2 IN SITU MEASUREMENTS OF INTERPLANETARY DUST

2.2 LUNAR STUDIES AND SIMULATION EXPERIMENTS

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2.2.1 LUNAR MICROCRATERS AND INTERPLANETARY DUST FLUXES

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Abstract

Conflicting data for depth-to-diameter ratios for lunar microcrater pits do not permit firm conclusions for distribution of meteoroid densities. The majority of meteoroids have equidimensional shapes. Meteoritic metal spherules have been detected in a small fraction of impact pit glasses, but contribution of meteoroidal material to most pit glasses is small to negligible. Impact pits less than 0.1 microns in diameter (impacting particle mass $\sim 10^{-16}$ grams) have been observed. Size distributions for microcrater pits less than 50 microns in diameter (particle mass $< 10^{-9}$ grams) measured on different samples differ significantly. An inflection in the cumulative size distribution curve at a diameter between 1 and 10 microns (particle masses between 10^{-14} and 10^{-11} grams) appears real, supporting the idea of a two-component model for the interplanetary dust. Data for the arrival direction of meteoroids at the moon are inconclusive.

Meteoroid flux determinations depend critically on surface exposure time measurements. Exposure time "clocks" are based on the accumulation of nuclear reaction products, etchable tracks, and sputter erosion produced by galactic cosmic ray, solar flare, and solar wind particles encountering the lunar surface. A serious problem for flux determinations is the difficulty in assuring that exposure time "clocks" measure only the time a surface is exposed to cratering. Therefore, suggestions of a lower meteoroid flux in the past must continue to be viewed with caution. Improved sample selection and cross-calibration of exposure time "clocks" should lead to better meteoroid flux and flux history measurements in the future.

Introduction

Before rocks were recovered from the surface of the moon, it was recognized by the workers in Heidelberg under the leadership of W. Gentner, J. Zähringer, and H. Fechtig that the exposed surfaces of lunar rocks would be of definite value to meteoroid science. During the last five years, the study of lunar rock surfaces in several laboratories has produced significant new data which should lead to an improved understanding of the interplanetary dust.

Reviews by Hörz et al. (1975a, 1975b) and Fechtig et al. (1975) described the

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progress made in this effort up to 1974. The objective of this paper is to present more recent results with particular emphasis on the problem of obtaining meteoroid flux information from lunar rock data. Also, because these authors presented results generally accepted in the field, we will emphasize those areas where conflicting interpretations and data exist.

Morphology

A description of the morphology of microcraters has been given by Hörz et al. (1971), Bloch et al. (1971), Hartung et al. (1972a), and others. A meteoroid impact origin for most microcraters has been argued by Hartung et al. (1972b).

Statistical data for the depth-to-diameter ratio for microcrater pits have been obtained. Brownlee et al. (1973, 1975) measured pits 4 to 70 microns in diameter, obtained a single peak in the depth-to-diameter distribution at a value of about 0.7, and, based on a comparison with laboratory data, concluded most interplanetary dust had a density between 2 and 4 g/cm^3. Smith et al. (1974) or Durrani et al. (1974) measured pits 1 to 8 microns in diameter and obtained three peaks in the distribution at values of about 0.3, 0.5, and 0.9 with an absence of cases at 0.7. These peaks were attributed to low density (1 to 2 g/cm^3), silicate, and iron meteoroids, respectively, with 40 to 50% of the impacts ($\sim$ 20% of the impacting mass) due to iron particles. Nagel et al. (1975) measured pits between 30 and 350 microns in diameter, obtained three peaks in the distribution, and concluded the impacts were due to particles similar to those reported by Smith et al. (1974). The discrepancies between these sets of data and the resulting interpretations have not been resolved.

Studies of the circularity of impact pits by Brownlee et al. (1973) has led to the interpretation that the majority of meteoroids have equidimensional shapes.

Chemistry

The colors of most pit glasses can be due to melting of host rock minerals. However, about 10% of the pit glasses, most often those which are dark brown to black in color, cannot consist of melted host rock alone, based on optical microscope studies by Hörz et al. (1971). For these, a contribution to the glass from impacting iron particles may have occurred.

Electron microprobe analyses of pit glasses have been made in search of contributions from impacting meteoroids. Chao et al. (1970) analyzed glasses from four pits. In general, the pit glass compositions reflected the host rock or mineral compositions. At least one pit in a microbreccia contained minute nickel-iron particles.

