Solar-Wind Hydrogen at the Lunar Poles

**H.H. Schmitt, G.L. Kulcinski, J.F. Santarius,
J. Ding, M.J. Malecki, M.J. Zalewski**

February 2000

UWFDM-1120

FUSION TECHNOLOGY INSTITUTE

UNIVERSITY OF WISCONSIN

MADISON WISCONSIN

Solar-Wind Hydrogen at the Lunar Poles

H. H. Schmitt, G. L. Kulcinski, J. F Santarius,
J. Ding, M. J. Malecki, M. J. Zalewski [1]

Fusion Technology Institute
Department of Engineering Physics
University of Wisconsin-Madison
1500 Engineering Drive
Madison, WI 53706

February 2000

UWFDM-1120

[1] Contact Schmitt at (505) 823-2616, fax (505) 823-2617, schmitt@engr.wisc.edu, or Kulcinski at (608) 263-2308, fax (608) 263-4499, kulcinski@engr.wisc.edu.

Abstract

The Lunar Prospector Team and others have interpreted epithermal neutron spectra from the lunar poles as potentially indicating the presence of large quantities of water ice. Water ice might be deposited as a consequence of cometary impacts on the Moon as has been predicted theoretically. The interpretation of the neutron spectra as indicating water ice at the poles appears premature, however, in the face of the proven presence of over 100 wppm solar-wind hydrogen in many soil and regolith breccia samples. Solar-wind hydrogen also would be concentrated and preserved as a distributed regolith component in permanently shadowed areas. No significant amount of implanted solar wind hydrogen in such areas would be lost to thermal cycling and both primary and pickup ions would be continuously deposited. Further, a continuous blanket of cometary water ice, precipitated on rare occasions in permanent shadow, would remain subject to solar-wind sputtering and micrometeoroid erosion comparable to the complete reworking of the upper few centimeters of regolith approximately every ten million years. Solar-wind hydrogen, therefore, probably accounts for most of the epithermal neutron signal. Other solar-wind volatiles of interest, such as ^{3}He, are probably also concentrated in permanent shadow; however, their relative value will be reduced relative to titanium-rich mare sources due to the higher cost of retrieval from the poles.

Introduction

The Lunar Prospector Team and others (1, 2, 3) have interpreted epithermal neutron spectra from the lunar poles as potentially indicating the presence of large quantities of water ice. Theoretically, water ice could be deposited in permanent lunar shadow as a consequence of cometary impact (4); however, its longevity in response to solar-wind sputtering and micrometeorite erosion has not been determined. An equally if not more plausible possibility exists, namely, that the Lunar Prospector neutron spectrometer has measured an expected increase in the polar concentration of solar-wind hydrogen disseminated within the polar regolith. Solar-wind hydrogen has been documented in the regolith samples returned by the Apollo astronauts up to 146 wppm, or 0.015 percent by weight (5). This Apollo sample maximum is actually a <u>minimum</u> due to known, but as yet unquantified, losses of hydrogen and other volatiles during sampling, transport, handling, splitting, and distribution prior to measurement in the laboratories of several lunar sample principal investigator teams (6). Further, in the senior author's field study of an avalanche deposit in the valley of Taurus-Littrow by Apollo 17, evidence was found of the release of volatiles and resulting fluidization of that avalanche during its emplacement (7). As a consequence, the vast majority of quantitative measurements of solar-wind components in the lunar regolith samples must be viewed as minimum amounts, possibly low by as much as a factor of two. The nature of the hydrogen at the lunar poles reflects on many other issues related to lunar volatiles, including ^{3}He. For example, if the concentration of hydrogen at the poles represents solar-wind hydrogen, then solar-wind ^{3}He, of interest as a future energy resource (8), also may be concentrated. Interest in volatile components associated with the lunar regolith has increased rapidly since their prediction and discovery as a component of the Apollo samples (5). The subsequent realization that solar-wind ^{3}He (helium-3) represents a fusion energy resource for terrestrial use as well as enabling access to other lunar volatiles (14, 8) rapidly accelerated this interest. In addition, lunar volatiles, particularly hydrogen, water, oxygen, and ^{4}He have potential applications in support of lunar bases and settlements, space stations, space propulsion, and initial exploration and settlement of Mars (8). Lunar Prospector (15) clearly has added significant and valuable new scientific information on the distribution of elements on the lunar surface. NASA and the Prospector team are to be congratulated for their highly successful mission.

