Polar Hydrogen Deposits on the Moon

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Abstract. Neutron and gamma-ray data measured using the Lunar Prospector spectrometers were analyzed to define the enhanced hydrogen deposits near both poles of the Moon. Combining the new low-altitude neutron data (30±15 km) with previous high-altitude (100±20 km) neutron data and the results of several recent radar investigations, sharply constrains the characteristics of each of the polar deposits. The deposits at the north appear to be in the form of many small pockets or of generally-distributed hydrogen that average to a 100 ppm weight fraction enhancement over that which exists in regolith at more equatorial latitudes. Those deposits in the permanently-shaded craters near the south pole are consistent with a thick FAN regolith containing an enhancement of 1670±890 ppm hydrogen, which if in the form of water ice, amounts to 1.5±0.8% weight fraction of H_2O. Neutron data alone cannot discriminate between hydrogen implanted in lunar soil from the solar wind, hydrated minerals, or H_2O. These craters appear to be surrounded by regolith that either contain small pockets of enhanced

hydrogen, or is soil that is uniformly impregnated with hydrogen enhanced on average by about 100 ppm above that contained in soils at more equatorial latitudes.

Introduction

Excess deposits of hydrogen at both poles of the Moon in the form of frozen water ice have been postulated by Watson et al. [1961] and Arnold [1979]. Water is thought to have been delivered to the Moon over aeons through multiple impacts with comets, meteorites, interplanetary dust, and perhaps infrequent encounters with the cores of galactic giant molecular clouds (GMCs) [Weissman, 1989]. It can also arise through reduction of metal oxides in soils at nearly all latitudes by hydrogen of solar wind origin. After delivery, the water migrates to cold traps on the lunar surface (see, e.g. Butler [1997], and references therein). Within those parts of the traps that are sufficiently cold, the ice can be stable to loss by sublimation for billions of years (see e.g., Vasavada et al. [1999], and references therein). However, other loss mechanisms besides sublimation may also be important, such as ablation by micrometeorite bombardment, irradiation by H Lyman α, and sputtering by energetic particles [Arnold, 1979; Morgan and Shemansky, 1991; Lanzerotti et al., 1981]. Until recently, analyses of a diverse set of observations of conditions within the inner solar system have not been sufficiently definitive to allow a decision as to whether the rate of delivery of water to the Moon is larger or less than the rate of its loss.

Scientific interest in the answer to this question rests on the record of the small-body population history of the inner solar system that would be provided by such deposits, if they exist. Impacts of these bodies with all planets are thought to figure importantly in the origin and evolution of planetary atmospheres (see e.g., Weissman [1989], and references therein). Because deposition of volatiles is expected to be episodic, superimposed on a more nearly constant accumulation, loss, and burial rate, one may expect to find several overlying, but distinctive horizons of water ice. Deposits in the various horizons might have differing water-ice mass fractions and, perhaps, isotopic signatures that would provide clues as to what type of source delivered each deposit and where they came from. For example, a comet having diameter larger than about 20 m could produce a temporary, collisionally-thick atmosphere [Vondrak, 1974] that may produce a nearly pure ice deposit having thickness that depends on the amount of water brought to the Moon by the comet. Perhaps a recent impact of Mercury by a reasonably sized comet [Vasavada et al., 1999] was responsible for the nearly pure water-ice deposits inferred to reside within several craters near both Hermean poles [Slade et al., 1992; Harmon and Slade, 1992; Butler et al., 1993]. In contrast, encounter with smaller comets, asteroids, interplanetary dust grains, and the core of a GMC, would migrate water molecules to polar cold spots at such a low rate that resultant deposits would be mixed with regolith, churned up by continuous low-level micrometeorite bombardment.

Several attempts have been made recently to resolve the issue of lunar water ice experimentally using the bistatic radar technique. This technique is sensitive only to rather pure deposits of water ice because it requires multiple (volume) scattering without absorption. Although an initial analysis of Clementine radio data seemed to indicate a positive detection of water ice near the south pole of the Moon [Nozette et al., 1996], a more detailed analysis of these same data [Simpson and Tyler, 1999] yielded sufficient ambiguity to question their interpretation in terms of water ice. In fact, other experiments using Earth-based radar having better spatial resolution and viewing geometry indicate that the weak signature seen by Clementine originated in sunlit areas near the south pole [Stacy et al., 1997], and similar signatures were observed far from the pole where water ice cannot be stable. The conclusion reached by the radar community is that if water ice deposits exist near the lunar poles, it cannot have a high purity, otherwise it would have been seen within those permanently shaded locations that can be probed from Earth [Stacy et al., 1997; Harmon, 1997; Simpson and Tyler, 1999].

Another attempt to detect and identify water ice near the lunar poles was made using Lunar Prospector (LP) neutron data [Feldman et al., 1998a]. This technique is sensitive to hydrogen regardless of its chemical association and purity. Inference of deposits of water ice therefore requires additional information and related arguments. Nevertheless, enhanced abundances of hydrogen were observed in epithermal (intermediate energy) neutrons at both poles during the high-altitude (100±20 km) portion of the Lunar Prospector mission. However, the signature expected for a high hydrogen abundance deposit in fast neutrons ($0.6 \text{ MeV} < E < 8 \text{ MeV}$) was not observed at the 1% detection threshold. Within the limits of the 190 km full width at half maximum (FWHM) spatial resolution of the LP epithermal neutron spectrometer at 100 km altitude, the observed hydrogen enhancements seemed to contain localized hot spots that argue for at least some of the deposit to be in the form of water ice. The lack of an observed signature in fast neutrons, coupled with a large uncertainty in the area of permanent shade at both poles [Spudis et al., 1994; Shoemaker et al., 1994] prevented an accurate quantitative estimate of the amount of hydrogen at either pole from these data.

Since the time of data cutoff for the study reported in Feldman et al. [1998a], more data have been accumulated in the 100±20 km altitude LP orbit and, more importantly, the altitude of LP has been lowered in two steps to 30±15 km. This lower orbit affords a higher sensitivity to smaller deposits by an order of magnitude in area, thereby allowing a more sensitive and definitive characterization of the nature of the enhanced hydrogen deposits at both poles. In addition, a new estimate of area in permanent shade poleward of ±87.5^o has been published recently [Margot et al., 1999]. As will be shown, knowledge of this area removes a large ambiguity in interpretation of the LP epithermal neutron data. We make use of both these improvements to revisit the lunar polar-ice problem. We find that a definitive signature of enhanced hydrogen is now visible in fast neutrons at the south pole but not yet at the north pole. In addition, the signature in epithermal neutrons is now more prominent in the south and remains nearly unchanged in the north. Both results argue for many spatially unresolved small deposits of enhanced hydrogen in the north, but larger area concentrations in the south that are, perhaps, surrounded by terrain containing many spatially unresolved deposits. Simulations of both the epithermal and fast neutron measurements in the south using the radar estimates of area within permanently shaded craters [Margot et al., 1999], indicates that a significant amount of the hydrogen observed in LP neutron data is consistent with dirty water ice containing 1.5±0.8 % by weight equivalent of water. The topmost surface of this water must be within about 10 g cm^{-2} of the lunar surface. However, these data cannot discriminate between a 1.5 % admixture of water ice and dry soil containing 1670±890 ppm by weight of hydrogen.

