

Abundance of ^3He and Other Solar-Wind-Derived Volatiles in Lunar Soil

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Abstract

Volatiles implanted into the lunar regolith by the solar wind are potentially important lunar resources. Wittenberg et al. (1986) have proposed that lunar ^3He could be used as a fuel for terrestrial nuclear fusion reactors. They argue that a fusion scheme involving D and ^3He would be cleaner and more efficient than currently-proposed schemes involving D and T. However, since the terrestrial inventory of ^3He is so small, they suggest that the lunar regolith, with concentrations of the order of parts per billion (by mass) would be an economical source of ^3He . Solar-wind implantation is also the primary source of H, C and N in lunar soil. These elements could also be important, particularly for life support and for propellant production.

In a SERC study of the feasibility of obtaining the necessary amount of ^3He , Swindle et al. (1990) concluded that the available amount is sufficient for early reactors, at least, but that the mining problems, while not necessarily insurmountable, are prodigious. The volatiles H, C, and N, on the other hand, come in parts per million level abundances (Fegley and Swindle, 1992). The differences in abundances mean that a) a comparable amount of H, C and/or N could be extracted with orders of magnitude smaller operations than required for ^3He and b) if ^3He extraction ever becomes important, huge quantities of H, C, and N will be produced as by-products.

Introduction

Previous work on identifying promising sites for ^3He mining has focused on ilmenite (and hence Ti) content (e.g., Cameron, 1991), since ilmenite retains a higher fraction of the implanted He than do other common lunar minerals. Discussions of the abundances of H, C, and N, which are less dependent on mineral chemistry, generally assume that these volatiles are rather uniformly distributed in the lunar regolith, with only local variations as a result of local impact cratering history (Haskin 1989; see also Taylor 1991).

However, there are geometric factors affecting the abundance of all solar-wind-derived volatiles that have not been previously considered in discussions of resource utilization. In particular, since the Earth's magnetosphere shields the Moon from the solar wind during the portion of each month in which the subsolar point is at the central nearside, that region has been exposed to considerably less solar wind than has the central farside. In addition, equatorial regions should receive more solar wind than polar regions because the direction of the flow of the solar wind is close to the plane of the Moon's equator. Whether this translates into a difference in volatile content depends on how important saturation effects are: if the surfaces of samples from the central near side (such as the well-studied Apollo samples) are saturated with solar-wind derived volatiles, additional exposure will not lead to higher volatile contents.

In a previous nine-month grant, calculations were made of the expected size of variations in the solar wind fluence. Under the current grant, we have combined these calculations with estimates of lunar chemistry based on both telescopic and Apollo observations to identify sites that are promising either as resources, or as areas to test for the effects of saturation. We have acquired some crucial lunar samples and have performed some of the analyses to test for saturation, although these experiments have not yet been completed.

Variations in solar wind fluence

As a first step, we calculated how the integrated solar wind fluence varies with latitude and longitude on the Moon. The latitude effect is simply proportional to the cosine of the latitude. The longitude effect is more complicated, since it depends on the details of the Earth's magnetotail and magnetosheath. Rather than modeling the magnetosheath in detail, we assumed that the Moon is completely shielded for 25% of the lunar cycle. Under those conditions, the central near side receives less than 30% of the fluence that the central far side receives, and only about 35% of the fluence received by the limbs. A map of the relative fluence is given in *Figure 1*. Changing the

