Lunar Crater Counts

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The cumulative numbers of lunar craters on the bright uplands larger than given diameters increase linearly on a log–log scale as the crater diameter decreases. The line is so steep that for craters smaller than four miles wide, there has been extensive overlapping. The craters on the maria in each size range are about 15 times less frequent than on the uplands. The maria are of one general age but do show differences in age. Comparison with the flux of smaller masses in the neighborhood of the earth leads to a probable age of the maria of 2 to 3 billion years. The use of lunar maria crater counts to give the slope and the observed flux of smaller masses in the neighborhood of the earth, including the Apollo asteroids, to give absolute frequencies leads to equations for cumulative impacts on earth of objects from 10^2 to 10^{19} g in mass. All existing data indicate that the frequencies of objects capable of producing craters on earth or moon less than about 2 miles in diameter are higher than straight-line extrapolations of lunar crater counts would indicate.

I. CRATERS ON THE TERRAE

ALL counts of craters made to date show that the cumulative numbers of craters larger than specific sizes, when plotted against crater diameters, each on a logarithmic scale, yield approximations to straight lines. The smaller craters are far more numerous than the larger.

Obviously the maria have developed later than most of the craters. Various studies (Baldwin 1949; Arthur 1954a; Öpik 1960; Shoemaker and Hackman 1961a; McGillem and Miller 1962) show that craters on the maria and on the uplands are distributed essentially at random in each region. Hence, to determine the total numbers of craters larger than given limits which have been formed, we should concentrate our efforts first on the bright uplands.

Crater counts made by the author from the *Lunar Photographic Atlas* on objects larger than 32 miles in diameter are listed in Table I. There are several large ancient structures which probably are very old craters scattered over the moon. They are only partially preserved and hence have not been counted here. Presumably small craters of equal age would have been destroyed. The counts of craters between 16 and 32 miles in diameter over the entire surface of the moon are so difficult to make accurately, particularly in the limb regions, that this has not been attempted. In the larger sizes, the counts should be essentially complete, even in the maria, for the crater walls of these giants project up through the lava flows. In Table I, the data for the 16- to 32-mile-diameter range have been interpolated from the consistent figures on either side, the smaller crater data coming from Table II.

TABLE I. Counts of large craters.

Diameter range (miles)	Number of craters/ 19×10^6 km²	Cumulative number of craters	Cumulative number of craters/10^5 km²
16–32	(1256)	(1712)	(9.000)
32–64	346	456	2.397
64–128	89	110	0.5783
128–256	15	21	0.1104
256+	6	6	0.0315

It has been shown elsewhere (Baldwin 1949, 1963) that the basement structure of Mare Imbrium is the youngest of the huge circular maria and that all of the circular maria were formed as dry basins over an extended period of time. The lava flows everywhere developed appreciably later than the Mare Imbrium crater. Mare Imbrium and several other large circular formations are considered to be large impact structures.

TABLE II. Average crater counts from three areas in lunar uplands (Palm and Strom).

Crater diameter km	miles	Number of craters	Cumulative number of craters	Cumulative number of craters/ 10^5 km²	Cumulative number of craters/ 10^5 km² including data of Table I
1.37	0.85	73.3	226.5	1584	1586.3
2.05	1.27	49.3	153.2	1071	1073.3
2.74	1.70	35.3	103.8	726	728.3
3.42	2.12	18.6	68.6	480	482.3
4.11	2.55	12.3	50.0	350	352.3
4.79	2.98	7.6	37.7	264	266.3
5.48	3.40	6.0	30.1	210	212.3
6.16	3.83	3.6	24.1	169	171.3
6.85	4.26	4.6	20.5	143	145.3
7.53	4.68	1.6	15.9	111	113.3
8.22	5.11	2.0	14.3	100	102.3
8.90	5.53	1.3	12.3	86.0	87.5
9.59	5.96	1.0	11.0	76.9	79.2
10.27	6.38	0.6	10.0	69.9	72.2
10.96	6.81	1.6	9.4	65.7	68.0
11.64	7.23	0.6	7.8	54.5	56.8
12.33	7.66	0.6	7.2	50.3	52.6
13.70	8.51	2.3	6.6	46.2	48.5
14.38	8.93	0.3	4.3	30.1	32.4
15.07	9.36	1.0	4.0	28.0	30.3
15.75	9.79	0.3	3.0	21.0	23.3
17.81	11.07	0.3	2.7	18.9	21.2
19.18	11.92	0.3	2.4	16.8	19.1
21.92	13.62	0.6	2.1	14.7	17.0
23.29	14.47	0.3	1.5	10.5	12.8
24.66	15.32	0.3	1.2	8.4	10.7
	16				(9.0)
26.03	16.17	0.3	0.9	6.3	
28.77	17.87	0.3	0.6	4.2	
45.21	28.09	0.3	0.3	2.1	

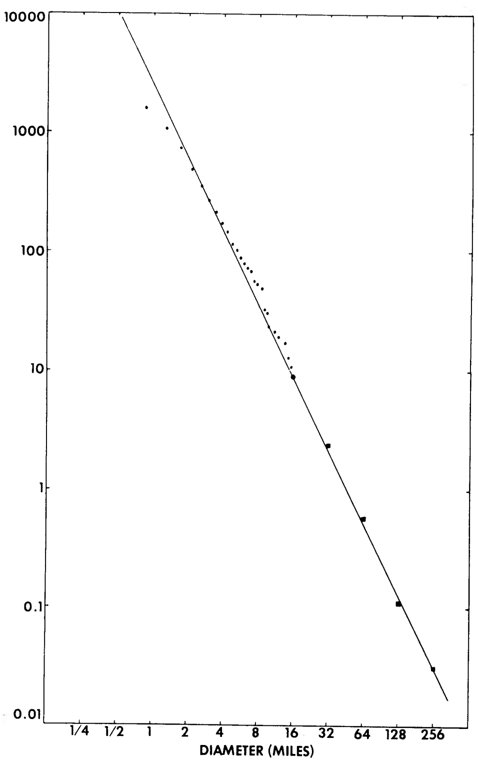

FIG. 1. Cumulative crater counts on terrae per 10^5 km². Points—observed. Line—first approximation [Equation (1)].

When these cumulative data are plotted in Fig. 1, the four largest crater groups define a straight line rather well.

In a study of the density of craters in Ptolemaeus, Palm and Strom (1963) have made similar counts in three areas, each of 14 300 km² and situated in the uplands near Ptolemaeus. The results are amazingly consistent from area to area. In their published paper covering these investigations, their observations were not given in detail. They have graciously furnished me with their original data. The average results for these three areas are listed in Table II.

TABLE III. Crater counts on the bright uplands (first approximation).

Diameter (miles)	N_c	ΔN	N_{vc}	$\frac{N_{vc}}{N_c}$
512	.0077	.0238 (use .0315)		
256	.0315	.0973	.0313	.9936
128	.1288	.3974	.1251	.9640
64	.5262	1.6238	.4906	.9197
32	2.150	6.639	1.9004	.8682
16	8.789	27.131	7.291	.8120
8	35.92	110.88	27.71	.7528
4	146.8	453.2	104.4	.6915
2	600.0	1852	389.2	.6284
1	2452	7568	1434	.5639
$\frac{1}{2}$	10020	30920	5201	.4978
$\frac{1}{4}$	40940			

When these data are plotted on Fig. 1, it is seen that they form a very consistent extension of the straight line yielded by the data of Table I.

Let us assume (1) that the counts of craters still visible (i.e., have not been destroyed by larger craters subsequently formed in the same area) are essentially complete, (2) that the crater counts by Palm and Strom are representative of non-lava-covered areas, (3) that the craters on the moon were formed at random over the moon's surface, (4) that the craters are of meteoritic origin, (5) that secondary impact craters may be considered together with primary impact craters, (6) that the distribution of colliding meteoritic masses is independent of time, (7) that the absolute rate of infalls may vary with time without affecting the conclusions to be drawn here.

We may now solve for the relationship between crater diameters and numbers of craters which have been formed. This is a two-step approximation.

Let us, as a first approximation, assume that the straight line

$$\log N_c = -2.03105 \log D + 3.38956, \qquad (1)$$

from Fig. 1, represents the total cumulative number of craters which have been formed with apparent diameters greater than D (miles). Actually, this is only an approximation to the total number of craters of each size which are still visible, but we shall use this erroneous approximation to determine the percentages of craters which have been masked by later and larger craters.

When a crater is formed, it possesses a rim which is one fifth as wide, on the average, as the diameter of the apparent crater (Baldwin 1963). Hence, a crater will obliterate or cover a circle 1.4 times its own apparent rim-to-rim diameter. The probability that a crater of diameter D will occur within a given area A is $AN/10^5$ km², where N is the total number of craters of this size range which have occurred in an area of 10^5 km². Now if D is the diameter of a crater which is to be obliterated by a later crater of diameter $2D$, then the center of the larger crater must lie within $0.9D$ of the center of the smaller crater. The area within which the larger crater must occur is thus $A = 0.81\pi D^2$. Similar equations may be found for any combination of crater sizes.

