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Solar wind and micrometeorite effects in the lunar regolith

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Using available data from the literature, we formulate an outline of the major physical and chemical effects expected during solar wind bombardment of the lunar regolith. In agreement with the results of Auger and e.s.c.a. analyses of the composition of lunar grain surfaces, this outline predicts that solar wind sputtering will tend to clean exposed grain surfaces by ejecting material at velocities exceeding lunar escape velocity. We also discuss results showing that Fe is partially reduced in the outer few 10 nm of grain surfaces and that this reduced Fe forms 10 nm diameter range metal spheres throughout the glass during agglutinate formation by micrometeorite impacts. These metal spheres give the agglutinates their distinctive optical and magnetic properties and are partially responsible for the decreasing albedo of the lunar surface with exposure age.

Introduction

The fines in the lunar regolith record a great deal of information concerning the ancient history of the Sun through the records they contain of the intensity, composition, and energy spectrum of ancient solar wind and solar flare particles. They record other events and processes in the solar system through the information they contain on ancient micrometeorite fluxes, compositions, and size distributions. Finally they probably contain information on the formation and evolution of the Moon over and above that which can be deduced from the solid rocks which have been sampled. In order to unambiguously decipher as much of this information as possible it will be necessary to understand in some detail the physical and chemical processes that take place in the regolith as a result of exposure to solar radiation and micrometeorites.

This understanding will in turn be useful in the interpretation of remote data on the surfaces of other objects in the solar system, unprotected by atmospheres and global magnetic fields, such as asteroids and satellites of the major planets. It could provide a useful basis for the design of experiments to be flown for example on a landing probe to one of the asteroids. It may also provide constraints which help define the origin and history of interplanetary dust.

In this status report on a rapidly evolving subject I will simply outline the model for major chemical and physical processes in the regolith which we currently use as a guide in planning experiments, and discuss some consequences of it. I will also mention some important controversies which point out some of the many areas where additional experimental work is needed.

Solar wind sputter sputtering

Velocity distributions, compositions, and ionization

Although a great deal of general information on sputtering exists in the literature none of it is directly applicable to the determination of the compositions, velocity distributions, and ionization fractions of material sputtered off lunar minerals and glasses by the solar wind. However, we can arrive at some reasonable general expectations from this available data.

Stuart & Wehner (1964) have measured the velocity distribution of atoms sputtered off Cu targets under a wide range of conditions. More than half the atoms sputtered off a Cu surface by a normal incidence He beam with less than 1 keV bombardment energy had velocities exceeding lunar escape velocity. Changes from normal incidence or increases in beam energy both shifted the velocity distribution to higher energies. If we assume that energy transfer during sputtering is to a first approximation controlled by the mass ratio then Cu sputtering by He should be analogous to O sputtering by H. It, therefore, seems plausible to suppose that more than half the material sputtered off lunar rocks by H leaves with velocities exceeding the lunar escape velocity, and that a majority of the material sputtered off by He does. It can also be seen that a significant fraction of even the heaviest elements can be expected to escape.

Müller & Benninghoven (1974) and Benninghoven & Wiedmann (1974) have used mass spectroscopy to measure the ion yields of various oxides when sputtered with 3 keV Ar ions. It can be seen from their results that in some cases up to 10% or so of the sputtered material is ionized. It can also be seen that in some cases more than half of it is in the form of diatomic or triatomic molecules.

All the positive ions generated near the lunar surface are expected to be accelerated off the Moon by the electric field which is generated by solar photoelectron emission from the surface, while most of the negative ions will be captured by the same electric field.

Angular distribution and resputtering

Material sputtered from polycrystalline or amorphous surfaces has a cosine squared distribution, with respect to the normal, in direction, regardless of the incident direction of the sputtering beam. On a rough surface such as the lunar surface a sizeable fraction of sputtered atoms collide with nearby surfaces and an appreciable fraction of these probably stick. Another sizeable fraction of the sputtered atoms do not acquire lunar escape velocity in any particular event, and eventually redeposit on other grain surfaces.

However, as the Moon rotates a very large fraction of the total exterior is exposed to direct bombardment by the solar wind. The surface where sputter deposits can build up without being resputtered appears to be largely limited to re-entrant cavities and cracks and crevices between grains. Qualitative consideration of regolith surface geometry and gardening processes leads us to suggest that the primary effects of solar wind sputtering are to clean vapour deposits of any origin off larger grains and to redeposit part of the material in the finer grain size fractions.

Vapour deposition versus sputter cleaning

Gault *et al.* (1972) have estimated, based on the present micrometeorite composition and velocity, and a rough calculation of the expected energy partitioning, that about 9 pm per year of material would be vaporized in micrometeorite impacts. Some of this material would directly escape from the Moon but most of it has been assumed to form a vapour deposit on grain surfaces. Vapour deposits could also have originated due to outgassing of the lunar interior or of hot debris generated by major impacts, although no quantitative estimates are available for these processes.

McDonnell & Flavill (1974) have recently measured an absolute sputtering rate for He incident on a lunar sample at solar wind velocities. Using this and an inferred ratio for the H to He sputtering rate, they estimated a total solar wind sputtering rate of 4.3 pm per year. It can be seen that this and the estimated vapour deposition rate due to micrometeorites are of comparable magnitude. Within the uncertainties in the estimates either process could dominate.