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The presence of these particles may indicate the impact of a nickel-iron bearing meteoroid or, alternatively, may be the result of in situ reduction of iron through the action of implanted solar wind hydrogen and subsequent impact melting, as suggested by Housley et al. (1971). Bloch et al. (1971) analyzed seven pit glasses, one of which showed a nickel-iron enhancement over the host rock composition, thus indicating possibly the impact of a nickel-iron meteoroid. Brownlee et al. (1975) analyzed fifteen pit glasses, six of which contained metal spherules. Of these six pits, five were in breccia samples containing indigenous metal grains, which could account for the metal in these pits, as well as in the one studied by Chao et al. (1970). The remaining pit was in a basalt and contained only trace amounts of submicron metal grains, which could have been incorporated into the glass by any of the above described mechanisms. Nagel et al. (1975) observed metallic spherules up to 2 microns in diameter in three out of at least fifteen pits on one sample. The spherules contained iron, nickel, and sulphur, suggesting but not demonstrating conclusively a meteoroidal origin for them. Hartung et al. (1975) analyzed two metallic spherules more than 10 microns in diameter found in one mm-sized pit for iron, nickel, and cobalt. The nickel and cobalt concentrations were demonstrably meteoritic and not those expected for indigenous metal or for solar-wind-hydrogen-reduced metal. In this case, at least one out of 28 pits on the sample was formed by a meteoritic-metal-bearing meteoroid.

The origin of metal grains in any particular pit glass is not easily determined, as indicated by the different mechanisms already mentioned and other shock-related, metal-sphere-producing, processes (e.g., Gibbons et al. 1975). The data presently available suggest impacts of metallic meteoroids can be identified based on chemical analysis of additions to pit glasses. Also, the data are consistent with the idea that the proportion of metallic meteoroids impacting the moon (1 to 10%) is essentially the same as the proportion of metallic meteorites observed to fall on the earth.

Brownlee et al. (1975) also observed iron and magnesium enhancements in two pits in monomineralic plagioclase feldspar samples. On the assumption that these enhancements were due to additions of chondritic composition, up to 0.1% of the glass formed could be derived from the impacting meteoroid. This confirms the view that, at most, only very small amounts of material from impacting meteoroids may be expected to remain in the pit glasses formed.

Size Distribution

Cumulative microcrater pit size distributions measured optically on sample 12054 by Hartung et al. (1973) and on sample 60015 by Neukum et al. (1973) and Fechtig et al. (1974) deviate from one another by less than 50% over the entire pit diameter range from 20 to 500 microns.

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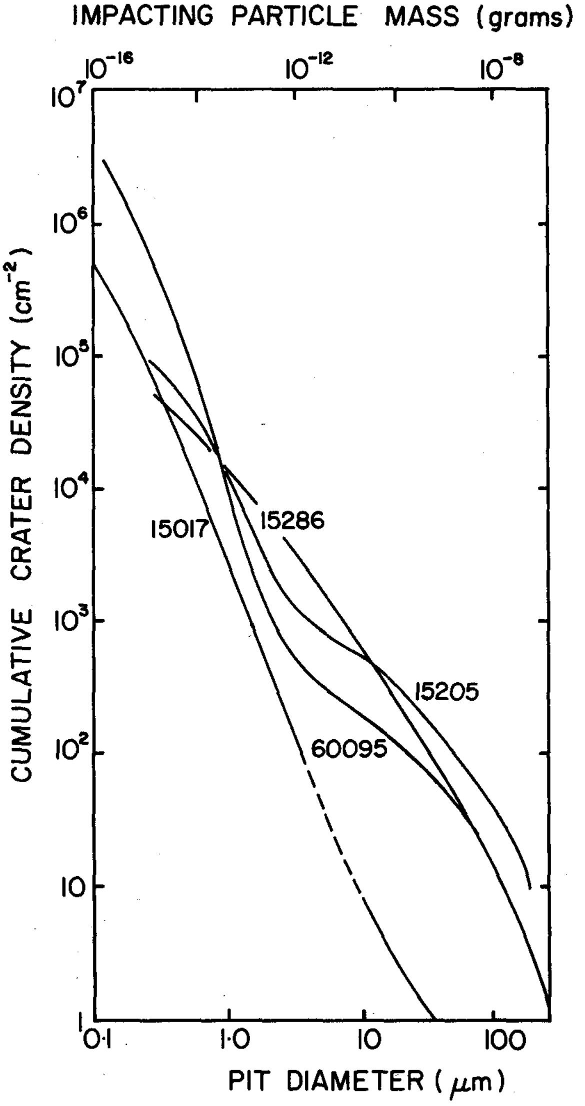

Figure 1. Cumulative microcrater pit size distributions for those samples providing data for a wide range of sizes on either side a pit diameter of 10 microns. Sources of data are for 15017, Morrison et al. (1973), 15205, Schneider et al. (1973); 15286, Brownlee et al. (1973), and 60095, Brownlee et al. (1975). Mass scale is based on calibration of Gault (1973).

