

Reports

Radiation Bleaching of Thin Lunar Surface Layer

Abstract. *The thin, lighter-colored, upper layer of lunar soil shown in the television pictures from several Surveyor missions may be due to reversible bleaching by solar radiation. Of several possible bleaching reactions, the one considered most important is the photoreduction of Fe^{+3} to Fe^{+2} .*

Surprisingly, the Surveyor I pictures have indicated that a thin, surface layer of lunar soil is lighter in color than the underlying material (Fig. 1). Explanations of this observation have been proposed by Hapke, by Felice, and by Shoemaker *et al.* (1), but none of these suggestions have been generally accepted. The lighter upper layer is apparently a characteristic of the entire lunar surface since it has been observed by all the successful Surveyors. Also, judging by the Surveyor III observations (2), the layer is very thin—less than 0.5 mm in thickness, which is the resolution limit of the optical system. We now offer a new hypothesis, namely that reversible bleaching by solar electromagnetic radiation of short wavelength is responsible for the lighter surface layer.

Absorption of visible light in silicates is generally associated with transition element impurities (Fe, Ti, and others) or with impurities or other imperfections (or both) related to color centers. The color centers are of two main types: trapped electron centers and trapped hole centers formed by the capture of a charge carrier by a lattice imperfection. These two types of centers usually are paired; that is, a trapped hole is created by removal of an electron, which is then captured elsewhere in the crystal to form a trapped electron center. In some cases, this loss or gain of an electron is quite similar to oxidation-reduction processes involving cation impurities. It has been proposed (3) that the low albedo of the moon is due to color centers associated with oxygen-ion vacancies formed by the sputtering and reducing effects of the solar wind.

Trapped electron centers may be bleached by removal of the electrons; this may be accomplished by exposure

to light of the proper wavelength or by heating to a critical temperature which is related to a specific center. Bleaching of a trapped electron center usually also results in the bleaching of the associated trapped hole center. If light of the appropriate wavelength falls on the lunar surface, traps of this type in the lunar soil could be partially bleached, thus increasing the albedo of the material. Similar effects have been observed in terrestrial silicates, such as α -quartz and glass (4). Solarized silicate glass can be further darkened by irradiation with ultraviolet light or

x-rays. The glass can also be bleached either by heating or by irradiation with light from an unfiltered mercury lamp, because both of these processes have the effect of emptying the trapped electron centers and annihilating the trapped holes in the glass.

If the composition of the lunar surface is a silicate dust similar to terrestrial basalt (5), the most important absorbing ion is probably iron. When appreciable iron is present, color centers in the conventional sense may not be able to form owing to the "poisoning" effect of the Fe^{+3} – Fe^{+2} couple, which gives radiation protection by changes in oxidation states of the iron rather than by production of new, radiation-induced absorption bands in the visible region. However, other coloration and radiation-bleaching mechanisms associated with valence changes of iron are possible.

If the basalt-like dust has much of its iron content in the form of free metal, it might be expected that the major portion of the iron remaining in the basalt is in the Fe^{+2} state due to the reaction

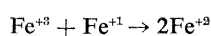


while the basalt was molten during its original formation either on the moon

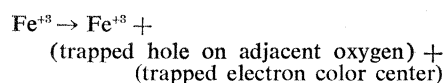


Fig. 1. Footpad of the Surveyor I spacecraft, showing the dark material thrown out by the impact of the foot on the lunar surface. [NASA photograph]

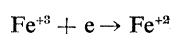
or elsewhere. Although a low metallic iron content of lunar material is indicated by both earth-based and Surveyor V data (6), the reducing conditions in the solar wind, to which the lunar surface is exposed, requires that most of the iron not be in the Fe^{+3} state. If the iron is all in the Fe^{+2} state, it is possible that radiation damage could create Fe^{+1} with an absorption maximum in the visible region of the spectrum. This species is thermally unstable and would be bleached when subjected to solar heating. However, if some Fe^{+3} is present, as is likely because of the reddish color of the moon, the presence of Fe^{+1} due to radiation damage is precluded because of the reaction



