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CORNELL UNIVERSITY

Center for Radiophysics and Space Research

ITHACA, N. Y.

FINAL TECHNICAL REPORT

to the

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

on

NASA Grant NGR 33-010-137

RESEARCH ON LUNAR MATERIALS

Principal Investigator: Professor Thomas Gold

In the period of February 1, 1971 to April 30, 1978 this grant supported all research involving lunar samples at the Center for Radiophysics and Space Research at Cornell University. The principal research topics were:

1. Optical properties of surface and core samples
2. Chemical composition of the surface layers of lunar grains: Auger electron spectroscopy of lunar soil and ground rock samples
3. High frequency electrical properties of lunar soil and rock samples and their relevance for the interpretation of lunar radar observations
4. The electrostatic dust transport process
5. Secondary electron emission characteristics of lunar soil samples and their relevance to the dust transportation process
6. Grain size distribution in surface soil and core samples
7. The optical and chemical effects of simulated solar wind (2keV proton and α particle radiation) on lunar material

All these topics constituted separate but often interrelated experimental research efforts. Some experimental methods and apparatus had been developed while investigating relevant properties of terrestrial material in anticipation of the accessibility of lunar samples. Others, such as the apparatus used for the chemical determinations, grain size analysis and for the electrostatic dust transport process were built under this grant and the methods involved were conceived in this program.

We consider that the major contributions resulting from our investigations of the various physical and chemical properties of lunar material are:

(a) The first and most extensive set of data to date on the surface chemical (major element) composition of lunar soil and rock samples, including a number of core samples, determined by Auger electron spectroscopy and verified by ESCA.

(b) The observation of an iron-enriched layer on the surface of soil grains and the establishment of a relationship between surface iron concentration and albedo.

(c) Experimental demonstration of the ability of simulated solar wind to produce both the surface iron enrichment of the grains and (most likely as a consequence) the darkening of rock powders to the albedo of the soil.

(d) Determination of high frequency electrical properties (dielectric constant and power loss) of numerous rock and soil samples, in the latter as a function of density. The samples constituted a representative set which included material from every Apollo mission. A relationship of power absorption and iron concentration in the samples was shown,but more significantly from the range of power absorbency measured in soil samples and with the help of available radar information important conclusions were drawn concerning the physical make-up of the subsurface of the Moon.

(e) Experimental demonstration of the electrostatic dust transportation process and observation of the different topographic phenomena created by such a process. Results of the measurement of the first crossover voltage (bombarding electron potential at which the number of electrons hitting a surface area is equal to the number of electrons emitted by it) for surface soil samples and core samples gave support to the supposition that layers of different soils might be deposited by an electrostatic transport process without being mixed due to differences in the secondary electron emission properties of these soils and their consequent "resistance" to mix under electron bombardment.

The following papers were published under this grant (an abstract is shown along with the title of each):

Proceedings of the Third Lunar Science Conference
(Supplement 3, Geochimica et Cosmochimica Acta)
Vol. 3, pp. 3187-3193
The M.I.T. Press, 1972

Grain size analysis, optical reflectivity measurements, and determination of high-frequency electrical properties for Apollo 14 lunar samples

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Abstract—The particle size distribution is measured for the Apollo 14 bulk and contingency fines as well as for two subsamples from the 14230 core sample. Among these samples there seems to be no significant variation in grain size distribution. Reflectivity measurements on lunar fines from different Apollo missions show that their albedo decrease significantly after being subjected to a dose of proton bombardment which would be equivalent to approximately 1.5×10^4 years of solar wind. Results of dielectric constant and power absorption length measurements are reported for Apollo 14 fines and an Apollo 14 rock sample. A strikingly long absorption length 28 wavelengths is observed for the rock sample 14310.161 at 450 MHz.