On the erroneous assumption that Eq. (1) is correct, we may now solve for the expected number of craters larger than given diameters which would still be visible, i.e., not destroyed or covered by later craters. The results are listed in Table III, Column 4. Column 5 gives the ratio between Columns 4 and 2. Over half of the tiny craters which once existed have been destroyed. In the table N_c is the cumulative number of craters whose diameters are larger than a given diameter and ΔN is the number of craters between successive diameter limits, the area considered is 10^5 km². Actually there is no crater larger than the 421-mile-wide Mare

Imbrium central crater, and in the smaller ranges, the observed numbers are less than calculated for at least two reasons. The craters become increasingly difficult to count in the smaller sizes, and the smaller craters must have been more frequently obliterated by the larger craters than is true in the larger sizes. It is also possible that the apparent falloff in numbers of small craters is real. In this case, extrapolations to very small crater sizes is impossible, and we can obtain no information about the roughness of the lunar terrain on a meter scale by this method.

Of course, the plot of Fig. 1 shows the cumulative numbers of remaining visible craters, not the total which have been formed over the eons. With fair accuracy, we may now reverse the procedure. From the smoothed curve and the above percentages, we find that an observed number of craters of 600 larger than two miles in diameter corresponds to a total production of 925 such craters. Similarly, there have been formed 0.0315 craters larger than 256 miles in diameter in our 10^5 km^2. A straight line drawn through these two points gives

$$\log N_c = -2.12025 \log D + 3.60439, \qquad (2)$$

which gives an approximation to the total cumulative production of craters on the moon per 10^5 km^2 since the earliest observable crater. Table IV lists the solution of this equation. [For general purposes, Eq. (2) should be used as $\log N_c = -2.120 \log D + 3.604$.]

The third column, or cumulative numbers of craters still visible, was derived by a method similar to that used in the first approximation. The straight line from Column 2 and the curved line from Column 3 may be plotted on Fig. 2 against the observed cumulative crater counts of Tables I and II. The fit is excellent, and Table IV would appear to give a fairly accurate approximation to the numbers of craters which have been formed during the moon's lifetime, as well as those which still remain visible.

It is emphasized that craters smaller than about $1\frac{1}{2}$ miles in diameter are observed, on these photographs, to be somewhat less frequent than this calculation would suggest. This effect probably is not real and is due to the difficulties in making crater counts on objects whose size is but little greater than the resolving power of the photographic plates used.

TABLE IV. Total cumulative production of lunar craters larger than specific diameters per 10^5 km^2.

Diameter	N_c	N_{vc}	N_{vc}/N_c
256	.0315	.0313	.9936
128	.1370	.1329	.9630
64	.5955	.5533	.9169
32	2.589	2.268	.8599
16	11.26	9.156	.7944
8	48.94	36.34	.7214
4	212.8	141.5	.6413
2	925	534.6	.5519
1	4022	1954	.4585
$\frac{1}{2}$	17485	6730	.3547

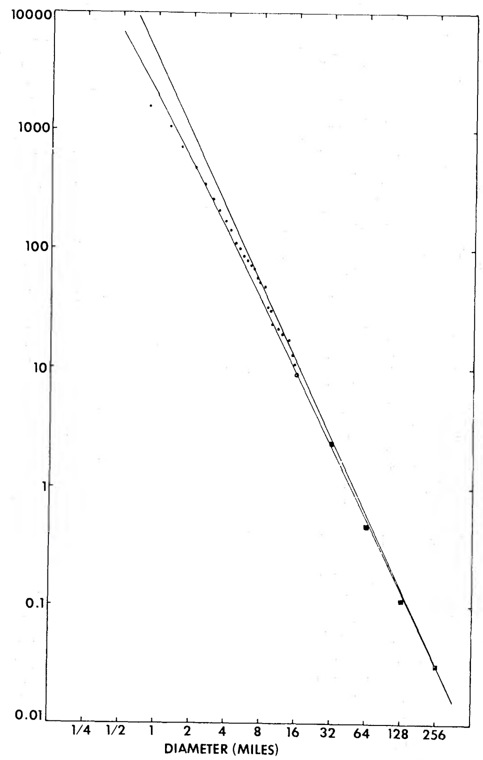

FIG. 2. Cumulative crater counts on terrae per 10^5 km^2. Points—observed. Upper line—numbers of craters formed [Equation (2)]. Lower curve—numbers of craters still visible (Table IV).

Equation (2) may be written

$$N_c = 4022 D^{-2.12025}. \qquad (3)$$

From this, we may find the expression for the area equation, i.e., the total cumulative area destroyed by craters larger than a given diameter within an area of 10^5 km^2.

$$A = 55700 D^{-0.12025} \Big]_{D_1}^{D_2}. \qquad (4)$$

From (4), we may find the total area destroyed by subsequent crater formations within 10^5 km^2. In addition, we remember that the crater rim buries a ring whose diameter is 1.4 times that of the apparent crater. Table V gives the solution of this equation, corrected for the rim effect.

Even allowing for the approximate nature of these calculations, the bright uplands of the moon must have been churned and rechurned into a thorough mishmash. It is noted that the bright uplands, based on these data, would have an area equal to 100% of the total area destroyed by craters larger than one-quarter mile in diameter and would have an area equal to 100% of the total area destroyed or covered by craters and their rims when the crater diameter is larger than four miles.

Due to the random nature of the infalls, however, there is no guarantee that any specific spot will have been struck. Much overlapping is inevitable.

TABLE V. Cumulative area destroyed or covered by crater formation.

Diameter (miles)	Cumulative area obliterated in $km^2/10^5$ km^2
256	11 600
128	24 200
64	37 900
32	52 800
16	69 000
8	86 600
4	106 000
2	127 000
1	149 000
½	174 000

It is clear that the coefficient of the log$D$ term in Eq. (2), being greater than -2, leads to more than 100% destruction or covering of the upland areas for crater diameters less than four miles. In this small-crater end of the line, the influx of particles could have been substantially greater than the straight line would suggest without changing significantly the numbers of small craters still visible. The straight line for craters larger than four miles wide would not be affected, but the small-crater end could be concave upward to an unknown degree.

II. CRATERS ON THE MARIA AND RAY CRATERS

The visible craters in the dark areas are substantially less frequent than those in the uplands and must necessarily represent essentially the total number that have been formed since the maria developed. Counts of these craters, in conjunction with the counts on the uplands, may possibly lead to improved estimates of relative ages of the maria and conceivably to improved absolute ages.

There are so many reasons for considering the dark areas as old lava flows (Baldwin 1963) (or possibly welded tuffs) that we will here consider them to be solidified lava extruded from the body of the moon.

TABLE VI. Size frequency distribution of primary impact craters on the lunar maria.

Region	Crater diameter (miles) 1	2	4	8	16	32	64	128	Area (km^2)
Mare Imbrium	199	117	37	10	5	1	0		864 000
Lacus Somniorum, Mare Frigoris	103	68	41	15	5	2	0		64 500; 439 000
Mare Serenitatis	88	41	7	1	1	0	0		318 000
Mare Fecunditatis	56	34	28	6	3	1	1		311 000
Mare Tranquillitatis	89	57	39	11	6	0	1		402 000
Palus Epidemiarum, Mare Humorum, Mare Nubium	111	64	27	11	0	1	0		288 000; 107 000; 261 000
Mare Nectaris	26	16	2	1	0	0	0		96 400
Mare Crisium	39	15	6	4	0	0	0		165 000
Oceanus Procellarum	60	31	11	3	2	0	0		315 000
Total	761	443	198	62	22	5	2		3 630 900

Data from Shoemaker and Hackman (1961a). Mare Crisium and Oceanus Procellarum data by author.

TABLE VII. Cumulative frequency of lunar craters larger than given limits per 10^5 km^2.

Region	Crater diameter (miles) 1	2	4	8	16	32	64
Mare Imbrium	42.7	19.7	6.2	1.9	.70	.12	...
Lacus Somniorum, Mare Frigoris	46.4	26.0	12.5	4.4	1.4	.40	...
Mare Serenitatis	43.4	15.7	2.8	.62	.31	...	...
Mare Fecunditatis	41.4	23.4	12.5	3.5	1.6	.64	.32
Mare Tranquillitatis	50.4	28.4	14.2	4.4	1.8	.25	.25
Palus Epidemiarum, Mare Humorum, Mare Nubium	32.6	15.8	6.0	1.8	.15	.15	...
Mare Nectaris	46.7	19.7	3.1	1.0	...	...	...
Mare Crisium	38.7	15.1	6.0	2.4	...	...	...
Oceanus Procellarum	33.9	14.9	5.1	1.6	0.63	...	...
Combined	41.1	20.2	8.0	2.5	0.80	0.19	0.06

These lava sheets are not one but many separate flows. There exist variations in color, tone, and surface texture.

Shoemaker and Hackman (1961a) have made crater counts as functions of crater diameters on most of the lunar maria. These data, slightly modified, are listed in Table VI. In addition, their count of craters on Mare Crisium is replaced by one made on a better photograph.

The values for Oceanus Procellarum resulted from a count made on the west half on Plate F4-b of the *Lunar Photographic Atlas*.