Hydrogen in the lunar regolith can be viewed in the context of available facts and proposed hypotheses relative to the origin and evolution of the Moon (9). Lunar evolution took place over 4.57 billion years (b.y.) and can be summarized as follows (10, 11, 12, 13):

Stage 1: Beginning (Pre-Nectarian) – 4.57 b.y. before present

Stage 2: Magma Ocean (Pre-Nectarian) – 4.57 - 4.2(?) b.y.

Stage 3: Cratered Highlands (Pre-Nectarian) – 4.4(?) - 4.2(?) b.y.

Stage 4: Large Basins –(Pre-Nectarian - Upper Imbrium) – 4.3(?) - 3.8 b.y.

Stage 4A: Old Large Basins and Crustal Strengthening (Pre-Nectarian) - 4.3(?) – 3.92 b.y.

Stage 4B: Young Large Basins (Nectarian - Lower Imbrium) – 3.92 - 3.80 b.y.

Stage 5: Basaltic Maria (Imbrium, Copernican and Eratosthenian) – 4.3(?) - 1.0(?) b.y.

Stage 6: Mature Surface (Upper Imbrium, Copernican and Eratosthenian) – 3.9 b.y. - Present.

The Mature Surface Stage, the stage of greatest interest relative to hydrogen in the regolith at the lunar poles, began on some surfaces at least at the beginning of the Cratered Highlands Stage and continues as the active stage today.

The Mature Surface Stage

Maturation of the surface of a geological unit anywhere on the Moon begins with the stabilization of the unit's upper surface. Primary and secondary impacts and space radiation cause some degree of surface modification on every surface formed, however transitory may be its exposure to the space environment. A quantitative maturity index has been developed (16); however, it has become increasingly clear that factors other than age can affect the measured maturity (17, 18). Although this index is useful in the comparison of similar units, relative iron and titanium contents of the original materials (19), starting particle size, and volcanic glass content (20) will affect its values significantly.

The lunar regolith constitutes the upper tens of meters of the surface materials in the highlands; however, over the oldest of the large lunar maria (~3.8 b.y.), such as that sampled at Apollo 11's Tranquillity Base, the regolith appears to reach an average maximum of only about 6 m depth. Near contacts between the maria and steep highland slopes, or where pyroclastic glasses have been added to the surface of earlier formed regolith, the overall depth of largely fine-grained debris increases. This has been studied best in the valley of Taurus-Littrow. Here, highlands debris from the North and South Massifs and glass beads from pyroclastic deposits have added several meters of thickness to the regolith (21).

Cosmic rays and solar-wind particles also modify the lunar regolith. Cosmic rays produce a variety of spallation isotopes useful in measuring the time materials have been exposed at or near the lunar surface (22). They also induce the production of neutrons; the energy or temperature of which can be measured from lunar orbit and used to determine the concentrations of interacting elements in the regolith (23). High-energy solar-wind ions, largely hydrogen and helium but with significant carbon and nitrogen and minor noble gases as well, stream continuously from the sun. The flux of the solar-wind ions impacting the Moon per unit area varies with the quantity ejected from the sun and because of interactions with the Earth's magnetosphere. Upon impinging the lunar surface, these ions are imbedded in the mineral and glass constituents of the regolith, being partially released later by micrometeoroid impact and diurnal heating and partially retained by burial under ejecta from impacts. To some degree, released volatiles will be ionized and entrained in the passing solar-wind ("pickup ions") and either be lost entirely or re-implanted elsewhere on the Moon. A definitive model of this overall process has not been published; however, the analysis of lunar soils has broadly defined the approximate steady state concentrations of solar-wind volatiles in samples and cores from the various Apollo landing sites (24, 25).

Apollo, Clementine and Lunar Prospector Data

The Apollo samples gave a broad indication of the distribution of hydrogen and other solar-wind volatiles in the lunar regolith at six widely separated sites on the near side of the Moon. The Lunar Prospector neutron spectrometer recently has provided information on the global distribution of hydrogen in the regolith (1, 3). More specifically, the Prospector Investigator Team has interpreted the epithermal neutron spectra as indicating concentrations of water-ice in the permanently shadowed areas of the lunar poles apparently related to the approximately 20,000 km^2 of permanent shadow in those two areas (26, 27). Concentrated solar-wind hydrogen represents an equally plausible if not more likely interpretation (9). Data from measurements at low altitudes (30±15 km) indicate the

highest hydrogen concentrations of 1500±800 wppm exist in two permanently shadowed craters the centers of which are within 2.5° of the South Pole (28, 3). This contrasts with concentrations measured in the Apollo samples of around 100±50 wppm (5). The low altitude data also show reduced hydrogen, but still higher than the lunar average, in polar areas outside permanent shadow.

