor layer overlying one rich in hydrogen, the effect on the neutron flux is quite different. For a given water content in the upper and lower layers, as the thickness of the upper layer decreases, both the epithermal and thermal neutron fluxes decrease, until the upper layer becomes quite thin, less than about 20 cm. At that point, the thermal neutron flux increases rapidly as the epithermal flux slowly decreases. The Odyssey data show a correlated decrease in both epithermal neutrons and thermal neutrons, suggesting that the regolith is layered.



Calculated flux of epithermal vs. thermal neutrons for two cases. In one (right hand curve) the regolith is homogeneous, with the amount of H_2O indicated on the curve. In the other (left curve) case the regolith is layered, with an upper layer containing 1 wt% water and the lower layer containing 35 wt%. The numbers along the curve represent the thickness of the upper layer, expressed in grams per square centimeters, which is roughly the same as the depth in centimeters if the density of the regolith is 1 g/cm^3.

Physicists like to express thickness in grams per square centimeter, g/cm^2. That's because they study the flux coming out from each square centimeter of the surface. To convert to depth, you divide by the regolith density. For example, suppose the depth is 60 g/cm^2. A reasonable density of the regolith, based on measurements by the Viking landers, is about 1 to 1.3 g/cm^3 (grams per cubic centimeter), which is mineral and rock grains with a lot of void space. Dividing 60 g/cm^2 by 1 g/cm^3 gives a depth of 60 cm. So, for the Odyssey results, as a rough rule of thumb, the depth in g/cm^2 is the same as the depth in centimeters.

The GRS team calculated the variation of epithermal and thermal neutrons for several cases. They used water contents in the upper layer of 1 or 2 wt% and water contents in the lower layer of 10, 20, 35, and 50 wt%. They also made the calculations for the thickness of the upper layer of 10 to 200 g/cm^2. They compared the curves produced to the data obtained by the GRS onboard the Odyssey spacecraft. The data (red squares in the diagrams below) vary in the way we expect them to for a layered surface. The data for high latitudes (-62^o to -77^o) match the calculations for a lower layer containing 35 wt% H_2O. The match is not as good for higher latitudes for the case shown below (2 wt% H_2O in the upper layer), but matches much better if the upper layer contains only 1 wt% H_2O (not shown in the diagrams below). This suggests that the amount of H_2O in the upper layer might increase with latitude.



Move your cursor over the buttons below to view curves that represent calculated neutron fluxes with the same H_2O content in the lower layer (10%, 20%, 35%, or 50%) of a two-layer model assuming 2% H_2O in the upper layer.