The crater counts in these widely scattered areas have been converted into cumulative numbers of craters larger than the given crater diameters per 10^5 km^2. Table VII shows the results; they are also

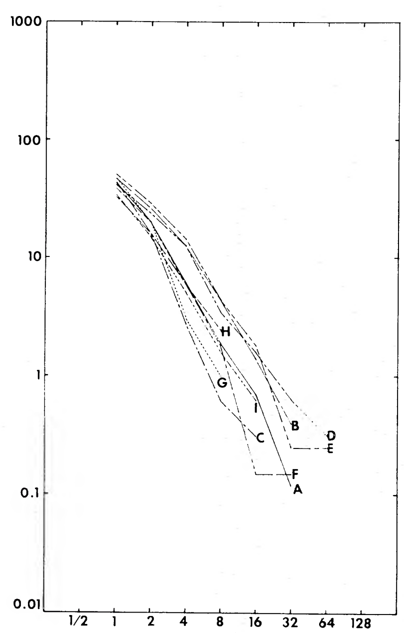

FIG. 3. Cumulative crater counts on various maria per 10^5 km^2. A—Mare Imbrium, B—Lacus Somniorum, Mare Frigoris, C—Mare Serenitatis, D—Mare Fecunditatis, E—Mare Tranquillitatis, F—Palus Epidemiarum, Mare Humorum, Mare Nubium, G—Mare Nectaris, H—Mare Crisium, I—Oceanus Procellarum.

plotted on Fig. 3. As before, the curves developed here may not be safely extrapolated into that region of craters too small to be visible from earth.

The data used in this paper are similar to those collected by McGillem and Miller (1962) for the Kepler region and by Lincoln (unpublished) for the Mare Tranquillitatis region and by Kreiter (1960). Dodd, Salisbury, and Smalley (1964) have an important paper on these subjects in press.

It is clear that the frequencies with which postlava craters occur per unit area are closely similar on each of the major dark regions. The dispersion becomes less at the small-crater end of the family of curves as we would expect if the differences were largely statistical. It is concluded that the frequencies with which craters of varying sizes were formed on the great lava flows were, to a first approximation, identical and that therefore the great lava sheets developed on the face of the moon within the same general period in the past.

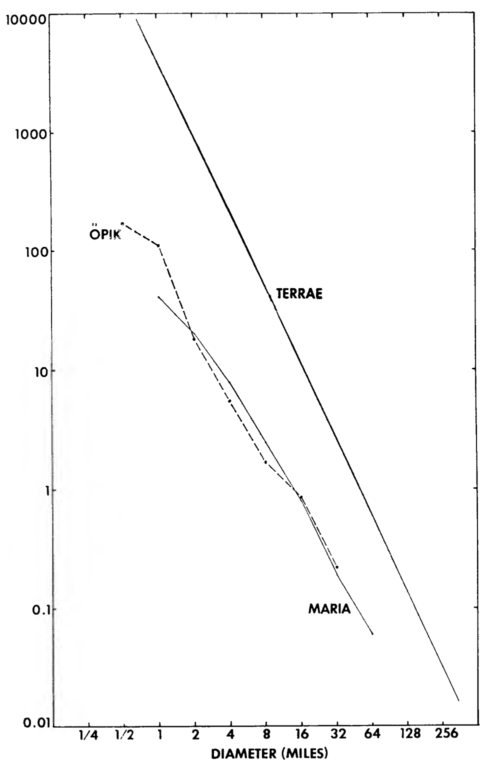

FIG. 4. Comparison between cumulative crater counts on terrae [Eq. (2)] and average mare (Table VII) per 10^5 km^2. Öpik's (1960) Mare Imbrium data also shown.

The straight line for Eq. (2) for the upland areas is shown on Fig. 4. Also on Fig. 4 is plotted the average curve from the data of Table VII for the frequency of postmare craters. An approximation to a straight line is indicated here, although the smaller craters seem to be less frequent than would be expected from the larger crater end of the line.

The slope of the line from the postmare craters seems to be slightly less than that for the craters observed in the bright areas, but this may well be statistical. Two or three fewer large craters on the maria would permit the lines to have about the same slope.

TABLE VIII. Size frequency distribution of postmare craters.

Region	Crater diameter (miles) ½	1	2	4	8	16	32	Area (km²)
Mare Imbrium	794	519	84	26	8	4	1	465 000
In Ptolemaeus	78	72	11	1	...	...		10 360
In Flammarion	16	8	1	...	...	...		1 250
Near Triesnecker	97	39	9	4	2	1		38 600
Mare Vaporum	93	33	10	2	0	1		100 000

Mare Imbrium crater counts interpolated from Öpik (1960) with Archimedes and Wallace omitted as premare craters. Other counts by author.

Against this is Öpik's (1960) curve for Mare Imbrium (see Tables VIII and IX. Öpik included many secondary impact craters from Copernicus and Eratosthenes in his count, while Shoemaker and Hackman limited their line to primary craters. Inasmuch as secondary craters cannot be distinguished from primary craters in much of the upland areas, the data of Öpik should be more nearly comparable with the upland data, although the counts of Shoemaker and Hackman would better represent primary meteoritic infalls since the maria were formed.

The total frequency of craters on the uplands, including the craters there of postmare age, is slightly more than one order of magnitude greater than the frequency of postmare craters, and the ratio becomes larger as the craters become smaller. The line

$$\log N_c = -1.707 \log D + 1.903 \qquad (3)$$

is an approximation to both sets of postmare data.

Each of the lava flows may be seen to be built up from a series of smaller flows. An obvious and distinct flow is the one fanning out from Sinus Iridum, but hundreds of them may be found, some large, some small.

The lavas which fill the two neighboring craters, Ptolemaeus and Flammarion, are rather light in color. Projecting into the open northern side of Flammarion is a distinct flow which is considerably darker than the earlier lava. This darker flow may be traced to the northwest in the broad trough which contains Triesnecker. It ends just south of the Hyginus Rille, although a very dark spot suggests a still later flow midway between Hyginus and Agrippa.

TABLE IX. Cumulative frequency of lunar craters larger than given limits per 10^5 km^2.

Region	Crater diameter (miles) ½	1	2	4	8	16	32
Mare Imbrium	171	112	18.1	5.6	1.7	0.86	0.22
In Ptolemaeus	753	695	106	9.6	...	...	...
In Flammarion	1280	640	80	...	...	...	...
Near Triesnecker	251	101	23.3	10.4	5.2	2.6	...
Mare Vaporum	139	46	13	3	1	1	...

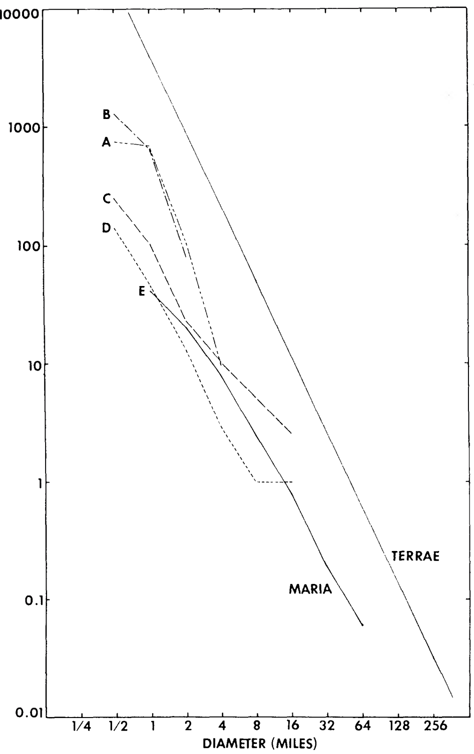

FIG. 5. Comparison between cumulative crater counts on terrae [Eq. (2)] and on various lava flows, per 10^5 km². A—in Ptolemaeus, B—in Flammarion, C—near Triesnecker, D— in Mare Vaporum, E—average mare (Table VII).

The Mare Vaporum lavas east of Manilius are also dark. They fill all the lowlands in that area and even send a probing arm along the south side of the east branch of the Hyginus Rille.

Crater counts have been made on each of these three overlapping lava flows. They are reported in Table VIII and as cumulative frequencies per 10^5 km² as functions of crater diameter in Table IX. The latter data are plotted on Fig. 5. In this figure, curve A comes from my count of postlava craters in Ptolemaeus. Curve B represents Flammarion and is effectively identical to the Ptolemaeus curve. Because the frequency curves are so similar, it is concluded that the dark material filling each crater developed at the same time.

From its appearance, the flow in the Triesnecker area is younger than that in Flammarion. It seems to have spread onto the older flow. Curve C is for this area. At the small-crater end, it is noticeably less densely covered by craters than are Flammarion and Ptolemaeus.

The Mare Vaporum lavas are still younger, and Curve D shows that the frequency of postlava craters is distinctly lower there than elsewhere, although not a great deal less than the Mare Imbrium frequency.

Curve E is the average curve from all the great dark flows as reported in Table VII. It represents reasonably well the frequency and size distributions of postlava craters on the maria. As such, it marks a blend of the frequency with which impacts occurred on lava flows of somewhat different ages. Curve C for the Triesnecker areas agrees well with it, and it is noted that the earlier flow is somewhat more densely populated by craters, and the later flow is more sparsely marked.

Shoemaker and Hackman did not report on postmare craters smaller than one mile in diameter, and indeed only the best photographs show craters smaller than this limit with sufficient clarity to permit accurate counts. As a result, the smaller crater ends of these curves probably reflect incomplete crater counts and so tend to fall off, although the major trends of each are clearly shown from the larger craters.

