The Relationship of Surface Chemistry and Albedo of Lunar Soil Samples

T. Gold, E. Bilson and R. L. Baron

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The relationship of surface chemistry and albedo of lunar soil samples

By T. Gold, F.R.S., E. Bilson and R. L. Baron
Center for Radiophysics and Space Research, Cornell University
Ithaca, New York 14853, *U.S.A.*

A relation between the albedo and the surface iron concentration (determined by Auger electron spectroscopy) of lunar soil samples is described. The effect of solar wind sputtering on the surface chemistry and albedo of the soil is discussed.

It has been suspected for over two decades now (Gold 1955) that the low albedo and other peculiar optical properties of the Moon can be explained by a surface cover which consists mostly of fine powder darkened by some kind of weathering process. Analysis of the lunar material indeed showed that the albedo of most of the soil samples is less than one half of that of ground up rock samples of similar chemical composition. We have found a relation between the albedo of the soil and the presence of an iron-rich substance covering much of the surface of the grains (Gold *et al.* 1974). Ground-up rock of similar composition, but lacking the surface film, shows generally a much higher albedo. We have analysed by Auger spectroscopy the surface chemistry of numerous soil and rock samples from all the Apollo missions and found that whereas the concentration of iron on the surface of grains of freshly ground-up rock is within experimental error the same as the bulk concentration, on soil grains the surface iron concentration is in most cases 2–3 times greater than the bulk iron concentration (see figure 1). The light absorption of the samples is also plotted in this figure, indicating its relation with the surface iron concentration. This latter relation is more strikingly demonstrated in figure 2. Here, the light absorption column was replaced by a column representing the surface iron concentration required to cause the observed albedo. This concentration was calculated by a least square fit of the albedo (A) and the measured surface iron concentration (n) to the law $A = A_0 e^{-n\sigma}$, which is the law expected for an absorption centre density proportional to the iron concentration. As figure 2 indicates, the measured iron concentration and the observed albedo fit this law very closely for all iron-rich samples. Indeed this relation does not represent the case of the iron-poor, light soil samples where the albedo is dominated by other effects.

Solar wind sputtering and meteoritic evaporation and condensation are the two processes that have been considered capable of causing the coatings on the soil grains. Both are presently being investigated in our laboratory. Hapke (1966) demonstrated that rock powders treated by simulated solar wind (2 keV proton or α-particle beams) were darkened to lunar albedo values. Using the same method as Hapke and similar doses of 2 keV energy proton or α irradiation we succeeded (figure 3) in demonstrating that the surface iron concentration of ground-up rock samples can be significantly increased by a dose corresponding to a few thousand years of solar wind. The Auger spectrum of irradiated rock powders is strikingly similar to that of soil samples collected from the same site and of similar bulk chemical composition. The albedo of the irradiated rock was also significantly lowered (although not precisely measured in this experiment). As the Auger spectra indicate, there was no carbon contamination caused by this irradiation. The thickness of the iron enriched coatings on lunar soil grains and laboratory irradiated rock grains has not been determined. Auger analysis offers information only to a depth of some 2 nm from the surface. Grant *et al.* (1974) reported that the observed iron peaks in the Auger spectrum of a *single grain* of an Apollo 17 soil sample disappeared after a short period of argon sputtering, indicating that in this particular case the coating was only a few tenths of a nanometre thick, thus presumably optically insignificant. This was, however, only one experiment on one soil grain. Our Auger spectra are taken of compacted powder samples and represent the average surface composition of many thousands of grains; with such samples however, the sputtering method cannot be applied to determine the thickness of surface coatings. On the other hand, the laboratory demonstration that solar wind type sputtering is clearly related to both lowering of the albedo and the creation of iron-rich coatings (similar to those observed on samples subjected to lunar weathering) makes the optical significance of the