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Four size distributions for smaller craters have been measured where statistically significant numbers of pits greater than 20 microns in diameter were counted. These sets of data are shown in figure 1 and illustrate discrepancies which remain unresolved. Two sets of data have a definite "break" at a pit diameter between 1 and 10 microns; the other two sets do not. The curves are not normalized, so different absolute crater densities may be explained partially by differences in exposure times, exposure solid angles, or both. Relative differences between the curves remain a controversy.

The trend of present thinking is toward accepting the steeper slopes (-2 to -3) at pit diameters less than 2 microns and the existence of an inflection in the distribution. This type of bimodal size distribution is evidence for a two-component model for the interplanetary dust. The differences in the distributions may be real or may be due to pit recognition problems or the poor quality of the surfaces observed. If two components of the interplanetary dust exist, then rock surfaces with different exposure solid angles exposed for different time intervals at different times in the past might be expected to yield different microcrater pit size distributions. Knowledge of these parameters is important for future pit size distribution measurements.

Conversion of pit size distribution data to meteoroid energy, mass, or size information requires application of empirical "calibration" curves based on laboratory produced data. This aspect of the problem has been reviewed by Hörz et al. (1975a).

Impact Directions

If the arrival direction of particles impacting the moon can be determined, then it is possible to obtain information on the orbital characteristics of the particles. Blanford et al. (1974) analyzed microcrater populations in lunar-north-facing and lunar-east-facing vugs or cavities and found no difference in the size distributions observed for pit diameters between 0.1 and 1 micron. Similar studies by Hutcheon (1975) indicated no differences in pit circularity or depth-to-diameter ratio for particles arriving along and out of the ecliptic. By measuring the exposure age for each surface studied Hutcheon (1975) found up to a factor of 20 more particles arriving along the ecliptic per unit time than those approaching from out of the ecliptic. However, using the same experimental approach on different samples, Morrison and Zinner (1975) found no difference in the flux of particles arriving from the two different directions. Clearly, more experimental work is needed.

"Clocks" to Measure Surface Exposure Time

Considerable effort has been expended to obtain data on the present flux of meteoroids by making satellite-borne meteoroid-detection experiments. Because lunar

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rocks are exposed to space for millions of years, it is, in principle, possible to obtain values for the past flux of interplanetary dust particles by studying the microcrater populations formed on lunar rocks.

Flux is a rate parameter, which implies a measurement of time is required as a part of determining meteoroid flux. For laboratory and satellite-borne experiments the measurement of time is straightforward, if not trivial. Measurement of time over periods of thousands or millions of years is not straightforward and is probably the most difficult and uncertain aspect of lunar microcrater studies. To provide a basis for evaluating results of meteoroid flux measurements, we will describe in this section each of the time-measuring techniques or "clocks" which have been used to measure the exposure times of lunar rock meteoroid "detector" surfaces. In the next section, we will discuss how the times measured have been related to numbers of meteoroid impacts to yield flux information.

In general, time is determined by measuring the quantity of something which accumulates with time and by dividing that quantity by the rate of accumulation, which is known or independently determined and usually assumed to be constant. Basically, there are two types of things that accumulate at or near the lunar surface, fast-moving particles from outside the solar system, galactic cosmic rays, and similar but less energetic particles from the sun, solar wind and solar flare particles. Both solar and galactic particles penetrate into lunar surface material and cause nuclear reactions, which yield a variety of identifiable products, and ionization damage to crystal structures, which may be revealed as etched tracks. Because galactic particles are more energetic, they penetrate deeper and depth profiles of their nuclear reaction products are flatter. Galactic cosmic ray nuclear reaction products are dominant at depths greater than about 1 cm, and their tracks are dominant at depths greater than a few mm. Solar particle tracks and nuclear reaction products have steeper depth profiles and are dominant at shallower depths. For each "clock" there is a characteristic depth range, such that material within that range will be considered "exposed." Thus, because a rock may be eroding by meteoroid impact or slightly buried in the regolith, an exposure time measured by one "clock," in general, will not agree with an exposure time measured by another clock. Perhaps the most difficult aspect of determining meteoroid fluxes from lunar rock data is establishing the fact that the exposure time measured for a surface corresponds directly to the time interval during which meteoroids were impacting the surface presently observed.