Curves A and B for the older flows in Ptolemaeus and Flammarion show far more small craters than would be expected from the counts in other areas. Two possibilities suggest themselves. The photographs used were superb and do show many tiny craters, so the trend in frequencies of impact craters may be real. It is possible that all areas would show this accelerated increase in numbers of small craters, if the counts were made on equally good plates. This is good evidence that we should not extrapolate these curves to the small, invisible crater regime. Alternatively, some of these tiny craters on the older flows may be of internal origin. Palm and Strom reached the same conclusion in their study of the Ptolemaeus area. Their results are listed in Table X. Because the Ptolemaeus and Flammarion type of lava flow appears to mark the oldest of the lava extrusions, or at least older than nearby flows, it is entirely possible that blow-hole craters may abound there. Craters of internal origin certainly are found on the lavas near Copernicus and elsewhere.

In addition to these two types of craters, there is a third category. This contains the craters which were formed on the original floor of Ptolemaeus before the lava flows came. These early craters have been called ghosts by Palm and Strom, who have studied them carefully. Their results are listed in Table XI. Arthur (1954b) has also reached similar conclusions and given similar tabulations.

TABLE X. Post-Ptolemaeus craters in Ptolemaeus.

Diameter (km)	Diameter (miles)	Cumulative number of craters N_c	N_c / 10^5 km²
1.37	0.85	171.5	1199
2.05	1.27	67.5	472
2.74	1.70	15.5	108
3.42	2.12	6.0	42
4.11	2.55	3.0	21
8.90	5.53	1.0	7

Data from Palm and Strom. Average of two determinations. Compare with independent crater counts by author, Tables VIII and IX.

On Fig. 6, the average cumulative frequency curve for post-Ptolemaeus craters from Table X is shown and the straight line best representing the terrae craters. (Several authors recently have made an attempt to revive the old name "terrae" for the lighter-colored uplands. This name is no more farfetched than the well-established "maria" and would simplify the description of the moon's surface considerably. The name was originally proposed by Riccioli in the 17th century but did not find acceptance.) The Ptolemaec ghosts from Table XI are plotted and fall systematically slightly below the straight line. This is consistent with the fact that roughly 95% of the moon's craters are premare and hence could be ghosts.

It has previously been shown (Baldwin 1963) that Ptolemaeus is one of the earliest of the moon's larger craters. If we add the Ptolemaec ghosts and postlava craters, we should have a fairly good approximation to the crater counts on the terrae. This tabulation is also plotted on Fig. 6, and the agreement with the straight line for the terrae counts is excellent.

Because small ghost craters probably would often be drowned in the lava and because of the difficulty of getting accurate counts of such craters less than perhaps $1\frac{1}{2}$ miles in diameter, the results here given suggest that the great age of Ptolemaeus found earlier is correct. It is also clear that Ptolemaeus had become nearly completely compensated isostatically before the lavas came. If the prelava floor had had its original concave shape, the ghost craters would not now be visible all over the floor. The lava cover in Ptolemaeus is relatively thin and relatively uniform.

It has been known for some time that the craters which show ray structures are postmare in age and are distributed essentially at random over the moon's disk (Baldwin 1949).

TABLE XI. Ghost craters on the floor of Ptolemaeus.

Diameter (km)	Diameter (miles)	Cumulative number of craters N_c	$\frac{N_c}{10^5 \text{ km}^2}$
2.05	1.27	100.5	703
2.74	1.70	87.5	612
3.42	2.12	70.5	493
4.11	2.55	61.0	427
4.79	2.98	50.0	350
5.48	3.40	40.5	283
6.16	3.83	28.5	199
6.85	4.25	18.0	126
7.53	4.68	11.5	80.4
8.22	5.11	10.5	73.4
9.93	6.17	9.0	62.9
10.96	6.81	7.5	52.4
11.64	7.23	6.0	42.0
12.33	7.66	4.5	31.5
13.01	8.08	4.0	28.0
14.38	8.93	2.0	14.0
15.75	9.79	1.0	7.0

Data from Palm and Strom. Average of two determinations.

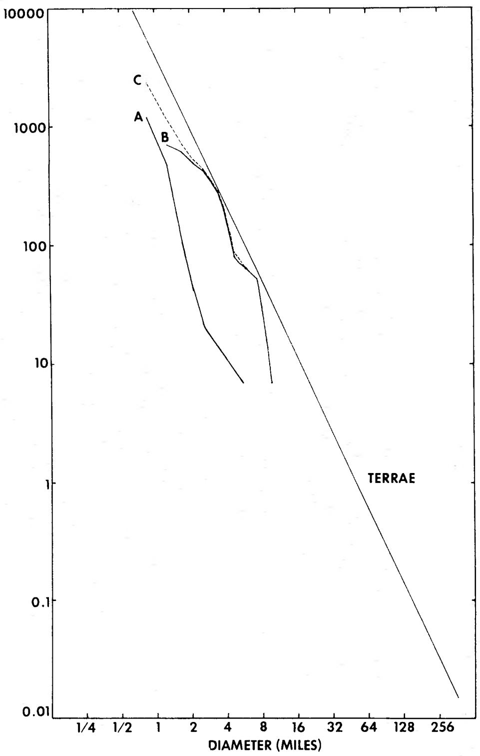

FIG. 6. Comparison between cumulative crater counts on terrae [Eq. (2)] and crater counts within Ptolemaeus per 10^5 km^2. A—post-Ptolemaeus craters, B—Ptolemaec ghosts, C—all craters within Ptolemaeus, =A+B.

Counts of ray craters were made on the plates of the *Lunar Photographic Atlas* and are reported in Table XII and plotted on Fig. 7.

It is noted that the slope of the cumulative ray crater counts versus diameter is less than that of the postmare craters. Similarly, the slope of the cumulative postmare crater curve is less than that of the premare craters. The progression in slopes with age of craters may be real. However, at least a portion of the discrepancy in the case of the small ray craters is the difficulty in ascertaining the existence of small ray systems in the *Lunar Photographic Atlas*. As a best estimate, it is concluded that the ray craters are about one-fifth as frequent as the postmare craters.

III. THE AGES OF THE MARIA AND RAY CRATERS

It is considered possible that these various cumulative crater frequency relationships may yield information on the absolute ages of the maria and the ray craters.

In order to compare cumulative counts of craters on the moon with cumulative counts of objects which strike the earth, we need to be able to relate crater size with meteoritic mass and velocity.

Judging by the observed velocities with which larger objects strike the earth, it appears that the velocity with which they strike the moon would average about

10 miles per second (Whipple 1963). This velocity will be used in the following solutions.

In *The Measure of the Moon* (Baldwin 1963), there are various equations relating crater dimensions and the energies needed to form the craters for various scaled depths of burst. From the above velocity of impact and various assumed meteoritic masses, we may solve for the kinetic energy, and from Eq. (8–3), we may solve for the resultant craters for meteoritic masses between 10 and 10^{11} g.

By interpolating between Eqs. (8–1) and (8–3), according to the table on page 186, we may solve for craters resulting from collisions with particles of masses between 10^{12} and 10^{15} g.

For masses in the range of 10^{16} to 10^{21} g, we may use Eq. (8–12).

Three comments are pertinent here. First, there is some evidence that smaller masses may strike the earth with slightly higher velocities than do the larger objects; and second, the lunar crater counts are valid only down to about one mile in diameter. Hence, the meteoritic objects we should consider are those whose masses are larger than about 10^{12} g, and for these, the average impact velocity of 10 miles per second seems to be about right for collisions with the moon. The cumulative frequency data for these large masses are the most uncertain of all.

It must be emphasized that some of the data used below are of very low accuracy, and the conclusions reached are interesting but tentative.

McCracken and Dubin (1963, 1964), in the course of their very important work on accretion rates on earth, have summarized similar data from other scientists. In addition, McCracken has graciously reviewed these publications for me and converted their equations to the same system so that they may be compared. These collected equations are:

	Meteors	Validity	
Watson (1941, 1956)	$\log N_{(M_v)}=5.87+0.4M_v$	$-3\leq M_v\leq 10$	(4)
Millman and Burland (1956)	$\log N_{(M_v)}=6.3+0.4M_v$	$3\leq M_v\leq 10$	(5)
[by McKinley (1961)]	$\log N_{(M_v)}=6.0+0.50M_v$	$0\leq M_v\leq 3$	(6)
	$\log N_{(M_v)}=6.0+0.57M_v$	$-10\leq M_v\leq 0$	(7)
Hawkins and Upton (1958)	$\log N_{(M_v)}=4.93+0.538M_v$	$0\leq M_v\leq 4.1$	(8)
Kaiser (1961)	$\log N_{(M_r)}=4.86+0.468M_r$	$8\leq M_r\leq 10.8$	(9)
	Fireballs		
Hawkins (1959)	$\log N_{(M_v)}=4.52+0.4M_v$	$-10\leq M_v\leq 3$	(10)
	Meteorites, Asteroids, and Comets		
Brown (1960, 1961) (stones and irons)			
	High limit—$\log N_{(m)}=3.52-0.8\log m$	$10^2\leq m\leq 10^{11}$ g	(11)
	Low limit—$\log N_{(m)}=3.04-0.8\log m$	$10^2\leq m\leq 10^{11}$ g	(12)
Hawkins (1960) (stones and irons)	$\log N_{(m)}=5.46-\log m$		(13)
Hawkins (1963) (stones)	$\log N_{(m)}=5.42-\log m$		(14)
(irons)	$\log N_{(m)}=2.64-0.7\log m$		(15)
Öpik (1958) (stones and irons) [taken from Hawkins' (1963) charts]	$\log N_{(m)}=4.35-0.9\log m$		(16)
(comets) [taken from Hawkins' (1963) charts]	$\log N_{(m)}=1.25-0.7\log m$		(17)

$N_{(\ )}$ is the cumulative accretion rate in particles/earth day
M_v is the visual magnitude ($m=1$ g at 30 km/sec $\rightarrow M_v=0$)
M_r is radar magnitude ($M_r=M_v$)
m is particle mass in grams (before interacting with the atmosphere) [except (11) and (12)] in grams.

