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V. THE PRESENT-DAY MOON: INTERACTION WITH ITS ENVIRONMENT

The characterization of lunar surface impact erosion and solar wind sputter processes on the lunar surface

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Introduction

A wide variety of processes have been instrumental in the evolutionary progression of the lunar surface towards its present state. During the early history of the Moon, chemical differentiation, volcanism and, particularly for the mare areas, infilling by magma flow have been major mass transport factors but, since further cooling some 3×10^9 years ago, the development of surface features has been primarily determined by impact erosion from remnants of the primeval stellar condensation and matter associated with asteroids and comets. As a result of the evolutionary decrement of interplanetary matter impact erosion is time dependent but even so at a particular epoch the relative importance of impact erosion to solar wind sputter erosion in the determination of the topology of a feature will be dependent on the scale of the feature examined.

1. Lunar crater erosion

An impact crater formed on the lunar surface is normally exposed to the 400 km s^{-1} solar wind spectrum which will result in sputter erosion of surface atoms. Under varying angles of incidence during the lunar cycle, features exposed to the solar wind will be gradually smoothed and will eventually disappear. A similar erosion effect is the abrasion of large craters due to the formation within them of much smaller craters, i.e. a process similar to sand blasting. We also have the possibility during these quasi-continuous processes of single and complete obliteration by an impacting particle at least as large as that which caused the original crater. Thus we may characterize any particular crater with three erosion lifetimes: (1) the sputter lifetime, (2) the (small particle) abrasion lifetime, and (3) the (large particle) erasure lifetime.

We extend this treatment to cover the case of a lunar rock. The sputter and small particle abrasion processes are similar to those for craters except for geometrical factors, but the single impact erasure lifetime is replaced by single particle catastrophic rupture, which results if a rock is struck by a particle capable of producing a crater of diameter only 0.1 times the rock diameter. Results of our calculations extend to the case of a meteorite in space at 1 AU (McDonnell & Ashworth 1972; Ashworth & McDonnell 1972).

2. Interrelation of erosion lifetimes

In order to compose an integrated erosion picture from these component processes it is necessary to combine these lifetimes to form a resultant lifetime, and extend the analysis to cover all dimensions of crater, rock and meteorite. We have therefore developed mathematical models and computer programs to accommodate the many orders of magnitude over which the problem extends, and such programs incorporate experimentally determined parameters of hypervelocity impact and solar wind sputter processes, obtained by laboratory simulation of lunar erosion processes on lunar samples.

Hypervelocity impact data has been obtained by electrostatically accelerating submicron size carbonyl iron particles to velocities in the range 1–20 km/s and impacting on targets of lunar rock, aluminium and quartz (McDonnell *et al.* 1972). These results are in good agreement with the comparable work of others in this field (e.g. Vedder 1971; Auer *et al.* 1968; Bloch *et al.* 1971) and no major uncertainties in the understanding of the magnitude of lunar impact erosion can be attributed to calibration uncertainties.

In solar wind erosion simulation the situation is more complicated. The relative sputter efficiencies of the components of the solar wind have been estimated and compared by McDonnell & Ashworth (1972) on the basis of laboratory measurements. The majority of sputter erosion is expected to be due to hydrogen, helium contributing only some 30 %. However, laboratory measurements using hydrogen are difficult due to (1) the several degrees of ionization present in a hydrogen ion beam, (2) the relatively low sputter efficiency of hydrogen which requires a very clean vacuum system and also leads to high power dissipations in samples unless observation times are to be unduly long.

Our measurements (McDonnell *et al.* 1973) therefore utilize analytical grade helium ions which are accelerated to 2.8 kV, corresponding to solar wind energies. For non-conducting samples a flood of thermal electrons is made available for surface charge neutralization, and the effective ion current is deduced from the neutralization current flowing from the electron source to the sample. From such measurements on lunar rocks a mean sputter rate of 43 pm/year on equatorial breccia surfaces is inferred, although this value does not take account of such effects as a possible reduction of sputter efficiency due to ions implanted by the solar wind, or an increase in mean sputter rate due to a high angular dependence of sputter efficiency such as the results of McDonnell & Flavill (1974) would suggest.

3. Erosion modelling

In the computer erosion model an input data set defines an assumed incident size flux distribution, which leads to expected crater equilibrium populations as a function of crater size. These results then allow comparison with real (i.e. observed) equilibrium distributions. By generating a difference function, the assumed influx distribution may be modified, and by repeating this feedback process, we can eventually derive an influx distribution commensurate with the observed equilibrium crater population. The convergence of this technique and uniqueness of the solution have been tested. The application of methods based on this reasoning together with an assumed primordial exponential flux decay have been used (Ashworth & McDonnell 1972) to obtain lifetimes as a function of size for lunar craters, surface rocks and meteorites in space at 1 AU subject to these three main erosion components.

Figures 1, 2 and 3 show some examples of our computer model results, both for a flux model determined from satellite data and for that inferred from lunar surface equilibrium crater distributions. Results are dependent on the particular flux model assumed and we must investigate the significance of this. However, we do note features that are common to the results of all models and, very significantly, size regimes where only one particular erosion process is dominant.