Galactic Cosmic Ray Track "Clock"

The upper few cm of material exposed at the lunar surface is regularly penetrated by energetic charged particles or cosmic rays. Damage to crystal lattice structure

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results from such penetration events. Under certain conditions, by properly etching polished crystal surfaces, the tracks produced by these events may be revealed. Observable etched cosmic ray tracks are produced effectively only by very heavy (VH) nuclei ($20 \leq Z \leq 29$) (Fleischer et al., 1967a, 1967b).

Nuclei with $Z < 20$ do not produce etchable tracks because the average energy loss or primary ionization rate is too low during penetration of these particles. Nuclei with $Z > 29$ are too few in number to be statistically significant. Through a limited depth range beginning a few mm below lunar rock surfaces, tracks produced by VH galactic cosmic ray particles predominate over those from by other processes, such as spontaneous fission, spallation reactions, and solar flare particle penetrations (Crozaz et al., 1970). The production rate of VH cosmic ray tracks at a given depth depends primarily on the flux of cosmic ray particles with different energies per nucleon, the penetration ranges corresponding to those energies, and the range over which a track may be revealed by etching. Flux-vs.-energy data are obtained through experiments to analyze cosmic rays. Range-vs.-energy data are derived from laboratory penetration experiments. The etchable range parameter is difficult to evaluate because it varies with the composition and crystal structure of the host material, the etching conditions, and also the technique used to observe the etched tracks. Furthermore, the etchable range may be affected by the time-temperature history of the host material. More detailed discussions of these parameters are given by Fleischer et al. (1967a) and Lal et al. (1969).

Even if the galactic-cosmic-ray-track "clock" works effectively, the time measured is "ideal" in the sense that it corresponds to an assumed constant depth (of the order 1 cm) below an exposed surface. There is no guarantee that a point 1 cm below the surface at the time a rock was collected had been so throughout its near-surface history. In fact, the reverse situation is more often the case. From studies of Gault et al. (1972) based on expected meteoroid impact rates and laboratory cratering experiments and from actual measurement of track populations found on different sides of lunar rocks (Crozaz et al., 1970; Fleischer et al., 1970, Lal et al., 1970), we would expect that due to burial and excavation, rupture, and erosion of lunar rocks the depth history of a point within a rock would be very complicated. Therefore, in most cases the galactic-cosmic-ray-track "clock" does not record the time a particular rock surface is exposed to impacts. What is recorded is an integrated value for time at a given depth, i.e. the subdecimeter exposure age of Bhandari et al. (1971).

However, we may expect that occasionally through excavation by an impact event or rupture of a larger rock a surface will become exposed on the lunar surface without having a cosmic ray track record acquired previously. If such a rock is collected before significant erosion occurs or before superposition of one crater by another is

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common, then the galactic-cosmic-ray-track "clock" would record the desired time interval. This latter requirement is important both because the interval recorded by the accumulation of tracks would be unambiguous and because there would exist a one-to-one correspondence between craters and impacting meteoroids, i.e. the surface would not have approached equilibrium with respect to crater superposition.

Cosmogenic Nuclide "Clocks"

Cosmic ray particles with low atomic numbers do not leave observable tracks, but they can alter exposed materials by causing nuclear reactions which results in changing the isotopic composition of a host rock. Two types of reaction products are especially useful because their concentrations may be measured with extremely high sensitivity. These are radioactive products, which can be measured using counting methods, and rare gases, which can be measured using mass spectrometry.

The main disadvantage of using the accumulation of cosmogenic radioactive nuclides or rare gases as an exposure time measurement technique is that most nuclear reactions producing these materials occur over range of depths of up to 1 meter. Thus, for the cosmogenic nuclide "clock" also, the time recorded usually does not correspond to the time during which impacts were occurring on the rock. Because cosmogenic nuclides are formed over a greater range of depth than are cosmic ray tracks, the exposure ages derived are systematically higher (see a recent summary of exposure age data by Crozaz et al., 1974 and Hörz et al., 1975c).