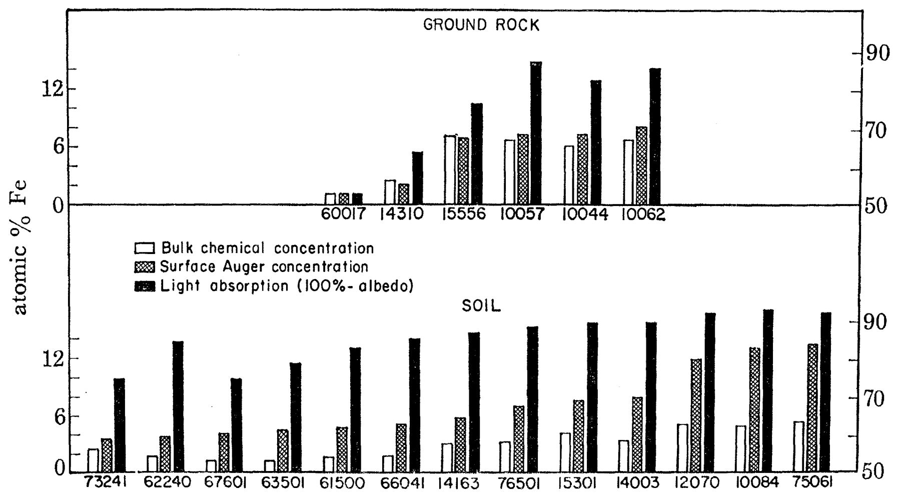

FIGURE 1. Comparison of the bulk iron content (obtained from the literature); the surface iron concentration, calculated from the Auger Fe and O peak ratios and normalized with respect to the bulk iron concentration of rock sample 60017; and light absorption in rock and soil samples.

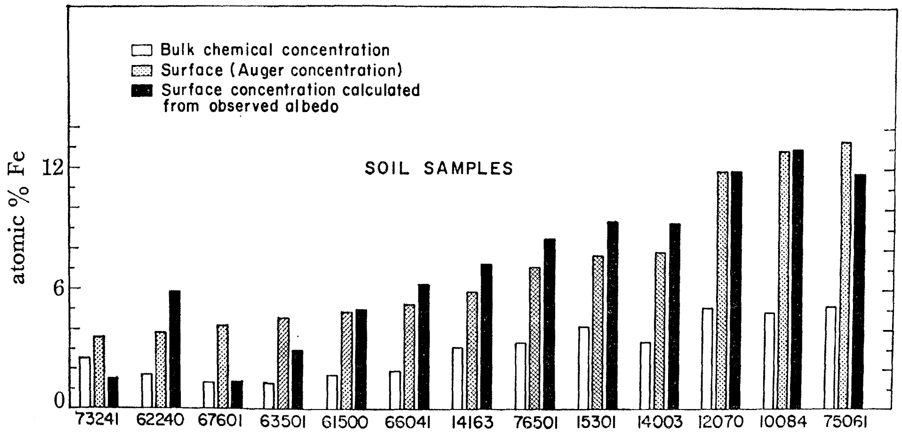

FIGURE 2. Similar to the soil sample plot of figure 1, except that the light absorption column has been replaced by a column representing the surface iron concentration required to cause the observed albedo. This concentration was determined from a least square fit of the albedo (A) and the surface iron concentration (n), to the law $A = A_0 \, e^{-n\sigma}$. The calculated values of A_0 and δ, by the least square method, are 0.2877 and 0.1125 respectively.

coatings quite clear. Auger analysis of lunar soils and ion irradiated rock powders seem to indicate that solar wind sputtering must play a major role in determining the surface chemical composition and also in determining the optical properties of the soil. During the process of impact vaporization, the vaporized species either leave the surface if their velocity is greater than the escape velocity, or enter ballistic trajectories that return to the surface. Those redeposit on the surface a material with a chemical composition not necessarily related to the local chemistry. The apparently strong dependence we observe of surface iron concentration on the bulk iron concentration of the soil suggests, however, that the chemistry of the surface coating is linked to the chemistry of the host grains. This observation favours an explanation by a process of selective removal of light elements by sputtering, rather than one of meteoritic evaporation and recondensation (although the latter process must also be operative, and we cannot determine its importance for soils in other locations than those of our samples).