The equations by Brown have been derived from his Table 3 (1960) as corrected (1961). Millard (1963) found the Brown lower limit equation slightly modified gave a close approximation to superior data on meteoritic falls. Brown had found the rate of recovery of meteorites from falls in high-population-density regions to be 1.1

TABLE XII. Ray crater counts.

Diameter range (miles)	Number	Cumulative number	Cumulative number/10^5 km^2	Cumulative number postmare craters/10^5 km^2	Postmare craters / Ray craters
1	77	351	1.845	41.1	22.3
2	114	274	1.441	20.2	14.0
4	90	160	0.841	8.0	9.5
8	44	70	0.368	2.5	6.8
16	17	26	0.137	0.80	5.8
32	7	9	0.047	0.19	4.0
64	2	2	0.011	0.06	5.5

to 3.4 meteorites/10^6 km^2 year. Millard improved this to 1.08±0.36. By extrapolating the straight line relationship found on the high mass side of the log-frequency-vs-log-mass curve into the low mass region, the "true" rate of infalls, according to Brown, would be 16 to 49 meteorites/10^6 km^2 year; and according to Millard, it would be 16±5 with mass >100 g. The latter figure agrees well with Millard's estimate (15±5) based on a population distribution and cultural level correction factor of 14.

If we accept Millard's value of 16±5 meteorites/10^6 km^2 year (mass >100 g) and a slope of −0.76 as used by Brown in his analysis, we may derive

$$\log N_{(m)} = 2.869 - 0.76 \log m \quad 10^2 \leq m \leq 10^{11} \text{ g}, \quad (18)$$

which is valid for the falls of meteorites.

To get an equation for the pre-atmospheric mass–frequency distribution, we use Hawkins' estimate that a 40 kg mass will ablate to a 10 kg mass at impact and assume a 3% loss of mass for an object which strikes as a 10^{11} g body. Actually, a range of ablation from 0 to 10% will yield very nearly identical equations. These assumptions yield:

$$\log N_{(m)} = 3.65 - 0.83 \log m \quad 6\times 10^2 \leq m \leq 10^{11} \text{ g}. \quad (19)$$

The constant term could range from 3.77 to 3.49.

Figure 8 shows the plotted lines from the above equations where certain equations are plotted against visual absolute magnitude of meteors and others against the logarithm of the particle mass in grams. The zero point of the visual magnitude scale is assumed to coincide with the log particle mass equal zero point for an impact velocity of 30 km/sec. The ordinate in all cases is logarithmic cumulative equation rate in particles/earth day.

The chart shows a rather clearly defined band relating cumulative accretion rate to the masses of the particles. The observations from which these

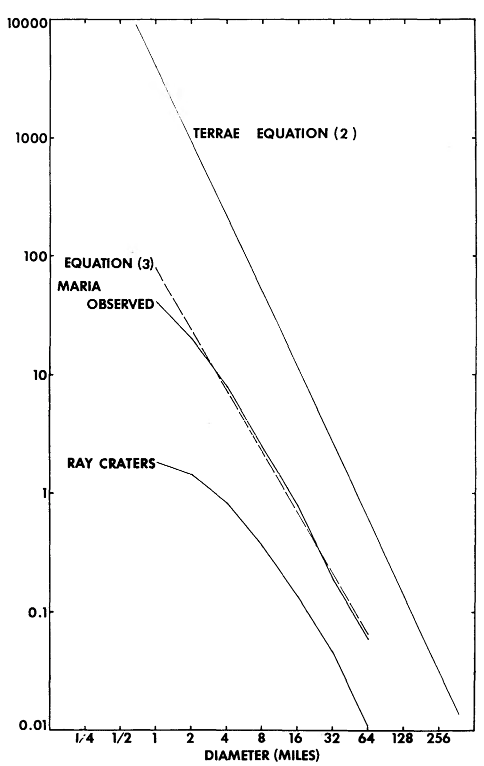

FIG. 7. Cumulative crater counts on terrae, maria, and ray craters, per 10^5 km^2.

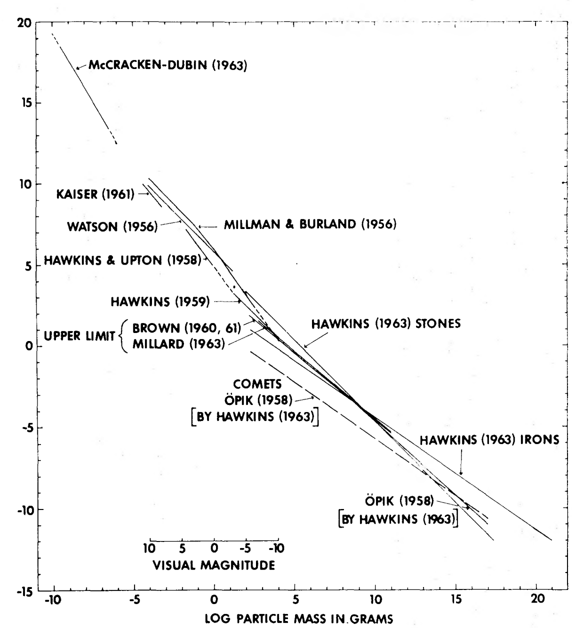

FIG. 8. Logarithmic cumulative accretion rates for the earth for particles of various masses.

TABLE XIII. Craters produced by meteorites striking at 10 miles per second.

Logarithmic meteoritic mass (g)	Logarithmic crater diameter (ft)	Logarithmic crater diameter (miles)	Logarithmic meteoritic mass (g)	Logarithmic crater diameter (ft)	Logarithmic crater diameter (miles)
1	0.4467	−3.2759	12	3.7609	0.0383
2	0.7621	−2.9605	13	4.0314	0.3088
3	1.0755	−2.6471	14	4.2944	0.5718
4	1.3869	−2.3357	15	4.5493	0.8267
5	1.6960	−2.0266	16	4.8251	1.1025
6	2.0021	−1.7205	17	5.1535	1.4309
7	2.3053	−1.4173	18	5.4819	1.7593
8	2.6052	−1.1174	19	5.8103	2.0877
9	2.9015	−0.8211	20	6.1387	2.4161
10	3.1937	−0.5289	21	6.4671	2.7445
11	3.4819	−0.2407			

equations were derived are still very preliminary, and their interpretations will permit significantly different slopes to be found for the equations without markedly stretching credulity. The satellite equation of McCracken and Dubin probably reflects the effect of the earth's magnetic field on micrometeoritic particles, and presumably the lunar curve would be lower in this region. With the data of Table XIII, we may now convert certain of these equations into equivalent lunar crater counts and see how they compare with the actual counts which led to Eqs. (2) and (3).

It is assumed that the velocity of impact on the moon is 10 miles per second. Probably the mean velocity for the objects which we on earth observe as meteors should be somewhat higher. A higher velocity will lead to a larger crater from a given mass. Inasmuch as the smaller objects at the lower velocity will be found not to agree with the extrapolations of the lunar crater counts to smaller sizes, it will not be necessary to consider possible higher velocities for the smaller objects, as these will still further increase the discrepancy. We cannot extrapolate from observed lunar crater counts to the numbers of smaller invisible craters.

With the advantage of hindsight, let us take the equations which yield the greatest frequencies of particles in the mass range above 10^6 g. Up to about 10^9 g, Hawkins' (1963) equation for stones yields higher frequencies than Öpik's (1958) equations for comets or meteorites, and it is also higher than Brown's (1960) equation as raised in 1961 or the equation derived from Millard's work. Above 10^{10} g, Hawkins' (1963) equation for irons yields the highest frequency of particles.

The solutions of these two equations are shown in Table XIV. These have been corrected from

$$\frac{\text{particles}}{\text{earth day}} \text{ to } \frac{\text{particles}}{10^5 \text{ km}^2\ 10^9 \text{ yr } (2\pi \text{ sr})}$$

for the moon. It has been assumed that the moon would sweep up only 50% as many particles per unit area as the earth.