For lunar surface boulders, craters and meteorites, solar wind sputtering is the dominant erosion lifetime mechanism at micrometre size diameters. For meteors in space this erosion lifetime is less than the Poynting–Robertson lifetime for an absorbing or reflecting body. Here sputter

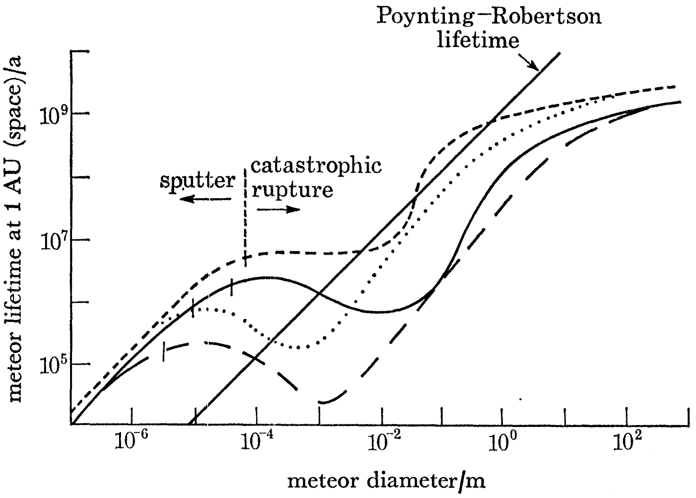

FIGURE 1. Erosion lifetimes calculated for stone and iron meteorites in space at 1 AU heliocentric distance. Sputter is the dominant erosion mechanism for small particles but is not significant compared to the Poynting–Robertson lifetime. For larger bodies catastrophic rupture is the dominant loss mechanism particularly for rock or stone materials. With all calculations in figures 1–3 the primeval increase of meteoric flux is included. . . ., iron meteor-flux from satellite data; – – –, iron meteor-flux from lunar surface data; — —, stone meteor-flux from satellite data; ——, stone meteor-flux from lunar surface data.

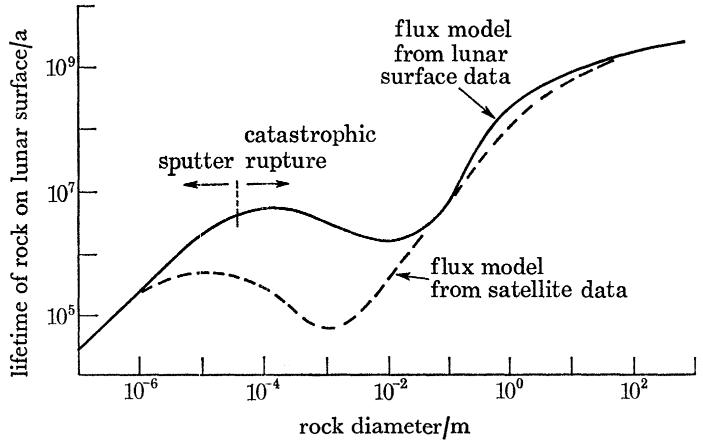

FIGURE 2. Erosion lifetimes computed for lunar surface rocks. For small rocks sputter is dominant while for larger bodies catastrophic rupture takes precedence as the major loss process. Calculations by Hörz *et al.* (1974) at three particle sizes confirm these calculations and are supported by dating of returned lunar rocks. – – –, flux model from satellite data; ——, flux model from lunar surface data.

erosion does not influence the heliocentric distribution of microparticles. A factor which is brought out by figure 1 however, is that single particle catastrophic rupture of stone meteors in space over the range greater than $\sim 10^{-4}$ m is dominant over the Poynting–Robertson lifetime and so we do have here an abundant microparticle source within 1 AU heliocentric radius by impact comminution. Above a critical size catastrophic rupture is shown to be always dominant for lunar surface boulders (figure 2) while for craters (figure 3), only in the middle size range is erasure the most important. For the larger craters considered, erasure causing impacts are so rare that their lifetimes will statistically be limited by the abrasion process.

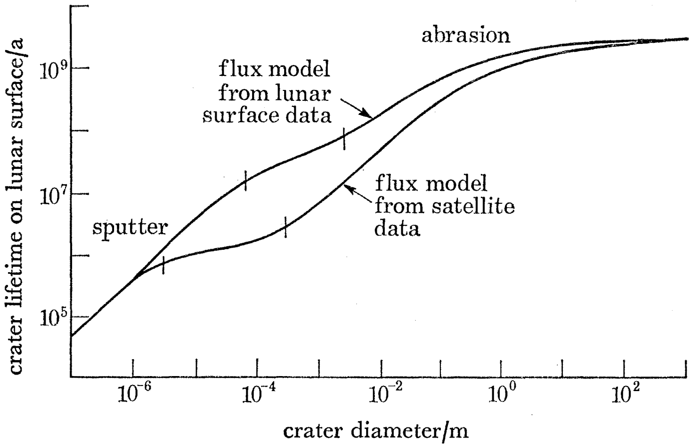

FIGURE 3. Erosion lifetimes computed for craters on the lunar surface due to solar wind sputter, crater erasure and crater abrasion. Different size regimes show the dominance of each one of these three processes.