Simulations of Neutron Signatures of Hydrogen

Neutrons are generated in all solar system bodies by galactic cosmic rays (GCRs) through reactions with the nuclear constituents of near-surface (within several hundred g cm^{-2}) material. These neutrons are produced at fast neutron energies (greater than several hundred keV) and then scatter down to lower energies through multiple elastic and inelastic collisions. An equilibrium flux energy distribution is quickly established, which reflects the balance between the rate of neutron production at high energies, their energy loss through the intermediate (or epithermal) energy range, and their absorption at thermal energies. Their rate of production is determined mostly by the incident flux of GCRs and less importantly by the relative abundances of certain elements such as Fe and Ti [Gasnault et al., 1999]. Their rate of energy loss is determined mostly by the abundance of hydrogen (because it alone has a mass equal to that of a neutron and has an unusually large cross section for elastic scattering at epithermal energies), and their rate of absorption is determined mostly by the relative abundances of Fe, Ti, Gd and Sm [Lingenfelter et al., 1972]. Because the rates of production and absorption are fixed, the intensity of the neutron flux spectrum at intermediate energies is determined by the rate of energy loss through collisions from the energy range where they are born (fast) to the range where they die (thermal). The more hydrogen that is present, the faster is the rate of energy loss, which establishes a reduced flux of epithermal neutrons. Although the cross section for elastic scattering on hydrogen decreases with increasing energy, it is sufficiently high within the fast-neutron energy range that the flux of fast neutrons is also reduced (but to a lesser extent). Isolated deposits of enhanced hydrogen can therefore be recognized by a local reduction in the flux of epithermal and fast neutrons. The relative magnitudes of these reductions provides information about the size, hydrogen abundance, and/or stratigraphy of the deposit.

Three main characteristics of hydrogen deposits affect their detectability by neutrons from orbit; 1) area, 2) weight fraction, and 3) burial depth. We present a quantitative survey of their effects on measured counting rates using the several components of the Lunar Prospector neutron spectrometer (LPNS). A description of this spectrometer along with some preliminary results has been given in the literature [Feldman et al., 1998a,b; 1999]. More details regarding the efficiency for detection of neutrons in the three energy bands (thermal, epithermal, and fast), as well as intercorrelations among the three measured flux components imposed by the moderation process, will be given in a separate study.

A result of this separate study [Feldman et al., in preparation, 1999] is that the measured flux of epithermal neutrons is marginally, although measurably sensitive to elemental composition other than to hydrogen. This sensitivity can be minimized by subtracting a small fraction of the thermal flux from the epithermal flux. For those parts of the Moon that do not contain significant amounts of hydrogen (which is most of the Moon), best correspondence with simulations (which are normalized to the number of fast neutrons produced in each GCR-induced nuclear cascade) can be achieved by constructing a quantity, $\text{Epithermal}^{\#}/\text{Fast}$ = (Epithermal - 0.222 x Thermal)/Fast [Feldman et al., in preparation, 1999]). However, where hydrogen is present (which we are searching for within the permanently shaded craters near both lunar poles), division by the fast flux reduces our sensitivity to hydrogen, removes information, and introduces statistical noise. We resolve this problem by choosing the quantity, Epithermal^{*} = (Epithermal - 0.07 x Thermal) instead, which minimizes the width of the Epithermal neutron histogram of global lunar measurements [Feldman et al., 1998b]. It turns out that this quantity provides less sensitivity to composition other than hydrogen than does the $\text{Epithermal}^{\#}/\text{Fast}$ quantity. We therefore use it exclusively in this paper, and shorten its name to Epi^{*}.

Variation With Area: Percent depressions in counting rate of epithermal and fast neutrons by the LPNS at 30 km altitude for deposits having circular areas that range between 100 km^2 and 10^4 km^2, are shown in Figures 1a and 1b, respectively. The Boltzmann-transport code, ONEDANT [Alcouffe et al., 1995], coupled with outward lunar gravitational boundary conditions [Feldman et al., 1989], was used for this purpose. The composition of the deposits is assumed to be a mixture of ferroan anorthosite (FAN) and either 1%, 3% or 10% by mass of H_2O. These deposits are surrounded by FAN that contains no H_2O and that covers the rest of the Moon. Inspection of the curves in Figure 1 shows that the magnitude of the detected signature (the percent reduction in counting rate from that calculated for the water-free background) increases with increasing area. The magnitude of the effect is also seen to; 1) be strongest in epithermal neutrons, 2) increase with increasing admixture of H_2O, 3) increase more quickly for the fast neutrons than for the epithermal neutrons as a function of weight-percent H_2O, and yet 4) maintain the same ratio (vertical offset in the figure) of effect as a function of area for a given neutron component and admixture of H_2O. Translation of these curves to a detection altitude of 100 km requires multiplication of the area axis by a factor of $(100/30)^2 = 11.1$. The percentage decrease in counting rates shown in Figure 1 are higher than that expected for an equal, but non-contiguous area in the sensor field of view because the detection efficiency of the LPNS decreases with increasing angular separation from the spacecraft nadir.

Variation With Percentage Weight of H_2O: Results of the previous simulations showed that the signature of enhanced hydrogen deposits is very sensitive to assumed area. The effect increases by 1.5 orders of magnitude for areas that range between 100 km^2 and 10^4 km^2. To make progress, we therefore have to choose a reasonable distribution of areas over the surface. We accomplish this goal by adopting the estimate of areas in permanent shade near the lunar south pole made from the topography measured using the Goldstone Solar System Radar [Margot et al., 1999]. Although the terrain near the south pole contains many small, isolated areas of permanent shade, the total such area is dominated by five craters, whose coordinates and estimated diameters are given in Table I. Two estimates for the three largest craters are listed. A check with J.-L. Margot (private communication, 1999) indicates that our high diameter estimates average about 10% higher in area than that determined directly from the radar data. Our low estimate yields an area that is 75% that of our high-area estimate. Percent reductions in simulated counting rates for Epi^* and Fast neutrons as a function of the weight percent admixture of H_2O to FAN within these craters, are shown in Figures 2a and 2b, respectively. Separate curves are given for a spacecraft positioned above the south pole at 30 and 100 km altitude. Here again, these craters are assumed to be surrounded by a planet-wide, hydrogen-free regolith having a FAN composition. Inspection shows that the percent decrease in detected signal increases with increasing weight percent of H_2O for both Epi^* and Fast neutrons. The effect is larger for the Epi^* neutrons and increases with decreasing spacecraft altitude.