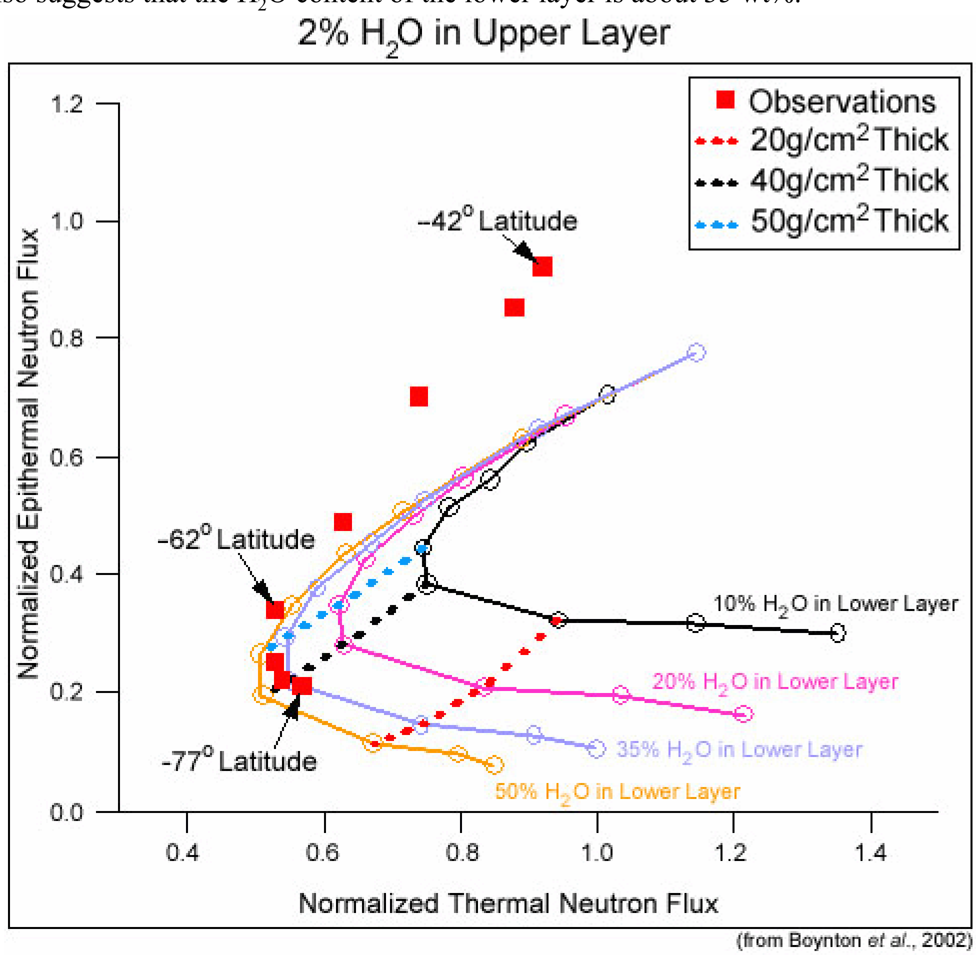
10% H_2O in Lower Layer

20% H_2O in Lower Layer

35% H_2O in Lower Layer

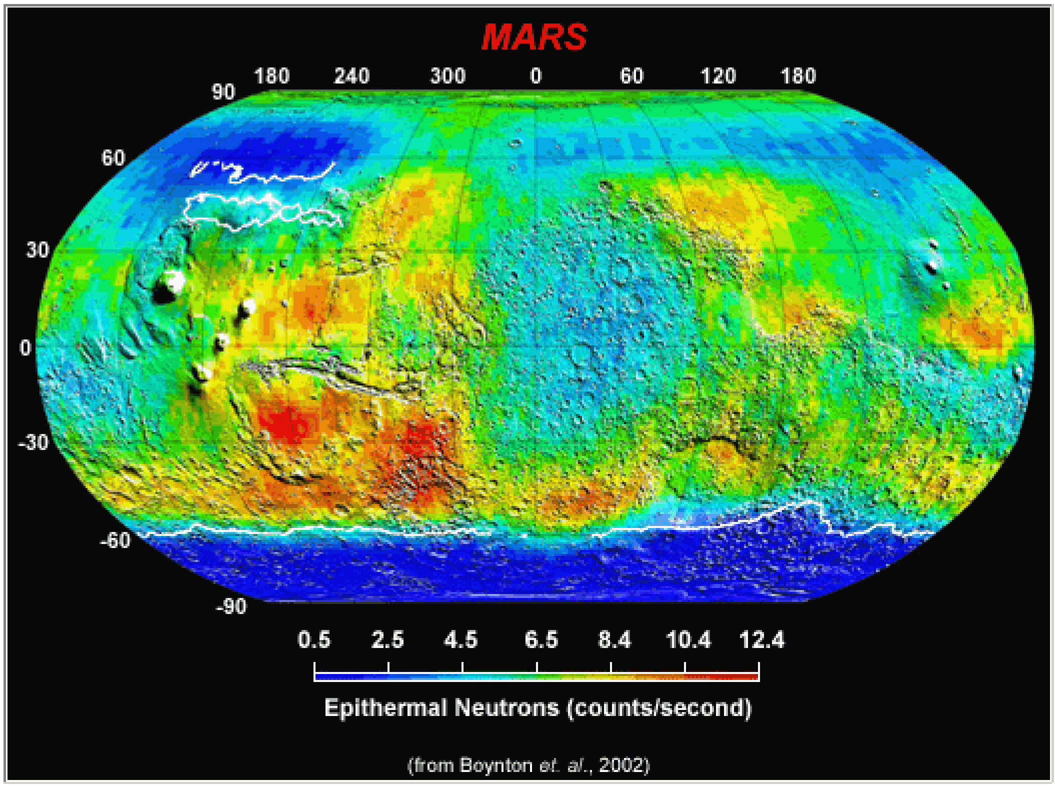
50% H_2O in Lower Layer

The dashed lines in the diagram below connect points on the curves corresponding to the indicated thickness of the upper layer. The correspondence with the measured data points between -62° and -77° suggests that the upper layer decreases in thickness toward the South Pole. A similar analysis can be made using the thermal neutron flux and the intensity of the hydrogen gamma-ray line. This also suggests that the H_2O content of the lower layer is about 35 wt%.