However, as mentioned, a rock may be brought to the surface without having suffered cosmic-ray-produced nuclear reactions. In this case, both the galactic-cosmic-ray-track and cosmogenic-nuclide "clocks" will start from zero at the same time and give concordant exposure ages until erosion affects the track population significantly or the rock is otherwise destroyed or buried. Therefore, by using different "clocks" to measure the exposure age of the same, carefully selected sample, one "clock" may be calibrated to a second "clock." Walker and Yuhas (1973) and Behrmann et al. (1973) have measured the depth distribution of galactic cosmic ray tracks and the Kr-Kr exposure age for the same, recently exposed lunar rock. Thus, they have obtained a value for the production rate of galactic cosmic ray tracks based on a Kr-Kr exposure age.

The Kr-Kr "clock" (Marti, 1967) relies on the accumulation of a stable cosmogenic isotope of Kr. For the purposes of measurement, a ratio of the abundance of this isotope to that of cosmogenic ^{81}Kr is taken. ^{81}Kr is radioactive, and its abundance reaches a constant equilibrium value after several mean lifetimes of 0.303×10^6 yr. If the ratio of the production rates of ^{81}Kr and the stable Kr isotope is known, then the time over which accumulation occurs, i.e. the exposure age, may be determined in

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terms of the number of ^{81}Kr mean lifetimes. The ratio of these production rates is obtained by interpolating between values for the abundance ratios of cosmogenic ^{80}Kr to the stable isotope and ^{82}Kr to the stable isotope. These abundance ratios are equivalent to production rate ratios because all isotopes involved are stable. Thus, for this method, in addition to Kr isotopic ratios, the critical parameter requiring laboratory measurement is the mean lifetime of ^{81}Kr atoms or the disintegration rate for ^{81}Kr. Only cosmogenic Kr is used in this approach, so corrections must be applied for solar and fission-produced Kr present in the sample. Several similar exposure time "clocks" based on accumulation of cosmogenic rare gases exist, but these will not be discussed because they have not been used in connection with microcrater measurements.

The other type of cosmogenic nuclide "clock" providing a type of exposure time information relies on the accumulation of radioactive nuclides produced by low-energy interactions. Depth profiles for the nuclear reaction products for different incident particles with different energies reacting with different target elements have been calculated by Finkel et al. (1971) and Rancitelli et al. (1971). After a time interval which is long compared to the mean lifetime of a radioactive nuclear reaction product equilibrium will be reached between the production and decay of the radioactive isotope. Equilibrium values or depth profiles may be calculated for surfaces experiencing different rates of impact erosion. For isotopes with half-lives short compared to the time required for significant erosion, measured and calculated depth profiles agree without introducing a correction for losses due to erosion. For isotopes with half-lives comparable to the time required for significant erosion, for example, ^{53}Mn and ^{26}Al with half-lives of 3.7 m.y. and 0.74 m.y., measured depth profiles can be made to fit calculated profiles if 0.5 mm/m.y. (Finkel et al., 1971) or 1 to 5 mm/m.y. (Rancitelli et al., 1971) erosion rates are assumed. As shown by Hörz et al. (1971) and Gault et al. (1972), erosion rates may be transformed through laboratory impact cratering experiments and knowledge of the crater or meteoroid size distribution into estimates of meteoroid flux. Unfortunately, these measurements of erosion rates are imprecise and require analyzing the radioactivity of lunar rocks on a layer-by-layer basis, which has not been done many times.

If in a special case the integrated exposure time for a rock was less than or comparable to the mean life time for a particular cosmogenic isotope, then the radioactivity measured for the whole rock would indicate that equilibrium had not been reached between production and decay of that isotope. The growth to equilibrium is a function of time, and, in principle, this process could be used as an exposure time "clock" in this special case (Keith and Clark, 1974). Disadvantages of this "clock" are the closer equilibrium is approached, the more imprecise the time measurement becomes; the equilibrium radioactivity depends on the composition of the rock in a

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way that is determined empirically; and only a few rocks have such a short exposure in the lunar regolith.

Solar Flare Track "Clock"

The most widely used "clock" to measure actual surface exposure time is based on the observation of tracks produced in the upper mm of lunar surfaces by VH nuclei accelerated during solar flares (Crozaz et al., 1971, Fleisher et al., 1971a, Bhandari et al., 1971). The restriction of solar flare tracks to the upper mm of surface material is a definite advantage for this approach because impact erosion events are also dominant at this scale (Hörz et al., 1971, Hartung et al., 1972b; Gault et al., 1972).

