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Distribution and flux of micrometeoroids

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Lunar rocks are useful micrometeoroid detectors, and have been used to determine the mass distribution, flux and distribution in space of interplanetary dust at 1 AU.

The micrometeoroid mass distribution is bimodal. Variations in slope of the cumulative mass frequency curve suggest that complex physical processes act upon one or more micrometeoroid sources.

Approximately 300 craters of 0.1 μm diameter, corresponding to particle masses of 10^{-16}–10^{-17} g cm^{-2} a^{-1} sr^{-1}, are produced. No anisotropy in this flux was observed between lunar north and the plane of the ecliptic in contrast to other observations of an anisotropy between lunar south and the plane of the ecliptic. Flux values in this mass range are the same for surfaces exposed for 10^6 and 10^4 years and are in agreement with extrapolated satellite results. No change in flux over a 10^6 year period is indicated.

Between 10 and 15×10^{-6} particles of mass 10^{-5}–10^{-6} g cm^{-2} a^{-1} $(2\pi \text{ sr})^{-1}$ impact the Moon.

Introduction

Surfaces exposed on the Moon record the impact of interplanetary particles over a wide mass range (Hörz *et al.* 1975). The data so preserved are of importance in determining the size frequency distribution, the flux, and the distribution in space of interplanetary particles at 1 AU. Comparisons can then be made with data obtained from satellites and with Earth based observations of zodiacal light and visual, photo, and radar meteoroids. In this paper we present estimates of the mass distribution, flux, and distribution in space of the micrometeoroid complex based upon new data from Apollo 17 rocks and recent recalibrations of the solar flare track production rates (Hutcheon, MacDougall & Price 1974; Yuhas 1974; Blanford, Fruland & Morrison 1975; Morrison & Zinner 1975).

Size frequency distribution

Glass-lined craters on lunar rocks range in diameter from less than 100 nm to several millimetres corresponding to micrometeoroid masses of $< 10^{-17}$–$\geqslant 10^{-4}$ g, thus it has been possible to determine the relative abundances of micrometeoroids over a wide range.

Figure 1 shows three size frequency distributions for crater diameters varying from 0.1 to 2500 μm. The data of Morrison, McKay, Fruland & Moore (1973) indicate a slope of -2 for craters $<$ 0.1–1.0 μm diameter, a -2.5 slope for craters 1–10 μm diameter, a -1 slope approximately for craters 10–*ca.* 50 μm diameter and a steepening of the slope to -3 for the larger craters. This distribution was determined on 2 rocks, 15015 and 15017, by scanning electron microscopy. Both rocks had production populations and were exposed for short periods thereby

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minimizing obscuration of craters by accretionary particles and superposition of younger craters. The data are not normalized.

A second size frequency distribution, differing in detail, has been reported by Fechtig *et al.* (1975), and is also shown in figure 1. The two distributions differ principally in the degree of depletion of craters 1–100 μm diameter. For example, the curve of Morrison *et al.* (1973) shows a ratio between 1 and 100 μm diameter craters of approximately 6600 whereas the ratio given by the Fechtig *et al.* (1975) data for the same diameters is 330, a difference of a factor of 20.