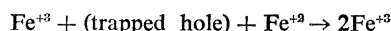
The most probable reaction if the powder contains the Fe^{+3} – Fe^{+2} couple is bleaching in the short wavelength side of the visible spectrum by solar ultraviolet, electrons, and protons through either or both of the following mechanisms



and



where the electron in the last reaction is a photoelectron or secondary electron released elsewhere in the silicate lattice by radiation. However, if appreciable Fe^{+2} is present, which is most likely, the trapped hole reaction is unlikely because of the probable reaction



The only important reaction, then, of Fe^{+3} in the presence of Fe^{+2} would be the radiation-reduction of Fe^{+3} to Fe^{+2} . Because Fe^{+3} absorbs so strongly in the ultraviolet [band maximum in crystalline quartz at 2250 Å (tetrahedral coordination) (7); band maximum in topaz at 2350 Å (octahedral coordination) (8)] that the long wavelength tail of its absorption band extends well into the visible, a decrease in the Fe^{+3} content would cause the absorptivity to decrease; therefore, the transparency and reflectivity of the dust over most of the visible region of the spectrum would increase. A decrease in reflectivity in the red could also be expected in view of the increase of the Fe^{+2} band in the infrared [1.1 to 1.2 μ in acidic volcanic glass (9)]; however, this decrease would be minor, because of the large oscillator strength of Fe^{+3} compared to Fe^{+2} .

The discussion here is probably an oversimplification, as the smaller amounts of manganese and titanium present may also be important in these reactions. If any of the lunar surface is sialic in composition, which appears doubtful, the preceding discussion concerning iron would probably still apply. The exact mechanisms and centers involved as well as rate processes of the radiation-induced reactions must await detailed examination of lunar surface material (10).

The bleaching reactions that we discuss are generally reversible. Thus, when the lunar surface material is removed from sunlight (such as through burial by meteorite gardening) it will darken and, when reexposed, will slowly lighten. Because there were no discernible changes in the albedo of the throw-out from the Surveyor footpads over a period of several weeks, the time constant of the bleaching reaction must be of the order of more than a year. This rate is quite reasonable; for instance, it is well known that amethyst quartz will bleach after exposure to sunlight for several years.

Predictions of the bleaching hypothesis are as follows:

1) Surface-bleaching by photoreduction of Fe^{+3} would cause the material to become less red in color.

2) The lighter layer should be only a few particle-diameters thick.

3) If shielded for a long time from sunlight the layer should slowly darken.

4) Portions of surfaces of clods of soil which are permanently shadowed (as at high latitudes) should be darker than portions exposed to sunlight.

5) The lighter upper layer should have the same composition as the darker material. Within the large experimental errors of the Surveyor VII analyses (5) this prediction agrees with observations.

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References and Notes

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10. In order to study possible chemical or physical differences between the lighter-colored top layer of lunar soil and the darker, underlying layers it is essential that the light material be as highly concentrated in a sample of soil as possible. Such concentration may be difficult because the lighter layer may be only a few particles thick. This difficulty could be circumvented by the following collection technique: if a flat piece of inert material, such as glass, were gently pressed against the lunar surface large numbers of small particles from the uppermost layers would stick to the glass because of surface-adhesive forces. Two pieces of glass could be used to pick up material and then placed with their contaminated faces together for storage and transport. A second, similar set of samples might be collected from subsurface material for comparison.

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Transform Faulting and

Growth of the Gulf of California Since the Late Pliocene

Abstract. *Seismic-reflection and magnetic profiles over more than 6000 kilometers suggest that spreading of the sea floor on the East Pacific Rise, at the mouth of the Gulf of California, began to broaden a proto-gulf about 4 million years ago. Movement occurred, on transform faults, offsetting the rise and other centers of crustal growth within the gulf, and translated the end of the peninsula about 200 kilometers to the northwest. Thick pelagic sediments on the east flank of the rise indicate that there was a lapse of spreading by crustal growth between 4 and 10 million years ago.*

The Gulf of California is commonly believed to have formed by separation of the peninsula of Baja California from mainland Mexico; therefore this is a critical region for examination of hypotheses of spreading of the sea floor and continental drift. Evidence

from our preliminary analyses of new geophysical data suggests that the present configuration of the gulf results from spreading of the sea floor by crustal growth beginning about 4 million years ago on the East Pacific Rise at the mouth of the gulf, and on other