For galactic cosmic ray tracks, exposure ages depended on knowledge of particle flux vs. energy and energy vs. particle penetration depth. Another apparent advantage for solar flare tracks resulted from the return of the glass filter from the Surveyor III camera system which was exposed to space for 2-1/2 years. Track densities and depth profiles were measured in silicate material exposed for a known length of time, thus providing a standard track production rate without the need to use laboratory-produced energy-vs.-depth data (Crozaz and Walker, 1971, Fleisher et al., 1971b, Barber et al., 1971).

However, several problems exist for this method also. The Surveyor III tracks were accumulated over a 2-1/2 year interval, which is only a fraction of the known 11-year solar cycle, and the cycle itself may have been anomalous. Thus, a question remains regarding the representivity of the standard track production rate data. Ionization tracks formed in silicate materials do not survive unchanged indefinitely. Tracks grow smaller in length and diameter under the influence of time and temperature (Storzer and Wagner, 1969). The effect is extremely nonlinear with respect to time and is different for different chemical compositions and crystal structures (Crozaz et al., 1970). Track annealing proceeds rapidly soon after formation and very slowly before the track becomes completely annealed. Tracks in glass anneal much more easily than those in crystalline material. The etchable range of a track is not a well-defined parameter (Walker and Yuhas, 1973). Values differ for different etching conditions and observing techniques. Etched tracks produced recently in laboratory experiments are significantly longer than those observed on exposed lunar surface samples.

To improve the solar flare track "clock" Hutcheon et al. (1974) measured a track density profile from a depth of 1 micron to 3.3 cm using a sample which had not suffered significantly from impact erosion. In this way, the solar flare track "clock" could be calibrated using the galactic cosmic ray "clock" instead of relying on a

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production rate derived from the tracks in the Surveyor III filter glass. The calibration of the galactic cosmic ray "clock" using the Kr-Kr cosmogenic nuclide "clock" was discussed previously. Solar flare track production rates using the galactic cosmic ray "clock" of Walker and Yuhas (1973) is about 50% less than those rates based on Surveyor III filter glass data, assuming an etchable range of 100 microns, not 30 microns as used before, and assuming the average particle flux during the Surveyor III exposure was one-quarter the long-term average flux. Similar work by others (Crozaz et al., 1974; Blanford et al., 1975) should lead to an improved, well cross-calibrated, solar flare track clock. At present, unfortunately, considerable uncertainty is associated with absolute time measurements made using the solar flare track "clock." Different workers using the same data could obtain ages different by as much as a factor of 10 due mainly to uncertainties in the solar flare track production rate (Morrison and Zinner, 1975). Relative ages obtained by the same worker are much more precise. We estimate for these an uncertainty of less than 50%.

Solar Wind Sputtering "Clock"

Ions, mainly of hydrogen and helium, accelerated by the solar wind encounter the lunar surface continuously and are capable of removing surface atoms by sputtering. If the amount of material removed by sputtering and the sputtering rate were known or measured, then an exposure time could be measured directly. The sputtering rate has been determined by McDonnell and Ashworth (1972) and others for lunar rock surfaces based on in situ measurements of solar wind ion fluxes and laboratory experiments to determine the sputtering yield or efficiency. Although the amount of material sputtered off lunar sample surfaces has not been measured, McDonnell and Flavill (1974) have determined the expected lifetime for microcraters of different sizes against gradual removal by sputtering. They have suggested that for craters smaller than some critical size sputtering is the dominant crater destroying mechanism. Therefore, we may expect an equilibrium to exist between production of craters by impact and destruction of craters by sputtering. Because the crater destruction rate is known (inverse of the expected crater lifetime), the crater production rate (meteoroid flux) may be calculated. The actual calculation is more complicated than described here because a range of crater sizes must be considered along with the effects of crater destruction by superposition and impact erosion (Ashworth and McDonnell, 1973, 1974).

Discussion of Meteoroid Flux Measurements

The problem of establishing a meteoroid flux may be approached from two directions. One is to measure the crater density and exposure time for a non-equilibrium surface. The ratio of these two parameters is equivalent to the flux, which can be compared to independent flux measurements. The other approach is to measure the crater density

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and apply an independently measured value for the flux to find an exposure time, which can be compared to other measured exposure times for the same surface. The two approaches are essentially equivalent, the one used depending on the objective of the worker. Meteoroid fluxes are of interest in meteoroid science, exposure times in lunar science.