Grain Size Analysis and High Frequency Electrical Properties of Apollo 15 and 16 Samples

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ABSTRACT: The particle size distribution was measured for Apollo 15 and 16 surface fines from various locations and for 11 Apollo 15 deep drill core samples from different depths below the surface. Significant differences are observed in the size distributions determined in core samples originating from layers a few cm apart. The relevance of this finding to the deposition process of soil layers is discussed. The dielectric constant and the power absorption length were determined for eight soil samples and three rock samples of the Apollo 15 and 16 missions at 450 MHz frequency. Strikingly low absorption is observed in rock samples 15597 and 60017, and a generally lower absorption was measured in all Apollo 15 and 16 soil samples than for earlier Apollo samples.

Proc. 4th Lunar Sci. Conf., Geochim. & Cosmochim. Acta 3, 3093-3100, Pergamon, 1973

CONJECTURES ABOUT THE EVOLUTION OF THE MOON*

The Moon 7, 293-306, 1973

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(Received 23 November, 1972)

Abstract. The principal questions about the derivation of the lunar surface have not yet been settled: is it the surface left over from the process of accumulation of the Moon, or is it a surface generated by magmatic processes on the Moon and subsequently altered by further infall from outside? The evidence derived from many sources now favors the former. Seismic data suggest an absence of bedrock down to a depth of several kilometers, and instead a compacted powder only. The 'mascon' evidence can be understood as a consequence of major impacts in a deep porous layer. The great abundance of cosmic ray tracks in most soil samples demands a much greater cosmic ray dosage than present rates would cause in the age of the Moon, unless the dust represented infallen material previously irradiated. The nuclear age, since freezing, of the dust is greater than that of the rocks found. The chemical composition of the dust is not the same as of the rocks. Strict layering of the dust has been seen, implying some process other than meteoritic impacts for its generation and deposition. These and other effects found can be understood in the framework of a cold accumulation description, in which the surface layers represent the last addition of meteoritic infall of a basaltic material similar to, but not identical with the present basaltic achondrites. The possible relation of this material to oceanic basalt on Earth is mentioned.

SPUTTERING AND DARKENING OF THE GRAINS ON THE LUNAR SURFACE

Photon and Particle Interactions with Surfaces in Space (Grard, ed.), 557-560, D. Reidel Publ., Dordrecht, 1973

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Abstract. Sputtering experiments have been carried out in the lunar laboratory at Cornell (first by B. Hapke) since 1964. These have shown that solar wind exposure will lead to the deposition of a dark layer on grains of most rocks. The nature of this layer is not yet known with certainty, but it is thought to be chiefly due to reduced metals. This confirms the supposition, first put forward in 1955, that the albedo of any part of the lunar surface is dependent on the length of time for which it has been exposed. This albedo effect is likely to dominate over effects due to regional chemical differences.

Proceedings of the Fifth Lunar Conference
(Supplement 5, Geochimica et Cosmochimica Acta)
Vol. 3 pp. [illegible]
Printed in the United States of America

Optical properties of the Apollo 15 deep core samples

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Abstract—The variations of albedo observed at different depths in a core tube show almost as large a range as occurs on the surface over the entire moon. Different regions in the core tube are very sharply separated from each other, demonstrating that little mixing had taken place in the deposition process or subsequently. A possible correlation between albedo and cosmic ray exposure is noted.

Proceedings of the Fifth Lunar Conference
(Supplement 5, Geochimica et Cosmochimica Acta)
Vol. 3 pp. 2413–2422 (1974)
Printed in the United States of America

Observation of iron-rich coating on lunar grains and a relation to low albedo

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Abstract—The outermost few atomic layers of lunar soil samples were studied by Auger spectroscopy and were found to contain in each case two to three times more iron than the mean bulk composition of the sample. The amount of excess iron is found to be closely correlated with the optical albedo in the manner that would be theoretically expected if the iron provided absorption centers. Crushed lunar rocks of similar mean composition, but lacking the extra iron coating of the soil grains, have a much higher albedo than most lunar soils sampled or observed on the lunar surface.

