TRAPPED SOLAR HYDROGEN IN LUNAR SAMPLES[*], D. A. Leich[†],
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The interaction of solar particle radiations with lunar surface materials has been studied using a resonant nuclear reaction depth analysis technique (1) to measure the depth distributions of hydrogen in lunar samples (2). Samples were irradiated with a ^{19}F ion beam (16-18 MeV) and prompt γ-rays from the ^{1}H$(^{19}$F$,\alpha\gamma)^{16}$O reaction were counted to measure the H content as a function of depth. The basic problem in the interpretation of these measurements lies in distinguishing the component of lunar H from terrestrial contamination, notably adsorbed H_2O. Contamination has been minimized for samples returned in a vacuum-sealed sample container (66044,8; 68124,3; and 68124,10) and handled entirely under dry N_2 gas prior to our analysis in a clean, ultrahigh vacuum scattering chamber. In addition to data reported previously (2) we have also analyzed for comparison surface glass from rock 65315 which was not returned in a sealed rock box. In all cases small amounts of surface absorbed H ($\sim 2 \times 10^{15}$ atoms/cm^2, equivalent to one monolayer of H_2O), are routinely observed on interior rock samples which have been exposed only to dry N_2 gas. The source of this absorbed H is undoubtedly terrestrial (most likely the small residual H_2O content of the "dry" N_2 gas), leading to the inevitable conclusion that similar features observed on lunar exterior surfaces of the same samples, including samples from the sealed rock box, are also due primarily to terrestrial contamination. This type of profile is illustrated for the 68124,3 glass sphere in Fig. 1. As noted previously (2), most lunar glasses appear to retain solar wind hydrogen very poorly; thus, it is likely that much of the near surface (less than 0.1 μm) H in 65315 (Fig. 1) is due to H_2O contamination from the LM cabin atmosphere. We conclude that storage in the sealed rock box has given significant protection to 68124,3 and presumably other rock box samples as well.

Several of the exterior surfaces, notably 68815,27 (Fig. 1) and some Apollo 11 and 15 coarse fines have shown an additional broad peak with a maximum H content near 0.1 μm and with a width of 0.2-0.3 μm. While extensive penetration of a terrestrial contaminant cannot be ruled out as a possible origin for this H component, contamination appears unlikely for the following reasons: (A) Exposure of artificially radiation-damaged fused silica surfaces to H_2O, even in liquid form, produced no penetration of H_2O to depths greater than 0.1 μm, even for surfaces which were heavily damaged with ^{16}O ions prior to H_2O exposure. (B) It appears doubtful that the exterior surface of 68815,27, which had never been exposed to atmosphere, could have adsorbed such large quantities of H_2O while the exterior surfaces of other samples, such as 68124,3 (Fig. 2), returned in the same sealed rock box, showed only small quantities of surface (within 0.03 μm) absorbed H. Given the known tendency of glasses to hydrate, the 68124,3 glass sphere would have been expected to absorb much more H_2O than the surface of a crystalline rock

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sample such as 68815. Because the H content in 68124,3 is much less, we
regard this as a strong argument that we are primarily measuring solar H in
68815 at all depths.

Taking the above at face value, the bulk of the H content at depths
between 0.1 and 0.4 μm in all samples is best interpreted as true lunar H
rather than terrestrial contamination.

At present, we have confined ourselves to the discussion of the type of
profile exhibited by 68815. Although implantation of solar wind protons is
the most likely source, the observed H profiles are significantly more pene-
trating than the expected 0.01-0.02 μm implantation depths, in agreement with
conclusions based on chemical etching experiments for implanted rare gases
(3). If solar wind H is the source of the 68815-type profile, extensive mod-
ification by diffusion is implied. Diffusion rates for H in terrestrial sil-
icates are too rapid to account for the observed concentrations; thus, it
appears that some sort of trapping has slowed down the diffusion process. A
hypothesis in which implanted solar wind H diffuses rapidly into (and out of)
the samples with a small remnant of the implanted dose being retained in
radiation damage traps seems plausible. The heavy radiation damage, as docu-
mented by high voltage electron microscopy (4), in the outer 0.05 μm pre-
cludes the existence of isolated traps in this region. Beneath this depth
relatively intense radiation damage (but below saturation levels) may persist
to a depth of ~ 0.2 μm, corresponding closely to the radiation damage range
of He ions with velocities near those of frequent high velocity (~ 800
km/sec) solar wind streams observed by satellites. The population of iso-
lated radiation damage traps by diffusing solar wind atoms may then result
in a hydrogen depth profile which reflects the distribution of radiation
damage. A discontinuity in the radiation damage gradient (i.e., a change in
the effective diffusion coefficient) near a depth of 0.2 μm may account for
the characteristic flattening observed in the measured H profiles below ~ 0.2
μm. In this region, diffusion is still controlled by radiation damage (due
here to solar flare and suprathermal ions) but the gradient of traps is much
less.

An alternative explanation for the observed H profiles is the direct
implantation of "suprathermal" (10-100 keV) protons. In this case, the mea-
sured H profiles would provide information about the energy spectrum of the
incident protons. A reasonably good fit to the initial set of H profile data
for 68815 (Fig. 2) can be obtained using the energy spectrum of Frank (5),
assuming that no post-implantation diffusion occurs and taking into account
the effects of erosion and of incidence from a solar direction. A two-
component energy spectrum is necessary to produce the characteristic bend in
the profile near ~ 0.2 μm deep. An atomic erosion rate of 5×10^{-9} cm/y has
been assumed, implying a long-term flux of suprathermal protons of ~ 10^{13}
$cm^{-2}y^{-1}$, within a factor of about 3 of the instantaneous flux for the event
reported by Frank (5). Since the long-term flux of protons in this energy
range is likely to be a few orders of magnitude lower than the flux during
such an event, it appears unlikely that the average flux has been high enough
to account for the measured H profiles by direct implantation. However,
little data has been obtained in this energy range, and it is possible that

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long-term fluxes may have been high enough to account for a significant por-
tion of the H distribution or at least to account for a significant radiation-
damage gradient in the 0.2 to 0.4 µm depth region.

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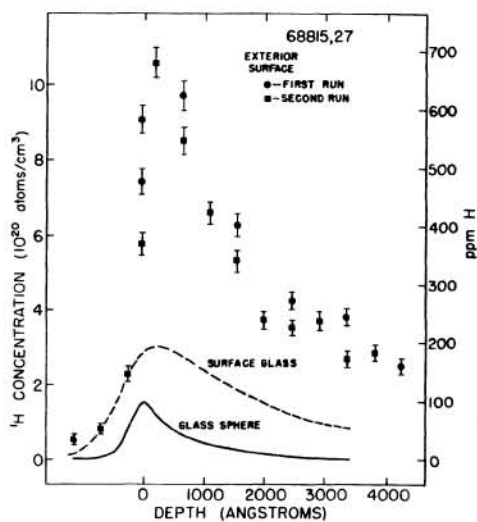(5) FRANK, L. A. (1970) in J. Geophys. Res. 75, 707.

Fig. 1: H profile data are shown for
samples 68815,27, 68124,3
(glass sphere), and 65315,6
(surface glass). For the
last two samples smooth
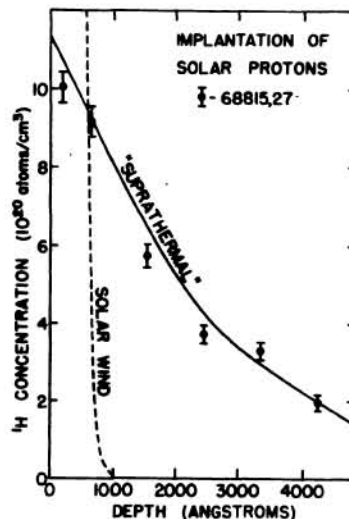curves have been drawn
through the data points.

Fig. 2: H profile data for breccia
sample 68815,27 are com-
pared with the tail of an
estimated solar wind pro-
ton implantation distribu-
tion (including range
straggling but neglecting
diffusion) and with a
"suprathermal" proton
implantation distribution.
An atomic erosion rate of
0.5 Å/yr is assumed.