Exposure times based on crater counts were determined by Neukum et al. (1970), but no comparison with an independent "clock" was made. Impact erosion rates were estimated by Hörz et al. (1971), Bloch et al. (1971), McDonnell and Ashworth (1972), and Gault et al. (1972), and compared to rates based on solar flare and cosmic ray track "clocks." In addition, Gault et al. (1972) considered the expected rate of lunar rock destruction. They concluded these rates were higher using present-day fluxes than those based on the track "clocks" which integrate over long times, thus the meteoroid flux must have been lower in the past. However, Crozaz et al. (1974) have shown that most cosmic ray track exposure ages give maximum values for surface exposure times. This, together with the tendency for older rocks, those surviving impact destruction, to be collected, removes part of noted discrepancy. They also point out erosion rates based on solar flare tracks refer to "microerosion" and not "mass-wastage" caused by mm-sized impacts. Other "mass-wastage" determinations, for example those based on cosmogenic ^{53}Mn and ^{26}Al "clocks" (Finkel et al. 1971; Rancitelli et al., 1971; Wahlen et al., 1972), give erosion rate values in agreement with those calculated. Thus, from erosion-rate or rock-destruction-rate arguments, no basis remains for suggesting a lower meteoroid flux in the past.

Populations of mm-sized craters on rocks for which independent exposure ages had been measured were studied by Hartung et al. (1972b, 1973) and Morrison et al. (1972, 1973). Morrison et al. (1972, 1973) assumed that the highest density of craters observed corresponded to a surface in equilibrium with respect to crater superposition and that all other surfaces having lower densities of craters had not reached equilibrium and, therefore, could yield exposure time or meteoroid flux results. Measured exposure times using the "clocks" described previously were found almost always to exceed the time required to form the observed microcrater populations using present-day meteoroid flux estimates. Consequently, they suggested a lower meteoroid flux may have existed in the past. In contrast, Hörz et al. (1971) and Hartung et al. (1972b, 1973) considered it likely that two surfaces having distinctly different densities of craters could both be in equilibrium. The differences presumably could be explained in terms of different mechanical properties of different rocks. Subsequent work by Neukum et al. (1973) and Schneider and Hörz (1974) supports this latter view, thus eliminating the need for a lower meteoroid flux in the past.

An approach to estimate rock exposure times from crater population data was used

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by Fechtig et al. (1975) based on the size of crater at which the transition from an equilibrium to a production population occurred. In this view, the smaller the crater size still in production, the younger the exposure age of the surface (Gault, 1970; Shoemaker, 1971). Results similar to those of Morrison et al. (1972, 1973) were suggested, but this approach also failed to demonstrate that the crater population observed developed over the same time interval measured by the "clock" being used for comparison. In addition, we may expect larger cratering events, those presumed to correspond to a production crater population, are necessarily under-represented on rock surfaces because these events contribute to rock destruction. The largest craters are also destroyed in this process. Only surviving rocks and the corresponding population of smaller craters can be observed (Hartung et al., 1973, Hörz et al., 1975c).

To estimate the meteoroid flux Hartung et al. (1972b, 1973) counted craters with pit diameters greater than 500 microns on rocks with exposure ages measured using different "clocks." Because some tracks or nuclides could have been produced before the rock was exposed to cratering, the age corresponding to the observed crater population was a maximum value. Because some of the craters may not have been observed due to superposition effects, a minimum value for the areal density of craters was obtained. Both of these factors led to a minimum value for the meteoroid flux using this approach. Because this resulted in a minimum value for the meteoroid flux which was less than that derived from satellite-borne experiments, no constraint could be placed on possible time variations of the flux.

Populations of micron-sized craters have been "dated" using the solar flare track "clock" by Neukum et al. (1972) and Schneider et al. (1973). For this work, mostly glass surfaces were used. This provided visual assurance that effects of crater superposition and erosion would be minimized. In addition, solar flare track depth profiles were measured and found to be similar to that obtained for the Surveyor III camera filter, thus confirming that crater and track production occurred over the same time interval. Because tracks in glass are severely reduced by annealing, wherever possible tracks were measured in pyroxene grains trapped in the glass. It was assumed that any track record in the grains before being trapped in the glass were annealed while the glass cooled. Meteoroid fluxes determined in this way also fell below the present-day values from satellite-borne experiments. The data for several surfaces exposed for different times could be interpreted as indicating a flux in the past lower than or equal to the present-day flux because of uncertainties involved. However, for all of these surfaces recent exposure, at the time of collection, could not be confirmed, so such an interpretation would be questionable.