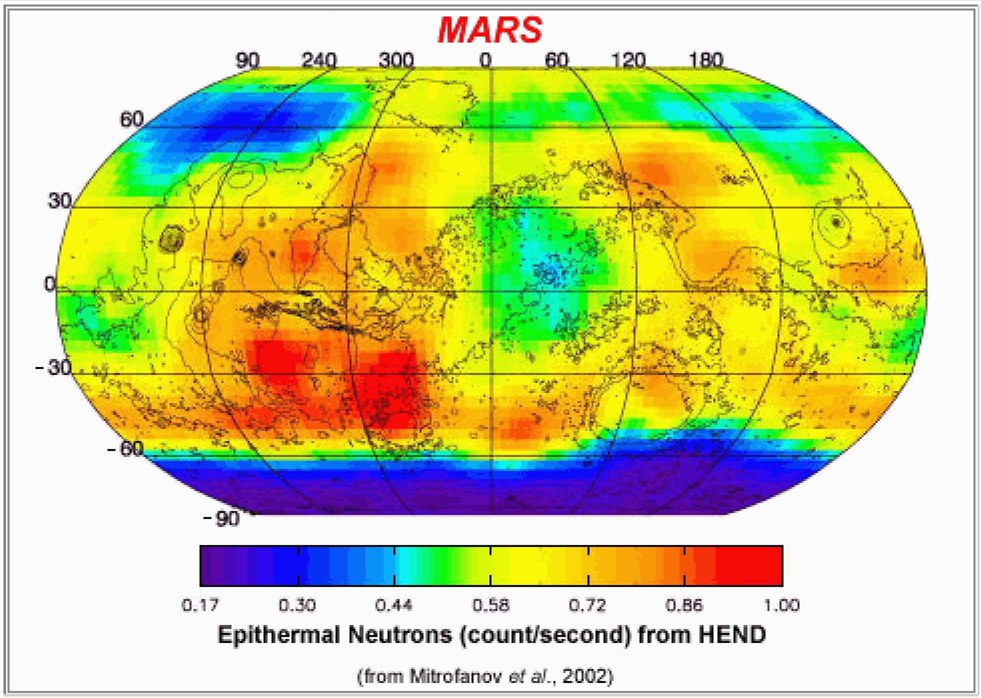


Calculated thermal and epithermal neutron fluxes compared to data measured by the Odyssey instruments (red squares). The best match at high latitudes (-62° and higher) occurs at 35 wt% H_2O. Considering all uncertainties, the Odyssey GRS team believes that H_2O is in the range 20 to 50 wt %.

The ice-rich regions are found only where it is cold. This is consistent with calculations that predicted where ice should be stable beneath the Martian surface. The map of epithermal neutrons (below) shows where the flux is low, hence H_2O is high. Measurements by the High Energy Neutron Detector (HEND) are consistent with this inference. The HEND insturments measured the distribution of epithermal and fast neutrons as well. It detected a deficiency of high-energy neutrons in the southern region., again indicating the presence of ice. The HEND team in Russia independently studied the structure of the near-surface layers and also concluded that it probably consists of an upper layer of regolith with about 5 wt% H_2O that covers a lower layer with a much higher percentage of H_2O. The icy areas correspond to places where Michael Mellon and Bruce Jakosky predict that ice occurs within 80 cm of the surface (white lines on the map below).

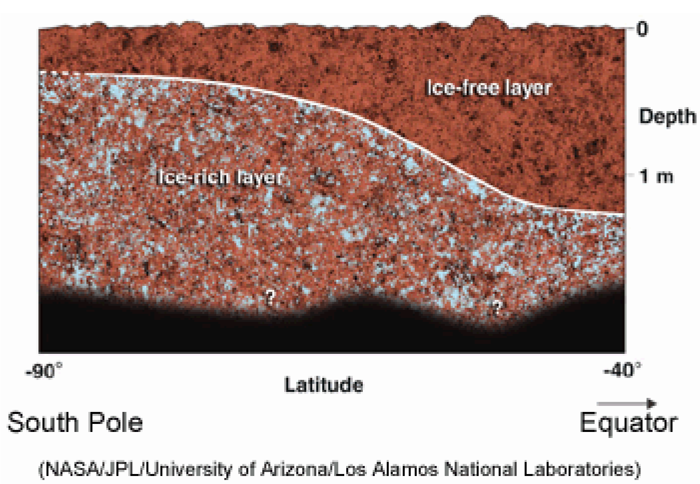


Map of the epithermal neutron flux measured by the Neutron Spectrometer on Mars Odyssey (click for higher resolution option.) Low levels indicate the presence of high hydrogen concentration, interpreted as H_2O or (especially for areas with higher epithermal neutron flux) as H_2O or OH^- bound in minerals. Note the high concentration of hydrogen south of -60° latitude. Theoretical calculations predict that these regions would have ice within 80 cm of the surface.