Most of the depression in Epi^*, and Fast-neutron counting rates comes from the largest crater, which is not named but is located at 88.1^o South latitude and 45^o East longitude. As will be shown later, the strongest signature of enhanced hydrogen is detected when the LP spacecraft is directly above this crater. Also shown will be that the general area that surrounds the pole has an enhanced hydrogen abundance that, if it is distributed uniformly over an area that is larger than the instrument field of view, amounts to about 100 ppm hydrogen. Because this amount is over and above what exists at more equatorial latitudes (determined by analyses of returned samples to average about 50 ppm hydrogen see e.g., Haskin and Warren [1991], and references therein) this more uniformly distributed background amounts to an equivalent of about 0.14 % H_2O. We approximated these conditions by simulating the percentage decrease from an assumed background containing 0.1% H_2O in detected counting rate when the spacecraft is centered on the unnamed crater at -88.1^o latitude and $+45^o$ longitude, at an altitude of 30 km.

Only the largest three craters listed in Table I were included. These simulations are shown in Figures 3a and 3b for Epi* and Fast neutron counting rates, respectively. Two estimates of the diameters of ice deposits within these craters (which bracket those estimated by Margot et al. [1999]), are used (see Table I). Inspection of Figures 3a and 3b shows that the predicted reduction in Epi* and Fast counting rates is slightly larger than those predicted for the five craters that surround the south pole and shown in Figures 2a and 2b. They also show a decrease with decreasing crater diameter (amounting to an areal ratio of 0.75) in accord with the area simulations shown in Figures 1a and 1b.

Variation With Burial Depth: Results of simulations for the percent decrease in predicted counting rates for Epi* and Fast neutrons as a function of thickness of overlying relatively dry (assumed to contain 0.1% H_2O) FAN soil (or burial depth), are shown in Figure 4. Separate simulations for the two sets of assumed crater diameters listed in Table 1 are included. Inspection shows that the signature of hydrogen decreases faster with increasing depth in fast neutrons than in Epi* neutrons. This result stems from the reduced cross section for elastic scattering of neutrons as a function of increasing energy. In effect, the cross section for elastic scattering is so large in the epithermal energy range (about 20 barns) that a discrete layer of enhanced hydrogen wicks up neutrons from surrounding layers, thereby reducing their flux intensity in the surrounding layers [Feldman et al., 1993]. This reduction translates into a reduced leakage flux from the lunar surface even though the layer of enhanced hydrogen is buried a considerable distance. We note though, that the effect for both Epi* and Fast neutrons is small for burial depths less than about 10 g cm^{-2} (or 5 cm at an assumed density of 2 g cm^{-3}). It also seems to be nearly independent of assumed crater diameters. The observed reduction in neutrons of any energy falls below 1% for burial depths greater than 200 g cm^{-2} (which is equivalent to 100 cm at a density of 2 g cm^{-3}).

Lunar Prospector Results

Neutrons: Because a quantitative interpretation of LP Epi^* and Fast neutron counting rates in terms of the simulations just presented, requires a spatially uniform composition (assumed here to be FAN) we test for composition variations poleward of $\pm 75^o$ using measured gamma-ray spectra and the known composition-dependent correlation between (Epithermal/Fast) and (Thermal/Fast) neutrons mentioned earlier [Feldman et al., in preparation, 1999]. Starting first with gamma rays, pulse height spectra were summed over longitude within nested latitude ranges centered on the north and south poles. The resultant spectra, offset vertically from one another for clarity, are shown for the north and south poles in Figures 5a and 6a, respectively. We note that all spectra have closely similar shapes. This fact is demonstrated more clearly by plotting difference spectra between those accumulated within 5^o of either pole, and those accumulated in succeeding 5^o-wide latitude annuli centered on each of the poles, respectively. These difference spectra are shown in Figures 5b and 6b. The lack of any significant structure in the difference spectra confirms our conclusion that both polar caps have closely homogeneous compositions.

A more sensitive test for homogeneity can be made using the three measured spectral components of neutrons. Correlations between the (Epithermal/Fast) and (Thermal/Fast) neutron counting rates poleward of $\pm 85^o$ and$\pm 80^o$, are shown in Figures 7 and 8, respectively. Inspection of Figure 7 shows no credible correlation in the north (Figure 7a) or the south (Figure 7b). We therefore conclude that both polar compositions are effectively uniform poleward of

±85^o. Although this is the case poleward of +80^o (as seen in Figure 8a), there appears to be a weak, but significant correlation poleward of -80^o (see Figure 8b). This result may reflect a small, but noticeable enhancement in the concentration of Fe within the South-Pole Aitken basin, identified by analysis of the Clementine infrared spectral reflectance data [Lucey et al., 1998]. However, the weakness of this correlation is such that a weakening of the hydrogen signature by using the Epi$^{\#}$/ Fast rather than the Epi* signature, outweighs the advantage in sensitivity gained by using the Epi* neutron counting rates in identifying and characterizing the polar hydrogen deposits near the south pole. We therefore proceed with an analysis of Epi* counting rates.

A map of the Epi* counting rates at a spatial resolution equivalent to a 2^o x 2^o latitude-longitude square at the equator is shown in Figure 9. This map overlies an airbrush rendition of the location of craters on the Moon. Inspection shows that the only significant concentration of low counting rates (magenta to dark blue colors) appears at both poles. Other occurrences of low rates appear as a salt-and-pepper pattern distributed randomly about the Moon. This result is shown graphically in Figure 10 by averaging the Epi* and Fast counting rates over 12, 2^o-wide polar bands, each separated in longitude by 15^o. The 'error' bars on successive 5^o latitude points give the standard deviations of variations encountered in each of the 12 samples at a given latitude. Inspection shows significant depressions at both poles in the Epi* counting rate and a significant depression in the Fast-neutron counting rate at the south pole but not at the north pole. A comparison of the low- and high-altitude data is shown in Figure 11. Whereas the percentage reduction in Epi* counting rate in the north is sensibly the same for both altitudes, it is larger at low altitudes in the south. Also the overlay of Fast-neutron counting-rate polar bands shows clearly that a significant effect exists at the south in the low-altitude data whereas it does not exist at high altitudes. Proof that these effects are real is shown in Figure 12 by the significant correlation between Epi* counting rates relative to their high-latitude mean and Fast counting rates relative to their mean, for each 2° x 2° equal-area pixel poleward of –85°. Whereas the correlation is significant in the south, poleward of -85° (R=0.82), it is not in the north (R=0.30).