Lunar Prospector's epithermal neutron spectrometry over the northern and southern polar regions (3), respectively, indicate an average increase in hydrogen concentration of about a factor of three (~150 wppm) with much higher concentrations in permanently shadowed craters. These specifically are measurements of hydrogen in lunar surface material (regolith) and not direct measurements of water ice. The inference that the polar regions and the approximately -230°C (29) permanently shadowed areas contain water ice mixed with regolith remains for now just that – an inference. Polar hydrogen concentrations outside permanent shadow would be unlikely to be the result of ice as initial cometary ice deposits at the surface would sublimate rapidly when exposed to sunlight unless protected in a timely manner by fortuitous impact ejecta. Thermal trapping of solar-wind hydrogen would appear to be the more plausible explanation for these data.

Co-author Ding has recently made comparisons of Lunar Prospector epithermal neutron data (30, 31) with the 750 nm albedo data from the Clementine orbiting optical spectrometer (32). Comparisons within the area between +60° and –60° latitude indicate that the nearside regolith averages 36.1 wppm and the far-side averages 27.7 wppm hydrogen. Figure 1 indicates that there exists a significant global correlation of hydrogen content with low albedo.

Qualitative examination of the global neutron and optical data also suggests that in non-polar regions, hydrogen concentrations are accentuated in the titanium-rich mare, in various irregular areas in the highlands, and in the KREEP-rich annulus around the Imbrium Basin. Solar-wind hydrogen and helium appear to be retained selectively by ilmenite and, in the case of hydrogen, by plagioclase feldspar. The strong correlation of helium with high titanium mare has been well
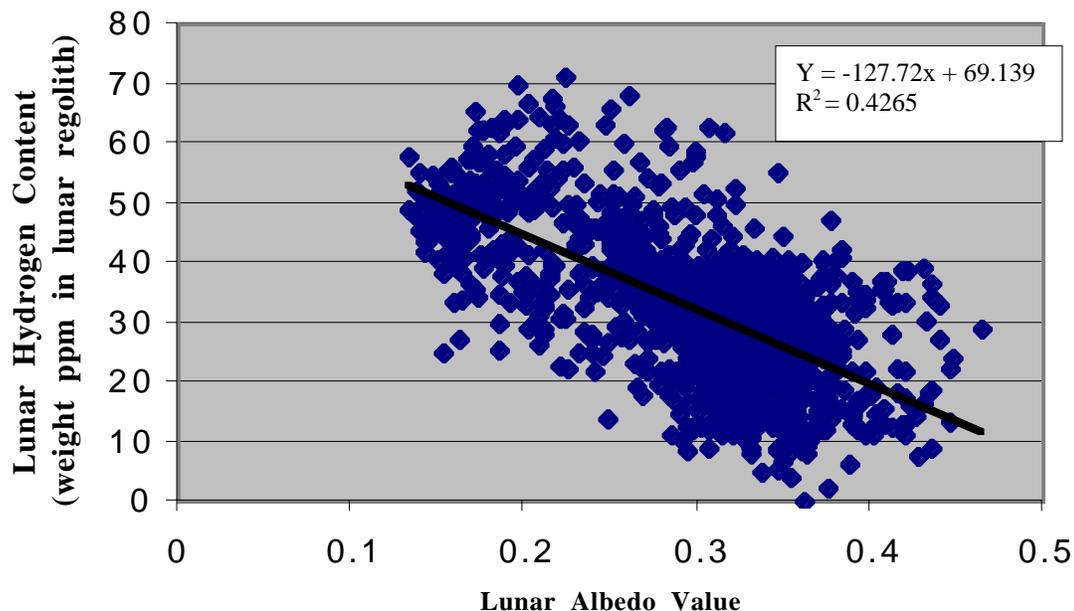
Figure 1. The Average Trapped Lunar Hydrogen is Highest in Regions with the Lowest Average Albedo Values.