Map of the epithermal neutron flux measured by the High Energy Neutron Detector on Mars Odyssey (click for higher resolution option.) Low levels indicate the presence of high hydrogen concentration, interpreted as H_2O or (especially for areas with higher epithermal neutron flux) as H_2O or OH^- bound in minerals. Note the very good consistency of independent measurements made by the Neutron Spectrometer (map above) and HEND instruments. Theoretical calculations made by the HEND team predict that southern regions would have ice below 60 cm of the surface.

The correspondence between the GRS data and the calculations is good, though not perfect. This suggests that the H_2O is not distributed in two uniform layers with a sharp boundary between them. Nevertheless, the conclusion that the regolith beneath 20 to 40 cm contains 35 wt% H_2O is completely consistent with the data. This corresponds to a lot of ice. Because the density of ice (0.9 g/cm^3) is much less than that of mineral grains (about 2.5 g/cm^3), 35 wt% ice corresponds to 60% ice by volume. It is dirty ice, not soil with ice in it. Some of the hydrogen might be sequestered in hydrous minerals, but most minerals do not contain such a large abundance of either H_2O or other hydrogen molecules (such as OH^-).



This diagram summarizes the interpretation made by the Odyssey GRS team. An upper, ice-poor layer overlies one rich in ice. Thickness of the ice-poor layer decreases to the south, to as low as about 20 centimeters. Even at -40°, the ice-rich layer might not be too much more than a meter below the surface.

Climate History, Surface Processes, and Martian Settlers

As noted above, estimates of the amount of water on Mars center on a quantity equivalent to a global layer a few hundred meters thick. The Odyssey results cannot address how much water could be present beneath the one-meter depth in which the gamma rays and neutrons are produced. The whopping amount of water is certainly consistent with the idea that the upper kilometer or so of the Martian regolith might be a substantial reservoir of Martian water.

The astonishing new discovery lies in the amount of ice and in the inferred pore space in the regolith. Pore space is simply the amount of empty space between solid, rocky grains. The pore space might have been produced by condensation of carbon dioxide frost in the winter. The condensing CO_2 would contain tiny grains of dust. When the CO_2 evaporated in the spring, it would leave behind a fluffy deposit of dust. Over time this fluffy, highly-porous deposit might occupy the upper meter of the regolith, providing a medium in which atmospheric water could condense as ice. If the water has been deposited by vapor exchange with the atmosphere, it holds clues to Martian climate. It may allow us to understand the atmospheric water cycle on Mars and perhaps even the history of the climate. This science story is just beginning.


NASA painting by Pat Rawlings

Understanding the climate history of Mars and the details of the deposition of ice in the upper meter will require more observations from Odyssey and future missions, but we do know something very important right now: Ice is very close to the surface in some places on Mars. This has enormous implications for human exploration and settlement of the planet. Although water can be extracted from hydrated minerals anywhere on Mars, it is much easier and cheaper to dig up some dirty ice, melt it, filter it, and use it. Water is essential for human life, for use in agriculture, and for converting into hydrogen and oxygen for fuel. There is a vast supply of water sitting within a meter of the surface for use by Martian settlers.

The surprising results reported by the GRS team show how our knowledge leaps when we make measurements in new ways. Orbital remote sensing measurements of Mars have been made in visible, near infrared, and thermal infrared wavelengths. Extending the measurements to gamma rays and neutrons has opened up new vistas for understanding the geological history of Mars.

Additional Resources

2001 Mars Odyssey homepage.

2001 Mars Odyssey Gamma Ray Spectrometer homepage.

Boynton, W. V. and others (2002) Distribution of hydrogen in the near-surface of Mars: Evidence for subsurface ice deposits. Published online May 30 2002; 10.1126/science.1073722 (*Science Express Reports.)* Author list

Feldman, W. C. and others (2002) Global distribution of neutrons from Mars: Results from Mars Odyssey. Published online May 30 2002; 10.1126/science.1073541 (*Science Express Reports.)* Author list

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psrd@higp.hawaii.edu