Color-coded maps of low-altitude Epi* and Fast-neutron counting rates are shown in Figure 13. Starting first in the south, inspection of the Epi* map shows the deepest depression in counting rate overlies the three colinear craters near the south pole identified by Margot et al. [1999] as having large permanently shaded floors (see locations in Table I). An equally deep depression overlies the crater Cabeus near 84.5° South latitude and -38° East longitude. However, we also note that large areas near the south pole have depressed Epi* counting rates, indicative of generally distributed, enhanced hydrogen abundances. Although the depression in Epi* counting rates is generally larger at low altitudes than reported previously at high altitudes [Feldman et al., 1998a], the high and low altitude maps generally correlate very well as shown in Figure 14. We note, however, that the slope of the correlation south of -80° is significantly greater than 1, as shown in Figure 14b. This result is consistent with our interpretation of Figure 11a in terms of concentrations of hydrogen deposits near the south pole that have size scales that are comparable to the ~57 km FWHM spatial resolution of the LPNS at an altitude of 30 km.

Inspection of Fast-neutron counting rates near the south pole also shows depressed values that overlay the three colinear craters identified by Margot et al. [1999] and listed in Table I. Intercomparison of the Fast and Epi* maps poleward of about -85° provide a visual confirmation of the positive correlation seen in Figure 12. No such correlation was seen in the high-altitude data at the 1% significance level [Feldman et al., 1998a]. However, we also note depressed counting rates of fast neutrons dispersed throughout the south polar region equatorward of -85° that have no counterparts in the Epi* map. These relative minima, no doubt, reflect compositional variations as indicated by the positive (but weak) correlation between Epithermal/Fast and Thermal/Fast neutrons shown in Figure 8b. This observation underscores the fact that Fast-neutron fluxes alone cannot be used to uniquely identify hydrogen. Nevertheless, they can be used to support the observed Epi^* rates to help refine their characterization where a correlation is observed.

The map of Epi^* counting rates north of $+70^o$ shows a general concentration of hydrogen along the Moon-Earth meridian that is tilted away from the Earth. The overall pattern of Epi^* counting rates is very similar to that observed at high altitudes, as seen by the good pixel-by-pixel correlation shown in Figure 14a. We note though, that the slope of the correlation is only marginally greater than unity, which we interpret to indicate that most of the enhanced hydrogen deposits have size and separation scales that are smaller than our best spatial resolution, 57 km. The maximum concentration is centered at about 88^o North latitude and 160^o East longitude. This location overlies a region on the Margot et al. [1999] map that is marked by many small areas of permanent shadow. We note here, as in the south, the Epi^* counting rates are generally low over large areas near the north pole. A likely cause of this depression is a general enhancement of hydrogen (which may not be in the form of H_2O) at high northerly latitudes.

The map of Fast neutrons poleward of $+70^o$ is very different from that observed in the south. Its overall appearance in the north is a salt-and-pepper pattern that does not correlate well with the depressed counting rate pattern seen in Epi^* neutrons, as demonstrated in Figure 12b. Indeed, there is no evidence at the 1% significance level of any depression in the Fast-neutron counting rate that could be attributed to enhanced hydrogen deposits. This result is the same as was noted in the high-altitude data, and presented previously [Feldman et al., 1998a].

Gamma Rays: Another way to detect enhanced deposits of hydrogen is to look for enhancements in the flux of 2.22 MeV gamma rays, which result from the capture of thermal neutrons by hydrogen to form deuterium. This task is difficult to carry out with a Bismuth Germanate (BGO) scintillator such as flown aboard Lunar Prospector [Feldman et al., 1999]. The spectral resolution of BGO is not sufficiently good to resolve the deuterium gamma ray line from the far more copious fluxes of 2.0 to 2.2 MeV gamma rays emitted by aluminum, uranium, and the single 0.511 MeV escape peak of thorium. Indeed, preliminary global maps of detected 2.2 MeV gamma rays show a pattern that closely resembles thorium (see Lawrence et al. [1998, 1999] for maps of the 2.6 MeV thorium gamma-ray line). Nevertheless, we can look for local enhancements in detected fluxes at the north and south poles of the Moon where the Epi* and Fast neutrons show enhancements in hydrogen.

Gamma-ray pulse height spectra summed over longitude within nested latitude ranges centered on the north and south poles, were shown in Figure 5a and 6a. As noted previously, all spectra have closely similar shapes. Close inspection of the difference spectra shown in Figures 5b and 6b reveal no evidence for enhanced fluxes of 2.2 MeV gamma rays that would indicate the presence of enhanced abundances of hydrogen.

We can quantify this result by estimating the background from the statistics detected within 11 channels centered on 2.2 MeV (spanning 2.1 to 2.3 MeV). The counts plotted in Figures 5 and 6 give the counts registered in each 32 s spectral accumulation time. An average of 17450 spectra was summed for each of the eight latitude bands (the orbit of Lunar Prospector is polar so that the number of spectra in equal latitude bands summed over 360° in longitude, is the same). The result gives a standard deviation of background counts in accepted GRS spectra,

σ(Bckgd), that amounts to 0.146 counts per spectrum in the south and 0.142 counts per spectrum in the north.

These standard deviations can be compared with the counts-per-spectrum expected for assumed products of abundance and areal concentrations of hydrogen. We estimated the counts expected in each 32 s accumulation interval from; 1) the efficiency of the LPGRS (0.413 in the south and 0.285 in the north for detecting 2.22 MeV gamma rays [Lawrence et al., 1999]), 2) the flux of hydrogen capture gamma rays per mg/g of hydrogen, estimated from Table I of Reedy [1978], and 3) the field of view of the detector (half of all gamma rays detected at 100 km altitude were emitted from within a circle centered on the spacecraft nadir of 118 km radius [Reedy et al., 1973]). Equating the estimated counts per spectrum for a deposit having a weight-percent water abundance, W_{H2O}, distributed over an area of permanent shade, A_S (in km^2), to the standard deviation of background counts, σ(Bckgd), yields, $W_{H2O}\ A_S = 0.757\text{x}10^4$ in the south and $1.07\text{x}10^4$ in the north. Combining these lower limit detection thresholds with the estimated area of permanent shade poleward of $\pm 87.5^o$ from Margot et al. [1999], yields a water-ice weight-percent threshold that ranges between 3.4% and 1.9% in the south (corresponding to shaded areas between 2250 and 4000 km^2, respectively) and equal to 10.4% in the north (corresponding to a shaded area of 1030 km^2). Of course the threshold for detection would be larger if the water-ice deposits were buried under dry regolith because of Compton interactions within overlying material. They are certainly lower limits because systematic uncertainties were not included in the foregoing estimates. These lowest-limit estimates are collected in Table II.