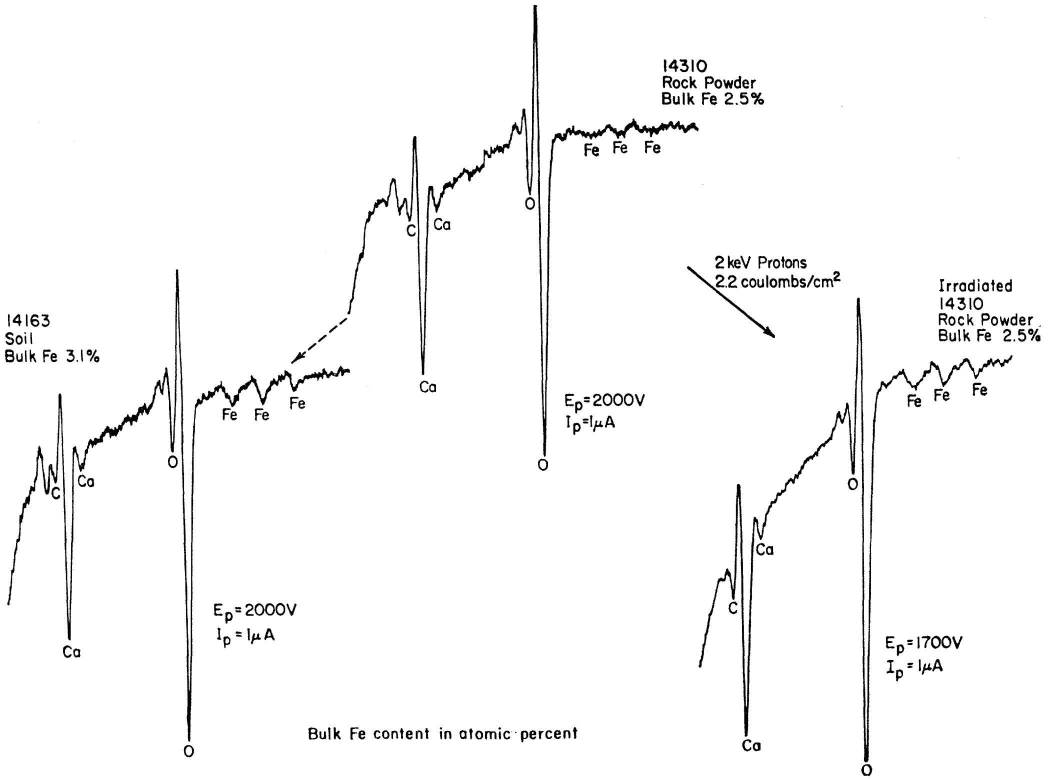

FIGURE 3. Auger spectrum of the pulverized rock sample 14310, along with the spectrum of the same sample after being irradiated by 2 keV energy protons with a dose of 2.2 C/cm^2. The spectrum of soil sample 14163 is also shown in the figure. The soil sample is from the same location as the rock and its bulk chemical composition is similar to that of the rock. The primary electron beam energies and beam currents are listed in the figure; the modulation voltage amplitude was 20 V peak-to-peak for all three spectra.

We propose that the soil grains we have sampled are enriched in heavy metals, principally through the action of the solar wind by the following mechanism: protons or α particles sputter off atoms from the surface with an efficiency which is dependent on the mass, as well as, of course, on the surface binding energies. The transfer of energy from the light ions of the solar wind is more efficient to light atoms, such as oxygen, than to the heavier atoms such as iron and titanium. Under prolonged sputtering bombardment, the concentration of the different species of atoms in the outermost layers will therefore gradually change, with the heavier atoms becoming concentrated. The final equilibrium of this concentration process will be reached when the concentrations have been changed to that value at which the relative probabilities of escape of each species is proportional to its bulk abundance in the substrate. (This is the condition of detailed continuity of flow for each of the atomic species.) This implies a particular saturation enhancement of the heavy atoms on surfaces being denuded by sputtering. It does not specify, however, the thickness of the layer in which such a concentration is reached. The latter must depend on the degree to which diffusion is effective. The destruction of crystal lattices and the energy shed by the embedding of foreign atoms in the outermost several hundred atomic layers by the solar wind presumably favours such diffusion, and it may well be that the entire thickness of the 'amorphous coatings' that have been reported by Borg *et al.* (1971) are subject to such diffusion. (These amorphous coatings have been observed by high voltage electron microscopy on both lunar dust grains and feldspar grains treated in the laboratory by simulated solar wind (Maurette & Price 1975).) We presume that it is this equilibrium composition that we observe by Auger spectroscopy, at least in the darker lunar soil samples, and it shows an augmentation of the iron-to-oxygen ratio of a factor between 2 and 3. With so large an augmentation it is clear that iron must be reduced to its metallic form.

In our laboratory simulations the directly bombarded grain surfaces are more enriched in iron than the underside of the grains; this would suggest that the above mechanism was in this case more important than the enrichment by sputter *redeposition* caused by a higher sticking coefficient for heavier atoms. Hapke (1966, 1973) reported the observation that the upper surfaces of rock pieces and tightly compacted powders did not darken, or darkened to much lesser degree than loosely compacted powders. He deduced from these results that it was sputter *deposition* of films on the undersides of the grains in loosely compacted powders that caused the darkening, such mechanism not being operative (or at least much less effective) in the case of flat surfaces with tightly compacted grains, and that the layers on the directly sputtered surfaces were optically thin. The sputter deposition mechanism and chemical analysis of sputter-deposited material from lunar-like glass was also described recently by Hapke *et al.* (1975).

Quite possibly, both types of process have been at work in the lunar case. Our own observations do not allow us to be certain in which circumstance the sputter removal or the sputter deposition has been the most important, but both appear to result in somewhat similar chemical surface changes. Enrichment by sputter deposition would not have a tendency to reach a fixed equilibrium limit as we appear to have observed. On an average, surfaces must be more affected by the sputter removal than by deposition, since for the Moon as a whole there must be a net loss by sputtering. It is therefore quite probable that selective removal rather than selective deposition is generally more important, although again different areas may be treated quite differently. Surface soil samples from locations shadowed from the solar wind by a rock may allow one to observe the distinction between the two processes.

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