
Summary: Observations bearing on the cause of the low albedo of lunar soil are reviewed, including previously unpublished data. It is concluded that the primary cause of lunar darkening is submicroscopic metallic Fe (SM Fe) generated in the soil by the lunar surface environment. This component is associated with, but not limited exclusively to, agglutinates, and is concentrated at the surfaces of the soil particles. The SM Fe is also primarily responsible for the g=2.1 characteristic ESR ferromagnetic resonance (FMR). Of the various processes which have been proposed to account for the darkening (including, impact vitrification, direct solar wind sputtering, deposition of sputtered material, vitrification of H-saturated grains, and condensation of impact-vaporized soil), limited evidence indicates that the dominant process is the condensation in a semi-closed system of vapor generated by micrometeorite impacts into adjacent soil.

A. Evidence for association of albedo and metallic Fe:
1. There is a correlation between albedo and ferromagnetic content. When the soil is separated into magnetic and non-magnetic fractions the magnetic component is markedly darker (1).
2. There is an inverse correlation between albedo and Fe concentration at the surfaces of fines, as shown by Auger (2) and ESCA (3).
3. There is an inverse correlation between albedo and amount of O2 uptake in thermogravimetric heating experiments (4).
4. It is necessary that the darkening component have strong, featureless absorption over the UV-visible-IR wavelength range. The only known component of the soil with this property is metallic Fe. Other suggested materials, such as glass, ilmenite or magnetite, have distinctive bands which are not present in the spectrum of the soil (5, 6).
5. It has been shown theoretically that SM Fe in amounts observed in lunar soil can account for the low albedo (5, 7).

B. Evidence for association of albedo and FMR:
1. There is an inverse correlation between the (FMR intensity): (Fe0 concentration) ratio and albedo (8).
2. Acid leaching of fines increases the albedo by about a factor of 2 but decreases the FMR intensity by 15 (4).
3. FMR intensity and albedo are correlated with other indices of maturity (9).
4. Heating the soil in a vacuum decreases the FMR intensity (10) and increases the albedo (4) slightly; this can be accounted for by partial coalescence of SM Fe. Heating in air increases the FMR (10) and albedo (4); this can be accounted for by partial oxidation of Fe0 to Fe2+ and Fe3+. This observation implies that the FMR is primarily due to SM Fe rather than to a phase
Albedo of Lunar Soil
B. Hapke

associated with Fe$^{+3}$.  

C. Evidence for association of albedo with agglutinate fraction:
1. There is an inverse correlation between albedo and magnetic fraction of the fines. Most of the magnetic fraction are agglutinates (1). However, both agglutinitic and non-agglutinitic fractions of the soil darken with increasing original agglutinate content, implying that the darkening component is not exclusively associated with agglutinates.

D. Evidence for association of albedo with surface coatings:
1. Surfaces of fines are enriched in Fe (2, 3, 12, 13).
2. There is an inverse correlation between albedo and fraction of grains coated with amorphous material (14).
3. There is an inverse correlation between albedo and surficial Fe enrichment (2).
4. There is an inverse correlation between albedo and weight loss by acid leach (15).
5. Size separates of soil all have about the same albedo, but pulverizing any size fraction to expose the interiors of grains increases the albedo (4).

E. Evidence for the nature of the darkening process:
1. Vitrification of rocks and quench-crystallization of ilmenite causes the appearance of strong absorption bands which are not present in the spectrum of soil (5, 16).
2. Direct sputtering by solar wind has been shown in the laboratory to not darken the exposed surfaces of most materials (except a few minerals highly enriched in Fe such as hematite) (17, 18). However, direct sputtering can cause an increase of Fe on the exposed surface (2).
3. Sputter-deposited coatings have been shown in the laboratory to produce a material with the correct spectrum and albedo (19). Such coatings will accumulate in a powder with time much faster than direct sputter-altered layers. In a complex, highly re-entrant material like lunar soil the loss of mass by sputtering is 10 times lower than from a flat surface (4), showing that in the soil most of the material sputtered by the solar wind will remain in the same locality.
4. The hypothesis of darkening by impact melting of grains saturated with solar wind H remains a possibility. However, this process has not been demonstrated in the laboratory, and there are certain arguments against it. The H molecule is very small and will rapidly diffuse out of a silicate lattice upon heating without reacting. After reduction of FeO the H should have been converted into H$_2$O, which is physically large and does not diffuse easily; thus there should be nearly as much H$_2$O as Fe present in the grains, contrary to observation.
5. Vapor-phase deposition: (a) Ample chemical evidence exists in

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the lunar soil for vapor-phase transport processes (5). (b) Vapor deposition has been demonstrated in the laboratory to produce a material with the correct albedo, spectrum and magnetic properties (5, 15). (c) Mercury has optical properties similar to the moon's. However, Mercury has a magnetic field which appears to be able to stand off the solar wind from the equatorial regions, but not from the poles. Thus if the dominant darkening process is solar wind-dependent the polar regions should be darker than the equatorial. There is no evidence for such polar darkening (20). (d) All lunar soils contain roughly the same amount of SM Fe, regardless of bulk total Fe (21). This observation implies that the process which produces the SM Fe is only weakly dependent on Fe content of the starting material. Of all the processes suggested, only impact-vaporization has this property, since the Fe content of the vapor (and thus of condensates from such vapors) will be primarily controlled by the local temperature in the impact cloud.

References cited: