Sci. Rep. Kanazawa Univ.
Vol.47, No.1,2, p.49-58, 2003

Rayed craters on the far side of the Moon

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Abstract : A fresh crater on the Moon is associated with bright rays, which are made of fresh ejecta from the main and secondary craters. Rays of a lunar crater generally become indistinguishable from the background materials with the age, and the lifetime of a ray is supposed to be about 0.8 Gyr. Using Clementine 750-nm mosaic images, we identify rayed craters mainly on the far side of the Moon. A total of 235 rayed craters which are larger than 5 km in diameter are identified in an area of about 1.55 x 10^7 km^2. The size-frequency distribution for the rayed craters indicates a lack of small rayed craters, implying that the preservation of ray depends on the crater size.

1. Introduction

There are many craters which have bright rays on the Moon. Rays of craters are made of fresh ejecta from the main and secondary craters [e.g., *Shoemaker*, 1966 ; *Schmitt et al*., 1967 ; *Trask and Rowan*, 1967]. They are gradually obliterated with the exposure time by soil maturation and impact gardening (i.e., a turnover of the ejecta layer). Lunar rays generally become indistinguishable from the background materials around the age of the Eratosthenian/Copernican boundary. The age of the Copernicus crater, whose ray is almost mature [*Pieters et al*., 1985 ; *McEwen et al*., 1993], is estimated as about 0.8 b.y. from Apollo 12 samples [*Silver*, 1971 ; *Eberhardt et al*., 1973 ; *Alexander et al*., 1977]. Therefore, the lifetime of a typical lunar rayed crater must be approximately 0.8 b.y. [*McEwen et al*., 1997]. It is expected that rayed craters provide important information on recent cratering on the Moon.

The main purpose of this study is to identify rayed craters on the Moon and make a complete catalogue on them. We also attempt to investigate the dependency of the ray on the crater size from the size-frequency distribution for the rayed craters.

2. Identification of rayed crater

In order to identify rayed craters on the lunar surface, we inspect Clementine 750-nm basemap mosaic images compiled by United States Geological Survey. We can accurately determine the rayed crater distribution with the uniform low-phase-angle images [*Nozette et al*., 1994, *McEwen et al*., 1997]. The crater identification is performed in a highland region spanning from 70° E to 290° E. This longitude range covers the far side of the Moon and rims of the near side (Figure 1).

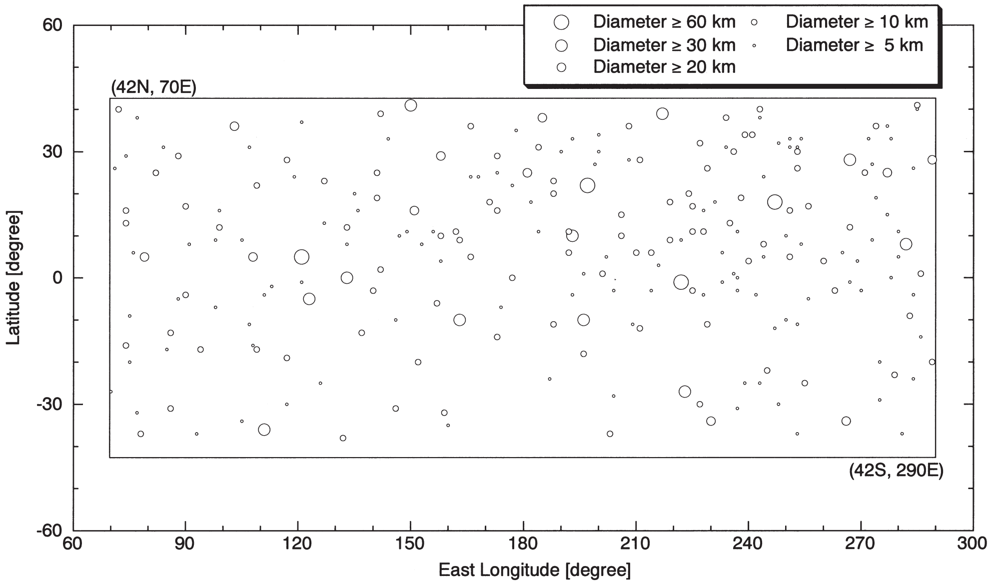

Figure 1. Location of rayed craters. The counting area is enclosed by a box.

There is an observational bias in the identification of rayed craters with respect to the latitude [*McEwen et al*., 1997 ; *Grier et al*., 1998]. It is generally difficult to identify rayed craters in high latitude regions. Since images in high latitude regions have high phase angles, they represent illuminated topography rather than the albedo difference. Therefore, the regions poleward of 42° latitude are ignored from the identification.

The total study area is 15.52 x 10^6 km^2. The diameters of the identified rayed craters are calculated by multiplying a crater diameter in a unit of image pixel and the pixel resolution, 0.1 km/pixel. A total of 235 rayed craters larger than 5 km in diameter are identified in the studied area. The locations and diameters of the rayed craters are listed in Table 1.

We briefly examine the extent to which our identification of rayed craters is complete. To our knowledge, there is no comprehensive catalogue of rayed craters on the Moon. *McEwen et al*. [1997] have identified 96 rayed craters larger than 10 km in diameter within a latitude zone from 60° N to 60° S on the far side. The names or the location data of 28 craters $\geq$20 km are given in their paper. 27 craters of their 28 craters are located in our study area. In this study, 24 craters among the 27 craters are identified as rayed craters ; the other three craters Joule T (37 km), Coriolis Y (31 km), and Dufay B (20 km), whose rays are described to be uncertain in *McEwen et al*. [1997], are regarded as non-rayed craters. Therefore, all the rayed craters larger than 20 km in the study area must be completely identified.

The location of the rest smaller craters are not reported in *McEwen et al*. [1997] ; they give the numbers of craters as a function of the diameter for a range from 10 to 19 km. Since we cannot compare the lists of the rayed craters in this diameter range, we examine

Table 1. Lunar rayed crates larger than 5 km in diameter.

Crater Name	Latitude [deg.]	Longitude [deg.]	Diameter [km]	Crater Name	Latitude [deg.]	Longitude [deg.]	Diameter [km]	Crater Name	Latitude [deg.]	Longitude [deg.]	Diameter [km]
Vavilov	-1	222	99	-	-22	245	17	-	29	173	12
King	5	121	77	-	-25	255	17	-	36	208	12
Jackson	22	197	71	-	-3	263	17	-	-30	227	12
Ohm	18	247	64	-	16	74	17	-	-23	279	12
Crookes	-10	196	49	-	5	166	16	-	25	82	12
Olbers A	8	282	43	-	-3	225	16	-	-4	90	12
Das	-27	223	39	-	-20	289	16	-	-17	94	12
Plante	-10	163	38	-	29	88	16	-	12	99	12
Milne N	-36	111	37	-	28	117	15	-	-17	109	11
Green M	0	133	37	-	31	184	15	-	23	127	11
Laue G	28	267	36	-	6	192	15	-	12	133	11
Zhukovsky Z	10	193	34	-	17	225	15	-	0	177	11
Necho	-5	123	31	-	11	225	15	-	9	219	11
Kulte W	39	217	31	-	30	253	15	-	32	227	11
p.o. Van Neuman F	41	150	30	-	41	285	15	-	-11	229	11
Steno Q	29	158	29	-	40	72	15	-	13	235	11
Giordano Bruno	36	103	26	-	2	142	14	-	19	238	11
-	28	289	26	-	-31	146	14	-	40	243	11
Al-Khwarizmi K	5	108	24	-	-20	152	14	-	36	274	11
Moore F	38	185	24	-	11	192	14	Goddard A	17	90	11
-	5	79	23	-	-37	203	14	-	-38	132	10
Larmor Q	25	181	23	-	15	206	14	-	-13	137	10
Focas	-34	266	22	-	38	234	14	-	-3	140	10
-	25	277	21	-	39	142	13	-	19	141	10
-	16	151	20	-	-32	159	13	-	10	158	10
-	-34	230	20	-	9	163	13	-	18	171	10
-	25	141	19	-	36	166	13	-	20	188	10
-	11	228	19	-	16	173	13	-	-11	188	10
-	26	229	19	-	-14	173	13	-	10	206	10
-	26	253	19	-	23	188	13	-	6	210	10
-	12	267	19	-	-18	196	13	-	-12	211	10
-	-19	117	18	-	6	214	13	-	30	236	10
-	1	201	18	-	20	224	13	-	34	239	10
-	18	219	18	-	4	240	13	-	34	241	10
-	8	244	18	-	16	251	13	-	17	256	10
-	5	251	18	-	25	271	13	-	4	260	10
-	1	286	18	-	13	74	13	-	-9	283	10
-	-37	78	18	-	-13	86	13	-	-16	74	10
-	-6	157	17	-	22	109	12	-	-31	86	10
-	28	211	17	-	11	162	12	-	26	71	9

Table 1. (continue)

Crater Name	Latitude [deg.]	Longitude [deg.]	Diameter [km]	Crater Name	Latitude [deg.]	Longitude [deg.]	Diameter [km]	Crater Name	Latitude [deg.]	Longitude [deg.]	Diameter [km]
-	-32	77	9	-	20	135	7	-	-3	270	6
-	-7	98	9	-	-10	146	7	-	27	273	6
-	-4	111	9	-	4	158	7	-	-29	275	6
-	-1	121	9	-	24	168	7	-	11	280	6
-	16	136	9	-	22	177	7	-	5	280	6
-	-7	174	9	-	30	190	7	-	-37	281	6
-	5	202	9	-	-4	193	7	-	40	285	6
-	3	216	9	-	1	196	7	-	-9	75	5
-	-12	247	9	-	27	199	7	-	6	76	5
-	32	248	9	-	30	200	7	-	-17	85	5
-	-1	267	9	-	6	233	7	-	-37	93	5
-	4	269	9	-	1	236	7	-	9	105	5
-	-14	286	9	-	11	237	7	-	31	107	5
-	29	74	8	-	5	244	7	-	-2	113	5
-	31	84	8	-	33	254	7	-	24	119	5
-	16	99	8	-	15	277	7	-	-25	126	5
-	-16	108	8	-	-27	70	6	-	33	144	5
-	13	127	8	-	-5	88	6	-	11	149	5
-	8	133	8	-	9	98	6	-	8	153	5
-	11	156	8	-	-34	105	6	-	-35	160	5
-	35	178	8	-	10	147	6	-	-11	209	5
-	18	182	8	-	24	166	6	-	16	228	5
-	28	208	8	-	25	173	6	-	18	231	5
-	9	222	8	-	11	184	6	-	-4	242	5
-	-4	228	8	-	-24	187	6	-	-30	248	5
-	-1	233	8	-	33	193	6	-	33	251	5
-	0	237	8	-	34	200	6	-	31	251	5
-	-3	237	8	-	-3	204	6	-	-11	253	5
-	-25	239	8	-	-28	204	6	-	6	265	5
-	31	253	8	-	-3	214	6	-	33	272	5
-	-37	253	8	-	31	234	6	-	19	274	5
-	9	273	8	-	-31	237	6	-	-20	275	5
-	36	277	8	-	38	243	6	-	33	278	5
-	-20	75	7	-	-25	243	6	-	0	278	5
-	38	77	7	-	24	244	6	-	26	284	5
-	8	91	7	-	10	250	6	-	-4	284	5
-	-11	107	7	-	-10	250	6	-	-24	284	5
-	-30	117	7	-	8	254	6				
-	37	121	7	-	-5	256	6				

the completeness by comparing the estimated crater densities. There are some differences between the study areas of this study and *McEwen et al*. [1997]. Our study area covers limbs of the near side (70-90° W, 70-90° E), while *McEwen et al*. [1997] identify craters in a wider latitude zone (60° N-60° S) than us (42° N-42° S). *McEwen et al*. [1997] report 96 rayed craters larger than 10 km in diameter in an area of 13.09 x 10^6 km^2. We identify 119 rayed craters ≥10 km in an area of 15.52 x 10^6 km^2. The crater densities obtained in the two studies are nearly identical within a difference smaller than 5 % (7.33 x 10^{-6} km^{-2} and 7.67 x 10^{-6} km^{-2}, respectively) to each other. A comparison of the cumulative size-frequency distributions for the rayed craters identified in the two studies is shown in Figure 2. The general features of the size-frequency distributions for craters larger than 10 km well agree with each other. Therefore, we conclude that our identification for rayed crater is sufficiently performed for craters ≥10 km.

There is a problem that the lifetime of rays is influenced by the geology of the background terrain [*e.g., Pieters et al*., 1985 ; *Grier et al*., 1998 ; 2000 ; *Hawke et al*., 2000]. Large impacts in maria excavate and eject highland materials which are overlain by the ba-

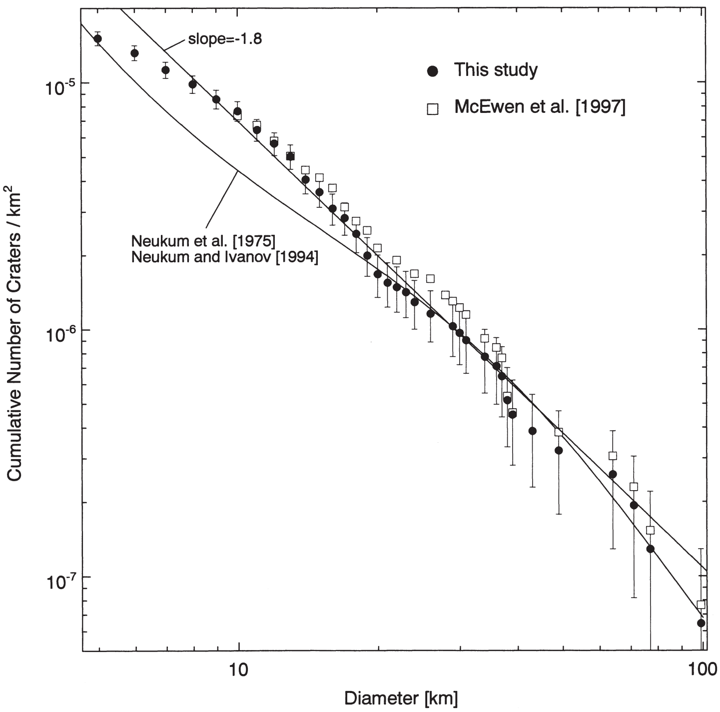

Figure 2. Comparison of cumulative size-density distributions for the rayed craters. Size distributions for the rayed craters identified by this study and *McEwen et al*. [1997] are shown. Error bars are estimated by the square roots of crater numbers. The standard curves for crater density [*Neukum et al*., 1975 ; *Neukum and Ivanov*, 1994] and a straight line with a slope of-1.8 are fitted at 30 km in diameter. The straight line is equal to the expected crater density of the Copernican craters.

saltic layer. These craters have bright rays due to not only immature soils but also the compositional difference between the rays (the highland material) and the surface (the basalt) [*McEwen et al*., 1997]. The rays due to the compositional difference are preserved for a longer period than those on the same rock type. It is supposed that many rayed craters which were formed before the Eratosthenian/Copernican boundary remain in the lunar maria. In reality, counting of superposed small craters [*Neukum and König*, 1976; *McEwen et al*., 1993] shows that several nearside rayed craters are older than 1 Ga. However, almost all the catalogued rayed craters, excepting ones in far side maria, are located on the highland area and are free from the compositional problem.

3. Size-frequency distribution for the rayed craters

Many recent studies [e.g., *Grieve*, 1984; *Baldwin*, 1985; *McEwen et al*., 1997; *Culler et al*., 2000] of terrestrial and lunar cratering rate suggest that the flux of impactors in the Earth-Moon system may have increased in the Phanerozoic. The recent high rate is probably due to bodies replenished in the inner Solar system from the Oort cloud. There is a possibility that the resupply of impactors from Oort cloud has been periodically caused [*Kumazawa and Mizutani*, 1981; *Furumoto and Kumazawa*, 1990; *Morota et al*., 1998]. If the hypothesis is real, it is likely that there is a difference between the size-frequency distributions for recent craters and old craters.

A comparison of the cumulative size-frequency distribution for the rayed craters identified in this study with the standard size-frequency curve for lunar craters [*Neukum et al*., 1975; *Neukum and Ivanov*, 1994] is shown in Figure 2. The standard curve is adjusted at a crater size of 30 km. The size-frequency distribution for rayed craters larger than 30 km in diameter is consistent with the standard curve. However, the size-frequency distribution from 10 to 20 km has a steeper inclination than the standard curve. The difference of the size distributions in this range of the crater size would suggest a possible change in the flux of impactors into the Earth-Moon system.