Examination of the features of lunar rocks and terrain gives convincing support for the existence of these distinct erosion size regimes. Hörz's calculations on lunar rock lifetimes over a size range of 2–20 cm (Hörz 1975) confirms these calculations and this is supported by measured lunar rock ages.

4. THE MICROPARTICLE FLUX – RECENT TIME DEPENDENCE

Current data from space probe plasma sensors, such as Pioneers 8 and 9 (McDonnell & Berg 1974) and recovered vehicle surfaces (Cour-Palais 1974) have been examined and compared to lunar data (McDonnell *et al.* 1974). Doubt has been raised on compatibility with the microparticle flux determined from production surfaces: these derived influx rates must incorporate a time clock, and one common technique for production surfaces is that of solar flare track dating; a second possibility is that they may be derived from equilibrium surfaces such as those of Fechtig *et al.* (1974), using the solar wind sputter rate as a clock. These two methods yield substantial self agreement and it would seem probable that their incompatibility with *in situ* measurements is due to some further effect rather than uncertainties in calibration errors.

Explanations of this disagreement – perhaps an order of magnitude – have largely fallen into one of two categories. The first is based on the spatial anisotropy of the microparticle flux as measured by Pioneer 8/9 and Heos 2 (Fechtig *et al.* 1974), and the second postulates an exponential increase in the microparticle flux over the past 10^7 years (McDonnell & Ashworth 1974; Hartung & Storzer 1974). The first explanation could indeed resolve differences between crater population densities and current *in situ* measurements. A question that has been raised is why this present epoch should be so privileged as to be experiencing an enhancement. We would answer that such variations are a normal feature of the microparticle flux. If we reject short timescale variations of the microparticle flux then we must also conclude not only that individual track dating results may be in error but that systematic under-estimation of the tracks on lunar samples by a factor of 5 has occurred, unless an error exists in Neukum's equilibrium crater counts. Furthermore, a very low surface sputter rate of about 10 pm/year would be required to satisfy our computer model. An explanation of such an enhancement to the microparticle flux could be provided if the major part of the micrometre size flux could be considered to be provided by comets – the number of comets able to contribute at a given time is relatively small and their behaviour is highly variable. The statistics of this kind of process yield fluctuations commensurate with such a short timescale increase (Whipple 1967), and imply that our present epoch is not dissimilar to preceding ones except within bounds provided by statistical fluctuation. Further evidence compatible with an increase of this kind has come from our recent submicrometre scale examination of a glassy hypervelocity impact pit dated relative to the surrounding sample from the crater number density over its spall area at around 10^5 years, on lunar sample 60015,6. A constant flux during the exposure time of this crater would imply that a significant fraction of craters of diameters less than 1 μm should be (if we assume a sputter rate of at least 40 pm/year), in widely differing states of sputter degradation. Our observations however showed no evidence of such erosion. This could imply a much lower sputter rate or alternatively, if Hartung's time constant of 3×10^4 years for an exponentially increasing flux is correct, not only would most of the micrometre size craters have been produced in considerably less than 10^5 years but also the large (240 μm) measurement pit would be younger than our original estimation. Although these arguments suggest a cometary source, microparticles need not be the direct expulsion products of the cometary nucleus, but could be impact comminution particles from the intermediate range of masses generated within 1 AU in their inward decaying spiral.

Uncertainties due to the assumed velocity of impacting bodies also have to be considered, but are not expected to be large enough to affect the area of doubt.

Conclusion

Analysis of lunar microcraters supported by experimental simulation of environmental erosion processes now permits us to derive probable meteoroid influx rates. Together with other data, this has enabled us to generate computer programs which evaluate single and compounded erosion lifetimes of lunar craters, rocks and meteors in space. While making an advance towards the characterization of the lunar and interplanetary impact erosion environment, we must have no doubt of the existence of significant areas where continuing experimental investigations are vital. We identify several key problems facing us at this stage.

(1) Although there is general acceptance of a primordial exponential solid particle flux decay, shorter term variations in the microparticle flux, particularly over the last 10^7 years are indicated. Evidence must be available in the lunar regolith decoding this picture yet remains to be achieved.

(2) No accurate *in situ* measurements have been made of the lunar surface sputter rate to support an experimental simulated measurement. Other factors such as the rate of redeposition of sputtered material and impact plasma remain to be examined.

(3) Even though calculations have shown sputtering to be the dominant erosion process for micrometre size craters observations have yet to be made which conclusively demonstrate this on lunar sample microcrater populations.

(4) In general the observation of less accretionary material on the more exposed lunar sample faces indicates the predominance of impact erosion over accretion which is to be expected if most accretionary particles are impact generated, although at present we do not know how many accretionary particles result from impact initiated transportation (McDonnell & Carey 1975). On the *selected* surfaces used for microcrater statistical measurements the fractional area covered is not significant but accretionary processes are no doubt vital to the wide regolith picture. In the micron and submicron size range crater statistics may have been affected by the existence of glassy splash impacts with forms sometimes very similar to impacts from extra-lunar material (McDonnell *et al.* 1975).

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