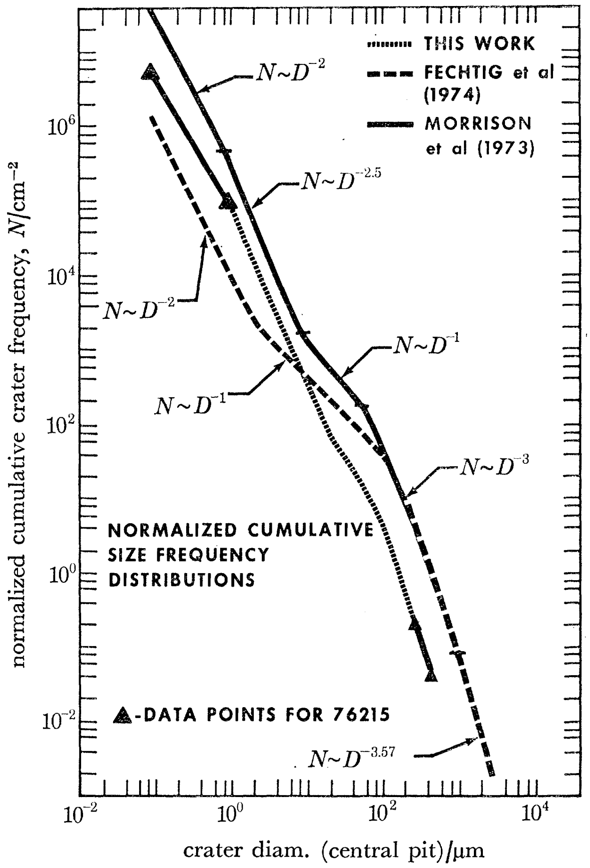

FIGURE 1. Comparison of cumulative size frequency distributions. Exponents refer to slopes of curve increments.

Figure 1 also shows the crater densities determined by us for rock 76215 for craters from 250 to *ca.* 500 μm central pit diameter and for submicrometre diameter craters. A dashed line is drawn between these two data sets. In this case the ratio of 1.0 to 100 μm diameter craters is about 25000, a factor of 3 greater than for Morrison *et al.* (1973), but approximately 2 orders of magnitude greater than the ratio we calculate for the Fechtig *et al.* (1975) curve. The data for 76215 therefore are in better agreement with the size frequency distribution of Morrison *et al.* (1973). Although we cannot rule out variations in the size frequency as a function, for example, of lunar surface orientation or exposure time, our data suggest that the distribution of Fechtig *et al.* (1975) shows too great a depletion in the 10–100 μm diameter range. The shape of the curve in this range in the Fechtig *et al.* (1975) distribution is dictated by data primarily from rocks 60015 and 15205.

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Conversion of crater size frequency data to a mass distribution for micrometeoroids requires assumptions concerning densities and impact velocities. Crater morphology measurements reflect particle densities. Brownlee *et al.* (1974) have measured depth to diameter ratios and circularity indices for craters 0.2–100 μm in diameter and derive an average density of 2–4 g/cm^3. Smith, Adams & Kahn (1975) present data suggesting that particles producing craters in the micrometre diameter range fall into three groups of approximately 8, 3 and 1–2 g/cm^3. The presence of submicrometre diameter craters on a variety of surfaces (Blanford, Fruland, McKay & Morrison 1974) argues against a radiation pressure cutoff which is compatible with densities of 2–4 g/cm^3 for submicron interplanetary dust particles (Grindilis, Divari & Reznova 1969). Hörz *et al.* (1975) conclude that most dust particles of < 50 μm diameter have densities of 2–4 gm/cm^2 and we will adopt this value. We recognize, however, that differences may occur, particularly in so far as smaller particles are concerned.

Velocity distributions are not well determined. Data comes primarily from satellite and Earth based measurements because crater morphology appears to be independent of velocity (Nagel *et al.* 1975). Velocities of submicrometre particles appear to be greater than 30 km/s. Morrison & Zinner (1975) point out that the presence of submicrometre craters in lunar rock cavities inclined to the plane of the ecliptic indicate that the heliocentric velocity of the crater-producing particles must have been at least equal to the heliocentric velocity of the Moon (29.9 km/s). The minimum heliocentric velocity thus is the resultant of the lunar heliocentric velocity plus the minimum velocity required to produce a glass-lined pit (3.5 km/s) and is calculated to be 30.3 km/s. Fechtig *et al.* (1975) conclude from satellite data that particles > 1 μm diameter have impact velocities of *ca.* 10 km/s implying a ratio of 1.4 to 2 for crater diameter versus particle diameter. These measurements are restricted, however, to masses of 10^{-11}–10^{-13} g and it is not clear that they can be applied to masses of 10^{-8} g and larger wherein most of the mass intercepting the Moon is concentrated (Hörz *et al.* 1975). Zook (1975) has recently evaluated velocity distribution models based on visual, photograhic and radar meteor data and concludes that an average velocity of 15 km/s is appropriate for particles of 10^{-6} g and larger, but this velocity probably is indistinguishable in terms of microcrater morphology from the value determined by Fechtig *et al.* (1975).