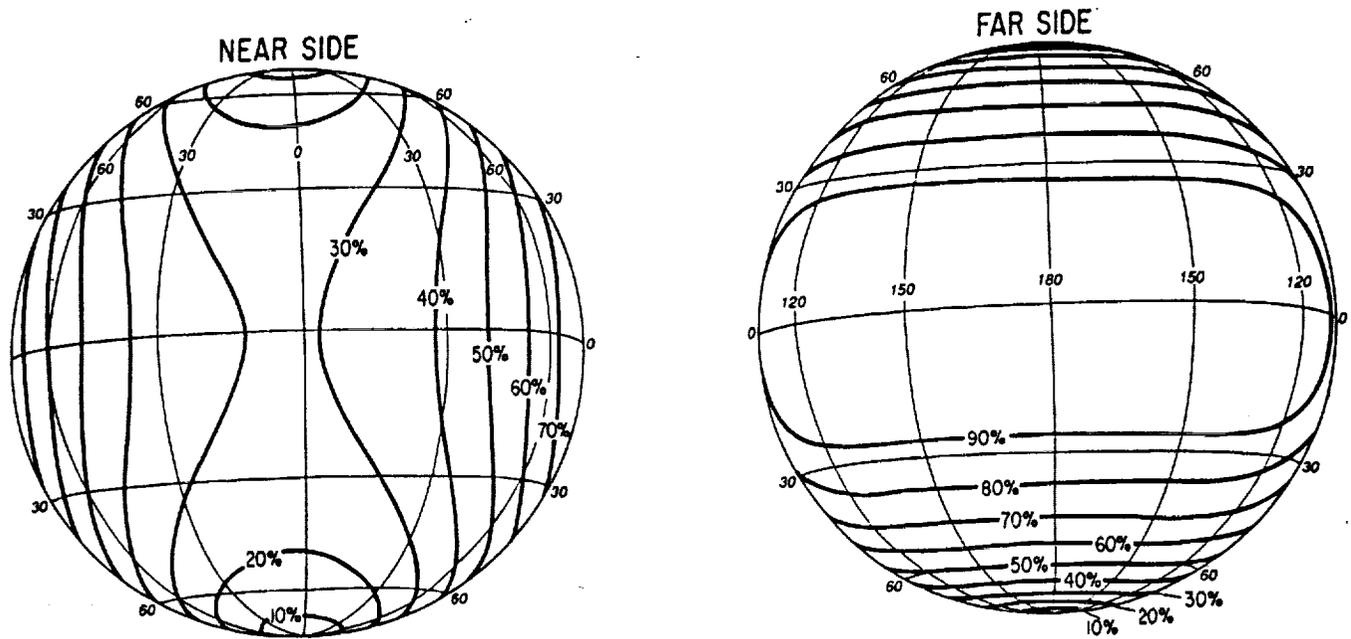


Figure 1: Relative fluence of solar wind incident on various lunar locations. The maximum fluence (defined as 100%) is received at the equator on the far side.

details of the shielding (i.e., changing the amount of time shielded, or including partial shielding for the whole duration of the magnetosheath passage, rather than total shielding for part of the duration) will change the details of the map, but not the overall pattern. For elements for which soil chemistry is not important (probably all the elements of interest except He), a global abundance map should look nearly the same (except for local variations in impact history), unless saturation effects are important. If saturation is important, the volatile abundances of high-solar-wind-fluence sites would still be expected to be higher than low-solar-wind-fluence sites, although there might be a saturation abundance which would be approached.

For ^3He , we must include soil chemistry to estimate abundances. Jordan (1989) has shown that the abundance of ^3He in Apollo (central nearside) samples is proportional to the product of a parameter called I_s/FeO (which measures duration of surface exposure, and will be discussed in more detail below) and Ti content. This is reasonable, since the first factor should be proportional to the amount of solar wind received, and the second is proportional to the fraction retained (since ilmenite retains far more than other minerals). Generalizing to consider fluence variations, we would expect the abundance to be proportional to the product of the fluence and the Ti content. We have generated a map of estimated ^3He abundance based on that assumption, using the fluence variations calculated as described above, and maps of estimated Ti abundance based on spectrophotometry of the Moon (Johnson et al. 1991) and on the Apollo gamma-ray spectrometer Ti results (Davis 1980). These maps are shown in *Figure 2*.

Since the highest Ti abundances are concentrated in the central near side, where the solar wind fluence is lowest, the two effects tend to cancel each other. Mare Tranquillitatis, with its very high Ti content, but low longitude, is still one of the best places to look for ^3He , but some other areas with moderate Ti content but higher longitudes (e.g., western Oceanus Procellarum, Mare Fecunditatis, Mare Smythii) are potentially as promising. With a few exceptions (most notably in and around Mare Smythii on the eastern limb), there are few promising sites on the far side, despite the higher solar wind fluence.

Testing the importance of saturation effects

We have noted that we can convert solar wind fluence to estimated volatile abundance only if saturation effects are not important. In the lunar sample literature, the question of whether or not some grain surfaces are saturated is not settled. The best solar-wind simulation studies were performed recently by Futugami et al. (1990), who bombarded pure mineral samples with He ions.