A definite value cannot be given for this accretion ratio. Öpik (1950, 1951, 1958, 1961, 1963) considers the average influx rate on the moon to be 80% of that of the earth. Brown (1960) uses 77%. Hawkins (1959) uses 50% as does Whipple (1963), in the large-particle range. The uncertainty lies in the lack of knowledge of the distribution of orbits applying over the entire range of particle masses. For example, meteoroids which produce meteors have orbital distributions that are similar to those of short-period comets, while those which yield meteorites have orbital distributions more like those of the asteroids. The use of the enhancement of infalls on earth by a factor of 2 over the moon implies that the larger particles considered here are in more nearly circular orbits of lower inclinations rather than in cometary orbits.

The data of Table XIV may be plotted on Fig. 9 against Eqs. (2) and (3) for the terrae craters and maria craters. It may be immediately seen that, in the smaller-crater end of the chart, the two Hawkins equations yield different slopes than do the lunar-crater count equations extrapolated into the small-invisible-crater regions. However, the large-crater end of the chart is decidedly different. In the region of craters larger than about one mile in diameter, the Hawkins stone equation yields a negligible number of craters; but in the case of irons, his equation yields a curve which approximately parallels the two lunar-crater-count lines. Table XV shows this comparison.

This table is most informative. It tells us that if the

TABLE XIV. Cumulative numbers of particles which strike the moon (per 10^5 km^2 10^9 yr) from Hawkins (1963).

log mass (g)	Irons $\log N_{(m)}$	Stones $\log N_{(m)}$
6	5.99	6.97
11	2.49	1.97
14	0.39	−1.03
16	−1.01	−3.03
18	−2.41	−5.03
21	−4.51	−8.03

TABLE XV. Crater counts per 10^5 km^2 on moon.

Crater diameter (miles)	Cumulative counts: Terrae craters	Cumulative counts: Maria craters	Cumulative counts: Hawkins' irons (10^9 yr)	Diameter range counts: Terrae craters	Diameter range counts: Maria craters	Diameter range counts: Hawkins' irons (10^9 yr)	Ratios of counts: Terrae craters / Hawkins' irons: Cumulative	Ratios of counts: Terrae craters / Hawkins' irons: By range	Ratios of counts: Maria craters / Hawkins' irons: Cumulative	Ratios of counts: Maria craters / Hawkins' irons: By range
256	.0315	(.00619	.0001622	.1055	(.01402)	.0005425	194	194	(38)	(26)
128	.1370	(.02021)	.0007047	.4585	.04579	.0024003	194	191	(29)	19
64	.5955	.0660	.003105	1.9935	.1495	.010355	192	192	21	14
32	2.589	.2155	.01346	8.671	.4882	.04583	192	189	16	11
16	11.26	.7037	.05929	37.68	1.5943	.25261	190	149	12	6.3
8	48.94	2.298	.3119	163.86	5.205	1.711	157	96	7	3.0
4	212.8	7.503	2.023	712.2	16.997	10.887	105	65	3.7	1.6
2	925	24.5	12.91	3097	55.5	64.36	72	48	1.9	0.86
1	4022	80.0	77.27				52		1.03	

particles of various masses had been striking the moon throughout its existence at the same rate as the *highest* estimate of collision rates yet advanced, the terrae regions of the moon are something close to 180 billion years old.

Inasmuch as we cannot assign such an extreme age to the moon, the rate of accretion in the distant past must have been very much greater than at present, particularly in the period before the maria came.

On the same assumption, the maria would be from 3 to perhaps more than 20 billion years old, probably about 10–12 billion years. This, too, is an excessive period.

It may be concluded that the maria are very old in terms of the moon's presumed age of 4.5 billion years, and not relatively recent as suggested by Fielder (1963) and Kreiter (1960). The method used here, of course, is rough; but the discrepancies are so great that it does not appear reasonable to postulate that the maria are young.

If Hawkins' iron curve is finally shown to be too high, then the arguments for the great age of the maria will be strengthened.

From Table XV, we may approximate the relative numbers of craters, in a mean diameter range, of 180 for the terrae; and, on the same scale, we may postulate one particle capable of producing such a crater per billion years from Hawkins' iron group.

Let us now make some guesses and see where they lead:

(1) The rate of infalls has fluctuated in an extreme fashion. In this case, no conclusions regarding the ages of the maria can be drawn.

(2) The rate has been constant at the present rate. Then the terrae are 180 billion years old and the maria 10 billions. This may be rejected.

(3) The present rate is very much less than the normal *constant* rate. Then the terrae are 4.5 billion years old, and the maria are $(4.5\times 10)/180$ billion years old, or 250 million years old. This solution may be rejected (see point 9).

(4) The rate has continually declined from the moon's beginning to the present. This implies *one* source of impacting particles. This may be interpreted as a sort of compound interest problem in reverse. It assumes that the number of particles which fall per unit time is proportional to the number which are left to fall (constant total of particles plus craters). The formula is

$$A=P(1+r)^n \text{ or equally well } A=Pe^{-n/0.864}, \quad (20)$$

where A is the relative number of objects originally (181 approximately), P is the remaining number of particles ($=1$), and n is the number of billion years.

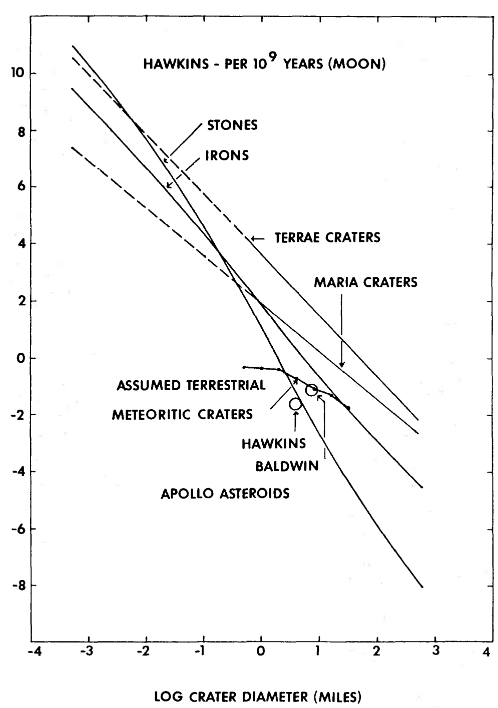

FIG. 9. Log cumulative number of craters per 10^5 km^2 vs log crater diameter.

TABLE XVI. Assumed terrestrial meteoritic craters.

Name	Diameter ft	Diameter miles	Name	Diameter ft	Diameter miles
Odessa No. 1	550		Keeley Lake		8
New Quebec	11 290		Holleford	7700	
Franktown		3/4	Brent	11 500	
Laborador	525		Deep Bay		$7\frac{1}{2}$
Clearwater No. 1		20	Flynn Creek Structure		2+
Clearwater No. 2		16−	Wells Creek Basin		6+
Manicouagan		40	Sierra Madera Dome		2+
Carswell Structure		18	Decaturville Structure		3+
Mecatina Crater		2	Kentland Structure		6
Lake Michikamau		$3\frac{1}{2}$	Howell Structure		1
Menihek Lake		3	Jeptha Knob		2+
Menïhek Läke		$2\frac{1}{2}$	Serpent Mound		4+
Sault au Cochons		7	Kilmichael Structure		7
Lac Couture		7	Crooked Creek Structure		3.5
West Hawk Lake		3			

In this case, $n=0$ is the present time, $n=-4.5$ is the beginning time for the moon, and $r=-0.685$.

If $A=10$, as determined from the maria, the age of the maria is two billion years.

(5) There may be two major sources of particles. One of these could be primal material present at the beginning of lunar history, and the other could be from the asteroid belt. The larger objects at present appear to show asteroidal characteristics. In this case, at least a part of the present infalls are asteroidal; and, therefore, the origin of the maria must be pushed back still further in time. For example, if one-tenth of the present large infalls is from primal material and nine-tenths are asteroidal bodies falling at a constant or declining rate throughout history, and the assumption is made as in 4 that the rate of primal infalls has regularly declined in proportion to the number of such objects left to fall, then the maria are at least $2\frac{3}{4}$ billion years old.

(6) If all of the large objects now falling are of asteroidal origin and none are of primal origin, then the maria are still older, provided that the premare craters were largely formed from primal objects according to the assumption in 4.

(7) Inasmuch as calculations suggest that objects near the earth would be swept up in a geologically short time, it would appear that there must be a continual replenishment of those objects which can still fall. Presumably this comes from the asteroid belt and from comets. Öpik (1961, 1963) considers the Apollo asteroids to be old comet nuclei.

(8) Unless the average rate of infalls in the last billion years has been at least 10 times higher than the highest estimate we can now give, the maria cannot be as young as one billion years.

(9) There is a little statistical information on terrestrial meteoritic craters which is pertinent to the above discussion. Some of this argument has been used earlier by Shoemaker and Hackman (1961a). In North America, we now know of many astroblemes and terrestrial meteoritic craters and possible terrestrial meteoritic craters. They are listed in Table XVI and include all such suggested objects given in *The Measure of the Moon*, except Haviland, Arizona, Nastapoka Arc, Gulf of St. Lawrence Arc, Ungava Bay, Upheaval Dome, and the Des Plaines structure. Haviland was omitted because of its small size. Its inclusion would not significantly change the conclusions. The Nastapoka Arc, Gulf of St. Lawrence Arc, and Ungava Bay were omitted because of their sizes and ages. Their presence close together in North America may be fortuitous and hence might bias the data. They appear to be very much older than the other structures. The size of the Des Plaines structure is unknown, and the Upheaval Dome and Arizona are widely separated from others. It is emphasized that many of these objects have not been accepted as of meteoritic origin.