We conclude that velocities equal to or greater than 30 km/s are appropriate for calculation of the mass of submicron diameter dust particles, whereas velocities of approximately 10–15 km/s are appropriate for larger particles. These assumptions are reflected in figure 2.

Meteoroid flux estimates

The size frequency distributions shown in figure 1 can be converted to crater production rates or meteoroid flux values if exposure ages can be determined for cratered surfaces. For this purpose, the most useful method is based upon the solar flare particle track production rate, consequently it is necessary to select a solar flare energy spectrum which accurately predicts the long term track production rate. Models for the long term spectrum have been proposed by Yuhas (1974), Blanford *et al.* (1975) and Hutcheon *et al.* (1974). These models differ in details of the solar flare energy spectrum, particularly for energies less than 50 MeV/μ and exposure ages determined by using each differ correspondingly (Morrison & Zinner 1975). All three models indicate that it is not appropriate to use the Surveyor III energy spectrum as a model for the long term track production rate.

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Using these track production rates, we have calculated flux values for three different samples, with the results shown in figure 2 and table 1. The three samples examined represent different situations in terms of exposure geometry and surface residence time as indicated in table 2. Sample 76215 was exposed for a relatively short period ($\approx 2\times10^4$ years) and includes data pertinent to submicron particles (10^{-17}–10^{-14} g) plus particles of 10^{-7}–10^{-5} g. Sample 76015,40 samples submicrometre particles intercepting the Moon normal to the plane of the ecliptic from the direction of lunar north whereas 76015,105 sampled submicrometre sized particles with orbits confined to the plane of the ecliptic. Details of the exposure geometries, and crater and track data for these samples are given in Morrison & Zinner (1975).

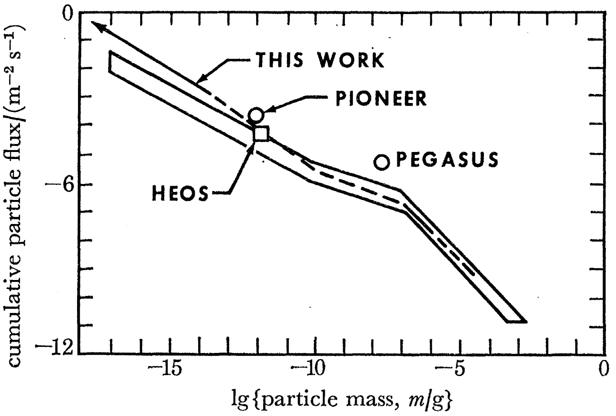

FIGURE 2. Flus of interplanetary particles after Fechtig *et al.* (1975). Broad band represents a compilation of lunar data by Fechtig *et al.* (1975). Units for curve labelled this work are particles $\mathrm{cm^{-2}\,s^{-1}}\,(2\pi\ \mathrm{sr})^{-1}$. Arrow indicates that craters as small as 15 nm corresponding to 10^{-18} g particles have been observed.

TABLE 1. THE EXPOSURE AGES AND DUST PARTICLE FLUXES FOR SAMPLES 76015,40, 76015,105 AND 76215 AS OBTAINED FROM THE OBSERVED TRACK DENSITIES AND THE TRACK PRODUCTION AT 100 μm DEPTH CALCULATED FROM DIFFERENT SOLAR FLARE ENERGY SPECTRA

sample	solar flare spectrum used for track production	track density at 100 μm depth (tracks/cm²)	pit density (pits > 100 nm/cm²)	exposure age (years)	dust particle flux (> 100 nm) (particles $\mathrm{cm^{-2}\,sr^{-1}\,a^{-1}}$)
76015,105	Yuhas (1974)	6×10^7	5×10^7	9.4×10^5	152
76015,40		1.2×10^8	10^8	1.05×10^6	255
76015,105	Blanford *et al.* (1975)	6×10^7	5×10^7	4.6×10^5	311
76015,40		1.2×10^8	10^8	5.3×10^5	505
76015,105	Hutcheon *et al.* (1974)	6×10^7	5×10^7	5.9×10^4	2435
76015,40		1.2×10^8	10^8	6.0×10^4	4490
76215	Blanford *et al.* (1975)	3×10^6	5×10^6	1.6×10^4	300