Summary and Discussion

Summary: Fluxes of Thermal, Epithermal, and Fast neutrons, as well as of 2.22 MeV gamma rays measured using the Lunar Prospector neutron and gamma-ray spectrometers, were studied to search for water-ice deposits near the lunar poles. Although a preliminary study based only on high-altitude Lunar Prospector neutron data (altitude = 100±20 km) found conclusive evidence for enhanced deposits of hydrogen at both poles [Feldman et al., 1998a], sufficient data were not available to uniquely characterize them. The present study adds new LP neutron observations at lower altitudes (30±15 km) thereby affording improved spatial resolution and hence sensitivity to hydrogen, and gamma-ray observations from the higher-altitude orbit. We also make use of improved estimates of areas in permanent shade at both poles using recent results from the Goldstone Solar System Radar [Margot et al.,1999], which was not available for our previous study. These new data are now sufficient to constrain the characteristics of these deposits to scientifically meaningful values.

Significant depressions in a combination of Epithermal and Thermal neutron counting rates that minimizes sensitivity to all elements but hydrogen (denoted by Epi^* = Epithermal - 0.07xThermal), were observed at both poles, and were observed in Fast neutron counting rates at the south pole. Such depressions are known from simulations to uniquely identify enhancements in the abundance of hydrogen. No depressions were observed in the Fast neutron fluxes near the north pole at about the 1% significance level, and no detectable enhancements in 2.2 MeV gamma rays were observed at either pole. Maps of the Epi^* and Fast-neutron fluxes showed localized depressions superimposed on levels that were generally depressed below average fluxes measured at more equatorial latitudes. Several of the areas of locally depressed counting rates overlay regions of permanent shade as identified by the Goldstone radar data [Margot et al. 1999].

Discussion: When all the information pertaining to possible lunar polar water-ice deposits are assembled and combined with data published previously [Shoemaker et al., 1994; Nozette et al., 1996; Stacy et al., 1997; Harmon, 1997; Feldman et al., 1998a; Simpson and Tyler, 1999], a fairly coherent picture emerges. We start first with the north pole of the Moon. No radar echoes are observed with same-sense polarization that are sufficiently large to require interpretation in terms of water-ice deposits [Stacey et al., 1997; Simpson and Tyler, 1999]. Indeed, a fair fraction of observed echoes having moderately enhanced same-sense polarization are from sunlit areas and so are likely caused by scattering from surfaces having roughness of order of the radar wavelength [Stacy et al., 1997]. The total area poleward of +87.5^o latitude in permanent shade is estimated to be less than 1030 km^2 [Margot et al., 1999], and there are no areal estimates based on measured topography for latitudes between +75^o and +87.5^o. Further, the shaded areas poleward of +87.5^o are observed to be dispersed in small pockets over the polar cap. Although it is not clear that such pockets can stably trap water ice (see Vasavada et al. [1999], for a discussion of requirements), enhanced hydrogen is observed in epithermal neutrons that covers a large portion of the north polar cap (see Figures 10a and 11a). The observed neutron signature averaged over all longitudes at the north polar cap (see Figure 11a) does not seem to depend on spatial resolution for areas larger than 2585 km^2 (the FWHM spatial resolution of the LPNS at 30 km altitude). Yet the lowest Epi* counting rates directly overly the terrain that appears to harbor the densest collection of small pockets in permanent shadow, as identified by radar observations [Margot et al., 1999], centered on 88^o N, 160^o E. This terrain may contain many small pockets of water ice just below the spatial resolution of LPNS at 30 km altitude because the percent depression in Epi* counting rates increases from 4.2% at a 100 km altitude to 5.4% at a 30 km altitude. Finally, no evidence for enhanced hydrogen deposits is seen in fast neutrons at the 1% significance level, or in 2.22 MeV gamma rays.

The fact that an enhanced abundance of hydrogen in the north is observed in only one observation channel, that of Epi* neutrons, restricts our ability to constrain the parameters of these deposits. For example, if many small pockets of enhanced hydrogen (relative to our best spatial resolution of 2585 km^2) cover the north pole, use of Equation 2 in Feldman et al. [1998a] predicts an average hydrogen abundance that is enhanced above that at more equatorial latitudes by 98 parts per million (ppm) by weight, or an effective H_2O abundance of 880 ppm. Use of Equation 3 in Feldman et al. [1998] predicts a percentage depression in the Fast neutron counting rate of 1% for a deposit of 880 ppm H_2O, which is just at our estimated detection threshold. Such a small effect would make it difficult to detect, in agreement with observations. Further, terrain containing only 100 ppm of hydrogen would be expected to produce an increase in the 2.22 MeV gamma-ray counting rate that is only at the 0.4σ level of our statistical detection threshold, also in agreement with observations. However, the data also allow a larger weight fraction of H_2O if it is buried beneath dry regolith because overlying layers preferentially reduce the Fast-neutron and gamma-ray signals, which are already observed to be at or just below threshold. The limit on burial depth allowed by all information presently known about the north pole is therefore only constrained by interpretation of the radar returns. The minimum weight fraction of H_2O in a thick, buried deposit is set by the maximum amount of absorbing regolith that would have prevented observation of the enhanced same-sense polarization signature that is used to identify a water-ice deposit in radar echoes. Such echoes have not been observed in radar experiments [Stacy et al., 1997]. The foregoing quantitative limits on our knowledge of the characteristics of enhanced deposits of hydrogen at the north pole are summarized in Table II and Table III.

The lunar south pole appears different from the north in several important ways. First, the topography in the south supports several large areas that are in permanent shadow [Margot et al., 1999], thereby providing potential sites for the long-term trapping of water ice [see, e.g., Vasavada et al. [1999], and references therein). Second, the signature for enhanced hydrogen is larger at low altitudes than at high altitudes. And third, significant reductions in the Fast-neutron flux poleward of -85° are resolved and correlated with those in the Epi^* flux at low-altitudes, whereas both these effects were not apparent at about the 1% significance level in the high-altitude data. Interpretation of these new results need also take account of the facts that no signature of enhanced hydrogen at the south pole is seen in 2.22 MeV gamma-rays, or is required by the radar data [Stacy et al., 1997; Simpson and Tyler, 1999].

Correlation of the Epi^* counting rates with topography can be shown by plotting individual cuts through the 2° x 2° Epi^* map in Figure 13 that bisect the permanently-shaded craters near the south pole identified by Margot et al. [1999]. Four such cuts that pass through an unnamed crater at 88.1° S and 45° E, Cabeus, Faustini, and an unnamed crater at 87.5° S and 0° E, respectively, are shown in Figure 15a. We note that the greatest depressions in Epi^* counting rates overly the unnamed crater at 45°E and Cabeus. The counting rate above Faustini is only marginally depressed relative to that in neighboring terrain and, although the lowest counting rate in the cut that passes through the longitude of the unnamed crater at 87.5° S and 0° E lies within that crater, the observed latitude trend in rates for that cut does not significantly separate this crater from its neighboring terrain.