LUNAR SCIENCE VI, Lunar Science Institute, Houston, Texas (1975)

EXTRALUNAR ORIGIN OF THE LUNAR SOIL. T. Gold, Center for Radiophysics & Space Research, Cornell Univ., Ithaca, N.Y. 14850

The possibility that the lunar surface represents merely the last stages of the accretion process that formed the Moon has not received much attention (1,2,3). Yet, this is clearly a question of overriding importance to the entire lunar investigation program.

Very strong evidence concerning the lunar soil, such as its exposure record, its state of deposition, as well as radar and seismic evidence, now appears to us to make the case that the surface material fell in more or less in its present form, rather than that it is the consequence of meteoritic grinding of a lunar endogenic crust. Further evidence concerning the Apollo 17 orange soil, the mascons and their absence on the back, and the many indications of surface denudation and deposition all speak for infall and surface transportation processes as having been the dominant effects.

Proc. Lunar Sci. Conf. [illegible] (197[illegible]), p. [illegible]
Printed in the United States of America

Auger analysis of the lunar soil: Study of processes which change the surface chemistry and albedo

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Abstract—The chemical composition of the outermost few atomic layers of thirteen soil samples and six rock samples from all Apollo sites was studied by Auger electron spectroscopy. All soil samples showed a large increase in the iron-to-oxygen ratio (and thereby of the surface concentration of iron) compared with samples of crushed rock or with results of the bulk chemical analysis. The negative correlation between the amount of this enhanced iron and the albedo of soil samples, reported earlier by us, is now greatly strengthened, and shows the functional dependence expected from a population of absorption centers that is proportional to the surface iron content.

Crushed lunar rock samples exposed to 2 keV protons that simulate solar-wind exposure for 2000–3000 yr exhibit both an increase of the surface iron and a lowering of the albedo that makes these resemble closely the lunar soil in both respects. While a variety of surface modification effects may have been present, it appears that an adequate explanation for the low albedo of the moon and the chemical surface properties of the soil can be found in the selective depletion of oxygen (and other light elements) by solar-wind sputtering.

Proc. Lunar Sci. Conf. 7th (1976), p. [illegible]
Printed in the United States of America

Electrical properties of Apollo 17 rock and soil samples and a summary of the electrical properties of lunar material at 450 MHz frequency

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Abstract—The dielectric constant and the voltage absorption length was measured for four Apollo 17 soil samples (73241, 74220, 75061, and 76501) and for two Apollo 17 rock samples (76315 and 79135) at 450 MHz frequency. The dielectric constant and absorption length measurements made on all our lunar samples are reviewed and related to the transition element concentration in these samples. The significance of the laboratory measurements for radar observations is discussed.

Proc. Lunar Sci. Conf. 7th (1976), p. [illegible]
Printed in the United States of America

The surface chemical composition of lunar samples and its significance for optical properties

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Abstract—The surface iron, titanium, calcium, and silicon concentration in numerous lunar soil and rock samples was determined by Auger electron spectroscopy. As reported previously all soil samples show a large increase in the iron to oxygen ratio (and thereby of the surface concentration of iron) compared with samples of pulverized rock or with results of their bulk chemical analysis. The surface titanium concentration of the soil is also significantly increased vs. the bulk concentration whereas the surface calcium and silicon concentration is not significantly different from the bulk concentration in these elements.

A solar wind simulation experiment using 2 keV energy α-particles showed that an ion dose corresponding to approximately 30,000 yr of solar wind increased the iron concentration on the surface of the pulverized Apollo 14 rock sample, 14310 to the concentration measured in the Apollo 14 soil sample 14163 and the albedo of the pulverized rock decreased from 0.36 to 0.07.

The low albedo (as compared to that of pulverized rock) of the lunar soil is seen to be closely in step with the surface concentration of iron and titanium as determined by Auger methods. A solar wind sputter reduction mechanism is discussed as a possible cause for both the surface chemical and optical properties of the soil.