Our solar flare track data (Morrison & Zinner 1975) suggest that an energy spectrum similar to the Yuhas (1974) or Blanford *et al.* (1975) models or possibly intermediate between these two, is the best representative of the long term solar flare particle spectrum, therefore we prefer the values derived by using these spectra. The data thus indicate an influx of approximately 300 particles of 10^{-17} g (corresponding to a crater diameter of 0.1 μm) $\mathrm{cm^{-2}\,a^{-1}\,sr^{-1}}$. Data from sample 76215 (Figure 1) indicates a production of 10–15 craters of 500 μm diameter or greater per cm² per Ma per 2π sr.

Impact pit to particle track ratios make a convenient measure for comparing flux results of

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different laboratories and varying sampling situations. Selecting the abundance of 0.1 μm craters and the track density at 100 μm, the values for which are given in table 1, we calculate a crater to track ratio of approximately one with no difference between samples irrespective of exposure age or geometry. In this respect our data disagree with the observations of Hutcheon (1975), whose crater to track ratios are about a factor of 50 lower than ours.

As shown in table 1, the flux values for 76015,105, sampling particles with orbits in the plane of the ecliptic, and 76015,40 sampling particles inclined to the plane of the ecliptic are approximately the same. Thus we conclude that there is no anisotropy in the distribution of submicron sized interplanetary dust at 1 AU between the plane of the ecliptic and the normal to the plane of the ecliptic in the direction of lunar north (the solar apex direction), In contrast, Hutcheon (1974), observed a depletion of a factor of 7 in comparing fluxes of particles intercepting the Moon from lunar south versus particles confined to the plane of the ecliptic. The different flux values for submicrometre sized particles for the normals to the plane of the ecliptic may reflect a genuine property of interplanetary dust particles in this size range but more data are required to establish these values.

The data in table 1 show no striking differences between short term and long term exposure (2×10^4 versus 10^6 years) suggesting no change in flux of submicron sized particles for the last 10^6 years, in contrast to the observations of Hartung & Storzer (1974).

Figure 2 summarizes our results. Good agreement is shown between our work and data from the satellites Heos (Hoffmann, Fechtig, Grün & Kissel 1975) and Pioneer 8 and 9 (McDonnell, Berg & Richardson 1975). Good agreement for larger masses is also shown in comparison with a compilation by Fechtig *et al.* (1975) of microcrater and exposure age data from lunar rocks. The compilation is shown as a broad band in figure 2.

Summary

The size frequency distribution of microcraters on lunar rocks suggests a bimodal distribution of micrometeoroids (Hörz *et al.* 1975), but the precise form of the curve requires further definition, particularly insofar as the degree of depletion of particles producing craters of 10–100 μm diameter is concerned. Irrespective of this question, variations in slope with crater diameter or particle mass increments indicate that different processes are acting upon one or more particle populations.

Recently refined solar flare energy spectra plus new microcrater data allow calculations of fluxes corresponding to varied lunar surface orientation and surface residence time. We observe no striking difference between the flux of submicron diameter particles with orbits in the plane of the ecliptic and the flux of particles with orbits normal to the plane in the solar apex direction, whereas Hutcheon (1975) observes a depletion of a factor of seven between the ecliptic and the anti-solar apex direction. These results place significant constraints upon the processes acting on these particles (such as radiation pressure) and their circum-solar orbital evolution. No striking difference is observed between surfaces exposed for 10^6 and 10^4 years, and our results are in reasonable agreement with extrapolations of satellite data, therefore no change in flux of submicron diameter dust particles is indicated over a 10^6 year period. The flux of particles producing craters with 500 μm diameter or greater central pits is compatible with previous results (Hörz *et al.* 1975; Fechtig *et al.* 1974) and with studies of gardening rates of the lunar regolith (Gault *et al.* 1974) and the catastrophic rupture of lunar rocks (Hörz *et al.* 1974).