The meridional cut through the crater at 88.1° S and 45° E is compared with that through the lowest Epi* counting rate in the north, in Figure 15b. This comparison supports the conclusion that regardless of relative hydrogen concentrations between the north and south lunar poles, both poles contain about the same inventory of total hydrogen abundance. An overlay of the Fast and Epi* rates for the four cuts of Epi* counting rates shown in Figure 15a are shown in Figure 16. Intercomparison supports the general correlation between Fast and Epi* counting rates poleward of -85° seen in Figure 12a, and also that the regions of enhanced hydrogen abundances are correlated with topography as shown in Figure 15a.

The positive results of all the foregoing tests encourages us to interpret observed depressions in both the Epi* and Fast-neutron counting rates within the permanently-shaded craters near the south pole in terms of water-ice abundances and stratigraphy. Quantitative measures of these depressions are collected in Table II and Table III. We start first with the south pole, which is surrounded by the first five craters listed in Table I. Percentage depressions in Epi* counting rates of 4.8% at 30 km altitude and of 3.3% at 100 km altitude are both consistent with just less than a 2% weight fraction deposit of H_2O in all five craters. A 2.4% depression in Fast neutrons at 30 km altitude is also consistent with the simulations shown in Figure 2b for about a 2% mass fraction of H_2O. The predicted depression in Fast neutrons at 100 km altitude for a 2% H_2O deposit is 1%, which is barely consistent with our observed upper limit of a 1% depression. This last observation argues for an upper limit of about 2% by mass of H_2O for the deposits.

Proceeding to the three-crater simulations in Figure 3, the measured 6.1% depression in Epi* counting rate above the crater at 88.1° S and 45° E is consistent with that predicted for a 1% mass fraction of H_2O using the low diameter estimates for the craters listed in Table I. Other simulations that explored the effects of different amounts of background hydrogen contents (not presented here) show that this value for the mass fraction is directly comparable to that just determined for the five craters that surround the south pole. The simulations shown in Figure 3b predict a 2% depression in Fast neutrons for a 1% mass-fraction of H_2O. This value is less than the 3.0% measured value, which is more consistent with a 2% mass fraction of H_2O for the low diameter estimate for these craters.

The data for a location that overlies Cabeus yields a potentially different result. The measured depression in Epi^* neutron counting rate is close to that observed above the crater at 88.1^o S and 45^o E, yet no sensible depression is observed in the Fast neutron counting rate. Although it is possible that the lack of observed Fast-neutron signature stems from a more mafic composition within this crater, inspection of Figure 4 indicates that the H_2O on the crater floor may also be buried beneath water-free regolith. An explanation in terms of a variation in composition cannot be ruled out. The floor of Cabeus cannot be observed from Earth by radar because it is surrounded by a high, Earth-blocking rim, and it cannot be observed optically because it is in permanent shadow. We investigate the possibility of burial beneath a water-free cover by noting the trends in the series of simulations shown in Figure 4. We note that the signature of a water-ice deposit in Epi^* neutrons is virtually unchanged at a burial depth of 50 g cm^{-2} yet that in Fast neutrons is reduced by about a factor of five. This factor would be sufficient to reduce the depression in Fast-neutron counting rate to below our 1% detection threshold, as observed.

In summary, all the neutron observations near the south pole are consistent with mass-fractions of H_2O in the regolith within all the permanently-shaded craters [Margot et al., 1999] of 1.5 ± 0.8 %. Our estimate of the H_2O mass fraction will increase if the diameters of the actual deposits decrease. However, the deposits cannot be buried beneath more than about 10 g cm^{-2}, as seen from the simulations in Figure 4. And, for diameters close to those assumed in Table I, burial cannot mask a 3% H_2O deposit by any amount of dry regolith overburden because the observed depression in Epi^* counting rates would then be too large, as shown in Figure 17. We emphasize though, that neutron data alone, cannot discriminate between hydrogen and water ice. The deposits that have just been quantitatively characterized in terms of deposits of water ice confined to the permanently-shaded craters near the south pole may, instead, be enhanced deposits of hydrogen.

Implications Regarding H_2O Acquisition and Deposition. The scenario that best fits our observation of a 1.5±0.8 % admixture of H_2O within the permanently shaded craters at the south pole, is the steady accumulation of H_2O on the Moon through many impacts with small comets, asteroids, interplanetary dust particles and perhaps, passage through the core of a GMC. When translated to a hydrogen abundance, this observation amounts to a factor of 34 enhancement relative to the average equatorial hydrogen abundance (~50 ppm). Butler [1997] has shown that exospheric transport can very efficiently deliver 20% to 50% of all water delivered to the Moon from all impact sources to the poles. Continuous gardening by micrometeorite impacts then creates the thick deposits that are needed to provide the observed neutron signature. The fact that this signature is observable indicates that the rate of acquisition of H_2O and its subsequent transport to, and deposition at the poles, must be larger, on average, than its rate of destruction by micrometeorite bombardment, irradiation by H Ly α, or sputtering by energetic particles. Although the LPNS cannot resolve deposits smaller than about 57 km in diameter, our data cannot rule out many small pockets of about 1% water ice within permanently-shaded depressions near the north pole.

However, the cuts of Epi* counting rates through the largest permanently-shaded craters near the south pole are consistent with islands of enhanced hydrogen deposits (which we have tentatively identified here as water ice) immersed within more generally distributed hydrogen that is enhanced relative to that at more equatorial latitudes by about 100 ppm by weight (which amounts to a factor of 3). These generally-distributed deposits are consistent with delivery to the Moon from the solar wind or the plasma sheet in the geomagnetic tail. They can also have contributions from all impacts with interplanetary debris that deliver H_2O to the Moon. Their hydrogen enhancement relative to that at more equatorial latitudes then must reflect a reduced rate of loss to space due to a lower rate of diffusion caused by lower temperatures near the poles.

A summary of our best estimate of the breakdown of enhanced hydrogen abundances between that contained in permanently shaded craters or pockets, and that contained generally in regolith near both lunar poles, is given in Table III. A total inventory can be made by summing the percentage depressions in Epi* counting rates over all (2^o x 2^o) equal-area spatial pixels poleward of ±75^o latitude. These depressions can be translated to weight-percent enhanced hydrogen content using equation 2 of Feldman et al. [1998a]. If we assume further that these deposits are 200 cm thick [Arnold, 1979] and have a density of 2 g cm^{-3}, this procedure yields 1.29 x 10^8 metric tons of hydrogen in the south and 0.99 x 10^8 metric tons in the north. An estimate of the fraction of this inventory that is contained within permanently shaded areas near both poles can be made by assuming a 1.5% admixture of water ice within these regions. Using areas in permanent shade estimated by Margot et al. [1999] we obtain; 1.5 x 10^7 (2.67 x 10^7) metric tons of hydrogen for an area in the south of 2250 (4000) km^2, and 0.69 x 10^7 metric tons of hydrogen for an area in the north of 1030 km^2. An estimate of the amount of hydrogen contained in the regolith outside of the permanently-shaded terrain can be made by fitting the depressions in measured Epi^* counting rates about both poles in Figure 10a by a conical distribution of the form,