documented (33, 34) and comparisons of the Lunar Prospector epithermal neutron data with Clementine optically derived titanium distributions indicate that a similar correlation may exist for hydrogen. As ilmenite is the only significant titanium mineral in the regolith, it would appear to accommodate helium and hydrogen in its lattice better than do other minerals and glasses. It is not yet known how helium and hydrogen are retained crystallographically in ilmenite; however, the feldspar crystal lattice can hold hydrogen in a cation position (35). Concentrations of hydrogen in the vicinity of relatively large and young impact craters (3), such as Tycho in the near side southern highlands, which appear to have excavated plagioclase-rich crust (9) suggest that such selective retention takes place on the Moon. This trapping mechanism may be enhanced in the more sodium-rich feldspars in KREEP materials and in turn may relate to the replenishment of the very diffuse sodium atmosphere recently noted around the Moon (36, 37). Helium release signatures from lunar samples containing ilmenite have recently been duplicated in terrestrial ilmenite, irradiated with helium ions at solar-wind energies (38).

Solar-Wind Considerations

The actual amount of solar-wind hydrogen in the lunar regolith, that is, the balance between adsorption and induced losses, has been affected by many variables. These include the solar-wind flux of protons relative to latitude and longitude, the tilt of the Moon's axis relative to the ecliptic plane, the non-ecliptic component of the solar-wind velocity, the diurnal temperature profiles experienced by the regolith as a function of latitude and slope, pickup ion redeposition on the lunar surface, the abundance of various minerals in the regolith, the interaction of the Moon with the Earth's magnetosphere, and the micrometeorite flux impacting the upper surface of the regolith.

As the Moon's axis of rotation probably settled into its present orientation relative to the flow of solar particles several billion years ago, it can be expected that the total primary flux of solar protons has been less at the lunar poles than at lower latitudes. A significant integrated flux over that period of time, however, would result from the approximate 1.5° inclination of the Moon's axis of rotation to the ecliptic as well as the variability of solar-wind flow due to perturbation of the flow by plasma instabilities and the Earth's magnetosphere. Preliminary analysis of these parameters by co-authors Zalewski and Santarius (39) has been made using a formalization of the general problem of solar-wind deposition on a rotating moon with its axis (or velocity) tilted at an arbitrary angle to the ecliptic plane and complete magnetospheric shielding for an arbitrary fraction of the Moon's orbit. Including the lunar-axis tilt and non-ecliptic component of the solar-wind is anticipated to have a significant effect on the volatile inventory near the lunar poles. Further, thermalized hydrogen released elsewhere on the Moon during daytime heating and by micrometeoroid impacts will be ionized and entrained in the solar-wind and either be re-deposited elsewhere or lost to space. The preliminary work of co-authors Malecki and Santarius (40) has indicated that such "pickup ions" are an important phenomenon affecting the distribution of volatiles across the surface of the Moon, particularly with respect to the contents of permanently shadowed craters.

In the cold polar regions, losses of adsorbed solar-wind hydrogen due to diurnal heating can be expected to be much lower than where the adsorbing regolith surface temperature reaches an equatorial diurnal maximum of about 123°C. This constitutes a maximum difference of 350°C between equator and permanently shadowed areas at the poles. In addition, the solar-wind hydrogen at and near the lunar poles would be disseminated throughout the regolith as it is elsewhere. Its concentration would increase gradually as areas of permanent shadow are approached due to the gradual reduction in solar heating per unit area and thus a reduction in daily thermal losses. This

latter gradation has been noted in the Prospector neutron spectrometer data gathered at low altitude (3).

At this point in our knowledge, then, a factor of three (3) or more concentration of solar-wind hydrogen around the poles should not be surprising. It should be noted that primordial hydrogen derived from the breakdown of accretionary water has almost certainly been released at the lunar surface, most recently during mare volcanism as indicated by vesicles in mare basalt (41). The relative importance of this source may be determined by future measurement of D/H ratios on returned hydrogen from permanently shadowed deep regolith.