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REFERENCES (Morrison & Zinner)

Blanford, G., Fruland, R., McKay, D. & Morrison, D. 1974 *Proc. 5th Lunar Sci. Conf., Geochim. cosmochim. Acta Suppl.* 5, **3**, 2501–2526.

Blanford, G., Fruland, R. & Morrison, D. 1975 *Proc. 6th Lunar Sci. Conf., Geochim. cosmochim. Acta Suppl.* 6, **3**.

Brownlee, D., Hörz, F., Vedder, J., Gault, D. & Hartung, J. 1973 *Proc. 4th Lunar Sci. Conf., Geochim. cosmochim. Acta Suppl.* 4, **3**, 3197–3212.

Fechtig, H., Gentner, W., Hartung, J., Nagel, K., Neukum, G., Schneider, E. & Storzer, D. 1975 Proc. of the Soviet-American Conf. on Comochem of the Moon and Planets, NASA SP (in the press).

Fechtig, H., Hartung, J., Nagel, K. & Neukum, G. 1974 *Proc. 5th Lunar Sci. Conf., Geochim. cosmochim. Acta Suppl.* 5, **3**, 2463–2474.

Gault, D., Hörz, F., Brownlee, D. & Hartung, J. 1974 *Proc. 5th Lunar Sci. Conf., Geochim. cosmochim. Acta Suppl.* 5, **3**, 2365–2386.

Grindilis, G. W., Divari, N. B. & Reznova, L. U. 1969 *Soviet Astron. A. J.* **13**, 114–119.

Hartung, J. & Storzer, D. 1974 *Proc. 5th Lunar Sci. Conf., Geochim. cosmochim. Acta Suppl.* 5, **3**, 2527–2541.

Hoffmann, H.-J., Fechtig, H., Grün, E. & Kissel, J. 1975 *Planet. Space Sci.* **23**, 215–224.

Hörz, F., Brownlee, D., Fechtig, H., Hartung, J., Morrison, D., Neukum, G., Schneider, E., Vedder, J. & Gault, D. 1975 *Planet. Space Sci.* **23**, 151–172.

Hörz, F., Schneider, E. & Hill, R. 1974 *Proc. 5th Lunar Sci. Conf., Geochim. cosmochim. Acta Suppl.* 5, **3**, 2397–2412.

Hutcheon, I. 1975 *J. geophys. Res.* **80**, 4471–4483.

Hutcheon, I., MacDougall, D. & Price, P. B. 1974 *Proc. 5th Lunar Sci. Conf., Geochim. cosmochim. Acta Suppl.* 5, **3**, 2561–2576.

McDonnell, J. A. M., Berg, O. E. & Richardson, F. F. 1975 *Planet. Space Sci.* **23**, 205–214.

Morrison, D., McKay, D., Fruland, R. & Moore, H. 1973 *Proc. 4th Lunar Sci. Conf., Geochim. cosmochim. Acta Suppl.* 4, **3**, 3235–3253.

Morrison, D. & Zinner, E. 1975 *Proc. 6th Lunar Sci. Conf., Geochim. cosmochim. Acta Suppl.* 6, **3**, 3373–3390.

Nagel, K., Neukum, G., Fechtig, H., Müller, O. & Schneider, E. 1975 *I.A.U. Colloquium No.* 31, Max-Planck-Institut für Kernphysik, Heidelberg.

Smith, D., Adams, N. & Kahn, H. 1974 *Nature, Lond.* **22**, 101–105.

Yuhas, D. 1974 Ph.D. dissertation, Department of Physics, Washington University, St. Louis, Missouri.

Zook, H. 1975 *Proc. 6th Lunar Sci. Conf., Geochim. cosmochim. Acta Suppl.* 6, **2**, 1653–1672.