$$w = w_{max} [1- \theta/(2\theta_{0.5})] \qquad (1)$$

where w_{max} = 100 ppm hydrogen by mass (see Table II), θ is the polar angle, and $\theta_{0.5}$ is the half-width polar angle of the depressions in Epi^* counting rates, equal to 8^o in the south and 6^o in the north. Combining the volume integral of this expression over both polar caps ($4\pi\theta^2 w_{max} R^2/3$ where R is the mean lunar radius, 1738 km) with an assumed regolith density of 2 g cm^{-3} and a depth of deposit of 200 cm, yields a mass content of generally distributed hydrogen of 9.86×10^7 metric tons in the south and 5.54×10^7 metric tons in the north. These amounts can be compared to the average hydrogen content of equatorial regolith of 50 ppm [Haskin and Warren, 1991] that must be added to the foregoing enhanced hydrogen abundances determined from the LPNS, yielding an additional 1.29×10^8 metric tons poleward of $\pm 75^o$ latitude.

All the foregoing estimates can be translated to equivalent mass-weights of H_2O by multiplying by 9. For example, it is reasonable to presume that the form of hydrogen within the permanently-shaded regions near both poles is water ice. If correct, then there may be as much as 1.35×10^8 (2.4×10^8) metric tons of water ice within the 2250 (4000) km^2 areas estimated to be in permanent shade in the south, and 0.62×10^8 metric tons of water ice within the 1030 km^2 of estimated shade in the north. Of course, these amounts can be larger if part of the hydrogen inventory just ascribed to hydrogen contained generally in the polar regolith is actually in the form of small pockets of water-ice crystals. Regardless, even if all the enhanced hydrogen inventory measured using the LPNS is in the form of water-ice crystals, the total only amounts to 2.05 x 10^9 metric tons of H_2O at both poles of the Moon.

This inventory is small compared to that estimated as possibly delivered to, and subsequently retained on the Moon from cometary and meteoritic impacts, and by accumulation of H_2O from interplanetary dust particles. The total inventory from these sources is estimated to be 10 to 100 x 10^9 metric tons [Arnold, 1979]. Comparison of this inventory with the maximum amount estimated from the neutron data (2.05 x 10^9 metric tons) shows that most of the water ice delivered to the Moon must have been lost to space either during the process of transport to the poles [Butler, 1997] or to loss by sublimation, micrometeorite bombardment, irradiation by H Lyman α, and sputtering by energetic particles [Arnold, 1979; Morgan and Shemansky, 1991; Lanzerotti et al., 1981].

Could the 1% mass-fraction deposits of H_2O that are consistent with the LP neutron observations mask a thick deposit of buried water ice, as interpreted from radar data to exist near the poles of Mercury [Slade et al., 1992; Butler et al., 1993, 1994; Harmon et al., 1994; Jeanloz et al., 1995]? To answer this question, we conducted a series of simulations shown in Figure 18. At the top we have varied the depth of burial of a pure, thick water-ice deposit, beneath varying thicknesses of FAN regolith containing 1% by weight of H_2O. Although a depth of 70 g cm^{-2} is sufficient to reduce the Fast neutron signature to the level that is observed, the Epi^* signal remains too high by a factor of three. At the bottom of Figure 18 we have varied the percent H_2O in a 40 g cm^{-2} overburden of a pure, thick layer of water ice. In all cases, both the predicted signatures in Epi^* and Fast-neutron counting rates are higher than observed. We conclude that no cover layer can hide a thick, pure water-ice deposit from view by a combination of Epi^* and

Fast neutrons. Such a deposit cannot therefore exist near the poles of the Moon within about 1 meter of the surface. Of course it can exist below the depth of sensitivity of the Lunar Prospector Neutron Spectrometer, which we estimate from Figure 4 to be about 1m. An answer to this question requires further experimentation to better define the parameters of both the Hermean and lunar water-ice deposits at polar latitudes.

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Figure Captions

Figure 1. Simulations of the percent decrease in Epi* and Fast neutron counting rates for various circular areas of FAN regolith containing 1%, 3%, and 10% H_2O by mass, that are completely surrounded by water-free FAN regolith.

Figure 2. Simulations of the percent decrease in Epi* and Fast neutron counting rates for the five permanently shaded craters identified by Margot et al. [1999] as measured from a position directly above the south lunar pole, at altitudes of 30 and 100 km. The weight percent of H_2O mixed with the FAN is varied between 0.01 and 100% for the Epi* rates and between 0.1 and 100% for the Fast rates.

Figure 3. Simulations of the percent decrease in Epi* and Fast neutron counting rates for the three largest permanently shaded craters identified by Margot et al. [1999], as measured from a position directly above the center crater , at altitudes of 30 and 100 km. The three craters are completely surrounded by FAN regolith containing 0.1% H_2O. The weight percent of H_2O mixed with the FAN is varied between 1 and 100% for both counting rates.

Figure 4. Simulations of the percent decrease in Epi* and Fast neutron counting rates for the three largest permanently shaded craters identified by Margot et al. [1999], as measured from a position directly above the center crater , at altitudes of 30 and 100 km. The depth of burial

beneath a FAN regolith containing 0.1% H_2O is varied between 0.1 and 100 g cm^{-2}. The craters are completely surrounded by FAN regolith containing 0.1% H_2O.

Figure 5. Gamma-ray spectra summed over all measurements made within four annular latitude bands between 16 Jan. and 5 Oct., 1998, when Lunar Prospector was in the high-altitude portion of its orbit (100±20 km). The accepted spectra at top are offset in 5a for clarity. Corresponding latitudes,Λ, in order from top to bottom, are; annulus 3 = ($70<\Lambda<75$), annulus 2 = ($75<\Lambda<80$), annulus 1 = ($80<\Lambda<85$) and the north polar cap = ($85<\Lambda<90$), respectively. Difference spectra between that measured at the north pole and the other three annular bands are shown in 5b. Here again, the difference spectra are offset for clarity.

Figure 6. Gamma-ray spectra summed over all measurements made within four annular latitude bands between 16 Jan. and 5 Oct., 1998, when Lunar Prospector was in the high-altitude portion of its orbit (100±20 km). The accepted spectra at top are offset in 6a for clarity. Corresponding latitudes,Λ, in order from top to bottom, are; annulus 3 = ($-70<\Lambda<-75$), annulus 2 = ($-75<\Lambda<-80$), annulus 1 = ($-80<\Lambda<-85$) and the south polar cap = ($-85<\Lambda<-90$), respectively. Difference spectra between that measured at the south pole and the other three annular bands are shown in 6b. Here again, the difference spectra are offset for clarity.