The areas of four Canadian provinces, Quebec, Ontario, Manitoba, and Saskatchewan, and twelve of the United States, Illinois, Ohio, Missouri, Arkansas, Louisiana, Texas, Mississippi, Alabama, Tennessee, Kentucky, Indiana, Ohio, total 2 145 484 miles^2, or 5.557×10^6 km^2. To convert to frequency/10^5 km^2, we multiply the cumulative counts of the craters in Table XVI by 0.018 as given in Table XVII.

The frequency with which these possible terrestrial meteoritic craters occur is plotted in Fig. 9. Inasmuch as these known objects seem to be distributed throughout the last 500 million years, the frequency per billion years should be twice as great, but to compare with the lunar crater counts, we should divide by 2 so the data are plotted as listed.

It is clear that the frequency with these possible terrestrial meteoritic craters occur approaches in value and slope the cumulative iron curve by Hawkins, both corrected to the moon, in the large-crater end and meets it at roughly a 15-mile crater diameter. On earth, there should still be many more 15-mile-diameter and smaller meteoritic craters remaining to be discovered, unless erosion has destroyed them.

Again, the nature of the data is such that great weight cannot be put on these conclusions, but at least it may be said that the frequencies with which terrestrial meteoritic craters exist on earth and the frequencies with which large bodies may collide with the earth or moon are consistent with an age for the lunar maria of 2 or 3 billion years.

Earlier, it was shown that the crater counts suggest that the ray craters have an areal density one-fifth that of the possible maria craters. This may be interpreted to mean that the ray craters were formed in the last fifth of the period since the maria were formed. Even this period is so long that it is still more evidence that the rate of accretion by the moon over some hundreds of millions of years is not sufficient to form an optically opaque layer. Small color and brightness differences have persisted over at least the period since the maria appeared. While some churning of the outer layers, and even the loss of some of its material, are to be expected when masses strike the moon, the total amount of material which has fallen since the maria were formed must be very small.

It is apparent that a long period of time stretched between the date of the earliest observable feature on the moon and the coming of the maria. This is best shown by the progressive changes (Baldwin 1949, 1963) in the rim heights and crater depths with age of the lunar craters, probably due to isostatic adjustments. The data of this paper suggest that a long time has elapsed since the maria were formed.

The most reasonable conclusion, in the light of present-day knowledge, is that the maria are perhaps 2 or 3 billion years old, and existing ray craters were formed within the last 400–600 million years if the moon is 4.5 billion years old. If the moon were captured at some later time and the surface features date from that time of capture, the age of the maria would be proportionately reduced. The rate of falls of large meteorites on the moon must have declined substantially since the maria were formed, possibly by a factor of 4 to 6.

IV. THE FLUX OF MASSIVE PARTICLES NEAR THE EARTH

The frequencies with which objects of different masses are observed to be in the neighborhood of the earth and to collide with the earth apparently are consistent with the above conclusions only for those objects capable of producing craters on the moon large enough to be adequately counted from the earth, i.e., about one mile wide and larger. The data for the smaller particles are not consistent with straight-line extrapolations to small crater sizes for either the maria or terrae craters. There are from one to several orders of magnitude too many such smaller meteoritic objects observed now to be consistent with the straight-line extrapolations of counts of the lunar craters.

TABLE XVII. Counts of assumed terrestrial meteoritic craters.

Diameter range (miles)	Number	Cumulative number	Cumulative number/10^5 km^2	Log cumulative number/10^5 km^2
0–1	3	29	0.522	−0.28
1–2	2	26	0.468	−0.33
2–4	12	24	0.432	−0.36
4–8	7	12	0.216	−0.67
8–16	2	5	0.090	−1.05
16–32	2	3	0.054	−1.27
32–64	1	1	0.018	−1.74

Figure 9 shows the cumulative numbers of craters larger than a given diameter for the terrae and the maria and also the two equations of Hawkins (1963) giving his estimate of the numbers of large stony meteorites and of irons. The iron equation gives the highest frequency yet postulated for these large objects. Hawkins' equations have been converted into equivalent lunar crater counts.

Let us take a different approach to the problem. First, let us try to gain an independent check on Hawkins' iron equation and then use the lunar crater counts on the maria, scaled to the present rate of infalls, to determine the mass distribution of large meteorites in space.

In 1936, the earth passed relatively close to the asteroid Hermes. Others, such as Apollo, have been found to approach the earth fairly closely. About eight such objects are now known. They are small. Judging by their brightnesses, we may assume a diameter of one kilometer for the smallest and, arbitrarily, a density of 3. Hence, a logarithmic mass in grams of 15.2 follows, which corresponds to a meteoritic crater diameter of 7.6 miles at an impact velocity of 10 miles per second. This is the same as the Deep Bay Crater in Saskatchewan.

Let us make some assumptions and see if they can lead to any clarification of the frequencies with which such objects abound in space near the earth and the rates of collision with earth and moon. These assumptions are that all of these bodies are asteroids which lie between 200 000 000 miles from the sun and Mercury and have orbits inclined less than 20° to the ecliptic. The volume of space included is 5.3×10^{24} miles^3.

Let us assume that we can see such objects when they are within 20 000 000 miles of the earth, a volume of 3.3×10^{22} miles^3. Therefore, we can see at one time $3.3\times10^{22}/5.3\times10^{24}=6\times10^{-3}$ of the space occupied by asteroids which can strike the earth.

We have seen 8 such objects in the last 28 years. Inasmuch as we undoubtedly miss some, we assume that one per year could be seen. This may be an underestimate. If correct, it would mean that there are about 170 such bodies. Presumably the supply is maintained from the asteroid belt.

Öpik (1950, 1951, 1958, 1961, 1963) has calculated that such asteroids would be swept up by the earth in

10^8 yr. This is probably correct for many of these bodies; but in those cases where the orbital nodes are distant from a major planet's orbit, the asteroid may last indefinitely. Eros is such an example. This modifying factor may partially counteract a possible underestimate of their numbers.

If each one lasts 10^8 years, there might be one collision with the earth per $10^8 \times 6/10^3 = 6\times 10^5$ years. If the hits are in proportion to the areas of the five major bodies, the earth should collect about 40% of these asteroids. Let us call it 50%, because the earth is in a more nearly central position in the belt and should get more than its share. Hence, the earth would be struck by one of these asteroids larger than 1 km in diameter every 1.2×10^6 yr. That is, a meteoritic crater 7.6 miles in diameter or larger should be formed on earth every 1.2×10^6 yr, including hits in the oceans.

The above frequency corresponds to a collision with one such Apollo asteroid every 6.1×10^9 yr for each terrestrial area of 10^5 km^2 at the present rate. It may be expressed as a logarithmic cumulative influx rate of

$$\frac{-0.8 \text{ particles}}{10^5 \text{ km}^2\ 10^9 \text{ yr } (2\pi \text{ sr})}$$

on earth or

$$\frac{-1.1 \text{ particles}}{10^5 \text{ km}^2\ 10^9 \text{ yr } (2\pi \text{ sr})}$$

for the moon.

When the latter value is plotted on Fig. 9, it agrees very nicely with the data from the terrestrial meteoritic craters and also with Hawkins' iron curve. There are several ways of calculating the flux of Apollo-type asteroids. As determined by Hawkins (1963), the Apollo point lies well below his iron curve, and, in fact, below his stone curve and a good order of magnitude lower than the point calculated above. Hawkins also attributed the discrepancy to the fact that the observational count of asteroids is seriously incomplete.

It is noted that, regardless of whose accretion equation is used, the smaller particles now falling on earth, when converted into lunar crater counts, are far too abundant to agree with linear extrapolations of the observed lunar crater counts for either terrae or maria.

The data on frequencies of the falls of meteorites seem to be rather well pinned down, but the equivalent masses of these objects before they struck the atmosphere are less well known. Unless ablation of these bodies is far more severe than now believed, the moon—even in the region of the maria—must be thoroughly speckled with small craters. Hopefully, television pictures from Ranger lunar probes will settle this question.

Perhaps we can reverse this process and use the slope of the cumulative lunar-crater-count line for craters on the maria and the absolute values estimated from the terrestrial meteoritic craters and the Apollo group of asteroids to yield the mass distribution of

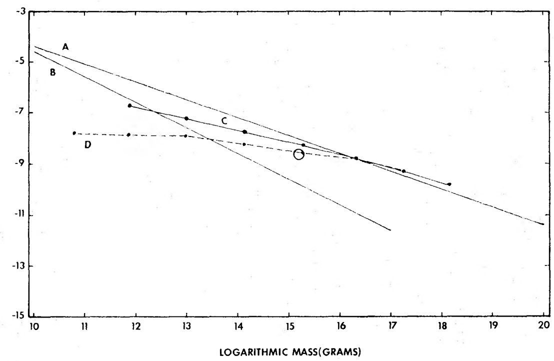

FIG. 10. Logarithmic cumulative accretion rate for earth in particles/earth day in large mass region. A—Hawkins (1963) irons, B—Hawkins (1963) stones, C—Maria crater counts converted to equivalent particle masses adjusted to agree in frequency with terrestrial meteoritic craters and Apollo asteroids, D—Assumed terrestrial meteoritic crater counts converted to equivalent particle masses, ○—Apollo asteroids.

those objects which can strike the moon at present and yield craters larger than perhaps one mile in diameter. Figure 10 and Table XVIII show this result. Curve C differs significantly from Hawkins' iron curve only in the small mass end. It is not rectilinear on a log-log scale.