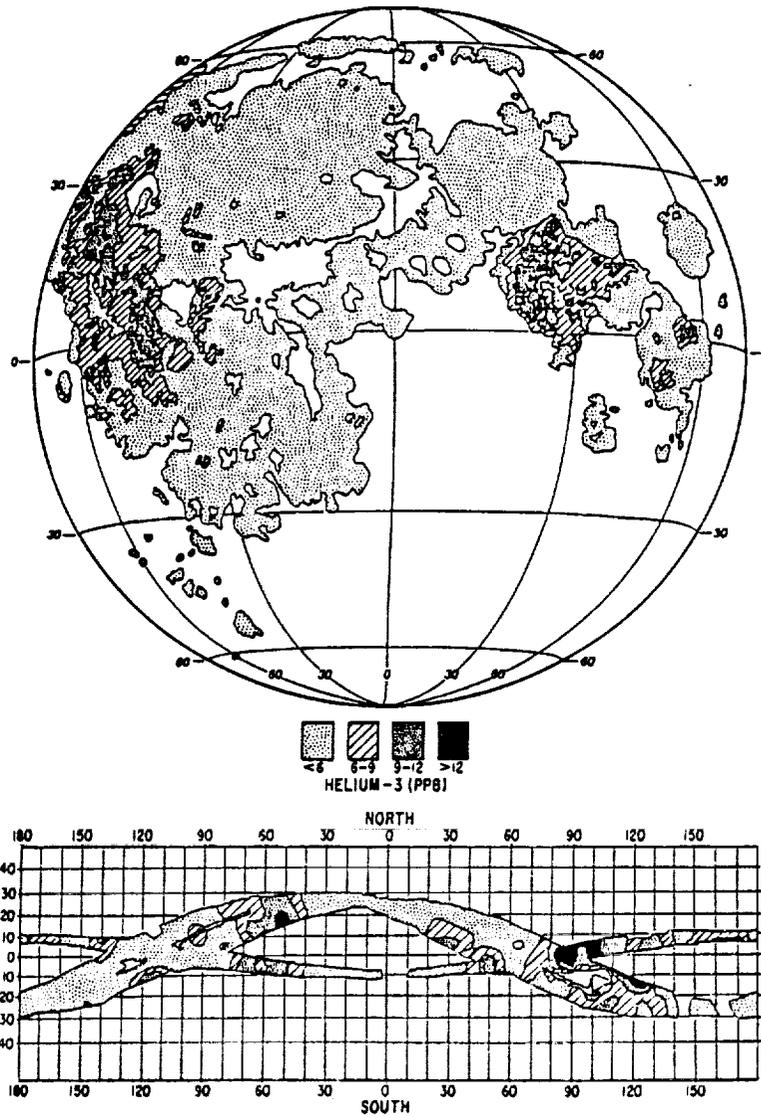


Figure 2: ^3He abundance at various lunar locations, based on the correlation of Jordan (1989), the relative fluence shown in Fig. 1, and estimates of Ti content. Top map uses estimates from visible and near-infrared spectroscopy (Johnson et al., 1991), bottom map uses estimates from Apollo gamma-ray spectrometry (Davis, 1980). Note that these assume that saturation does not occur.

They concluded that saturation of a free grain in space could occur in about 10 years of completely unshielded exposure (corresponding to a few decades of exposure on the Moon). Under these conditions, saturation of He, at least, would be expected to be important. In a study of actual lunar samples, Wieler et al. (1980) concluded that He saturation of grain surfaces occurs for "a considerable fraction" of the grains they analyzed. However, they also concluded that saturation of Ar occurs for few samples. Since Ar abundances correlate well with abundances of C and N (and, with poorer data, H), even at high abundances, it seems likely that these species are not saturated either.

To test for saturation effects, we should compare volatile abundances in samples from locations which we would predict to have a range of solar wind fluences. The Apollo samples all come from a limited geographic range on the central near side. The location with the highest estimated fluence (Apollo 17) would have only 50% more than the location with the lowest fluence (Apollo 15), and only 15% more than the mean of the Apollo samples. The ideal samples would be ones from documented locations on the central farside, but such samples are, of course, not available. The best samples, then, are the Russian Luna samples, which come from closer to the eastern limb of the nearside, and hence would be expected to have about twice the solar wind fluence as the average Apollo sample, and more than 60% more than even Apollo 17.

We acquired samples of two soils each from Luna 16 and Luna 20 ferromagnetic resonance (FMR) and noble gas analyses. The FMR analyses, which were performed by R. V. Morris of NASA Johnson Space Center, are essential to determining the ratio of reduced to oxidized iron (I_s/FeO), a widely-used, probably impact-driven, measure of "maturity" or exposure history (Morris 1976). These measurements, the first I_s/FeO measurements on Luna 16 or Luna 20 samples, suggest that both are quite mature. The few previous noble gas analyses on Luna samples scatter by more than would be expected from heterogeneity (i.e., some of the calibrations were probably incorrect), so we are in the process of measuring the noble gas abundances in these four Luna soils. The He analyses are obviously relevant to the question of 3He abundances, while the analyses of the heavier noble gases (Ar, Kr and Xe), whose abundances are not affected by the chemistry of the soil, provide a good analog for volatiles such as C and N. At the time of submission of the progress report, instrument calibration for these measurements is underway, and the measurements should be completed during the final weeks of the grant.

Well-calibrated measurements are essential to answering the question of saturation. The previous He measurements of Luna 16 and Luna 20 soils, when combined with Ti abundances and the new I_s/FeO results, scatter enough to overlap predictions based on either no saturation or complete saturation, although the mean is more consistent with complete saturation. For Xe, the scatter in abundances measurements is even larger, although the mean is considerably higher than predicted based on I_s/FeO . Although it would not be surprising if saturation effects were stronger for the more abundant gas, He, our conclusions will have to await our own analyses.

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