Erosion of Water Ice

A continuous blanket of cometary water ice and other volatiles, precipitated on rare occasions in permanent shadow, constitutes a likely transient phenomenon on the Moon. Unless protected in some way this blanket would remain subject to micrometeoroid induced erosion comparable to the stirring or gardening of the upper few centimeters of regolith elsewhere approximately every ten million years (9). Additional erosion probably will occur due to sputtering in reaction to solar-wind particles (42). Unless fortuitously covered by protective ejecta from larger, but very infrequent impacts, or originally deposited on a particularly deep and thus largely protected crater floor, the water ice blanket probably would steadily erode. Under normal conditions, the blanket would be dispersed in a geologically short interval before much of its volatiles could be incorporated and preserved in the polar regolith. On the other hand, small amounts of water ice of cometary origin may be buried locally in this regolith due to fortuitous combinations of events related to local impacts and regolith generation near the boundaries of permanently shadowed areas. Exploration by roving vehicle would be required to quantify the presence and distribution of such scattered water ice deposits.

Conclusion

The Lunar Prospector neutron spectrometer apparently has measured a significant polar concentration of hydrogen. The preliminary hydrogen concentrations reported by the Prospector Team are 1500±800 wppm in permanently shadowed craters near the South Pole. This would be about 5-15 times the maximum solar-wind hydrogen measured in the Apollo regolith samples after return to Earth. In the polar regions generally, the concentrations are about three times the maximum in returned samples. If this constitutes a concentration of solar-wind hydrogen, it raises the possibility that the light isotope of helium (^{3}He) also is enhanced at the lunar poles. ^{3}He holds great promise as a future lunar resource export to supply future fusion power plants on Earth (14, 7). Up until the Lunar Prospector's results, early mine planning attention had been paid largely to large areas in Mare Tranquillitatis due to the positive correlation of helium concentration with that of titanium-rich regolith (33, 34). The 2000-km long volcanic province of central Mare Procellarum constitutes another high titanium region of the Moon (34). Until a direct evaluation of the strength of the titanium-helium correlation can be made in this province, however, Tranquillitatis probably will remain the preferred target area for early production. Whether a concentration advantage at the lunar poles can offset the higher cost of mining, living, and transportation inherent to polar operations remains to future studies.

Clearly, water ice and other exotic volatiles at the lunar poles would be extraordinarily interesting scientifically, as they would likely be derived from impacting comets rather than any internal lunar source. Many suggestions also have been made that water ice at the lunar poles enables permanent human habitation of the Moon. If a justification for such habitation exists, and we believe that the

potential of lunar ^{3}He as a terrestrial fusion fuel justifies lunar settlement (8), the presence of solar wind hydrogen in the regolith everywhere on the Moon allows water to be produced as needed with or without polar ice. The regolith must be heated to about 700°C to extract the hydrogen (43), causing some of that hydrogen to react with oxygen-bearing regolith minerals to form water. The economics of processing regolith for water where needed probably favor such an approach over landing at the poles, mining and processing low concentrations of water ice, if present, and transporting water to a place of use elsewhere on the Moon. Such a trade study should be undertaken to quantify this conclusion as a function of possible hydrogen and water concentrations and the latitude of the user.

Acknowledgments

References

1) Feldman, W. C., and co-workers, 1998, *Science,* 281, pp. 1496-1500.

2) Nozette, S. and co-workers, 1999, *Lunar and Planetary Science Conference 30*, Abstract #1665.

3) Feldman, W. C., and co-workers, 1999, *Workshop on New Views of the Moon II,* LPI 980, pp. 14-15.

4) Watson, K., and co-workers, 1961, *Journal of Geophysical Research*, 66, p. 3033.

5) Heiken, G. H., and co-workers, 1991, *Lunar Sourcebook,* p. 444.

6) Carrier, W. D., III, and co-workers, 1973, *Journal of Soil Mechanics*, Foundation Division, American Society of Civil Engineering, 99, pp. 979-996.

7) Schmitt, H. H., *Science*, 182, 1973, pp. 681-690.

8) Schmitt, H. H., 1997, *Journal of Aerospace Engineering*, pp. 60-67.

9) Schmitt, H. H., 1999, in Mark, H., editor, *Encyclopedia of Space* (in press).

10) Wilhelms, D. E., 1987, *Geologic History of the Moon*, U.S. Geological Survey Professional Paper 1348.

11) Schmitt, H. H., 1991, *American Mineralogist,* 76, pp. 171-184.

12) Spudis, P. D., 1996, *The Once and Future Moon,* Smithsonian, Washington, pp. 83-69.

13) Taylor, S. R., 1999, in P. R. Weissman, and co-workers, *Encyclopedia of the Solar System,* Academic Press, San Diego, pp. 247-275.