If this curve from the maria crater counts is correct, it means that the moon has collected about 12 times more craters of each size on the maria since they were formed than the curve would allow per billion years at the present rate. This is consistent with an age for the maria of 2 or 3 billion years, because crater counts on the terrae show that the frequency of collisions with the moon was far greater in the early days than since the maria developed.

Conversely, if the curve is low by a factor of 12, then the maria could be as young as a billion years, provided that the infall rate were constant over this period. If the rate were declining, then the maria could be less than a billion years old. However, if the curve is actually too low by a factor such as 12, then we run into serious problems with the number of meteoritic craters or possible meteoritic craters larger than 8 miles in diameter in 5.6×10^6 km^2 in the best-studied region on earth, central United States and the Canadian

TABLE XVIII. Conversion of lunar maria crater counts to particles/earth day.

Diameter (miles)	N_c craters / 10^5 km^2	Log particle mass (g)	Log $N_c-8.633$ (particles/earth day)
1	80	11.86	−6.730
2	24.5	12.97	−7.244
4	7.503	14.12	−7.758
8	2.298	15.28	−8.272
16	.7037	16.31	−8.786
32	.2155	17.23	−9.310
64	.0660	18.14	−9.813

shield (Baldwin 1963; Beals, Innes, and Rottenberg 1963). An increase by a factor of 12 would call for 60 large terrestrial meteoritic craters to have been formed in this area in the last half-billion years. Such a large number of large craters simply does not exist. Beals and his Canadian colleagues and the numerous United States geologists would have located many more if the true frequency were as high as suggested.

Actually, the listing of terrestrial meteoritic craters used here may include some objects that are not impact structures. In this case, the accretion curve should be lowered by a factor of perhaps 2. This would bring it into slightly better agreement with the point for the Apollo group of asteroids, and it would still be reasonably consistent with Hawkins' iron curve.

Is there any way out of the dilemma that the crater counts on the maria show too few small craters to agree with the observed distribution of equivalent masses near the earth? So far, there is only one clue. Crater counts on the maria to date have been made on photographic plates whose resolution is such that the smallest craters are difficult to see and count. However, on a few of Dinsmore Alter's photographs of the Ptolemaeus region, the small craters do appear better defined.

In Tables VIII and X and as plotted on Fig. 5, the crater counts in lava-filled Ptolemaeus and nearby Flammarion show a considerable excess of small craters. This was there attributed to possible craters of internal origin. An alternate solution would be to consider such an excess of small craters as normal. In this view, all maria should show them if the photographs were of sufficient quality. Counts made on the beautiful Lick Observatory 120-inch Plates L35 in Archimedes and L32 in west central Mare Serenitatis do seem to support the idea that the $\frac{1}{2}$-to-2-mile-wide craters are more numerous than has been suspected and may even approach the Ptolemaeus abundances. To demonstrate this beyond doubt will require still better photographs, because many of the prominent white spots have been considered to be small ray craters larger than $\frac{1}{2}$ mile in diameter, and they might have been smaller than this limit. On Fig. 11, the Ptolemaeus and Flammarion counts replace the small-crater end of the maria crater counts. The resulting curve fairly well parallels the Hawkins iron curve. The discrepancy is reduced but not completely eliminated, and there may still be a need to call one some endemic craters to complete the total. On Fig. 12, the same crater counts, reduced in absolute number of craters by a factor of 6, are converted into particle mass-vs-log cumulative number of particles (see Table XIX) and plotted against the lines derived by Hawkins for the frequencies of particles near the earth. The factor of 6 is used here, because we wish to consider impacts on the earth instead of the moon.

At both ends, the new points agree fairly well with Hawkins' iron equation, but in the middle region, the 2- to 4-mile-wide craters in Ptolemaeus and Flammarion

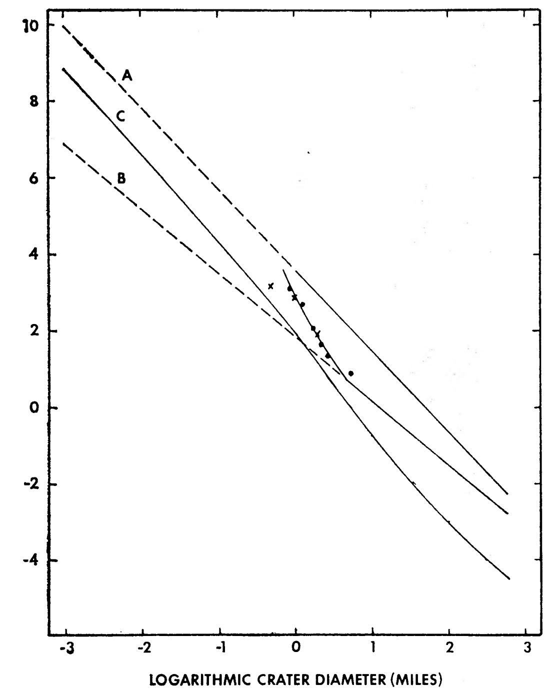

FIG. 11. Logarithmic cumulative lunar crater counts (10^5 km^2). A—Terrae craters, B—Maria craters, C—Conversion of Hawkins' (1963) iron equation to equivalent crater count curve per 10^9 yr, ●—Crater counts in Ptolemaeus (Palm and Strom), ×—Crater counts in Flammarion (author).

are too few to give a good fit. Actually, from these data, the Hawkins iron equation (15) gives about as good a fit to the reduction from lunar crater counts on the maria and in Ptolemaeus and Flammarion as we should expect at this level of knowledge. However, there is an alternate solution which will agree slightly better with the terrestrial-meteoritic-crater counts, the Apollo-asteroid point, and the particle-accretion frequency at

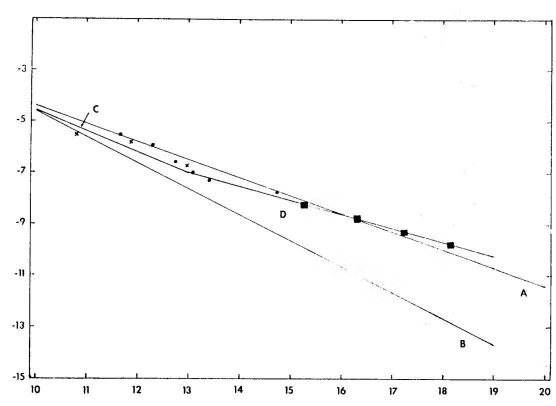

FIG. 12. Logarithmic cumulative accretion rate for earth in particles/earth day in large mass region, A—Hawkins (1963) irons, B—Hawkins (1963) stones, C—Baldwin Eq. (21), D—Baldwin Eq. (22), ●—Reduced crater counts in Ptolemaeus (Palm and Strom), ×—Reduced crater counts in Flammarion (author), ■—Reduced crater counts on maria.

TABLE XIX. Conversion of crater counts in Ptolemaeus and Flammarion to particles/earth day.

Diameter (miles)	N_c craters / 10^5 km^2	Log particle mass (g)	$\log N_c - 8.633$ (particles/earth day)
Ptolemaeus[a]			
0.85	1199	11.66	−5.554
1.27	472	12.30	−5.939
1.70	108	12.74	−6.600
2.12	42	13.08	−7.010
2.55	21	13.40	−7.311
5.53	7	14.74	−7.788
Flammarion[b]			
½	1280	10.80	−5.526
1	640	11.86	−5.827
2	80	12.97	−6.730

[a] Counts by Palm and Strom.
[b] Counts by the author.

lower masses. If we take an equation differing only slightly from that derived earlier from Millard's data (1963) as corrected to outside the earth's atmosphere

$$\log N_{(m)} = 3.53 - 0.81 \log m \quad (21)$$

we can extend this equation region of validity to 10^{13} g particle mass. Thereafter, toward the larger-mass region, the equation

$$\log N_{(m)} = 0.02 - 0.54 \log m \quad (22)$$

would be fairly consistent with all data, including the maria crater counts. These two equations are plotted on Fig. 12. They give a reasonable approximation to present-day accretion rates of particles on earth in the mass range of 10^4 to 10^{19} g with a rather appreciable change in accretion rate at about 10^{13} g. They are consistent with the best estimates of falls of meteorites in the small end and with the terrestrial meteoritic craters, the Apollo asteroids, and the slope of the equation for lunar crater counts on the maria at the large end.

It would not be wise to predict the frequency of small lunar crater pits from the data in this paper. Our understanding of the relationship between the brightness of a meteor and the mass of the object which produced it has been changed repeatedly in the last few years. Usually the mass is reduced for a given absolute magnitude. However, we may conclude that, unless future research shows that the mass of a particle for a given absolute magnitude must be reduced by more than a factor of 100, the moon is covered by many times more small craters than straight-line extrapolations of crater counts on maria or terrae will permit.

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