Figure 7. Correlations between Epithermal/Fast and Thermal/Fast neutron counting rates in all (2^o x 2^o) equal area spatial resolution elements north of $+85^o$ latitude (top) and south of -85^o latitude (bottom). The respective correlation parameters are listed in the insets at the upper left in each plot.

Figure 8. Correlations between Epithermal/Fast and Thermal/Fast neutron counting rates in all (2^o x 2^o) equal area spatial resolution elements north of +80^o latitude (top) and south of -80^o latitude (bottom). The respective correlation parameters are listed in the insets at the upper left in each plot.

Figure 9. Map of Epi* counting rates at a spatial resolution equal to that of equal-area pixels equivalent to 2^o x 2^o latitude-laongitude squares at the equator. The bottom panel is a mercater projection spanning latitudes between ±45^o latitude and ±180^o longitude, and the upper two circles are stereographic projections for latitudes poleward of ±45^o.

Figure 10. Epi* (top) and Fast (bottom) counting rates measured during the low altitude portion of the LP orbit, averaged over 12, 2^o-wide polar bands, equally spaced in longitude at 15^o intervals. The vertical lines through each latitude point give the standard deviation of counts at that latitude for the 12 different longitudes.

Figure 11. Comparison between the Epi* (top) and Fast (bottom) counting rates measured during the high (100±20 km) and low (30±15 km) altitude portions of the LP orbit.

Figure 12. Correlations between measured Epi* neutron counting rates relative to their mean, and Fast neutron counting rates relative to their mean, for all (2^o x 2^o) equal area spatial resolution elements north of +85^o latitude (bottom) and south of -85^o latitude (top). The respective correlation parameters are listed in the insets at the upper left in each plot.

Figure 13. Color-coded maps of the Epi^* (left) and Fast (right) neutron counting rates for all (2^o x 2^o) equal area spatial resolution elements north of $+70^o$ latitude (top) and south of -70^o latitude (bottom). The dashed circles in all maps correspond to $\pm 75^o$, $\pm 80^o$, and $\pm 85^o$, respectively. Lowest values of all Epi^* counting rates reflect enhanced hydrogen abundance.

Figure 14. Correlations between Epithermal neutron counting rates measured at low (30±15 km) and high (100±20 km) altitudes for all (2^o x 2^o) equal area spatial resolution elements north of $+80^o$ latitude (top) and south of -80^o latitude (bottom).

Figure 15. An overlay of meridional cuts of Epi^* counting rates measured across the south polar cap (at top), and representative cuts through the north and south poles, respectively (bottom). The longitude of each of the cuts is given in the inset at tops of both panels, and positive polar angles are oriented toward the Earth. The vertical line below the curves at the left in the top panel and below the curves in the bottom panel identifies the location of the central crater in the three co-linear craters near the south pole pole that were modeled in Figure 3 and 4. The vertical line just to the right in the top panal identifies Cabeus.

Figure 16. Overlays of meridional cuts through Epi^* and Fast neutron counting rates that pass through four prominant, permanently-shaded craters near the south pole. The meridion of each cut is given at the tops of each plot.

Figure 17. Simulations of the percent decrease in Epi* and Fast neutron counting rates for the three largest permanently shaded craters identified by Margot et al. [1999], as measured from a position directly above the center crater at an altitudes of 30 km. The depth of burial of a thick FAN layer containing 3% H_2O, beneath a dry FAN regolith, is varied between 0.1 and 40 g cm^{-2}.

Figure 18. Simulations of the percent decrease in Epi* and Fast neutron counting rates for the three largest permanently shaded craters identified by Margot et al. [1999], as measured from a position directly above the center crater at an altitudes of 30 km. The depth of burial of a thick, pure water-ice layer, beneath a FAN regolith containing 1% H_2O is varied between 0.1 and 70 g cm^{-2} at the top. A Moon-wide, thick layer of FAN containing 0.1% H_2O surrounds these craters. At the bottom, a 40 g cm^{-2} thick cover layer of FAN that contains varying percentages of H_2O is assumed to overlay a thick, pure water-ice layer.

Table I

Permanently-Shaded Crater Floors Near the South Pole

		High Estimate		Low Estimate	
Crater Name	Location	Diameter	Area	Diameter	Area
	(Latitude, Longitude)	km	km^2	km	km^2
Faustini	87.3 S, 77 E	31.1	760	26.9	568
Unnamed	88.1 S, 45 E	35.4	984	30.7	740
Unnamed	87.5 S, 356 E	32.1	809	27.8	607
Shackleton	89.7 S, 110 E	17.0	227		
Unnamed	88.5 S, 273 E	22.6	401		
Cabeus	84.5 S, 322 E	____	___		
Total			3181		1915

Table II

Measured and Model Parameters for Excess Hydrogen Near the Lunar Poles

Parameter	Location (Latitude, Longitude)			
	(90S, ---)	(88.1S, 45E)	(84.5S, 38W)	(88N, 150E)
% Decrease in Epi[*], h=30 km	4.8%	6.1%	6.0%	5.4%
% Decrease in Epi[*], h=100 km	3.3%	3.5%	3.5%	4.2%
% Decrease in Fast, h=30 km	2.4%	3.0%	< 1%	< 1%
% Decrease in Fast, h=100 km	< 1%	< 1%	< 1%	< 1%
Average ppm H (Epi[*]), h=30 km	87	111	109	98
% H_2O From Sims, h=30 km[†]	1.9±0.6%	1.3±0.5%	---	---
% H_2O From 2.2 MeV γ Rays[‡]	<1.9%, <3.4%			<10%

† Used Figure 2 for 90S, and low diameter curves in Figure 3 for 88.1S estimates.

‡ Assumed permanently shaded areas of 4000, 2250 km^2 in south and 1030 km^2 in north.

Table III

Summary of Hydrogen Abundance Near the Lunar Poles

Location	Area km^2	Mass Content (metric tons)
Poleward of -75°	6.47×10^5	1.29×10^8
Poleward of +75°	6.47×10^5	0.99×10^8
Permanent Shade Poleward of -87.5°	2250	1.5×10^7
Permanent Shade Near the South Pole (Upper Limit)	4000	2.67×10^7
Permanent Shade Poleward of +87.5°	1030	6.87×10^6
Enhanced H Content of Non-shaded Terrane in South	7.35×10^5	9.86×10^7
Enhanced H Content of Non-Shaded Terrane in North	4.15×10^5	5.54×10^7
Solar Wind Implanted H @ 50 ppm, Poleward of -75°	6.47×10^5	1.29×10^8
Solar Wind Implanted H @ 50 ppm, Poleward of +75°	6.47×10^5	1.29×10^8
Water Equivalent in Permanent Shade Poleward of -87.5°	2250	1.35×10^8
Water Equivalent in Permanent Shade Near the South Pole	4000	2.40×10^8
Water Equivalent in Permanent Shade Poleward of +87.5°	1030	0.62×10^8