14) Wittenberg, L.J., and co-workers, 1986, *Fusion Technology* 10, 167, and Wittenberg, L. J., and co-workers, 1992, *Fusion Technology,* 21, p. 2230.

15) Binder, A. B., and co-workers, 1998, *Science*, 281, pp. 1475-1500.

16) Heiken, G. H., and co-workers, 1991, *Lunar Sourcebook,* pp. 317-321.

17) Keller, L. P., and co-workers, 1999, *Workshop on New Views of the Moon II,* LPI 980, pp. 32-34.

18) Hawke, B. R., and co-workers, 1999, *Workshop on New Views of the Moon II,* LPI 980, pp. 22-23.

19) Staid, M. I., and Peiters, C. M., 1999, *Lunar and Planetary Science Conference 30,* Abstract 1724.

20) Wolfe, E. W., and co-workers, 1981, *The Geologic Investigation Of The Taurus-Littrow Valley: Apollo 17 Landing Site,* Geological Survey Professional Paper 1080, p. 208.

21) Wolfe, E. W., and co-workers, 1981, *The Geologic Investigation Of The Taurus-Littrow Valley: Apollo 17 Landing Site,* Geological Survey Professional Paper 1080, pp. 103 and 207.

22) Lipschutz, M. E., and Shultz, L., 1999, in Weismann, P. R., and co-workers, Eds. *Encyclopedia of the Solar System*, pp. 664-665.

23) Feldman, W. C., and co-workers, 1998, *Science*, 281, pp. 1489-1500.

24) Heiken, G. H., and co-workers, 1991, *Lunar Sourcebook,* pp. 354-356 and 436-448.

25) Fegley, B., Jr., and T. D. Swindle, 1993, in J. Lewis, and co-workers, Eds., *Resources of Near-Earth Space*, University of Arizona Press, 1993, pp. 393-395.

26) Margo, J. L. and D. B. Campbell, *Lunar and Planetary Science Conference 30*, Abstract #1897, 1999.

27) Bussey, D. B. J., and co-workers, *Lunar and Planetary Science Conference 30*, Abstract #1731, 1999.

28) Feldman, W. C., and co-workers, 1999, *Science*, 285, p. 531.

29) Heiken, G. H., and co-workers, 1991, *Lunar Sourcebook,* p. 28-36.

30) Lunar Prospector Neutron Spectrometer homepage in LANL web site: http://nis-www.lanl.gov/nis-projects/lunar/pages/spectros.html.

31) Lunar Prospector Neutron Spectrometer homepage in NASA web site: http://nssdc.gsfc.nasa.gov/cgi-bin/database/www-nmc?98-001A-02.

32) Clementine mission homepage in NASA web site: http://cass.jsc.nasa.gov/expmoon/clementine/clementine.html.

33) Cameron, E. N., 1993, *Evaluation of the Regolith of Mare Tranquillitatis as a Source of Volatile Elements*, University of Wisconsin Technical Report, WCSAR-TR-AR3-9301-1.

34) Johnson, J. R., and co-workers, 1999, *Geophysical Research Letter*, 26, 3, pp. 385-388.

35) Behrens, H. and G. Juller, 1995, *Mineral Magazine*, 59, pp. 15-24.

36) Mendillo, M., and Baumgardner, J., 1995, *Nature,* October 5. (Reported in Science News, 1995, 148.)

37) Stern, S. A., 1999, *Workshop on New Views of the Moon II,* LPI 980, p. 64.

38) Harris-Kuhlman, K. R., 1998, *Trapping and Diffusion of Helium in Lunar Materials,* Ph.D. Dissertation, University of Wisconsin-Madison.

39) Zalewski, M. J., 1999, University of Wisconsin Report UWFDM-1109, and Zalewski, M. J., and Santarius, J. F.

40) Malecki, M. J., 1999, University of Wisconsin Report UWFDM-1110, and Santarius, J. F., and Malecki, M.J..

41) Schmitt, H. H., 1999, *Workshop on New Views of the Moon II,* LPI 980, p. 56-58.

42) Lanzerotti, L. J., and Brown, W. L., 1981, *Journal of Geophysical Research,* 86, pp. 3949-3950.

43) Pepin, R.O., and co-workers, 1970, *Proceedings Apollo 11 Lunar Science Conference,* 2, pp. 1435-1454.