Hartung and Storzer (1974) successfully observed solar flare tracks in individual sub-mm-sized glass-lined pits. Exposure-ages estimated for over fifty individual

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craters were concentrated toward younger ages, thus indicating a lower flux in the past. Although differential flux data may be obtained with this approach, severe annealing corrections (up to a factor of 50), which are poorly understood, were required. This result may also be questioned because it indicates a flux increasing during only the last $\sim 10^4$ years with no similar peak occurring any time during the preceding $\sim 10^5$ years.

By applying the solar wind sputtering "clock" McDonnell and Flavill (1974), McDonnell et al. (1975), and McDonnell and Carey (1975) also have concluded meteoroid fluxes have been lower in the past. Flux information, which is equivalent to rate or time information, was derived by using an equilibrium population of craters. At first glance, it would appear this approach could not succeed because time information cannot be extracted from an equilibrium situation. However, because two processes are acting to destroy craters, sputtering and "erasure" (crater superposition), each affecting different-sized craters to a different extent, the shape of the equilibrium crater size distribution becomes diagnostic. If the shape of the production crater size distribution, the size and shape of the equilibrium size distribution, and the crater destruction rate by sputtering as a function of crater size are known, the production rate of different-sized craters (the flux) may be determined.

One question related to this approach involves the assertion that both sputtering and "erasure" (superposition) are effective mechanisms for destruction of craters about 1 micron in diameter. So far no workers using scanning electron microscopes capable of resolution better than 0.1 micron have reported observing any effects attributable to sputtering. A second problem is that no measurement of an equilibrium crater size distribution for craters less than about 50 microns in diameter exists. Because mm-sized-and-larger craters dominate in the superposition of all smaller craters (a consequence indicated by the flattening of the crater size distribution in this range), the relative numbers of all smaller craters should reflect directly the relative numbers of those craters produced, i.e. the equilibrium distribution for small craters should parallel the production distribution for those craters. No attempt has been made to scan a large, representative, equilibrium, surface on a scale of 10 microns or less.

More recently, Blanford et al. (1974), Hutcheon et al. (1974), and Morrison and Zinner (1975 and this volume) have selected samples from within vugs, cavities, and crevices of lunar rocks to avoid "background" tracks. Even with this approach, Hutcheon et al. (1974) found it necessary to distinguish between acceptable and background tracks based on an evaluation of their penetration direction into the rock, a procedure requiring extreme care. The use of vug crystals for flux measurements may not satisfy entirely the requirement to avoid pre-exposure accumulation of tracks. Although cosmic rays entering from directions off the axis of the vug or cavity are effectively reduced

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in number by the additional overlying material, those entering along the vug axis before it is exposed have no difficulty accumulating at the base of the vug just as if it were near the surface. Nevertheless, using this approach, Morrison and Zinner (1975) obtained flux estimated for 10^{-15}-gram-and-larger meteoroids averaged over times of $\sim 10^4$ and $\sim 10^6$ years which were consistent with extrapolations of Pioneer 8 and 9 data. However, to illustrate further that not all problems are solved, data obtained using this same sample, have led Morrison and Zinner (1975) to conclude that ecliptic and out-of-ecliptic fluxes of these particles are about the same, a result which is at odds with current thinking on this question based on Pioneer 8 and 9 and Heos data (Fechtig *et al.*, 1974; Zook and Berg, 1975).

Concluding Remarks

Up to this point, no independent approach to evaluate the flux or flux history of meteoroids is without question, and some have been shown to be invalid. To improve meteoroid flux estimates, special care must be taken in sample selection. The optimum sample should have been exposed only directly to space, with no evidence for erosion, dust covering, or residence near the surface of a larger rock before catastrophic rupture. The sample should be crystalline material which contains no tracks at the time exposure to space occurs and which collects tracks only during the time and from the direction of exposure. The ideal sample should have been excavated and exposed to space for the first time relatively recently ($\sim 10^5$ years ago) from a depth in excess of tens of cm with no subsequent tumbling until it is collected.

The possibility exists that most of the suggestions that a lower flux existed in the past stems from the fact that crater densities tend to be under estimated because craters can be lost by superposition or otherwise not accounted for and exposure times tend to be over estimated because accumulation of tracks, nuclides, or other "things" can proceed before the crater-recording surface becomes exposed and operative.

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