Grant *et al.* (1974) have used Auger spectroscopy to search for vapour deposits on the surfaces of large anorthite grains from three different lunar fines samples. Although the total number of grains examined so far is not large, the failure to find any evidence of vapour deposits suggests that sputter cleaning of exposed grain surfaces dominates over all vapour deposition processes. Clearly more experimental data is desirable.

Chemical and isotopic effects

Sputtering is expected to lead to large chemical and isotopic fractionation effects, the magnitude of which will depend primarily on how many times a given component is sputtered before it either lands in a sheltered site or escapes from the Moon. It seems likely that solar wind sputtering can explain the enrichments of heavy isotopes of Si and O in the lunar fines (Taylor & Epstein 1973; Clayton *et al.* 1974). It might also explain the observed enrichments in heavy isotopes of K and S if it is assumed that significant fractions of these elements were at some time deposited from a vapour on grain surfaces.

Surface compositions and reduction

E.s.c.a. studies of lunar fines have shown that the outer 2 nm or so of grain surfaces are depleted in Mg, Al, and Ca relative to Si and Fe (Nefedov *et al.* 1972; Housley & Grant 1975).

E.s.c.a. studies have also shown (Vinogradov *et al.* 1972; Housley & Grant 1975) that a sizeable fraction of the Fe in this outer layer is in the reduced form even for samples which have been exposed to air for a long time.

Forrester (1973) and Housley *et al.* (1974) have used Mössbauer spectroscopy to show that a large fraction of the Fe within a few tens of nanometres of grain surfaces in lunar fines samples is reduced.

Yin *et al.* (1975) have shown, using e.s.c.a. techniques, that reduction of Fe silicates can take place during He sputtering. Gold *et al.* (1974, 1975) and Yin *et al.* (1975) take the point of view that the reduction of Fe in the surfaces of lunar grains is primarily a result of the process of sputtering itself, and largely independent of the composition of the solar wind. We take the view that the chemical composition of the solar wind is essential and feel that the majority of the reduced Fe in the surfaces lunar grains is compensated by trapped H and C in the form of OH and CO. This can be resolved by future experiments. In any case, most workers agree that Fe in the surfaces of lunar grains is reduced.

AGGLUTINATION AND METAL PRECIPITATION

When lunar fines containing reduced Fe in grain surfaces are melted and rapidly quenched to form agglutinates during micrometeorite impacts, we would expect fine-grained Fe metal spheres to precipitate throughout the glass. Transmission electron microscopy has shown 10 nm size range metal spheres to be abundant in the glass of agglutinates (Agrell *et al.* 1970; Housley *et al.* 1973, 1974; Pillinger *et al.* 1975). Quantitative estimates (Housley *et al.* 1974) indicate that all the excess metal observed in lunar fines can be accounted for by this process.

Agglutinates are always observed to be highly vesicular. This requires the release of a considerable volume of gas during their formation (Housley *et al.* 1973). This, in turn, is consistent with chemical reduction of the surface Fe, the required H and C being evolved as H_2O and CO during agglutination. Because of the high temperatures a significant fraction of the H_2O might directly escape from the Moon. The remainder of these gases might fairly rapidly be photodesorbed or sputtered from grain surfaces where they were absorbed, with velocities exceeding lunar escape velocity.

In view of the above it seems practical to define an agglutinate glass as any inhomogeneous vesicular glass containing fine-grained metal regardless of shape and size, and whether or not it welds other grains together.

ALBEDO

Because of the fine-grained Fe metal it contains, the glass of agglutinates is extremely dark when observed either in transmission or reflexion. It is much darker than homogeneous metal-free glass of similar composition. Most of the grains in a mature fines sample are seen to be abundantly splattered with this dark glass. Those which are not do not appear to be unusually dark. Therefore, the direct observational evidence strongly suggests that agglutination is an important process by which the albedo of exposed lunar regolith is reduced with increasing surface exposure age.

Hapke (1973) has shown that darkening can also be produced by sputtering under laboratory conditions. It results from the build up of sputter deposited films on the unexposed surfaces of loosely packed powders. He obtained negligible darkening on compacted powder samples.

We thus conclude that both solar wind exposure and agglutinate formation may contribute significantly to the exposure darkening of a rock powder as observed on the Moon. This may be useful in the interpretation of the remotely determined optical properties of other objects in the solar system.

MAGNETIC PROBING

The fine-grained Fe metal produced during agglutination has a high magnetic susceptibility in low applied fields and exhibits a strong characteristic ferromagnetic resonance. It, therefore, provides a convenient means of looking for exposure age stratigraphy in lunar core samples (Housley *et al.* 1974) and suggests possible experiments that might be designed for unmanned landing probes.

SUMMARY

We have presented arguments and experimental evidence suggesting that solar wind sputtering effectively cleans most surfaces of larger grains exposed in the lunar fines. We have also shown that much of the Fe in the surfaces of lunar grains is reduced although the processes responsible for this reduction remain to be resolved. During agglutination by micrometeorites this reduced Fe forms 10 nm diameter spheres which dominate the optical and magnetic properties of the glass.

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