Proc. Lunar Sci. Conf. 8th (1977), p. [illegible]
Printed in the United States of America

Chemical and optical properties at the Apollo 15 and 16 sites

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Abstract—The bulk chemical composition, the surface chemical concentration of four major elements, and the optical albedo were determined for six core samples, from two sites and from four different depths below the lunar surface, and also for surface soil samples from the vicinity of the sites of the cores. The chemical composition of the core samples was found to be related to that of the surface samples from the same sites, and the correlation of the albedo with the surface iron plus titanium content that has previously been demonstrated for the surface samples was also verified for the core samples. A soil layer near the bottom of the Apollo 15 deep drill core was found to be unusual in two respects: the grain surface and the bulk chemical compositions were found to be more similar than is usual, and the albedo was exceptionally high, though still only 0.6 of the albedo of crushed rock of similar composition.

The mechanism of darkening of lunar soil is discussed in the light of these observations.

Proc. Lunar Sci. Conf. 8th (1977), p. [illegible]
Printed in the United States of America

Electrical properties at 450 MHz of Apollo 15 and 16 deep drill core samples and surface soil samples at the same site

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Abstract—The dielectric constant and the voltage absorption length were measured for Apollo 15 and 16 deep core samples at 450 MHz frequency. The measured values are compared to those obtained for surface soil samples from the same mission.

The absorbencies in the core samples were found to be in the same range as those of the surface samples. The significance of these results for radar observations is discussed.

Phil. Trans. R. Soc. Lond. A. 285, 4[illegible] 31 (1977) [427]
Printed in Great Britain

The relationship of surface chemistry and albedo of lunar soil samples

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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.

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The Search For the Cause of the Low Albedo of The Moon

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The effects of different weathering processes on the albedo of the lunar surface cover is discussed. The surface chemical composition of numerous lunar soil and pulverized rock samples was determined by auger electron spectroscopy. The optical albedo of these samples was also measured. The chemical concentration of iron and titanium is greater on the surface of soil samples than it is on the surface of crushed rock samples with similar bulk composition, whereas the albedo of soil samples is lower than that of the crushed rock samples. A correlation is presented between the surface iron + titanium content and the albedo. Results of solar wind simulation experiments show that irradiation of crushed lunar rock samples with a small dose (corresponding to 3000 years of solar wind) of 2-keV energy protons changed the surface chemistry of the rock to that of the soil. A much larger dose of protons (corresponding to 30,000 years of solar wind) was needed to darken crushed rock to the albedo of the soil of similar bulk chemical composition. The mechanism of darkening by solar wind is discussed, and its effectiveness is compared to that of other darkening processes.

Earth and Planetary Science Letters, 37 (1977) 263–272
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THE SURFACE COMPOSITION OF LUNAR SOIL GRAINS: A COMPARISON OF THE RESULTS OF AUGER AND X-RAY PHOTOELECTRON (ESCA) SPECTROSCOPY

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ESCA spectra of lunar soil and crushed rock samples are compared to previously obtained Auger spectra of the same samples. The ESCA data confirm the increase of Fe concentration on the surface of soil samples over their bulk Fe content, and strongly support the existence of layers on the surfaces of lunar soil grains which are significantly enriched in Fe, some of which is in the Fe⁰ state. The significance of the ESCA information on the major elemental composition of lunar soil grain surfaces for the understanding of the processes that affect the state of the regolith is discussed.

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SOLAR WIND EFFECTS ON THE SURFACE CHEMISTRY OF LUNAR GRAINS

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__Abstract__. Surface enhancements of iron and magnesium in crystals from lunar rock and soil samples have been measured by ion microprobes and were attributed to solar wind implantation of these elements. In this paper it is shown that these surface enhancements and in particular the Fe/Mg surface concentration ratios can also be explained as resulting from the sputter action of solar wind protons and He ions. Furthermore, since these ions are ten thousand times more abundant in the solar wind than ions of the elements which principally constitute the lunar grains, calculations demonstrate that sputtering by protons and He ions moves approximately a hundred times more Mg atoms, for example, than the number of solar wind Mg ions striking the surface. Ion implantation is unlikely, thus, to have a dominant effect on the major element composition of the surface of lunar grains.