The observed crater density in a diameter range of 5-10 km is below the general trend of the larger craters on the size-frequency distribution for the rayed craters (Figure 2). It is unlikely that any rayed craters in this range are overlooked owing to image resolution limits. *McEwen et al*. [1997] suggest that the resolution should be at least 20 times finer than the crater diameter in identification of rayed crater. Since original Clementine images have resolutions of 0.1-0.2 km/pixel, the resolution of the Clementine images is fine enough to identify rays of craters larger than 5 km.

A possible reason for the deficiency of rayed craters < 10 km is that the persistence of rays depends on the crater size. It is known that rays of smaller craters darken more rapidly than those of larger craters [e.g., *Grier et al*., 1998]. For example, *Lucey et al*. [2000] report that the ray of the Tycho crater (85 km) is less mature than those of South Ray Crater (0.8 km) and North Ray Crater (1.0 km) which are younger than the Tycho crater. Rayed craters < 10 km may be obliterated faster than large craters.

We attempt to estimate the lifetime of ray of small craters from the size-frequency distribution. To avoid a terminological confusion in the following part, we call here young craters Copernican craters regardless of rays. The size-frequency distribution for the rayed craters ≥30 km has a slope of about -1.8. It is expected that the distribution for Copernican craters smaller than 30 km also has the same slope. The Copernican crater density obtained by fitting the line with the slope of -1.8 is indicated in Figure 2. The lifetime of ray as a function of the crater size can be calculated from the ratio of the observed crater density of the rayed craters and the expected density of Copernican craters. Figure 3 shows the lifetime of rays as a function of the crater diameter. The lifetime is normalized to that of the rayed crater with the diameter of 30 km. For example, since the lifetime of ray of the craters of 30 km is 0.8 Gyr., the lifetime of craters of 5 km in diameter is calculated to be about 0.5 Gyr. The straight line fitted to the data ≤10 km in diameter is also shown in Figure 3. The relation between the crater diameter and the lifetime of ray can be described by a simple power function with an exponent of 0.80.

There is a power law with an exponent of 0.74 between crater radius and ejecta thickness at the rim [*McGetchin et al*., 1973]. This corresponds with the power law of 0.80 between the diameter of large lunar crater and the lifetime of ray. It means that the lifetime of ray of a crater smaller than 10 km is roughly proportional to the ejecta thickness.

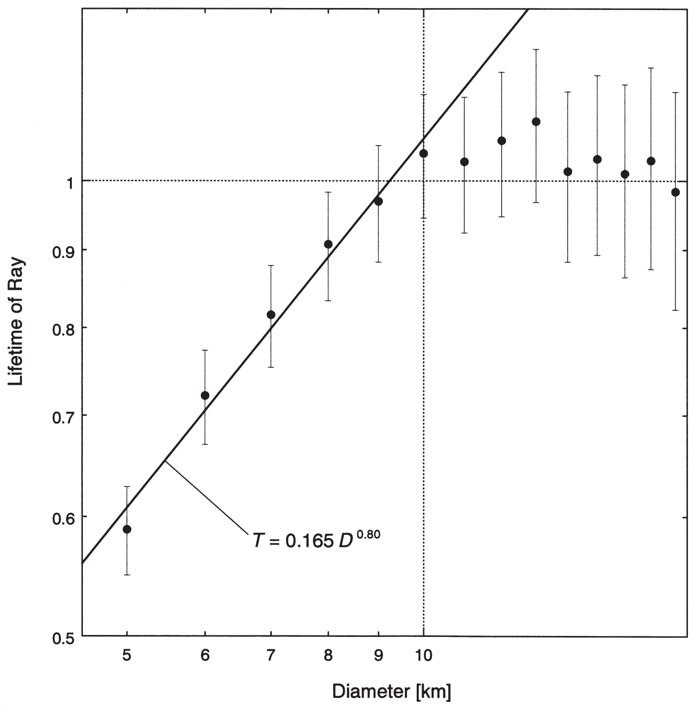

Figure 3. Lifetime of ray normalized by lifetime of ray of craters ≥30 km in diameter. A straight line is fitted to the distribution of craters ≤10 km by the least square method.

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